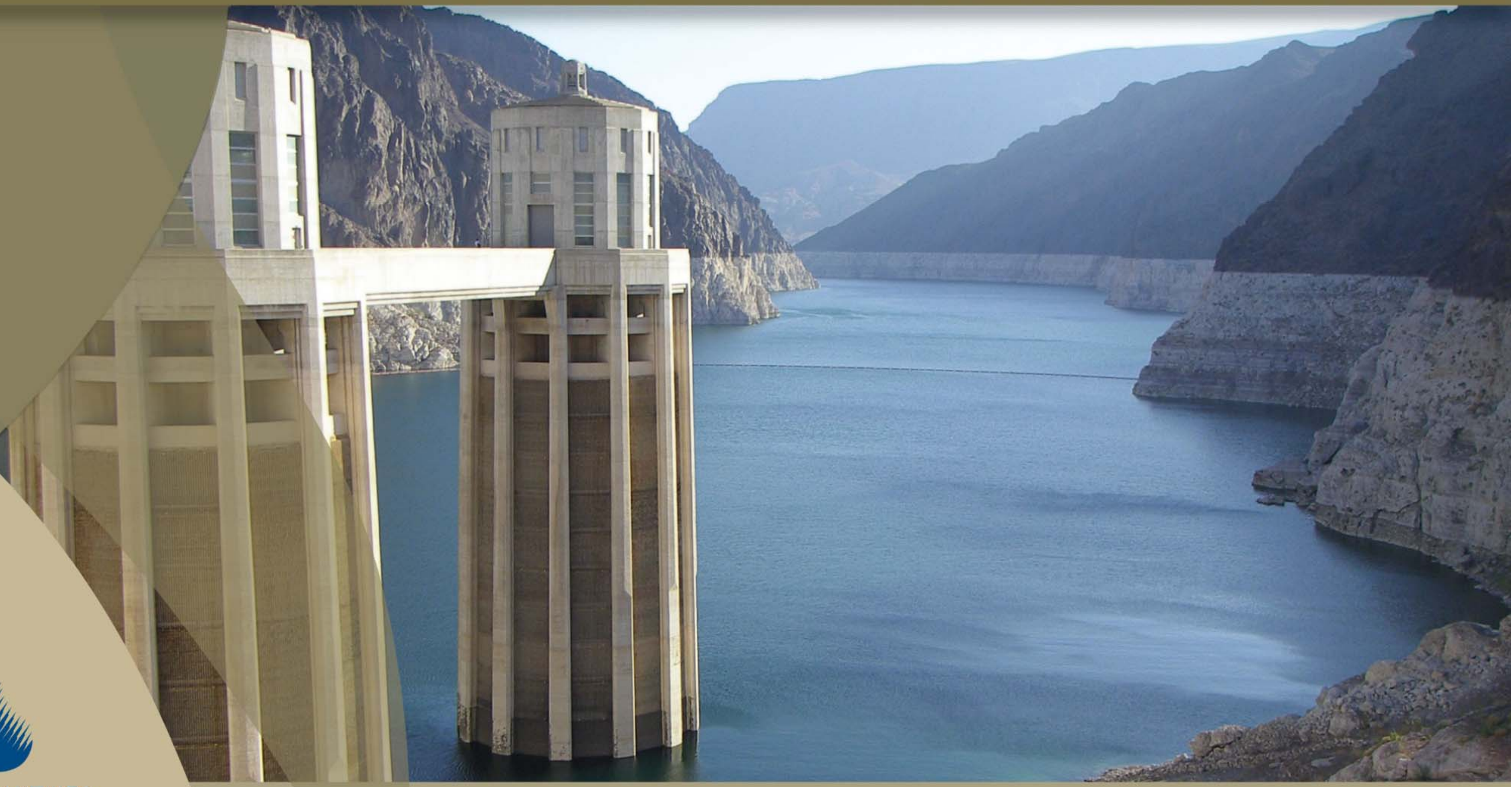
Spring, Cave, Dry Lake and Delamar Valleys



SOUTHERN NEVADA
WATER AUTHORITY

Presentation for
Bredehoeft Cross

ground water

Guest Editorial/

It Is the Discharge

by John Bredehoeft

We all know the mantra *Keep It Simple*—the principle KISS. I have been thinking of another mantra for ground water—*It Is the Discharge.* Let me explain: In a recent conversation with one of my distinguished colleagues, he bemoaned our lack of understanding of ground water recharge. I keep thinking about that conversation. In a broad sense as hydrogeologists, we are hoping to understand how aquifer systems function, more particularly how much water is flowing through a particular system—the focus on recharge is simply one facet of the larger task. In studying the system, there are at least three aspects that we can focus on—(1) the recharge; (2) the aquifer itself as a transmission mechanism; and (3) the discharge from the aquifer.

One of the first principles of hydrogeology is that the recharge is balanced by the discharge before the system is perturbed. One tack commonly taken is to focus on the discharge and assume that recharge equals discharge. Of course, when we model a system in a virgin state, the mathematics demand conservation of mass, and the recharge, flow through the aquifer, and the discharge are balanced (or we do not have a solution to the problem). Often it is the capacity of the aquifer to transmit water that determines both the recharge and the discharge—the aquifer can accommodate only so much flow.

Generally, the recharge is the most difficult component of the ground water system to quantify, which brings me back to my colleague's comment—Shouldn't we be spending additional research effort to understand the recharge? My response is that it is more fruitful to examine the discharge. However, rarely do I hear hydrogeologists say that they are studying ground water discharge, especially in the academic community. Yet, the discharge is generally there to be observed—it occurs as springs, as base flow to streams, and as water for phreatophytes in the desert environment. There is a reason why hydrogeologists in Nevada still use the Maxey/Eakin method to estimate recharge, a method published in 1949—no one has come up with an improved procedure to estimate recharge even given 50+ years of further investigation. On the other hand, the methods of measuring phreatophyte discharge are greatly improved.

The Hydrodynamics Group, 127 Toyon Lane, Sausalito, CA 94965; (415) 332-0666; jdbrede@aol.com; and member of Board of Directors AGWSE.

doi: 10.1111/j.1745-6584.2007.00305.x

Furthermore, human activities that impact a ground water system ultimately impact the discharge. It is usually the ground water discharge that is captured during ground water development. The USGS (1972) in *Definitions of Selected Ground Water Terms* 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.

Many aquifers can be analyzed mathematically as if they are linear systems; this includes all confined aquifers and even water table aquifers where the change in head, caused by a given stress, does not change the saturated thickness greatly. In this case, neither the recharge nor the discharge is of concern; rather, the changes in these quantities, caused by the stress—the capture, are of interest. In the linear mathematical system, if one knows (1) the geometry of the aquifer system, (2) its hydrologic properties (permeability and storage), and (3) the boundary conditions, one can determine the impact of a given stress on the system. Often it is the discharge that we end up capturing.

Even if the recharge is not of pragmatic concern, it still may be of interest—we would like to fully understand the ground water system. Other factors such as how contaminants are transported through the system sometimes depend upon the recharge.

I have no doubt that studying recharge will be high on the list of research topics for the future. I am also confident that the recharge is better understood through the discharge where there is an integrated and observable hydrologic signal, and that discharge is of much more pragmatic concern than recharge. Harold Thomas, the distinguished professor of Water Resources at Harvard, was working on the problem by studying stream hydrographs; unfortunately, he died before he could publish his ideas. I tried unsuccessfully to point out the importance of the discharge in commenting on a proposed National Academy of Sciences/National Research Council research agenda—my remarks had no impact. Still, my argument is—*It Is the Discharge*.

Editor's Note: Opinions expressed in the editorial column are those of the author(s) and do not necessarily reflect those of the National Ground Water Association or the staff of the journal.

GBWN_Exh_243

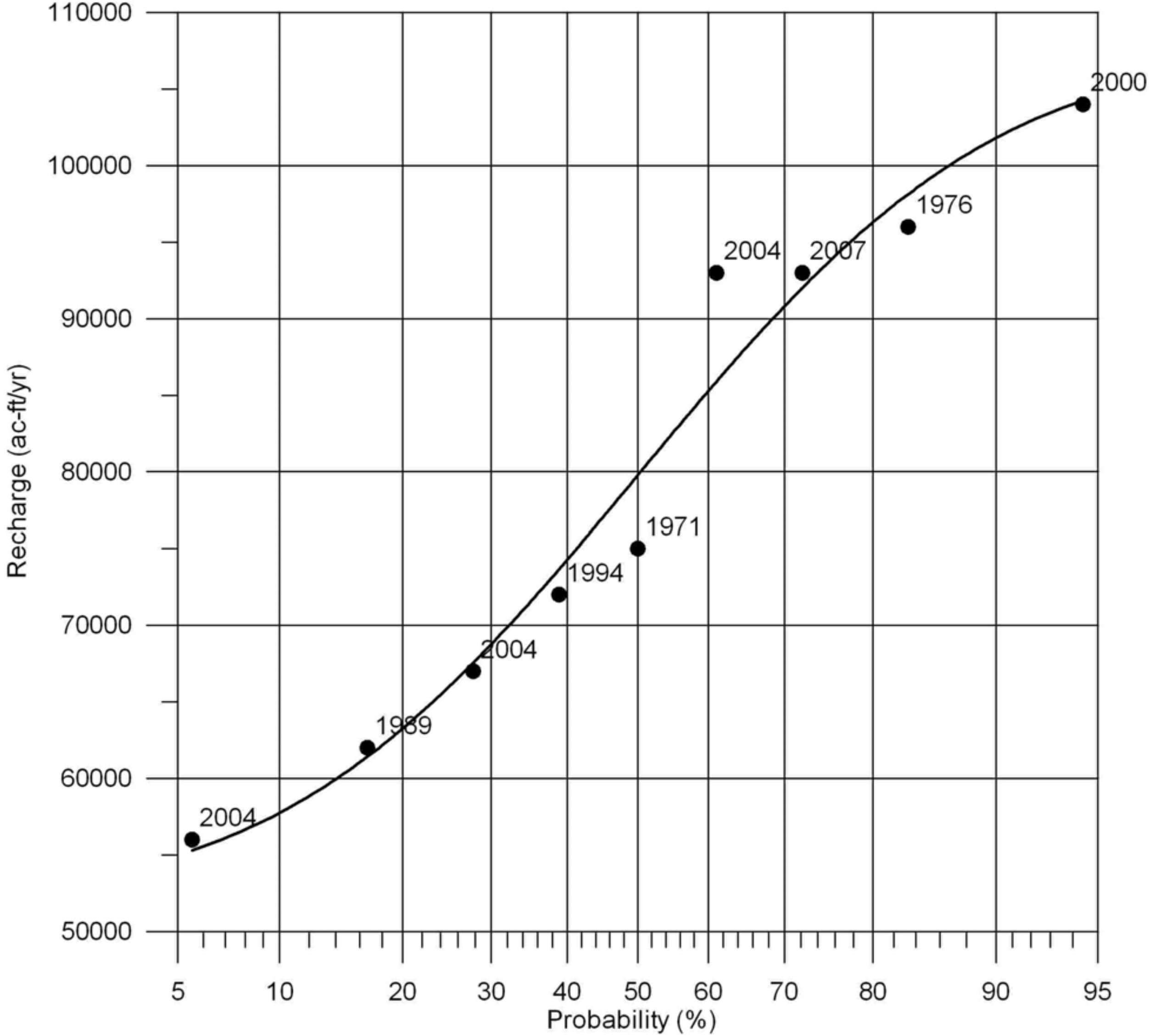


Figure 1. Probability distribution for nine estimates of recharge for Spring Valley. The line is a linear fit through the data.

adequate, suggested that Tom's water budget probably was not adequate. And so I would be willing to say, you know, probably Tom underestimated, and I think Tom Myers says, well, that Tom Eakin underestimated the dis -- under- estimated the recharge in Dry Lake and Delamar Valleys, and therefore underestimated the outflow.

Okay. Now -- excuse me. Now -- so -- so the one water budget that Thomas tended to favor was this Southern Nevada Water Authority 2007 Water Budget. He -- his analysis -- he assessed three water budgets. One was Tom Eakins' earlier water budget, then a combination of Southern Nevada, BARCASS, then this 2007. It looked like the 2007 could be a little better.

And if you did the same sort of analysis, you'd say to yourself, well, how much was going to Cave Valley? And then you looked at the pumping. Again, you'd take about 80 percent of the pumping that would have been outflow to Cave Valley, would have been pumped, and it would have been about 80 percent of the outflow that would have been gone to Cave Valley.

And then of the outflow from Delamar and Dry Lake, again, which is now 24,100 -- they're talking about taking 23,000 -- you take 95 percent of it. So you're talking almost -- you're talk taking a lot, you know, more than 80 percent of what the outflow from these valleys

ground water

Issue Paper/

Ground Water Development—The Time to Full Capture Problem

by J. Bredehoeft[1] and T. Durbin[2]

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

[1]Corresponding author: Hydrodynamics Group, 127 Toyon Lane, Sausalito, CA 94965; (415) 332-0666; fax (530) 364-8541; jdbrede@aol.com

[2]Timothy J. Durbin Inc., Sacramento, CA 95608.

Received May 2008, accepted November 2008.

doi: 10.1111/j.1745-6584.2008.00538.x

GBWN_Exh_012

ground water

Issue Paper/

From Models to Performance Assessment: The Conceptualization Problem

by John D. Bredehoeft[1]

Abstract

Today, models are ubiquitous tools for ground water analyses. The intent of this paper is to explore philosophically the role of the conceptual model in analysis. Selection of the appropriate conceptual model is an a priori decision by the analyst. Calibration is an integral part of the modeling process. Unfortunately a wrong or incomplete conceptual model can often be adequately calibrated; good calibration of a model does not ensure a correct conceptual model. Petroleum engineers have another term for calibration; they refer to it as *history matching*. A caveat to the idea of history matching is that we can make a prediction with some confidence equal to the period of the history match. In other words, if we have matched a 10-year history, we can predict for 10 years with reasonable confidence; beyond 10 years the confidence in the prediction diminishes rapidly. The same rule of thumb applies to ground water model analyses. Nuclear waste disposal poses a difficult problem because the time horizon, 1000 years or longer, is well beyond the possibility of the history match (or period of calibration) in the traditional analysis. Nonetheless, numerical models appear to be the tool of choice for analyzing the safety of waste facilities. Models have a well-recognized inherent uncertainty. Performance assessment, the technique for assessing the safety of nuclear waste facilities, involves an ensemble of cascading models. Performance assessment with its ensemble of models multiplies the inherent uncertainty of the single model. The closer we can approach the idea of a long history with which to match the models, even models of nuclear waste facilities, the more confidence we will have in the analysis (and the models, including performance assessment). This thesis argues for prolonged periods of observation (perhaps as long as 300 to 1000 years) before a nuclear waste facility is finally closed.

Introduction—Models

Models play a key role in the analysis of many, if not most, ground water problems. They are especially important in predicting the behavior of nuclear waste facilities far into the future. The Waste Isolation Pilot Plant (WIPP, a geologic repository for transuranic wastes in New Mexico) was recently opened and is receiving nuclear weapons waste. Yucca Mountain (the proposed high-level nuclear waste repository in Nevada) is near the licensing stage. Hydrogeological models play a key role in assessing the safety of these facilities.

The purpose of this paper is to discuss philosophically the use of models in making predictions. Many of these ideas have been expressed elsewhere, yet they seem worth restating. In particular, I want to examine the role that the conceptual model plays in analysis. I take a historical perspective in developing these ideas.

In the 19th century, various laws that describe the movement of heat, electricity, and ground water through a continuum were derived. Of special concern to those of us that investigate ground water is Darcy's law. By applying the principle of conservation of mass and incorporating Darcy's law as a constitutive relationship, we can derive a partial differential equation that describes the hydraulic head throughout a porous medium. Once the head is determined, we can apply Darcy's law to derive the ground water flow vectors throughout the system. These principles form the basis for all ground water flow and transport models.

For many ground water problems with simple geometry, simple parameter distributions, and simple boundary conditions analytical solutions to the mathematical problem can be derived. Because there is an analogy between the flow of ground water and the flow of both electricity and heat, we often can find the mathematical solution for the appropriate boundary value problem in the literature on

[1]The Hydrodynamics Group, 127 Toyon Lane, Sausalito, CA 94965; jdbrede@aol.com

Calibration

An integral part of the modeling procedure is calibration. Calibration involves fitting the model output to a set of observations. Hopefully, at some point in the process, the model parameters are adjusted so that an *adequate* fit to the observations is achieved. Originally, calibration was a trial-and-error procedure. In recent years, the process of adjusting the parameters to achieve an adequate fit has been automated.

Numerical measures of the goodness-of-fit between the observations and the model predictions have been devised. The numerical measures provide the appearance that judging the adequacy of fit during calibration is no longer subjective. However, in the end, what constitutes an adequate fit is a subjective decision. Statistical measures of the goodness-of-fit can be calculated, but the question of whether a model is calibrated is a decision left to the analyst.

There are problems in the calibration procedure. As suggested by the previous discussion of pumping test analysis, the calibration commonly does not test our conceptual model. *In other words, a model involving a wrong or incomplete conceptual model can be adequately calibrated.* It is generally conceded that a model, even if it is well calibrated, is nonunique; another parameter set might result in an equally good calibration (Bethke 1992).

Post Audits

Since models have now been around for several decades, it is possible in certain limited instances to evaluate their performance. Predictions were made that can now be compared to what happened to a particular system. Many audits do not really test the adequacy of the model because what took place with the real system was not a scenario that was analyzed initially. Typically, pumping followed a different pattern than anticipated.

There are a limited number of post audits of model predictions; they are not reassuring. Many models did not provide good predictions (Anderson and Woessner 1992; Konikow and Bredehoeft 1992). Many models suffered from a conceptual omission: an important process was overlooked. In other cases, the range of parameters was much larger than was included in the model analysis. Models are known to have provided poor predictions, even models that were thought to have been well calibrated.

Validation

Validation is a term promoted by the nuclear waste community. Different people variously define validation; there is no consensus on what it means. Furthermore, in most cases, the goal of calibration and validation are the same: In both cases, we seek to create the best possible representation of the system. We as a community have formulated restrictive, and rather special, definitions of what it means to validate a code.

Recognizing that the traditional history match was impossible, the nuclear waste community set out to test different codes in situations where shorter histories of performance were available. They called this test of the models *validation*. This is only one of many specialized definitions of validation. This test of the codes was no different than the calibration procedure models normally undergo. If the model of a specified system could be adequately calibrated, the code was deemed validated. In many instances, we can substitute the words *well calibrated* for *validated* without changing significantly the author's meaning.

There are both pragmatic and philosophical grounds to avoid the idea of validation. The idea of validation (or invalidation) is deeply rooted in the philosophy of science. On philosophical grounds, Popper (1968) argued that scientific theory can be invalidated—not validated. Of course, Popper is not the only philosopher of science. Others, notably the pragmatists, of which John Dewey is perhaps the best known, argued that we learn from experience, observations, and mistakes (Menand 2001). The pragmatists argued we never find real truth, but we do get closer to understanding. Kuhn (1970) suggested that scientists try to make existing theory work until finally the evidence indicates that it does not; then they embrace a new theory. None of these philosophers argued that one could validate.

It is unfortunate that we have allowed the term *validation* to become a part of the model lexicon. Oreskes and Belitz (2001) summarize the status of validation:

> "The inherent uncertainties of models have been widely recognized, and it is commonly acknowledged that the term 'validation' is an unfortunate one, because its root—valid—implies a legitimacy that we are not justified in asserting. . . . But old habits die hard and the term persists. In formal documents of major national and international agencies that sponsor modeling efforts, and in the work of many modelers, 'validation' is still widely used in ways that assert or imply assurance that the model accurately reflects the underlying natural processes, and therefore provides a reliable basis for decision-making. This usage is misleading and should be changed. Models cannot be validated. The reasons why have been outlined in detail elsewhere (Konikow and Bredehoeft 1992; Oreskes et al. 1994)."

Reservoir Engineering: A Pragmatic Approach

The ground water community could take a lesson from petroleum reservoir engineering. The usual practice is to history match the reservoir simulator output to some temporal history of production. This is calibration in the ground water lexicon. Based on the match, a prediction of future performance is made, but one is cautious in extending that prediction much beyond a period equal to the production history. In other words, the rule of thumb is that, if we make a 10-year history match, we might be reasonably confident in predicting the next 10 years of performance; however, beyond 10 years, the confidence in a prediction greatly diminishes.

The reservoir engineering community makes no claims about the validity of the model. They simply imply: (1) we have a model that we think incorporates the appropriate physics and chemistry, including the appropriate parameter set, that matches an observed temporal history of reservoir performance; and (2) we will use that model to predict future reservoir performance. Furthermore, continued monitoring of the system is used to refine and improve the model.

Reservoir simulation is important in the petroleum industry. A small improvement in the fraction of petroleum

Spring Valley 2006 Hearing Ex. 689

A Yes.

Q And you also say that that's an important statement, because, especially today, when anyone can run codes such as MODFLOW. Do you agree with that?

A Yes.

Q You also state that a wrong or incomplete conceptual model can be adequately calibrated, but good calibration does not ensure a correct conceptual model?

A That's right.

Q Okay. And then you go on to give an example of a lesson that could be learned from the petroleum engineers. And they have another name for calibration, and that's called history matching, correct?

A Yes.

Q So history matching means that if you have ten years of history, say, on pumping aquifer properties, one can predict ten years with reasonable confidence in the future, right?

A It's a general rule of thumb in the petroleum industry.

Q Then you go on to say that -- in the same Exhibit 2036, that predictions out 1,000 years or longer are well beyond the possibility of history matching. Do you agree what that?

A That's correct.

The conceptualization model problem—surprise

John Bredehoeft

Abstract The foundation of model analysis is the conceptual model. Surprise is defined as new data that renders the prevailing conceptual model invalid; as defined here it represents a paradigm shift. Limited empirical data indicate that surprises occur in 20–30% of model analyses. These data suggest that groundwater analysts have difficulty selecting the appropriate conceptual model. There is no ready remedy to the conceptual model problem other than (1) to collect as much data as is feasible, using all applicable methods—a complementary data collection methodology can lead to new information that changes the prevailing conceptual model, and (2) for the analyst to remain open to the fact that the conceptual model can change dramatically as more information is collected. In the final analysis, the hydrogeologist makes a subjective decision on the appropriate conceptual model. The conceptualization problem does not render models unusable. The problem introduces an uncertainty that often is not widely recognized. Conceptual model uncertainty is exacerbated in making long-term predictions of system performance.

Résumé C'est le modèle conceptuel qui se trouve à base d'une analyse sur un modèle. On considère comme une surprise lorsque le modèle est invalidé par des données nouvelles; dans les termes définis ici la surprise est équivalente à un change de paradigme. Des données empiriques limitées indiquent que les surprises apparaissent dans 20 à 30% des analyses effectuées sur les modèles. Ces données suggèrent que l'analyse des eaux souterraines présente des difficultés lorsqu'il s'agit de choisir le modèle conceptuel approprié. Il n'existe pas un autre remède au problème du modèle conceptuel que: (1) rassembler autant des données que possible en utilisant toutes les méthodes applicables—la méthode des données complémentaires peut conduire aux nouvelles informations qui vont changer le modèle conceptuel, et (2) l'analyste doit rester ouvert au fait que le modèle conceptuel peut bien changer lorsque des nouvelles informations apparaissent. Dans l'analyse finale le hydrogéologue prend une décision subjective sur le modèle conceptuel approprié. Le problème du le modèle conceptuel ne doit pas rendre le modèle inutilisable. Ce problème introduit une incertitude qui n'est pas toujours reconnue. Les incertitudes du modèle conceptuel deviennent plus importantes dans les cases de prévisions à long terme dans l'analyse de performance.

Resumen La base para hacer un análisis de un modelo es el modelo conceptual. Se define aquí la sorpresa como los datos nuevos que convierten en incoherente al modelo conceptual previamente aceptado; tal como se define aquí esto representa un cambio de paradigma. Los datos empíricos limitados indican que estas sorpresas suceden entre un 20 a un 30% de los análisis de modelos. Esto sugiere que los analistas de modelos de agua subterránea tienen dificultades al seleccionar el modelo conceptual apropiado. No hay otra solución disponible a este problema del modelo conceptual diferente de: (1) Recolectar tanta información como sea posible, mediante la utilización de todos los métodos aplicables, lo cual puede resultar en que esta nueva información ayude a cambiar el modelo conceptual vigente, y (2) Que el analista de modelos se mantenga siempre abierto al hecho de que un modelo conceptual puede cambiar de manera total, en la medida en que se colecte mas información. En el análisis final el hidrogeólogo toma una decisión subjetiva en cuanto al modelo conceptual apropiado. El problema de la conceptualización no produce modelos inútiles. El problema presenta una incertidumbre, la cual a menudo no es tenida en cuenta de manera adecuada. Esta incertidumbre en los modelos conceptuales se aumenta, cuando se hacen predicciones a largo plazo del comportamiento de un sistema dado.

Keywords Numerical modeling · Conceptual models · Groundwater mangement · Data collection and analysis · Mistaken model predictions

Received: 2 April 2004 / Accepted: 13 December 2004
Published online: 25 February 2005

J. Bredehoeft (✉)
The Hydrodynamics Group,
127 Toyon Lane, Sausalito, CA, 94965, USA
e-mail: jdbrede@aol.com
Tel.: +1-415-332-0666
Fax: +1-530-364-8541

DOI 10.1007/s10040-004-0430-5

most unlikely. Zheng and Bennett (1995) in their definition of a conceptual model, quoted above, expressed this view of model use.

In many instances data are lacking on certain parameters, the model provides a means to estimate the numerical value of these parameters. One can then ask questions—are the parameters values reasonable, or do we need a new conceptual model? For example, often one does not have hydraulic conductivity values for confining layers because of the difficulties associated with acquiring such data. The model can be used to estimate confining layer conductivities.

Analyzing more than a single process at a given site provides different information; often this information provides new insights. For example, analyzing both flow and transport at a site provides more information than flow alone. Transport introduces quantitative estimates of porosity and dispersivity that can provide better insights into the actual mechanism of groundwater flow at the site.

Using models for conceptual model synthesis is most appropriate; they provide the analyst with improved professional judgment. In the end, this may be the most important use of models, more import than future predictions.

What if—model predictions in the near future

Models are useful in making predictions on how a groundwater system will behave if one takes certain actions. For example, how will the system respond if we put a new well field at a particular location? Models can be used to analyze management options.

Petroleum engineers have perfected the art of short-term reservoir predictions. They look at the models from a pragmatic perspective. They create the mathematical model from their best understanding of the prevailing theory. They then apply the model to a particular petroleum reservoir. They adjust the parameters to match an observed history of reservoir performance—they call this match a "history match" (rather than model calibration). They then use the history-matched model to make a prediction of reservoir performance. However, they have caveats regarding their predictions. The rule of thumb is not to rely on the predictions much beyond a period equal to the period of history match. In other words, if one matches a 10-year reservoir history the engineer has some confidence in making a 10-year prediction. Beyond the 10-year prediction the engineer questions his confidence in the prediction.

Petroleum reservoir engineers avoid making claims that they have the correct conceptual model. They say simply we did the best we could to create what we think is an appropriate model of the reservoir. We will use this model to make a prediction of performance in which we have confidence, for a period equal to our history match. These rules of thumb could well be applied to groundwater analyses.

Groundwater models are especially useful in assessing the sustainability of a groundwater reservoir. Using the model one can estimate whether the system, given a particular development, will be able to sustain the stress indefinitely into the future, or will there be unwanted impacts. For example, can pumping from a particular aquifer be sustained indefinitely? This author argued that a model analysis is the best tool to answer this question (Bredehoeft 2002).

There are many other examples of management questions for which the model is most useful. For example, will pumping from an aquifer near the seacoast induce seawater intrusion? A corollary question—is there a better location for the pumping that will minimize, or control the intrusion? Another example, how best does one cleanup a contaminated aquifer?

Groundwater systems that are large and involve the water table are slow to respond to stress. Often it takes several hundred years for such systems to reach a new equilibrium state where there is no additional change in groundwater storage. Even so, the author includes these in this class of analysis.

The short-term predictive model is useful for making enlightened management decisions. The list of examples where models were used to address management questions is very extensive.

Long-term management decisions—long-term predictions

Hydrogeologists are now being asked to make long-term predictions of groundwater system performance, especially in association with the site selection of nuclear waste facilities. Groundwater models are being the basis for "Performance Assessment (PA)" in the site evaluation of nuclear waste facilities. Predictions of performance are being made to 1,000 and 10,000 years—sometimes longer. It is in these instances that the conceptual model problem becomes most daunting. There is no history for the system that comes anywhere close to the period that is being predicted—the petroleum engineer's rule of thumb cannot be applied.

Performance Assessment treats the uncertainty in the model parameters by running the model iteratively with parameters sampled from a probable range of possible values. The model predictions are examined statistically. If a large majority of the predictions fall within a range considered safe, then at least one criterion for a safe repository is satisfied. Performance Assessment does not test the adequacy of the conceptual model. The conceptual model may be all-important in making good long-term predictions of performance.

When predictions extend to 1,000 years, or longer, one can expect science itself to change. For example, the current transport theory, with its changing dispersivity with distance, is thought by many to be inadequate. One might expect a different transport theory to emerge in the next 1,000 years. This could change long-term predictions of transport.

Long-term model predictions are subject to the greatest error. One can expect great uncertainty in these predictions. Conceptual model problems play a large role in the uncertainty of these analyses. As suggested above, ana-

DOI 10.1007/s10040-004-0430-5

Spring Valley 2006 Hearing Exh. 690

ground water

Issue Paper/

From Models to Performance Assessment: The Conceptualization Problem

by John D. Bredehoeft[1]

Abstract

Today, models are ubiquitous tools for ground water analyses. The intent of this paper is to explore philosophically the role of the conceptual model in analysis. Selection of the appropriate conceptual model is an a priori decision by the analyst. Calibration is an integral part of the modeling process. Unfortunately a wrong or incomplete conceptual model can often be adequately calibrated; good calibration of a model does not ensure a correct conceptual model. Petroleum engineers have another term for calibration; they refer to it as *history matching*. A caveat to the idea of history matching is that we can make a prediction with some confidence equal to the period of the history match. In other words, if we have matched a 10-year history, we can predict for 10 years with reasonable confidence; beyond 10 years the confidence in the prediction diminishes rapidly. The same rule of thumb applies to ground water model analyses. Nuclear waste disposal poses a difficult problem because the time horizon, 1000 years or longer, is well beyond the possibility of the history match (or period of calibration) in the traditional analysis. Nonetheless, numerical models appear to be the tool of choice for analyzing the safety of waste facilities. Models have a well-recognized inherent uncertainty. Performance assessment, the technique for assessing the safety of nuclear waste facilities, involves an ensemble of cascading models. Performance assessment with its ensemble of models multiplies the inherent uncertainty of the single model. The closer we can approach the idea of a long history with which to match the models, even models of nuclear waste facilities, the more confidence we will have in the analysis (and the models, including performance assessment). This thesis argues for prolonged periods of observation (perhaps as long as 300 to 1000 years) before a nuclear waste facility is finally closed.

Introduction—Models

Models play a key role in the analysis of many, if not most, ground water problems. They are especially important in predicting the behavior of nuclear waste facilities far into the future. The Waste Isolation Pilot Plant (WIPP, a geologic repository for transuranic wastes in New Mexico) was recently opened and is receiving nuclear weapons waste. Yucca Mountain (the proposed high-level nuclear waste repository in Nevada) is near the licensing stage. Hydrogeological models play a key role in assessing the safety of these facilities.

The purpose of this paper is to discuss philosophically the use of models in making predictions. Many of these ideas have been expressed elsewhere, yet they seem worth restating. In particular, I want to examine the role that the conceptual model plays in analysis. I take a historical perspective in developing these ideas.

In the 19th century, various laws that describe the movement of heat, electricity, and ground water through a continuum were derived. Of special concern to those of us that investigate ground water is Darcy's law. By applying the principle of conservation of mass and incorporating Darcy's law as a constitutive relationship, we can derive a partial differential equation that describes the hydraulic head throughout a porous medium. Once the head is determined, we can apply Darcy's law to derive the ground water flow vectors throughout the system. These principles form the basis for all ground water flow and transport models.

For many ground water problems with simple geometry, simple parameter distributions, and simple boundary conditions analytical solutions to the mathematical problem can be derived. Because there is an analogy between the flow of ground water and the flow of both electricity and heat, we often can find the mathematical solution for the appropriate boundary value problem in the literature on

[1]The Hydrodynamics Group, 127 Toyon Lane, Sausalito, CA 94965; jdbrede@aol.com

Calibration

An integral part of the modeling procedure is calibration. Calibration involves fitting the model output to a set of observations. Hopefully, at some point in the process, the model parameters are adjusted so that an *adequate* fit to the observations is achieved. Originally, calibration was a trial-and-error procedure. In recent years, the process of adjusting the parameters to achieve an adequate fit has been automated.

Numerical measures of the goodness-of-fit between the observations and the model predictions have been devised. The numerical measures provide the appearance that judging the adequacy of fit during calibration is no longer subjective. However, in the end, what constitutes an adequate fit is a subjective decision. Statistical measures of the goodness-of-fit can be calculated, but the question of whether a model is calibrated is a decision left to the analyst.

There are problems in the calibration procedure. As suggested by the previous discussion of pumping test analysis, the calibration commonly does not test our conceptual model. *In other words, a model involving a wrong or incomplete conceptual model can be adequately calibrated.* It is generally conceded that a model, even if it is well calibrated, is nonunique; another parameter set might result in an equally good calibration (Bethke 1992).

Post Audits

Since models have now been around for several decades, it is possible in certain limited instances to evaluate their performance. Predictions were made that can now be compared to what happened to a particular system. Many audits do not really test the adequacy of the model because what took place with the real system was not a scenario that was analyzed initially. Typically, pumping followed a different pattern than anticipated.

There are a limited number of post audits of model predictions; they are not reassuring. Many models did not provide good predictions (Anderson and Woessner 1992; Konikow and Bredehoeft 1992). Many models suffered from a conceptual omission: an important process was overlooked. In other cases, the range of parameters was much larger than was included in the model analysis. Models are known to have provided poor predictions, even models that were thought to have been well calibrated.

Validation

Validation is a term promoted by the nuclear waste community. Different people variously define validation; there is no consensus on what it means. Furthermore, in most cases, the goal of calibration and validation are the same: In both cases, we seek to create the best possible representation of the system. We as a community have formulated restrictive, and rather special, definitions of what it means to validate a code.

Recognizing that the traditional history match was impossible, the nuclear waste community set out to test different codes in situations where shorter histories of performance were available. They called this test of the models *validation*. This is only one of many specialized definitions of validation. This test of the codes was no different than the calibration procedure models normally undergo. If the model of a specified system could be adequately calibrated, the code was deemed validated. In many instances, we can substitute the words *well calibrated* for *validated* without changing significantly the author's meaning.

There are both pragmatic and philosophical grounds to avoid the idea of validation. The idea of validation (or invalidation) is deeply rooted in the philosophy of science. On philosophical grounds, Popper (1968) argued that scientific theory can be invalidated—not validated. Of course, Popper is not the only philosopher of science. Others, notably the pragmatists, of which John Dewey is perhaps the best known, argued that we learn from experience, observations, and mistakes (Menand 2001). The pragmatists argued we never find real truth, but we do get closer to understanding. Kuhn (1970) suggested that scientists try to make existing theory work until finally the evidence indicates that it does not; then they embrace a new theory. None of these philosophers argued that one could validate.

It is unfortunate that we have allowed the term *validation* to become a part of the model lexicon. Oreskes and Belitz (2001) summarize the status of validation:

> "The inherent uncertainties of models have been widely recognized, and it is commonly acknowledged that the term 'validation' is an unfortunate one, because its root—valid—implies a legitimacy that we are not justified in asserting. . . . But old habits die hard and the term persists. In formal documents of major national and international agencies that sponsor modeling efforts, and in the work of many modelers, 'validation' is still widely used in ways that assert or imply assurance that the model accurately reflects the underlying natural processes, and therefore provides a reliable basis for decision-making. This usage is misleading and should be changed. Models cannot be validated. The reasons why have been outlined in detail elsewhere (Konikow and Bredehoeft 1992; Oreskes et al. 1994)."

Reservoir Engineering: A Pragmatic Approach

The ground water community could take a lesson from petroleum reservoir engineering. The usual practice is to history match the reservoir simulator output to some temporal history of production. This is calibration in the ground water lexicon. Based on the match, a prediction of future performance is made, but one is cautious in extending that prediction much beyond a period equal to the production history. In other words, the rule of thumb is that, if we make a 10-year history match, we might be reasonably confident in predicting the next 10 years of performance; however, beyond 10 years, the confidence in a prediction greatly diminishes.

The reservoir engineering community makes no claims about the validity of the model. They simply imply: (1) we have a model that we think incorporates the appropriate physics and chemistry, including the appropriate parameter set, that matches an observed temporal history of reservoir performance; and (2) we will use that model to predict future reservoir performance. Furthermore, continued monitoring of the system is used to refine and improve the model.

Reservoir simulation is important in the petroleum industry. A small improvement in the fraction of petroleum

Spring Valley 2006 Hearing Ex. 689

INTRODUCTION

SNWA is proposing a massive water mining development that violates the spirit, if not the letter, of Nevada groundwater law; let me explain. Nevada's Water Resources—Report 3 defines both perennial yield and storage depletion reserve; I quote:

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. Perennial yield cannot be more than the natural recharge to a ground water basin and in some cases is less.*

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).*

These definitions imply that one expects that the developed groundwater system will reach a new equilibrium state in which the pumping is balanced by the natural discharge that can be salvaged—i.e. balanced by the amount of the natural discharge captured by the pumping. As a corollary, one expects that the new equilibrium state will be reached in some reasonable period.

GROUNDWATER MODELS

The tool to predict how a groundwater system will behave in the future is the groundwater model. I believe, that the applicant, in this case SNWA, has an obligation to predict the response of the system to pumping, especially since they created an elegant groundwater model. SNWA did not make predictions of the impacts of their proposed pumping because, I believe, it damages their application—more on this below.

Groundwater models are calibrated in two modes: 1) in the virgin state—prior to pumping, 2) in the pumping or development mode. In the case of Spring Valley there is insufficient pumping to calibrate the model in a development mode. This does not preclude a prediction; it means that predictions of the impacts of pumping will have a higher degree of uncertainty—more on this below.

Virgin State Model

SNWA (Durbin) presents a sophisticated model analysis of the system in the virgin state. To do the analysis he needed transmissivity (permeability times thickness) data for the hydrologic elements used in the model to characterize the geology. The aquifer test data are sparse, especially in the area modeled; Durbin examined data from the entire and we're lawyerizing a process where the State Engineer is asking you to bring him information.

Objection sustained, Mr. Taggart. Go ahead, Dr. Bredehoeft.

THE WITNESS: Well, I want to come back and say to you if you want to make predictions about how these systems are going to behave, this is the only tool you've got. This is it. You don't have anything else.

I guess I would, at the risk of -- I'll try to answer the question you asked the other day. What do we have to do to improve the capability of the model to predict? Well, what you need to do is get ten or 20 years of development and see how the system responds.

There's a problem with that. That means you've got to make an investment out there in order to get that ten or 20 years of development, including probably a very major investment if you're going to take that water to Las Vegas.

At that point I think you're in a situation where it's going to be very difficult to shut the system down. If you don't like what you've got, it's going to be very tough to say, hey, we made this massive investment and now we're going to shut the thing down? I don't think so.

STATE ENGINEER TAYLOR: Let me ask you a question, and I understand about the investment part of it but I'm managing the water resources. Do you think you have

to pump 90,000 acre feet a year for 20 years to make that determination or are there amounts much less than that that you can get the information?

THE WITNESS: I think there are amounts much less than that that you can get the information but I think you're talking about substantial amounts of water. It's not going to be pumping tests, it's not going to be pumping test range quantities. You're talking about development, real development.

STATE ENGINEER TAYLOR: When you talk about substantial, what is that amount?

THE WITNESS: Well, in my mind something like 20,000, 25,000.

STATE ENGINEER TAYLOR: Is that over a 20-year period or is that 20,000 --

THE WITNESS: A year.

STATE ENGINEER TAYLOR: -- a year. And can you get that information after one year?

THE WITNESS: No.

STATE ENGINEER TAYLOR: You need 20 years of pumping at 10,000?

THE WITNESS: You need ten.

STATE ENGINEER TAYLOR: Thank you.

THE WITNESS: One more slide and I think I'll finish with this slide. One of the things that Tim did with

Q Okay. Now, isn't it true that all ground water development initially removes water from transitional storage?

A Yes, of course. That's the "Drawdown" column.

Q Isn't it true that at the prior hearing regarding DDC, you testified that you agreed with the statement that within the perennial yield concept, there is an allowance for the development of transitional storage?

A Oh, absolutely. That's well established in even -- in the literature including the State Engineer's literature.

Q Now, you indicated during cross-examination that data from large-scale pumping stresses is not available in Spring Valley, correct?

A That's correct.

Q And you agree that if large-scale pumping stresses were available, your model and other models could be calibrated to represent those pumping activities and the hydrologic responses to those pumping activities; isn't that correct?

A Absolutely.

Q And you agree, do you not, that if that additional calibration occurs, an expert like yourself could make accurate local-scale predictions to the State

Engineer on how pumping in Spring Valley will impact water discharges in Spring Valley and adjacent basins, right?

A The -- the accuracy and precision of the estimates and the modeling would improve with additional pumping data. So I -- so, yes, I agree with your statement.

Q And you believe that a model could be built to make the type of predictions that are local-scale, correct?

A With time, yes.

Q Now I want to quickly go through some of the testimony that you've offered regarding Spring Valley, and then I'll do the same with DDC.

And I want to clarify that in Spring Valley, there's a number of components to the water budget, right?

A Yes.

Q And one of those components is recharge, correct?

A Right.

Q And for recharge in those basins in your model for Spring Valley, you averaged prior studies, correct?

A I -- I estimated the -- I estimated the recharge based upon averaging the prior studies, that is correct.

Q And then for discharge, you did not choose

CONCLUSIONS

The current analyses leave little doubt that there will be significant harmful impacts associated with SNWA's proposed development—large drawdowns will be created over very large areas; streams, springs, and phreatophytes will be eliminated, and wells will go dry, in the areas of drawdown—existing water rights will be damaged, if not totally destroyed. As further explained in this report, the proposed mitigation measures will not compensate for those major impacts.

GBWN_Exh_009 p. 10

The following vegetation community changes could occur in response to groundwater pumping, as outlined under the assumptions. The specific vegetation community responses cannot be predicted on a site-specific basis. The rate of change in plant community composition also would be highly variable, depending on groundwater drawdown rates and local water elevation recovery, as well as the influence of precipitation and overland and runoff in channels.

SNWA_Exh_408, P. 3.5-43

understanding of the groundwater flow system, provide the most reasonable means available at this time to identify areas where impacts associated with the proposed action (or alternative) pumping are likely to occur. This drawdown impact evaluation for springs and streams is limited to a prediction of areas of risk with the recognition that actual impacts to individual springs and streams distributed over this broad region cannot be determined precisely prior to pumping.

SNWA_Exh_408 p. 3.3-88

CONCLUSIONS

The current analyses leave little doubt that there will be significant harmful impacts associated with SNWA's proposed development—large drawdowns will be created over very large areas; streams, springs, and phreatophytes will be eliminated, and wells will go dry, in the areas of drawdown—existing water rights will be damaged, if not totally destroyed. As further explained in this report, the proposed mitigation measures will not compensate for those major impacts.

GBWN_Exh_009 p. 10

Model Limitations

All models have limitations and the CCRP model is no exception. A detailed discussion of the model limitations and accuracy of the model to reproduce measured groundwater levels and estimated groundwater budget components is provided in the numerical model report (SNWA 2009b). Although the model results provide valuable insight as to the general, long-term drawdown patterns and relative trends likely to occur from the various pumping scenarios, the model does not have the level of accuracy required to predict absolute values at specific points in time (especially decades or centuries into the future). Two major limitations of the model for predictive studies include: 1) a lack of reliable information regarding the hydraulic properties of faults included in the model; and 2) representation of future climate as discussed below.

SNWA_Exh_408 p. 3.3-86

Impacts to Groundwater Rights

For the purposes of this evaluation, it is assumed that wells located within the areas affected by drawdown of 10 feet or greater could experience impacts. Specific impacts to individual wells would depend on the: 1) well completion, including pump setting, depth, yield, predevelopment static and pumping groundwater levels; 2) interconnection between the aquifer in which the well is completed in and the aquifer targeted by the GWD Project; and 3) the magnitude and timing of the drawdown that occurs at the specific location.

SNWA_Exh_408 p. 3.3-111

CONCLUSIONS

The current analyses leave little doubt that there will be significant harmful impacts associated with SNWA's proposed development—large drawdowns will be created over very large areas; streams, springs, and phreatophytes will be eliminated, and wells will go dry, in the areas of drawdown—existing water rights will be damaged, if not totally destroyed. As further explained in this report, the proposed mitigation measures will not compensate for those major impacts.

GBWN_Exh_009 p. 10

Water Rights Impact Evaluation

This impact evaluation is not intended to determine reasonable (or unreasonable) effects to water rights allowable under state law such as the Nevada Statue (NRS 534.110{4}) that allows for a reasonable lowering of the static water level at the points of diversion for existing water rights provided that the existing water rights can be satisfied. The water rights impacts evaluation is intended to provide a disclosure of potential effects to existing surface and groundwater rights resulting from the various proposed pumping alternatives.

SNWA_Exh_408 p. 3.3-93

charge is equal to the natural discharge. We can write the following expression for the system as a whole

$$R_0 - D_0 = 0, \tag{4.1}$$

where R_0 is the mean recharge under virgin conditions and D_0 is the mean discharge under virgin conditions.

Some disturbance of the system is necessary to have a development. At some time after the start of pumping we can write the following expression:

$$(R_0 + \Delta R_0) - (D_0 + \Delta D_0) - Q + \frac{dV}{dt} = 0, \tag{4.2}$$

where ΔR_0 is the change in the mean recharge, ΔD_0 the change in the mean discharge, Q the rate of withdrawal due to development, and dV/dt the rate of change in storage in the system. From Eqs. (4.1) and (4.2) we can obtain

$$\Delta R_0 - \Delta D_0 - Q + \frac{dV}{dt} = 0. \tag{4.3}$$

Assuming water-table conditions we can them compute an average drawdown for the system as a whole in the following manner:

$$s_a = \Delta V_t / (S_y \cdot A_b), \tag{4.4}$$

where s_a is average basinwide drawdown, ΔV_t the volume removed from storage at time t, S_y the specific yield of the aquifer, and A_b the area of the basin. Such an input-output analysis treats the system just as we would treat a surface water reservoir. The response of the system is assumed to take place rapidly with effects equally distributed throughout the basin. In most groundwater systems the response is not equally distributed.

RESPONSE OF GROUNDWATER SYSTEMS

In groundwater systems the decline of water levels in a basin because of withdrawal will occur over a period of years, decades, or even centuries. Some water must be taken from storage in the system to create gradients toward a well. There are two implications to be gathered from these facts: (1) some water must always be mined to create a development, and (2) the time delays in a groundwater system differ from those in surface-water systems.

It is apparent from Eq. (4.3) that the virgin rates of recharge R_0 or discharge D_0 are not of paramount importance in groundwater investigations. For the system to reach some new equilibrium, which we define as $dV/dt = 0$, there must be some change in the virgin rate of recharge and/or the rate of discharge D_0. It is these changes, ΔR_0 and ΔD_0, that are interesting.

The response of groundwater systems depends on the aquifer parameters (transmissivity and storage coefficient), the boundary conditions, and the positioning of the development within the system.

Lohman (1972a), referring to the High Plains of Texas and New Mexico, made the point again. The following discussion is a synopsis of Lohman's argument taken from Bulletin 16 of the U.S. Water Resources Council (1973):

Withdrawals cannot exceed the rates of recharge or discharge for a prolonged period of time without resultant "mining" of ground water. Adjustments in recharge and discharge rates as a result of pumping can be referred to as capture, and, inasmuch as sustained yield is limited by capture and cannot exceed it, estimates of capture are fundamentally important to quantitative groundwater analysis and planning for long-term water supply.

Decline of water levels in response to sustained withdrawal may continue over a long period of time. At first, some water must be taken from storage in the system to create gradients toward pumping wells. Two important implications of these statements concerning a long-term water supply are that (1) some water must be removed from storage in the system to develop a groundwater supply, and (2) time delays in areal distribution of pumping effects in many groundwater systems demonstrate that balanced (equilibrium or steady-state) conditions of flow do not ordinarily exist. In the clearest examples, water levels decline drastically, and some wells go dry long before the system as a whole reaches a new equilibrium balance between replenishment and natural and imposed discharge rates.

The most well-known example of such a condition of nonequilibrium is the major groundwater development of the southern High Plains of Texas and New Mexico. Water is contained in extensive deposits (the Ogallala formation) underlying the plains (Figure 4.1). Average thickness of these deposits is about 300 feet. They consist of silt, sand, and gravel and form a groundwater reservoir of moderate permeability. The reservoir rests on relatively impermeable rock and constitutes the only large source of groundwater available to the area.

The southern High Plains slope gently from west to east, cut off from external sources of water upstream and downstream by escarpments,

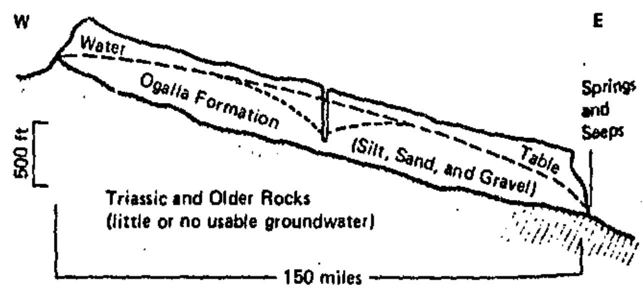


FIGURE 4.1 Development of groundwater in the southern High Plains of Texas and New Mexico. Withdrawal has resulted in a pronounced decline of water levels in the middle of the southern High Plains, but it has had little effect on the gradient to the east (natural discharge) or on natural recharge.

charge) is entirely salvaged (captured) by pumping, i.e., phreatophyte water use equals zero (we define equilibrium as $\delta V/\delta t = 0$). In Case I, phreatophyte-water use (Figure 4.8) is still approximately 10 percent of its initial value at year 1000. In Case II it takes 500 yr for the phreatophyte-water use to be completely captured.

We can illustrate the same point by looking at the total volumes pumped from the system, along with the volume taken from storage "mined" (Figure 4.9).

In both cases, for the first 100 yr, nearly all of the water comes from storage. Obviously, as the system approaches equilibrium, the rate of change of the volume of water removed from storage also approaches zero. If the aquifer was thin, it is apparent that wells could go dry long before the system could approach equilibrium.

This example illustrates three important points:

1. The rate at which the hydrologic system can be brought into equilibrium depends on the rate at which the discharge can be captured.
2. The placement of pumping wells in the system significantly changes the dynamic response and the rate at which natural discharge can be captured.
3. Some groundwater must be mined before the system can be brought into equilibrium.

CONCLUSIONS

We have attempted to make several important points:

1. Magnitude of development depends on hydrologic effects that you want to tolerate, ultimately or at any given time (which could be dictated by economics or other factors). To calculate hydrologic effects you need to know the hydraulic properties and boundaries of the aquifer. Natural recharge and discharge at no time enter these calculations. Hence, a water budget is of little use in determining magnitude of development.
2. The magnitude of sustained groundwater pumpage generally depends on how much of the natural discharge can be captured.
3. Steady state is reached only when pumping is balanced by capture $(\Delta R_0 + \Delta D_0)$, in most cases the change in recharge, ΔR_0, is small or zero, and balance must be achieved by a change in discharge, ΔD_0. Before any natural discharge can be captured, some water must be removed from storage by pumping. In many circumstances the dynamics of the groundwater system are such that long periods of time are necessary before any kind of an equilibrium condition can develop. In some circumstances

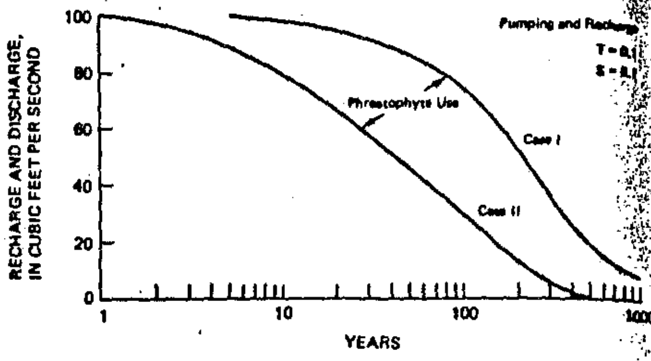


FIGURE 4.8 Plot of the rate of recharge, pumping, and phreatophyte use versus time.

TABLE 4.1 Aquifer Parameters

Basin dimensions	50 x 25 miles
Aquifer	
Hydraulic conductivity (k)	0.5×10^{-3} ft^2/sec
Storage coefficient (S)	0.1
Initial saturated thickness (h)	2000 ft
Phreatophytes	
Area	172 miles^2
Average use (annual)	100 ft^3/sec
Recharge	
Area	7 miles^2
Average recharge rate	100 ft^3/sec
Development	
Area	30 miles^2
Average pumping rate	100 ft^3/sec

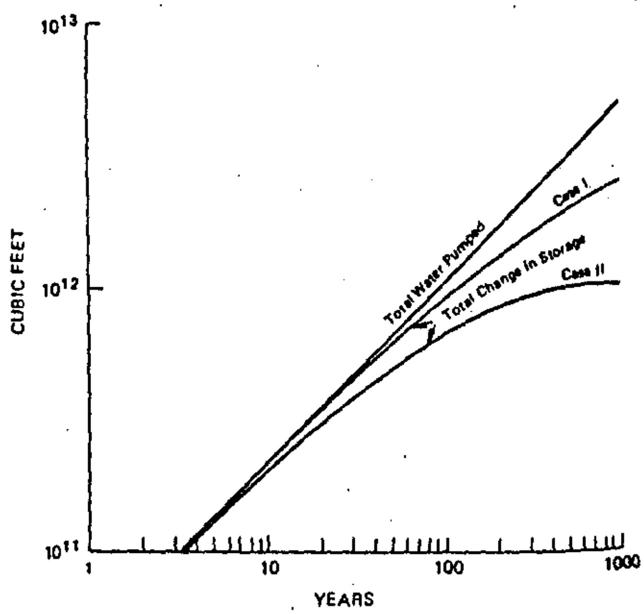


FIGURE 4.9 Total volume pumped and the change in storage versus time.

DEATH VALLEY BASIN, continued

227	Forty Mile Canyon				R14, R54
	a) Jackass Flats	8,000a	4,000c	7,400	R14, R54
	b) Buckboard Mesa	7,000a	3,600c	Minor	R14, R54
228	Oasis V.	3,500a	2,000c	4,000	R10, R54
229	Crater Flat	1,700a	900c	3,500	R14, R54
230	Amargosa Desert	43,000a	34,000c	35,000	R14, R54
231	Grapevine Canyon	400a	400c	1,600	R45
232	Oriental Wash	300a	150c	3,700	R45
BASIN TOTAL		62,000a	61,000c	57,000	
STATE TOTAL		2,000,000a	1,700,000c	2,500,000	

TABLE 1-A — TRANSITIONAL STORAGE

Hydrographic Region Number	Hydrographic Region	Transitional Storage Reserve (Acre Feet)
1	Northwest Region	1,000,000
2	Black Rock Desert Region	8,000,000
3	Snake River Basin	500,000
4	Humboldt River Basin	10,000,000
5	West Central Region	1,500,000
6	Truckee River Basin	1,600,000
7	Western Region	340,000
8	Carson River Basin	3,800,000
9	Walker River Basin	2,600,000
10	Central Region	45,000,000
11	Great Salt Lake Basin	3,000,000
12	Escalante Desert Basin	70,000
13	Colorado River Basin	5,000,000
14	Death Valley Basin	2,000,000
	TOTAL	84,000,000

Recharge	100 cfs	100 cfs
Pumping	100	0
From storage	90	
Into storage		10
Spring flow	90	90

We see that in the 70th year, while pumping, we are depleting storage at a rate of 90 cfs—pumping has captured 10 cfs of spring flow. However, once we stop pumping we replace storage at an initial rate of only 10 cfs. This simple analysis suggests that it will take at least nine times as long as the pumping period to replace the depletion in storage in the valley. The system will not fully recover until the depleted storage is fully replaced. This indicates the infeasibility of resting valleys and returning to them later, if we intend to return after they have sufficiently recovered to something like their initial state.

In conclusion, the projected impacts clearly indicate that there will be a need for mitigation, but only limited augmentation and, perhaps, cloud seeding seem at all realistic, and neither of those forms of mitigation, or the combination of both, appears adequate to provide much mitigation for the predicted impacts. In other word, there is no real mitigation for the widespread impacts projected by all of the models, other than not pumping in the first place.

THE FUTURE—Beyond Two Hundred Years

We know from first principles that the drawdown created by continued pumping will extend outward until it can ***capture*** sufficient water (principally discharge) and create a new equilibrium; the discussion in Water for Nevada—Bulletin 2 recognizes this fact. The modeling of impacts for the Draft EIS indicates that at 200 years the system, in most places, is nowhere near reaching a new equilibrium state—at the new equilibrium, water levels will stabilize. The model indicates that the wells are continuing to decline with little or no indication of leveling off. This is not surprising. Durbin and I suggested that the system because of its size might take more than 1000 years to reach a new equilibrium (Bredehoeft and Durbin, 2009).

Of the present models, only Myers (2011) has carried the modeling out to look at how long the system might take to reach the new equilibrium. Myers' modeling again shows that the system will reach a new equilibrium, but it will take a long time—more than 1000 years.

CONCLUSIONS

The current analyses leave little doubt that there will be significant harmful impacts associated with SNWA's proposed development—large drawdowns will be created over very large areas; streams, springs, and phreatophytes will be eliminated, and wells will go dry, in the areas of drawdown—existing water rights will be damaged, if not totally destroyed. As further explained in this report, the proposed mitigation measures will not compensate for those major impacts.

Now, what's been surprising is when we've looked at these systems and said to ourselves -- you know, we've looked at systems like Paradise Valley, and said, how long's it take for Paradise Valley to come to a new equilibrium? Well, it surprised us, but it looks like it's 300 years, something like this, two or 300 years, but that's a reasonable time, probably, something that we can think about reasonably, two to 300 years.

Okay. Now, we come along, and we throw you a curve. We say you to you: This system that we're looking at here doesn't come to a new equilibrium for 2500, 3,000 years. When does this new water budget apply? Well, the new water budget, that takes into account the pumping, doesn't apply until I get out there to the new equilibrium. That's the time when that new water budget applies. It doesn't apply at any interim time. It only applies at here, at equilibrium.

Now, you've got a conundrum. You've got a problem, because if this thing is out there 2500 years, you're looking like -- we're talking about Roman time or back beyond Roman time. And to -- before that new water budget applies. It doesn't have any meaning until I get out there to the new equilibrium.

So you can come back and say -- then you can say to yourself, well, let's look at some intermediate

Table 1
Aquifer Properties for Our Hypothetical Basin and Range Aquifers

Basin size	50×25 miles (Figure 2)
Cell dimensions	1×1 mile
Hydraulic conductivity	0.0005 and 0.00025 ft/sec
Saturated thickness	2000 ft
transmissivity	1.0 and 0.5 ft²/sec (approximately 90,000 and 40,000 ft²/day—both highly transmissive)
Storage coefficient	0.1%–10% specific yield
Phreatophyte area	170 mi²
Average consumption	100 cfs
Wellfield area	30 mi²
Average pumping	100 cfs
Recharge	100 cfs

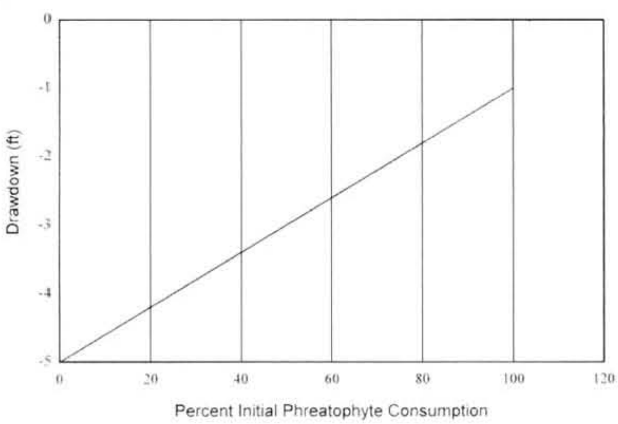


Figure 3. Linear function relating phreatophyte use to drawdown in the aquifer.

To simulate a well development in this aquifer, I will make the size of the development equal to the recharge (and the discharge) 100 cfs. We consider two locations for our wellfield, shown as Case I and Case II in Figure 2. The Case II wellfield is closer to the area of phreatophyte vegetation. To simulate the system, we need aquifer properties; the aquifer properties are specified in Table 1.

In our hypothetical system, we will eliminate phreatophyte ground water consumption as the pumping lowers the water table in the area containing phreatopyhtes. I deliberately created a ground water system in which capture of ET can occur. A linear function is used to cut off the phreatophyte consumption. As the water table drops from 1 to 5 feet, we linearly reduce the phreatophyte use of ground water—the function is shown in Figure 3. The reduction in phreatophyte use does not start until the ground water declines 1 foot; by the time the water table drops 5 feet, the phreatophyte use is eliminated in that cell. The phreatopyhte reduction function is applied cell by cell in the model.

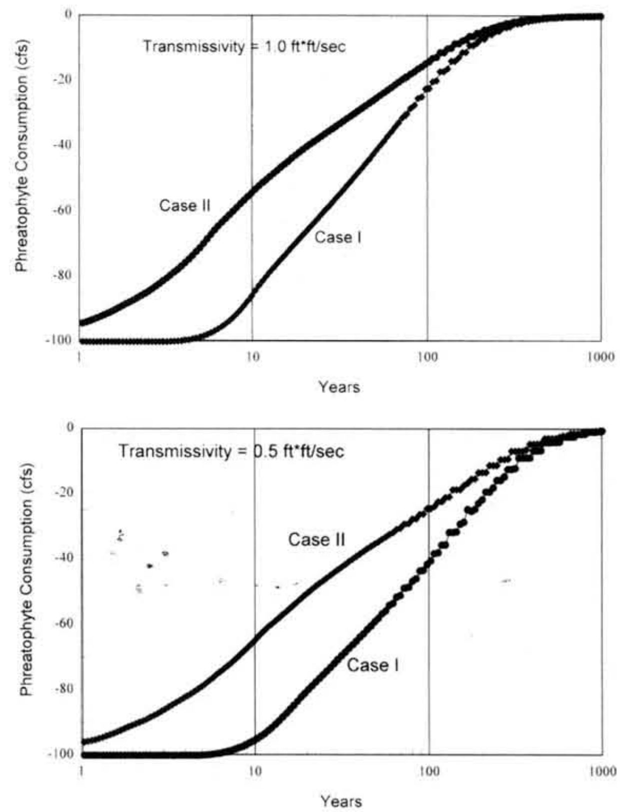


Figure 4. Plots of phreatophyte use vs. time.

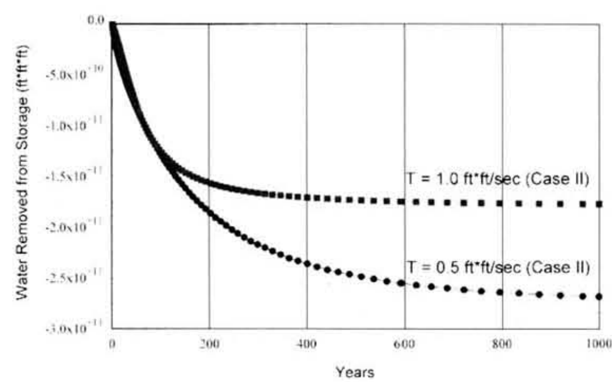


Figure 5. Plots of the change in storage vs. time.

For this system to reach a new state of sustainable yield, the phreatophyte consumption must be eliminated entirely. Using the model, we can examine the phreatophyte use as a function of time. Figure 4 is a plot of the phreatophyte use in our system versus time since pumping was initiated. I have considered two transmissivities for the hypothetical system (1.0 and 0.5 ft²/sec); both are high transmissivities. In the higher transmissivity aquifer, the phreatophyte consumption is very small after 400 years; in other words, the system has reached a new steady state in approximately 400 years. The new steady state is a sustainable development. In the lower transmissivity case, it takes approximately 900 to 1000 years for the phreatophyte consumption to be become very small.

IN SUMMARY

The Muddy River streamflow tells an additional story. The Muddy River flow at Moapa has steadily declined since 1960. Prudic (USGS, Carson City) tells me that the same decline is not observed in other streams in the region that he has investigated, including the Virgin and Mojave Rivers (Prudic, personal communication, December 2007). This suggests that the decline in the flow of the Muddy River is not the result of some change in the climate, but rather the result of developments that have been ongoing since the 1950s in the overall watershed of the entire White River Flow System.

The downstream springs and senior water rights holders in the White River Flow System fully utilize the interbasin flow out of Cave, Dry Lake, and Delamar Valleys. The decline of the Muddy River at Moapa further indicates that there is no downstream non-beneficial use to be captured by the pumping, and therefore the pumping in the valleys under consideration should not be authorized.

Nevada water law has only an implied reference to time; it only requires that the system reach a new equilibrium state at some undetermined future time. The law was written before the tools were available to predict the future of groundwater developments. I venture to say that no one at the time the law was written could imagine that it would take more than 2000 years for any conceivable pumping scheme to reach a new equilibrium. The fact that the model predicts times greater than 2000 years to reach a new equilibrium changes one's entire view of the system. The time to reach a new steady state is of the order of recorded history; the fact that a new equilibrium may ultimately be reached is meaningless—it is too far into the future. Too much can happen on the earth in this kind of a time frame—civilizations change, the climate may change dramatically. One must concern one's self with what happens in the next several hundred years, perhaps 500 years. After 500 years of pumping, the models predict that for the larger SNWA development, the wells will still obtain approximately 30 percent of their water from the depletion of groundwater storage. From this perspective, one has in essence a groundwater mining scheme—it can hardly be viewed otherwise. Approving such a development seems contrary to the spirit of the Nevada water law.

that's mining." I'm pumping out of the storage. That's where the water's coming from. I'm mining the groundwater.

Now, it may not be mining as defined by some law that Nevada has established. Within the Nevada Water Law it may not be mining, but by, I think, anybody's reasonable definition of what mining turns out to be, this -- this looks like mining to me. I mean, it looks like mining, as I think any sort of reasonable person who look at it. That's my judgment. You can fault my judgment.

Okay. Now, Simeon asked me a question. I want to go back and try to answer Simeon's question.

Okay. All right. Now, let's suppose I've got a spring. This spring over here -- I've got a spring over here, and it's flowing ten-second feet. Okay? And I start a well over here, and I'm going to pump this well at two-second-feet. So I'm pumping this well over here at two-second-feet, and this spring is discharging ten-second-feet.

All right. So what happens? A cone of depression develops and so forth, reaches out, reaches the spring here. When it gets to the spring it says, oh, I'll change the gradient in the spring to get enough water to two-second-feet, to divert to the well. Okay? So it diverts two-second-feet from the well -- from the spring to

One last question, and that is: Assuming that it's acceptable to take water out of transitional storage, SNWA could pump in Dry, Delamar, and Cave Valleys, say, for 75 or a hundred years, and then that pumping could be rested, and those valleys would be recharged. Isn't that correct?

A You would have to rest those valleys something of the order of the length of the pumping. So if you said to yourself, "I'm going to pump for a hundred years, and then I'll going to rest the valley for a hundred or so years," yes, the valley would probably recover, most of it.

MR. VAN ZANDT: Thank you. Just a second.

(Discussion off the record)

MR. VAN ZANDT: No further questions.

HEARING OFFICER JOSEPH-TAYLOR: Thank you. Are you planning any Redirect, Mr. Herskovits?

MR. HERSKOVITS: No, Madam Hearing Officer.

HEARING OFFICER JOSEPH-TAYLOR: Dr. Bredehoeft, will you mind staying in case staff has questions? But I'm going to take 15-minute recess here. We'll be off the record.

THE WITNESS: That's fine.

HEARING OFFICER JOSEPH-TAYLOR: Thank you.

(Proceedings recessed from 2:31 p.m. until 2:45 p.m.)

HEARING OFFICER JOSEPH-TAYLOR: Let's be on the

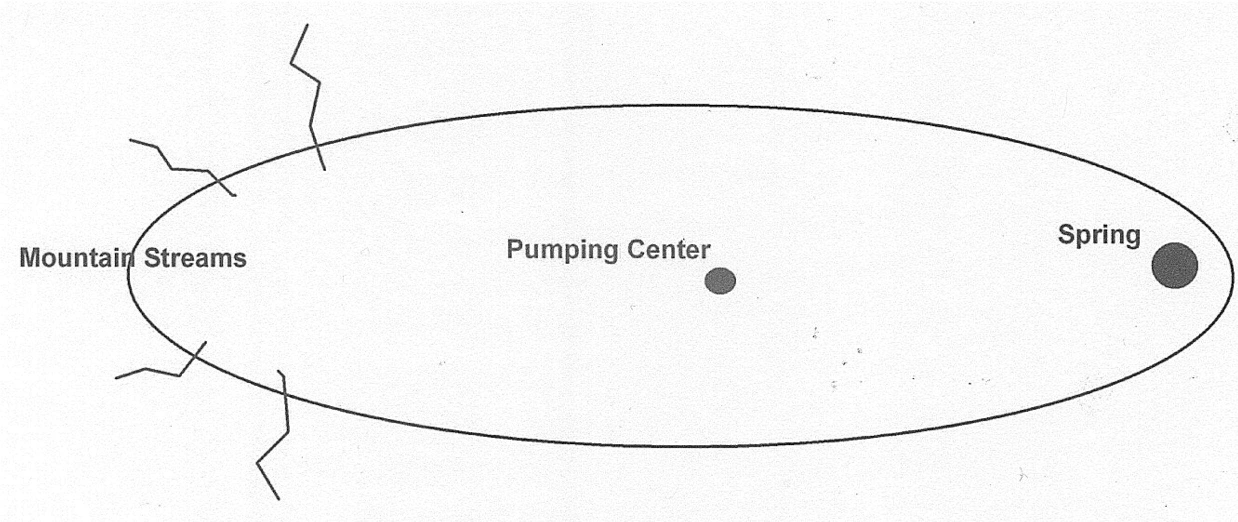


Figure 4. Hypothetical Valley 100 miles long and 25 miles wide, with recharge of 100 cfs from mountain streams to the left, and a spring discharging at a rate of 100 cfs to the right. The pumping is centered in the valley 50 miles from the spring.

In the hypothetical valley pumping is initiated at 100 cfs, equal to the recharge and the initial spring flow. The valley is rather permeable with a transmissivity of 25,000 ft^2/day, and storativity of 0.1 (10% specific yield). The pumping gradually captures flow from the spring. At the point at which the spring flow drops by 10% (90 cfs) pumping is stopped. Figure 5 is a plot of the spring discharge during the period of pumping and after it is stopped:

we integrate the point discharge along the entire shoreline of the island we obtain the total discharge from the island:

$$\int T\,(dh/dl)\,ds = D_0$$

We now go into the middle of the island, install a well and initiate pumping (Figure 1—second cross section). At any new time, we can write a new water balance for the island:

$$(R_0 + \Delta R_0) - (D_0 + \Delta D_0) - P + dV/dt = 0$$

where ΔR_0 is the change in the virgin rate of recharge caused by our pumping; ΔD_0 is the change in the virgin rate of discharge caused by the pumping; P is the rate of pumping; and dV/dt is the rate at which we are removing water from ground water storage on the island.

We know that the virgin rate of recharge, R_0, is equal to the virgin rate of discharge, D_0, so our water budget equation following the initiation of pumping reduces to

$$\Delta R_0 - \Delta D_0 - P + dV/dt = 0$$

or

$$\Delta R_0 - \Delta D_0 - P = dV/dt$$

For a sustainable development, we want the rate of water taken from storage to be zero; in other words, we define sustainability as

$$dV/dt = 0$$

Now our water budget for sustainable development is

$$\Delta R_0 - \Delta D_0 = P$$

We are now stating that, to reach a sustainable development, the pumping must be balanced by a change in the virgin rate of recharge, ΔR_0, and/or a change in the virgin rate of discharge, ΔD_0, caused by the pumping. Traditionally, the sum of the change in recharge and the change in discharge caused by the pumping, the quantity $(\Delta R_0 - \Delta D_0)$, is defined as the "capture" attributable to the pumping. To be a sustainable development, the rate of pumping must equal the rate of capture.

Notice that to determine sustainability we do not need to know the recharge. The recharge may be of interest, as are all the facets of the hydrologic budget, but it is not a determining factor in our analysis.

Recharge is often a function of external conditions—such as rainfall, vegetation, and soil permeability. In many, if not most, ground water situations, the rate of recharge cannot be impacted by the pumping; in other words, in terms of our water budget,

$$\Delta R_0 = 0$$

In most situations, sustainability of a ground water development occurs when the pumping captures an equal amount of virgin discharge:

$$P = \Delta D_0$$

Let's return to the island aquifer and see how the capture occurs conceptually. When we start to pump, a cone of depression is created. Figure 1 (second cross section) shows the cone of depression at an early stage in the development of our island aquifer. The natural discharge from the island does not start to change until the cone of depression changes the slope in the water table at the shore of the island; remember: Darcy's law controls the discharge at the shoreline. Until the slope of the water table at the shoreline is changed by the pumping, the natural discharge continues at its virgin rate. Until the point in time that the cone reaches the shore and changes the water table gradient significantly, all water pumped from the well is supplied totally from storage in the aquifer. In other words, the cone of depression must reach the shoreline before the natural discharge is impacted (Figure 1—third cross section). The rate at which the cone of depression develops, reaches the shoreline, and then changes the slope of the water table there depends on the dynamics of the aquifer system—transmissivity, storativity (or specific yield), and boundary conditions. The rate of capture in a ground water system is a problem in the dynamics of the system. Capture has nothing to do with the virgin rate of recharge; the recharge is irrelevant in determining the rate of capture.

Figure 1 (third cross section) shows the water table in our island aquifer at a point in time when the natural discharge is almost eliminated; the slope of the water table is almost flat at the shoreline. I deliberately created an aquifer system in which one can induce water to flow from the lake into the aquifer (Figure 1—fourth cross section). In this instance, the sustainable development can exceed the virgin recharge (or the virgin discharge). This again suggests that the recharge is not a relevant input in determining the magnitude of a sustainable development.

Often the geometry of the aquifer restricts the capture. For example, were the aquifer on the island to be thin, we might run out of water at the pump long before we could capture any fraction of the discharge. In this case all water pumped would come from storage. It would be "mined." In the island example, with a thin aquifer, the well could run dry before it could impact the discharge at the shoreline. Notice in Figure 1 (fourth cross section) that I have drawn the situation where the drawdown reached the bottom of the aquifer; the aquifer geometry and diffusivity limit the potential drawdown at the well. This again points out that the dynamic response of the aquifer system is all-important to determining the impacts of development. It is for these reasons that hydrogeologists are concerned with the dynamics of aquifer system response. Hydrogeologists model aquifers in an attempt to understand their dynamics.

Clearly, the circular island aquifer is a simple system. Even so, the principles explained in terms of this simple aquifer apply to all ground water systems. It is the dynamics of how capture takes place in an aquifer that ultimately determines how large a sustainable ground water development can be.

Water Law in the West

Nevada recognized in the early 1900s that the water supply for many of the valleys within the state would have

The accepted principle in Nevada of perennial yield carries an implicit recognition that eventually the system is expected to reach a new equilibrium state, in which there will be no further drawdown anywhere within the system.

HYDROLOGIC ANALYSIS

In assessing the perennial yield of a groundwater system, two basic tools are widely used:

1. Water budget analysis;
2. Numerical models that portray the hydrogeology of the system.

Water Budgets

The water budget, as generally applied to a hydrologic system (for example a particular valley), is a global estimate of the inflow, outflow, and rate of change in storage for the system at a point in time. Commonly, these estimates are made for the system prior to development; usually with the assumption that the system is at steady state. One attempts to estimate from the global budget how large the perennial yield might be—is it feasible to think about an additional development of a given size?

Groundwater impacts depend upon the hydrogeology of the system. The impacts can be quite different depending upon where the pumping is located within the system. Usually budgets provide no information on the place and timing of impacts (Bredehoeft, 2002)

Models

Groundwater models were invented in an attempt to estimate the timing and location of groundwater impacts. They evolved, as our computer technology has exploded over the past 60 years, to sophisticated analytical tools. With present technology, anyone hoping to project potential future impacts in both time and place almost certainly uses a model to make a credible analysis. Currently there are at least six models that are relevant to the analysis of the proposed SNWA Development—BLM (2011), Durbin (Bredehoeft and Durbin, 2009), Myers (2011), Prudic et al (1995), Schaefer and Harrill (1995), Halford (2011).

DATA

Much of the hydrologic data for the area in question involves measurements that are made at widely separated points or small plots, and must be extrapolated to the entire area of interest. The estimates differ in their underlying conceptual models. Not surprisingly, the resulting water budgets differ widely; the following two tables are from Myers (2011). The variations in these estimates reflect their uncertainty—they are estimates at best. The tables are only for recharge, but the valley-level budgets have quite similar variability.

Table 1. Estimates of pre-development basin-wide recharge (lower table in 1000s ac-ft/yr).

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}

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

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

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.

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

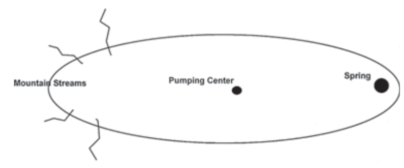


Figure 1. Schematic plan of the hypothetical valley. The pumping center is 50 miles from the spring.

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

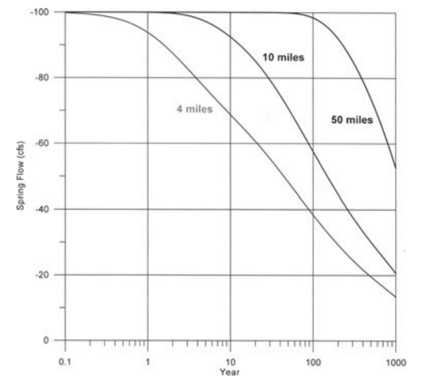


Figure 2. Simulated spring flow resulting from wells pumping 100 cfs in three different scenarios: pumping at 4, 10, and 50 miles from the spring.

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.

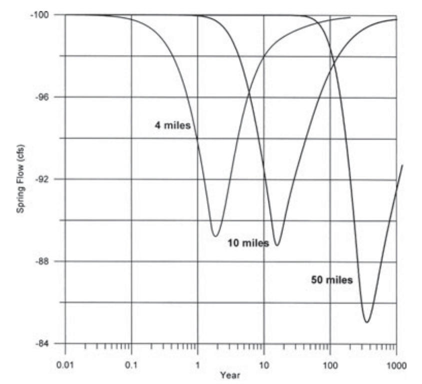


Figure 3. Three scenarios of pumping 100 cfs: at 4, 10, and 50 miles from the spring. Pumping ceased in each scenario when the spring flow declined by 10% to 90 cfs.

GBWN_Exh_011

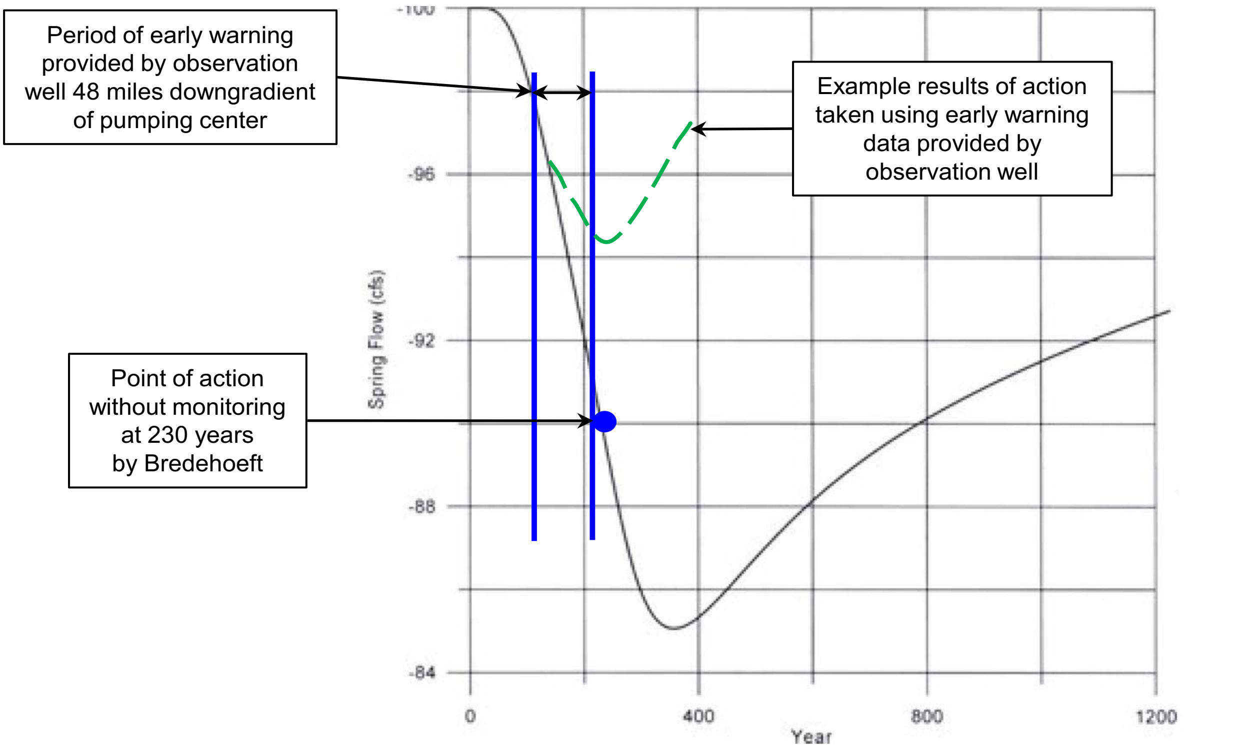


Figure 4. Plot of spring flow for pumping 100 cfs, 50 miles from the spring. Pumping was stopped after 230 years.

Source: Modified from Bredehoeft (2011b), Note: Text boxes and blue ranges added to original figure.

Figure 14
Effectiveness of Early Warning Monitor Well

SNWA_Exh_428

pumping from other hydrologic impacts on the system. Using the drawdown (a superposition approach) is tricky in these valleys because both the springs and phreatophyte plant discharges are dependent upon the drawdown—in mathematical terms they are non-linear effects. Durbin, et al, (2006) provided a methodology to handle the drawdown dependency of both the springs and the phreatophytes. Halford (2011) provides a graphical explanation of the Durbin method. The drawdown procedure removes the modeling uncertainty associated with the water budget estimates for the system. Durbin (Bredehoeft and Durbin, 2009) used the drawdown procedure to make future projections.

Model Projections

All of the models give similar projections of drawdown, even given the fact that the procedures used to create the models differed. This is not as surprising as it might seem. All of the models represent the same conceptual model of the hydrogeology. The system is dominated by the regional carbonate aquifer; the carbonate rocks are more or less ubiquitous and tens of thousands of feet thick throughout the region. The carbonate aquifer is generally very transmissive—in places very highly transmissive. The valleys contain alluvial sediments that also contain transmissive units and have a high capacity to store groundwater. All of the models reflect these basic hydrogeologic elements and their geographic distribution.

The conclusion from all the models is that there will be significant hydrologic impacts imposed on the system over a wide area as a result of the SNWA's proposed development—the Draft EIS (BLM, 2011) makes this point explicitly for not only Cave, Dry Lake, and Delamar Valleys, but Spring and Snake Valleys as well. The question is: what can be done about the impacts?

MONITORING

The rationale for monitoring has changed. Earlier, the argument was made that there would be no anticipated adverse impacts, and monitoring was intended to detect potential impacts with a thought to mitigation. The situation is now changed. All of the analyses agree, including that by SNWA (BLM, 2011), that widespread impacts are projected. Much of the monitoring will now be directed to comparing observed impacts versus impacts projected by the models. The models can be improved as the observations are made more coherent with the model results. Monitoring now becomes an iterative process between observations and model improvements—projections can be improved as the monitoring provides new system response data.

Should the SNWA project go forward, it must include extensive monitoring, but one should not expect the impossible from the monitoring. Monitoring will clearly record impacts where the features being monitored are relatively close to the pumping. One will be able to correlate drawdown created by the pumping with impacts. The difficulty comes where the features of concern are far removed from the pumping.

The problem is especially difficult for the proposed pumping in Cave, Dry Lake, and Delamar Valleys. The current conceptual model is that recharge in these valleys largely discharges in other down gradient valleys. The current accepted concept is that the outflow from Delamar Valley passes through Coyote Springs Valley and creates some of the spring discharge to the

Q How will that data be used in the monitoring of ground water development in Spring Valley?
A The water chemistry date that would -- it gives a general clue of the hydrogeologic conditions and the water chemistry conditions around each well as well as to see if there would be any changes over time of those areas. But it -- it's another tool to be able to determine, provide information on the hydraulic system in the study area.
Q I want to ask you about the management tools that will be used to predict potential impacts associated with development of ground water near Spring Valley.
What is the purpose of ground water modeling in the -- in managing the water resource?
A Well, numerical flow modeling or analytical models are used as predicative tools to be able to basically assess where additional data is needed; where there's the lowest level of certainty in a particular area within the hydrologic system.
It also provides an opportunity to evaluate various pumping scenarios under a range of different properties in the aquifer.
The main part of the data collection effort with the monitoring plant is to be able to use the model as a predictive tool. As we gather more data, especially

transient data or stress data, to be able to use that, put it back into the model to better refine that, and then to use that to better predict either where additional monitoring might be needed or additional effects.
These tools are also then used to either change pumping regimes in a well that's in place or be able to better utilize to site future production wells and design them in a way where you can have optimal discharge and minimizing effects and maximum amount possible.
Q Does the hydrologic monitoring plan that's in SNWA include a ground water modeling requirement?
A Yes. There's the requirement to develop, calibrate, and maintain a ground water flow model.
Q How will stressing the aquifer improve a model for monitoring management?
A By stressing an aquifer, you gain a great insight on the aquifer parameters, the hydraulic conductivity, and the storage of that area of the aquifer around the area that you're stressing.
In addition, you would be able to see what type of timing and distribution the drawdown there is at different distances where you have observation points.
From that, you can then basically tune in and refine your understanding of the hydrologic system around that pumping center and then utilize the model basically

using the all the higher-resolution information to better predict what would occur under different pumping regimes.
Q Is the well test data that's been collected to date sufficient to provide the stress condition information that you need for the model?
A No. Basically all these tests were short-term in duration, usually 3 to 5 days, with one observation point. Usually we had others in the area, but mainly we're looking at two to three -- one to three observation wells.
Longer-term stresses, you would be able to see boundary conditions that you might not see in a shorter period of time as well as be able to see the response in the aquifer at a wider distance or at a longer period of pumping.
Q You're familiar with the Draft Environmental Impact Statement Model that Dr. D'Agnese was discussing earlier?
A Yes. I'm familiar with it.
Q Is the data from the completed well test that he had been involved in, is that data included in the model that Dr. D'Agnese see configured?
A No. It's not.
Q Why is that?
A Because first the tests were performed after

the data set for the model was established. But the results from the test, the transmissivities storage, are all within a range that were used in the model.
Q Is there also data-controlled protocols included in the hydrologic monitoring plan?
A Yes, there are. There's a -- a data management and quality control program that we utilize where we basically look at how data's collected from the very beginning in terms of designing or locating and monitoring point to make sure that we're getting representative data for the objectives of the program.
For instance, a surface water gauging station that's located in a -- in a segment of a stream where the slope is proper and the banks are proper; that the wells, we know the communication interval with the aquifer. So once that's in place, then we want to make sure that the locations are surveyed so we can -- by a professional survey -- so we can compare those locations.
Then we determine what is the most appropriate instrumentation to equip the well with depending on the purposes of what we have, either with gas bubbler systems or use similar systems to USGS or, say, the industry instrumentation.
All of our water level indicators that are for manual measurements are calibrated against a master tape

From the Direct Testimony of James Prieur

its conclusion.
All those instances I've -- I've listed here might equate to half a dozen. Only one, though, ended up before a judge.
Q. When you talked about slide 7, you talked about -- again, I'm trying to read some of my notes here as I'm asking these questions, but you talked about the way to model the impacts that occur from a well on a sensitive environmental area; right?
A. Yes.
Q. And you talked about how you would look for places between those two locations to monitor; right?
A. Yes.
Q. And has it been your experience that you've been able to use that kind of a monitoring network to observe the impact of pumping and how that pumping impact is observed at the monitoring wells?
A. How the effect of pumping is observed in monitoring wells, have we been able to detect that?
Q. Yes.
A. Yes.
Q. And have you then been able to detect the time it takes for that observed impact to occur at the monitoring well?
A. Yes. We've been able to observe that where

there's not so many interfering factors that it wasn't observable in the water level.
Q. So when you say "other factors," were you able to filter out natural fluctuations in water levels so that you could actually observe the impact of pumping at a monitoring location?
A. In some instances, yes; in some instances, no. It -- well, I'll leave it at that.
Q. Um-hum. And based upon that information, you determined where to set triggers and thresholds; right?
A. Well, the -- the soil moisture plant water use mechanism for management of pumping that I described, that's what we have in place. And the preferable arrangement where we manage based on water levels observed in monitoring wells is what we're trying to implement with Los Angeles, and it's also what we've implemented for other water transfer projects.
Q. And what I'm trying to get at is what your experience tells us about the ability to anticipate what may occur at an area of interest from pumping, and so haven't you been able to predict impacts may occur from pumping at a certain area of interest through the monitoring program?
A. Yes.
Q. And some say that if an impact occurs at a sensitive area, it may be too late.
You understand what I mean by that?

A. Some say that if an impact occurs at the sensitive area, it may be too late?
Q. Well, I can ask the question differently.
A. Okay.
Q. The question I have is: Do you have experience where you have been able to anticipate what a certain observation at a monitoring location means in terms of when an impact will be felt at an environmentally sensitive area?
A. In the case where the monitoring location is not at the -- yes.
Q. And -- and if you wanted -- sorry, strike all the ands. And you can effectively set a trigger knowing that time line might exist between the time of pumping -- the time the pumping is observed at the monitoring well and the time that impact would hit the area of interest; correct?
A. Yes, I'd say it's critical to design a monitoring network to do that.
Q. It is possible to do that, though; correct?
A. Yes.
Q. And you've done that effectively in Owens Valley?
A. In Rose Valley, a different groundwater basin in Inyo County where we've permitted groundwater transfer outside of the Inyo/Los Angeles water agreement, that's the strategy we used.
Q. And that's the strategy you're trying to

implement with Los Angeles and Owens Valley, right?
A. Yes.
Q. I wanted to ask you about something that's been -- GBWN 121. I don't know if you have that in front of you.
A. Yeah.
Q. That's the long-term water agreement.
A. Yeah.
Q. And could you turn to page 18 of that.
A. Yeah.
Q. And again, here's this word "significant," and I want -- I just want to read what it says. It says:
"In determining whether" -- "in determining, one, whether a decrease in live vegetation area is significant or whether a change in vegetation from one vegetation classification to another is significant or whether a significant effect on the environment occurred, it is recognized that it is infeasible to develop definition of these terms for use in all areas and under all conditions."
Then it says:
"Therefore, a determination of what is

Q Okay. Now, isn't it true that all ground water development initially removes water from transitional storage?

A Yes, of course. That's the "Drawdown" column.

Q Isn't it true that at the prior hearing regarding DDC, you testified that you agreed with the statement that within the perennial yield concept, there is an allowance for the development of transitional storage?

A Oh, absolutely. That's well established in even -- in the literature including the State Engineer's literature.

Q Now, you indicated during cross-examination that data from large-scale pumping stresses is not available in Spring Valley, correct?

A That's correct.

Q And you agree that if large-scale pumping stresses were available, your model and other models could be calibrated to represent those pumping activities and the hydrologic responses to those pumping activities; isn't that correct?

A Absolutely.

Q And you agree, do you not, that if that additional calibration occurs, an expert like yourself could make accurate local-scale predictions to the State

Engineer on how pumping in Spring Valley will impact water discharges in Spring Valley and adjacent basins, right?

A The -- the accuracy and precision of the estimates and the modeling would improve with additional pumping data. So I -- so, yes, I agree with your statement.

Q And you believe that a model could be built to make the type of predictions that are local-scale, correct?

A With time, yes.

Q Now I want to quickly go through some of the testimony that you've offered regarding Spring Valley, and then I'll do the same with DDC.

And I want to clarify that in Spring Valley, there's a number of components to the water budget, right?

A Yes.

Q And one of those components is recharge, correct?

A Right.

Q And for recharge in those basins in your model for Spring Valley, you averaged prior studies, correct?

A I -- I estimated the -- I estimated the recharge based upon averaging the prior studies, that is correct.

Q And then for discharge, you did not choose

Typically springs discharge through multiple orifices that are spread over a fairly wide area. Rarely is there one well-defined channel where it is feasible to measure the entire discharge of the spring. Usually one is left with a wet area of perennial vegetation that is supported by the spring discharge. Often the best measure of the total spring discharge is an estimate of the evapotransipiration (ET) of the vegetated area.

Phreatophytes (plants with their roots in the water table) create groundwater discharge from the water table. The plants act like little pumps, distributed across the landscape, discharging groundwater. It is feasible to measure the moisture transferred from a plant colony to the atmosphere. However, one has the problem of distributing the measurement from small plots to plant communities spread across a wide fraction of the landscape. One has to be concerned with both the distribution of plants and their density. Satellite images have improved the mapping of the vegetation, but small plot measurements still have to be extrapolated to the plant distribution. The whole process leads to estimates with uncertainty.

Head measurements are also problematical; they are usually made at one point in time. Only a handful of wells with continuous well hydrographs exist in the region. For most of the single measurements, one has to judge if the data represents the system in a pre-development, or a partially developed state. Head is also subject to measurement errors; often these are quite small relative to the other uncertainties.

The point is that while one might think that certain "hydrologic facts" are known about the systems in question, much of what we think of as data are really estimates with rather high degrees of uncertainty. Given the high degree of uncertainty the older water budget analyses based on some variation of the Maxey-Eakin method seem as valid as some of the new budgets based upon more modern techniques.

MODELS

A simplistic view of groundwater models is that they provide both global and local water budgets though time. The mathematics forces a global, as well as a local water budget. In fact, at any point in the simulated time there is a balanced water budget for every cell in the model domain—so much water in, so much water out, balanced by the rate of change of water into or out of storage within the cell. Conservation of water mass is always maintained in the model.

The groundwater model can also be thought of as creating a sequence of time dependent flow nets. The flow net problem can be non-unique where only head measurements are defined; hydraulic conductivities that have the appropriate relative relationships with one another are possible, without having the corresponding absolute value. This is a long winded way of stating that estimating hydraulic conductivities using the model, a usual procedure, requires that the flow be known at some points within the system being analyzed. This condition dictates that either: 1) the flow be known (or estimated) at as many places as possible in the model (boundaries, pumping, springs, etc.), and/or 2) the hydraulic conductivity be known (hydraulic tests in wells) in as many places as possible. In other words, the better our estimates of flow and/or hydraulic conductivity the more confidence we can have in our model projections (assuming our modeling process is good).

1.4 Availability of Groundwater Data

Bredehoeft (2011a) page 5, states "*Only a handful of wells with continuous well hydrographs exists in the region.*" While this statement does not appear to directly relate to the conclusions derived by Bredehoeft, it is a mischaracterization of current groundwater, stream and spring monitoring data associated with Spring Valley and DDC.

At this time, there are 54 monitor wells in place specific to the monitoring plans in Spring Valley and DDC with continuous recording instrumentation at 23 locations. Thirty-three (33) springs are currently being monitored with continuous discharge or piezometer instrumentation in place at 19 locations. Installation of 12 additional wells with continuous instrumentation is planned in the future prior to project initiation. These wells and springs, coupled with numerous stream discharge continuous gages, provide an expansive baseline hydrologic monitoring program. Data from the Spring Valley and DDC programs are submitted quarterly to NSE and USGS for publication on their respective publicly accessible databases. Continuous and historic hydrographs for monitoring locations in Spring Valley and DDC are included in annual reports submitted to the NSE.

Additional regional data in the vicinity of the project area is collected in Nevada through joint funding agreements with SNWA, USGS, and NSE. Regional data is also collected in western Utah through a joint funding agreement with SNWA and the Utah office of USGS. Other data collection efforts are ongoing in the project area by USGS and the Utah Geological Survey. An example of hydrologic studies in the region include the SNPLMA hydrologic study led by Dr. David Prudic of UNR, which studies surface and groundwater interaction in and near Great Basin National Park. The study included evaluation of hydrogeologic conditions of in the vicinity of Big Springs. The preliminary study results were summarized at a public meeting in Ely on August 16, 2011 (Prudic, 2011).

1.5 Identification and Examination of Mitigation Alternatives

Bredehoeft (2011a), p.8 again mischaracterizes model results as he states the "Given that the models all project similar results, some or all of these measures will need to be considered." As discussed in Watrus and Drici (2011), widespread impacts are not the consensus from all models. Bredehoeft dismisses any form of mitigation, does not consider adaptive management practices, or remedies for specific impacts which are available. Examples include modification and optimization of well field operations, artificial recharge of excess peak streamflow or rejected recharge, and use of SNWA non-project surface and groundwater water rights for mitigation. He does not consider the lowering of pumps and deepening or replacement of wells which may be impacted. He also does not consider alternative mitigation measures available for springs such as discharge flow augmentation or other measures such as habitat restoration, improved and/or modified grazing and irrigation practices to benefit target species and habitats as explained in Marshall and Luptowitz (2011).

Rejected recharge and excess flood streamflow in Spring Valley are discussed in Rush and Kazmi, 1965. Substantial volumes of runoff have been documented reaching Yelland Dry Lake and to a lesser degree Baking Soda Flats. A photo of Yelland Dry Lake taken in July 2011 is presented in Figure 10. SNWA has performed volumetric estimates of water volume present on Yelland Dry Lake over several decades using satellite imagery. The estimated volume in just Yelland Dry Lake in July

Figure 10

Yelland Dry Lake Photo from Taft Creek (July, 2011)

SNWA_Exh_428

WALKER LAKE, NEVADA—Environmental Coalition
Walker Lake, a remnant of Pleistocene Lake Lahontan, declined from a volume of 8,600,000 ac-ft in 1882 to less than 2,000,00 ac-ft today. The decline was caused by irrigation in the Walker River Basin diverting water that originally flowed to the lake. As the lake declined in volume, the total dissolved solids in the lake water rose from 2,500 to 16,000 mg/l. The environmental community is attempting to save the ecosystem in the lake that includes Lahontan Cutthroat Trout. This is a classic western water problem in which irrigators, Indians, and environmentalist are competing for the available water. Bredehoeft was the hydrologic consultant to the Western Environmental Law Center, whose clients are trying to save the lake and its ecology.

FOUR CORNERS GROUNDWATER, Montana—Trout Unlimited, Montana Department Conservation
Groundwater is being pumped to support a development in the Four Corners area, near Bozman, Montana. Pumping groundwater impacts the nearby Gallatin River. A deal was struck, in 2006, in which surface water was recharged to the aquifer to fully offset the impact of the pumping on the river. This was the first time in Montana that the impacts of groundwater pumping on a stream were recognized, and fully offset. Bredehoeft did the groundwater analysis.

PUMPING GROUNDWATER FOR LAS VEGAS—Environmental Coalition
The Southern Nevada Water Authority in attempting to pump 150,000 acre-feet/year of groundwater in an area near Ely, NV that will be piped to Las Vegas for water supply. Much of the groundwater will come from the regional Paleozoic Carbonate Aquifer that underlies the area. Environmental consequences will result from the groundwater pumping. Bredehoeft testified in opposition to the project at the initial Nevada State Engineer hearing that granted permits for the project.

DECOMMISSIONING NUCLEAR FACILITIES, WEST VALLEY, New York—NYSERDA & DOE
Nuclear fuel rods were reprocessed at a facility at West Valley, NY. On the facility grounds are nuclear burial sites that are supervised by both the State of New York and DOE. The U.S. Congress instructed DOE to cleanup the site. Bredehoeft participated on a committee that reviewed the decommissioning plan of DOE for the major facilities at the site.

PINE COVE WATER DISTRICT, California—Environmental Coalition
There was a dispute between the local water company and the environmental community over how much groundwater should be pumped from a newly purchased well field. Bredehoeft proposed a compromise between the groups that was accepted.

DICKSON COUNTY LANDFILL, Kentucky—Environmental Defense Fund
The landfill creates TCE contamination in an underlying carbonate aquifer. Bredehoeft reviewed the thesituation for EDF.

OWENS LAKE DUST CONTROL, CITY OF LOS ANGELES—MWH
Bredehoeft was a member of a 5-member expert panel that advised the project on the availability of groundwater for dust abatement of the lake.

MOUNTAIN SPRING, YELLOWSTONE NATIONAL PARK—Federal Highway Administration
There was a problem with sediment in a spring associated with a gravel mine in the park. Bredehoeft advised on the source of the sediment in the spring.

127 Toyon Lane, Sausalito, CA 94965
(415) 332-0666
jdbrede@aol.com
jd.bredehoeft@gmail.com

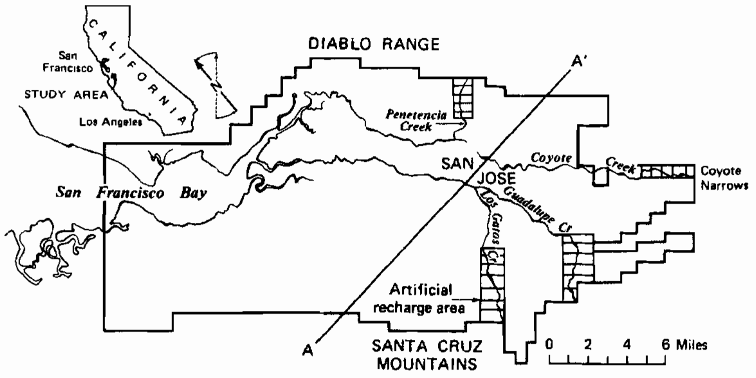


Figure 1. Map of Study Area with Location of Artificial Recharge Areas.

from the Sierras. The volume of annual artificial recharge increased significantly in 1965 when water from the South Bay Aqueduct of the California Water Project became available. Currently, an average of 140,000 acre-feet of water is imported annually.

Associated with the extensive pumping of groundwater in the Santa Clara Valley has been land subsidence due to compaction of fine-grained materials in the basin. This subsidence has been discussed in great depth by Poland (Poland and Green, 1962; Poland and Davis, 1969). Figure 2 shows estimated subsidence in the northern Santa Clara Valley for the period from 1934 to 1967. Water levels recovered significantly in the late 1960's and early 1970's. Poland (1978) attributed this recovery to a combination of increased availability of imported water, favorable climatic conditions, decreased pumpage, and increased recharge. Associated with the rise in water levels was a halt to additional subsidence. Land that had already subsided, however, did not recover.

Hydrogeology

Of greatest hydraulic significance in the Valley are the quaternary alluvial deposits. Coarse sand and gravel are mainly found in abandoned stream channels near the outer margins of the basin. Materials become finer toward the Bay. Figure 3 shows a geologic cross-section across the valley. The discontinuity of the deposits is typical of the structure within the alluvium. This heterogeneous nature of the alluvium leads to a rather complicated groundwater flow sytem.

Groundwater conditions along the margins of the valley are essentially unconfined and it is there where most natural recharge occurs and where all the artificial recharge facilities are located (see Figure 1). Toward the center of the valley, as the amount of fine-grained deposits increases, groundwater conditions become confined. Most of the groundwater development has occurred near the center of the valley, where the alluvium is thickest.

GROUNDWATER MODEL

Leaky Aquifer Formulation

To model the system, numerous simplifications had to be made. The flow regime was treated as two layers: a confined aquifer and a water table aquifer separated by a confining unit. Only heads in the confined unit were active; heads in the upper unconfined unit were held at constant values which were set as a subdued replica of the land surface topography.

A leaky aquifer formulation was adopted in which flow between the two aquifers is a function of the relative hydraulic heads as well as the thickness and vertical conductivity of the confining layer. To account for the fact that there are numerous layers of clay rather than one large unit, the system was idealized as a confined aquifer containing a series of 10-foot-thick clay layers and overlain by an upper clay unit with a thickness equal to 10 percent of the total clay thickness. It was assumed in the model that communication between the unconfined and confined aquifers occurs only across the upper clay unit. Land subsidence was considered to be due to transient leakage from the series of 10-foot thick clay layers. Figure 4 is a schematic representation of how the hydrologic system was conceptualized.

Original input data for the groundwater model used in this study was based, to some extent, on previous unpublished work done by Perry Wood at the U.S.G.S. The actual code used was a slightly modified version of the alternating-direction-implicit finite difference model of Bredehoeft and Pinder (1970).

Transient Leakage Routine

The land subsidence described earlier represents compaction when water is released from storage in the fine-grained layers. A subroutine was included in the groundwater model to account for the transient leakage of water from the clay units. Bredehoeft and Pinder (1970) suggested a routine for modeling the transient leakage from a single clay layer in response to changes in head at one boundary. In the Santa Clara Valley,

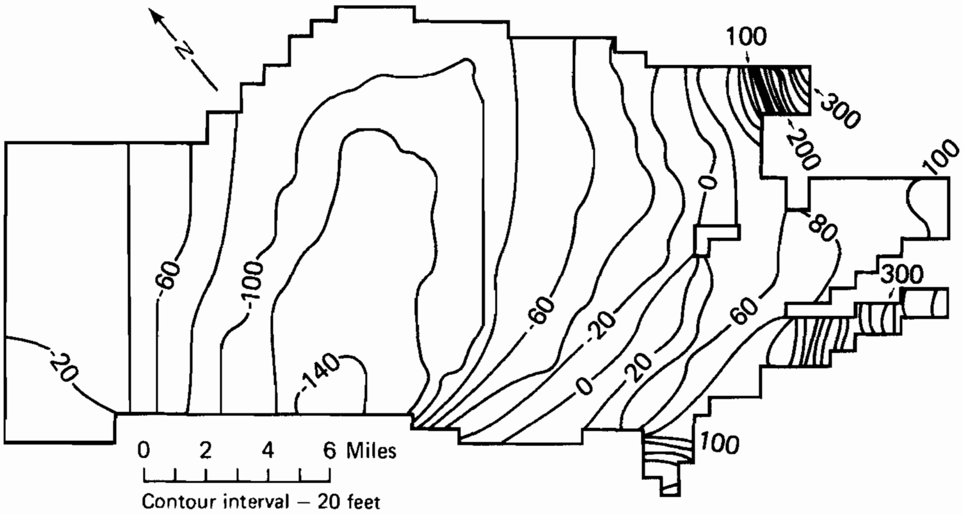


Figure 8. Model-Calculated Groundwater Levels at the End of 40 Years Without Artificial Recharge (elevation above mean sea level).

Comparison of Figures 7 and 8 indicates that the artificial recharge program in Santa Clara Valley has maintained hydraulic heads at a significantly higher level than they would have been otherwise. Resulting land subsidence was also computed for both runs. There was no additional subsidence with artificial recharge. Total additional subsidence for the entire period without artificial recharge averaged 1 foot in the center of the valley.

The model results suggest that the system could achieve steady state with no artificial recharge, without drastically drawing down water levels. As the model is formulated, all 150,000 acre feet of annual pumping is drawn from leakage from the constant water table. The key question is whether there is actually enough water available from streamflow, direct rainfall, and return flow from lawn and agricultural irrigation to provide this quantity of water. A water balance for the basin indicates that such a long-term annual rate of recharge is not unreasonable. The fact that water levels remained nearly constant in the early 1960's, when there was much less artificial recharge and average annual pumpage of more than 180,000 acre feet, also indicates that considerable natural recharge can be induced in the Valley. However, an institution responsible for providing water supply for a region is also concerned with possible future increases in groundwater demand and the occurrence of such extreme events as droughts.

In the Santa Clara Valley, 150,000 acre feet per year is probably close to the limit of natural plus man-induced recharge in the basin. Since there is uncertainty as to how much more could be supported, artificial recharge provides a useful buffer against future increases in pumping. Such increases in pumping could occur as a result of a regional increase in water demand or from a decrease in the supply of imported water. In addition, the SCVWD is responsible for attempting to meet water demands every year, including periods of drought. The added storage provided by artificial groundwater recharge allows the basin to withstand a longer drought than it would otherwise be able to do. In the economic analyses described below, only the benefits of average reductions in pumping lifts and subsidence are quantified. In actually determining the utility of an artificial recharge program, however, consideration should also be given to these sorts of potential hydraulic risks.

An estimate of the hydraulic effects that could result from a drought was obtained from the groundwater model. To simulate periods of water scarcity, leakage from the water table was allowed only along the margins of the basin. Two additional runs were carried out for both the "with artificial recharge" and "without artificial recharge" cases. Results show that water levels without artificial recharge would fall to as much as 350 feet below sea level, whereas with artificial recharge, no water levels were below –200 feet.

ECONOMIC ANALYSIS

The following two analyses are based on the results of the groundwater simulations described above. As in those simulations, 1966 groundwater levels are taken as initial conditions.

Analysis 1: Artificial Recharge vs. No Project

Economic Value of Reduced Pumping Lifts and Reduced Subsidence. This first analysis considers benefits associated with a reduction in the net rate of pumping. In the Santa Clara Valley, these benefits relate to reduced pumping lifts and reduced land subsidence. The benefits of reduced pumping lifts are calculated in terms of savings in energy costs. A 100 percent efficient pump would require 1.02 kwh to lift discharge. We can move the pumping to a new location further away from say a spring in an effort to minimize its impact. However, if the spring is within the zone of ultimate groundwater drawdown eventually it will be impacted. In the end, moving the pumping is simply a method of delaying the ultimate response—in the vernacular it is a means of ***kicking the can down the road.***

2. **Augmentation:** If we assume that the pumping is already at the perennial yield, then augmenting a local user means diverting water that would normally be put into the pipeline for local use. Presumably this would entail some small fraction of the total quantity pumped. This measure does not seem to be intended to keep widespread areas of vegetation that are impacted by declines in spring discharge, or phreatophyte use, alive.
3. **Recharge:** Currently in the valleys under consideration all of the available water for recharge to the groundwater system is being recharged naturally. It is hard to imagine how one might increase the recharge over what is already occurring—all the water available to the system is currently utilized naturally. It is implausible to presume that once Las Vegas has invested billions to export water from these valleys that water would in turn be imported into the impacted valleys to artificially create additional recharge.
4. **Cloud Seeding:** This always seems to be mentioned as an additional source of water for the system. Perhaps it is—most discussions I have heard suggest that one might get, at best, an increase in precipitation of 10%, or so.
5. **Reducing or Ceasing to Pump:** While feasible, this seems the most unrealistic management alternative of all those suggested. Let's presume that SNWA, a public agency, builds a multibillion dollar project to pump and deliver groundwater to Las Vegas, a city of now two million people. I cannot imagine that any future State or Federal Agency will have the political will to stop pumping in order to save the vegetation or protect the livelihoods of the people in these rural valleys. If the projected impacts, as portrayed in the Draft EIS, are insufficient to prevent the project from going forward now, I cannot imagine that in the future those impacts would be perceived as so much more dire as to lead to the curtailment of pumping once so many billions of dollars have been invested in the project and so many Clark County residents have been encouraged to grow dependent on the groundwater from years of pumping.

Geographic Redistribution of Pumping Between Valleys

There is another suggestion talked about of pumping in a particular valley until an adverse impact occurred, and then stopping pumping, resting the valley until it can recover. Once the valley had recovered one would pump again. I addressed this problem (Bredehoeft, 2011) and showed that the time for the valley to fully recover from a period of pumping is very long.

One can illustrate the recovery problem like this: I simulated a rather large valley with a thick alluvial fill aquifer where the recharge averaged 100 cfs, and prior to development a spring at the lower end of the valley discharged at 100 cfs—the system was in balance. I then imposed pumping of 100 cfs on the system some 50 miles up the valley away from the spring, midway in the valley. After 70 years the pumping caused the spring flow to decline by 10% to 90 cfs, at which point I stopped the pumping. It is instructive to examine the water budget for the system in the 70th year of pumping, and in the 71st year just after pumping stopped.

Table 2. Water budgets 70th year (pumping), and 71st year (stopped pumping)