REPORT ON THE HYDROGEOLGY OF

PROPOSED SOUTHERN NEVADA WATER AUTHORITY

GROUNDWATER DEVELOPMENT

Prepared for Office of the Nevada State Engineer
on behalf of
Great Basin Water Network

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FIRST PRINCIPLES

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

Water withdrawn artificially from an aquifer is derived from a decrease in storage, a reduction in the previous discharge from the aquifer, an increase in the recharge, or a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

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

When pumping occurs, the hydraulic head in the groundwater system declines. As the head declines, water is removed from storage in the aquifer. At some point the hydraulic head declines in the vicinity of the discharge from the system, and the discharge is reduced—in Lohman's words captured by the pumping. This means that in the vicinity of phreatophyte plants that draw water directly from the water table, the water table declines, and the plants can no longer get water, and they die. The head decline produced by the pumping lowers heads in the vicinity of springs, and the spring flow declines. The head declines in the vicinity of streams that receive groundwater that creates baseflow, and the streamflow declines (Bredehoeft, 2002).

As the definition of capture implies, water will be drawn from storage until the pumping can be fully balanced by the capture. The State Engineer of Nevada (1971) acknowledged this in a Statement in Water for Nevada--Bulletin 2:

Transitional storage reserve is the quantity of water in storage in a particular ground water reservoir that is extracted during the transition period between [initial] *equilibrium conditions and new equilibrium conditions under perennial-yield concept of ground water development.*

In the arid environment of Nevada, 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).

… The transitional storage reserve estimates for the regions are based upon an average dewatering of 30 to 40 feet of the valley-fill reservoir. These values are shown for each region in Table 1-A…

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).

Basin	Recon Report or Water for Nevada	Flint et al (2004) (mean year)	Flint et al (2004) (time series)	Flint and Flint (2007)	LVVWD (2001)	Kirk and Campana (1990)[2]
Cave Valley	14000	10264	9380	11000	19500	11999
Dry Lake Valley	5000	10627	11298		13300	6664
Delamar Valley	1000	7764	6404		4600	1926
White River Valley	38000	34925	30759	35000		35001
Pahroc Valley	2200	4432	4832			1994
Pahranagat Valley	1800	7043	7186			1508
Coyote Spring Valley[1]	1900	5184	5951			5344
Kane Springs[1]	500	5421	6328			997
Garden/Coal Valley	12000	21813	18669			10994

1 - The recon report estimated 2600 af/y for Coyote Spring and Kane Springs Valleys together. The estimates here are from Water for Nevada.

2 - Values adjusted from m^3/s

	Snake Valley	Spring Valley	Steptoe Valley	Tippett Valley	Deep Creek
Reconnaissance Reports (Hood and Rush, 1965; Rush and Kazmi, 1965; Eakin et al, 1967; NV Div of Water Resources, 1971)	103	75	85	7	17
Watson et al (1976)		63	75	5	
		33	45	6	
Nichols (2000)		104	132	13	
Epstein (2004), as referenced in Welch et al (2008)		93	101	9	
Dettinger (1989)		62			
Flint and others (2004)	93	67	111	10	12.3
	82	56	94	8	11.4
Brothers et al (1993 and 1994), as referenced in Welch et al (2008)	110	72			
Flint and Flint (2007); Welch et al (2008)	111	93	154	12	

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).

In the early days of models, calibrating a model (matching model output to hydrologic "facts") was done by trial and error. As the models became more complex the calibration procedure was automated. There are several widely used automated schemes to do the calibration. Care is required in adjusting the model variables to their target values even with automated procedures.

The usual model strategy is to decompose the problem into two parts:

1. Steady flow in the system prior to any development is simulated with the intent of adjusting primarily the internal hydraulic conductivities.
2. Once a hydraulic conductivity distribution is determined, then transient model runs are made with the model, usually to fit a history of known development.

Commonly one has to iterate back and forth with these procedures until a "satisfactory" fit between simulated and "known" data are achieved. Once the model meets these tests to the analyst's satisfaction, projections of future states of the system are made.

The models are known to be non-unique. Future projections have varying degrees of uncertainty. Nevertheless, these are virtually the only realistic tools available to the hydrogeologist/engineer with which to estimate future impacts in both space and time (Konikow and Bredehoeft, 1992).

EXISTING MODELS—Projected Impacts

As suggested above there are at least three models that have been used to estimate the impact of the SNWA development upon the hydrology of the valleys in question—Spring, Cave, Dry Lake, and Delamar Valleys:

1. Durbin's model in the Cave, Dry Lake and Delamar State Engineer's hearing (Bredehoeft and Durbin, 2009)
2. BLM (2011)
3. Myers (2011)

These models were developed using different techniques. Durbin used a finite-element approach; his model layers were based upon the geology and followed the "aquifers" and other hydrogeologic units. SNWA (BLM, 2011) used a finite difference model approach in which the layers were topographically based slices of the crust in which the hydrogeologic properties corresponding to each grid cell, in three dimensional space, was input into the model—there was no attempt for model layers to follow "aquifer," or geologic layer boundaries. This was an approach used by the USGS in its regional aquifer model for the Nevada Test Site and the Yucca Mountain proposed nuclear repository. Myers (2011) used a similar modeling approach to that used by SNWA. Other than Durbin, all the modelers used the USGS model code MODFLOW to make the analyses.

There are differing procedures for making future projections with the model. The simplest procedure is to simply run the model out into the future, evaluating various scenarios of development. A second method is to calculate the drawdown created by only the proposed development. This procedure is analogous to assessing the drawdown produced in a pumping test—one looks only at the drawdown created by the pumping. This isolates the impacts of the 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

Muddy River Springs. Delamar Valley is 50 miles, or so, north of the Muddy River Springs, while Dry Lake is 100 miles to the north. The current SNWA model suggests that there will be no impact on the Muddy River Springs from the pumping within the simulated 200-year planning horizon. However, we know from first principles that sooner or later the springs will be impacted by the pumping—the pumping will ultimately capture the spring flow.

However, it is infeasible to monitor the Muddy River Springs and discriminate a pumping signal created by the pumping in these valleys (Bredehoeft, 2011). The drawdown caused by the SNWA pumping will be superimposed on drawdown from other pumping that impacts the springs, as well as long-term variation in recharge to the system, including the impacts of climate change. It is a virtually impossible signal discrimination problem. It can only lead to arguments among the various interest groups of ***"what/who caused each observed decline in spring flow".***

The monitoring can also be full of surprises. For example: as suggested above, the current conceptual model has the recharge from Delamar Valley providing outflow to the Muddy River springs. However, the Pahranagat shear zone is an east-west geologic feature that cuts across the south end of the Delamar Valley. Eakin's (1966) concept was that the springs in the Pahranagat Valley were fed by the outflow from Delamar Valley.

The plumbing system within the Carbonate Aquifer is not well understood. We know that there are wells drilled into the Carbonate Aquifer that produce large amounts of water with very little drawdown in the short term; so there must be very permeable conduits within the aquifer at least locally. One can also imagine that the conduits extend great distances in the aquifer—perhaps the plumbing system in the Carbonate Aquifer is dominated by a network of highly permeable conduits. One can only speculate given the available data; nevertheless, one can anticipate the monitoring to provide surprises.

MITIGATION

The Draft EIS lists five adaptive management measures that might be implemented to mitigate undesirable impacts:

1. Geographic redistribution of groundwater withdrawals
2. Augmentation of water supply for Federal and existing water rights and Federal resources using surface and groundwater sources
3. Conduct recharge projects to offset local groundwater withdrawals
4. Implement cloud seeding programs to enhance groundwater recharge
5. Reduction or cessation in groundwater withdrawals

Given that the models all project similar impacts, some or all of these measures will need to be considered. Let's assume that the SNWA project is fully implemented, and groundwater is being pumped from each of the valleys at the State Engineer's specified perennial yield. Given this assumption we can examine the implications of the adaptive management measures:

1. **Relocate Pumping:** The drawdown created by pumping will spread outward in an attempt to capture the discharge—for example, spring flow, or phreatophyte plant groundwater

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)

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.

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