White Pine County Exhibit II

Report on the Known Economic Market and Non-Market Values of Water in Nevada's Spring, Cave, Dry Lake, and Delamar Valleys

Submitted by:

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June 30, 2011

Introduction

This report briefly enumerates and explains the economic values of the agricultural and recreational uses of water, as well as the 'existence value, also known as the non-use of water, in four valleys in the state of Nevada. The report also updates the existing estimates of the economic losses that are likely to result from the proposed withdrawal of groundwater from these valleys by the Southern Nevada Water Authority (SNWA). The Spring Valley Basin and Cave Valley Basin are in both White Pine and Lincoln Counties. Dry Lake and Delamar Basins (or watersheds) are in Lincoln County.

Figure 1 is a map showing the four basins in the two counties. Maps in the appendices show the associated communities, ranches, recreational, and other relevant sites. The four valleys host resident ranchers, thousands of acres of irrigated pastures and cropland, and public grazing land that support thousands of head of cattle and sheep. The valleys are also home to thousands of head of big game, springs, lakes, dozens of fishable streams, and a dozen unusual or endangered species of fauna and flora. Thus the area is also a recreational destination used by hikers, bikers, birdwatchers, nature photographers, and hunters from across the state and around the world.

All these activities and attractions are the basis of the livelihoods of about 6,000 people, plus public sector employment for about 1,000 more individuals. As this report shows, the water withdrawals may undermine employment of over 3,000 people, causing the unemployment rate in **White Pine County to rise to 53%** from 8% in April 2011, and **Lincoln County's unemployment rate to rise to 46%** from 12% in April, 2011.

Clearly the proposed water withdrawals would devastate the local economies. The relocation of the humans from the areas dependent upon the water would also add to the current unemployment burdens in other Nevada counties or states that the people displaced from White Pine and Lincoln counties relocate to.

Water cannot be in two places at once. If it is piped to the Las Vegas area it would not be available to maintain the pastures, cropland, streams, wetlands, forests or the water table in the basins of origin and downgradient basins that depend on interbasin flow from the basins of origin. Guzzlers would go dry. Livestock and game would not be able to graze. The fragile ecosystem would be altered and flora and fauna populations would dwindle. The water withdrawals could turn the region into an uninhabitable wasteland

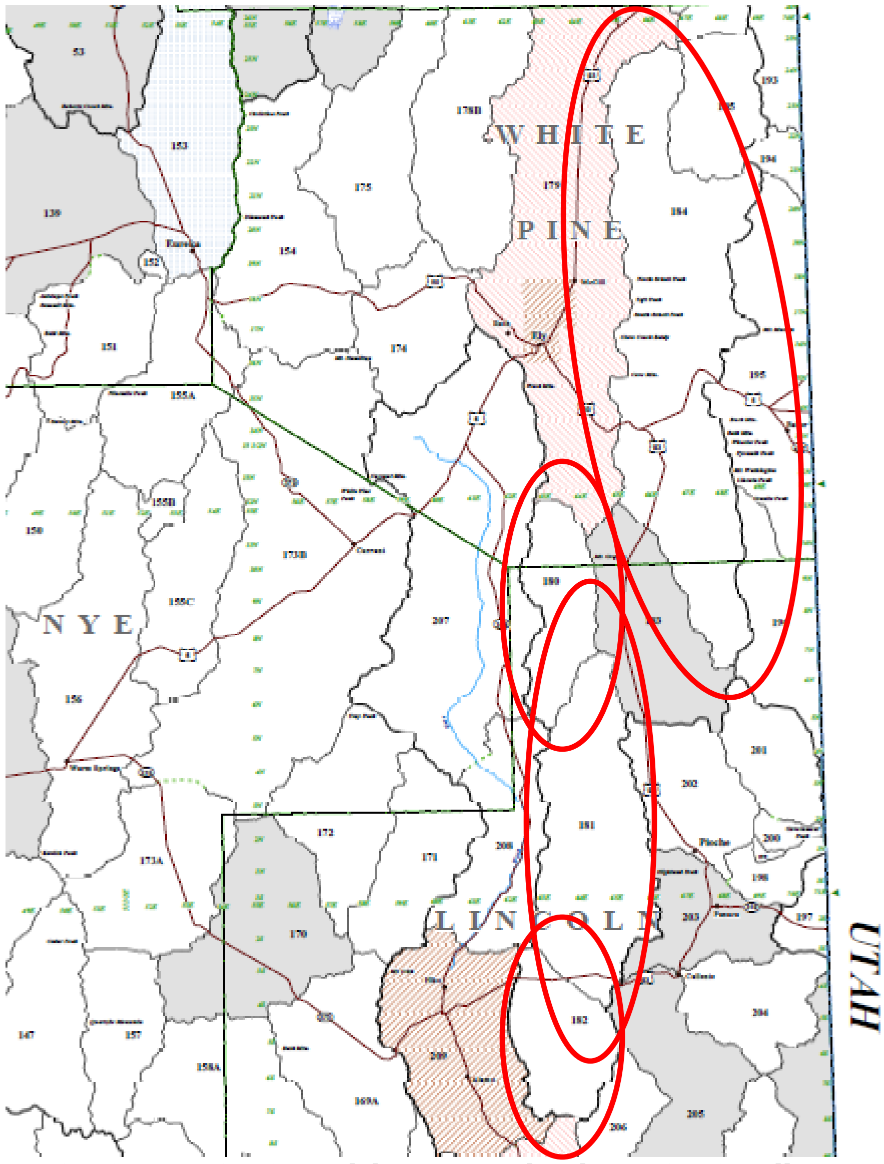


Figure 1. Spring (184), Cave (180), Drylake (181) and Delamar (182) Valley Basins
Source: State of Nevada http://water.nv.gov/mapping/maps/designated_basinmap.pdf.

Although the natural and human communities in the basins are **priceless** in terms of the historical and cultural heritage they contribute to Nevada and the nation, and in terms of the biological and economic diversity they support, one is required to estimate the dollar values for use in deciding whether the loss of these values is reasonable as part of the price of SNWA's proposed groundwater withdrawal. However, it should be borne in mind that such an attempt to quantify these values in simple dollar terms carries a high risk of undervaluing them. This report updates all economic measures of industry or market uses of water in agriculture, hunting, and recreation. It updates or summarizes the existing estimates of the indirect or interindustry market economic values at stake due to the proposed water withdrawals as well. Furthermore, it summarizes the most recent estimates of the non-market values of the water resources and amenities in the counties where the basins are.

Water resources in a place provide at least five types of economic values. The first is the value of the industrial use of the water, measured by the income and employment directly related to the use of water by businesses such as agriculture and mining. The second is the market value of the use for recreational purposes, measured by the expenditures of the hunters and recreational users required to enjoy the natural resources. The third economic value is the interindustry spillover, measured by the indirect or inter-industry multiplier linkages that arise when businesses or people involved in direct use buy local inputs or services, or pay local employees.

The fourth is the *non-market* use value that people who visit the areas derive from experiencing the natural amenities, which are difficult to measure because no expenditure is required to use or directly experience them. The fifth benefit is the value that people anywhere -- even people who never visit the area or directly use the water -- place on the existence of the natural amenities in the place. This last type of economic benefit is the "existence" or "non-use" non-market value.

This report includes a summary of the existing non-market valuation of the uses and non-uses or existence values of the water-based natural resources and amenities in the four valleys. As noted by Moeltner (2006), non-market valuation became an essential aspect of environmental economic analysis in 1989, when a federal court of appeals ruled that non-use values should be included in environmental damage assessments and instructed the Department of the Interior to redraft the CERCLA stipulations (Mathis et al., 2003). CERCLA is the 1980 Comprehensive Environmental Response, Compensation, and Liability Act. It is administered by the Department of the Interior (DOI) and the U.S. Environmental Protection Agency (EPA). In 1992 a "Blue Ribbon" panel of economic experts convened by NOAA officially confirmed the legitimacy of non-market valuation techniques to assess environmental assets and damages within judicial process (Jones, 1997). Since then, non-market valuation has been employed in numerous legal proceedings around the country, including water management disputes (e.g. Loomis, 1997).

The report proceeds as follows. A summary of the five measures is presented in Table 1, below. The next section documents the people, places, and economic activities occurring today in the area of the basins, by county. The third section details the economic value of the ranching, hunting, tourism, picnicking, and other uses of the water in each basin that would be lost if the water is withdrawn. The fourth section presents the dollar *non-market* use values, and the non-market *existence,* (or non-use) *values* of the water-related natural amenities in one of the basins that would be lost if the water is withdrawn, as well as the discounted present value.

Table 1 summarizes all five types of economic values of the water in the four basins that have been estimated to date. . The **overall annual value is $74 million, which has a cumulative discounted present value of $2.85 billion** at 2% discount rate over the SNWA's 70 year planning horizon. Note that this amount includes only the values of the portions of the resources in the four valleys that have been measured to date. It is therefore an incomplete measure that <u>underestimates</u> the economic value of the water in the four valleys.

Table 1. Summary: Market and Non-Market Value of Water in the Four Basins					
activity	type			Measure or approach	Annual value
Agriculture	Use	market	direct	production revenue	$30,511,000
			interindustry	Input-Output	$22,273,030
Hunting	Use	market	direct	expenditures	$4,900,000
			interindustry	input-Output	$3,000,000
Park Visitation	Use	market	direct	expenditures	$6,750,000
			interindustry	Input-Output	$4,000,000
Recreation	Use	non-market	direct	benefit transfer	$756,000
Existence	non-use	non-market	direct	benefit transfer /meta regression	$2,000,000
				Total:	$74,190,030
Source: tabulated by author					

2. People, Places, and Economic Activity Status Quo

2a. White Pine County spans 8,876 square miles or 5.6 million acres. According to the 2010 Census, 10,030 people live in White Pine County. The county population grew 9.2% from 2000 to 2010. There are over 3,600 households and over 4,500 housing units.

The most recent official statistics indicate that 5,074 people worked in public service, as private business employees, or self-employed. They worked in 893 private firms, farming operations, and 752 non-farm establishments (See Figure 2. for data sources).

The State of Nevada's Department of Agriculture reports that in 2008 there were 97 ranches or farms in White Pine County, raising 22,000 head of cattle, 18,000 head of sheep; and 12,000 acres of alfalfa hay yielding 43,000 tons. (Nevada Agricultural Statistics, 2009; http://www.nass.usda.gov/Statistics_by_State/Nevada/Publications/Annual_Statistical_Bulletin/-Bulletin_Complete_with_Cover_09.pdf).

Figure 2 presents the most recent data on employment by sector in White Pine County, compiled using all four data sources, and reconciled to total the Burea of Economic Analysis (BEA)'s 2009 official total employment count. The legend reports the number of employees or self-employed persons in each sector and the percentages show each sector's relative contribution. For example, 11% of the jobs, or 535 people are employed or self-employed in hotel and restaurant businesses in White Pine County.

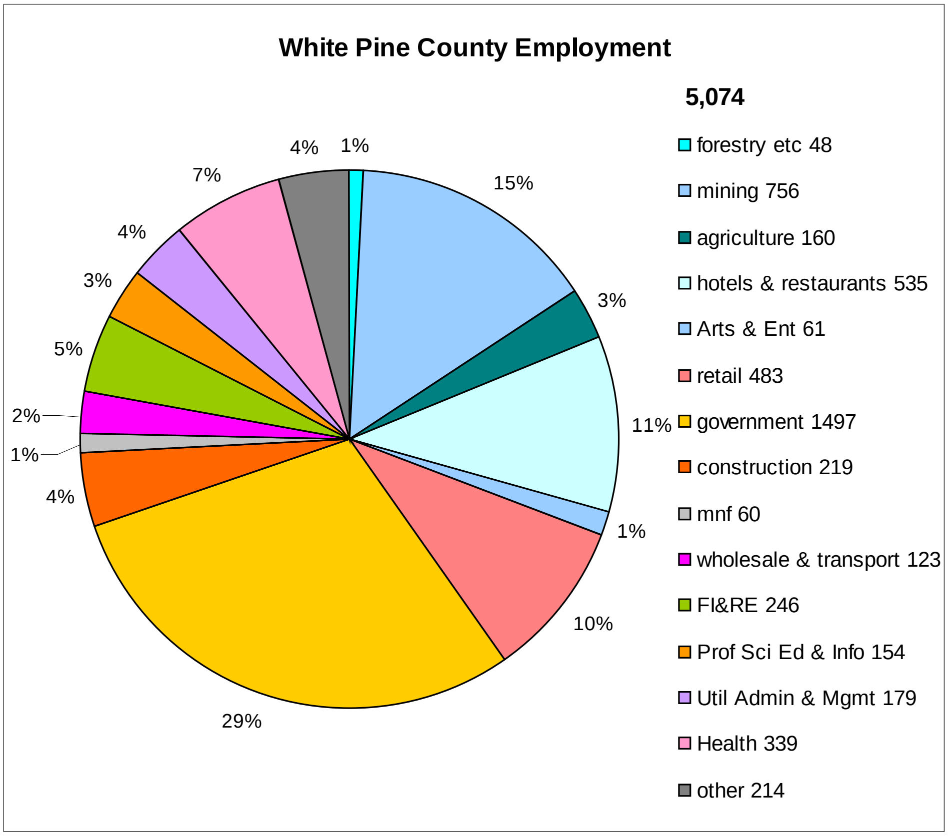


Figure 2. White Pine County employment by sector, 2009
Data Sources (reconciled by authors & used to estimate non-disclosed counts)
Bureau of Economic Analysis, 2009 Total Employment by NAICS Sector,Table CA25N
http://www.bea.gov/iTable/iTable.cfm?reqid=70&step=1&isuri=1&acrdn=5
2008 County Business Patterns http://censtats.census.gov/cgi-bin/cbpnaic/cbpsect.pl
2008 Non-Employer Statistics http://censtats.census.gov/cgi-bin/nonemployer/nonsect.pl
2007 Census of Agriculture http://quickstats.nass.usda.gov/?source_desc=CENSUS

19% of the jobs, which is more than a quarter of White Pine County's *private sector* employment (27%, not shown) depends directly on water in the County. The sectors that would not be there without the local water are mining, ranching and farming, forestry and hunting sectors. Clearly associated with these are the tourism and recreation activities in the county such as hotels, restaurants, and the retail activity that accommodates the hunters and tourists in the area. Without the employment in all those sectors (57% of the *private* economy, not shown), it is possible that there would *be virtually no economic activity at all* in the county. The loss of that large a percentage of the economic base or activity in the county could well pass a tipping point that would undermine the viability of any other economic activity.

The proposed water withdrawals would directly displace 1,503 working people and farmers, and 1,173 people from linked sectors, according to the 1.78 employment multiplier estimated by Harris and Wright (2004). The estimated total employment impact would be 2,676 jobs lost in the county. If the displaced workers stay in the county, the proposed water withdrawals would **raise White Pine County's unemployment rate to 53%** from 8% (April 2011 county unemployment levels and rate source: NV DETR).

2.b. Lincoln County contains 10,633 square miles of land area, and 6.8 million acres. According to the 2010 Census, the population of Lincoln County was 5,345. Its growth rate of 28.3% since the year 2000 was much faster than the U.S.-wide 9.7% decennial rate of population growth. There are 1,480 households and 2,300 housing units in the County.

According to the most recent (2009) data there are about 2,172 people working in Lincoln County, of which 131 people are in the public sector, on agricultural operations, or in about 409 private firms as sole proprietors or employees in about 377 establishments (see Table 3 for data sources.) The State of Nevada Department of Agriculture reported that in 2008 there were 98 ranches or farms in Lincoln County raising 16,000 head of cattle, 800 sheep; and 12,000 acres of alfalfa hay yielding 63,000 tons (Nevada Agricultural Statistics, 2009; http://www.nass.usda.gov/-Statistics_by_State/Nevada/Publications/Annual_Statistical_Bulletin/Bulletin_Complete_with_Cover_09.pdf).

Figure 3 presents the most recent data on employment by sector in Lincoln County, compiled using all four data sources, and reconciled to total the BEA's 2009 official total employment count. Ten percent, or about 13% of the county's employment in *private* sectors (not shown), depends directly on the water remaining in the county. The sectors that would not be there without the local water are mining, ranching and farming, forestry, hunting and recreation. Indirectly, all sectors, but especially the hotels, restaurants, and retail activity are dependent on the water without which there would not be recreational users, farmers, or ranchers in the area.

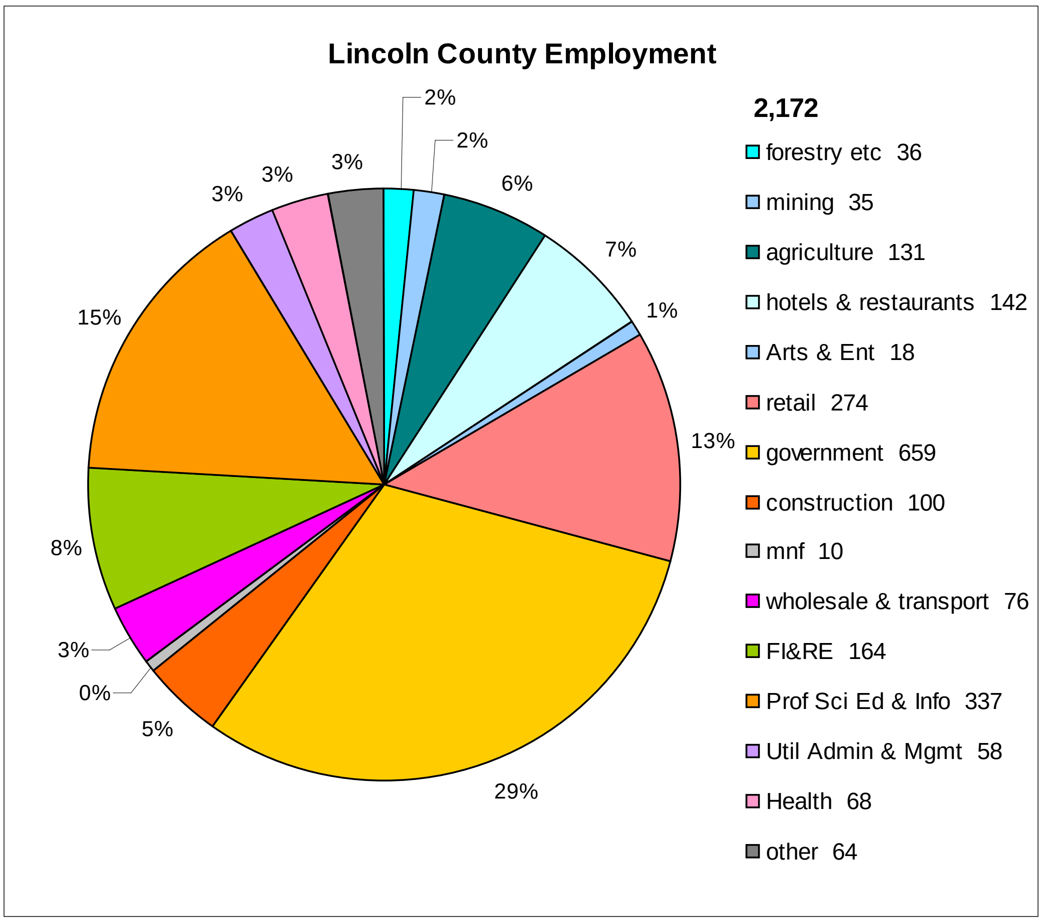


Figure 3. Lincoln County Employment by sector, 2009.

Data Sources (reconciled by authors & used to estimate non-disclosed counts)
Table 3 data sources, continued:
Bureau of Economic Analysis, 2009 Total Employment by NAICS Sector, Table CA25N
http://www.bea.gov/iTable/iTable.cfm?reqid=70&step=1&isuri=1&acrdn=5
2008 County Business Patterns http://censtats.census.gov/cgi-bin/cbpnaic/cbpsect.pl
2008 Non-Employer Statistics http://censtats.census.gov/cgi-bin/nonemployer/nonsect.pl
2007 Census of Agriculture http://quickstats.nass.usda.gov/?source_desc=CENSUS

The proposed water withdrawals would directly displace 419 people from their jobs in agriculture and hunting and recreation sectors, 327 people from jobs in linked sectors, to total an estimated loss of 746 jobs. A **deterioration of employment of that magnitude would raise Lincoln County's unemployment rate to 46%** from the current rate of 12% (current unemployment data source: NV DETR).

3. Economic Use Values

3.a. Agriculture

As noted above, of the five types of economic values of water-based ecosystem services, the first type is measured by the income from their use. The second is measured by the indirect inter-industry multiplier linkages that arise when the businesses serving the using industries buy other inputs and pay local employees. Agriculture-- alfalfa cropland and ranching --are the first of the water using industries we analyze. Table 2 summarizes the latest data about agriculture in the two counties.

Table 2. Census of Agriculture Lincoln and White Pine Counties	White Pine Co.	Lincoln Co.	units
Total Land Area	5,680,349	6,804,896	acres
Pasture Land	167,266	21,877	acres
Area In Farm Operations	113,147	44,648	acres
Irrigated	30,877	18,320	acres
Cropland	23,756	17,903	acres
Ag Woodland	1,551	368	acres
Total Commodity Sales	$15,172,000	$15,339,000	dollars
Total Animal Sales	$10,836,000	$7,649,000	dollars
Avg. Net Cash Farm Income	$32,131	$21,063	dollars/op
Hired Labor	193	120	workers
Ag Operations	97	98	operations

Source: USDA National Agricultural Statistics Service (NASS) http://quickstats.nass.usda.gov/?source_desc=CENSUS tabulated by author

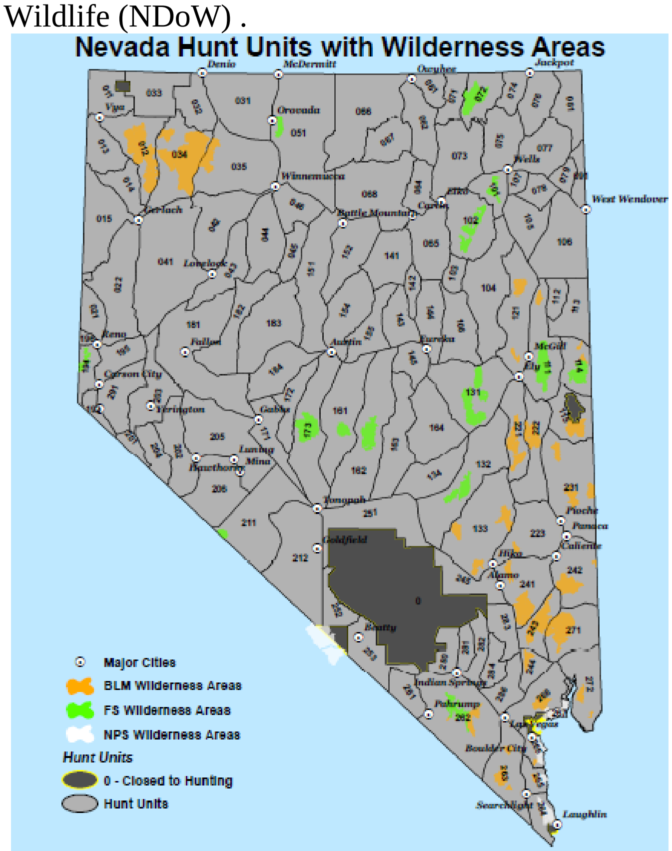
The most recent economic impact analysis by Harris and Wright (2004) estimates the dependence of the local non-farm economy on agricultural in White Pine County. The non-farm economy includes sectors that are directly related to farming such as farm and ranch supply stores, implement dealers, fuel stations, feed, seed, fertilizer, vehicle repair, banks, and marketing services. It also includes sectoral activity that is indirectly related such as grocery markets and retail stores. Harris and Wright (2004) estimated that every dollar $1.00 of agricultural output supports $1.73 of total economic output. This is a very reasonable *output multiplier* of 1.73.   Harris and Wright also estimated that every agricultural sector job is associated with 1.78 total jobs. This is a very reasonable employment multiplier of 1.78.

The data in Table 2 indicates total direct value of $30 million in the two counties' agricultural sectors. Given the two multipliers noted above, the estimated impact of the closure of the farms and ranches associated with the SNWA's acquisition of the water rights in the two counties is calculated. **The estimated impact of the contraction in agricultural activity is a $53 million dollar reduction in total economic output and 518 jobs lost from the two counties together.**

The local farm and ranch sector is expected to contract completely even if SNWA manages an operation with the same total head of livestock, because a single operation of that scale would purchase all inputs from suitably large suppliers located outside the local area.

3.b. Economic Use Values and Total Impacts from Hunting and Fishing

The four basins are home to deer, elk, native bighorn sheep, and antelope, that attract hunters from within Nevada and out of state, whose numbers are recorded by the Nevada Department of Wildlife (NDoW) .



Source: NDoW http://ndow.org/hunt/maps/hunt_unit_wilderness.pdf

The basins are also home to waterfowl and upland game birds that attract upland game bird and waterfowl hunters. Although no lakes or reservoirs are developed for sport fishing, the Nevada Department of Wildlife (NDoW) lists twenty fishable streams in Spring Valley alone, and it reported fishing activity on Cleve and Kalamazoo Creeks.

Table 3 summarizes NDoW's estimates of the big game populations in the eight hunt units in the four basins in 2010. Notably, Spring Valley (hunt units 111-112) is home to at least a third of Nevada's entire elk population.

Table 3. 2010 Big Game populations in the four basins (by hunt unit)

			hunt units					
		Nevada	111-113	114-115	221-223	241+	All basins	% NV
Mule Deer	Table 22	107,000	5,200	2,200	4,900	750	13,050	12%
Elk	Table 23	12,300	4100			500	4,600	37%
Bighorn Sheep	Table 27	7690		90	40	250	380	5%
Pronghorn Antelope	Table 24	26,000	1500	400		290	2,190	8%

Source: Nevada DoW 2010-2011 Big Game Status Book: Appendix: Harvest, Survey, and Population Tables as indicated; 2010 estimates. Tabulated by author.

Table 4 summarizes NDoW's reports about the amounts hunters pay to acquire the rights to hunt each species in the basins. All big game hunting in Nevada requires both a license and a tag for the specific hunt and hunt area. The hunters depend on the big game and the big game depend on the guzzlers at which they drink the water in the basins.

Table 4. 2009 Tag Receipts For hunting in the four basins	All Tag purchases	Residents only	% out of state
Deer	$77,160	$40,020	48%
Elk	$235,920	$161,520	32%
Bighorn Sheep	$600	$600	0%
Pronghorn Antelope	$16,440	$11,640	29%
total	$330,120	$213,780	35%

Source: Nevada DoW, Hunt Units 111-115, 221-223, 241; tabulated by author
http://www.ndow.org/hunt/resources/odds/

According to the Nevada Department of Wildlife 2009 Nevada Hunter Information Sheet for big game hunting in Spring, Cave, Dry Lake and Delamar Valleys, hunting service providers are in the city of Ely in White Pine County. They also note that limited services can be found on Hwy. 93 at the Schellbourne and Lages Station, on SR 318 at Lund and Preston, and just off Hwy. 50 in Baker or at The Border Inn on the NV/UT state line. Public camping areas exist at Cave Lake State Park, at Timber Creek and East Creek on Forest Service lands in Duck Creek Basin of Unit 111, at Baker Creek and Lehman Creek on National Park lands in Unit 115, and at Cleve Creek in Unit 111 on BLM land. Primitive camping is allowed throughout the basins on both BLM and USFS lands.

Rajala (2006) estimated the direct impact of hunting and angling as a function of the number of hunter or angler days reported, times the conservative estimate of $70 dollars spending per hunter or angler day. Table 5 below summarizes the hunting and angling days in Spring Valley or White Pine County as documented by Rajala (2006). Furthermore, it presents the estimated county-wide direct and total economic impact assuming an output multiplier of 1.6 (Harris, et al, 1994). The **total market economic impact of hunting in the basins was estimated to be $7.9 million annually**.

Table 5. 2005 Hunter & Angler Days and Economic Impact in the 4 Basins

	Hunter days	Spending @$70/hunter day
Mule Deer	6,351	$444,570
Elk	11,395	$797,650
Pronghorn Antelope	114	$7,980
Small game and fowl	1,484	$103,880
Angling	51,107	$3,577,490
Total	70,451	$4,931,570
Economic Impact		*$ 7,890,512*

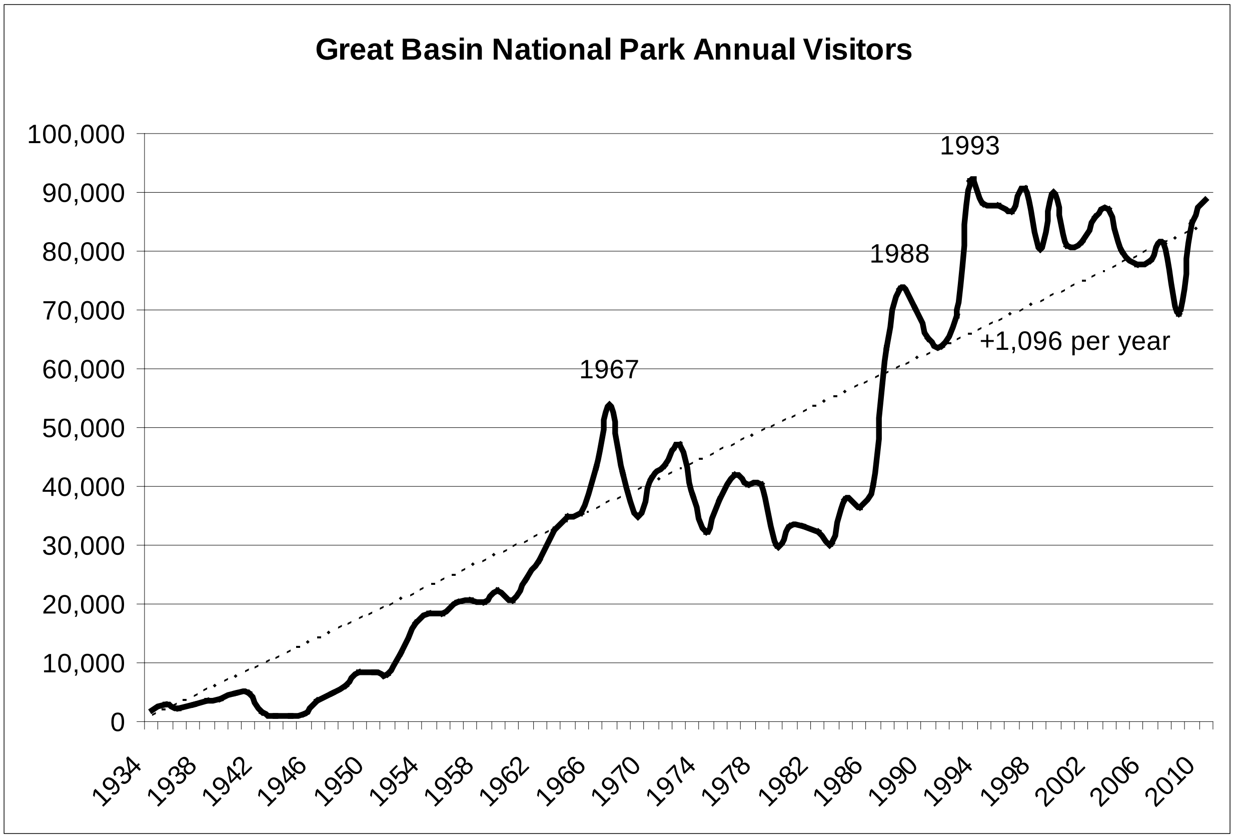
Sources: Rajala (2006), Harris, et al (1994), tabulated by author

3.c. Economic Use Values: Park Visitation

The mountains, foothills, and creeks in the four basins provide opportunities for not just hunting and fishing, but many other year round outdoor recreation activities such as hiking, biking, backpacking, camping, cross country skiing, pine nut gathering, sight seeing and photography, and rock hounding, for example.

Primitive camping is also allowed throughout the basins on both BLM and USFS lands. The right to sleep under the stars and to cook over a real campfire has become very rare. This area is one of the few left in the country where it is still allowed. Because entry, use, and camp site permits are not required there, much of the recreational use is not documented. Therefore this section can report the values of just the portion of visits that are documented. According to the 2006 testimony by Rajala, to measure the economic impact of park visitors, one first estimates the *party visitor days* from data on the number of visitations and the conservative average rate of $70 local spending per party visitor day.

Great Basin National Park is located in White Pine County surrounding Mt. Wheeler in the Snake Range. Its western slope is in Spring Valley. According to the National Park Service there were 88,870 visitors to the Great Basin National Park in 2010 (figure below). At the visitor day:*party visitor day* conversion rate implicit in Rajala (2006), that amounts to 55,633 *party visitor days*. At $70 spending per *party visitor day* this indicates $3.89 million in recreational visitor related economic activity in the area.



Source: National Park Service, Public Use Statistics, Great Basin National Park Annual Visitation http://www.nature.nps.gov/stats/park.cfm?parkid=382, chart by author.

Furthermore, according to Harris, et al (1994) 1.59 is the output multiplier for the Amusement and Recreation Sector in White Pine County, as calculated by the IMPLAN model (Minnesota IMPLAN Group, 2000). This indicates that each dollar spent on recreation and amusement is associated with another $0.59 dollars in the rest of the White Pine County economy. Thus, the **total annual economic impact** of the $3.89 million spent by the 88,870 **annual park visitors** is estimated to be **$6.2 million.**

Spring Valley is bordered by the Schell Creek Range on the west. However, according to Rajala (2006), The Bureau of Land Management maintains a campground at Cleve Creek and the U.S. Forest Service maintains a trail register at the Big Canyon Trailhead in the Mt. Moriah Wilderness Area. The Bureau of Land Management reported 65,900 visitors at Cleve Creek between October 1, 2004 and September 30, 2005 and the U.S. Forest Service reports that they have 100 people register at Mt. Moriah Wilderness Area each year (Rajala, 2006). These counts amount to 40,920 party visitor days at the conversion rate implicit in Rajala (2006). This leads to $2.86 million in expenditures at $70 per party visitor day, **and a total of $4.55 million annual economic impact from the measured recreational uses of Spring Valley** alone.

4. Non-Market Values

This section presents the estimated *non-market* values associated directly with the water in the basins that would be lost if the water is withdrawn. Non-market valuation is "*The measurement and translation, into dollars, of the economic values society derives from environmental amenities and natural resources other than those that can be directly sold and bought in existing markets.*" Page 2, Moeltner, 2006. See Loomis and Walsh (1997) for a general reference that explains the non-market valuation of outdoor recreation and existence values of natural amenities.

4.a. Habitat and Species Diversity

Distinguishing features of Spring Valley include its high elevation (5500 – 6000 feet) and its relatively abundant surface water, arising from over 100 natural springs (Charlet, 2006). These springs, together with snowmelt retained by a hardpan soil layer (Lanner, 2006) support numerous wetlands throughout Spring Valley. At stake is not only our opportunity to look at the water in streams, ponds, lakes, and swamps; or to fish in the waters in the valleys. The valleys are also habitats that support critical and valuable species diversity.

Destruction of the habitat of protected species is prohibited by law. "Section 9 of the Federal ESA of 1973, as amended and Federal regulations prohibit the take of fish and wildlife species listed as endangered or threatened (16 U.S.C. 1538). The term ''take'' means to harass, harm, pursue, hunt, shoot, wound, kill, trap, capture, or collect, or to attempt to engage in any such conduct (16 U.S.C. 1532). **Harm includes significant habitat modification or degradation** that actually kills or injures listed wildlife by significantly impairing essential behavioral patterns, including breeding, feeding, and sheltering [50 CFR 17.3(c)];." (Emphasis added) Federal Register / Vol. 73, No. 178 / Friday, September 12, 2008 / Notices; http://www.fws.gov/nevada/highlights/comment/csi/091208_csi_fed_reg.pdf

The table below lists the protected species that would be harmed by the withdrawals of water from the four basins. The map below shows the geographic distribution of the Greater Sage-Grouse (bird) that is currently a candidate for federal endangered species protection. It has habitat in three of the four basins (Spring, Cave, and Dry Lake).

LINCOLN COUNTY		
Birds		
C	Greater sage-grouse	*Centrocercus urophasianus*
E	Southwestern willow flycatcher	*Empidonax traillii extimus*
C	Yellow-billed cuckoo (Western U.S. Distinct Population Segment)	*Coccyzus americanus*
Fishes		
T	Big Spring spinedace ●	*Lepidomeda mollispinis pratensis*
E	Hiko White River springfish ●	*Crenichthys baileyi grandis*
E	Pahranagat roundtail chub	*Gila robusta jordani*
E	White River springfish ●	*Crenichthys baileyi baileyi*

Plants

C Las Vegas Buckwheat — *Eriogonum corymbosum* var . *nilesil*

T Ute lady's tresses — *Spiranthes diluvialis*

Reptile

T Desert tortoise (Mojave population) ● — *Gopherus agassizii*

WHITE PINE COUNTY

Birds

C Greater sage-grouse — *Centrocercus urophasianus*

Fishes

E Pahrump poolfish — *Empetrichthys latos*

E White River spinedace — *Lepidomeda albivallis*

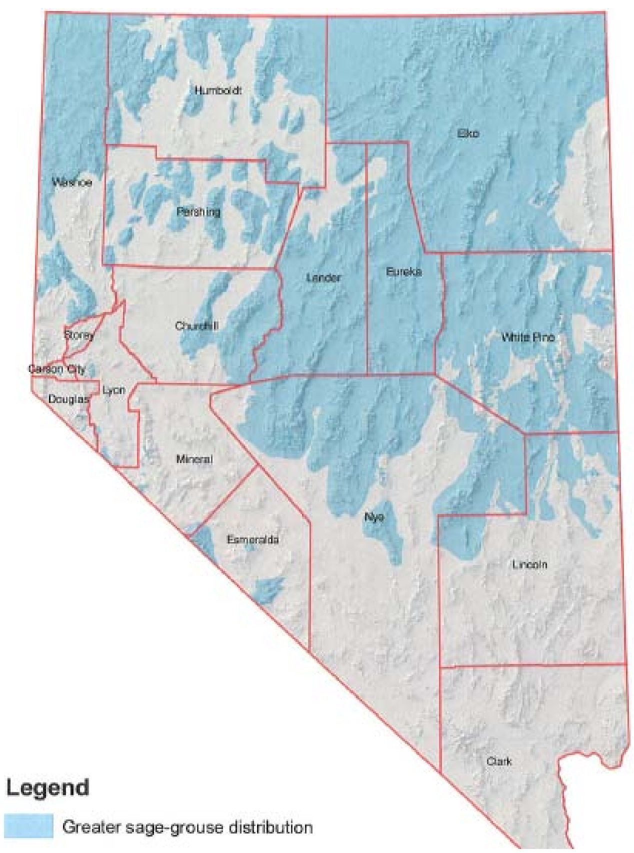
E = Endangered — T = Threatened — C = Candidate

Δ = Proposed for delisting — ● = Designated Critical Habitat in County — * = Believed extirpated from Nevada

+ = Endangered only in the Virgin River, Muddy River population is a sensitive species.

Last updated: March 17, 2011

Source: U.S. Fish and Wildlife Service, Nevada Fish and Wildlife Office, http://www.fws.gov/nevada/protected_species/species_by_county.html



Source: Source: U.S. Fish and Wildlife Service, Nevada Fish and Wildlife Office, http://www.fws.gov/nevada/nv_species/documents/sage_grouse/NV_ssage-grouse_distribution_030510.pdf

4.b. Non-market Use Values

While endangered species are protected from being 'used up' by law, rational people do not 'use up' water and other natural amenities or wildlife either, because we value those resources. As noted in the beginning of this report, the fourth type of environmental economic value is the value that people who visit the areas derive from experiencing the natural amenities. These values are difficult to measure if no dollar outlay is required to use or directly experience them. Currently, no fees are charged for either day use or overnight stays in the recreation areas in the valleys. Lacking a market expenditure measure of value, the ideal non-market valuation technique entails directly surveying users' with respect to their willingness-to-pay to enjoy the natural area. In the absence of a direct survey, the non-market valuation technique known as *Benefit Transfer* was employed by Moeltner (2006) regarding Spring Valley.

The "Benefit Transfer" (BT) technique has been widely embraced by government agencies such as the EPA (U.S. EPA, 2000, U.S. EPA, 2005). For a description of the technique and applications of Benefit Transfer, see Rosenberger and Loomis (2003) and Moeltner et al. (2007).

As noted earlier, Spring Valley has relatively abundant surface water provided by over 100 natural springs and numerous wetlands (Charlet, 2006; Lanner, 2006). Moeltner (2006) used a version of the BT technique to evaluate the non-market use value of two recreation areas with camping facilities located in or near Spring Valley: Cleve Creek (CCCG) and Sacramento Pass (SPRA). In that report he also used BT to evaluate the non-market existence value of the two specific wetland areas in Spring Valley: (i) the Swamp Cedar Natural Area (SCNA), and (ii) the Shoshone Ponds Natural Area (SPNA), which will be summarized in section 4.c.

Moeltner's (2006) evaluation of the status quo use value benefits focused on the two recreation areas with camping facilities in the Spring Valley area: Cleve Creek and Sacramento Pass. Both are administered by the BLM. The Cleve Creek Campground (CCCG) is located at the western edge of Spring Valley on the East side of the Shell Creek Range approximately 45 miles east of Ely, and five air miles northwest of the Swamp Cedar Natural Area. It can be reached via a maintained dirt road off State Route 893. The camping area includes eight designated sites. It features a picnic area, toilets, and garbage facilities. Most sites are situated along Cleve Creek, a year-round stream that offers some fishing opportunities. The area also affords access to hiking trails and hunting opportunities. The campground is open year-round. Moeltner reported that according to the Ely BLM office, Cleve Creek received 5723 visitation days in the first nine months of 2006.

The Sacramento Pass Recreation Area (SPRA) is located off Highway 6-50, approximately 50 miles east of Ely, and five air miles east of the Swamp Cedar Natural Area. The area features shaded picnic facilities, toilets, and a fishing pond. It allows for dispersed camping in undesignated sites. It is open year-round and can also be used free-of-charge. Moeltner (2006) reported that the Ely BLM office recorded 11,503 visitation days during the first 9.5 months of 2006.

Moeltner (2006) relied on an existing BT study valuing outdoor recreation per visitation day by Rosenberger and Loomis (2001) to estimate the economic value of these two areas. His per visitation day use-value estimate is $42. Rounding up the visitation counts slightly to 6,000 and

12,000 respectively, because the counts ended in mid October, he estimated that the **sum non-market use values for the CCCG and SPRA areas together is $756,000 per year.**

4.c Existence (Non-Use) Value

The fifth type of environmental economic value is the existence (or non-use) value that people anywhere-- even people who never visit or use the environment in the area-- place on the existence of it. Moeltner (2006) evaluated the non-market values of the two wetland areas in Spring Valley: (i) the Swamp Cedar Natural Area (SCNA), and (ii) the Shoshone Ponds Natural Area (SPNA). He employed a state-of-the-art meta-regression Benefit Transfer approach (see also Moeltner and Woodward, 2009).

The Swamp Cedar Natural Area (SCNA) is a marshy ecosystem with natural ponds and meadows in Spring Valley that is approximately 23 air miles east of the town of Ely, NV. It contains 3200 acres of public land administered by the Bureau of Land Management. The SCNA area supports a large stand of Rocky Mountain Junipers (*Juniperus scopulorum*), commonly referred to as "Swamp Cedars." The Spring Valley Cedars merit recognition as their own unique variety (Lanner, 2006). The SCNA can be reached via dirt roads branching from Highway 50. It offers recreational opportunities for hiking, primitive camping, nature and wildlife viewing (BLM, 1980).

The Shoshone Pond Natural Area (SPNA) contains 1240 acres of public land managed by the BLM. It features two important natural resources: (i) a second stand of "Swamp Cedars" of the same ecotypical variety as those found in the SCNA, and (ii) three manmade, spring-fed pools and a stockpond that harbor two rare species of fish, the Relict Dace (*Relictus solitarius*) and the Pahrump poolfish (*Empetrichthys latos*). The Relict Dace is listed by the Nevada Natural Heritage database as "imperiled and vulnerable in Nevada and globally", while the Pahrump poolfish, for which the Shoshone ponds constitute one of only three remaining habitats, has been federally listed as an endangered species since 1969. The SPNA has a designated access road off of Highway 93. The SPNA also offers recreational opportunities for hiking, primitive camping, nature and wildlife viewing (BLM, 1980(b)).

The value of the two wetlands is estimated by associating the dollar non-use values reported by people about the features of other wetland areas to the features of the two wetlands in question. The *willingness to pay* (WTP) for the benefits associated with each feature of other wetland areas is ‘transferred.’ In particular, survey respondents contacted by other researchers about other similar areas were asked what they would be willing to pay into a nature conservation fund or as additional taxes to preserve other, similar, wetlands. The reported values reflect the value of the entire bundle of wetland services, including habitat and biodiversity provision, flood control, water filtration, and opportunities for non-consumptive uses (wildlife viewing, hiking, photography) and consumptive uses (hunting, fishing) recreational activities, as well as pure existence (non-use) values. The share of users that had visited the wetland under consideration in each survey, however, was very small. Therefore, Moeltner emphasized that the “lion's share of estimated economic benefits (i.e. reported WTP) is likely associated with non-use or existence values.” (Moeltner, 2006; page 7). A summary of his findings are in Table 7.

Table 7. Non-Market Value of the SCNA and SPNA

concept	measure	data	Estimated average Willingness to Pay	Estimated Total Annual Value
Number of potential stakeholders (users and non-users)	Total # of households in Nevada and Utah (2000 Census)	1,452,446	$1.35 per household per year	$1,966,122
Ability to pay	Median HH Income in 2003 (expressed in 2006 dollars)	50,549		
Proportion of users	Estimated % of households who actually visit Spring Valley per year	1		
Source: adapted from Moeltner, 2006, Table 4; tabulated by author.				

In sum, conservatively estimating the stakeholding public by the number of households in just the two states of Nevada and Utah**, the estimated non-market value of the two wetlands together is more than $2 million annually.** It must be emphasized that people who hate wetlands as well as people who are indifferent about the existence of wetlands are 'stakeholders' or potential beneficiaries. The total value estimates do not presume that every household has a positive value for wetlands. Some value wetlands much more than average. Others consider wetlands a net social cost. More people consider then a benefit. The average estimated WTP in Table 7 is the scientifically estimated average of the valuation by people with all types of preferences.

Finally, Moeltner also estimated the cumulative discounted present value of the annual WTP estimate to a 70-year time horizon. This time span reflects the amortization period for the proposed groundwater transfer projected by the Southern Nevada Water Authority (SNWA). He chose a rate of 2% for this application, as recommended by the U.S. Congressional Budget Office (CBO) for policies that have long-term social implications. It is considered the "Social Rate of Time Preference", i.e. the rate that best reflects society's collective preferences for trade-offs between present and future generations' consumption. The estimated **70 year horizon cumulative discounted present value of the wetlands status quo (no withdrawals) is $74 million**.

5. Conclusion

The existing measures of the economic impact of the proposed water withdrawals from the four basins summarized in this report show that the proposed withdrawals would include:

- 1,503 direct job losses and 1,173 jobs lost in linked sectors, totaling 2,676 lost jobs; raising the unemployment rate to 53% in White Pine County
- 419 direct job losses and 327 jobs lost in linked sectors, totaling 746 lost jobs; raising the unemployment rate to 46% in Lincoln County
- $42 million annual *direct* loss of market revenues due to the loss of farming, ranching, hunting, and recreation visitors in the areas
- $29 million annual *indirect*/interindustry losses of market revenues due to the reduction in the demands for other linked sectors' goods or services due to the loss of farming, ranching, hunting, and recreation visitors
- $2.8 million annual loss in *non-market* values of the ecosystem services, amenity, and existence values
- The sum loss of $74 million in value annually
- Cumulative loss of $2.8 billion in present discounted terms over the 70-year planning horizon

These losses are, however, an underestimate of the actual values at risk for many reasons, most notably because many of the non-consumptive uses of the water in the valleys have not been documented, and that the impacts of the loss of water in the downgradient valleys (White River, Pahranagat, Snake, and other Valleys) have not even been considered.

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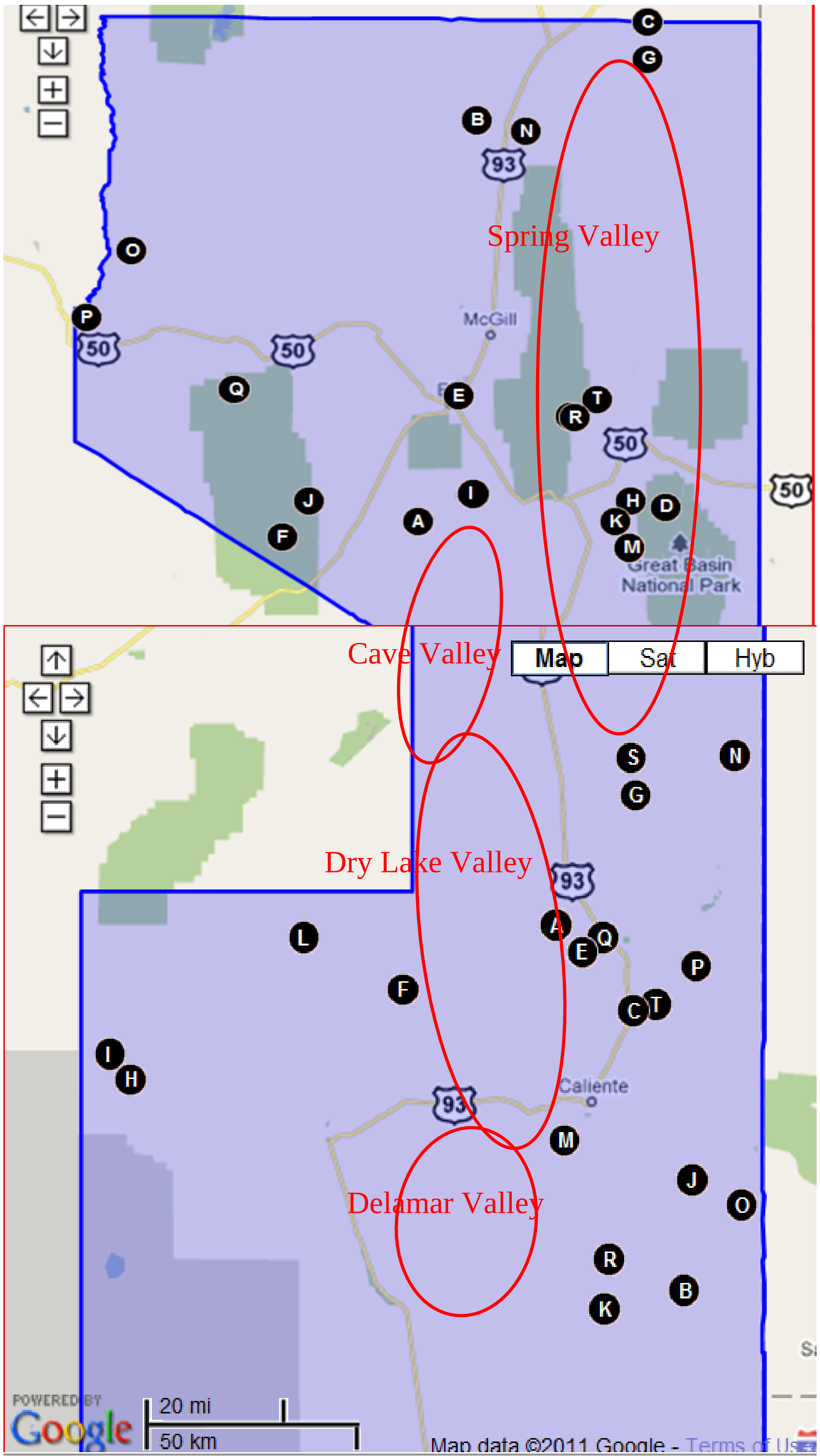
APPENDIX: **Maps of the Counties, Watersheds, Communities, and Relevant Sites**

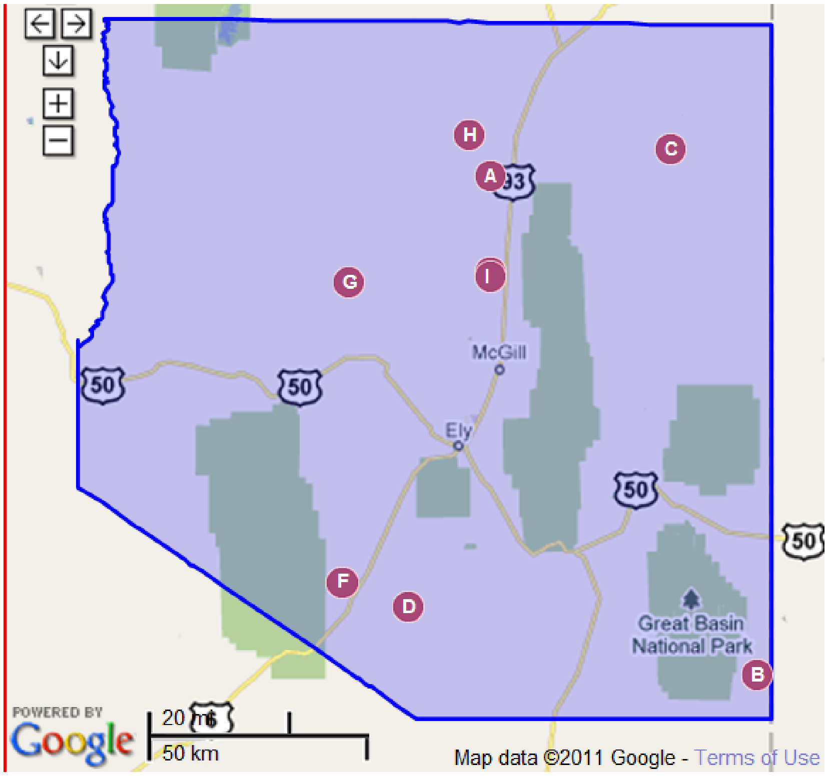


WHITE PINE COUNTY: Water Canyon Holding Corral (A) Cherry Creek Station (B), Western Marble Mining Camp (C), Wheeler Peak Campground (D), White Pine Golf Course (E), White River Campground (F), Chin Creek Ranch (G), Willard Creek Ranch (H), Willow Creek Ranch (I), Willow Grove (J), Yelland Ranch (K), Yelton Ranch (L), Ziege Ranch (M), Zips Cabin (N), Circle Ranch (O), Angelo Belli Cabin (P), Illipah Campground (Q), Cleve Creek Administrative Site (R), Cleve Creek Campground (S-under R), Cleveland Ranch (T).

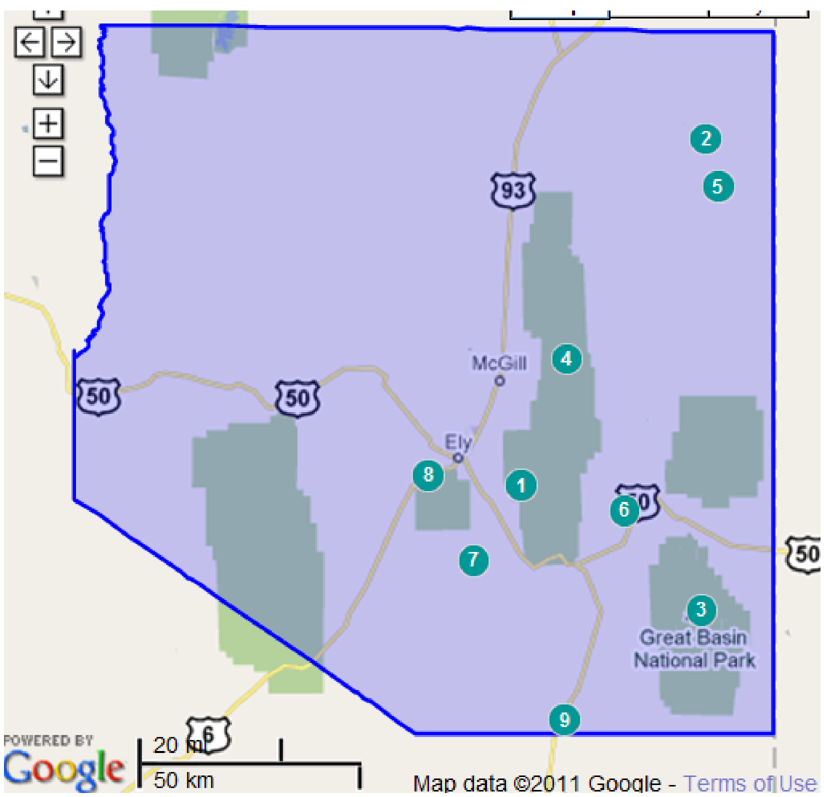
LINCOLN COUNTY: Abbotts Fork (A), West's Camp (B), Chicago Mill (C), Wheeler Mill (D), Wheeler Ranch (E), White River Petroglyphs Archeological Site (F), Wilson Creek VORTAC Station (G), Windmill Number One (H), Windmill Number Two (I), Wood Ranch (J), Cloud (K), Coal Valley Holding Field (L), Coburn Ranch (M), Johnson Ranch (N), Ash Spring Exclosure (O), Flatnose Ranch (P), Atlanta (Q), Kiernan Ranch (R), Cole and Dolan Ranch (S), Landmark Letter (T).

http://www.city-data.com/county/Lincoln_County-NV.html#ixzz1PlaDKLLL

Source: Google Maps



White Pine County streams, rivers, and creeks: Schell Creek (A), Chokecherry Creek (B), Chin Creek (C), Eph Creek (D), Third Creek (E-under I), Ellison Creek (F), Thirtymile Wash (G), Cherry Creek (H)Second Creek (I).



Parks in White Pine County include: Cave Lake State Park (1), Pony Express Historical Monument (2), Great Basin National Park (3), Schell Creek State Game Refuge Number 7 (4), State Game Refuge Number Twelve for Antelope (5), Swamp Cedar Natural Area (6), Ward Charcoal Ovens State Park (7), Ward Mountain Recreation Area (8), North Creek Scenic Area (9).

White Pine County Exhibit JJ

SNWA's Proposed Groundwater Withdrawals and Interbasin Transfers
Will Harm and Unduly Limit Future Growth and Development

Rebuttal of Materials Submitted by SNWA pertaining to
Groundwater Applications 54003 through 54021 in Spring Valley
and Groundwater Applications 53987 through 53992 in Cave, Dry Lake, and Delamar Valleys.

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Maureen Kilkenny   August 24, 2011

OVERVIEW

The Southern Nevada Water Authority (SNWA; "Applicant") has proposed to appropriate and export in perpetuity 91,200 afa (acre-feet annually) of groundwater from Spring Valley of eastern Nevada and 34,700 afa of groundwater from Cave, Dry Lake and Delamar Valleys of eastern Nevada. (Table 1-1, page 1-5, SNWA, March 2011 "GWD Project - Conceptual Plan of Development" http://www.snwa.com/assets/pdf/wr_gdp_concept_plan_2011.pdf).

This report refutes the arguments that the proposed withdrawals would not harm, and supports protestants' assertions that the proposed groundwater withdrawals will harm and will unduly limit, the future growth and development in the targeted basins and surrounding communities in the Great Basin thereby harming the public interest (Nevada Revised Statutes 533.370).

The proposed withdrawals will negatively impact the basins of origin, as well as neighboring and downgradient basins in roughly a quarter of the state of Nevada, including the Great Basin National Park (Elliott, et al, 2006; SNWA Exhibit 069). According to numerous hydrologists and hydrogeologists (Bredehoeft 2006; 2007, 2011; Elliot, et al., 2006; Durbin 2006; Myers 2011; Van Liew 2006) the proposed withdrawals exceed the sustainable yield of the targeted valleys or significantly draw down water levels in the interbasin flow systems of which they are major components. Withdrawing more groundwater in perpetuity than the perennial yield is not allowed in Nevada.

Three immediate socio-economic implications of these facts are that (1) the proposed withdrawals would affect a far larger geographic area than the Applicant's testimonies admit, (2) the proposed withdrawals would undermine most of the economic activity in White Pine and Lincoln counties in perpetuity, and (3) expectations of both aforementioned outcomes stifles investment in the region.

The Applicants' arguments that there is no economic or social justification for keeping the groundwater in the four valleys are fatally flawed in at least seven ways outlined below and explained subsequently:

(1) The appropriate geographic scope of the social and economic impact is not limited to the four basins as implied by the Applicant. Given the scope of the project and likely extent of the ecological impacts, the relevant geographic scope is the broader surrounding region of the Great Basin that is hydrologically and economically tied to these four valleys. The environmental implications and potential legal precedents make the proposed project a state-wide concern. The SNWA Exhibits incorrectly focus only on the four basins of origin, suggest that the communities surrounding and dependent on the valleys are an easily dismissed second-order concern, and erroneously suggest that the majority of the citizens of the state approve the proposed interbasin transfers. Not so. The Applicant's evidence provides incomplete and biased estimates of the scope and severity of human and social impacts, and it underestimates the values at stake.

(2) The appropriate temporal scope is not limited to one decade before the present and a few decades into the future. By limiting its analysis to a single prior decade and explicitly refusing to acknowledge that local feed and livestock trends reflect the dozen-year-long national cattle cycle, SNWA's Exhibit 103 does not provide credible information about the future economic development potential of agriculture in White Pine or Lincoln Counties.

(3) The Applicant's experts also failed to address the facts that investment decisions are inherently forward-looking, and that the threat of groundwater mining has hung over White Pine and Lincoln counties for more than two decades-- since 1989 when the applications were originally filed. A downtrend in either county must be understood to be in part a consequence of the water withdrawal applications rather than a justification for the withdrawals.

(4) In SNWA Exhibit 241 the Applicant seriously misrepresented the findings of the report (Aldrich and Kusmin, 1997; SNWA Exhibit 248) upon which the Applicant based the erroneous claim of no growth prospects in the counties containing the targeted valleys. In Exhibit 241 the Applicant also ignored the actual findings in that same report which suggest growth in White Pine and Lincoln Counties. These misrepresentations undermine the claims made in Exhibit 241.

(5) The Applicant failed to recognize the lessons of Clark County's own history over the past 70 years when purporting to predict the growth prospects of White Pine or Lincoln Counties over the next 70 years. The Applicant's reports do not provide sufficient information to rule out future economic development in White Pine or Lincoln County.

(6) By focusing exclusively on short-run local time-series and ignoring long-run cross-sectional patterns underlying the unrefuted scientific principle commonly known as Central Place Theory and the Rank-Size Rule, the Applicant incorrectly underestimated the urban growth prospects in White Pine. The Applicant's biased and incomplete evidence does not provide credible information sufficient to justify the proposed interbasin water transfers.

(7) SNWA Exhibits 103 and 241 incorrectly ignore the deleterious effects of the groundwater mining. The proposed interbasin transfer will excessively limit the key natural resource, water, upon which almost all economic activity in the region is based. By ignoring the circular flow of income through local expenditure, inter-industry interdependencies, the lack of redundancy, and the cumulative economic effects in White Pine and Lincoln Counties, the Applicant's experts failed to consider the full long-run damage to the local economies of those counties. The Applicant's evidence does not provide sufficient information to persuasively contradict the likelihood that the proposed withdrawals will unduly limit future growth and development of the local communities.

Arguments- pro or con- about estimates of economic growth in the targeted valleys or in White Pine and Lincoln Counties are relevant insofar as those counties are home to the state's most dedicated stewards of the region's natural resources. The state does not remunerate the citizens of White Pine and Lincoln Counties for that service. The residents work to earn their livings using the regions' resources sustainably. Their economic activities are 'canaries in the coal mine.' Who will make beneficial use of our land and environmental resources after all the sales, closures, retirements, and out-migrations caused by the proposed interbasin water transfers? Groundwater withdrawals and interbasin transfers that threaten the local communities are the tip of the iceberg of a greater set of threats.

Among the wider long run threats to the public interest are the conversion of this vast rural area into an uninhabitable and economically vacant wasteland, and the initiation of a trend toward doing the same to more of rural Nevada in the name of promoting urban growth. Because the Applicant's proposed project would profoundly undermine the continued economic viability of this rural region, it would undermine the economic diversity and resilience of Nevada as a whole, which is also contrary to the state's long-term greater public interest.

The deleterious impacts of the proposed project are likely to be geographically far-reaching, multifaceted, and unmitigatable. The choice is not between allocating groundwater to either a small number of ranchers or a large number of urbanites in one metro area. It's about ensuring the long run inhabitability of the state beyond one city's limits, or not. Society has created habitable cities in deserts. But we must not create uninhabitable deserts in an attempt to grow cities. It would be a futile attempt in any case. Groundwater mining is unsustainable and ultimately both the city and the rest of the state would lose.

The following pages briefly elaborate and document the seven rebuttal arguments outlined above. The evidence that the proposed withdrawals will desiccate the watersheds, and rebuttals to erroneous claims that the withdrawals will not unduly harm the natural balance in a significant section of the Great Basin, are being provided by other experts in other testimony.

(1) Appropriate Geographic Scope for Economic and Social Impact Analysis

The appropriate geographic scope for the analysis of the economic and social impact of the proposed water withdrawals and transfers is, at a minimum, the rural counties containing the four valleys and the downgradient basins in the same flow systems that also will experience a drawdown in their groundwater levels. The Bureau of Land Management (BLM) has reported that the impacts of the withdrawals on water availability extend well beyond the targeted valleys (BLM 2011). According to Nevada Revised Statutes § 534.110 (4.):

> In determining a reasonable lowering of the static water level in a particular area, the State Engineer shall consider the economics of pumping water for the general type of crops growing and may also consider the effect of using water on the economy of the area in general.

The State Engineer could at a minimum apply the national standard practiced by the (BLM) in the draft environmental impact statement (BLM, 2011):

> "The study area for socioeconomics and environmental justice is defined in terms of local county boundaries and includes Clark, White Pine, and Lincoln counties in Nevada and Juab and Millard counties in Utah. These five counties encompass virtually the entire extent of the four basic areal geographies associated with the proposed development and operation of the proposed ROW, groundwater development areas, and most of the area of potential indirect effects from groundwater level declines associated with groundwater pumping." DEIS at p. 3.18-1.

The State Engineer should consider the area in general in order to adjudicate equitably and to avoid using a double standard. For the Applicant to argue that the focus should be only on the targeted valleys themselves would be disingenuous. The Applicant has stated that "the impacts on water resources will likely be in the developed areas such as Ely, Baker, and Caliente, where visitor and guest services are available, and not in the basins themselves." SNWA Exhibit 241, at p. 5 (June 2011).

With respect to equitable treatment it must be noted that the Applicant, in basin 212 (Las Vegas Valley), is permitted to argue that it is the most relevant human community with respect to water rights issues in any hydrologic basins in its neighborhood, such as the contiguous basins 210 (Coyote Springs Valley), 215 (Black Mountain Valley), and 216 (Garnet Valley), for example. By the same token, the towns of Ely, in basin 179, (Steptoe Valley), and the towns of Pioche, Panaca, Caliente and other urbanized areas in basins contiguous to Spring, Cave, Dry Lake, and Delamar Valleys are communities that depend directly and indirectly on consumptive and non-consumptive uses of the water in the origin basins. According to the US Environmental Protection Agency, Steptoe and Spring Valleys are in the same watershed, the Spring-Steptoe Watershed (http://cfpub.epa.gov/surf/huc.cfm?huc_code=16060008). And just like Las Vegas' concerns about future access to water in its neighboring basins, these towns also have future interests in locally available groundwater.

The Applicant is also allowed to concern itself with non-contiguous basins, including basins in other watersheds, such as basin 213 (Colorado Valley). Basins 213 and 212 are not even in the same watershed as Las Vegas. Basin 213 is in the Lake Mead watershed while 212 is in the Las Vegas Wash watershed.

However, the most important point is that even a county-wide focus is too narrow. The owners of the groundwater in the basins of origin are the citizens of the entire state of Nevada (NRS § 533.025).

The citizens of Nevada made their preferences known about the disposition of the groundwater by responding to an opinion poll commissioned by the pro-pipeline Las Vegas Review Journal in 2009 (Brean, 2009). Economics is the study of choice among competing alternatives for the allocation of limited resources. Preferences are the foundation of choice.

The 2009 Mason-Dixon poll found that only 39 percent of Nevada's citizens statewide (plus or minus a 5 percent margin of error) favor the pipeline; 26 percent were undecided, and 35 percent opposed. That statewide measure reflects the opinions of a preponderance of Las Vegas metro area resident respondents, proportional to the metro area's share of state population. Yet, among the subset of the respondents who are from Clark County-- the purported beneficiaries-- only a slight majority of 52 percent (+/- 6%) supports it. In the rest of the State of Nevada outside Clark County, support for the project was measured at 13 percent. Thirteen percent in favor. The proposed withdrawals might serve the interests of one metro area, but not indefinitely; and in contradiction of public preferences statewide.

The choice the State Engineer must make is not between two competing local interests of vastly unequal magnitudes, as the Applicant insists, but between the long-term general public interest and a short-run local interest.

The State Engineer is responsible for ensuring the general public interest:

> ….history has indicated that water resources should be developed, but cautiously, as it would threaten to prove detrimental to the public interest to allow large scale development of water resources to go forward in support of municipal development when the confidence in predictions as to water availability long-term without damaging impacts is low and dire consequences could result." State Engineer Ruling #5746, at p. 42 (2007).

In contrast, the Applicant is of course responsible to a specific local interest:

> "We're responsible, essentially, that this valley can become what it wants to become and that water is not a limiting factor." Patricia Mulroy, quoted October 20, 2002 in the Las Vegas Review-Journal (Berns, 2002)

The unfortunate fact is that water *is* a limiting factor. It is not available in unlimited quantities. It cannot be in two places at the same time. The Las Vegas-Paradise metropolitan area is not exempt from nature's limitations. Not unless one is willing to pay exorbitant prices to cover the true cost of the infrastructure, which was estimated to be $14 - 18 billion in current (2011) dollar terms (or $9.6-12.4 billion in 1992 dollars) by Mifflin, et al. (1992). And not unless one is willing to desiccate many thousands of acres of meadows, woodlands, and wildlife habitat in the process.

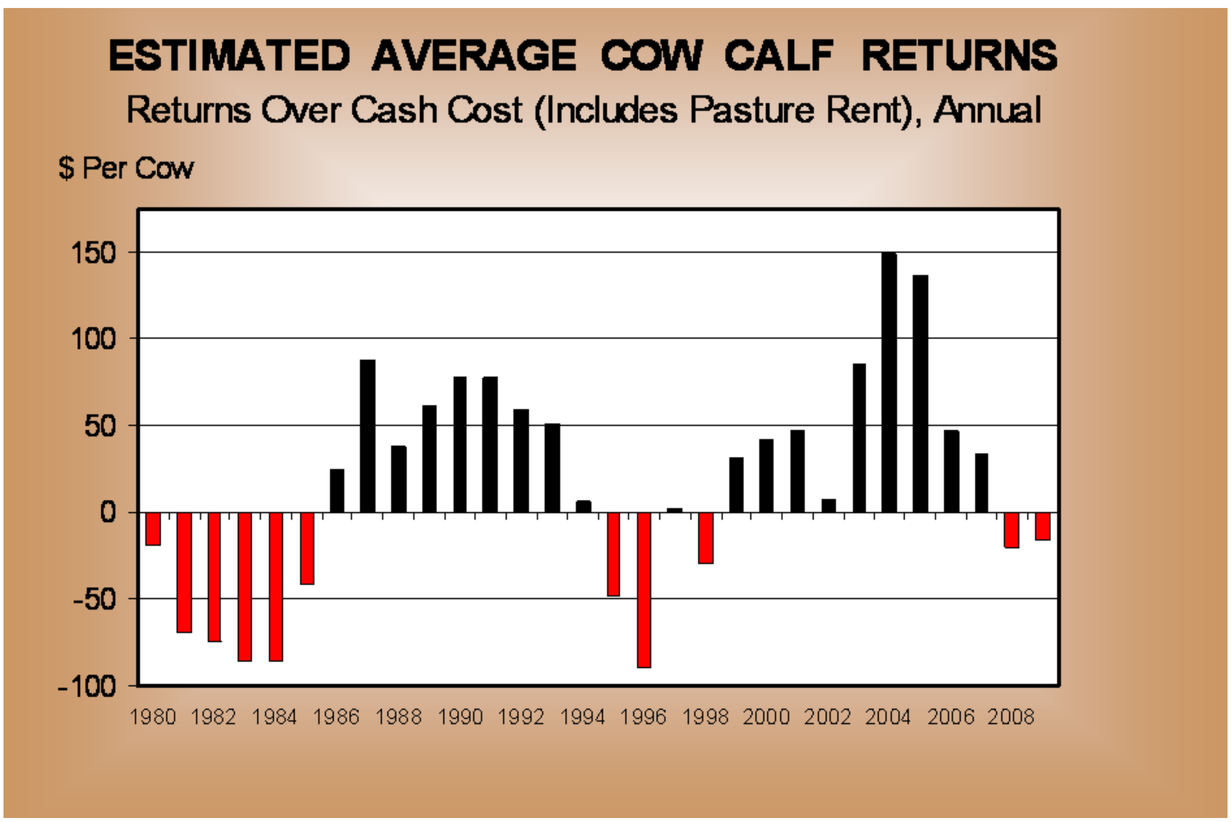
Nevada Revised Statute § 534.120 authorizes the State Engineer to make rules, regulations and orders where groundwater is being depleted as are deemed essential for the welfare of the area involved. Nevada Revised Statute § 533.370(6)(c) states that in determining whether an application for an interbasin transfer of ground water must be rejected the State Engineer shall consider whether the proposed action is environmentally sound as it relates to the basin from which the water is exported, among other things, as well as any other factor the State Engineer determines to be relevant.

In sum, the geographic scope of the project is a large portion of the Great Basin, and the economic and social impacts extend far beyond the basins of origin. The eastern quarter of the state that currently contains towns, ranches, fisheries, and nature preserves could become an uninhabited economic wasteland. The choice the State Engineer must make is not between two competing local interests, but between the long-term general public interest of the state and a short-run local interest. The local-interest application should be rejected.

(2) Appropriate Temporal Scope for Economic and Social Impact Analysis

The appropriate temporal scope is not limited to just one decade before the present and two decades into the future. One recent decade of observation is insufficient information for a long-term forecast. There are two reasons that are particularly relevant to this case. One is that ten years is not long enough to observe multi-decade cycles. The implications of the Applicant's failure to recognize cycles are documented in this section. The second key reason is that current economic activity reflects previous investment decisions. The implications of the Applicant's refusal to recognize that fact will be discussed in the subsequent section. Numerous hydrologists and geologists estimate that it may take 70 years for the proposed withdrawals to desiccate a quarter of the State of Nevada. Thus a much longer view of the past and national trend data is required for a reasonable forecast of the potential for agriculture in White Pine and Lincoln County.

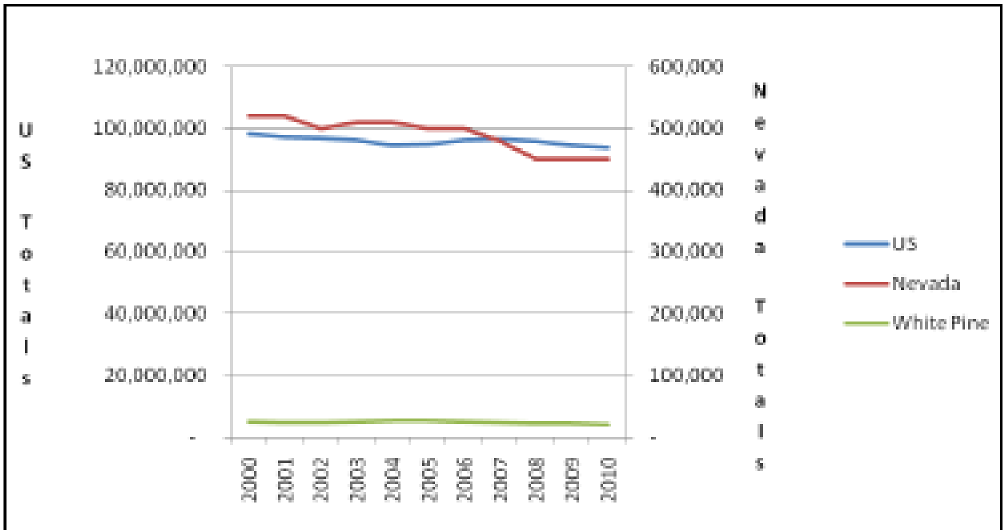
In particular, in SNWA Exhibit 103, the Applicant's experts erroneously interpreted a short-run decline that is in fact but one segment of the long-run national cattle cycle as the local long-run trend. The national long-run cattle cycle is illustrated below.



Source: Livestock Marketing Information Center *Chart of the Week*; http://www.lmic.info/memberspublic/pubframes.html date accessed: May, 2008.

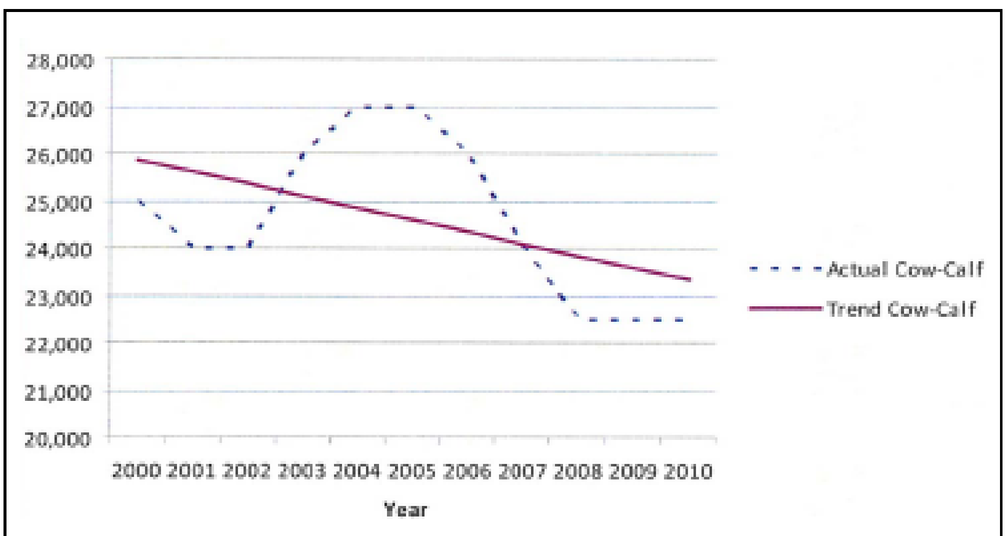
Compare the cycle shown above to the portion of the cycle illustrated in SNWA Exhibit 103, Figures 10 and 11 reproduced below:

Future Economic Development Potential of Agriculture in White Pine and Lincoln Counties



Source: USDA Statistics (2000-2010, last accessed May 25, 2011)

Figure 10
Cow Calf Inventory



Source: USDA Statistics (2000-2010, last accessed May 25, 2011).

Figure 11
White Pine County Cow-Calf Inventory

Source: Page 15 in Peseau & Carter, 2011; SNWA Exhibit 103

Figure 11 shows a build up and decline in the number of cattle in White Pine County that mirrors the national cycle in net returns, which is the market signal for herd size management, with at most a one year lag as expected (Foster and Burt, 1992). This coherence is to be expected from market-oriented producers like the ranchers in White Pine County.

In contrast, the Applicant's analysts insisted that:

> "From a practical standpoint however, efforts to correlate and then extrapolate broader national and international economic and spatial factors that ordinarily influence agricultural markets are largely irrelevant to this distant and remote region of eastern Nevada.[1]
>
> [1] This opinion is based on several sources examined and identified throughout this report (see Section 11.0, References). (SNWA Exhibit 103, ES-1)

It must be noted that there is not a single refereed journal article listed in the reference section, much less one that justifies their opinion. For example, they might have consulted Foster and Burt 1992; Dahlgren and Blank 1992; or Marsh 1994 or 1999; all well-known refereed articles in top peer-reviewed journals, for examples of how to test or verify such a claim. Instead the authors simply proceeded to base the conclusions of their report on that untested opinion. They erroneously extrapolated the long run from a short-term segment of a cycle.

The recent decade downtrend in cow-calf inventory in White Pine County reflects, in part, economically-rational local feed and livestock producer responses to national long run cattle cycle net revenue trends. Thus SNWA Exhibit 103's conclusion of no potential for agricultural intensification in the valleys is simply an ill-informed opinion. The conclusions in SNWA Exhibit 103 are not scientifically sound and not credible.

SNWA Exhibit 103 also predicted no growth in alfalfa production because "[n]ew investment in irrigation pivots for new land put into alfalfa production is not economic even at higher prices," "[l]imited grazing allotment expansion and associated lack of demand for alfalfa for supplemental grazing feed," and "[a] relatively flat production of and markets for local calves and lambs." (Peseau and Carter (2011) page 8).

In this case the error is that all three of those proximate explanations are arguably consequences of the proposed water withdrawals. The ultimate explanations are that it is "not economic" to make investments that are not expected to have salvage value. Rational producers pull back from the sector in anticipation of declining capacity in the vertical market chain, and an expected dismantling of the local input supply sector. Those expectations have in fact been based on observations of the sales of a significant share of local ranches (regardless of the consolidation of herds into a single operation). A rational local feed and livestock sector would not expand given those expectations.

Thus the Applicant may have confounded consequences with causes with respect to "lack of demand for alfalfa and supplemental grazing feed" and "flat production of and markets for local claves and lambs" because the analysts wholly ignored the buyouts by SNWA of seven producers (twelve ranches) in Spring Valley that occurred mid-decade. The buyout reduced the number of rancher-customers in White Pine County's Spring Valley by 60 percent, from twenty to eight. These facts are well-known by the Applicant and the public at large:

> "In July 2006, a month after the deadline lapsed for White Pine County to withdraw its protest, she [SNWA General Manager Pat Mulroy] announced the purchase of the huge Spring Valley Robison Ranch for $22 million. Soon, almost every ranch in Spring Valley was in negotiation with Las Vegas, and the sales were going too fast to count: Harbecke, Phillips, Bransford, Wahoo, El Tejon, Huntsman**. The ranchers figured that once a big city started pumping and the water table fell, they would have no way to keep their alfalfa irrigated or water troughs full. Their ranches would all be worthless. Better to get out at the front end.** As one of them

> explained as she wept with shame in a local grocery store, she had no choice. None of them did." Green (2008) **emphasis added** http://www.lasvegassun.com/news/2008/jun/22/not-water/

As well as noted by the BLM (2011):

> "Among the more tangible effects to date of the proposed project on the social context of the rural part of the assessment area are SNWA's purchase of seven ranches [sic] in Spring Valley and the subsequent relocation of some of the ranching families whose properties were acquired. Residents of Snake Valley also cite the inability to obtain commercial water rights due to the SNWA water filings as a dampening effect on growth and development in the valley." Page 3.18-32 Draft EIS.

A lack of recent growth does not justify limiting future growth. There is little doubt that the appropriation and export of water in excess of perennial yield will render the valleys inhospitable to agriculture within one's lifetime. The expectation of the collapse of agriculture in the future rationally undermines any investment in agriculture today. This is related to the third and seventh fundamental errors in the SNWA's arguments.

(3) A Downtrend in Either County Must Be Understood To Be a Consequence of the Water Withdrawal Applications Rather Than a Justification for the Withdrawals.

Investment decisions are inherently forward-looking. The threat of groundwater mining has hung over White Pine and Lincoln counties since 1989 when the applications were originally filed. The purchases of land and surface water rights have been widely debated and discussed for three decades. One example of the widespread public awareness of the consequences of these expectations is an internet posting by Rick Spilsbury on Friday, September 01, 2006:

> "…a number of counties in Rural Nevada already have been forced to stop growth. … Back in the late 1980's SNWA applied to the State of Nevada for much of Central Nevada's water rights. Since then, growth in many places in Rural Nevada has been put on permanent hold. … In a way it's as if their applications have already been approved." http://noshootfoot.blogspot.com/2006/09/snwa-halts-growth-in-rural-nevada.html (date accessed August 15, 2011).

The effect of expectations on local investment cannot be disputed. The Applicant itself has warned that expectations of future water scarcity results in current economic contractions. For example, in 2006 an SNWA official observed that:

> "…State Engineer Tracy Taylor, will have hearings in September [2006] and then decide in the coming months whether to approve the agency's proposal to pump the water more than 200 miles south. ***If he does not, Mulroy said, the economic effect*** on Las Vegas ***will be immediate. Even before the agency could appeal the decision in court, lenders who bankroll construction and business expansion in Las Vegas would begin turning down loans," she said***. Without the rural water, "the whole economic confidence of Southern Nevada would start eroding," she said. "There's a whole market collapse that would happen." (Rake; August 19, 2006 Las Vegas Sun http://www.lasvegassun.com/news/2006/aug/16/a-matter-of-survival/ ***emphasis added***).

A downtrend in either White Pine or Lincoln County therefore must be understood to be a consequence of the water withdrawal applications rather than a justification for the withdrawals.

(4) SNWA Exhibit 241 Misrepresents SNWA Exhibit 248 to Support a Claim of No Growth Prospects in Origin Basin Counties

In SNWA Exhibit 241 the Applicant seriously misrepresented the report (Aldrich and Kusmin, 1997; SNWA Exhibit 248) upon which the Applicant based the erroneous claim of no growth prospects in the origin basin counties.

The author of the Applicant's exhibit, SNWA Deputy General Manager of Engineering/Operations Richard Holmes (2011) wrote:

> "Academic studies related to growth and development are often applied in more practical terms by agencies such as the USDA in their work to enhance rural prosperity. For example, the 1997 report by the USDA Economic Research Service titled, "Rural Economic Development; What Makes Rural Communities Grow?" identifies certain factors that lend economic growth potential to a region. Some of the most fundamental factors include close proximity to large, established metropolitan centers and markets, a sufficient population size and skilled labor force, a diversity of employment opportunities, location along a major transportation corridor, substantial infrastructure, including electricity, roads, and access to modern communications, and the availability of basic public utilities and services.
>
> All of the above listed factors that are fundamental and typical for economic development to occur are absent within the Basins of Origin." Page 2-1, Holmes (2011)

The fact is, Aldrich and Kusmin (1997) did not identify those factors. They identified other factors that were positively associated with rural county growth, and most of the identified factors are features of White Pine and Lincoln Counties:

> "Recent research on county economic development found some factors that were consistently associated with rural growth in the 1980's, when tested by a variety of statistical methods. The factors included low initial labor costs (earnings per job), retirement county status, high education spending per pupil, and the presence of a passenger service airport within 50 miles. Some other factors were consistently associated with lagging growth. These were relatively large transfer payments to county residents and the relative size of the African-American population. Other factors positively associated with rural growth, when the preferred statistical methods were used, included State right-to-work laws, the percentage of adults who had completed high school, and access to the interstate highway system." (page 1)

All but one of the seven factors positively associated with growth named above are present in White Pine and Lincoln Counties. Labor costs (wage rates) are relatively low. County demographics clearly indicate the attraction and retention of retirees. 15 and 28 percent are over age 65 in White Pine and Lincoln Counties, respectively, compared to 8.1 percent statewide. There is a passenger airport in Ely, and the town is linked to both coasts by U.S. Route 50. Nevada is a right-to-work state. There is also a higher percentage of adults with high school degrees than statewide: 84.9 and 85.6 in White Pine and Lincoln Counties respectively compared to 83.7 statewide. The data source is the 2010 U.S. Census, accessed at http://quickfacts.census.gov/qfd/states/32/32033.html. Education spending per pupil, however, is well-known to be relatively low in Nevada compared to elsewhere in the U.S.

Clark County has a lower percentage of adults who have completed high school, 83 percent, than either rural county. Clark County is not rural, however, and we do not misapply the findings of SNWA Exhibit 248 to predict the decline of Clark County.

Aldrich and Kusmin also noted that:

> "Industry structure was an important determinant of county earnings growth. Counties experienced significantly greater earnings growth if they had higher concentrations of employment in transport services, real estate, hotels, miscellaneous business services, education services, or State and local government." (page 3).

Again, all Exhibits from both the Applicant and protestants have documented that White Pine County and Lincoln County have relatively high concentrations of employment in service and public sectors.

In addition to Aldrich and Kusmin's unrefereed bulletin, there is also uncontested support in the refereed scientific literature that subsequent rural growth is statistically significantly positively associated with both relatively larger initial employment shares in service and public sectors (Kilkenny and Partridge, 2009) and, relatively more natural and scenic amenities (Deller, et al, 2001). White Pine and Lincoln Counties display both of those key features as well. Finally, peer-reviewed refereed scholarly journal articles conclude that rural counties with robust service sectors sustain despite downturns in mining or manufacturing employment (e.g., Kilkenny and Partridge, 2009).

The list of misinterpretations by Holmes, however, is not yet complete. Aldrich and Kusmin explicitly stated that most of the factors Holmes called "fundamental and typical for economic growth to occur," were not even statistically significant. Quoting Aldrich and Kusmin:

> "Some variables yielded little or no evidence of a significant relationship with earnings growth. These variables include total population of nearby metro areas, urban population within the county itself, presence of an airport within the county itself, presence of an intersection of two major highways within the county, population aged 25 to 64, …college completion rate, … and topography." (page 3).

In sum, Holmes got it backwards. The analysis contained in Exhibit 241 is incorrect. It is invalid and should be ignored.

(5) An Important Lesson from Clark County History

The Applicant failed to recognize the lessons of Clark County's own history over the past 70 years when analyzing the need for water for the growth of White Pine or Lincoln Counties over the next 70 years. The Applicant's testimony does not provide sufficient information to rule out future economic development in White Pine or Lincoln County if the counties are not water-constrained. As White Pine Commissioner Gary Perea, quoted in an August 16, 2006 article in the Las Vegas Sun said, "Who's to say that it's not White Pine County that is the future of Nevada? ... The future of Nevada is not necessarily in Clark County." (Rake, 2006).

Over the 70 years since 1940, a similarly remote low-density place in a hotter and less hospitable desert grew into the Las Vegas-Paradise metropolitan area. It could not have grown without its water resources. In 1928 there were fewer people in Clark County than in either Lincoln or White Pine County today. Who would have thought at that time that the county needed or deserved much more water? Las Vegas believes it was poorly represented in the State of Nevada's negotiations of the Colorado Compact in 1928,

> "Only when Las Vegas began to outgrow its water did the Colorado Compact and its 1928 allocations come to be seen as a blunder, one that hits a regional nerve. Richard Bunker [Clark County manager in 2008] will tell you that it's Northern Nevada's fault. There were no Southern Nevadans at the table. Moreover, according to Bunker, the Northern ones just might have been

drunk…   …"For them to say 300,000 acre-feet was a lot of water for a place that was sand dunes, mosquitoes and rattlesnakes sounds fair," Bunker says. "But when you look at what Arizona got, 2.8 million ..." he drifts off, then sighs. "It is what it is."" SOURCE: Green (2008) http://www.lasvegassun.com/news/2008/jun/01/satiating-booming-city/

"Those who cannot remember the past are condemned to repeat it." George Santayana.

(6) The Applicant Incorrectly Underestimates the Urban Growth Prospects in The Counties:

By focusing exclusively on short-run local historic time-series trends and ignoring cross-sectional patterns underlying the unrefuted scientific evidence commonly known as the Central Place Theory and the Rank-Size Rule, the Applicant incorrectly underestimates the urban growth prospects in White Pine and Lincoln Counties. The Applicant's biased and incomplete testimony does not provide credible information to justify the proposed water withdrawals and transfers.

The pattern of urban settlement, even in the west, possesses an amazing regularity called Zipf's Law. More commonly known as the Rank-Size Rule, the law holds that the magnitude of the r^{th} observation in rank equals $1/r^{th}$ of the magnitude of the first or largest observation (see, for example, Gabaix, 1999). The table below shows how well western U.S. cities conform to Zipf's Law (note the correspondence between the predicted and observed 1/r):

Rank "r"	State	City	population	Predicted 1/r	Observed 1/r
1	CA	Los Angeles city	3,831,868	100%	100%
2	AZ	Phoenix city	1,593,659	50%	42%
3	CA	San Diego city	1,306,300	33%	34%
4	CA	San Jose city	964,695	25%	25%
5	CA	San Francisco city	815,358	20%	21%
6	NV	Las Vegas city	567,641	17%	15%
7	AZ	Tucson city	543,910	14%	14%
8	CA	Fresno city	479,918	13%	13%
9	AZ	Mesa city	467,157	11%	12%
10	CA	Sacramento city	466,676	10%	12%

The alert reader might notice that the example above is based on cities, and may well wonder if the regularity applies to metropolitan areas as well. The answer is yes:

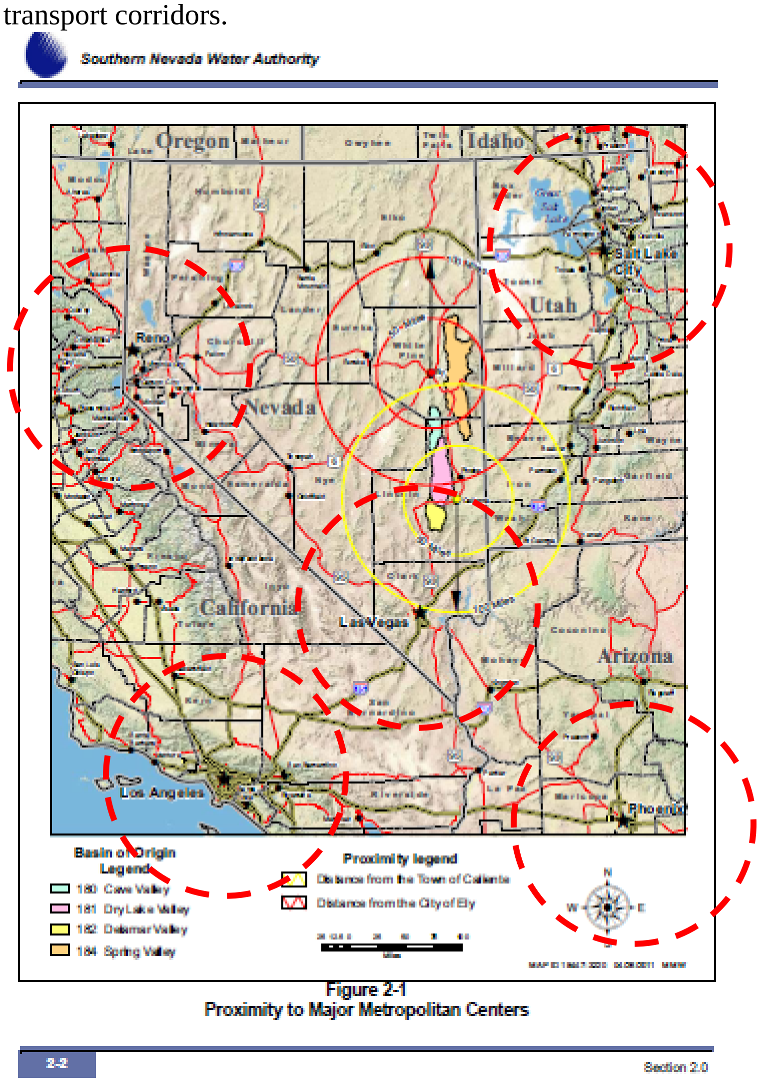
Rank "r"	State	Metropolitan Area	population	Predicted 1/r	Observed 1/r
1	CA	Los Angeles-Long Beach-Santa Ana	12,874,797	100%	100%
2	AZ	Phoenix-Mesa-Scottsdale	4,364,094	50%	34%
3	CA	San Francisco-Oakland-Fremont	4,317,853	33%	34%
4	CA	Riverside-San Bernardino-Ontario	4,143,113	25%	32%
5	CA	San Diego-Carlsbad-San Marcos	3,053,793	20%	24%
6	CO	Denver-Aurora-Broomfield	2,552,195	17%	20%
7	OR	Portland-Vancouver-Beaverton	2,241,841	14%	17%

8	CA	Sacramento—A-A—Roseville	2,127,355	13%	17%
9	NV	Las Vegas-Paradise	1,902,834	11%	15%
10	CA	San Jose-Sunnyvale-Santa Clara	1,839,700	10%	14%

Data Source: http://www.census.gov/compendia/statab/cats/population.html; tabulations by author

This empirical regularity has been documented at all spatial scales around the world for many centuries. The exceptions to the pattern are the cities of the People's Republic of China, where city size is directed by government fiat rather than free market forces. Historical, in-sample analyses also show that this long-run cross-sectional relationship also predicts the locations of new cities as well as their long-run size. And the law suggests that more medium size metro areas can be predicted to develop in the State of Nevada.

A related well-known and easy to visualize model of the location and sizes of cities, Central Place Theory (Berry and Garrison, 1958; Mulligan, 1984) can be applied to predict where Nevada's future urbanized areas might be. Since the late nineteenth century, after the initial development of port locations into cities (Los Angeles, San Francisco, Sacramento) the west has seen the rise of 'in-fill' cities, efficiently located between the original metro areas. This second wave of metro areas such as Phoenix, Fresno, and Las Vegas did not, however, cover the region. There remains plenty of room for more metro areas. To be connected by yet-to-be-developed interstate transport corridors.



The map originally provided in SNWA Exhibit 241 has been elaborated to show the predictive power of Central Place model over space and time. Notice how Las Vegas fits into the geography between Los Angeles and Phoenix.

The original version of this map showed the four valleys and the towns near them, plus the concentric circles around Ely at 50 and 100 'crow-fly' miles. The dashed 100 mile crow fly circles have been added to illustrate that Ely, NV is efficiently located midway between the existing interior metro areas of Salt Lake City, Las Vegas, and Reno. The development of Ely, NV as a regional central place would provide coverage of the region in which metropolitan central places are within about a half-day's drive.

With its scenic beauty, variety of local amenities, hospitable climate, and the amount of water currently available locally, there is every reason to anticipate the future development of a central place in White Pine County, such as Ely, Nevada; according to Central Place Theory, Zipf's Law, and the consensus of research on rural development.

(7) SNWA Fails to Account for the Cumulative Damage to Local Economies

SNWA Exhibits 103 and 241 incorrectly ignore the deleterious effects of the proposed water mining. By ignoring the circular flow of income through local expenditure, inter-industry interdependencies, and ignoring the lack of redundancy in White Pine and Lincoln counties, the Applicant's experts failed to account for the widespread and cumulative damage to the local economies associated with the proposed interbasin transfer of the limiting natural resource upon which all economic activity in the region is based. Thus the Applicant's testimony does not provide sufficient information to refute the likelihood that the proposed withdrawals will unduly limit future economic growth and development and harm the public interest.

It has been argued that the construction of the pipeline will benefit the communities in the valleys (Ruling #5476, 2007). This may be true in the short term during pipeline construction, but the benefit would only last a few years after which the anticipated negative impacts accelerate. The claim that there will be no further declines in the agricultural sectors in White Pine and Lincoln Counties as a result of the pipeline project has already been disputed in this rebuttal. The fact that the valleys generate business for other households employed in agricultural supply and tourism support activities in the towns is documented in Harris and colleagues (1994, 2004) as well as in Rajala, Spring Valley Exhibit 3054 (2006), summarized in Kilkenny, GBWN Exhibit 066 (2011). The wider economic impact also has been amply noted in the BLM's 2011 DEIS:

> "The seasonal nature of tourism has implications for local businesses and the jobs they provide. As noted above, a sense of tenuousness exists across the rural counties regarding their economic future. Tourism and recreation, though much smaller in scale than in Clark County, are viewed as vital elements of the local economies. Many local businesses are economically dependent on tourism and recreation, at least to a degree, whether they cater to all-terrain vehicle (ATV) enthusiasts, shed hunters (collection of antlers shed by deer and elk), big game hunters, overnight visitors drawn by scenic vistas, solitude and the night skies, or part-time residents owning second homes in the region. The purchases of private ranches by non-local corporate and institutional interests, including the Southern Nevada Water Authority, and future groundwater development are seen as threatening the region's tourism and recreation industry. Possible threats include limits on historical hunter access, changes in farming and ranching practices that affect wildlife, the potential indirect effects of groundwater drawdown and soil stability that affect visibility, night skies, and travel patterns of tourists; all of these could adversely affect the level of tourism and the economic contributions it provides. Tertiary effects of the water rights appropriation process and long-term groundwater drawdown effects on wildlife and tourism are viewed as threatening long-term second home development, which is viewed as another important dimension of economic development in the rural areas." Draft EIS: SNWA's Clark, Lincoln, White Pine Counties Groundwater Development Project – June 2011 Chapter 3, Page 3.18-18 and 18.

There are three more critical economic processes. The first is human behavior with respect to investment. That topic was briefly addressed in point three of this rebuttal. The other two are lumpiness and time. Lumpiness, or the fact that all economic activity requires set-up costs and therefore requires a minimum scale to survive, is scientifically known as imperfect divisibility. Over time, responses to initial changes accumulate. The ultimate outcome may be qualitatively quite different from the initial impact.

Very briefly, the implications of lumpiness and time are that:

> "…traditional marginal analysis doesn't work when assessing the effect of ag transfers on rural communities, because there is no margin. "There is only one of everything. It's not a matter of

one food store leaving the rural community; it's the *only* food store leaving the community." Page 44, Arkansas Round Table, 2008.

"… impacts become important when the accumulation of net impacts crosses some threshold and has either a qualitatively different impact, or exceeds some line or standard. Losing the last medical service or grocery store is different from losing one of three big stores or losing a specialist. Biologically, the problems of cumulative impact are common. That is why we recommend that all considerations be examined for cumulative as well as site specific impacts." Page 8, Arkansas Round Table, 2008.

CONCLUSION

In conclusion, White Pine and Lincoln Counties are home to the state's most dedicated stewards of the region's natural resources. Their economic activities are 'canaries in the coal mine.' Who will make beneficial use of our land and environmental resources after all the sales, closures, retirements, and out-migrations caused by the proposed interbasin water transfers? Groundwater withdrawals and interbasin transfers that threaten the local communities are the tip of the iceberg of a greater set of threats. One of the wider long run threats to the public interest is the conversion of this vast rural area into an uninhabitable and economically vacant wasteland. These threats to our society and economy are consequences of the environmental threats described by numerous hydrologists, hydrogeologists, plant scientists, and others.

The proposed groundwater withdrawals and transfers will harm and unduly limit the future growth and development of the local communities in the near term and ultimately the whole state. The applications should be denied to ensure the long run inhabitability of the state beyond one city's limits. Society has created habitable cities in deserts. But we must not create uninhabitable deserts in an attempt to grow cities. It would be a futile attempt in any case. Groundwater mining is unsustainable and ultimately both the city as well as the rest of the state would lose.

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White Pine County Exhibit KK

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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June 27, 2011

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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White Pine County Exhibit LL

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

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Received May 2008, accepted November 2008.

doi: 10.1111/j.1745-6584.2008.00538.x

with predictions (Konikow and Bredehoeft 1992; Bredehoeft 2003, 2005). Nowhere in these discussions of uncertainty did the authors argue that the predictions are not useful. Quite the contrary, we argued that predictions were worthwhile but should be used with a full awareness of the difficulties and resulting uncertainties.

We use Nevada as a prototype for our discussion. Nevada ground water law codifies some of the basic principles of ground water hydrology; for this reason, it is a nice example. Hence, we illustrate our ideas with two examples from Nevada. The most recent example is the proposal by the Southern Nevada Water Authority (SNWA) to develop a large ground water supply in eastern Nevada. The proposed SNWA development is ongoing and in the news. We present model predictions of the proposed SNWA development as an illustration of the major point of our paper. We also discuss how the water manager, in this instance the Nevada State Engineer, dealt with the model prediction that a long time would be required to reach a new equilibrium that includes the proposed pumping.

Nevada, with a few exceptions, treats each individual valley as a legally distinct ground water system. Some of the valleys are hydrologically self-contained; others are integrated by the underlying Carbonate Aquifer that underlies the region. SNWA is seeking water rights in a number of valleys. Each of these valleys requires a separate hearing and ruling by the State Engineer—granting or denying applications to pump ground water. So far there have been two hearings and ruling by the State Engineer who provided SNWA with rights to pump in Spring Valley and more recently in Cave, Dry Lake, and Delamar valleys.

The Water Budget

Meinzer (1931) elaborated on the idea of the water budget to estimate the "safe yield" of aquifers. Meinzer was not the first to express these ideas; he refers back to the earlier work of C.H. Lee from 1908 to 1911 in Owens Valley, California. According to Meinzer (1931), "Before any large ground-water developments are made, the average rate of discharge for any long period is obviously equal to the average rate of recharge." This was obvious to Meinzer and presumably his colleagues in the ground water community of the day—we have yet to find who first stated this idea. The principle establishes the reciprocal relationship between recharge and discharge in the undeveloped state and allows us to measure one as a surrogate of the other. Meinzer went on to urge the periodic inventory of the system in order to establish the elements of the budget through time.

A budget is a static accounting of the state of the system at a given time, often before the system is developed. Meinzer's idea was that the amount that could be developed depended upon the quantity of discharge from that system that could be salvaged. Nevada water law codified this idea in their definition of perennial yield:

> *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 . . . .

It follows that:

$$R_0 = D_0 \quad (1)$$

where R_0 is the undeveloped recharge and D_0 is the undeveloped discharge. We can introduce pumping into this expression:

$$R_0 - (D_0 - \Delta D_0) - P = \mathrm{d}V/\mathrm{d}t \quad (2)$$

where ΔD_0 is the change in the discharge created by the pumping (the salvage or capture), P is the rate of pumping, and $\mathrm{d}V/\mathrm{d}t$ is the rate of change of ground water in storage in the system.

Meinzer and others recognized that water must be removed from storage before a new equilibrium state could be reached. Again, Nevada water law codified this storage:

> *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).

At the new equilibrium state, the water budget is as follows:

$$\mathrm{d}V/\mathrm{d}t = 0 \quad \text{(by definition)} \quad (3)$$

$$P = \Delta D_0, \quad \text{where } \Delta D_0 \leq D_0 \quad (4)$$

and we constrain the pumping to be less than or equal to the discharge in order to allow a new equilibrium. If we allow for pumping to induce recharge, then at the new equilibrium:

$$P = \Delta R_0 + \Delta D_0 \quad (5)$$

where ΔR_0 is the change in undeveloped recharge produced by the pumping, ΔD_0 is the change in recharge produced by the pumping, and $\Delta R_0 + \Delta D_0$ is defined as the *capture*.

Capture

Theis (1940) introduced the principle of capture. Later, the USGS in Lohman (1972) 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.

Capture is an all-important concept in managing ground water; a ground water system can only be maintained indefinitely if the pumping is equaled by the capture—a combined *decrease* in the undeveloped discharge and *increase* in undeveloped recharge. If pumping continually exceeds capture, then water levels in the system can never stabilize, and the system will continue to be depleted. In other words, if pumping exceeds the potential capture in the system, a new equilibrium state that includes the pumping can never be reached. Again, let us remind the reader that our focus in this discussion is ground water systems that, when developed, can be maintained indefinitely.

The water budget applies to the system at a given time—a snapshot in time. The usual practice is to calculate a budget for the undeveloped state and then for the final state when the system reaches the new equilibrium. In discussing the budget, or inventory idea, Meinzer (1931) drew the analogy to a surface water reservoir. One can pump anywhere from a surface water body and have a similar impact; however, where one pumps in a ground water system becomes important, as we show subsequently. While the water budget describes the state of the system at a given time, it does not inform us about the time path the system will take to reach the new equilibrium state; the time path depends upon aquifer dynamics. It should be remembered that in 1931, when Meinzer wrote his paper, Theis' (1935) seminal paper that presented a general transient ground water flow equation had not yet been published.

In 1931, hydrogeologists did not have the ability to predict the time to reach a new equilibrium state. However, we argue that the expectation of Meinzer's work, and the work of others, was that once pumping was introduced, a new equilibrium would be reached in a reasonable period of time. However, it takes some ground water systems an inordinately long period to reach a new equilibrium. The time may be so long that the fact that a new equilibrium eventually is reached becomes meaningless. It is this problem we address subsequently.

Aquifer Dynamics

Theis (1935) introduced time into ground water theory. This allowed hydrogeologists to make temporal predictions. Historically, the profession went through several phases of prediction. In the 1940s, well hydraulics blossomed. Led by Theis and Jacob, ground water hydrologists solved the boundary value problem associated with various conceptual models of the aquifer and the associated confining layers. The predictive capability associated with the solutions allowed hydrogeologists to estimate relevant parameters of the ground water system—transmissivity, storage coefficient, leakance of a confining layer, and so forth. Armed with a theoretical conceptual model, one could predict response to pumping, which in turn allowed for well design, the sizing of pumps, and well spacing, among other facets of development.

Hydrologists of the day also sought to investigate ground water systems; however, they recognized the limitations imposed by the theoretical approach. Bob Bennett and Herb Skibitski, working at the USGS in the 1950s, developed the resistor/capacitor network, analog model of ground water systems. This allowed the creation of analog models of field systems in which realistic boundary conditions and internally variable parameter distributions could be simulated. The USGS created an analog model laboratory in Phoenix in approximately 1960, where models were constructed and predictions made for several tens of ground water systems. Walton and Prickett (1963) created a similar laboratory at the Illinois State Water Survey where they built analog models of Illinois ground water systems.

By the late 1960s, digital computers had advanced to the point that realistic ground water models could be constructed and analyzed using digital methods (Pinder and Bredehoeft 1968). The technology for solving the resulting massive matrix inversion problems had been pioneered by petroleum reservoir engineers and applied mathematicians working for petroleum companies. Reservoir engineers are involved with solving the same basic flow equation that we use for ground water, and the techniques were readily adapted to ground water problems. Digital computers have become increasingly more powerful; as the computer advanced, so did the ground water modeling technology. One can now create very realistic ground water models on a PC. Techniques are available to optimize the parameter distributions within the models (Hill and Tiedeman 2007). Advances in technology now make it feasible to make predictions of the behavior of complex ground water systems. Predictions, even in the best-calibrated model, have an associated uncertainty. Our predictive capability has grown steadily since Theis (1935) used the analogy between the flow of ground water and the flow of heat and Jacob (1940), starting from first principles, showed that the analogy was correct. Hydrogeologists now routinely predict ground water system behavior.

The Time to Reach a New Equilibrium

Given our ability to predict, it is of interest how long it takes for a ground water system to reach a new equilibrium, assuming that a new equilibrium state is possible. One can envision ground water systems in which the pumping greatly exceeds any potential capture. In such an instance, the system can never reach a new equilibrium, and water levels within the system will continue to decline until the system is depleted. We are concerned here with systems in which a new equilibrium state is feasible—that is, pumping can ultimately be balanced by capture.

Hypothetical Basin- and Range-Valley-Fill Aquifer

We first examine a hypothetical system that resembles some of the valleys in the Basin and Range (Figure 1). The two streams entering the basin on the left provide on

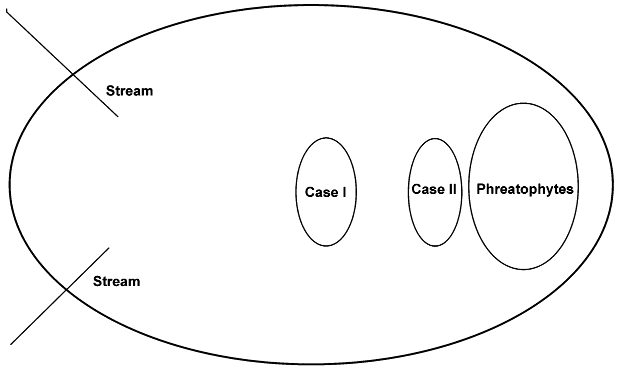

Figure 1. Plan view of a hypothetical valley-fill aquifer in the Basin and Range.

average 100 cubic feet per second (cfs) of recharge to the aquifer. The area of phreatophytes, to the right, discharges on average 100 cfs of ground water through evapotranspiration (ET) before ground water development. We consider two scenarios of ground water development located in the areas labeled case I and case II, respectively; each development pumps at a rate equal to the recharge—100 cfs.

We assume two-dimensional horizontal flow and the properties listed in Table 1. In our hypothetical system, we assume that ground water consumption by phreatophytes is diminished as pumping lowers the water table in the area containing phreatophytes. We deliberately created a ground water system in which capture of water that would otherwise be lost by ET can occur. As the water table drops between 1 and 5 feet, the consumption of ground water by ET is linearly reduced. The phreatophyte reduction function is applied to each cell in the model.

In order for this system to reach a new state of sustained yield, the phreatophyte consumption must be eliminated entirely. Using the model, we can examine the phreatophyte use as a function of time. Figure 2 is a plot of the phreatophyte use in our system vs. time since pumping was initiated. The location of the pumping makes a significant difference in the dynamic response of the system. In case II, where the pumping is close to the phreatophytes, the ET is reduced to 65 cfs in 10 years. In contrast, in case I, the ET is reduced to approximately 5 cfs in 10 years. Case I takes a long time to fully eliminate

Table 1
Aquifer Properties for Hypothetical Basin Shown in Figure 1

Basin size	50 × 25 miles
Model cell dimensions	1 × 1 mile
Hydraulic conductivity	0.00025 ft/s
Saturated thickness	2000 feet
Transmissivity	0.5 ft^2/s (~43,000 ft^2/d)
Storage coefficient	0.1%–10%
Phreatophyte consumption	100 cfs
Wellfield pumping	100 cfs
Recharge	100 cfs

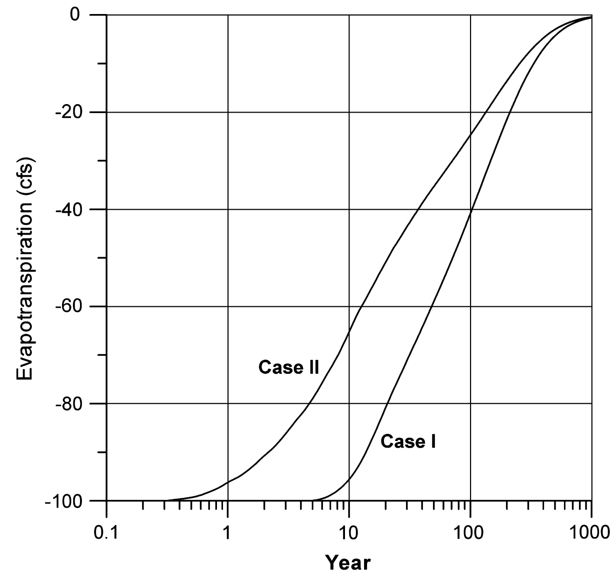

Figure 2. ET vs. time in our hypothetical valley-fill aquifer.

the ET; it is approximately 1000 years before the ET is totally eliminated. Even seasoned hydrologists are surprised at how long it can take an unconfined system to reach a new equilibrium state in which no more water is removed from storage.

We can also investigate the total amount of water removed from storage in our hypothetical valley-fill aquifer (Figure 3). It is important to notice that even though the two developments (case I and case II) are equal in size, the aquifer responds differently depending upon where the developments are sited. In case II, where the pumping is close to the phreatophytes, the amount of water removed from storage is approximately 50% less than that in case I. In case I, a large cone of depression must be created in order to impact the phreatophyte ET.

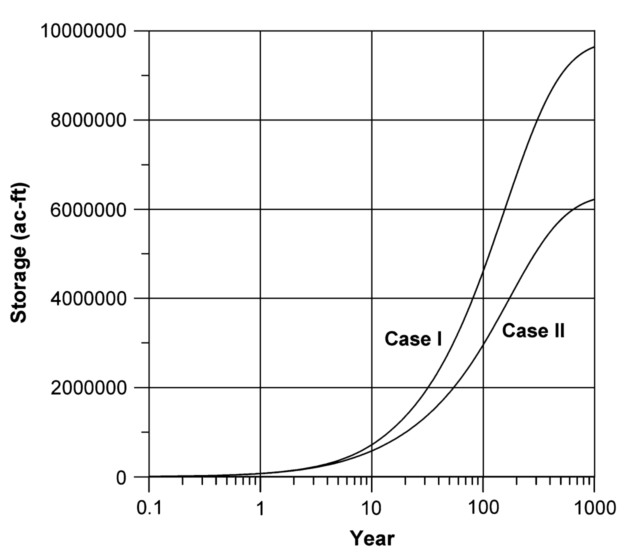

Figure 3. The volume of water removed from storage as a function of time in our hypothetical valley-fill aquifer with two developments—case I and case II (Figure 1).

This example of our rather simple Basin- and Range-valley-fill aquifer illustrates the importance of understanding the dynamics of aquifer systems. While this is a simple example, the principles illustrated apply to aquifers everywhere. In this case, it is the rate at which the phreatophyte consumption can be captured that determines how this system reaches sustainability; this is a dynamic process. Capture always involves the dynamics of the aquifer system. It makes a big difference in the response of the system where the wells are located. Thomas et al. (1989) describe the ground water hydrology of Smith Creek Valley, Nevada, where the USGS did a Regional Aquifer Systems Analysis (RASA) investigation; our simple example has many of the elements of Smith Creek Valley.

Paradise Valley

Alley and Leake (2003) explored the concept of "sustainability"; they used as their example a development in Paradise Valley in northern Nevada. The Humboldt River flows across the southern end of the valley. They used a model of ground water pumping near the southern end of the valley, not too far to the north of the Humboldt River, to examine the source of the ground water pumped vs. time (Figure 4). There are four sources of water that support the pumping: (1) water from storage; (2) capture of ET; (3) capture of surface water leaving the valley; and (4) induced recharge from the Humboldt River. Each of these sources varies with time.

The principal source of ground water in Paradise Valley during the early period is depletion of storage in the system. The storage declines to only 4% of the supply in year 300. The capture of water from ET grows from 20% in year 1 to approximately 75% of the total in year 300. The induced recharge from the Humboldt River grows from 0% in the early years to approximately 20% of the total in year 300. The capture of outflow from the valley grows to 3% in 300 years. The ground water system in Paradise Valley will take more than 300 years to reach a new equilibrium state. The time is about one-third as long as in case I in our hypothetical valley-fill aquifer explored earlier. Even after 300 years, 4% of the water pumped is still coming from storage.

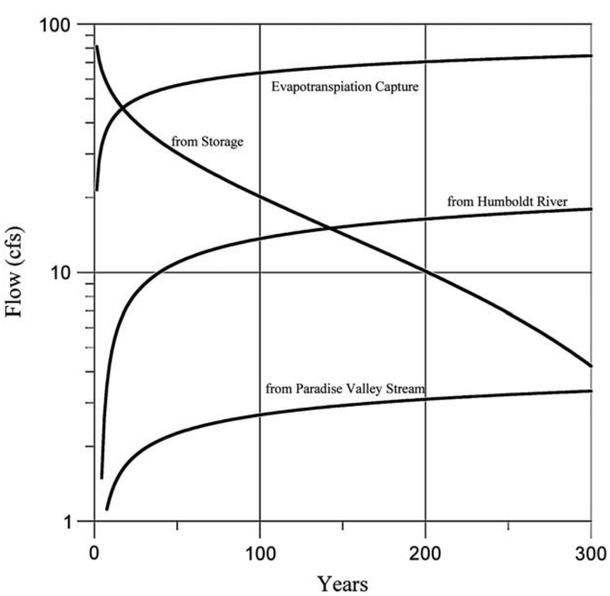

Figure 4. Computed sources of ground water to supply the pumping in Paradise Valley, Nevada (data from Alley and Leake 2003).

Both the induced recharge from the Humboldt River and the reduced outflow from the valley decrease the streamflow of the Humboldt River. This poses a potential future problem since the surface water in the Humboldt River, like most streams in the West, is overappropriated. Downstream surface water users will be hurt as this ground water development goes forward. An investigation of the undeveloped water budget for Paradise Valley would not have indicated induced recharge from the Humboldt River to be a significant source of water to the wells.

SNWA Development

The SNWA is proposing to pump 170,000 acre-feet/year of ground water just to the south of Ely, Nevada—approximately 200 miles north of Las Vegas. The water will be conveyed, via a pipeline, to Las Vegas. This will increase the water supply for Las Vegas by perhaps 40%; the fraction depends upon how much water is available in the future for Las Vegas from the Colorado River. The cost of the pipeline is currently estimated to be more than $3.5 billion.

The area under consideration for development is within the Carbonate Rock Province as defined by the USGS RASA investigation (Prudic et al. 1995), where there is a thick sequence of Paleozoic carbonate rocks. This sequence of rocks usually contains a Carbonate Aquifer that has the potential to integrate ground water flow between the valleys in the area (Eakin 1966). Analyzing ground water flow in this system entails investigating a much larger set of valleys than simply those that contain the pumping. The proposed SNWA pumping is situated mostly within the White River Regional Flow System (Figure 5).

There are several estimates of the recharge and/or discharge for portions of the ground water system pictured in Figure 5 (Eakin 1966; Las Vegas Valley Water District 2001; Welch and Bright 2007). A USGS RASA study of the system indicated that the pumping would reach a new steady state (Schaefer and Harrill 1995). The RASA, while calculating the impacts of a new equilibrium that included the pumping, did not estimate the time to reach the new state, other than to indicate that it was more than 200 years.

We realize that uncertainties associated with models and model predictions place confidence bounds around predicted values. However, we present single-valued graphs of predicted results to illustrate our points; we recognize that this oversimplifies the results. Figure 6 is a model prediction of the expected drawdown of the water table at the new equilibrium state that includes the

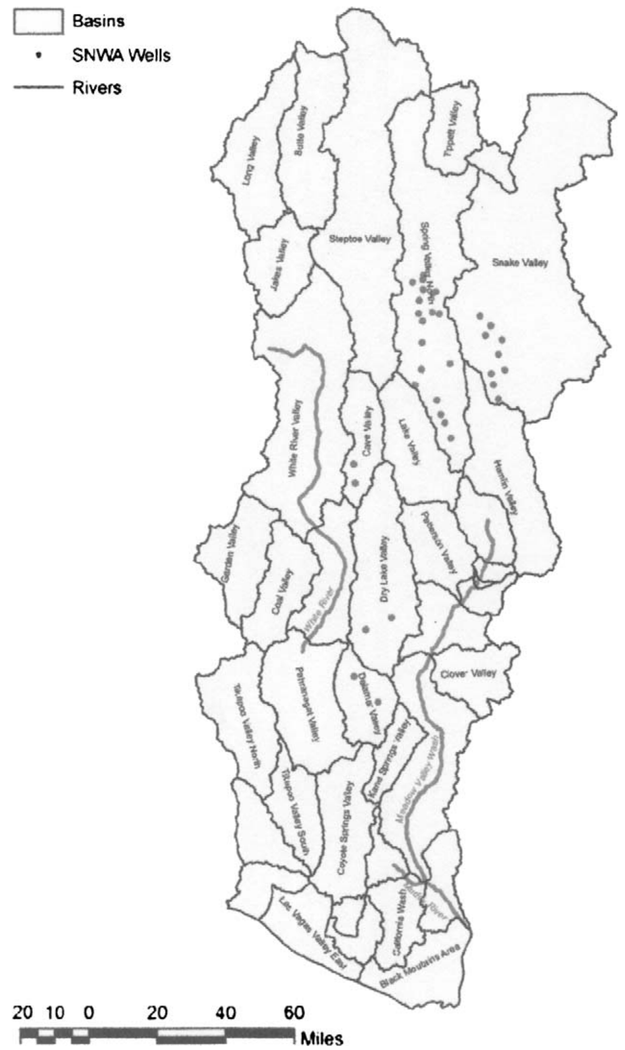

Figure 5. Map of the valleys in Nevada impacted by the proposed SNWA development. The proposed pumping wells are indicated.

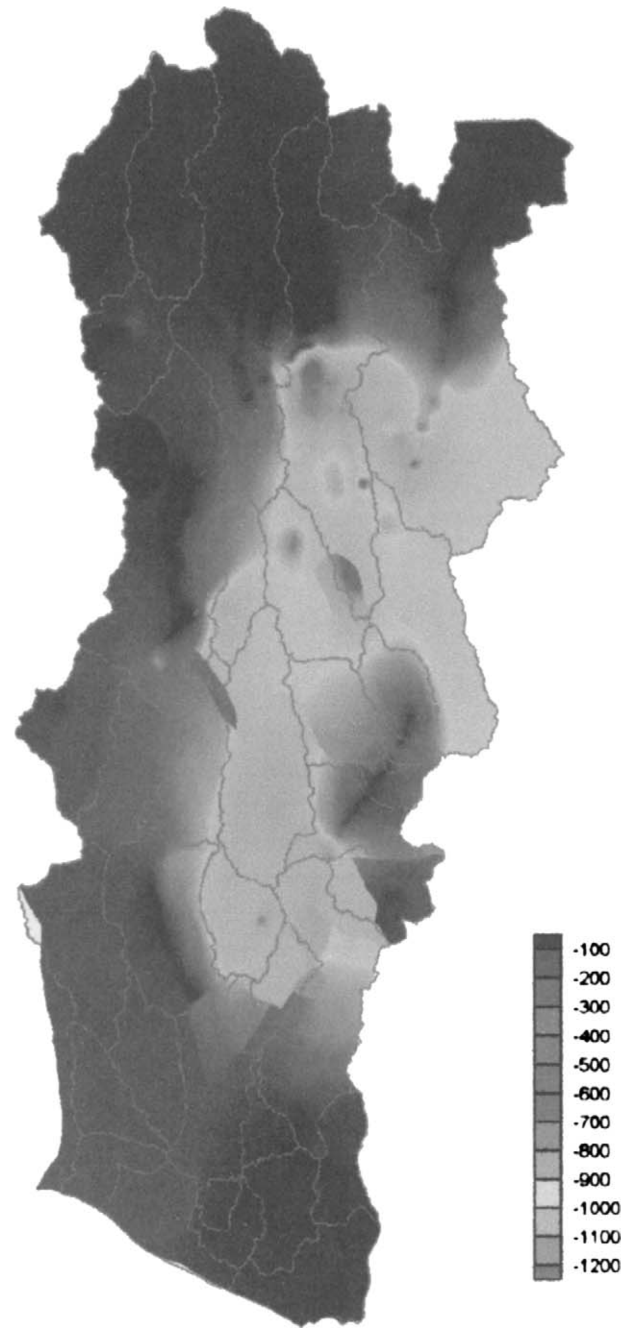

Figure 6. Computed expected drawdown in the water table at the new equilibrium state that includes the proposed SNWA pumping—predicted steady-state model.

proposed SNWA pumping. There is a very large area where the drawdown exceeds 700 feet. The deeper Carbonate Aquifer has similar drawdowns. Of particular interest is how long this system takes to reach the new equilibrium. Figure 7 is a plot of the change in storage in the system vs. time.

This figure is especially telling. The storage should level out and reach a stable level as the system reaches a new equilibrium (as in Figure 3), but this system is not close to reaching a new equilibrium state after 2000 years of projected pumping. A plot of the predicted ET vs. time (Figure 8) shows that the system has not reached a new equilibrium in 2000 years.

Combining Figures 7 and 8, we see that at 500 years, approximately 32% of the water pumped is coming from the depletion of storage and 65% from capture of ET. At 1000 years, 23% is coming from storage and 74% from capture of ET. At 2000 years, 14% is still coming from storage, while 82% is from capture of ET.

Nevada water law has only an implied reference to time; it only requires that the system reaches a new equilibrium state at some undetermined future time. The law was written before the tools were available to predict the future dynamics of ground water developments. The fact that the model predicts times more than 2000 years to reach a new equilibrium should change one's perspective on ground water management of this system.

Monitoring to Control Impacts

A strategy known as adaptive management relies on preventing impacts by monitoring the ground water

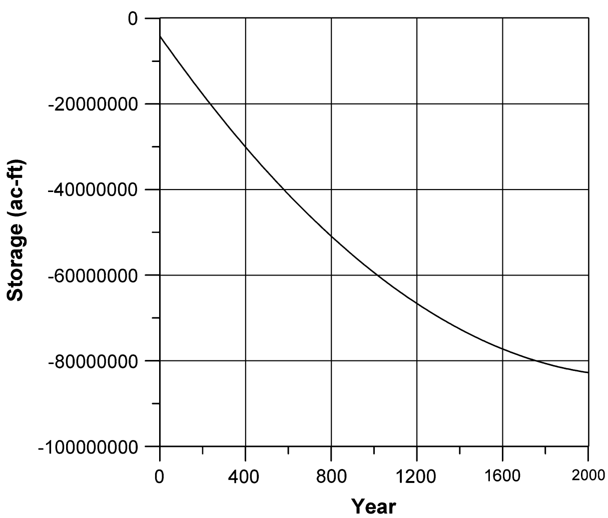

Figure 7. Predicted change in storage with proposed SNWA pumping.

system and changing the pumping stress when an undesirable impact is observed. The federal government entered into such agreements with SNWA before withdrawing their objections to the project. However, long-term monitoring also suffers from a prediction problem associated with the response time of the ground water system. We illustrate the monitoring problem with our hypothetical aquifer (Figure 1). We will examine a situation where we are attempting to maintain a spring at the lower end of our valley. Let us imagine that rather than having an area of phreatophytes discharging ground water, we have a single spring that discharges at 100 cfs before development. Our objective is to maintain the spring flow. We now start the case I ground water development that also pumps at 100 cfs.

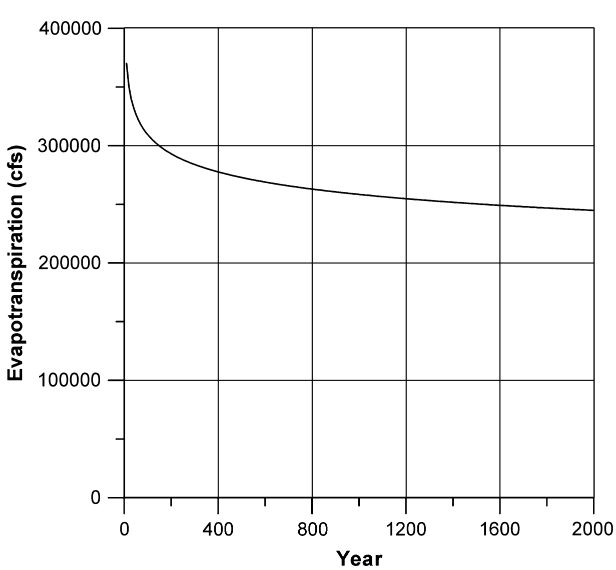

Figure 8. Computed plot of ET vs. time.

Let us further suppose we impose a monitoring and control strategy on the system. We monitor the spring with the intent that once the spring flow drops below 90 cfs (a 10% decline in flow), we will stop pumping ground water; in other words, our intent (as stated earlier) is to preserve the spring flow. We will use a 10% drop in flow as an observable signal that indicates that pumping is impacting the spring; smaller drops in flow could be ambiguous. (We are not arguing that this is a rational policy; rather we are illustrating a point.) Figure 9 shows the discharge of our spring vs. time; pumping stopped in area 1 in approximately 50 years when the spring discharge dropped to 90 cfs. The minimum spring flow occurs at approximately 75 years, 25 years after we stopped pumping. The reduction in flow is 13 cfs—larger than what it was when we stopped pumping. The maximum drawdown at the spring, created by the pumping, takes 25 years after pumping stops to work its way through the system.

We also see that the system does not recover readily to its predevelopment state even though the spring discharge equaled the recharge and was 100 cfs. Perhaps this is best understood if we look at the water removed from storage by the pumping and the rate at which it is replenished. During the period of pumping, the spring flow drops more or less linearly from 100 to 90 cfs. The amount of water removed from storage during this period averages approximately 95 cfs. The reduction in spring discharge averaged 5 cfs over the 50-year period—the capture of spring discharge averaged 5 cfs over the period. In other words, 95% of the ground water pumped during the 50 years of pumping came from storage. During the remaining 250 years since pumping stopped, the spring discharge averaged approximately 90 cfs. During that period, we are putting back in storage, on average, 10 cfs. This means that during the 250 years since the pumping ceased, we have restored just more than 50% of the water that was removed from the storage during the pumping period. You can easily see that this simple system will take approximately 500 years to return to its original state.

This hypothetical model illustrates the monitoring problem. If the monitoring point is some distance removed from the pumping, there will be (1) a time lag between the maximum impact and the stopping of pumping and (2) the maximum impact will be greater than what is observed when pumping is stopped (unless one has reached a new equilibrium state during the pumping period). The time for full recovery of the system will be long, even in the case where one has not reached the new equilibrium.

The real world is more complex. Those that advocate monitoring seldom envision totally stopping the pumping; rather, they imagine changes in the development that minimize damages. Stopping the pumping is a management action of last resort and we showed that it has problems. Less stringent management actions have a correspondingly lesser beneficial impact and even more problems.

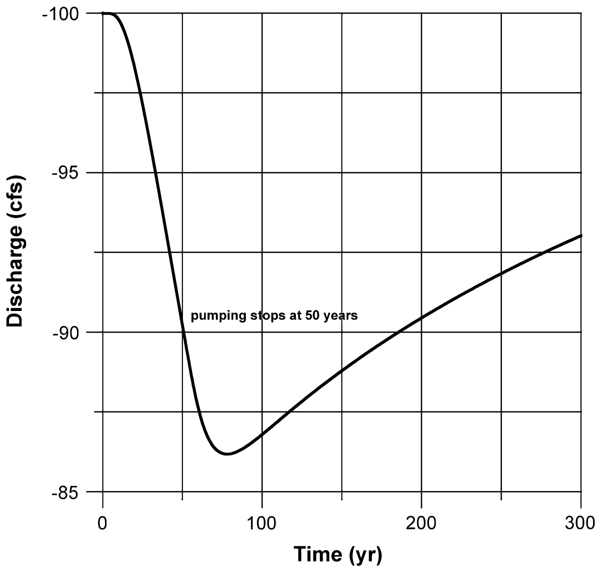

Figure 9. Predicted spring flow from a hypothetical aquifer (Figure 1 with phreatophytes in area 1 replaced by a spring). Pumping ceases after 50 years when the spring flow drops to 90 cfs.

Discussion

We do not think that the SNWA development in Nevada is all that unique nor do we think that this is typically only a western problem. Large aquifer systems exist throughout the country and the world. The response time problem is typical of large systems; there are other developments where the hydrologic boundaries where capture can take place are far from the pumping. Long times will be involved before the system can reach a new equilibrium—assuming that a new equilibrium is feasible. When the time to reach, or even approach, a new equilibrium exceeds a millennium or more, one has to ask—"Is the fact that the system will ultimately reach a new equilibrium meaningful?" It may be too distant in the future to have much meaning—too much can happen, civilizations change, the climate itself may change, and so forth. The bottom line is—it is important to predict the time trajectory of ground water systems, especially if one hopes to manage the system. Hydrogeologists have the tools to make these predictions.

The more vexing problem faces the water managers. For example, the SNWA development in Nevada can, given thousands of years, reach a new equilibrium. The question for the water manger, in this case the State Engineer, is how to deal with a system that takes so long to reach the new state—clearly, the law did not anticipate such long times.

Monitoring for control also has fundamental problems. The maximum impacts are larger than those observed at the time pumping stops, and they occur some time after the pumping stops. This is especially true if the monitoring is some distance away from the pumping. In addition, ground water systems will be very slow to recover to their predevelopment state once pumping is stopped.

In the case of SNWA's recent applications to pump in Cave, Dry Lake, and Delamar valleys, the Nevada State Engineer (2008) dealt with the problem as follows:

> The State Engineer finds that there is no dispute that the basins of the White River Flow System are hydrologically connected, but that does not mean that isolated ground-water resources should never be developed. The State Engineer finds he has considered the hydrologic connection and is fully aware that there will eventually be some impact to down-gradient springs where water discharges from the carbonate-rock aquifer system, but the time frame for significant effects to occur is in the hundreds of years.

> The State Engineer finds that a monitoring-well network and surface-water flow measurements will be part of a comprehensive monitoring and mitigation plan that will be required as a condition of approval and will provide an early warning for potential impacts to existing rights within the subject basins and the down-gradient basins of White River Flow System. The State Engineer finds that if unreasonable impacts to existing rights occur, curtailment in pumping will be ordered unless impacts can be reasonably and timely mitigated.

Conclusions

Some ground water systems in which a new equilibrium state that includes pumping can be achieved may take a long time to reach the new equilibrium. This is especially true where the discharge from the system that can potentially be captured by the pumping is a long distance away from the pumping center. Such a system may take more than a millennium, some more than two millennia, to reach the new equilibrium state.

This can pose a problem for the water manager, especially if the manager seeks to achieve a new equilibrium that will allow the pumping to persist for a prolonged period—essentially indefinitely.

One strategy, adopted by the State Engineer in Nevada, is to allow a large amount of pumping, more that can be sustained by a new equilibrium, while monitoring the system for adverse impacts. This strategy poses two problems: (1) a large ground water system creates a delayed response between the observation of an impact and its maximum effect and (2) there is a long time lag between changing the stress and observing an impact at a distant boundary.

If a water manager allows more pumping than the pumping can capture, then sooner or later the pumping must be curtailed or a new equilibrium can never be reached and the system will be depleted.

Acknowledgments

The authors wish to thank the editor and reviewers for their helpful suggestions.

Disclaimer

In fairness to the reader, we need to state that both authors of this paper acted as consultants on issues related to proposed ground water development in eastern Nevada. We consulted on opposing sides—Durbin for SNWA and Bredehoeft for the environmental coalition that opposes the development. Durbin's model of the proposed development for SNWA was documented, including its calibration, in a public document presented to the Nevada State Engineer at a hearing on SNWA's application for permits to pump ground water in Spring Valley, Nevada. Both authors presented the results of Durbin's model analysis in a public statement to the Nevada State Engineer at a hearing on SNWA's application to pump ground water in Cave, Dry Lake, and Delamar valleys, Nevada. The results are presented here as an example of model predictions; the predictions reflect all the caveats stated earlier.

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White Pine County Exhibit MM

ground water

Monitoring Regional Groundwater Extraction: The Problem

by J.D. Bredehoeft

Abstract

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

Introduction

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

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

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

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

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Received September 2010, accepted December 2010.

doi: 10.1111/j.1745-6584.2011.00799.x

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

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

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

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

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

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

First Principles

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

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

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

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

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

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

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

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

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

Periodic Signal

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

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

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

Table 1
Range of Aquifer Parameters

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

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

$$S = Q/(4\pi T)W(u) \tag{3}$$

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

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

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

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

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

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

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

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

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

What to Monitor

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

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

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

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

The Hypothetical Groundwater System

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

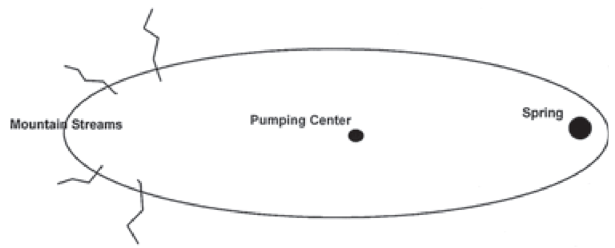

Figure 1. Schematic plan of the hypothetical valley. The pumping center is 50 miles from the spring.

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

Figure 1 is a plan view of my hypothetical valley.

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

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

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

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

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

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

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

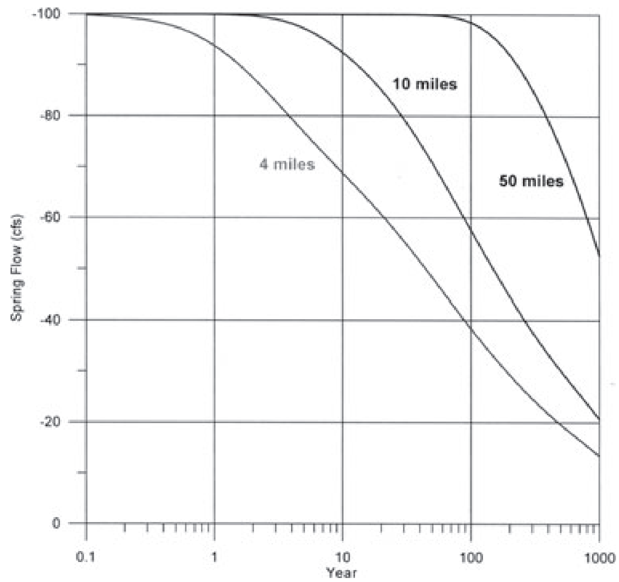

Figure 2. Simulated spring flow resulting from wells pumping 100 cfs in three different scenarios: pumping at 4, 10, and 50 miles from the spring.

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

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

Pumping at 4 Miles

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

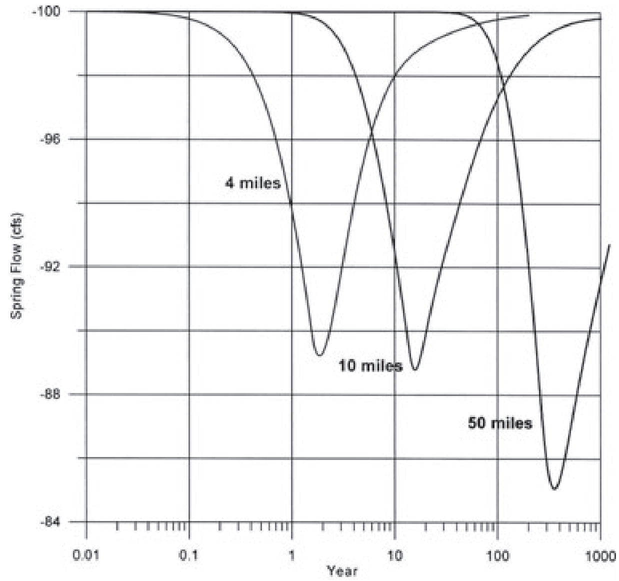

Figure 3. Three scenarios of pumping 100 cfs: at 4, 10, and 50 miles from the spring. Pumping ceased in each scenario when the spring flow declined by 10% to 90 cfs.

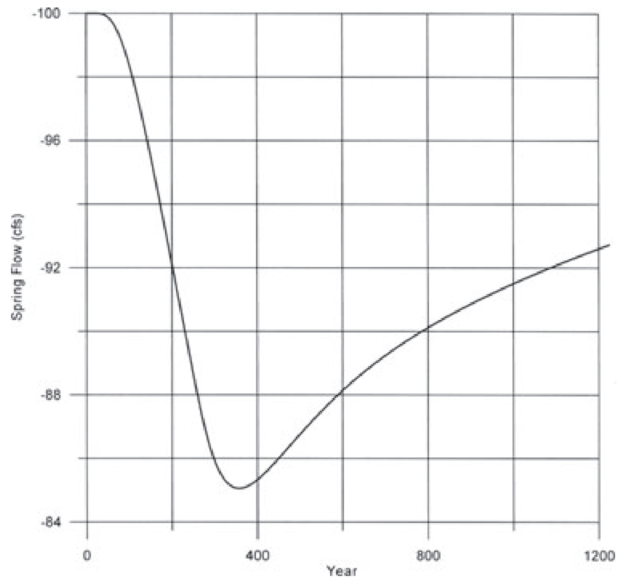

Figure 4. Plot of spring flow for pumping 100 cfs, 50 miles from the spring. Pumping was stopped after 230 years.

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

Pumping at 10 Miles

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

Pumping at 50 Miles

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

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

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

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

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

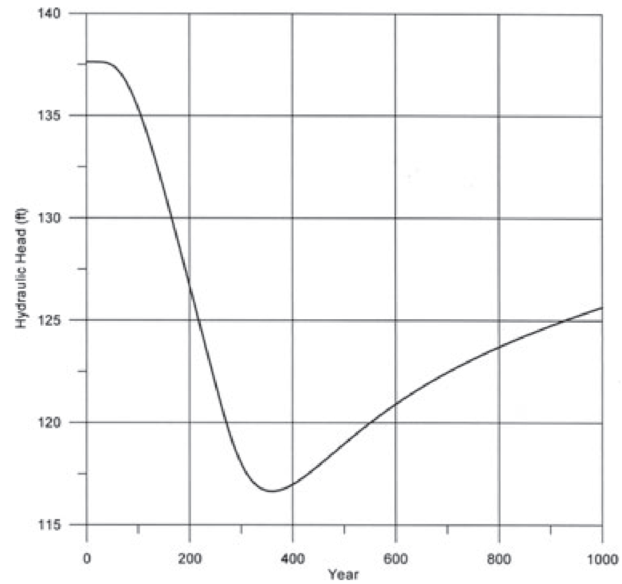

Figure 5. Plot of hydraulic head for the 50-mile pumping scenario; the observation well is 2 miles upstream, toward the pumping well from the spring. Pumping was stopped after 230 years.

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

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

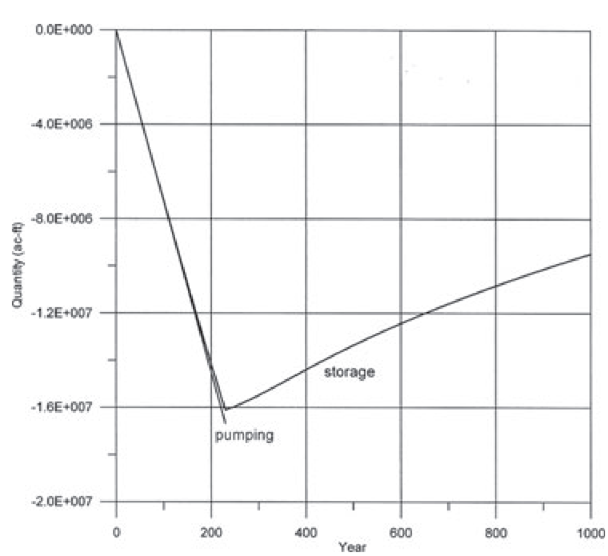

Figure 6. Plot of cumulative quantity of water pumped and cumulative change in storage for the scenario where the pumping is 50 miles from the spring.

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

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

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

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

Discussion

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

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

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

> ...... The State Engineer finds the discussion of impacts that are not manifested until several hundred years after the initiation of pumping is far too uncertain to be the basis of reasonable and responsible decision making. The State Engineer finds that there is no dispute that the basins of the White River Flow System are hydrologically connected, but that does not mean that isolated ground-water resources should never be developed. The State Engineer finds he has considered the hydrologic connection and is fully aware that there will eventually be some impact to down-gradient springs where water discharges from the carbonate-rock aquifer system, but the time frame for significant effects to occur is in the hundreds of years.
>
> The State Engineer finds that a monitoring-well network and surface water flow measurements will be part of a comprehensive monitoring and mitigation plan that will be required as a condition of approval and will provide an early warning for potential impacts to existing rights within the subject basins and the down-gradient basins of White River Flow System. The State Engineer finds that if unreasonable impacts to existing rights occur, curtailment in pumping will be ordered unless impacts can be reasonably and timely mitigated.

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

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

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

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

Aquifer Mechanics

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

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

Conclusions

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

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

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

Acknowledgments

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

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White Pine County Exhibit NN

ground water

Issue Paper/

The Water Budget Myth Revisited: Why Hydrogeologists Model

by John D. Bredehoeft[1]

Abstract/

Within the ground water community, the idea persists that if one can estimate the recharge to a ground water system, one then can determine the size of a sustainable development. Theis addressed this idea in 1940 and showed it to be wrong—yet the myth continues. The size of a sustainable ground water development usually depends on how much of the discharge from the system can be "captured" by the development. Capture is independent of the recharge; it depends on the dynamic response of the aquifer system to the development. Ground water models were created to study the response dynamics of ground water systems; it is one of the principal reasons hydrogeologists model.

Introduction

The idea persists within the ground water community that if one can determine the recharge to an aquifer system then one can determine the maximum magnitude of a sustainable development. One commonly hears the statement, "the pumping must not exceed the recharge (if the development is to be sustainable)."

The idea that the recharge (by which one usually means the virgin recharge before development) is important in determining the magnitude of sustainable development is a myth. A number of hydrogeologists have tried to debunk the myth, starting with Theis (1940) in a paper titled "The Source of Water Derived from Wells: Essential Factors Controlling the Response of an Aquifer to Development." Brown (1963) and Bredehoeft et al. (1982) wrote papers debunking the myth. Unfortunately, the message in Brown's paper was apparent only to those deeply schooled in ground water hydrology. The Bredehoeft et al. paper, while more readily understandable, was published in an obscure National Academy of Science publication that is out of print. At the time the Bredehoeft et al. paper was published, Theis congratulated the authors, commenting that he had intended to write another paper on the subject, but now he did not see the need. Needless to say, in spite of these efforts the myth goes on; it is so ingrained in the community's collective thinking that nothing seems to derail it.

It is presumptuous and perhaps arrogant of me to imply that the entire community of ground water hydrologists does not understand the principles first set forth by Theis in 1940; clearly this is not the situation. There are good discussions in recent papers that indicate other hydrogeologists understand Theis' message. The 1999 USGS Circular 1186, *Sustainability of Ground-Water Resources* (Alley et al. 1999), states the ideas lucidly. Sophocleous and his colleagues at the Kansas Geological Survey have published extensively on the concept of ground water sustainability; Sophocleous (2000) presents a summary of his ideas that contain the essence of Theis' principles.

On the other hand, I do not find Theis' principles on sustainabilty expressed clearly in the texts on ground water. These ideas were taught to me, early in my career, by my mentors at the U.S. Geological Survey. Also I find in discussions with other ground water professionals that these ideas, even though they are 60 years old, are not clearly understood by many individuals. It is my purpose in this paper to address again the myth that recharge is all important in determining the size of a sustainable ground water development, and show that this idea has no basis in fact.

Analytical Methods in Hydrogeology

Before digital computer modeling codes, hydrogeologists used traditional analytical methods to assess the impacts of wells on ground water systems. The traditional method of analysis used is the principle of superposition. In this approach, one assumes that the hydraulic head (or the water table) before development resulted from the inputs and outputs (recharge and discharge) from the system. One

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Received January 2002, accepted March 2002.

analyzes the impact of pumping independent of the initial (virgin) hydraulic head. The cone of depression is calculated as a function of time. This cone of depression is then superposed upon the existing hydraulic head (or water table). The resulting head after superposition is the solution to the development.

To make such a superposition calculation, one needs: (1) the transmissivity and storativity distribution within the aquifer, (2) the boundary conditions that will be reached by the cone of depression, and (3) the rate of pumping. Those trained in classical hydraulic theory are well aware of reflection boundaries and image wells to account for the boundary conditions.

Missing from the classical analysis is any mention of recharge. The recharge is taken into account by the initial hydraulic head (or the water table). The initial head is a solution to an initial boundary value problem that includes the recharge and discharge.

Prior to the widespread use of digital computer models most analyses in ground water flow were made using the principles of superposition. This was also the methodology used in the analog computer models of the 1950s, '60s, and '70s. With the advent of digital computer models, it became feasible to specify the varying distributions of recharge and discharge with the idea of solving for the virgin water table. The calculated water table can then be compared to the observed water table (or hydraulic head). To do such an analysis requires knowledge of the distribution of both the virgin rate of recharge and the virgin rate of discharge—in addition to the transmissivity distribution and the boundary conditions.

With an estimate of the rainfall, there is still no idea of how large the recharge is, except that it cannot exceed some unknown fraction of rainfall. The researcher may know the transmissivity of the aquifer at a few places and the aquifer discharge that makes up the baseflow of streams associated with the aquifer. Based on this set of limited information, a steady-state model analysis is made in an attempt to estimate the transmissivity of the aquifer. This is a common model analysis. In this context, knowledge of the virgin recharge is useful in estimating the transmissivity.

The recharge and the discharge are the inputs and outputs from a ground water system. Both quantities are important in understanding how a particular ground water system functions. However, it is not my purpose in this paper to discuss recharge or discharge. My focus is on how recharge and discharge enter into the determination of the sustainable yield of a ground water system.

In the classical analytical method, the important variables for determining the impacts of pumping are those that describe the dynamic response of the system—the distribution of aquifer diffusivity and the boundary conditions. This argument was the thrust of Brown's 1963 paper. The argument makes sense to one trained in classical analytical methods; it is more obscure to others. Brown's paper made almost no impact. I will attempt to further simplify the mathematical argument.

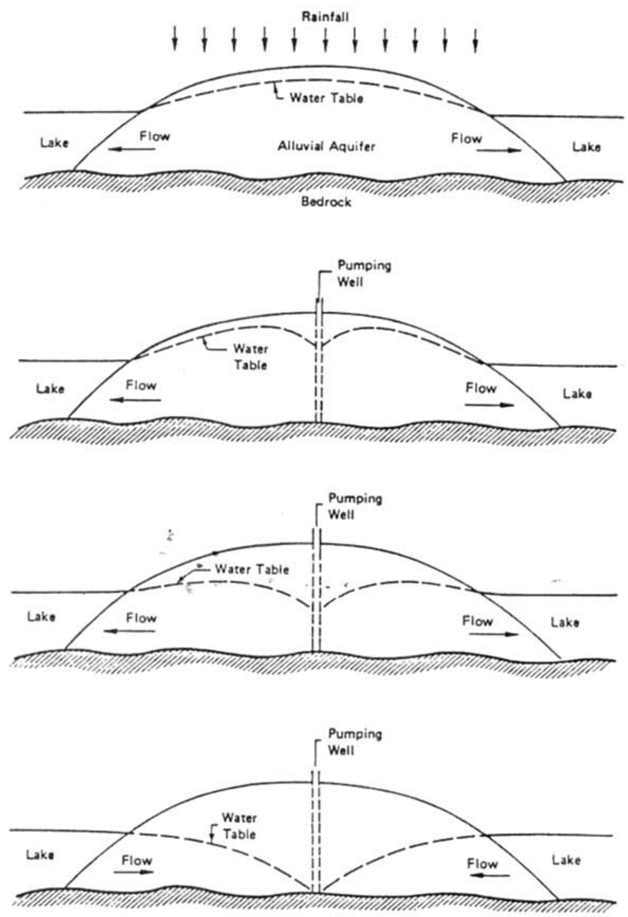

Figure 1. Schematic cross section of an aquifer situated on a circular island in a fresh water lake that is being developed by pumping. (Reprinted with permission from *Scientific Basis of Water-Resource Management*. Copyright 1982 by the National Academy of Sciences. Courtesy of the National Academy Press, Washington, D.C.)

The Water Budget

To illustrate the basic premise, I want to consider a simple aquifer system. A permeable alluvial aquifer underlies a circular island in a fresh water lake. Our intent is to develop a well on the island. The island aquifer is shown schematically in various stages of development in Figure 1.

Before development, recharge from rainfall creates a water table. The recharge over the island is balanced by discharge from the permeable aquifer directly to the lake (Figure 1—top cross section). We can write the following water balance for virgin conditions on our island:

$$R_0 = D_0 \qquad \text{or} \qquad R_0 - D_0 = 0$$

where R_0 is the virgin recharge (this is the recharge generally referred to in the myth), and D_0 is the virgin discharge. A water table develops on the island in response to the distribution of recharge and discharge and the transmissivity of the alluvial aquifer (Figure 1—top cross section).

The discharge to the lake can be obtained at any point along the shore by applying Darcy's law:

$$d = T\,(dh/dl)$$

where d is the discharge through the aquifer at any point along the shore; T is the transmissivity at the same point; and dh/dl is the gradient in the water table at that point. If 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 to come totally from local ground water. Enlightened individuals in Nevada decided to attempt to make the ground water supply within these valleys sustainable. The total discharge in many of the closed valleys in Nevada is by evaporation from the playas and from the transpiration (evapotranspiration [ET]) of phreatophytic plants that tap the water table. Nevada was willing to let the ground water pumping capture both the evaporation of ground water and the ground water that went to support the phreatophytic plants. This thinking led to the Nevada Doctrine that ground water pumping must not exceed the recharge. Perhaps the Nevada Doctrine perpetuates the myth. In reality the Nevada Doctrine is a roundabout statement that the development must not exceed the potential capture of ET (because as shown previously, the virgin ET is equal to the virgin rate of recharge).

As an aside, it has been difficult for the state engineer in Nevada to administer this doctrine in places of heavy urbanization such as Las Vegas, even though Nevada law codified the doctrine. The law also has been difficult to administer where discharge from a valley occurs as perennial streamflow (surface water) that is already appropriated.

The case of the perennial stream with an associated aquifer raises the problem of stream depletion, where pumping impacts streamflow that is appropriated by downstream users. Again, stream depletion is a dynamic ground water problem in capture—all the principles of the simple island example apply. Western water law recognizes the process of stream depletion with varying degrees of success—from zero to full recognition, depending upon the particular state.

Aquifer Dynamics and Models

Since the development of the Theis equation in 1935, hydrogeologists have been concerned with the dynamics of aquifer response to stress: pumping or recharge. Once Theis (1935) and later Jacob (1940) showed the analogy of ground water flow to heat flow, the ground water community has been busy solving the appropriate boundary value problems that describe various schemes of development. This endeavor has gone through several stages.

The 1940s and 1950s were a time during which the ground water profession was concerned with solving the problems of flow to a single well. Numerous solutions to the single well problem were produced. These solutions were used both to predict the response of the aquifer system and to estimate aquifer properties—transmissivity (or permeability) and storativity.

Hydrogeologists of that day saw the limitations in analyzing wells and sought a more robust methodology by which to analyze an entire aquifer, including complex boundary conditions and aquifer heterogeneity. The search led a group at the U.S. Geological Survey (USGS) to invent the analog model in the 1950s; the genius behind this development was Herb Skibitski, one of those individuals who rarely published. The new tool was the electric analog computer model of the aquifer. The model consisted of a finite-difference network of resistors and capacitors. In the analog computer, aquifer transmissivity is represented by the network of resistors; the storativity is represented by the network of capacitors. The resulting resistor-capacitor network is excited by electrical function generators that simulate pumping or other stresses. Voltage is equivalent to hydraulic head in the analog computer; electrical current is equivalent to the flow of water.

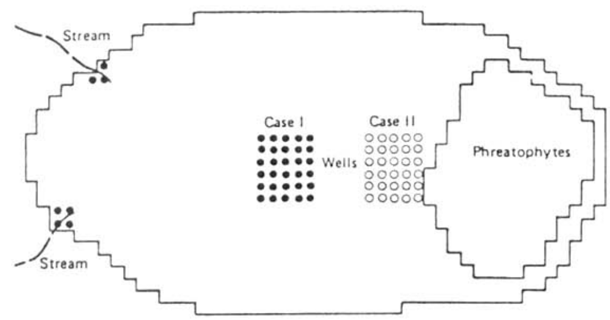

Figure 2. **Plan view of a hypothetical closed basin aquifer that is being developed.** (Reprinted with permission from *Scientific Basis of Water-Resource Management*. Copyright 1982 by the National Academy of Sciences. Courtesy of the National Academy Press, Washington, D.C.)

In reality, these were elegant finite-difference computer models of aquifer systems. By 1960, the USGS had a facility in Phoenix, Arizona, where analog models of aquifers were routinely built on a production basis. Some of these analog models had multiple aquifers; some had as many as 250,000 nodes. At the time, it was infeasible to solve the same problems with digital computers; the digital computers of the day were too small and too slow. However, by 1970 the power of digital computers increased to the point that digital aquifer models could begin to compete with the analog models. By 1980 digital computer models had replaced the analog models, even at the USGS. The models of the 1980s have now grown to include solute transport, pre- and postprocessors, and automatic parameter estimation. By far the vast majority of ground water flow problems are simulated using the USGS code MODFOW; there is a new version MODFLOW 2000.

The ground water model is a tool with which to investigate the dynamics of realistic aquifer systems. As suggested previously, it is only through the study and understanding of aquifer dynamics that one can determine the impact of an imposed stress on an aquifer system.

Dynamics of a Basin and Range Aquifer

To illustrate the dynamic response of aquifers, I will use closed basin aquifers such as those in the Basin and Range of Nevada as the prototypes. The aquifer geometry is illustrated in plan view in Figure 2. The basin is approximately 50 miles in length by 25 miles in width. At the upper end of the valley, two streams emerge from the nearby mountains and recharge the aquifer at an average combined rate of 100 cfs; approximately 70,000 acre-feet annually. At the lower end of the valley, an area of phreatophyte vegetation discharges ground water as ET at an average rate of 100 cfs. The system before development is in balance; 100 cfs is being recharged, and 100 cfs is being discharged by ET.

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 ft^2/sec (approximately 90,000 and 40,000 ft^2/day—both highly transmissive)
Storage coefficient	0.1%–10% specific yield
Phreatophyte area	170 mi^2
Average consumption	100 cfs
Wellfield area	30 mi^2
Average pumping	100 cfs
Recharge	100 cfs

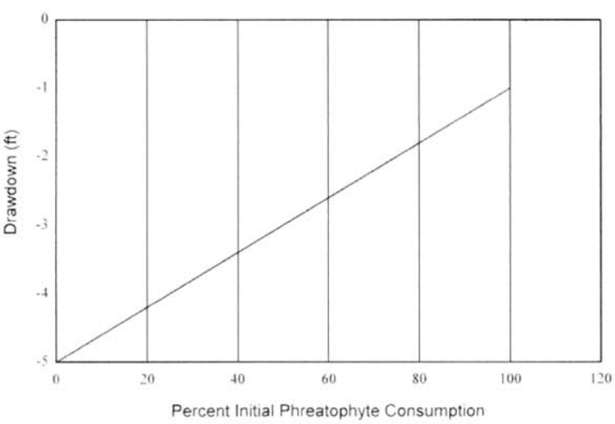

Figure 3. Linear function relating phreatophyte use to drawdown in the aquifer.

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.

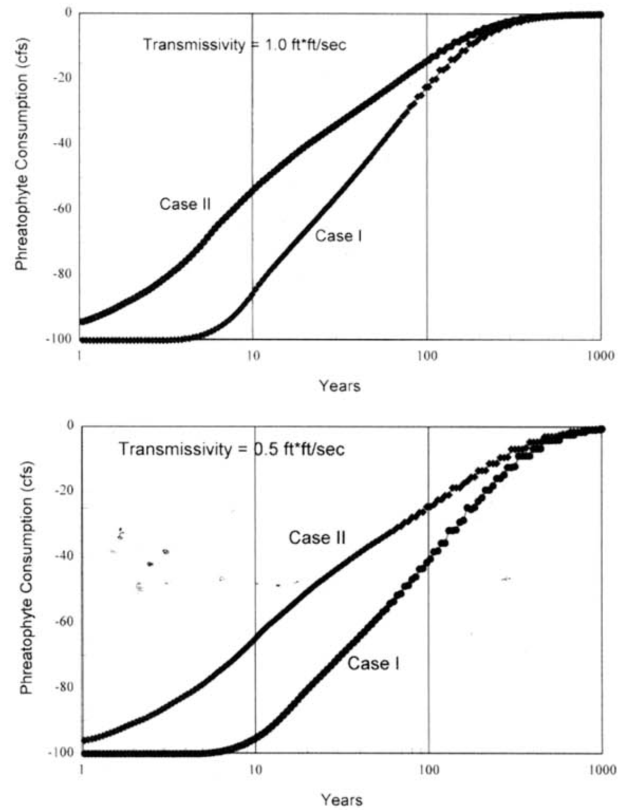

Figure 4. Plots of phreatophyte use vs. time.

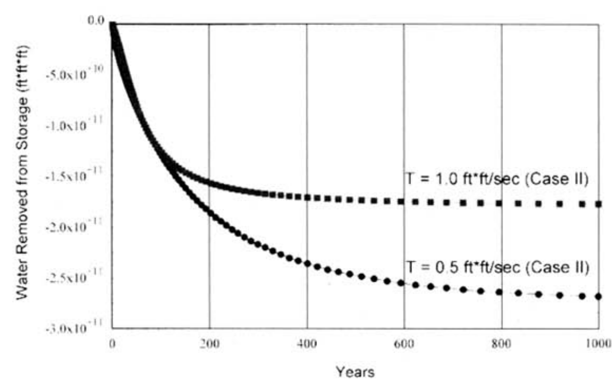

Figure 5. Plots of the change in storage vs. time.

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 ft^2/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 both aquifers, the phreatophytes are impacted faster where the pumping is closer to the phreatopytes (Case II). The point of considering Cases I and II is to show that the location of the pumping makes a difference in the dynamic response of the system. Most individuals, even trained hydrogeologists, are surprised at how slowly a water-table ground water system, like both the two systems simulated, responds to development.

We can look at the output from the model another way by examining the total amount of water removed from storage in our aquifers (Figure 5). In the high transmissivity aquifer, the amount of water removed from storage stabilizes in ~400 to 500 years, indicating we have reached a new steady state. Figure 5 shows that something of the order of 10^{11} cubic feet (approximately 3 million acre-feet) of water has been permanently removed from storage as the system changed to reach this new steady-state condition. This illustrates the important point that water must be removed from storage to reach a new steady state (sustainable) condition. In the lower transmissivity aquifer, water is still being removed from storage at 1000 years, and we have not yet reached a new steady state. In the lower transmissivity aquifer, ~5.7 million acre-feet of water have been removed from storage in 1000 years of pumping. Figure 5 again illustrates how slowly a water table aquifer responds.

It is important to notice that, even though the two developments (Case I and Case II) are equal in size, the aquifer responds differently depending on where the developments are sited. This again emphasizes the importance of studying the dynamics of the aquifer response: the response is different depending on where the development is located.

This example of our rather simple basin and range aquifer illustrates the importance of understanding the dynamics of aquifer systems. Again, while this is a simple example, the principles illustrated apply to aquifers everywhere. It is the rate at which the phreatopyte consumption can be captured that determines how this system reaches sustainability; this is a dynamic process. Capture always entails the dynamics of the aquifer system.

Conclusions

The idea that knowing the recharge (by which one generally means the virgin rate of recharge) is important in determining the size of a sustainable ground water development is a myth. This idea has no basis in fact.

The important entity in determining how a ground water system reaches a new equilibrium is capture. How capture occurs in an aquifer system is a dynamic process. For this reason, hydrologists are occupied in studying aquifer dynamics. The principal tool for these investigations is the ground water model.

These ideas are not new; Theis spelled them out in 1940. Somehow the ground water community seems to lose sight of these fundamental principles.

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Appendix

Conversion of Relevant Units—English versus Metric

1 foot	=	0.305 m
1 mile	=	1.61 km
1 square foot	=	0.0929 m^2
1 square mile	=	2.59 km^2
1 acre-foot	=	1234 m^3
1 cubic foot per second (cfs)	=	0.0283 m^3/sec