INTERBASIN GROUNDWATER FLOW FROM SOUTHERN SPRING VALLEY TO NORTHERN HAMLIN VALLEY AND SOUTHERN SNAKE VALEY, WEST-CENTRAL UTAH AND NEVADA: COMMENTS ON ESTIMATES OF FLOW RATE, POSSIBLE EFFECTS OF PROPOSED GROUNDWATER DEVELOPMENT IN SOUTHERN SPRING VALLEY, AND GROUNDWATER MONITORING

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Pertaining to:
Groundwater Applications 54003 through 54021 in Spring Valley
and
Groundwater Applications 53987 through 53992 in Cave, Dry Lake, and Delamar Valleys

August 2011

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For a statement of my qualifications as an expert witness on the foregoing, please see my curriculum vitae, attached

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PRESENTATION TO THE OFFICE OF THE NEVADA STATE ENGINEER

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Introduction

This submission presents scientific evidence and reasoning showing that 1) interbasin flow from southern Spring Valley to northern Hamlin Valley and southern Snake Valley (hereafter collectively referred to as southern Snake Valley) (figure 1) occurs at rates sufficient to form an important part of the groundwater budget of southern Snake Valley, 2) that this interbasin flow would be drastically reduced or eliminated by proposed groundwater pumping in southern Spring Valley, 3) such reduction in interbasin flow would negatively impact groundwater levels and, therefore, the ecology and economy of the Utah part of southern Snake Valley, and 4) implementation of the groundwater monitoring and mitigation plan established in the Stipulation for Withdrawal of Protests between SNWA and the U.S. Department of the Interior Bureaus for SNWA's original applications for groundwater appropriation in Spring Valley (hereafter referred to as the Spring Valley Stipulation Agreement), supplemented by groundwater monitoring in the Utah part of southern Snake Valley using sites established by the Utah Geological Survey (UGS) will help limit negative impacts of the proposed pumping in Spring Valley to the Utah part of southern Spring Valley.

Evaluating Interbasin Flow

One major goal of UGS work in Snake Valley and adjacent areas is to improve understanding of regional (miles to tens of miles) scale groundwater flow, including flow below and across surface-drainage divides (interbasin flow). Interbasin flow is difficult to quantify, and a wide range of scientific evidence and opinion regarding the feasibility and/or amount of interbasin flow from southern Spring Valley to southern Snake Valley exist (e.g., Prudic and others, 1995; Nichols, 2000; Lundmark and others, 2007; Gillespie, 2008; Welch and others, 2008; Burns and Drici, 2011; Rowley and Dixon, 2011). In evaluating interbasin flow in the west desert, the UGS strives to assemble as many scientifically sound lines of evidence as exist, and find the best interpretation that accommodates all of the data, bearing in mind their uncertainty levels. This approach forms the context for the following discussion of interbasin flow and groundwater monitoring.

Types of data typically employed to delineate interbasin flow include: 1) hydrologic data, including groundwater levels and hydrologic budgets (recharge and discharge estimates), (2) geologic framework, including hydrostratigraphy, extent and hydraulic properties of aquifers, and evaluation of the role of faults in groundwater flow, and (3) geochemical data as applied to evaluating proposed groundwater flow paths, principally through age-dating and flow-path modeling. Each of these methods has important strengths and uncertainties.

The basic hydrologic requirements for postulating interbasin flow from basin A to basin B are that basin A has an excess of recharge over discharge (including possible interbasin flow to and/or from other basins) to provide the groundwater available for flow, and that water levels in the aquifer(s) connecting the two basins are higher in basin A than in basin B, providing the potential difference to drive flow. Geologic criteria include the presence of sufficiently permeable aquifers and/or fault zones to provide the physical flow pathways. Geochemical criteria supporting interbasin flow include chemical and geochronological variations in groundwater that are consistent with the postulated flow direction, including possible open-system behavior (input of local recharge along the long-scale flow path).

Groundwater Flow from Southern Spring Valley to Southern Snake Valley

Hydrologic Studies

The concept of interbasin flow in the Great Basin evolved from basic hydrologic observations recorded during reconnaissance studies, that the discharge in many of the larger springs far exceeds the possible recharge from precipitation and stream flow in local (several to a few tens of miles) catchment areas (Mendenhall, 1909; Meinzer, 1911). Later reconnaissance studies of individual drainage basins focused on the imbalance of estimated recharge and discharge within hydrographic areas, as typically defined by surface-drainage divides, demonstrating that in some basins insufficient recharge exists to balance observed discharge including spring flow, and that in basins having constant water levels (i.e., no change in storage), the difference is balanced by interbasin flow from adjacent basins (Hood and Rush, 1965; Rush and Kazmi, 1965; Eakin, 1966; Gates and Kruer, 1981). Since that time techniques for estimating recharge and discharge have become much more detailed and advanced (e.g., Flint and others, 2004; Harrill and others, 1988; Prudic and others, 1995; Flint and Flint, 2007; Nichols, 2000; Mizell and others, 2007; SNWA, 2009a, 2010a; Burns and Drici, 2011).

Recent studies conclude that the area adjoining southern Spring Valley and southern Snake Valley (hereafter referred to as the interbasin flow area) meets the hydrologic criteria for interbasin flow stated above, and that 4,000 to 12,000 acre-feet per year flow from west to east (table 1).

***Table 1**. Recent estimates of interbasin flow from southern Spring Valley to southern Snake Valley.*

Study	**Interbasin Flow Rate (acre-feet/year)**
Gates and Kruer (1981)	4,000
Harrill and others (1988)	4,000
Nichols (2000)	10,000 to 12,000
Lundmark and others (2007) and Welch and others (2008)	33,000
SNWA (2009a)	5,740
Burns and Drici (2011)	4,400

Lundmark and others (2007) and Welch and others (2008) estimate a substantially greater interbasin flow rate than the other studies (table 1). The primary reasons for this difference are (1) they use the recharge estimates of Flint and Flint (2007), who employ a greater permeability value for Paleozoic carbonate rocks exposed at the surface, which leads to greater calculated recharge rates and, therefore, higher estimates of total recharge in basins that include carbonate-dominated mountain blocks, especially the southern Egan and Schell Creek Ranges; and (2) they assume high transmissivity in areas of interbasin flow where the carbonate aquifer is predominant. Compared to recharge estimates for those basins in common with other recent studies, the recharge estimates of Flint and Flint (2007) are substantially greater for hydrographic basins having predominantly carbonate rocks in their mountain blocks, but are similar in basins containing a lower relative percentage of carbonate rocks (Welch and others, 2008, table 5, p. 44).

Groundwater contours (figure 2; Gardner and others, 2011) suggest that flow is approximately west to east through the interbasin flow area, and becomes north to south below the valley center where it merges with recharge from adjacent ranges within the surface-drainage boundary.

Flint and Flint (2007) and Welch and others (2008) estimate that recharge to southern Snake Valley (their Snake Valley sub-basin 4 [figure 1]) from infiltration of precipitation and runoff is about 20,500 acre-feet per year (Welch and others, 2008, appendix A).

Groundwater recharge to southern Snake Valley, therefore, includes a mixture of (1) recharge of precipitation and runoff within the basin, mostly within the mountain block and along the alluvial fans along the range margin (20,500 acre-feet per year), and (2) interbasin flow from Spring Valley (4000 to 12,000 acre-feet per year [my preferred range], or up to 33,000 acre-feet per year [Welch and others, 2008]). Total recharge is about 24,500 to 32,500 acre-feet per year, and interbasin flow contributes about 15 to 35 percent of this rate. Based on the water budget values of Welch and others (2008), total recharge to southern Snake Valley is 52,500 acre-feet per year and interbasin flow comprises about 60 percent of this total.

Geologic Framework Studies

The hydrologic studies cited above include evaluation of the hydrogeologic framework of east-central Nevada, either within that work or in a companion report. Hydrogeologic framework analysis involves evaluation of the nature, extent, and hydraulic properties of aquifers and aquitards and the role of geologic structures in groundwater flow. The studies cited above produce similar conceptual hydrostratigraphy, hydrogeologic maps, and subsurface geometry of hydrogeologic units, though in varying detail, for east-central Nevada and west-central Utah. Welch and others (2008) and Rowley and Dixon (2008, 2011) present more detailed analyses of the relations among stratigraphy, structure, and groundwater flow than previous studies. Rowley and Dixon (2011) emphasize the role of fractures (especially faults) in controlling groundwater flow, and provide detailed descriptions of the structure of proposed interbasin flow areas. They conclude that no significant groundwater crosses major range-bounding normal-fault zones, except where they are breached by transverse faults. Rowley and Dixon (2011, p. 4-70 to 4-74) assert that normal-fault zones within and bounding the area of interbasin flow from southern Spring Valley to southern Snake Valley form barriers to interbasin flow, and that significant interbasin flow occurs only along the northern and southern ends of the Limestone Hills where the range-bounding normal-fault zones are cut by roughly east-west striking faults.

Welch and others (2008) and Burns and Drici (2011) use the Darcy groundwater flow equation (appendix A) to evaluate their estimates of interbasin flow from southern Spring Valley to southern Snake Valley. Welch and others (2008) use the Darcy flow equation, assuming their estimate of 33,000 acre-feet per year of interbasin flow, a hydraulic gradient of 0.00758, an aquifer thickness of nearly 15,000 feet, and that flow occurs uniformly along the entire area, to calculate a transmissivity for the carbonate aquifer of 5,800 ft^2/day and a hydraulic conductivity of 0.4 ft/day; this value is within the range of values calculated from aquifer tests of the carbonate aquifer in the Great Basin (Dettinger and others, 1995, p. 12-19, tables 1 and 2). Burns and Drici (2011) calculate an interbasin flow rate of 4,400 acre-feet per year, assuming that significant flow occurs only at the north and south ends of the Limestone Hills and using a hydraulic conductivity of 8 ft/day derived from a local aquifer test, an aquifer thickness of 2,000 feet, and a hydraulic gradient of 0.0008866. Note the strong difference in aquifer thickness and hydraulic gradient assumed by the two studies.

My application of the Darcy equation to the southern Spring Valley to southern Snake Valley interbasin flow area (appendix A) assumes that (1) the east-west horizontal hydraulic conductivity of the carbonate aquifer is (a) 8 ft/day in the faulted areas at either end of the Limestone Hills, and (b) 0.4 ft/day in the central Limestone Hills; (2) the hydraulic gradient driving interbasin flow is 0.00274 in the northern and southern Limestone Hills and 0.00407 in the central Limestone Hills, and (3) the aquifer thickness is 2000 feet along the entire length of active interbasin flow, for ease of comparison with Burns and Drici (2011). Using these input values, all of which are consistent with credible, widely reported data but which differ from Burns and Drici (2011) and Welch and others (2008) by varying amounts, the transmissive zones at the northern and southern ends of the Limestone Hills together can accommodate up to about 13,000 acre-feet per year of interbasin flow, and the central Limestone Hills can accommodate about 1200 acre-feet per year (appendix A). Reduction of groundwater levels in southern Spring Valley would reduce the hydraulic gradient between southern Spring Valley and southern Snake Valley, drastically reducing or eliminating (for drawdown of greater than 150 feet) interbasin flow (appendix B).

Geochemical Studies

Hershey and others (2007) present geochemical modeling of major-element solutes and stable and radiogenic isotopes showing that geochemical changes in groundwater from southern Spring Valley to southern Snake Valley are consistent with the postulated interbasin groundwater flow path discussed herein, and that the time scale for flow is on the order of 1000 to >6000 years. They also conclude that groundwater in the Needle Point Spring monitoring wells in Utah (UGS site 23, appendix C) contains a component of water derived from this interbasin flow, and that Big Springs in Nevada also contains a fraction of similarly old groundwater. Discharge from Big Springs and other nearby springs flows into Utah along Big Spring Creek (which becomes Lake Creek in Utah). Based on contours of stable isotopes and geochemical modeling, Gillespie (2008) concludes that little interbasin flow of relatively young (less than about 1000 years) groundwater occurs from southern Spring Valley to southern Snake Valley, compared to the volume of relatively young recharge that enters the basin fill from the southern Snake Range.

Discussion

Hydrologic Budgets. Estimates of the amount of groundwater available for interbasin flow from individual groundwater basins depend on the difference between estimated recharge by infiltration of precipitation and runoff, discharge by evapotranspiration, well withdrawal, and the amount of interbasin flow (if any) across other parts of the basin. Several different approaches have been used to estimate these values (Nichols, 2000; Flint and Flint, 2007; SNWA, 2009a), and each estimate is internally consistent and potentially valid. The large interbasin flow estimates of Lundmark and others (2007) and Welch and others (2008) cannot, therefore, be entirely dismissed at this time.

Groundwater Flow Across Major Faults. Manning and Solomon (2005) use groundwater temperature and environmental tracer chemistry in Salt Lake Valley, Utah, to show that about 16,000 to 37,000 acre-feet per year of groundwater flows in the subsurface from its recharge area in the Wasatch Mountains into the basin-fill aquifer along 10 miles of the range front in the southeastern part of the valley. This groundwater must cross the Wasatch Fault Zone, a major range-bounding normal-fault zone. The work of Manning and Solomon (2005) demonstrates that substantial groundwater flow can occur across major range-bounding normal-fault zones. They do not address the mechanisms or locations of cross-fault flow.

A similar geochemical tracer study has not been conducted in the southern Spring Valley to southern Snake Valley interbasin flow area, and groundwater and structural conditions are different there than in the Wasatch Range and Salt Lake Valley, but groundwater flow across the normal-fault zones bounding the Limestone Hills cannot be ruled out. The amount of cross-fault flow is likely small compared to fault-parallel flow, but no quantitative calibration between fault-zone structure and cross-fault flow exists. The structure and spatial distribution of permeability in fault zones is heterogeneous and difficult to predict (appendix B), but most fault zones likely contain areas where fault-zone fabrics and geometry permit cross-fault flow.

Big Springs and Stateline (aka Dearden Ranch) Springs. Hershey and others (2007, p. 70) use modeling of radiogenic isotope data to show that some of the groundwater discharging from Big Springs is about 8500 to 10,000 years old. The location of Big Springs is controlled by north-south striking faults (Kistinger and others, 2009, p. 314 and 316; Rowley and Dixon, 2011, p. 4-74). Stateline Springs (aka Dearden Ranch Springs by UGS usage) issue from bedrock just east of the Nevada-Utah border, and their location is controlled by north-south striking faults (Kistinger and others, 2009, p.318). Detailed geochemical analyses of environmental tracers have not been published for Stateline Springs, so this water may or may not contain a component of older groundwater derived from interbasin flow.

Groundwater issuing from Big Springs and Stateline Springs may be hydrologically connected to the interbasin flow area, based on (1) the presence of smoothly varying, potentiometric-surface contours and a south-to-north decrease in hydraulic head, from the area where interbasin flow enters southern Snake Valley to the springs, (2) the presence of a north-south striking fault system that links the two areas (Rowley and Dixon, 2011, p. 4-74), that forms a potential physical flow pathway, and (3) the presence of old groundwater in Big Springs, which could be derived from interbasin flow. If this hydrologic connection exists, flow at these springs would decrease due to reduction in the interbasin flow rate caused by groundwater pumping in southern Spring Valley. Big Springs and Stateline Springs form the headwaters and contribute significant input, respectively, to a local hydrologic system that consists of interdependent surface water and groundwater and includes Big Springs and Big Springs Creek in Nevada, and Lake Creek, Stateline Springs, and Pruess Lake in Utah (figure 1), and groundwater in southern Snake Valley in both states. This hydydrologic system is used by local ranchers and, in places, forms habitat for ecologically sensitive species.

UGS Groundwater Monitoring Network

Water-level changes at the UGS groundwater-monitoring sites in southern Snake Valley (figure 1; appendix C) reflect groundwater discharge by pumping and evapotranspiration and recharge in southern Snake Valley. Hydrographs from several of these sites show strong seasonal response to pumping and overall steady decline over the past two to three years, demonstrating the high sensitivity of water levels to current pumping and suggesting that any long-term change in recharge, including reductions of interbasin flow from Spring Valley, would adversely affect the current groundwater system.

Groundwater Monitoring

Bredehoeft (2011) and Bredehoeft and Durbin (2009) show that drawdown of groundwater levels due to groundwater pumping propagate outward from the pumping area at a rate that is controlled by the permeability of the aquifers from which the groundwater is extracted. In the southern Spring Valley to southern Snake Valley interbasin flow area, measurable groundwater declines will move from west to east and may not affect southern Snake Valley until tens of years after pumping has commenced (Bredehoeft, 2011; SNWA, 2010a). The groundwater monitoring wells in the interbasin flow area agreed to in Section 2 of the Spring Valley Stipulation Agreement are designed to detect drawdown and hydraulic gradient changes in the carbonate aquifer and to track these changes as they propagate to the east, and to better establish the hydraulic gradient in the carbonate aquifer through the interbasin flow area.

Conclusions

- Interbasin flow from Spring Valley comprises a substantial percent of the total groundwater recharge to southern Snake Valley.
- Groundwater pumping in southern Spring Valley at proposed rates would depress groundwater levels there, and would substantially reduce the hydraulic gradient between southern Spring Valley and southern Snake Valley, thereby reducing, eliminating, or even reversing interbasin flow. Reduction in interbasin flow would, in turn, reduce the total amount of groundwater and spring discharge present in southern Snake Valley.
- Hydrographs from monitoring wells and springs in southern Snake Valley suggest that some combination of current groundwater pumping and variation in natural recharge rates within the basin likely causes continuous decline of groundwater levels. Reducing recharge to this groundwater system by reducing or eliminating interbasin flow from Spring Valley would increase present rates of water-level decline southern Snake Valley.
- The ecology and economy in southern Snake Valley depend on the groundwater-surface water system. Reducing the groundwater input to this system would result in negative environmental and economic impact to the area.

Suggestions for Groundwater Monitoring

I recommend that to account for possible impacts to the groundwater-surface water hydrologic system in the Utah part of southern Snake Valley, the following groundwater monitoring should be included in any approval of SNWA's application for water rights in Spring Valley:

1) The full monitoring and mitigation program delineated in section 2 of the Spring Valley Stipulation Agreement.

2) Selected UGS groundwater monitoring sites within the initial biological monitoring zone of the Spring Valley Stipulation Agreement): sites 15, 23, 2, and 28 (Stateline [aka Dearden Ranch] Springs).
3) Measurable impacts to the southern Snake Valley groundwater system from drawdown due to groundwater pumping in southern Spring Valley may take several to at least tens of years after pumping commences, therefore any monitoring and mitigation plan should extend for at least a similar time period.

References

Bastesen, E., Braathen, A., Nottveit, H., Gabrielsen, R.H., and Skar, T., 2009, Extensional fault cores in micritic carbonate – Case studies from the Gulf of Corinth, Greece: Journal of Structural Geology, v. 31, p. 403-420.

Bredehoeft, J.D., 2011, Monitoring regional groundwater extraction: The problem: Ground Water, DOI: 10.111/j.1745-6584.2011.0079.x.

Bredehoeft, J.D., and Durbin, T.J., 2009, Ground water development – the time to full capture problem: Ground Water, v. 47, p. 506-514.

Burns, A.G., and Drici, W., 2011, Hydrology and water resources of Spring, Cave, Dry Lake, and Delamar Valleys, Nevada and vicinity: submitted for this hearing.

Caine, J.S., Evans, J.P., and Forster, C.B., 1996, Fault zone architecture and permeability structure: Geology, v. 24, p. 1025-1028.

dePolo, C.M., Clark, D.G., Slemmons, D.B., and Ramelli, A.R., 1991, Historical surface faulting in the Basin and Range province, western North America: implications for fault segmentation: Journal of Structural Geology, v. 13, p. 123-136.

Dettinger, M.D., Harrill, J.R., Schmidt, D.L., and Hess, J.W., 1995, Distribution of carbonate-rock aquifers and the potential for their development, southern Nevada and parts of Arizona, California, and Utah: U.S. Geological Survey Water-Resources Investigations Report 91-4146, 100 p.

Eakin, T.E., 1966, A regional interbasin ground-water system in the White River area, southeastern Nevada: Water Resources Research, v. 2, p. 251-271.

Faulds, J.E., and Varga, R.J., 1998, The role of accommodation and transfer zones in the regional segmentation of extended terranes, *in* Faulds, J.E., and Stewart, J.H., editors, Accommodation zones and transfer zones – The regional segmentation of the Basin and Range Province: Boulder, Colorado, Geological Society of America Special Paper 323, p. 1-45.

Flint, A.L., Flint, L.E., Hevesi, J.A., and Blainey, J.M., 2004, Fundamental concepts of recharge in the desert Southwest: A regional modeling perspective, *in* Hogan, J.F., Phillips, F.M., and Scanlon, B.R., eds., Ground-water Recharge in a Desert Environment: The Southwestern United States: American Geophysical Union, Water Science and Application Series, 9, p. 159-184.

Flint, A.L., and Flint, L.E., 2007, Application of the basin characterization model to estimate in-place recharge and runoff potential in the Basin and Range carbonate-rock aquifer system, White Pine County, Nevada and adjacent areas in Nevada and Utah: U.S. Geological Survey Scientific Investigations Report 2007-5099, 20 p.

Gardner, P.M., Masbruch, M.D., Plume, R.W., and Buto, S.G., 2011, Regional potentiometric surface map of the Great Basin carbonate and alluvial aquifer system in snake Valley and surrounding areas, Juab, Millard, and Beaver Counties, Utah and White Pine and Lincoln Counties, Nevada, in preparation; submitted for this hearing.

Gates J.S., and Kruer, S.A., 1981, Hydrologic reconnaissance of the southern Great Salt Lake Desert and summary of the hydrology of west-central Utah: Utah Department of Natural Resources Technical Publication 71, 55 p.

Geraud, Y., Diraison, M., and Orellana, N., 2006, Fault zone geometry of a mature active normal fault: a potential high permeability channel (Pirgaki fault, Corinth rift, Greece): Tectonophysics, v. 426, p. 61-76.

Gillespie, J.M., 2008, A conceptual model of groundwater flow in spring Valley, NV, and Snake Valley, NV-UT: Provo, Utah, Brigham Young University M.S. Thesis, 80 p.

Harrill, J.R., Gates, J.S., and Thomas, J.M., 1988, Major ground-water flow systems in the Great Basin region of Nevada, Utah, and adjacent states: U.S. Geological Survey Hydrologic Investigations Atlas HA-694-C, scale 1:1,000,000, 2 sheets.

Hershey, R.L., Heilweil, V.M., Gardner, P., Lyles, B.F., Earman, S., Thomas, J.M., and Lundmark, K.W., 2007, Ground-water chemistry interpretations supporting the Basin and Range regional carbonate-rock aquifer system (BARCAS) study, eastern Nevada and western Utah: University of Nevada Desert Research Institute Publication 41230, 86 p.

Hintze, L.H., and Davis F.D., 2002, Geologic map of the Wah Wah Mountains North 30' x 60' quadrangle and part of the Garrison 30' x 60' quadrangle, southwest Millard County and part of Beaver County, Utah: Utah Geological Survey Map 182, scale 1:100,000.

Hood, J.W., and Rush, F.E., 1965, Water-resources appraisal of the Snake Valley area, Utah and Nevada: Utah State Engineer Technical Publication No. 14, p. 43.

Kistinger, G.M., Prieur, J.P., Rowley, P.D., and Dixon, G.L., 2009, Characterization of streams and springs in the Snake Valley area, Utah and Nevada, *in* Tripp, B.T., Krahulec, K., and Jordan, J.L., editors, Geology and geologic Resources and Issues of Western Utah: Utah Geological Association Publication 38, p. 300-323.

Lundmark, K.W., Pohll, G.M., and Carroll, R.W.H., 2007, A steady-state water budget accounting model for the carbonate aquifer system in White Pine County, Nevada, and adjacent areas in Nevada and Utah: University of Nevada, Desert Research Institute Publication 41235, 56 p.

Manning, A.H., Solomon, D.K., 2005, An integrated environmental tracer approach to characterizing groundwater circulation in a mountain block: Water Resources Research, v. 41, W12412, doi:10.1029/2005WR004178.

Meinzer, O.E., 1911, Ground Water in Juab, Millard, and Iron Counties Utah: U.S. Geological Survey Water-Supply Paper 277, 162 p.

Mendenhall, W.C., 1909, Some desert watering places in southeastern California and southwestern Nevada: U.S. Geological Survey Water-Supply Paper 224, 98 p.

Mizell, S.A., Russell, C.E., and Kluesner, T.L., 2007, Reconnaissance estimation of groundwater recharge to selected hydrographic basins of eastern Nevada and western Utah using the chloride mass-balance method: University of Nevada, Desert Research Institute Publication 41232, 35 p.

Nichols, W.D., 2000, Regional ground-water evapotranspiration and ground-water budgets, Great Basin, Nevada: U.S. Geological Survey Professional Paper 1628, 82 p.

Prudic, D.E., Harrill, J.R., and Burbey, T.J., 1995, Conceptual evaluation of regional ground-water flow in the carbonate-rock province of the Great Basin, Nevada, Utah, and adjacent states: U.S. Geological Survey Professional Paper 1409-D, 102 p.

Rowley, P.D., and Dixon, G.L., 2008, Geology of, White Pine and Lincoln Counties and adjacent areas, Nevada and Utah: The geologic framework of regional groundwater flow systems, *in* Baseline Characterization Report for Clark, Lincoln, and White Pine Counties Groundwater Development Project: U.S. Bureau of Land Management Draft Environmental Impact Statement 11-18, Document BLM/NV/ES/11-17+1793, Supplements CD.

Rowley, P.D., and Dixon, G.L., 2011, Geology and geophysics of Spring, Cave, Dry Lake, and Delamar Valleys, White Pine and Lincoln Counties and adjacent areas, Nevada and Utah: The geologic framework of regional groundwater flow systems: submitted for this hearing.

Rush, F.E., and Kazmi, S.A.T., 1965, Water-resources appraisal of Spring Valley, White Pine and Lincoln Counties, Nevada: Nevada Department of Conservation and Natural Resources Water Resources Reconnaissance Report 33, 39 p.

Southern Nevada Water Authority, 2009a, Conceptual model of groundwater flow for the central carbonate-rock province - Clark, Lincoln, and White Pine Counties groundwater development project, *in* Clark, Lincoln, and White Pine Counties Groundwater Development Project Draft Environmental Impact Statement: U.S. Bureau of Land Management Draft Environmental Impact Statement 11-18, Document BLM/NV/ES/11-17+1793, Supplements CD.

Southern Nevada Water Authority, 2009b, Transient numerical model of groundwater flow for the central carbonate-rock province - Clark, Lincoln, and White Pine Counties groundwater development project, , *in* Clark, Lincoln, and White Pine Counties Groundwater Development Project Draft Environmental Impact Statement: U.S. Bureau of Land Management Draft Environmental Impact Statement 11-18, Document BLM/NV/ES/11-17+1793, Supplements CD.

Southern Nevada Water Authority, 2010a, Draft Addendum to the groundwater flow model for the central carbonate-rock province - Clark, Lincoln, and White Pine Counties groundwater development project, *in* Clark, Lincoln, and White Pine Counties Groundwater Development Project Draft Environmental Impact Statement: U.S. Bureau of Land Management Draft Environmental Impact Statement 11-18, Document BLM/NV/ES/11-17+1793, Supplements CD.

Southern Nevada Water Authority, 2010b, Simulation of groundwater development scenarios using the transient numerical model of groundwater flow for the central carbonate-rock province - Clark, Lincoln, and White Pine Counties groundwater development project, *in* Clark, Lincoln, and White Pine Counties Groundwater Development Project Draft Environmental Impact Statement: U.S. Bureau of Land Management Draft Environmental Impact Statement 11-18, Document BLM/NV/ES/11-17+1793, Supplements CD.

Welch, A.H., Bright, D.J., and Knochenmus, L.A., 2008, Water resources of the Basin and Range carbonate-rock aquifer system, White Pine County, Nevada, and adjacent areas in Nevada and Utah: U.S. Geological Survey Scientific Investigations Report 2007-5261, 96 p.

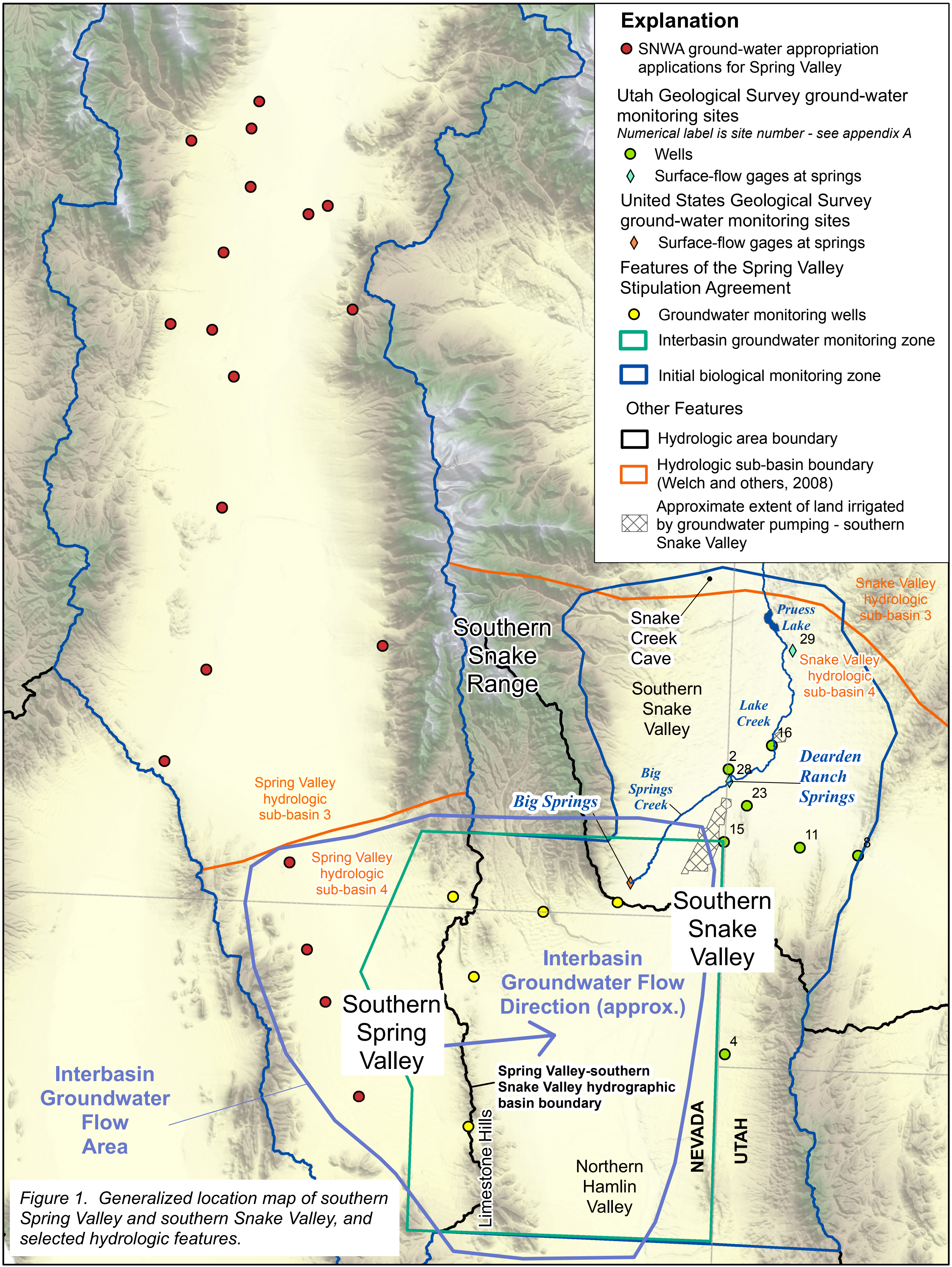
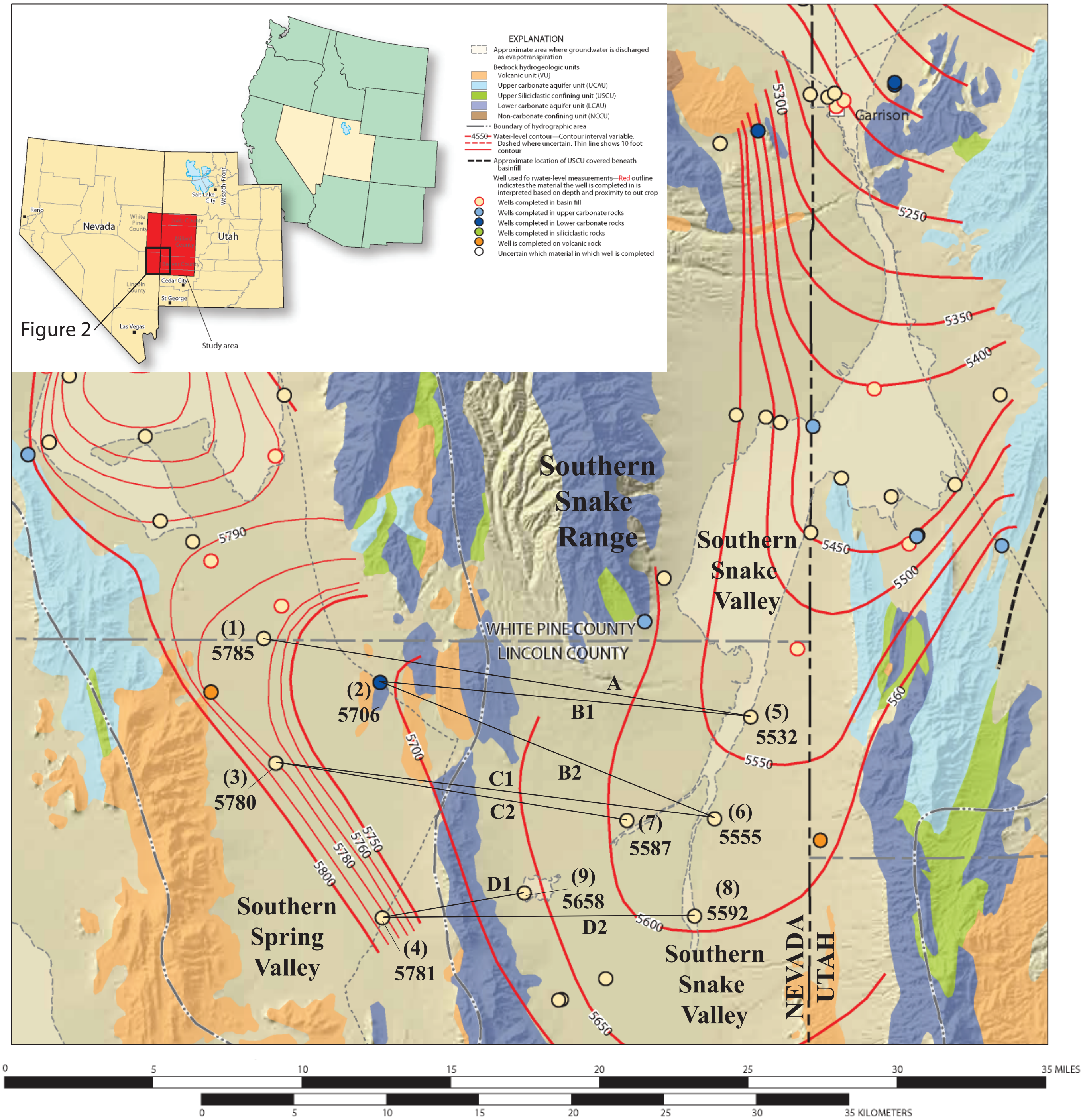


Figure 1. Generalized location map of southern Spring Valley and southern Snake Valley, and selected hydrologic features.



Parameters for Hydraulic Gradient Estimates (appendix A)

(1) **5785**	**Well number and static water level (feet) (table A1)**
C1	**Traverse**

Figure 2. Annotated detail from potentiometric surface map of Gardner and others (2011). Countour levels are in feet above mean sea level. Well numbers and hydraulic-gradient traverses are keyed to numbers in table A1 and "Regional Hydraulic Gradients" section of appendix A.

Appendix A

Applications of the Darcy equation for flow in porous media to the issue of interbasin flow from southern Spring Valley to southern Snake Valley

The Darcy flow equation is a widely used tool to evaluate simple groundwater flow problems in a general manner. Although the basic physics of the equation in its simplest (unexpanded) form are correct, its applications to groundwater flow involves many simplifying assumptions, including porous-media flow, spatially homogeneous distribution of hydraulic conductivity and hydraulic gradient, and that the hydraulic conductivity and aquifer thickness are reasonably well known. The results, therefore, are best used to approximately estimate flow rates and to illustrate the consequences of varying parameters, rather than to make precise predictions. The calculations on the following page and the interpretations presented here and in the main text are made with these assumptions in mind.

Here I apply the Darcy equation to the issue of interbasin flow from Southern Spring to southern Snake Valley across the Limestone Hills and areas to the north and south, to provide an alternate interpretation to those of Welch and others (2008) and Burns and Drici (2011, p. E-1). I use the approach and equation form of Burns and Drici (2011, p. E-1 and E-2):

$Q = (K*b)*I*W*C$

where

Q = groundwater flow rate (acre-feet per year),
K = hydraulic conductivity (feet perday),
b = aquifer thickness (feet), the depth of significant flow in the aquifer,
I = horizontal hydraulic gradient (water level difference in feet per unit length in feet),
W = horizontal width of flow section (feet), and
C = unit conversion factor = 0.0084.

The model geometry (see following page) is meant to represent flow through the Limestone Hills, including fault zones on its northern and southern ends. I use the same hydraulic conductivity of 8 ft/day as Burns and Drici (2011) for faulted Devonian carbonate rocks derived from their aquifer test. I also use the same width of fault zones and aquifer thickness as Burns and Drici (2011). For flow through the central Limestone Hills, I use a hydraulic conductivity of 0.4 ft/day derived by Welch and others (2008, p. 72) in their application of the Darcy flow equation. This value is ten times smaller than the median hydraulic conductivity of the lower Paleozoic carbonate aquifer (Welch and others [2008], table 3, p. 33). The value of 0.4 ft/day probably represents an average value of fractured carbonate rock having greater hydraulic conductivity and fault-zone rock having lower hydraulic conductivity.

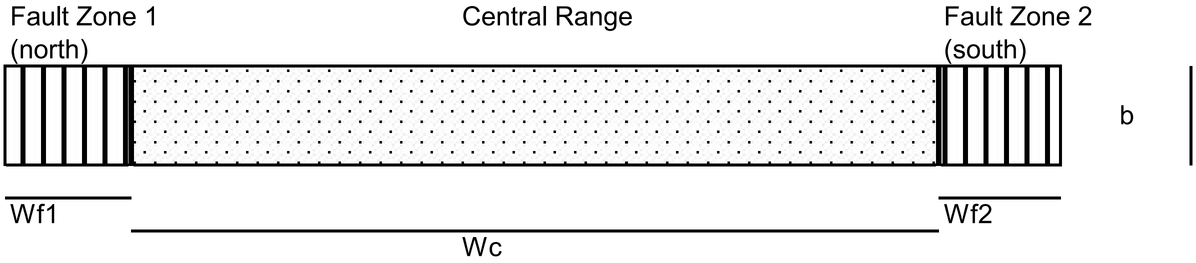
The hydraulic gradients through the northern fault zone and the central range are derived from water-well records available from the U.S. Geological Survey (table A1). These gradients are up to five times greater than that used by Burns and Drici (2011), and the wells used here are more widely separated and most are in basin fill. This approach assumes that the length scale of the driving force for interbasin flow is from basin center to basin center, and that the basin-fill and carbonate aquifers are hydraulically connected. This approach assumes that some groundwater flow passes through the normal-fault zone that bounds the western Limestone Hills; please see discussions in the main text and appendix B justifying this assumption. The hydraulic gradients through the southern fault zone is assumed to be the same as that through the northern fault zone, in the absence of nearby water-level data.

The results show that the Limestone Hills and adjacent faults can accommodate up to 14,500 acre-feet per year of interbasin flow from southern Spring Valley to southern Snake Valley. Even if no flow crosses the central Limestone Hills, use of the hydraulic gradient derived here suggests that interbasin flow can be up to 13,000 acre-feet per year.

The Darcy Equation can be used to evaluate, in a general way, possible effects on interbasin flow of lowering of groundwater levels in southern Spring Valley due to pumping. The “Flux Changes” section of the following pages shows that interbasin flow would be substantially reduced or reversed (based on changes in the hydraulic gradient and resulting changes in flow rates) for drawdown in southern Spring Valley predicted by SNWA (2009b, 2010b) for their Proposed Action and Alternatives A through E. The hydraulic gradient through the faulted area in the northern Limestone Hills would be reversed if over 150 feet of drawdown occurred in southern Spring Valley. This would eliminate nearly all interbasin flow from southern Spring Valley to southern Snake Valley.

Application of Darcy flow equation to interbasin flow from Spring Valley to southern Snake Valley.

PHYSICAL MODEL not to scale



REGIONAL HYDRAULIC GRADIENTS See figure 2 and table B1.

Traverse	Water level in up-gradient well	Water level in down-gradient well	Water Level difference (ft)	Distance (ft)	Gradient
A	5785	5532	253	88,268	0.00287
B1	5706	5532	174	66,620	0.00261
B2	5706	5555	151	64,529	0.00234
C1	5780	5555	225	79,191	0.00284
C2	5780	5587	193	63,730	0.00303
D1	5781	5658	123	25,818	0.00476
D2	5781	5592	189	55,935	0.00338

Averages

Northern Limestone Hills	**0.00274**	Traverses A, B1, B2, C1, and C2
Central Limestone Hills	**0.00407**	Traverses D1 and D2

INTERBASIN FLUXES Q = K*b*I*(Wf1 or Wf2, or Wc)*C

Estimates should be rounded to the nearest 500 acre-feet per year for purposes of discussion.

Using SNWA hydraulic gradient:

Flow Area	K	Q
Wf1	8	3575
Wf2	8	775
Wc	0.4	267
Sum		**4617**

Using average hydraulic gradients from above:

Flow Area	K	Q
Wf1	8	10765
Wf2	8	2333
Wc	0.4	1227
Sum		**14325**

b	2000	SNWA aquifer thickness
Wf1	30,000	width of northern fault segment
Wf2	6,500	width of southern fault segment
Wc	44,880	width of central Limestone Hills
C	0.0084	unit conversion factor (Burns and Drici, 2011)
I from SNWA	0.0008866	(Burns and Drici, 2011)
I from Hurlow	0.00267	in fault zones Wf1 and Wf2
I from Hurlow	0.00407	across central Limestone Hills Wc

K = hydraulic conductvity in feet per day (see text)
Q = flux in acre-feet/year

FLUX CHANGES

NLH B1 = northern Limestone Hills along gradient estimate B1
" Q decrease" for NLH B1 is difference between flux for Wf1 calculated using
Hurlow's average hydraulic gradient for Northern Limestone Hills, and flux calculated using new gradient.
CLH D = central Limestone Hills using averages of D1 and D2 values.
" Q decrease" for CLH D is difference between flux for Wc calculated using
Hurlow's average hydraulic gradient for Central Limestone Hills, and flux calculated using new gradient.

10 feet of drawdown in southern Spring Valley

Flow	Water Levels (ft)		Water Level	Linear	New		Q	Percent
Area	Spring V.	Snake V.	Difference[1] (ft)	Distance (ft)	Gradient[2]	New Q[3]	Decrease[4]	Decrease[4]
NLH B1	5696	5532	164	66,620	0.00246	9926	840	8
CLH D	5771	5625	146	40,877	0.00357	1077	150	12

50 feet of drawdown

Flow	Water Levels (ft)		Water Level	Linear	New		Q	Percent
Area	Spring V.	Snake V.	Difference[1] (ft)	Distance (ft)	Gradient[2]	New Q[3]	Decrease[4]	Decrease[4]
NLH A2	5656	5532	124	66,620	0.00186	7505	3261	30
CLH D1	5731	5625	106	40,877	0.00259	782	445	36

100 feet of drawdown

Flow	Water Levels (ft)		Water Level	Linear	New		Q	Percent
Area	Spring V.	Snake V.	Difference[1] (ft)	Distance (ft)	Gradient[2]	New Q[3]	Decrease[4]	Decrease[4]
NLH A2	5606	5532	74	66,620	0.00111	4479	6287	58
CLH D1	5681	5625	56	40,877	0.00137	413	814	66

150 feet of drawdown

Flow	Water Levels (ft)		Water Level	Linear	New		Q	Percent
Area	Spring V.	Snake V.	Difference[1] (ft)	Distance (ft)	Gradient[2]	New Q[3]	Decrease[4]	Decrease[4]
NLH A2	5556	5532	24	66,620	0.00036	1453	9313	87
CLH D1	5631	5625	6	40,877	0.00015	44	1183	96

1 - difference in static water levels of wells used to estimate gradient, after drawdown.
2 - hydraulic gradient after drawdown based on new water-level difference divided by linear distance between wells.
3 - from Darcy equation using new hydraulic gradient and previous parameters for traverses B1 and D (average values).
4 - difference between flow estimate before drawdown as estimated using Hurlow's hydraulic gradient values and new flow estimate after drawdown.

Table A1. Water-well data used to estimate hydraulic gradient from Spring Valley to southern Snake Valley. Data are from Gardner and others (2011).

USGS Site ID	Well Name	Latitude	Longitude	Water Level (ft)	Borehole Depth (ft)	Aquifer	Label on figure 2	Traverse(s) on figure 2
384039114232701	184 N10 E68 31CDDB1 USGS-MX	38.67806	-114.39194	5785	150	Valley Fill	(1)	A
383925114190801	184 N09 E68 11BDBD1 184W502M	38.65700	-114.31894	5706	1820	Carbonate	(2)	B1, B2, B3
383704114225001	184 N09 E68 30AAAB1 USGS-MX (Spring Valley S.)	38.61767	-114.38411	5780	700	Valley Fill	(3)	C1, C2
383351114180201	184 N08 E68 23BDBA1 USBLM	38.54333	-114.31694	5781	495	Valley Fill	(4)	D1, D2
383826114051201	196 N09 E70 14DABD1 20A	38.64042	-114.08678	5532	165	Valley Fill	(5)	A, B1
383545114070101	196 N09 E70 34DCDC1 MILLER CROSSING WELL	38.59161	-114.10917	5555	217	Valley Fill	(6)	B2, C1
383533114102901	196 N08 E70 06ABAA1 USBLM - MONUMENT WELL	38.59067	-114.16392	5587	164	Valley Fill	(7)	B3, C2
383252114075101	196 N08 E70 21AADA1 TAIT WELL	38.54461	-114.12150	5592	153	Valley Fill	(8)	D2
383325114134901	196 N08 E69 15BCDD1 HYDE WELL	38.55558	-114.22808	5658	110	Valley Fill	(9)	D1

All water levels were measured by the U.S. Geological Survey in March, 2010.
Water-level records are available at < http://groundwaterwatch.usgs.gov/googlemaps/NV_gm.html > using the USGS Site ID for each well.

Appendix B

Groundwater flow in fault zones

The following paragraphs summarize my scientific reasoning for concluding that groundwater flows across the normal-fault zones that bound the central Limestone Hills. I agree with Rowley and Dixon's (2011) fundamental premises that fractures exert strong control on regional and local groundwater flow, and, in a limited manner, that large-displacement (greater than about several hundred meters) fault zones impede groundwater flow across their planes, but my best scientific opinion is that substantial groundwater flow crosses major faults in localized zones. Fault-zone fabrics in the normal-fault zones bounding the Limestone Hills may inhibit or limit cross-fault groundwater flow along the much of their planes, but some cross-fault flow may occur.

Geometry and Structure of Fault Zones

Structural and seismotectonic studies (e.g., dePolo and others, 1991; Faulds and Varga, 1998) show that large range-bounding normal fault zones in the Great Basin are not simple planar features along the entire range front, but are composed of geometric segments, jogs, and stepover zones, and total displacement and fault-zone fabric development vary spatially within and along the fault plane. The Limestone Hills are bounded on the east and west by range-bounding normal-fault zones that intersect east- to southeast-striking faults at either end (Rowley and Dixon, 2011, p. 4-73). East-west trending bedrock spurs (projections into the adjacent valley) occur along the western and eastern range fronts, at about the north-south midpoint of the range (Rowley and Dixon, 2011, p. 4-73). These range-front spurs may mark jogs, segment boundaries, or stepover zones in the range-bounding normal-fault zones through which groundwater flow could occur.

Fault-Zone Fabrics

Fault-zone fabrics are heterogeneous with respect to geometry and grain size (Caine and others, 1996; Bastesen and others, 2009), containing relatively planar zones composed of fine-grained fault gouge that impede cross-fault flow, and irregularly shaped zones, steps, and jogs that include fault gouge and lenses of jointed but otherwise relatively intact rock, and fractures that transect the entire fault core, that may allow cross-fault flow (Bastesen and others, 2009; Geraud and others, 2006). Cementation of the fault core by precipitation of minerals from fluids circulating along the fault plane would substantially reduce or eliminate cross-fault permeability, whereas solution widening of joint surfaces within the fault core and disruption of the fault zone by younger fractures would enhance cross-fault permeability; both processes may occur within a fault zone (Bastesen and others, 2009).

Appendix C

Hydrographs from UGS groundwater monitoring wells and surface-flow gages in southern Snake Valley

The following figures show hydrographs from wells and surface (spring)-flow gages in the Utah Geological Survey's groundwater monitoring network that are within the Utah part of the Initial Biological Monitoring Zone of the Spring Valley Stipulation Agreement in southern Snake Valley. Figure 1 shows the site locations, and the figure captions below provide some basic information about the sites. More detailed information can be obtained at < http://geology.utah.gov/databases/groundwater/projects.php >. All plots show data from the beginning of the recording period through early June, 2011, and were accessed from the UGS Web site on August 17, 2011. In mid-September 2011, the hydrographs will be updated to show data from early June through early September 2011.

I interpret the seasonal water-level changes at sites 2, 15, 16, and 23 to result from local groundwater pumping for irrigation, and the progressive decreases in maximum water levels during the non-pumping season at sites 2, 15, and 23 to reflect either removal of groundwater from storage by pumping or reduced recharge during low-precipitation years. Separating the effects of decreased recharge from those of removal of groundwater from storage requires a longer period of record. Mean annual precipitation at Great Basin National Park, which represents the principal recharge area for southern Snake Valley, have fluctuated about the long-term annual mean of 13.21 inches per year during the past 20 years (figure C9). Site 8 is relatively far removed from groundwater-pumping areas and shows little or no seasonal response to pumping but shows similar overall water-level declines to those observed at sites 15 and 23, which are near the pumping sites; whereas site 11 shows no water-level decline but is relatively closer to the pumping. Whether the observed declines in groundwater levels are caused by climate, groundwater pumping, or some combination of the two, the hydrographs suggest that groundwater in southern Snake Valley is highly sensitive to changes in recharge and discharge and would be adversely affected by long-term reduction of flow into the system that would be caused by reduced interbasin flow from Spring Valley due to increased groundwater pumping there.

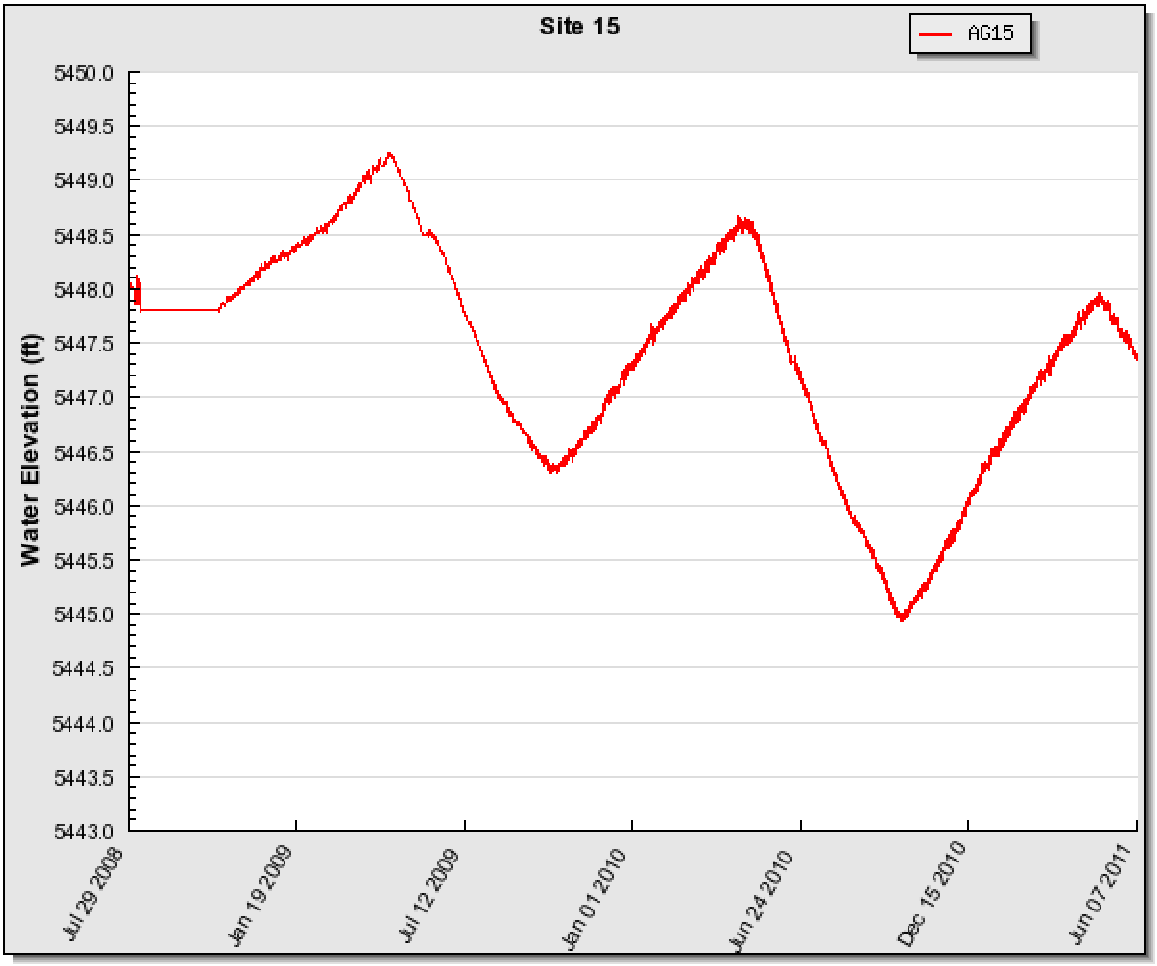


Figure C1. Hydrograph from UGS groundwater monitoring site 15. Piezometer AG15A is screened from 159 to 179 feet in the basin-fill aquifer. Plot shows seasonal drawdown and recovery related to nearby agricultural pumping, and a decline in the maximum annual water level of about 1.4 feet from March 2009 to March 2011.

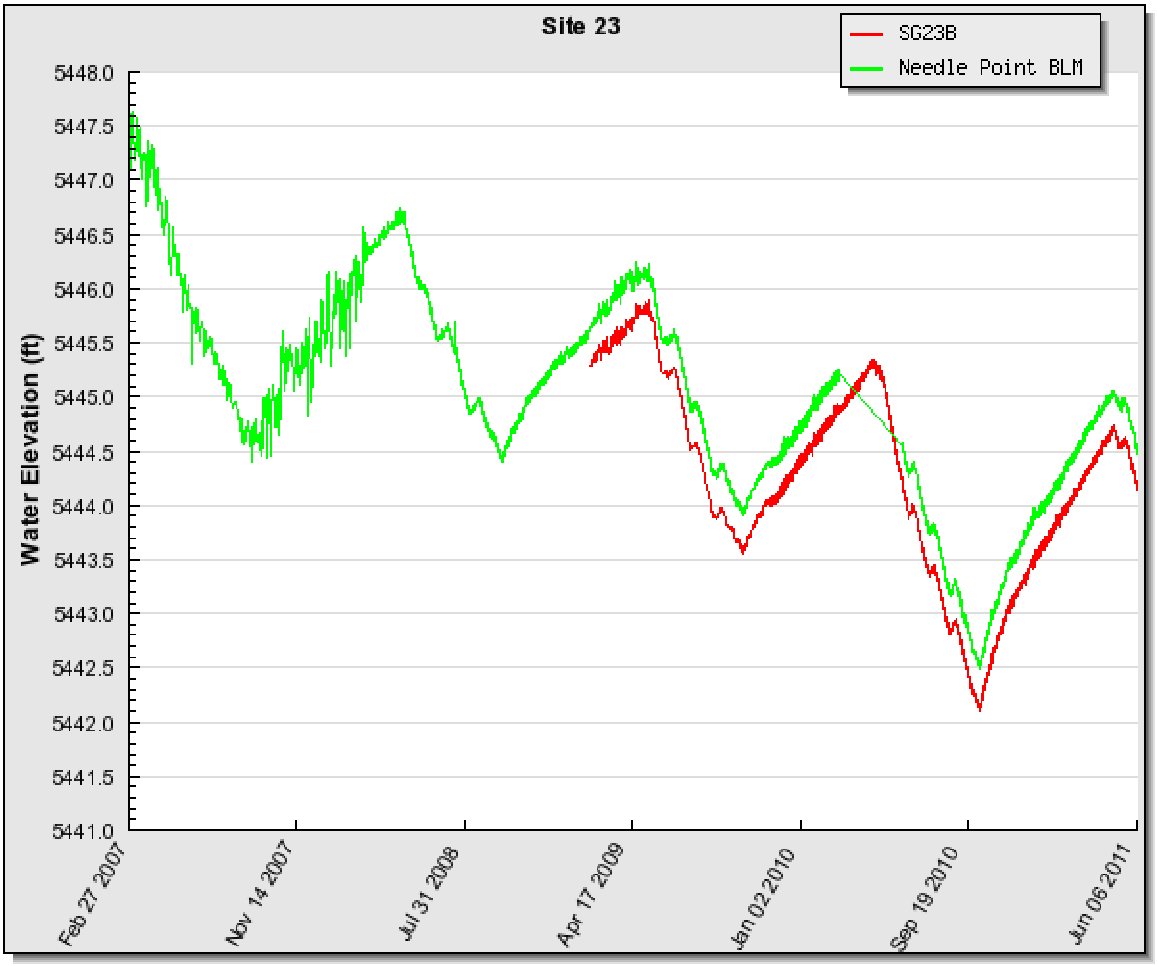


Figure C2. Hydrograph from UGS groundwater monitoring site 23 at Needle Point Spring. Piezometer SG23B is screened from 55 to 60 feet and the BLM monitoring well is screened from 16 to 46 feet, both in the basin-fill aquifer. Plots from both wells show seasonal drawdown and recovery related to nearby agricultural pumping, and a decline in the maximum annual water level of about 1.1 feet over three years in the BLM well and 1.1 feet in over two years in SG23B.

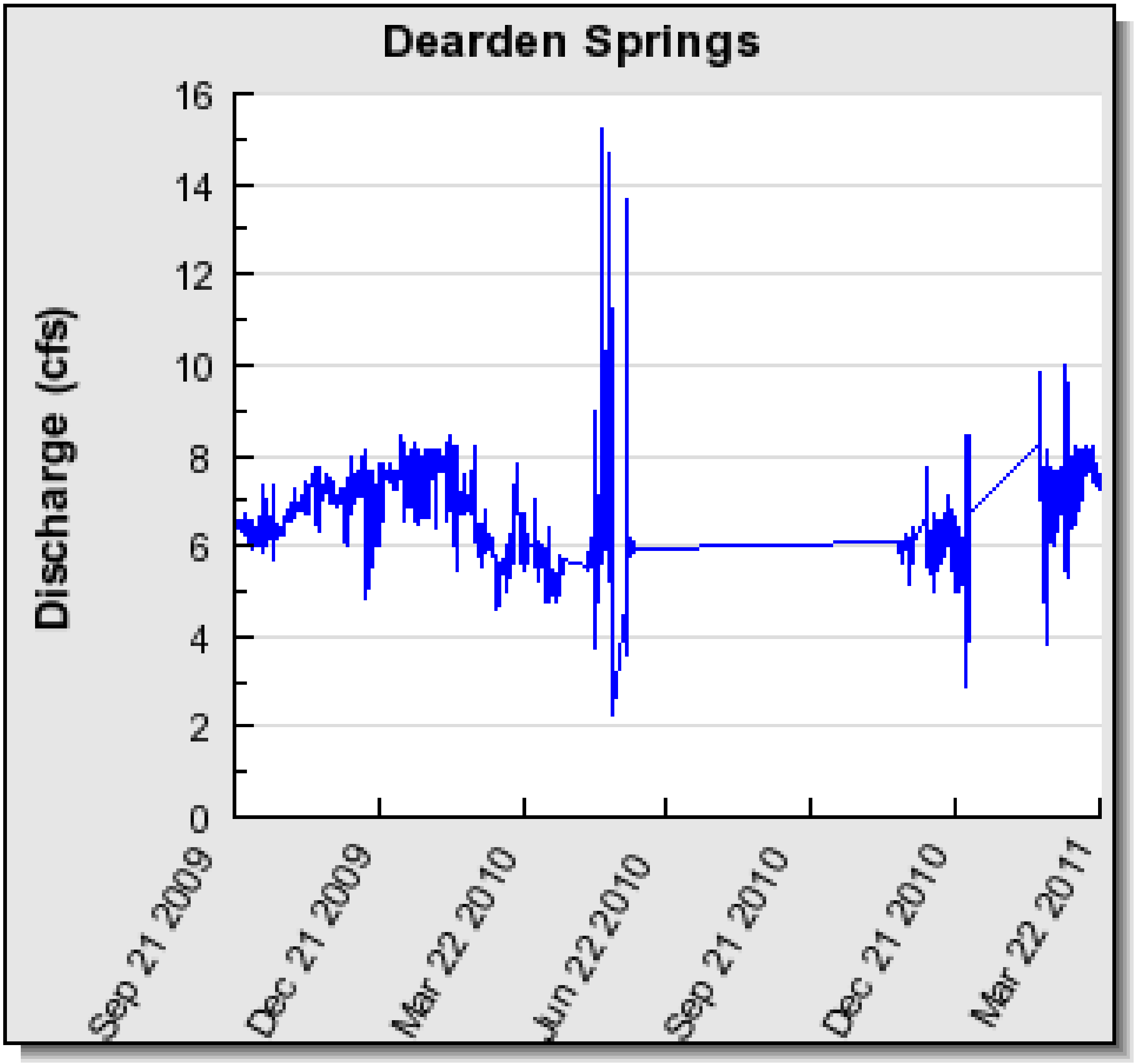


Figure C3. Hydrograph from UGS groundwater monitoring site 28 at Stateline (aka Dearden Ranch) Springs. Record shown is surface flow from the springs, estimated as the difference between surface-flow gages upstream and downstream from the springs. Period of record is insufficient for interpretation.

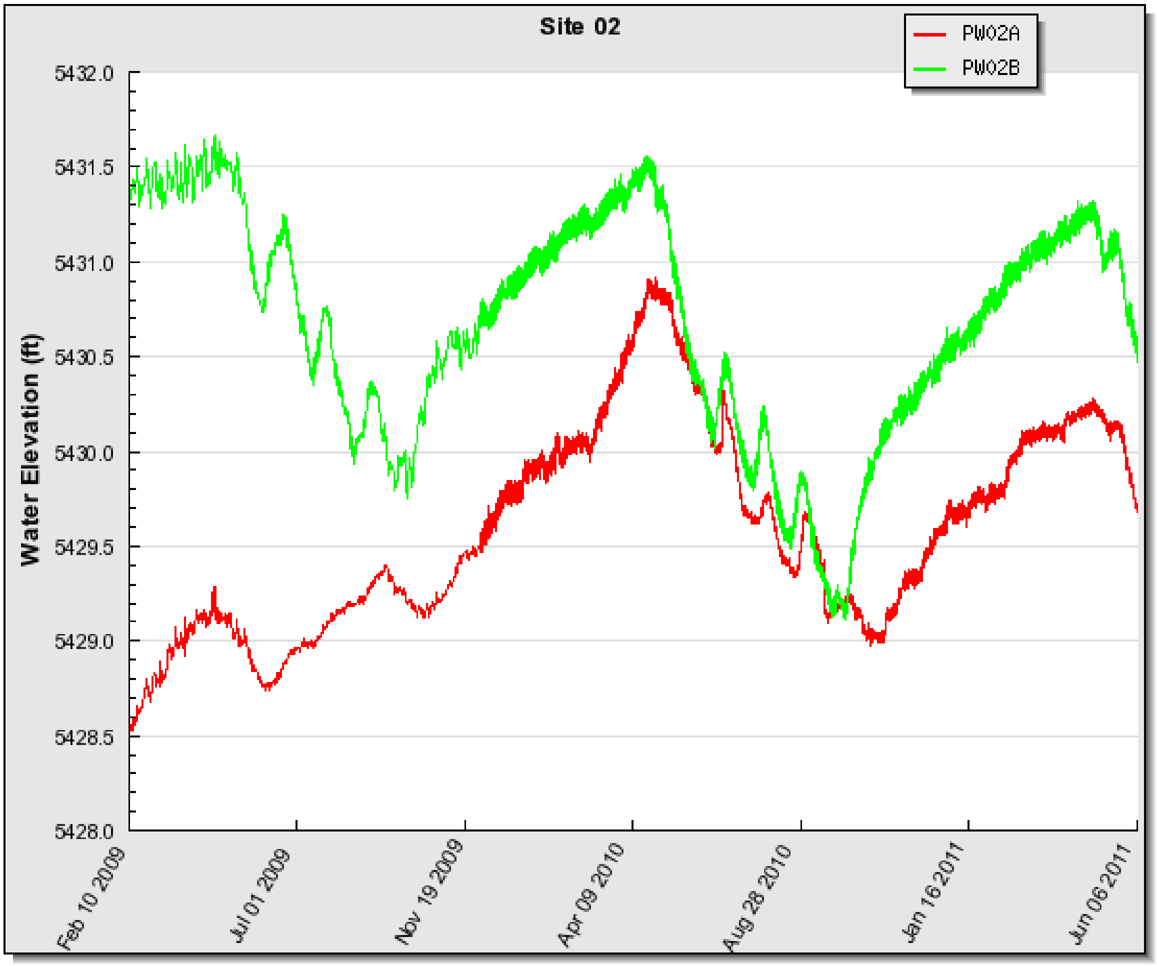


Figure C4. Hydrograph of wells at UGS groundwater monitoring site 2. Piezometer PW02A is screened from 405 to 425 feet and piezometer PW02B is screened from 615 to 635 feet, both in the Permian Arcturus Formation of the upper Paleozoic carbonate aquifer. Plots from both wells show seasonal drawdown and recovery related to nearby agricultural pumping, and a decline in the maximum annual water level of about 0.6 feet over one year in PW02A and 0.4 feet over two year in PW02B.

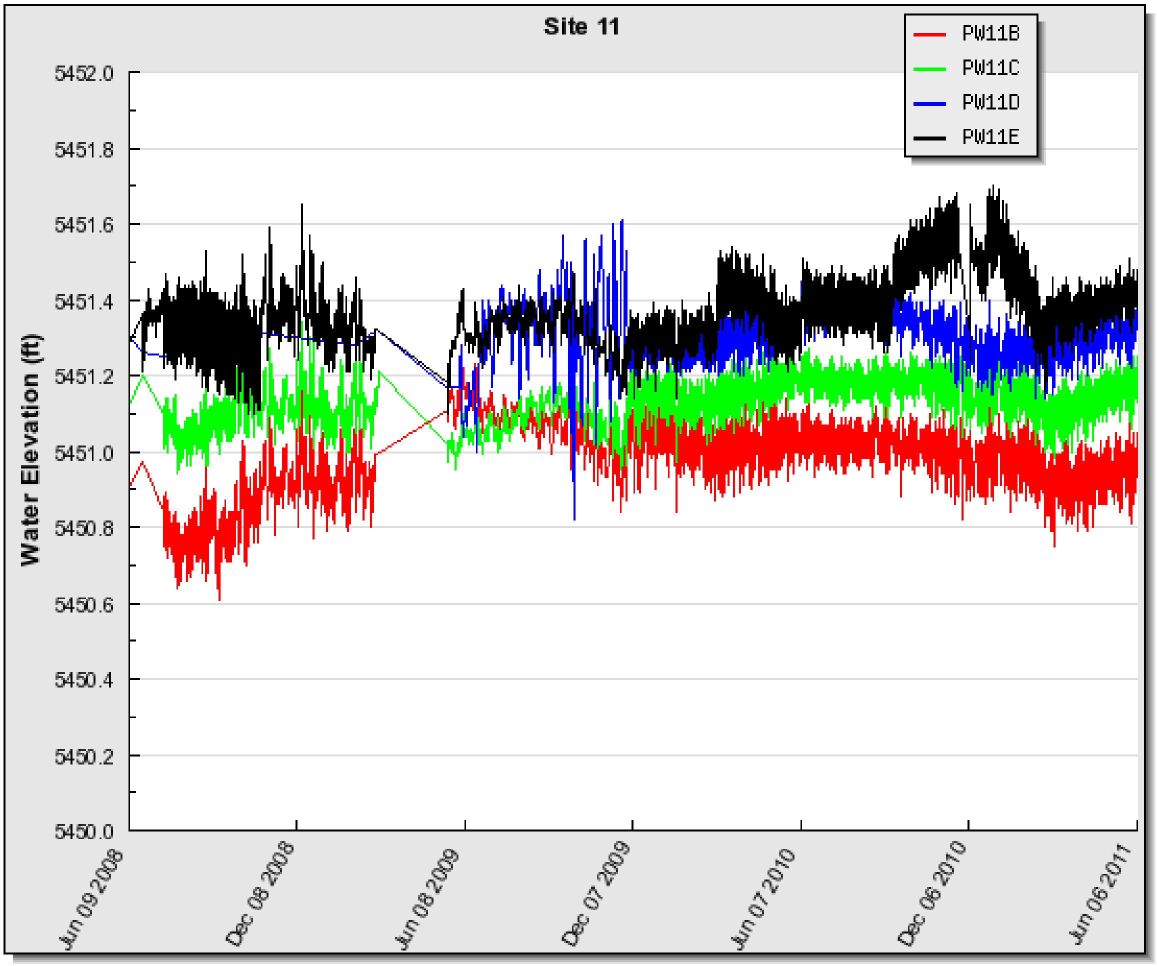


Figure C5. Hydrograph of wells at UGS groundwater monitoring site 11. Piezometer PW11B is screened from 435 to 455 feet in the basin-fill aquifer; and piezometer PW11C is screened from 519 to 539 feet, piezometer PW11D is screened from 720 to 740 feet, and piezometer PW11E is screened from 1139 to 1159 feet, all in the Permian-Mississippian Ely Limestone of the upper Paleozoic carbonate aquifer. Plots show no clear trend.

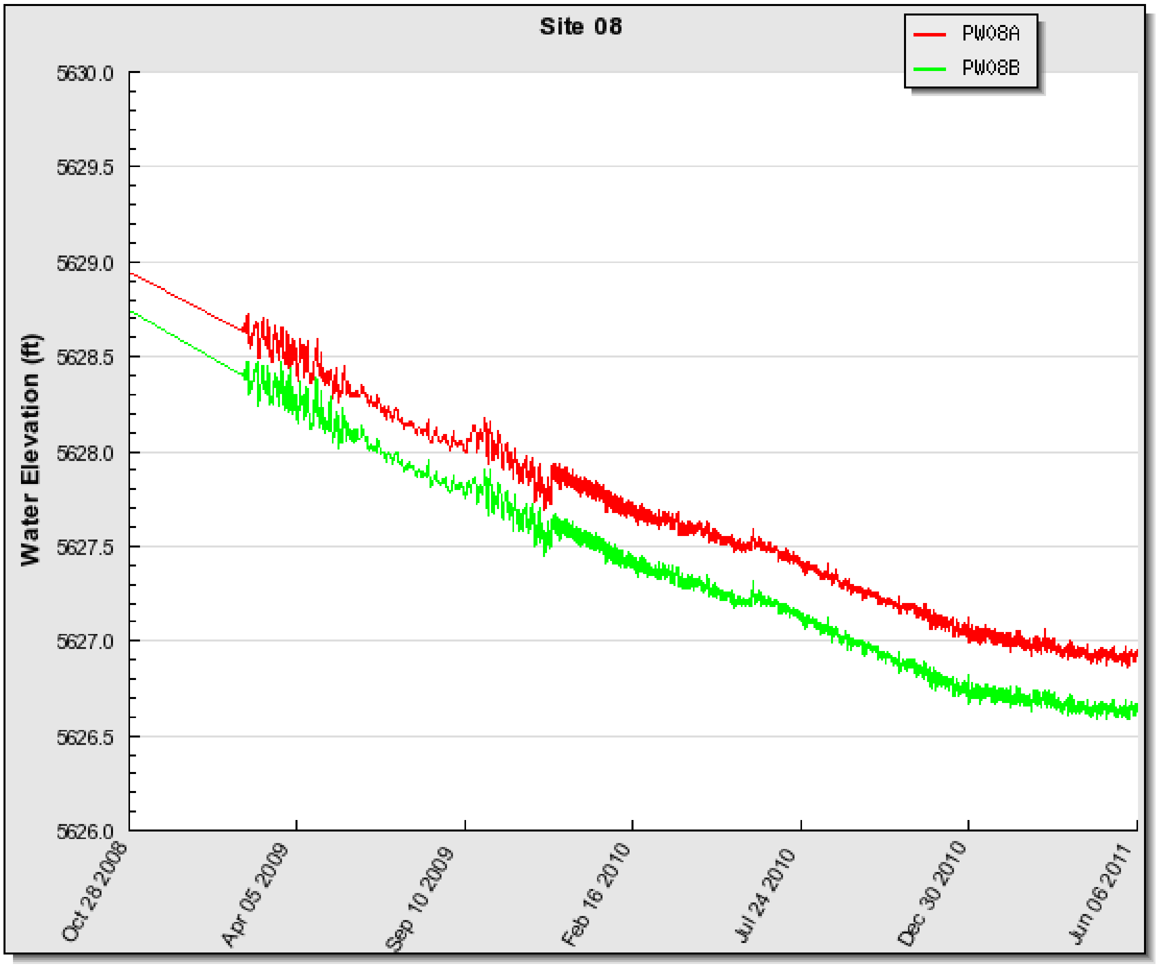


Figure C6. Hydrograph of wells at UGS groundwater monitoring site 8. Piezometer PW08A is screened from 140 to 160 feet and piezometer PW08B is screened from 380 to 400 feet, both in the Permian-Mississippian Ely Limestone of the upper Paleozoic carbonate aquifer. Plots show a decline in water levels in both piezometers of about 1.7 feet over two years.

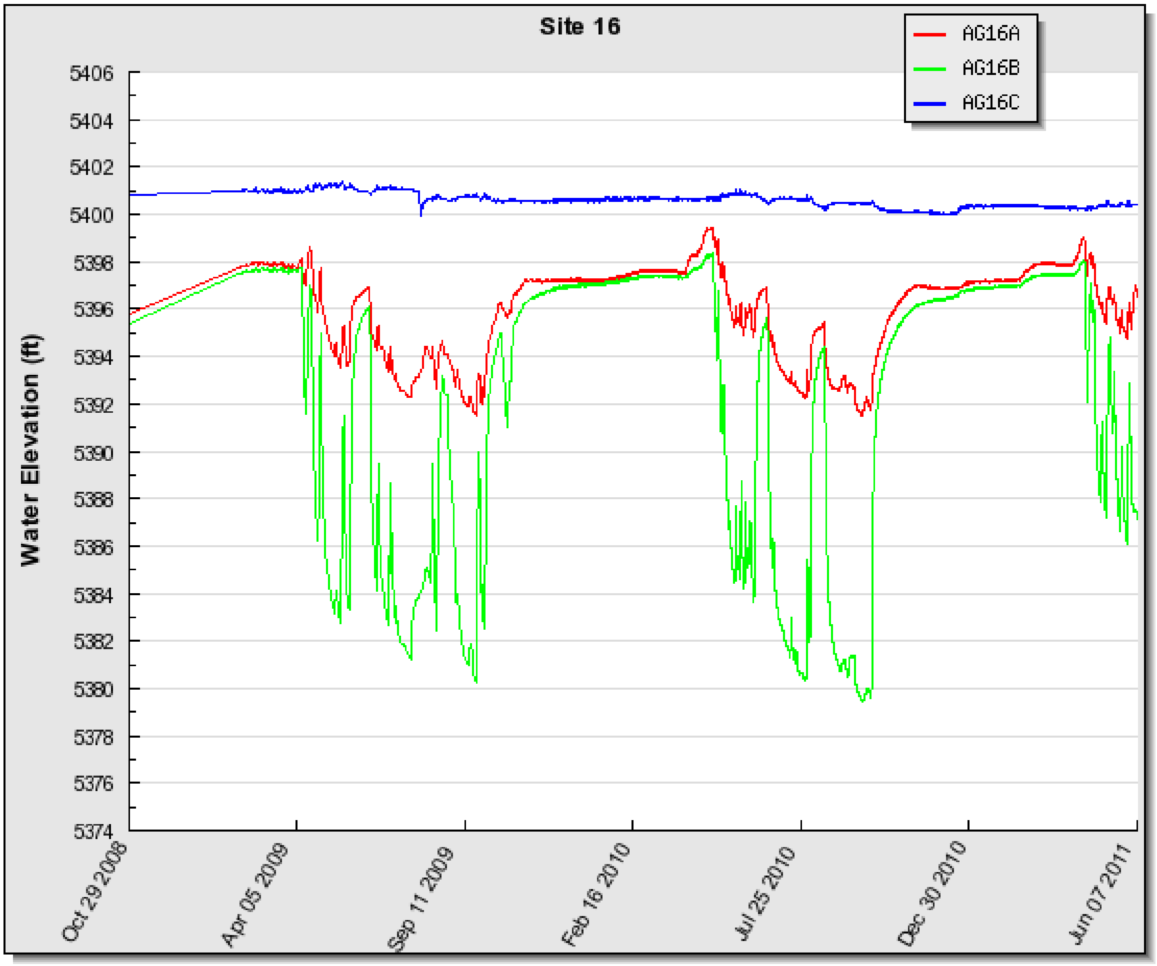


Figure C7. Hydrograph of wells at UGS groundwater monitoring site 16. Piezometer PW16A is screened from 50 to 60 feet, piezometer PW16B is screened from 80 to 100 feet, and piezometer PW16C is screened from 305 to 315 feet, all in the basin-fill aquifer. Plots from show seasonal drawdown and recovery related to nearby agricultural pumping and, in contrast to sites 2, 15, and 23, no decline in the maximum annual water level.

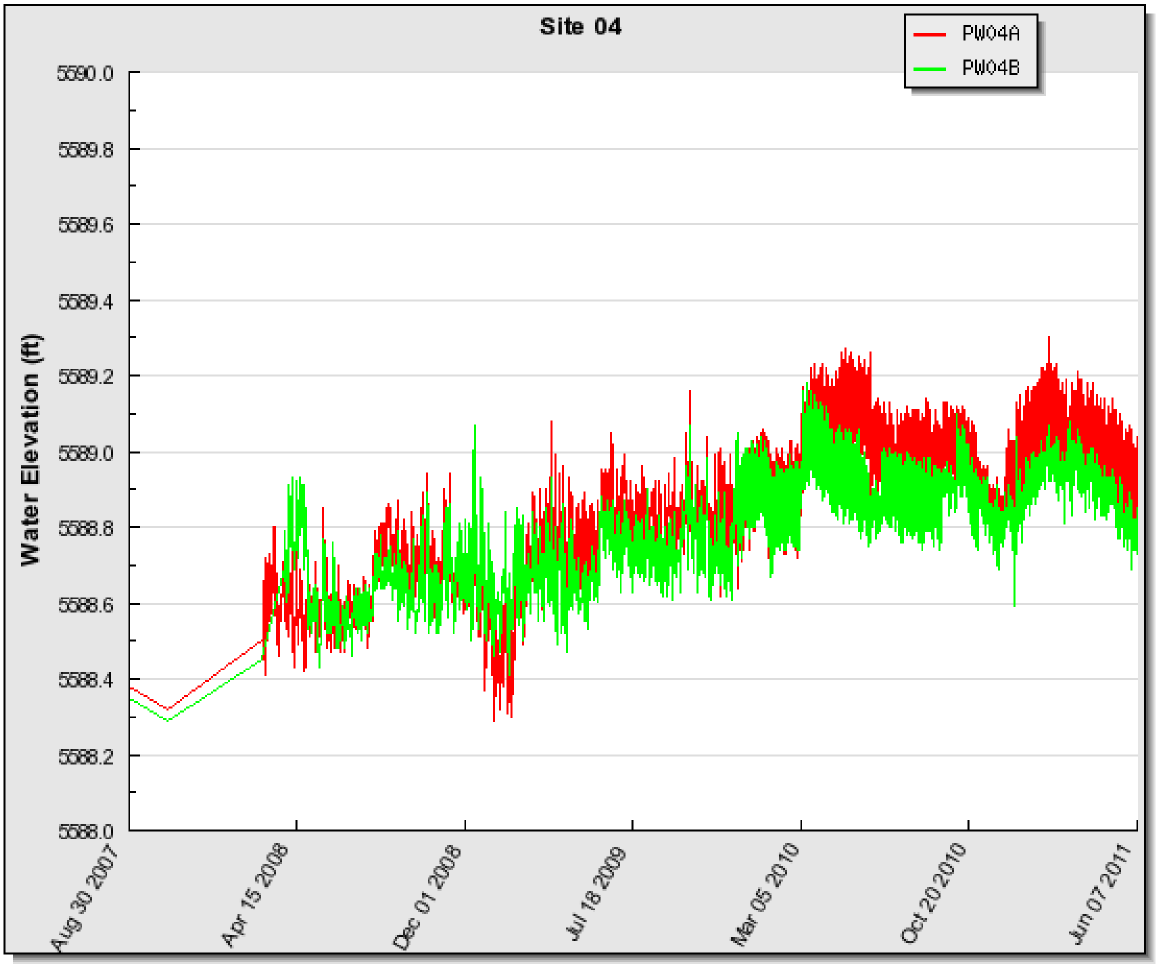


Figure C8. Hydrograph from UGS groundwater monitoring site 04. Piezometer PW04A is screened from 730 to 750 feet and piezometer PW04B is screened from 895 to 915 feet, both in the Tertiary volcanic aquifer. Plot shows an approximately 0.3 foot increase in water levels from April 2008 to April 2011.

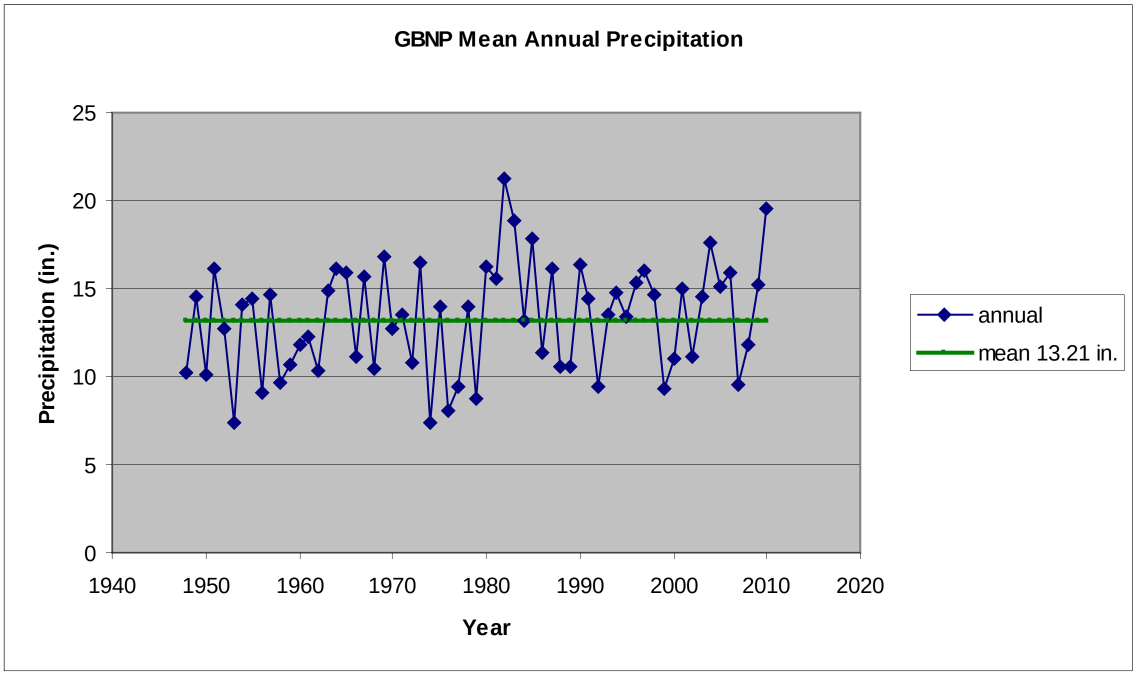


Figure C9. Mean annual precipitation at Great Basin National Park, 1948 to 2010 (Western Regional Climate Center, http://www.wrcc.dri.edu/summary/Climsmut.html, accessed January 12, 2011).

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CURRENT EMPLOYMENT – UTAH GEOLOGICAL SURVEY

Work Description

Application of structural geology, geophysics, and stratigraphy to investigate the flow and storage of ground water. Specific topics include analysis of the influence of fractures on ground-water flow, development of conceptual hydrostratigraphy for ground-water basins, and use of structural, GIS, and geophysical methods to interpret the structure, stratigraphy, and hydrogeology of ground-water basins. Products include geophysical and geologic maps, cross sections, isopach maps, structure-contour maps, fracture domain maps, analysis of fracture patterns and their relation to ground-water flow, and final reports.

Snake Valley-Related Activities

2007-present: Planned and supervised implementation of a ground-water monitoring network in Snake Valley and adjacent hydrologic basins, west-central Utah. Primary tasks included planning and managing installation of ground-water monitoring wells and surface-flow gages, and chemical sampling. Related activities include 1) as part of the State of Utah's role as a cooperating agency in the Environmental Impact Statement for the Southern Nevada Water Authority's Clark, Lincoln, and White Pine Counties Groundwater Development Project, reviewed draft versions of the EIS and related documents and participated in on technical review and discussion sessions for construction of the groundwater flow model for the EIS; 2) Participated in drafting of the groundwater monitoring component of the Agreement for Management of the Snake Valley Groundwater System between Utah and Nevada (presently unsigned by Utah); 3) part of the research team which advises Utah's Snake Valley Aquifer Advisory Committee.

2004-2007: Conducted geophysical and geological investigations of Snake Valley and adjacent ground-water basins, including stratigraphic and structural analysis and collection and interpretation of gravity data.

Positions Held

4/2/11-present: Senior Scientist
8/27/05-4/1/211: Senior Geologist
3/21/98-8/26/05: Project Geologist
8/21/95-3/20/98: Geologist

Publications

Thomas, K., Williams, Q., Bowman, S., Jordan, L., and Hurlow, H., 2011, Groundwater monitoring data portal: online, http://geology.utah.gov/databases/groundwater/projects.php.

Hurlow, H.A., Lowe, M., Matyjasik, M., and Gettings, P., 2011, The Weber River basin aquifer storage and recovery pilot project: Utah Geological Survey Special Study 136, 128 p., 2 plates (CD).

Hurlow, H.A., and Burk, N., 2008, Geology and ground-water chemistry, Curlew Valley, northwestern Utah and south-central Idaho – Implications for hydrogeology: Utah Geological Survey Special Study 126, 185 p., 2 plates (CD).

Kirby, S., and Hurlow, H.A., 2005, Hydrogeologic setting of the Snake Valley hydrologic basin, Millard County, Utah, and White Pine and Lincoln Counties, Nevada – implications for possible effects of proposed water wells: Utah Geological Survey Report of Investigations 254, 39 p. (CD).

Hurlow, H.A., 2004, The geology of Cedar Valley, Utah County, Utah, and its relation to ground-water conditions: Utah Geological Survey Special Study 109, 74 p., 4 plates (CD).

Lowe, M., Wallace, J., Bishop, C.E., and Hurlow, H.A., 2004, Ground-water quality classification and recommended septic tank soil-absorption-system density maps, Castle Valley, Grand County, Utah: Utah Geological Survey Special Study 113, 61 p., 8 plates (CD).

Hurlow, H.A., and Biek, R.F., 2003, Geologic map of the Pintura quadrangle, Washington County, Utah: Utah Geological Survey Map, 196, 20 p., 2 plates, scale 1:24,000.

Hurlow, H.A., and Bishop, C.E., 2003, Recharge areas and geologic controls for the Courthouse-Sevenmile spring system, western Arches National Park, Grand County, Utah: Utah Geological Survey Special Study 108, 55 p., 3 plates (CD).

Hurlow, H.A., 2002, The geology of Cedar Valley, Iron County, Utah, and its relation to ground-water conditions: Utah Geological Survey Special Study 103, 74 p., 2 plates.

Hurlow, H.A. 2002, The geology of the Kamas-Coalville region, Summit County, Utah, and its relation to ground-water conditions: Utah Geological Survey Water Resources Bulletin 29, 55 p., 6 plates.

Hurlow, H.A., 1999, Preliminary hydrogeologic framework characterization – Ground-water resources along the western side of the northern Wasatch Range, eastern Box Elder County, Utah: Utah Geological Survey Circular 101, 50 p.

Hurlow, H. A., 1998, The geology of the central Virgin River basin, southwestern Utah, and its relation to ground-water conditions: Utah Geological Survey Water-Resource Bulletin 26, 53 p.

Hurlow, H. A., 1997, Heterogeneous joint and fault systems in the Navajo Sandstone, southwestern Utah, and their influence on permeability, *in* Close, J. C., and Casey, T. A., editors, Natural Fracture Systems in the Southern Rockies: Durango, Colorado, Four Corners Geological Society, p. 41-52.

Awards

2009: Arthur F. Crawford Award

1997: Utah Geological Survey Incentive Award for developing quantitative relation between fracture parameters and specific capacity of water wells, southwestern Utah.

1996: Utah Geological Survey Incentive Award for collaborative efforts with the U.S. Geological Survey during research project in southwestern Utah.

PREVIOUS EMPLOYMENT

6/94 to 8/95 **University of Montana - Research Assistant Professor**

Structural analysis of faulting in southwest Montana, including geologic mapping and mechanical analysis of fractured conglomerate clasts. Structural analysis of faulting in the

Ross Lake Fault zone, North Cascades National Park, Washington, including field mapping, structural analysis, and petrographic work. Assistant instructor for undergraduate course in hydrogeology.

8/93 to 6/94 **University of Montana - Visiting Assistant Professor**

Taught undergraduate courses in structural geology, mineralogy and introductory geology, and field geology, and a graduate seminar entitled "Principles of Geochronology and Applications to Tectonic Problems in the U. S. Cordillera".

1/93 to 7/93 **University of Washington - Postdoctoral Researcher**

Performed U-Pb isotopic analyses and geochronology of granitic rocks from the North Cascades Range, Washington. Operated mass spectrometer and performed clean laboratory geochemistry (ion chromatography).

9/87 to 6/92 **University of Washington - Graduate Research Assistant**

Established procedures and techniques for measurement of U and Pb isotopes for geochronologic analysis in the Isotope Geochemistry Laboratory. Performed U-Pb isotopic analyses and geochronology of zircon from plutons and dikes from the North Cascades Range, Washington. Analyzed Pb systematics of soil samples from EPA superfund site in Leadville, Colorado. Operated mass spectrometer.

9/87 to 6/92 **University of Washington - Graduate Teaching Assistant**

Taught laboratory sections of undergraduate courses in introductory geology and Geology of National Parks, and a graduate/undergraduate course in geochemistry.

EDUCATION

Ph.D.: 1992, University of Washington.
Dissertation: Structural and U-Pb geochronologic studies of the Pasayten fault, Okanogan Range batholith, and southeastern Cascades crystalline core, Washington.
Advisor: Dr. Darrel S. Cowan.

M.S.: 1987, University of Wyoming
Thesis: Structural geometry, fabric, and chronology of a Tertiary extensional shear zone-detachment system, southwestern East Humboldt Range, Elko County, Nevada.
Advisor: Dr. Arthur W. Snoke.

Sc.B.: 1984, Brown University
Summa Cum Laude with Honors in Geological Sciences.

OTHER PUBLICATIONS

Baldwin, J.A., Whitney, D.L., and Hurlow, H.A., 1997, Metamorphic and structural evidence for significant vertical displacement along the Ross Lake fault zone -- a major orogen-parallel shear zone in the Cordillera of western North America: Tectonics, v. 14, p. 662-681.

Stewart, M. E., Taylor, W. J., Pearthree, P. A., Solomon, B. J., and Hurlow, H. A., 1997, Neotectonics, fault segmentation and seismic hazards along the Hurricane fault in Utah and Arizona: An overview of environmental factors in an actively extending region: Brigham Young University Geology Studies, v. 42, p. 235-277.

Hurlow, H. A., 1995, Pliocene or younger paleostress directions from fractured conglomerate clasts, Sixmile Creek Formation, lower Red Rock Valley, southwestern Montana: Northwest Geology, v. 24, p. 229-236.

Hurlow, H. A., 1995, Structural style of Pliocene-Quaternary extension between the Red Rock and Blacktail faults, southwestern Montana: Northwest Geology, v. 24, p. 221-228.

Sears, J. W., Hurlow, H. A., Fritz, W. J., and Thomas, R. C., 1995, Late Cenozoic disruption of Miocene grabens on the shoulder of the Yellowstone hotspot track in southwest Montana: Field guide from Lima to Alder, Montana: Northwest Geology, v. 24, p. 201-220.

Hurlow, H. A., 1993, Mid-Cretaceous strike-slip and contractional fault zones in the western Intermontane terrane, Washington, and their relation to the North Cascades-southeastern Coast Belt orogen: Tectonics, v. 12, p. 1240-1257.

Hurlow, H. A., and Nelson, B. K., 1993, U-Pb zircon and monazite dates for the Okanogan Range batholith, Washington: Implications for the magmatic and tectonic evolution of the southern Canadian and northern United States Cordillera: Geological Society of America Bulletin, v. 105, p. 231-240.

Hodges, K. V., Snoke, A. W., and Hurlow, H. A., 1992, Thermal evolution of a portion of the Sevier hinterland: The Northern Ruby Mountains-East Humboldt Range and Wood Hills, northeastern Nevada: Tectonics, v. 11, p. 154-164.

Hurlow, H. A., Snoke, A. W., and Hodges, K. V., 1991, Pressure and temperature of mylonitization in a Tertiary extensional shear zone, Ruby Mountains-East Humboldt Range, Nevada: Geology, v. 19, p. 82-86.