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GROUNDWATER-LEVEL TRENDS IN SNAKE VALLEY AND ADJACENT BASINS, UTAH AND NEVADA

by Hugh A. Hurlow, Rebecca Molinari, Paul C. Inkenbrandt, and J. Lucy Jordan

Cover photo: A monitoring well in the Sevier Dry Lake basin and the tools of the trade—electronic water level meter, GPS antenna, and tape measure.

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### CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>1</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td> Objectives</td>
<td>1</td>
</tr>
<tr>
<td> Background and Previous Work</td>
<td>2</td>
</tr>
<tr>
<td> Hydrostratigraphy and Structure</td>
<td>2</td>
</tr>
<tr>
<td>METHODS</td>
<td>4</td>
</tr>
<tr>
<td> Groundwater Levels</td>
<td>4</td>
</tr>
<tr>
<td>  Depth to Water</td>
<td>4</td>
</tr>
<tr>
<td>  Location and Elevation Control</td>
<td>4</td>
</tr>
<tr>
<td>  Water Level Correction for Salinity</td>
<td>4</td>
</tr>
<tr>
<td>  Potentiometric Surface and Contouring</td>
<td>4</td>
</tr>
<tr>
<td> Groundwater-Level Changes</td>
<td>5</td>
</tr>
<tr>
<td>  Vertical Hydraulic Gradients</td>
<td>5</td>
</tr>
<tr>
<td> Climate Data</td>
<td>7</td>
</tr>
<tr>
<td> Groundwater Pumping Data</td>
<td>7</td>
</tr>
<tr>
<td> Statistical Analyses</td>
<td>7</td>
</tr>
<tr>
<td>RESULTS</td>
<td>8</td>
</tr>
<tr>
<td> Groundwater-Level Changes and Potentiometric Contours</td>
<td>8</td>
</tr>
<tr>
<td>  Northern Snake Valley</td>
<td>8</td>
</tr>
<tr>
<td>  Central Snake Valley</td>
<td>10</td>
</tr>
<tr>
<td>  Southern Snake Valley and Northern Hamlin Valley</td>
<td>10</td>
</tr>
<tr>
<td>  Southern Spring Valley</td>
<td>12</td>
</tr>
<tr>
<td>  Fish Springs Flat</td>
<td>12</td>
</tr>
<tr>
<td>  Tule Valley</td>
<td>12</td>
</tr>
<tr>
<td>  Pine Valley and Wah Wah Valley</td>
<td>12</td>
</tr>
<tr>
<td>  Sevier Dry Lake Basin</td>
<td>12</td>
</tr>
<tr>
<td> Groundwater-Level Trends</td>
<td>12</td>
</tr>
<tr>
<td> Vertical Hydraulic Gradients</td>
<td>12</td>
</tr>
<tr>
<td> Climate Data</td>
<td>24</td>
</tr>
<tr>
<td> Groundwater Pumping</td>
<td>24</td>
</tr>
<tr>
<td>INTERPRETATIONS</td>
<td>24</td>
</tr>
<tr>
<td> Groundwater-Level Changes, Groundwater Pumping, and Climate Variations</td>
<td>24</td>
</tr>
<tr>
<td> Vertical Hydraulic Gradients, Groundwater Pumping, and Spring Flow</td>
<td>28</td>
</tr>
<tr>
<td> Interbasin Flow (or Not)</td>
<td>28</td>
</tr>
<tr>
<td>  Northern Snake Valley</td>
<td>28</td>
</tr>
<tr>
<td>  Fish Springs Flat</td>
<td>29</td>
</tr>
<tr>
<td>  Central Snake Valley</td>
<td>29</td>
</tr>
<tr>
<td>  Tule Valley</td>
<td>29</td>
</tr>
<tr>
<td>  Southern Snake Valley</td>
<td>29</td>
</tr>
<tr>
<td>  Pine Valley and Wah Wah Valley</td>
<td>29</td>
</tr>
<tr>
<td>  Sevier Dry Lake Basin</td>
<td>29</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>30</td>
</tr>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>31</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>31</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>34</td>
</tr>
</tbody>
</table>
FIGURES

Figure 1. Study area for this project showing locations of wells.............................................................................................................. 3
Figure 2. Conventions used to calculate vertical hydraulic gradients at nested monitor-well sites................................................................. 6
Figure 3. Changes in depth to groundwater at wells measured in 2010 and 2020 .................................................................................. 9
Figure 4. Histograms of measured groundwater-level changes............................................................................................................. 10
Figure 5. Potentiometric contours based on data from Appendix A ........................................................................................................ 11
Figure 6. Wells and climate stations analyzed in this study .................................................................................................................. 13
Figure 7. Groundwater levels from 1980 to 2021 and results of trend analysis in select wells ................................................................. 15
Figure 8. Water-level elevation vertical gradients in select wells from 2008 to 2020 ............................................................................. 18
Figure 9. Records of precipitation from the Wheeler Peak and Mather climate stations from 1980 to 2021 ........................................... 25
Figure 10. Estimates of groundwater pumping in Snake Valley from 1940 to 2021 ............................................................................. 26
Figure 11. Groundwater-level elevations and changes for different time intervals ................................................................................ 26

TABLES

Table 1. Summary statistics of groundwater level changes ................................................................................................................ 8
Table 2. Results of break point and Mann-Kendall analyses of water-level trends for select groundwater-monitoring wells in Snake Valley ...................................................................................................................................... 14
GROUNDWATER-LEVEL TRENDS IN SNAKE VALLEY AND ADJACENT BASINS, UTAH AND NEVADA

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ABSTRACT

Snake Valley and adjacent groundwater basins in west-central Utah and east-central Nevada have long been of interest for potential groundwater development and scientific investigations of regional-scale groundwater flow. Groundwater-level monitoring by the Utah Geological Survey and the U.S. Geological Survey has produced data useful to evaluate the relative effects of climate and groundwater pumping on groundwater levels, and to investigate the utility of various statistical approaches to the data. We present the results of an intensive groundwater-level campaign conducted in 2020, designed to build on and contrast with a similar survey conducted by the U.S. Geological Survey in 2010. We also investigate the use of hydrographs of vertical hydraulic gradients in nested piezometers to illustrate changes in groundwater dynamics, and application of breakpoint analysis combined with Mann-Kendall analysis to identify key times of change.

Groundwater levels in areas of greater pumping, chiefly for agriculture, declined by about 3 feet from 2010 to 2020, whereas groundwater levels in remote areas declined by about 1 foot. Potentiometric contours show only minor changes from 2010, mainly reflecting groundwater-level declines in pumping areas. We drew speculative contours through regions having little or no groundwater-level control to illustrate horizontal hydraulic gradients between adjacent basins, building on previous investigations that evaluated potential interbasin groundwater flow, and these contours support our previous evaluations of the most likely zones of interbasin groundwater flow. Consistent with the hydrogeology and groundwater chemistry summarized in our previous work, interbasin flow likely occurs from northeastern Snake Valley and northern Tule Valley to central Fish Springs Flat, central Snake Valley to central Tule Valley, southern Snake Valley to east-central Snake Valley, and western Sevier Dry Lake basin to southern Tule Valley. Elsewhere in the study area, steep horizontal hydraulic gradients, reflected by closely-spaced potentiometric contours, suggest low transmissivity and low groundwater flux between adjacent basins.

The vertical hydraulic gradient between two wells at a nested piezometer site is the ratio of the difference in groundwater-level elevations to screen-midpoint depths, where values from the deeper well are subtracted from those of the shallower well. This convention results in a) negative vertical hydraulic gradient values for sites in which the groundwater-level elevation in the deeper well is higher than that of the shallower well (i.e., the vertical potential gradient is upward toward the land surface), and b) positive vertical hydraulic gradient values for sites in which the groundwater-level elevation in the deeper well is lower than that of the shallower well (i.e., the vertical potential gradient is downward away from the land surface). Hydrographs of vertical hydraulic gradients reflect changes in the dynamics at a site over time. Our analyses identified sites where the gradient changed from upward (negative) to downward (positive), and where groundwater levels changed at different rates at different depths.

Breakpoint analysis of annual groundwater-level data from selected wells yielded statistically significant changes in trends in three distinct time intervals: 1988 to 1990, 2001 to 2003, and 2012 to 2014. For the precipitation data (1980 to 2020), no break points were calculated for two climate stations in Great Basin National Park, whereas Mann-Kendall trend tests indicated trends of -4.7 and -3.4 millimeters per year. For groundwater pumping, break points marking significant increases in pumping occurred in 1975, 1987, and 2006.

INTRODUCTION

Objectives

The Utah Geological Survey (UGS) conducted a regional groundwater-level campaign during 2020 in west-central Utah and parts of east-central Nevada to document changes in groundwater levels from 2010 to 2020 and produce updated potentiometric contours map for Snake Valley and adjacent groundwater basins. To place the groundwater-level changes in a broader spatial and temporal context and identify likely drivers of observed declines, we performed statistical analyses of water-level records from the UGS West Desert Groundwater Monitoring Network (WDGMN) (Utah Geological Survey, 2022) and the U.S. Geological Survey (USGS) National Water Information System (NWIS; USGS, 2022) and compared the results to compiled precipitation and groundwater-pumping records.

Specific objectives were to (1) document changes in groundwater levels over a 10-year period by measuring as many of the same wells as possible that Gardner et al. (2011) measured in their 2010 groundwater-level campaign; (2) increase the extent and detail of coverage where possible; (3) draw updated potentiometric contours map representing 2020 conditions; and (4) conduct statistical analyses of water-level data, climate data, and groundwater pumping estimates. Hurlow and Inkenbrandt (2016) presented preliminary statistical analyses...
of daily groundwater-level data from the WDGMN, but six additional years of data are now available, adding confidence to the results.

The project area includes the Snake Valley, Hamlin Valley, southern Spring Valley, Tule Valley, Fish Springs Flat, Pine Valley, Wah Wah Valley, and Sevier Dry Lake groundwater basins (Figure 1). Although remote from major population centers, this region’s groundwater resources have been of great interest from water-resource development and scientific perspectives for many years (Hood and Rush, 1965; Mason et al., 1985; Harrill et al., 1988, Harrill and Prudic, 1998; Dixon et al., 2007; Welch et al., 2007; Southern Nevada Water Authority, 2009a, 2009b; Gardner et al., 2011; Heilweil and Brooks, 2011; Brooks et al., 2014; Hurlow, 2014a; Masbruch and Gardner, 2014; Masbruch et al., 2014; Brooks, 2017; Gardner et al., 2019). Most investigators consider these groundwater basins to be connected, in various degrees, through fractured-carbonate bedrock aquifers in the mountain blocks that divide the surface-drainage valleys. Groundwater levels in some wells monitored by the USGS and UGS have shown steady decline for more than 20 years (Hurlow and Inkenbrandt, 2016). These trends are not severe compared to rates of decline observed in more heavily developed groundwater basins in western Utah, but they show no sign of decreasing and should be evaluated before economic and ecological impacts become severe or irreversible.

Background and Previous Work

Groundwater in the central Basin and Range Province of western Utah and east-central Nevada supports the livelihood of farmers and ranchers and provides wildlife habitat via spring flow, including habitat for several aquatic conservation species, migratory birds, and big game. A large-scale plan by the Southern Nevada Water Authority (SNWA) to pump groundwater from several of these basins in east-central Nevada (U.S. Bureau of Land Management, 2012) generated a great deal of intensive scientific work and monitoring to evaluate baseline groundwater conditions and estimate the potential impacts of the proposed development (Dixon et al., 2007; Welch et al., 2007; Rowley et al., 2009; SNWA, 2009a, 2009b; Heilweil and Brooks, 2011; Brooks et al., 2014; Hurlow, 2014a). Although the SNWA has suspended its project as originally proposed, efforts to develop significant amounts of groundwater in parts of this region continue by both private and public entities (e.g., Central Iron County Water Conservation District, 2021).

Groundwater levels in the study area are well constrained considering its remoteness. The USGS has measured water levels in 30 wells annually in Snake Valley and 23 wells in the valleys to the east, some for 40 years or more (USGS, 2022). The UGS installed the WDGMN between 2007 and 2009 to characterize regional baseline groundwater conditions, measure the effects of possible future groundwater development, and understand groundwater flow paths (Hurlow et al., 2014). Data from the WDGMN are available from the UGS Groundwater Monitoring Data Portal: https://apps.geology.utah.gov/gwdp/. The USGS conducted a survey of groundwater levels throughout this region in 2010 (Gardner et al., 2011), including wells from the UGS network, test and monitor wells installed by SNWA (reported in U.S. Bureau of Land Management, 2012), stock watering wells, test wells from the MX-missile program (Mason et al., 1985), and private wells.

Valley-floor springs in Snake Valley and Tule Valley have special importance because they provide rare habitat for wildlife including Utah Conservation Species/Species of Greatest Conservation Need (Bailey et al., 2005, 2006; Goodwin et al., 2021), and support agriculture and grazing. The UGS installed nested piezometers at key Snake Valley spring complexes characterized by numerous, distributed point sources, to measure the vertical hydraulic gradient as a potential proxy for spring discharge (Hurlow et al., 2014). Twin Springs (site SG24 in this paper) has two distinct point sources having well-defined outflow channels where we monitor discharge to evaluate the possible correlation between vertical hydraulic gradient and spring flow. Leland Harris Spring complex (site SG25 in this paper) is intensively studied and monitored as an example of a desert valley-floor spring complex that supports both ranching and conservation species (Grover, 2019; Inkenbrandt, 2020; Goodwin et al., 2021).

Hydrostratigraphy and Structure

Harrill et al. (1988), Harrill and Prudic (1998), Dixon et al. (2007), Welch et al. (2007), and Hurlow (2014b) defined the regional hydrostratigraphy and interpreted that the Quaternary-Tertiary basin-fill hydrostratigraphic unit (HSU) supports most human and wildlife uses whereas interbasin flow most likely occurs through the upper and lower Paleozoic carbonate-rock HSUs. The basin-fill and carbonate-rock HSUs are hydraulically connected along the mountain fronts where nested monitoring wells can be installed in both aquifers (Gardner et al., 2011; Hurlow et al., 2014). The hydraulic connection between the two aquifers below the valley floors is not known, but they are separated by Tertiary sedimentary and volcanic rocks in most places (Hurlow, 2014b). Recharge to the basin-fill HSU is from infiltration of precipitation on the adjacent mountain blocks, principally the Snake Range and Deep Creek Mountains, via subsurface groundwater flow; and from infiltration of runoff along the mountain fronts (Prudic et al., 1995). The Mississippian Manning Canyon Shale confining unit separates the upper and lower Paleozoic carbonate-rock HSUs. Several major springs, including Twin Springs in east-central Snake Valley, the Fish Springs complex in Fish Springs Flat, and Coyote Spring in Tule Valley, are sourced by deep flow within the carbonate-rock HSUs and are localized by fault zones (Harrill et al., 1988; Prudic et al., 1995). Using hydrostratigraphy, structural geology, groundwater chemistry and age, and groundwater levels, Hurlow and Kirby (2014) and Kirby et al. (2014) delineated zones in the mountain ranges bounding the valleys most likely to accommodate interbasin
Groundwater-level trends in Snake Valley and adjacent basins, Utah and Nevada

Figure 1. Study area for this project, showing locations of wells measured for depth to groundwater, color coded by the aquifer in which they are open. Inset: Thirty-year (1981 to 2010) average precipitation from PRISM Climate Group (2016) data.
flow. Based on these criteria, the most likely interbasin flow paths are (1) from Snake Valley to Tule Valley through the Conger Range, (2) from Tule Valley to Fish Springs Flat through the southern Fish Springs Range, and (3) from Pine Valley and Wah Wah Valley to Tule Valley through low bedrock hills in the Confusion Range. Range-bounding fault zones likely form low-flow zones or flow barriers along parts of the range fronts, depending on the details of stratigraphic juxtaposition and fault-zone fabrics.

### METHODS

#### Groundwater Levels

**Depth to Water**

We measured depth to groundwater in wells using electronic water-level sounders or steel tapes depending on wellhead access and presence of line-shaft pumps. Based on repeat measurements, the accuracy of both methods is approximately 0.02 feet. We measured the offset of the wellhead measuring point from the adjacent land-surface reference point using a steel measuring tape graduated in hundredths of feet. We selected wells to measure based on the following criteria: (1) repeating measurements of wells measured in 2010 by the USGS; (2) no evidence of degradation of the well casing or surface seal or other damage, and no evidence of significant recent (past 24 hours) pumping; (3) providing as wide a distribution over the entire study area as possible; (4) providing more detailed coverage in areas of intensive agricultural pumping, and (5) where possible, measuring a variety of well depths and screened aquifers within a relatively close area. The wells we measured are tightly cased and are likely under confined conditions; however, some of the shallower wells near the mountain fronts may be under unconfined conditions. The campaign occurred primarily during late February to mid-March 2020, to coincide with the timing of the USGS’s annual water-level measurement campaign. Many priority wells, however, are owned by the U.S. Bureau of Land Management (BLM) and were in operation to support late-winter grazing during this time. We measured those wells in March and revisited them in May or early June 2020, at least one week after pumping had ended. Groundwater pumping for agriculture typically begins in early to mid-April in this region; however, the BLM wells measured in May and June are remote from areas of intensive pumping so were not likely affected at the time of our groundwater-level measurements.

**Location and Elevation Control**

We measured latitude, longitude, and elevation of the land surface adjacent to the wellhead or, where possible, at the wellhead access port, using differential GPS. Accuracy of latitude and longitude was 0.07 feet or better, and accuracy of elevation was 0.33 feet or better. We converted depth to water measured at the wellhead to water-level elevation by subtracting the depth to water and the offset of the measuring point from the land surface, from the land-surface elevation.

### Water Level Correction for Salinity

We calculated the equivalent freshwater head for 16 wells having brackish or saline water in the Sevier Dry Lake basin so that we could contour groundwater levels in the brackish to saline wells along with the other wells in the study area. The equivalent freshwater head is defined as the height of fresh water from a vertical datum that would create the equivalent pressure exerted by more dense water of a specific height from the same vertical datum (Kuniansky, 2018). We used a Microsoft Excel spreadsheet developed by the USGS (Kuniansky, 2018) that estimates water density from water quality measured in the well (specific conductivity, total dissolved solids concentration, and/or chloride concentration), then corrects the measured head of the dense, saline water to what it would be if the water were the density of fresh water (i.e., the equivalent freshwater head). We used water quality measured in December 2019 where available (Crystal Peak Minerals, 2020, six wells). For the remaining wells we used older water quality data queried from NWIS, or estimated water quality from a nearby well. The spreadsheet requires the user to establish a common vertical datum at the vertical midpoint of the freshwater part of the aquifer in the vicinity of the wells that will be contoured together. We set this datum at 4400 feet. Equivalent freshwater head ranged from 1 to 8 feet higher than the measured head. Kuniansky (2018) cautions against using the spreadsheet to calculate an equivalent freshwater head for wells having salinity more than half as dense as sea water, which most of our wells had; however, the exercise was undertaken for comparative purposes. Our contours in the Sevier Dry Lake area would shift to the east slightly if we had contoured the measured, uncorrected saline groundwater elevation.

### Potentiometric Surface and Contouring

Consistent with the approach of Gardner et al. (2011) and Hurlow et al. (2014), we contoured water levels from the basin-fill, volcanic-rock, and carbonate-rock aquifers together. Groundwater levels and trends in the basin-fill and carbonate-rock aquifers are nearly identical in nested wells in the UGS WDGMN (Hurlow et al., 2014; Hurlow and Inkenbrandt, 2016). An aquifer test conducted by the UGS in 2008 showed good connectivity between the two aquifers (Jordan et al., 2014). For sites having nested wells completed at different depths, we chose the groundwater level of the well screened in the 100- to 300-foot-depth range as representative of the potentiometric surface for contouring purposes, because most wells in the project area are open over this depth range.

We drew potentiometric contours by hand at 50-foot intervals throughout the project area and added supplemental contours.
in areas of low horizontal hydraulic gradient, chiefly in northern Snake Valley and Fish Springs Flat, to illustrate more detail. In areas having reasonably dense and uniformly distributed well coverage, we gridded the water-level elevation using the inverse-distance weighted method to provide a guide for contour placement. We used a point-density grid to guide contour symbolization as solid, dashed, and dotted lines, reflecting increasingly lower spatial density of data points and associated greater degrees of uncertainty, respectively.

Considering the long-term interest in and controversy over interbasin groundwater flow in this region (Harrill et al., 1988; Harrill and Prudic, 1998; Dixon et al., 2007; Welch et al., 2007; SNWA, 2009a, 2009b), we included additional interpretive potentiometric contours in the mountain blocks. These speculative contours illustrate the relationships between water levels in adjacent basins assuming some level of hydraulic connectivity, and illustrate regions of likely steep hydraulic gradients that indicate restricted or nonexistent interbasin flow (Gardner et al., 2011).

**Groundwater-Level Changes**

We calculated changes in groundwater levels at each well as the difference between depth to water from the measuring point in wells measured in 2010 and 2020. Using this convention instead of the difference in water-level elevation eliminates the need to correct for potential differences in land-surface reference elevation. Well heads included in our data had only one clear choice for a measuring point and did not appear to have been modified recently. We used USGS field-data sheets showing the measuring point where available. In analyzing and presenting the data, we judged that well density is insufficient to conduct meaningful interpolation, geostatistics, or gridding of water-level changes.

**Vertical Hydraulic Gradients**

Twenty-two of the 36 sites in the UGS WDGMN have monitoring wells screened at two or three different depths in the basin-fill and/or bedrock aquifers. We calculated vertical hydraulic gradients for daily average water levels from 2010 to 2021 for selected sites, plotted hydrographs of the vertical gradients, and calculated slopes using linear regression. We analyzed data from sites within and marginal to areas of intensive agricultural pumping; from a remote site in Tule Valley to represent baseline conditions far from significant valley-floor springs; and adjacent to important valley-floor springs.

We calculated the vertical hydraulic gradient between two wells as the ratio of the difference between the groundwater-level elevations to the difference between the screen-midpoint elevations, subtracting the values for the deeper well from those for the shallower well (Figures 2a and 2b). The equation is:

\[ VHG = \frac{(WLS - WLD)}{(SMS - SMD)} \]

where:

- \( VHG \) = vertical hydraulic gradient
- \( WLS \) = water-level elevation in the shallower well
- \( WLD \) = water-level elevation in the deeper well
- \( SMS \) = screen-midpoint elevation in the shallower well
- \( SMD \) = screen-midpoint elevation in the deeper well

In this convention a positive vertical hydraulic gradient between two wells indicates the groundwater-level elevation in the deeper well is lower than that in the shallower well, implying a potential downward flux of groundwater between the two points and potential groundwater recharge conditions (Figure 2a). Conversely a negative vertical hydraulic gradient indicates the groundwater-level elevation in the deeper well is higher than that in the shallower well, implying a potential upward flux of groundwater between the two points and potential groundwater discharge conditions (Figure 2b). A simple way to remember this convention is that for a positive hydraulic gradient, groundwater tends to move away (down) from an observer standing on the land. The actual flow of groundwater depends on several factors, primarily the hydrogeology of the site.

Hydrographs of vertical hydraulic gradients illustrate changes in groundwater dynamics over time. A sloping hydrograph indicates that groundwater levels are changing at different rates in the two wells used to calculate the gradient. Schematic examples in Figure 2c through Figure 2f illustrate cases in which groundwater levels in both wells are declining, but at different rates, as is typical in our study area.

Where the vertical hydraulic gradient is positive (groundwater-level elevation in the shallower well is higher; downward gradient and potential groundwater-recharge conditions) a positive hydrograph slope indicates that the vertical hydraulic gradient is increasing over time, i.e., the difference in groundwater levels between the two wells is increasing (Figures 2c and 2g). In this case the groundwater level in the deeper well is declining faster than that in the shallower well (Figures 2c and 2g). Conversely, for the same conditions a negative hydrograph slope indicates that the vertical hydraulic gradient is decreasing over time, i.e., the difference in groundwater levels between the two wells is decreasing (Figures 2d and 2f).

Where the vertical hydraulic gradient is negative (groundwater-level elevation in the deeper well is higher; potential groundwater-discharge conditions), a negative hydrograph slope indicates that the vertical hydraulic gradient is increasing over time (Figures 2e and 2g). In this case the groundwater level in the shallower well is declining faster than that in the deeper well.
Figure 2. Schematic diagrams of convention used to calculate vertical hydraulic gradients at nested monitor-well sites, and conceptual diagrams illustrating the relationships between groundwater-level changes and resulting hydrographs of the vertical hydraulic gradient. This convention uses groundwater-level elevations, as opposed to depth from land surface. A) A site where the groundwater-level elevation in the deeper well is lower than that in the shallower well, has a positive vertical hydraulic gradient, and the hydrologic flux is downward relative to land surface. Such a site is potentially a groundwater recharge zone. B) A site where the groundwater-level elevation in the deeper well is higher than that in the shallower well, has a negative vertical hydraulic gradient, and the hydrologic flux is upward relative to land surface. Such a site is potentially a groundwater discharge zone because upward-moving groundwater maintains a water table at or near the land surface and can generate spring flow and support phreatophytes and hydrophytes, depending on the height of the potentiometric surface relative to the land surface. C) If groundwater-level changes result in a progressively greater vertical hydraulic gradient, the slope of the resulting hydrograph is positive (Figure 2G). D) If groundwater-level changes result in a progressively lesser vertical hydraulic gradient, the slope of the resulting hydrograph is negative (Figure 2G). E) If groundwater-level changes result in a progressively greater negative vertical hydraulic gradient, the slope of the resulting hydrograph is negative. F) If groundwater-level changes result in a change from positive to negative vertical hydraulic gradient, the site may change from a groundwater discharge zone to a groundwater recharge zone (Figure 2G). G) Simplified hydrographs illustrating the scenarios described in Figures 2C through 2F.
In a special case, the vertical hydraulic gradient may change from negative to positive (upward to downward), i.e., from groundwater discharge to groundwater recharge conditions (Figures 2f and 2g).

Climate Data

We compiled water year precipitation data for 1980 to 2021 for the Wheeler Peak (elevation 10,060 feet) and Mather (elevation 9268 feet) climate stations in Great Basin National Park, on the western boundary of the Snake Valley surface-drainage basin (Utah Climate Center, 2022). We used grid-ded precipitation data from gridMET hosted on Google Earth Engine in order to have a complete dataset for the period of interest (Abatzoglou, 2012). GridMET uses a combination of point climate data, elevation models, and land-surface models to create a continuous spatial and temporal dataset.

The majority of recharge to the aquifers measured in this study falls as precipitation in the high mountain ranges bounding the valleys, and reaches the basin-fill aquifers by direct flow through the mountain block into the adjacent basin fill and by infiltration of runoff into the alluvial fans along the mountain fronts (Heilweil and Brooks, 2011; Prudic et al., 2015). Kirby et al. (2014) used solute chemistry, tracers, and stable and radiogenic isotopes to confirm this conceptual flow path model in the study area. Prudic et al. (2015, p. 129) asserted that little or no recharge occurs in this part of the Great Basin in areas having less than about 12 inches per year mean annual precipitation. Based on these studies, precipitation records in the mountains (as opposed to the valley floor) are the most relevant in considering the impact of climate on groundwater-level changes. Climate also indirectly affects groundwater levels by reduced groundwater pumping in agricultural areas during wet growing seasons and following high valley snowpack that may result in high soil moisture content, which leads to greater runoff to the valley floors.

Groundwater Pumping Data

We compiled previously published estimates of groundwater withdrawals from wells (principally irrigation wells for agriculture) in the Utah part of Snake Valley from 1940 to 2021, based on values reported by Masbruch et al. (2014, Figure 7), and data from the USGS’s Groundwater Conditions in Utah website (Smith and O’Leary, 2022). Significantly less groundwater is pumped in Tule, Pine, and Wah Wah Valleys and Fish Springs Flat where no major agricultural operations exist. Welch et al. (Appendix A, 2007) estimated about 34,500 acre-feet per year of groundwater pumping (all uses; about 33,700 acre-feet for agriculture) for 2005 in the Utah and Nevada parts of Snake Valley combined, and about 132,300 acre-feet of discharge from non-agricultural evapotranspiration. These estimates cover the entire Snake Valley groundwater basin, most of which has no groundwater pumping. From these estimates, groundwater pumping accounted for about 21% of the total groundwater discharge in Snake Valley in 2005.

We do not have groundwater pumping records from the Nevada part of Snake Valley. Masbruch et al. (2014, Figure 7) estimated 11,000 acre-feet of groundwater pumping for the Utah part of Snake Valley in 2005, whereas Welch et al. (Appendix A, 2007) estimated 34,500 acre-feet per year of groundwater pumping for the entire valley (Utah and Nevada combined). Assuming that methods in the two studies are roughly comparable, groundwater withdrawals in 2005 in Nevada were about 23,500 acre-feet, roughly twice as great as those in Utah.

Statistical Analyses

Hurlow and Inkenbrandt (2016) delineated changes in groundwater-level trends based on visual inspection of hydrographs, and calculated rates of change for the time between the interpreted inflection points using linear regression based on annual data from the U.S. Geological Survey (1978 to 2015) and daily average water levels from the UGS WDGMN (2008 to 2015). For this study we applied breakpoint analysis (minimum segment length of eight values) to identify changes in daily water-level trends, and applied Mann-Kendall analysis to calculate whether the data between break points had a statistically significant trend and, if so, quantify the slope. We performed breakpoint and Mann-Kendall analyses on annual water year precipitation records and annual groundwater pumping estimates to compare breakpoint times in these values with those observed in the groundwater levels. We performed the breakpoint analyses using the “strucchange” package in R and the Mann-Kendall analyses were run using the “modifiedmk” package (Zeileis et al., 2002; Zeileis et al., 2003; Patakamuri and O’Brien, 2020).

We obtained annual water-level data for select wells in Snake Valley from NWIS (U.S. Geological Survey, 2022) and added our data for wells discontinued by the USGS but continued in the WDGMN. We chose wells having continuous or nearly continuous annual water-level records from 1978 to 2021 from sites representing a range of impacts of pumping and climate on groundwater levels: a) in or adjacent to areas of intensive agricultural groundwater pumping (SVSMX, NSVMX, ESKMx), b) about 5 miles from the approximate geographic center of the pumping (PWO6MX), and c) more than 20 miles from any significant pumping (TSMX). The wells we analyzed are open to the basin-fill aquifer, are 100 to 200 feet deep, and are screened only in the lower 20 feet of the casing. To compile the time series for the annual data, we preferentially chose the March values from each year because this time is the most common for annual water-level measurement when groundwater levels have recovered as much as possible from the previous irrigation season’s pumping. The breakpoint analysis requires a value for each year in the analysis range. If a March value did not exist, we chose one from the non-pumping season (October–February) with preference for values closer to March, and
if neither of those options existed we used data from the pumping season (April–September) having the value most similar to the non-pumping data in prior and subsequent years. The minimum breakpoint analysis interval (“chunk”) was eight analysis steps (i.e., years) so that Mann-Kendall trend analysis could be performed on data between the break points, yielding average rates of change of groundwater levels for each chunk. We applied breakpoint analyses to the climate data using annual water-year precipitation, and to the pumping data using our estimated annual pumping for the Utah part of Snake Valley.

RESULTS

Groundwater-Level Changes and Potentiometric Contours

Well records and water-level data from our study (Appendix A) show that groundwater levels throughout the study area declined by 0.25 to 13.62 feet from 2010 to 2020 in 137 of 152 wells (Table 1; Figures 3 and 4). The median decline was 2.24 feet, and 135 wells experienced declines of greater than 0.25 feet (Table 1; Figures 3 and 4). Groundwater levels in 15 wells, distributed throughout the study area, increased by 0.12 to 7.04 feet. Groundwater level changes in higher-use areas (northern, central and southern Snake Valley) ranged from 0.12 to -13.62 feet (excluding results from an anomalous well explained in the Interpretations section), and the median groundwater-level change was -2.97 feet. Groundwater level changes in the rest of the study area ranged from 6.40 to -4.42 feet (excluding results from an anomalous well explained in the Interpretations section), and the median groundwater-level change was -1.30 feet.

Our potentiometric contours (Figure 5) are generally similar to those of Gardner et al. (2011) throughout the study area, with some comparatively minor differences due to groundwater-level changes, interpretations, or land-surface reference elevation. Land-surface elevation differences in the two studies ranged from -19.61 to 44.09 feet (UGS value minus USGS value) and had a median value of 0.18 feet and a standard deviation of 7.44 feet. The difference was less than 10 feet in 137 of 152 sites. Considering the contour interval is 50 feet, differences in potentiometric contours between the two studies resulting from differences in land surface elevation are minor, if any, in most places.

The following paragraphs summarize water-level changes from 2010 to 2020 and the characteristics of our new potentiometric-surface contours, subdivided by geographic area.

Northern Snake Valley

Groundwater levels in northern Snake Valley declined by 1.31 to 7.04 feet in 10 wells and increased by 0.12 feet in one well. The median groundwater-level change was -2.18 feet. Potentiometric contours in northern Snake Valley are closely spaced along the eastern mountain front of the Deep Creek Mountains (Figure 5), indicating a steep horizontal hydraulic gradient. Contours are more widely spaced, indicating a shallower horizontal hydraulic gradient, to the northeast below the valley floor. Our contours in this area are generally straight and trend northwest, in contrast to a pronounced northeast-trending high illustrated by Gardner et al. (2011). We include a supplemental contour at 4320 feet in northern Snake Valley, delineated by water-level measurements in the Callao, Utah, area.

<table>
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<th>Median</th>
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</table>

N - Number of data points
SD - Standard deviation

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<th>Min</th>
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<td>-13.62</td>
<td>-2.24</td>
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</table>

Higher-use basins

Lower-use basins
Figure 3. Changes in depth to groundwater at wells measured in 2010 (Gardner et al., 2011) and 2020 (this study).
Central Snake Valley

Groundwater levels in central Snake Valley declined by 0.18 to 13.62 feet in 45 wells and increased by 2.89 to 7.04 feet in six wells. The median groundwater-level change was -3.79 feet. The well with the greatest groundwater-level increase is in the Eskdale agricultural area, where all other wells showed declines. We do not have an explanation for this anomaly.

Three of the other wells showing increased groundwater levels are nested wells at UGS WDGMN site AG13, which increased from 2.89 to 5.89 feet from 2010 to 2020. In contrast, groundwater levels in three wells at UGS site PW01, one mile west of AG13 and also in the WDGMN, decreased by 3.01 to 13.62 feet from 2010 to 2020. This significant difference in groundwater-level changes over a comparatively small area results from the year-to-year volatility of groundwater levels at sites within the agricultural areas.

Potentiometric-surface contours in central Snake Valley trend northwest, suggesting that groundwater flows predominantly northeast, from recharge areas in the Snake Range to discharge areas in Snake Valley and Tule Valley (Hurlow and Kirby, 2014). Spacing of potentiometric contours indicate that horizontal hydraulic gradients are steep near the northern part of the southern Snake Range and Eskdale agricultural area, and shallower to the north.

Southern Snake Valley and Northern Hamlin Valley

Groundwater levels in southern Snake Valley and northern Hamlin Valley declined by 0.58 to 8.35 feet in 30 wells and increased by 0.21 and 2.96 feet in two wells, respectively.

Figure 4. Histograms of measured groundwater-level changes. A) All wells in the study area. B) Binned by geographic area. Geographic abbreviations are: NSV, northern Snake Valley; CSV, central Snake Valley; SSV, southern Snake Valley; HMV, Hamlin Valley; SPV, Spring Valley; FSF, Fish Springs Flat; TLV, Tule Valley; PNV, Pine Valley; WWV, Wah Wah Valley; SDL, Sevier Dry Lake basin.
Groundwater-level trends in Snake Valley and adjacent basins, Utah and Nevada

Figure 5. Potentiometric contours based on data from Appendix A.
Median declines were 2.93 feet in southern Snake Valley and 0.77 feet in northern Hamlin Valley. Our potentiometric contours in southern Snake Valley are similar to those of Gardner et al. (2011) and Prudic et al. (2015, Figure 61) and the contours are relatively uniformly spaced, concave to the northeast, and decrease to the northeast, suggesting that groundwater flows predominantly northeast.

### Southern Spring Valley

Groundwater levels in southern Spring Valley declined by 0.48 to 3.96 feet in 13 wells. The median groundwater-level change was -2.22 feet. Our potentiometric contours in southern Spring Valley are based on those of Gardner et al. (2011) with little change. We found no basis to revise the position of the groundwater divide between southern and central Spring Valley shown by Gardner et al. (2011).

### Fish Springs Flat

Groundwater levels in Fish Springs Flat declined by 0.47 to 3.50 feet in 15 wells. The median groundwater-level change was -2.24 feet. Spacing of potentiometric contours indicate a steep horizontal hydraulic gradient in the south and a shallower gradient in the north. We include supplemental contours at 4320 and 4330 feet in northern Fish Springs Flat.

### Tule Valley

Groundwater levels in Tule Valley declined by 0.57 to 4.29 feet in 14 wells, including wells that are pumped for grazing and wells that are far from any groundwater pumping. The median groundwater-level change was -2.11 feet. Our potentiometric contours in eastern Tule Valley are similar to those of Gardner et al. (2011). The horizontal hydraulic gradient is steep in western Tule Valley and very shallow in the north, possibly representing greater transmissivity in the northern part of Tule Valley (Harrill and Prudic, 1998).

### Pine Valley and Wah Wah Valley

Groundwater levels in Pine Valley declined by 1.86 feet in one well and increased by 0.39 to 1.14 feet in three wells. The median groundwater-level change was 0.47 feet. Groundwater levels in Wah Wah Valley declined by 0.25 to 2.55 feet in six wells. The median groundwater-level change was -1.77 feet. Potentiometric contours in Pine Valley and Wah Wah Valley are similar to those of Gardner et al. (2011), showing U-shaped contours concave to the north, indicating groundwater flow to the north.

### Sevier Dry Lake Basin

Groundwater levels in the Sevier Dry Lake basin declined by 1.03 to 1.51 feet in three wells and increased by 0.13 to 6.4 feet in three wells. The median groundwater-level change was -0.45 feet. Potentiometric contours trend generally north and decrease to the west, suggesting predominantly west-directed groundwater flow. In the northern Sevier Dry Lake basin, potentiometric contours suggest groundwater flow through Paleozoic carbonate rocks of the southern House Range to southern Tule Valley. Farther south, water levels in three wells on the Confusion Range margin west of Sevier Dry Lake suggest a local depression in the potentiometric surface (Figure 5). Our potentiometric contours are otherwise similar to those of Gardner et al. (2011). The contours indicate that Sevier Dry Lake is not a groundwater-discharge zone but is likely perched above shallow impermeable sediments.

### Groundwater-Level Trends

Breakpoint analysis of annual groundwater-level data from five selected wells (see Figure 6 for locations) yielded one to three break points over the 30- to 40-year analysis periods (Table 2). Break points occurred in consistent time ranges: 1988 to 1990, 2001 to 2003, and 2012 to 2014. Groundwater levels in well SVSMX (Figure 7a), 2 miles north of the Eskdale agricultural area, declined by 0.03 feet per year from 1999 to 2021 following a break point in 1998. Groundwater levels in wells SVNMX (Figure 7b) and ESKMX (Figure 7c), near the Eskdale agricultural area, declined by 0.62 to 0.69 feet per year following break points in 2003 and 1998, respectively. Groundwater levels in well PW06MX (Figure 7d), 4 miles north of the northern end of the Eskdale agricultural area, declined by 0.32 feet per year from 2015 to 2021 following a break point in 2014. Groundwater levels in the remote well TSMX (Figure 7e) experienced little absolute change throughout the period of record although the analysis revealed break points in 1988 and 2001 (Table 1; Figure 7e).

### Vertical Hydraulic Gradients

Nested wells AG14A, AG14B, and AG14C (shallowest to deepest, respectively) are in the Eskdale agricultural area in central Snake Valley (Figure 6). Groundwater levels fluctuated by about 2 to 3 feet during annual pumping and recovery cycles, superposed on a consistent decline of about 0.6 feet per year (Figure 8a). During the analysis period, the vertical hydraulic gradient between the shallow (AG14A) and intermediate-depth (AG14B) wells changed from slightly negative to slightly positive in 2015 (Figure 8a). The vertical hydraulic gradient between the intermediate-depth (AG14B) and deep (AG14C) wells had negative values and a positive slope throughout the analysis period (Figure 8a). At AG14, the vertical hydraulic gradient changed from upward to approximately neutral above a depth of approximately 130 feet (AG14B screen midpoint) in 2015, and remained upward below 130 feet. The rate of groundwater-level decline increased with depth, and the site may be in transition from a groundwater discharge zone to a recharge zone.
Figure 6. Wells and climate stations analyzed in this study.
Table 2. Results of breakpoint and Mann-Kendall analyses of water-level trends for select groundwater-monitoring wells in Snake Valley, using data from the U.S. Geological Survey and Utah Geological Survey, and for precipitation records and estimated groundwater withdrawals. See figure 5 for locations.

<table>
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<th>Well or Feature</th>
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<th>Chunk 1</th>
<th>Breakpoint 1</th>
<th>Chunk 2</th>
<th>Breakpoint 2</th>
<th>Chunk 3</th>
<th>Breakpoint 3</th>
<th>Chunk 4</th>
<th>Distance from Pumping Center (mi)</th>
<th>Well Depth (ft)</th>
<th>Screened Interval (ft)</th>
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1. The P value is defined as the probability under the assumption of no effect or no difference (null hypothesis), of obtaining a result equal to or more extreme than what was actually observed. The P stands for probability and measures how likely it is that any observed difference between groups is due to chance.
Figure 7. Groundwater levels from 1980 to 2021 and results of breakpoint and Mann-Kendall trend analysis in select wells in the UGS WDGMN. Vertical scale varies among the plots. See Figure 6 for well locations and Table 2 for well data. A) Well SVSMX in southern Snake Valley, about 2 miles northwest of the nearest groundwater pumping. B) Well SVNMX in central Snake Valley, about 2.5 miles northwest of the nearest groundwater pumping.
C. Manual Water Levels
March
May
June
July
August
September
Other data not used in analysis
Break Point
Trend Line Between Chunks
Chunk Number and Slope (ft/yr)

D. Manual water levels
March
May
June
July
August
September
Other data not used in analysis
Break point
Trend line between chunks
Chunk number and slope (ft/yr)

Figure 7 Continued. Groundwater levels from 1980 to 2021 and results of breakpoint and Mann-Kendall trend analysis in select wells in the UGS WDGMN. Vertical scale varies among the plots. See Figure 6 for well locations and Table 2 for well data. C) Well ESKMX in central Snake Valley, about 1 mile east of the nearest groundwater pumping. D) Well PW06MX in central Snake Valley, about 4 miles north of the nearest groundwater pumping.
Nested wells PW05A, PW05B, and PW05C (shallowest to deepest, respectively) are about 5 miles south of the Eskdale agricultural area (Figure 6). Groundwater levels did not show the pronounced annual cycling related to pumping that are observed at AG14, but declined steadily at about 0.7 feet per year (Figure 8b). During the analysis period, the vertical hydraulic gradient between the shallow (PW05A) and intermediate-depth (PW05B) wells had negative values, and its hydrograph slope changed from positive to negative in 2016 (Figure 8b). The vertical hydraulic gradient between the intermediate-depth (PW05B) and deep (PW05C) wells had negative values close to zero, and its hydrograph slope changed from negative to positive in 2016 (Figure 8b). At PW05, the vertical hydraulic gradient is upward, and the site is in a groundwater discharge zone. The rate of groundwater-level decline was lower at around 630 feet (screen midpoint of PW05B) than above and below.

Nested wells PW06A, PW06B, PW06C (shallowest to deepest, respectively) are about 3 miles northeast of the Eskdale agricultural area. Groundwater levels fluctuated annually by less than about 0.4 feet, reflecting groundwater pumping cycles, superposed on an overall decline of about 0.3 feet per year (Figure 8c). The vertical hydraulic gradient between the shallow (PW06A) and intermediate-depth (PW06B) wells was negative and near zero and its hydrograph had a slight positive slope (Figure 8c). The vertical hydraulic gradient between the intermediate-depth (PW06B) and deep (PW06C, screened in bedrock) wells was positive, changing to near zero in 2020, and its hydrograph had a slight negative slope (Figure 8c). At PW06, the vertical hydraulic gradient is very low, perhaps indicating unconfined conditions, and the rate of groundwater-level decline is greatest in the intermediate-depth well.

Nested wells PW17A, PW17B, and PW17C (shallowest to deepest, respectively) are in Tule Valley, about 27 miles northeast of the Eskdale agricultural area, and the sites are separated by the Confusion Range (Figure 6). Only a few stock watering wells are pumped in Tule Valley, so groundwater level trends are essentially entirely due to climate effects. Groundwater levels increased by about 0.2 feet per year from 2009 to 2013 then decreased at an average rate of about 0.09 feet per year (Figure 8d). The vertical hydraulic gradient between the shallow (PW17A) and intermediate-depth (PW17B) wells was negative, and its hydrograph had a very slight positive slope (Figure 8d). The vertical hydraulic gradient between the intermediate-depth (PW17B) and deep (PW17C) wells was positive and close to zero, and its hydrograph had a very slight negative trend (Figure 8d). At PW17 the vertical hydraulic gradient is very low to neutral, and the rate of groundwater-level decline decreases with depth.

Twin Springs in east-central Snake Valley is about 7 miles from the nearest groundwater pumping and 18 miles north of the Eskdale agricultural area and, therefore, shows minimal or no influence from groundwater pumping. The UGS monitors flow from the two main spring pools, providing an opportunity to test correlations between spring discharge and vertical hydraulic gradients in nearby nested piezometers.
Figure 8. Hydrographs of water-level elevation (NAVD88) vertical gradients in select wells in the UGS WDGMN from 2008 to 2020. A) Well site AG14.

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Linear regression line & slope (ft/ft/yr)

Vertical gradient change rates: C > B > A
Groundwater-level trends in Snake Valley and adjacent basins, Utah and Nevada

Figure 8 Continued. Hydrographs of water-level elevation (NAVD88) vertical gradients in select wells in the UGS WDGMN from 2008 to 2020. B) Well site PW05.
Figure 8 Continued. Hydrographs of water-level elevation (NAVD88) vertical gradients in select wells in the UGS WDGMN from 2008 to 2020. C) Well site PW06.
**Figure 8 Continued.** Hydrographs of water-level elevation (NAVD88) vertical gradients in select wells in the UGS WDGMN from 2008 to 2020. **D)** Well site PW17.
Figure 8 Continued. Hydrographs of water-level elevation (NAVD88) vertical gradients in select wells in the UGS WDGMN from 2008 to 2020. E) Well site SG24.
**Figure 8 Continued.** Hydrographs of water-level elevation (NAVD88) vertical gradients in select wells in the UGS WDGMN from 2008 to 2020. **F)** Well site SG25.

<table>
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Linear regression line & slope (ft/ft/yr)

- $y = -1.02 \times 10^{-3} \, x - 0.01$
- $y = 1.49 \times 10^{-3} \, x + 0.01$

Vertical gradient change rates: B > A, B > C
Groundwater levels in nested wells SG24A, SG24B, and SG24C (shallowest to deepest, respectively) at Twin Springs fluctuated annually by about 0.5 to 1.5 feet (Figure 8e), driven primarily by evapotranspiration by wetland and phreatophyte-shrub vegetation. During the winter of 2014–2015, dense thickets of Russian olive trees lining the outflow streams were cut as part of an environmental restoration project. Groundwater levels increased sharply after the treatment by approximately 1.3 feet in SG24A, 1.2 feet in SG24B, and 0.2 feet in SG24C, determined by comparing seasonal low water levels in 2014 and 2015. Groundwater levels in well SG24A showed a downward trend both before and after the treatment, whereas wells SG24B and SG24C did not show statistically significant trends before and after the treatment (Figure 8e). The vertical hydraulic gradient between the shallow (SG24A) and intermediate-depth (SG24B) wells had negative values, and its hydrograph had negative slopes before and after the treatment (Figure 8e) reflecting the declining groundwater levels in SG24A. The vertical hydraulic gradient between the intermediate-depth (SG24B) and deep (SG24C) wells had negative values, and its hydrograph had negligible slopes before and after the treatment (Figure 8e).

Spring discharge showed no statistically significant trends for the entire period of record or when the time periods before and after the tree removal were analyzed separately. This is not surprising considering the deep source of groundwater feeding the springs (Meinzer, 1911; Prudic et al., 1995). At Twin Springs, groundwater levels near the surface are declining, whereas no statistically detectable changes are observed in groundwater levels below about 45.5 feet (screen midpoint of SG24B) (Figure 8f).

Groundwater levels in nested wells SG25A, SG25B, and SG25C (shallowest to deepest, respectively) at Leland Harris spring complex fluctuate annually by about 0.6 to 1.0 feet, driven by evapotranspiration by wetland and phreatophyte-shrub vegetation and groundwater pumping 3 to 4 miles to the north. Beginning in 2016, groundwater-level declines in all three wells changed from negligible to rates of 0.04 to 0.11 feet per year. The vertical hydraulic gradient between the shallow (SG25A) and intermediate-depth (SG25B) wells changed from negative to positive values in 2016 and its hydrograph showed a consistent positive slope (Figure 8f). The vertical hydraulic gradient between the intermediate-depth (SG25B) and deep (SG25C) wells had negative values and its hydrograph had a negative slope before 2017 and a near-zero slope after 2017 (Figure 8f). At Leland Harris Springs, the vertical hydraulic gradient is upward below about 65 feet depth (screen midpoint of SG25B) but recently switched to downward above 65 feet, and the rate of groundwater-level decline is greatest at and below 65 feet.

Climate Data

The 1980 to 2021 total water year precipitation hydrographs (Figure 9) from the Wheeler Peak and Mather climate stations in Great Basin National Park indicate high-precipitation water years (qualitatively determined as > 800 mm [31.5 inches]) were 1980, 1982–84, 1986, 1995, 1997, 1998, 2005, 2011, and 2019. Low-precipitation water years (≤600 mm [23.6 inches]) were 2006, 2007, 2008, 2013, 2015, 2018, 2020, and 2021. The frequency and intensity of high-precipitation water years decreased substantially after 2000, whereas the opposite occurred for low-precipitation years. No break points were calculated for either station, and Mann-Kendall trend tests indicated an overall trend of -4.7 millimeters per year (P-value of 0.014) for the Wheeler Peak station and an overall trend of -3.4 millimeters per year (P-value of 0.018) for the Mather station.

Groundwater Pumping

Groundwater pumping increased substantially in 1974, declined during the high-precipitation water years of the mid- to late 1980s, and has increased steadily since the early 2000s (Figure 10). Following the relatively wet 2010 and 2011 water years, average well withdrawals in Utah were about 21,000 acre-feet per year from 2012 to 2021. Break points occurred in 1975, 1987, and 2006. Pumping increased at an average rate of 300 acre-feet per year after the 1987 break point and at an average rate of 360 acre-feet per year after the 2006 breakpoint (Table 2).

INTERPRETATIONS

Groundwater-Level Changes, Groundwater Pumping, and Climate Variations

Groundwater levels in most wells within about 6 miles of the agricultural areas declined by as much as 13 feet, substantially greater than declines measured in more remote areas. The median groundwater-level decline in remote areas was about 1 foot, which we interpret as primarily climate-driven. Groundwater-level declines in the agricultural areas were, therefore, a composite signal resulting from changes in pumping and climate. Groundwater levels are expected to decline in areas of intensive pumping, but the observed long-term downward trends that are relatively insensitive to high-precipitation years suggest that pumping and capture of discharge have not reached equilibrium and, therefore, groundwater levels will very likely continue to decline.

The groundwater-level changes calculated in this study need to be interpreted in the context of year-to-year fluctuations. For example, groundwater levels at UGS site AG13 were higher in 2020 than in 2010 in contrast with all other wells in the vicinity. Hydrographs from the shallow wells at AG13 and PW01 (Figure 11), one mile to the west (Figure 6), illustrate that seasonal and annual groundwater-level fluctuations at both sites are substantial, and that the magnitude of fluctuations...
Figure 9. Records of precipitation from the A) Wheeler Peak and B) Mather climate stations in Great Basin National Park, 1980 to 2021.
Figure 10. Estimates of groundwater pumping in Snake Valley from 1940 to 2021, from Masbruch et al. (2014, Figure 7—our interpretations of values shown on their figure) and Smith and O’Leary (2022).

Figure 11. Hydrograph of groundwater-level elevations (NAVD88) from sites AG13 and PW01 near Garrison, Utah, and groundwater-level changes for different time intervals. All three piezometers at AG13 showed increased groundwater levels from 2010 to 2020, in contrast to results from nearby wells including PW01, 1 mile to the west, which showed declines. Groundwater levels at AG13 were unusually high at the time of manual measurement, and all three piezometers would have shown declines had the comparison been done between 2010 and 2021. This scenario illustrates the need to interpret the water-level change data in context of larger temporal trends and spatial variations.
Groundwater-level trends in Snake Valley and adjacent basins, Utah and Nevada

Groundwater pumping in Snake Valley is measurably and consistently reducing groundwater levels over time periods of several years to tens of years within 6 miles of active pumping areas (Figures 7a through 7c and 8a through 8c; and additional sites in the WDGMN). Convex-to-the-southeast potentiometric-surface contours in the agricultural areas (Figure 5) result from the groundwater pumping; however, closed depressions around the pumping areas have not yet formed. Locally high groundwater use, in other words, has not reversed basin-scale groundwater flow paths. Daily groundwater-level records show consistent patterns of drawdown during the irrigation seasons followed by recovery during the winter, superposed on an overall downward trend (Figures 7 and 8) (Hurlow and Inkenbrandt, 2016, Figure 7).

Groundwater pumping in Snake Valley increased substantially more than those at PW01 in the winter of 1990–1991 preceding the groundwater-level campaign for this study. The perception of groundwater-level changes at these sites would vary depending on the time interval chosen to calculate the change. For example, the change in groundwater level in well AG13A from 2010 to 2020 was +2.09 feet, whereas the change from 2010 to 2021 was +7.56 feet (Figure 11). At site PW01, the change in groundwater levels from 2010 to 2020 in well PW01A was +6.61 feet, whereas the change from 2010 to 2021 was -0.15 feet (Figure 11). Change values would have been even more strongly negative from 2012 to 2020 or 2021 (Figure 11).

These conditions exist throughout the agricultural areas; similar fluctuations in groundwater levels occur at site AG14 (Figure 8a), 9.5 miles north of site AG13 (all three piezometers at site AG14 showed declines from 2010 to 2020). Records from wells affected by the pumping but having less pronounced fluctuations, such as PW05 (Figure 8b) and PW06 (Figure 7d and 7c), reflect regional long-term groundwater-level changes more clearly.

Regardless of the declining groundwater recharge rates, current groundwater pumping in Snake Valley captures groundwater discharge to the valley floor (Halford and Plume, 2011; Masbruch, 2019). The observed groundwater-level trends demonstrate that groundwater storage is decreasing, and capture by pumping either 1) exceeds groundwater discharge rates and groundwater levels will continue to decline indefinitely, or 2) has not reached equilibrium with discharge capture and the current groundwater-level rates of decline will continue until that occurs (see Bredehoft and Durbin, 2009, Figures 4 through 8; and Barlow and Leake, 2012, for a thorough discussion of groundwater pumping and capture). Groundwater budgets and numerical flow models indicate that in Snake Valley, most groundwater discharge occurs by evapotranspiration from shrublands, local wetlands, and dry playa (Welch et al., 2007, appendix A). Groundwater pumping would capture this evapotranspiration discharge and would also affect streams and surfacewater bodies that are connected to groundwater (Halford and Plume, 2011; Masbruch, 2019). Surface water that could potentially be captured includes Lake Creek and Prewitt Lake in southern Snake Valley and surface water in the outflow areas of the major spring complexes in central Snake Valley (Halford and Plume, 2011; Masbruch, 2019), all of which are ultimately sourced by groundwater (Kirby et al., 2014). Groundwater pumping could potentially affect these areas by reducing spring flow and capturing surface water in the springs’ outflow areas. Snake Creek and Baker Creek flow out of the Snake Range and are derived from precipitation runoff and snowmelt (Prudic et al., 2015). These streams are vulnerable to capture by groundwater pumping where they are in hydraulic connection with the underlying basin-fill or carbonate-rock aquifers, chiefly along the Snake Range mountain front (Prudic et al., 2015). Capture of groundwa-
ter-derived and runoff-derived surface water may slow the rates of decline of groundwater levels, but would adversely impact agricultural operations and habitat.

**Vertical Hydraulic Gradients, Groundwater Pumping, and Spring Flow**

Trends in vertical hydraulic gradients reflect different rates of change of groundwater levels at different depths. Groundwater levels at sites AG14, PW05, and PW06 (Figures 8a, 8b and 8c, respectively) are declining, but their vertical hydraulic gradients indicate a variety of conditions. Vertical hydraulic gradient values are negative at AG14 and PW05, indicating groundwater flow toward the land surface (i.e., they are in groundwater discharge zones). The sites show opposite trends in changing rates of groundwater-level decline with depth; rates of decline increase with depth at AG14 and decrease with depth at PW05. Vertical hydraulic gradient values and rates of change are near zero at PW06, perhaps indicating unconfined conditions or the large distance from the groundwater pumping.

In Tule Valley, where agricultural pumping is absent, climate is likely the most significant stressor on water levels. Groundwater level rates of change at PW17, vertical gradients, and vertical gradient rates of change are some of the lowest we calculated, likely indicating climate effects are experienced throughout the aquifer.

At Twin Springs (site SG24), shallow (<50 feet) groundwater levels are declining slightly whereas deeper groundwater levels, vertical hydraulic gradients, and spring flow appear steady. The vegetation treatment (Russian olive removal) affected groundwater levels in all three wells, with the effect decreasing with increasing well depth, but apparently did not affect long-term groundwater-level trends. Declining groundwater levels in the shallow well may reflect overall lower precipitation at the land surface. Deeper (>50 feet) groundwater levels have not been measurably affected by climate trends or groundwater pumping and experienced a step-change in elevation but no change in trend following the vegetation treatment. Although trends in spring flow and the vertical hydraulic gradient between the deeper two piezometers are consistent, we cannot evaluate whether the vertical hydraulic gradient is a reliable proxy for spring flow until measurable change occurs in spring flow to compare to changes in groundwater levels during the same time period. Regardless, discharge toward the land surface of deeper (from >50 feet) groundwater sustains the spring flow.

At Leland Harris spring complex (site SG25), groundwater levels in all three wells began to decline in 2016; the intermediate depth well (SG25B) declined at the greatest rate, as shown by the slopes of the vertical hydraulic-gradient hydrographs (Figure 8f). Groundwater pumping for agriculture occurs 3 to 4 miles north of the spring complex. The groundwater-level declines at SG25 are likely a composite signal of pumping and overall declining precipitation. The seasonal fluctuations in groundwater levels likely result predominantly from local evapotranspiration by wetland plants, because UGS sites in similar hydrogeologic settings that are farther from active pumping show similar patterns (Hurlow et al., 2014), but may be magnified by seasonal groundwater pumping. Recent increases in groundwater pumping north of Leland Harris springs may impact groundwater levels and spring discharge in the future, because the groundwater flow system that discharges to the Leland Harris springs is likely shallow, indicated by cooler temperatures and lower total-dissolved-solids values, as compared to groundwater discharging at Twin Springs (Kirby et al., 2014).

Considering the results from sites SG24 and SG25 together, and comparing trends observed in open water levels in the outflow areas of both spring complexes (Goodwin et al., 2021), we suggest that water availability and ecologic conditions at these important sites fluctuate due to shorter-term (one to several years) local climate and land-use changes, but ultimately depend on long-term groundwater discharge as represented by trends in groundwater levels and vertical hydraulic gradients. Capture of discharge by pumping could also potentially remove surface water in the outflow area of the spring complex if hydraulic connection exists between the part of the aquifer that is pumped and the land surface. By comparison with UGS groundwater monitoring sites in central Snake Valley (PW05 and PW06), new groundwater pumping within about 6 miles of these springs would very likely affect the vertical hydraulic gradients and, therefore, water availability at these and similar sites.

**Interbasin Flow (or Not)**

We summarize our interpretations of interbasin flow here referring to the speculative contours on Figure 5, and briefly compare our interpretations to those of Gardner et al. (2011). Many previous studies, cited in the “Objectives” section of this report, have published generalized potentiometric surface contours and proposed interbasin groundwater flow through the mountain blocks in this region. Our results aim to refine (depending on one’s level of confidence in the speculative potentiometric surface contours), and do not contradict, these previous studies.

**Northern Snake Valley**

Speculative contours indicate interbasin flow to the east through the central and southern Fish Springs Range. Interbasin groundwater flow from northern Snake Valley to Fish Springs Flat through the central and southern Fish Springs Range is plausible based on the presence of highly fractured lower Paleozoic HSU and on the difference in potentiometric-surface elevations on either side of the range. Gardner et al. (2011) also drew contours through the Fish Springs Range.
indicating interbasin flow. In the northern part of the range, an unexposed pluton and associated contact metamorphic rocks likely inhibit interbasin flow.

**Fish Springs Flat**

Based on the hydrogeologic setting, we interpret that if a hydraulic connection exists between Fish Springs Flat and Dugway Valley, flow occurs predominantly if not exclusively through the lower Paleozoic carbonate rocks of the Dugway Range. Gardner et al. (2011) drew interpretive contours indicating north-northwest-directed groundwater flow through Tertiary volcanic and plutonic rocks and altered Paleozoic carbonate rocks of the Thomas Range, implying hydraulic connection between eastern Fish Springs Flat and western Dugway Valley.

**Central Snake Valley**

Gardner et al. (2011) drew interpretive contours indicating northeast-directed interbasin flow from central Snake Valley to central Tule Valley through tightly folded and highly faulted upper Paleozoic carbonate rocks in the Confusion Range north of Cowboy Pass. As illustrated by our 4750- and 4800-foot potentiometric contours, we interpret that interbasin flow to the northeast occurs through Cowboy Pass, but not likely to the north, where tightly folded Mississippian Manning Canyon Shale is present near the surface (Gardner et al., 2011; Hurlow and Kirby, 2014). In this area, the potentiometric surface slopes northeast from the valley toward the Confusion Range and several major springs occur along the western range margin. These springs discharge premodern and older groundwater having chemistry and recharge temperatures estimated from dissolved noble gas concentrations consistent with derivation in the Snake Range to the west (Kirby et al., 2014) rather than the adjacent Confusion Range. Hurlow and Kirby (2014) suggested that these springs represent impediment of eastward groundwater flow by the Manning Canyon Shale. This scenario contrasts with a more typical hydrogeologic setting in the Basin and Range in which mountain-front springs are supplied by groundwater that is recharged in the adjacent mountain block and flows toward the valley (e.g., Heilweil and Brooks, 2011, Figure C-1); the springs are localized by range-bounding faults or facies transitions in the basin-fill sediments. Our interpretation is inspired by Prudic et al.’s (2015, p. 127) discussion of the lack of mountain-front springs along the western margin of the Fortification Range between southern Spring Valley and northern Hamlin Valley (Figure 1), where the potentiometric surface slopes east toward the range, as partial evidence of interbasin flow through the lower Paleozoic carbonate rocks that comprise the range.

Our potentiometric contours illustrate interbasin flow to the northeast from Snake Valley to Tule Valley through lower Paleozoic carbonate HSU rocks of Conger Mountain, based on structural and geochemical interpretations of Hurlow and Kirby (2014). Southeast of Conger Mountain, our contours and those of Gardner et al. (2011) indicate that the horizontal hydraulic gradient is very steep, likely due to a very low-transmissivity zone created by tightly folded, steeply dipping Manning Canyon Shale and a north-south-striking fault zone (Hurlow et al., 2014). The contours are highly speculative because they are based on data from two wells, one in basin-fill deposits in Little Valley and one in lower Paleozoic carbonate rocks to the east, in which the potentiometric surface drops from 4884 feet in the valley fill to the west to 4424 feet in the lower Paleozoic carbonate HSU 3.5 miles to the northeast.

Our contours suggest interbasin flow from Ferguson Desert (southeastern part of central Snake Valley) to southern Tule Valley through the lower Paleozoic HSU of the Confusion Range south of Highway 50.

**Tule Valley**

Interbasin flow from northern Tule Valley to southern Fish Springs Flat may be accommodated by densely fractured lower Paleozoic carbonate HSU rocks in a complex transverse fault zone through Sand Pass (Hurlow et al., 2014). Our potentiometric contours suggest a hydraulic connection between the Sevier Dry Lake basin and southern Tule Valley through the upper Paleozoic carbonate HSU.

**Southern Snake Valley**

Our contours illustrate northeast-directed interbasin flow from southern Snake Valley to Ferguson Desert through the upper Paleozoic carbonate HSU in the Burbank Hills. Gardner et al. (2011) did not draw contours through this range.

**Pine Valley and Wah Wah Valley**

The potentiometric-surface elevation decreases abruptly to the east from southern Snake Valley to Pine Valley, and from Pine Valley to Wah Wah Valley. These abrupt changes across the valley-bounding mountain ranges suggest limited or no connection of groundwater between these valleys. Volcanic rocks, scattered intrusive rocks, and range-bounding normal-fault zones may result in lower west-to-east transmissivity through the mountain ranges and from the ranges to the basin-fill aquifers, than through the Paleozoic carbonate rocks of the Confusion Range where interbasin flow seems more likely to occur.

**Sevier Dry Lake Basin**

North-northeast-trending, west-decreasing potentiometric contours in the Sevier Dry Lake basin suggest that interbasin flow may occur from the eastern margin of the Confusion Range to southern Tule Valley through lower Paleozoic carbonate rocks in the southern House Range. This interpretation is speculative because we have only one water level in
southern Tule Valley. The local depression in the potentiometric surface west of Sevier Dry Lake is primarily drawn around two relatively deep bedrock-completed wells. The wells contain fresh water, and one of them is a stock watering well that was in good repair (and therefore potentially recently used) during our water-level measurement campaign. The apparent depression may be a drawdown cone from pumping, or it may be a consequence of contouring different aquifers and calculated freshwater heads as a connected aquifer.

CONCLUSIONS

In Snake Valley and groundwater basins to the east and southeast, groundwater levels declined by 2 to 4 feet in most places and locally by as much as 13.6 feet from 2010 to 2020. The greatest changes occurred in and near areas of intensive groundwater pumping for agriculture. Groundwater levels in UGS monitor wells in these areas fluctuate seasonally and annually by far greater amounts than in wells more than a few miles from the geographic centers of the pumping. Although none of these results are surprising, we conclude that a) rates of groundwater-level declines in the agricultural areas show no sign of slowing, indicating that removal of groundwater from storage and capture of discharge continue, and b) records from wells on the fringe of the pumping areas are perhaps more useful for understanding long-term trends. Groundwater levels in wells more than about 6 miles from the nearest significant groundwater pumping and in basins having no pumping other than dispersed stockwatering wells declined by about 1 foot from 2010 to 2020, providing an approximate estimate for the amount of change within the pumping areas that may have been due to ambient conditions.

Our thorough coverage of new groundwater levels provided data to construct potentiometric contours for 2020. The majority of wells we measured were in the basin-fill aquifer on or near the valley floor, but wells screened in bedrock are widely spaced. Because groundwater levels in wells completed in the basin-fill aquifer and those nearby in the carbonate-bedrock aquifers are similar in elevation, seasonal fluctuations, and long-term trends, we contoured water levels from wells in both types of completions together. These contours can be compared to those derived by Gardner et al. (2011) to illustrate regional changes in groundwater levels. The main observed changes reflect large-scale lowering of groundwater levels in areas of high use.

We speculatively extended potentiometric-surface contours into the mountain blocks to illustrate the differences in groundwater levels between basins and aid interpretations of interbasin flow. Interbasin flow likely occurs from central Snake Valley northeast to Tule Valley through Conger Mountain and the northern Confusion Range; from Snake Valley northeast to Fish Springs Flat through the northern Confusion Range and central and southern Fish Springs Range; from southern Snake Valley northeast to the southeastern part of the central Snake Valley through the Burbank Hills; from Pine Valley north to southern Tule Valley; and from the southern Sevier Dry Lake basin to southern Tule Valley. Tightly spaced contours and hydrogeologic setting suggest little or no interbasin flow occurs from southern Snake Valley eastward to Pine Valley; from central Snake Valley eastward to Tule Valley through the central Confusion Range; from northern Snake Valley eastward to Fish Springs Flat through the northern part of the Fish Springs Range; from central Pine Valley eastward to southern Wah Wah Valley; and from northern Wah Wah Valley northeastward to the southeastern part of the Confusion Range.

Precipitation in the Snake Range on the eastern boundary of Snake Valley is the ultimate source of recharge to the basin-fill and bedrock aquifers. These aquifers are used for agriculture, culinary water, and supply springs on the valley floor. Water-year precipitation at the Wheeler and Mather climate stations in the southern Snake Range fluctuates significantly but both stations show gradual declines of 3 to 5 mm per year from 1980 to 2021. Groundwater pumping on the valley floor has increased substantially during the past 40 years, particularly since the mid-2000s; average pumping rates in the Utah part of Snake Valley were about 9000 acre-feet per year from 1980 to 2006, and about 20,000 acre-feet per year from 2006 to 2021.

Time-series analyses of groundwater levels proved useful for long-term records. Breakpoint analysis revealed distinct time intervals of two to three years during which the rates of groundwater-level declines abruptly changed. Groundwater-level hydrographs of wells analyzed in this study showed abrupt changes in trajectories during 1988 to 1990, 2001 to 2003, and 2012 to 2014. Mann-Kendall analysis identified whether trends between break points were positive or negative and calculated the slopes (i.e., the rate of change of the groundwater levels). Precipitation data contained no break points using an eight-year interval, however, an overall downward trend occurred from 1980 to 2021. This change suggests groundwater recharge rates may be slowly declining. Groundwater pumping shows two break points when analyzed at eight-year intervals. We do not observe a clear correlation between the timing of break points in the water-level hydrographs and those in the pumping. Breakpoint analysis at shorter time intervals may reveal more break points in the precipitation and pumping records that correlate with break points in the groundwater-level hydrographs, but the Mann-Kendall analysis would not be valid.

Hydrographs of vertical hydraulic gradients measured in nested monitor wells illustrate variable rates of change of groundwater levels at different depths, driven in part by climatic fluctuations and land use changes in the shallow (<30 feet) wells and driven by changing rates of groundwater discharge toward the land surface in deeper (>50 feet) wells. Near spring complexes, gradients between the deepest and intermediate-depth piezometers mainly reflect regional groundwater flow and discharge to the land surface, whereas gradients between
the medium-depth and shallowest piezometers mainly reflect climatic and vegetation changes in addition to groundwater flux from below. At Twin Springs, we had hoped to demonstrate that the vertical hydraulic gradient correlated with spring flow and, therefore, could serve as a reasonable proxy in areas having diffuse springs. Twin Springs are regionally sourced and their flows have not fluctuated measurably since 2009 when we established continuous spring flow monitoring there. The vertical hydraulic gradient between the deepest and medium-depth piezometers has also remained consistent, but this is not a rigorous test of our hypothesis.

ACKNOWLEDGMENTS

Many people kindly granted access to their wells, including land owners in Snake Valley and adjacent areas, the U.S. Bureau of Land Management, and SNWA. The UGS Groundwater & Wetlands Program is particularly grateful to Snake Valley residents for their hospitality and partnerships throughout the past 20 years while we have studied many aspects of the hydrogeology of this area. Hugh Hurlow, Lucy Jordan, Stefan Kirby, and Paul Inkenbrandt of the UGS Groundwater & Wetlands Program collected water levels for this project. Will Hurlbut (previously with UGS) helped process the GPS data, and Nathan Payne (UGS) drafted the map illustrations.

REFERENCES


Crystal Peak Minerals, 2020, Unpublished monitoring well information and quarterly water level and water quality sampling summary for the Sevier Playa Potash Project, Utah Division of Oil, Gas and Mining permit M/027/0125.


APPENDIX A

Well locations and water-level measurements

Link to supplemental data: