Shallow groundwater flow and inverted fresh/saline-water interface in a hypersaline endorheic basin (Great Basin, USA)

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Abstract

Pilot Valley is an 828-km² arid-region endorheic basin in western USA. Bounding mountain ranges rise as much as 1,900 m above the nearly flat 379-km² playa floor. Up to 3.8 m of Pleistocene Lake Bonneville mud and thin oolitic sand layers form the surface layer of the basin floor. Groundwater conditions were evaluated using data from shallow monitoring wells and borings, springs, infiltrometer measurements, slug and dilution tests, geophysical transects, and precision elevation surveys. Alluvial fan groundwater discharges at fan/playa interface springs and underflows to the shallow basin sediments along the western side of the basin; the groundwater only underflows along the eastern side. Precision surveying established a Lake Bonneville shore-line break in slope as the cause of the spring discharges. Tectonic tilting causes groundwater to flow from east to west and to the topographic low. Monthly measured and pressure transducer data established seasonal pressure responses and upward groundwater gradients. All basin groundwater is lost to evapotranspiration at the topographic low, where a thin salt pan has developed. Groundwater evolves from fresh to hypersaline near the alluvial fan/playa interface where there is an inverted salinity gradient and a groundwater pressure ridge. The pressure ridge and inverted salinity interface are due to: (1) osmotic pressure established between the oolitic sand of high hydraulic conductivity and the overlying low-hydraulic-conductivity lake mud at the fan/playa interface, and (2) the collision between fresh groundwater flow driven by a steep hydraulic head and hypersaline groundwater flow driven by a nearly flat hydraulic head.

Keywords Alluvial fan–playa interface · Arid regions · Salt water/fresh-water relations · Shallow groundwater flow · USA

Introduction

Endorheic basins are catchments with internal drainage and do not terminate in a marine environment. They are found on all continents and cover approximately 20% of the total Earth’s surface (Fig. 1; Dorsaz et al. 2013; Nichols, 2007). Particularly notable endorheic regions include the Caspian Sea and Aral Sea in Asia, and Central Asian Internal Drainage Basin, the Great Artesian Basin (GAB) in Australia, portions of the South American Altiplano, much of the Sahara Desert in Africa, and the Great Basin in the western United States. Most endorheic basins develop in arid regions with drainage networks terminating in alluvial plains, lacustrine mud and salt flats, and fresh to hypersaline lakes (Yechieli and Wood 2002).

Groundwater systems in endorheic basins are regulated by water inputs (precipitation, surface water and groundwater inflows), outputs (evapotranspiration and groundwater discharge), structural and stratigraphic relationships, soil texture, groundwater salinity, aeolian processes, and climatic effects (Tyler et al. 2006; Tweed et al. 2011). Because the average worldwide precipitation in endorheic regions is only 54.1 mm year⁻¹ compared to the average for exoreic regions of 321.5 mm year⁻¹ (Meybeck et al. 2001), these regions only account for 2.3% of the total worldwide annual
river runoff (UNESCO 2014). Despite their low precipitation and runoff rates, Wang et al. (2018) and Pavelsky (2018) found that in recent years evaporative losses from the basins have increased significantly in response to climate change and that these losses contribute disproportionally to sea level rise.

Although endorheic basins cover extensive portions of the land surface, investigations into their groundwater circulation and geochemistry has not received the same level of attention as have other aspects of hydrogeology. Region wide investigations have been conducted on the mature landscape of the GAB (National Water Commission 2013) and the tectonically active immature landscape of the Great Basin (Heilweil and Brooks 2011). The GAB, one of the largest groundwater basins in the world, underlies 22% of Australia and contains sediments up to 2 km thick. Groundwater in the GAB is up to $2 \times 10^7$ years old. In contrast to the GAB, the Great Basin regional studies are for a geologically immature and tectonically active terrain covering most of the state of Nevada, the western portion of Utah, a portion of eastern California, and small regions of Oregon (Fig. 2).

In recent years, local studies have been conducted on groundwater flow in large and small groundwater systems in endorheic basins (Chen et al. 2014; Corenthal et al. 2014; Eugster 1980; Fisher and Kreitler 1987; Johnson et al. 2010; Mayo et al. 2007; Mayo et al. 2010; Miguel et al. 2005; Ortega-Guerrero 2003; Tejeda et al. 2003).

The purpose of this investigation is to develop and analyze a robust data set that will add insight into the recharge, hydrodynamics, flow, and discharge of shallow hypersaline endorheic basin groundwater flow. Understanding shallow flow is critical because the shallow zone is where active groundwater systems are recharged and where most active flow occurs. Pilot Valley, in the Great Basin (Fig. 3), was selected for study because it is readily accessible, has not been significantly impacted by anthropogenic processes, is partially covered by a salt pan, and is of a manageable size for in-depth research.

**Previous Pilot Valley investigations**

Stansbury (1852) published the first scientific account of Pilot Valley in the chronicle of his crossing the northern portion of the valley in October 1849. In Gilbert’s (1890) investigation of Pleistocene Lake Bonneville (Fig. 4), he concluded that much of the basin fill was deposited in lakes that preceded Lake Bonneville and that basin fill had responded to isostatic rebound accompanying the evaporative shrinking of the lake. Nolan (1928) mapped the extent of the salt crust in the Great Salt Lake Desert including Pilot Valley. More recently the geology of Pilot Valley and surrounding mountains has been mapped and described (Anderson 1957, 1960; McCollum and Miller 1991; Miller 1984, 1985, 1990a, b, 1993; Miller and Lush 1994; Miller and Phelps 2016; Miller et al. 1990, 1993; O’Neil 1968; Schaeffer and Anderson 1960; South et al. 2016). Harrill (1971) and Stephens and Hood (1973) conducted hydrologic reconnaissance investigations of Pilot Valley. Lines (1979) described zonation of evaporative minerals in the shallow playa subsurface, provided an overview of the aquifers, and mapped potentiometric and salinity contours of the shallow subsurface. Peterson (1993) and Mason et al. (1995) described the shallow groundwater geochemistry and water level surfaces. Carling et al. (2012) investigated Pilot Valley mountain front groundwater recharge rates and mechanisms, and Rey et al. (2016) used core data to characterize the basin’s Lake Bonneville stratigraphy. Liutkus and Wright (2008) investigated the relationship between playa margin rhizolith isotopic compositions and ambient water conditions. The freshwater/saline-water interface along the base of the Pilot Range alluvial fan has been investigated by Duffy and Al-Hassan (1988), Oliver (1992), Fan et al. (1997), and Winkel (2007). Most of the work undertaken in recent years was part of the overall work program that is summarized herein (Peterson 1993; Winkel, 2007; Carling et al. 2012; Rey et al. 2016; South et al. 2016).
Methods of investigation

Field and laboratory investigations included: (1) geophysical studies and lake bed coring to help define the shallow hydrostratigraphy, the depositional relationships between alluvial fan and lake bed deposits, and the evolution of Lake Bonneville sedimentation (2) the development of a water budget, (3) precision elevation surveying to evaluate the origin of alluvial fan/playa interface springs, and to provide ground surface elevation data for analysis of water levels and the spatial orientation of hydrostratigraphic units, (4) construction of shallow monitoring wells and manual and pressure transducer water level measurements to define horizontal and vertical groundwater flow directions and timing, (5) infiltrometer measurements to determine infiltration rates of alluvial fan, stream channel, and playa sediments, and (6) laboratory determinations of groundwater density.

Data were collected from 242 shallow monitoring wells and 23 boreholes constructed between 1992 and 2014, 15 springs, and 3 ephemeral streams. One hundred thirty-two wells were constructed by Oliver (1992), Peterson (1993), Mason et al. (1995), and Carling et al. (2012). This investigation included the construction of 110 wells and the 23 boreholes. Well depths range from <1 to 30 m. Most wells were completed within 6 m of the ground surface, a few are as deep as 14 m, and one well is 30.5 m deep. Most wells were completed in hand-augured boreholes with 2.54-cm inside diameter (ID) polyvinyl chloride (pvc) pipe and fitted with factory perforated screens that were typically 0.3 m long. Well-screen sand packs were sealed with bentonite pellets and the
remaining annulus backfilled with native material. Pressure transducers were deployed in 26 wells at various times with measurement frequencies ranging from 1 to 6 h. Transducers were deployed for up to 2 years.

Field measurements and laboratory analyses were undertaken between 1991 and 2019. Approximately 4,300 manual water levels were measured on selected wells between 1991 and 2014 and all water level data have been density corrected. Monthly basin-wide water level measurements were conducted in 2000–2001, and detailed basin-wide measurement campaigns were completed in 2007 and 2014. Eight tipping-bucket rain gauges were installed in the two Silver Island Range catchments in 2005 (Carlin et al. 2012) and four remained operational until late 2014. The 30-year mean annual precipitation was determined using the 800 m PRISM grid (PRISM Climate Group 2018).

Slug and single-well dilution tests were performed on 5-cm ID wells at the Silver Island and Pilot Ranges alluvial fan/playa interfaces. Slug tests were performed by either introducing or removing 1 L of native water into the well bore. Water level responses were recorded with pressure transducers. Dilution and slug test data were analyzed by the methods of Pitrak et al. (2007) and Bower and Rice, Hvorslev and Cooper (Butler 1998).

Relative infiltration rates were measured using a falling head, 0.305-m diameter double ring infiltrometer. The infiltrometer was set 2–3 cm into the soil leaving a 14–15 cm water column. Water level changes were measured for about 15 min or until the infiltrometer no longer contained a free water surface. Longer test periods were not deemed necessary because, except for flooded stream channel and playa conditions, the initial water column height was several orders of magnitude greater than realistic for precipitation events.

Ground surface and well collar elevations were determined by precision, closed circuit leveling methods using a US Geological Survey bench mark as the reference datum. High-resolution seismic reflection profiling was conducted between 2012 and 2016. Ground surface and density corrected water levels were adjusted to a local 100-m datum.

**Geologic setting**

**The Great Basin and Lake Bonneville**

Pilot Valley is located in the northeast region of the Great Basin (Fig. 2). The Great Basin has a maximum east-west width of about 800 km and estimates of total east–west
extension range between about 50 and 100% (Bogen and Schweickert 1985; Wernicke et al. 1982). Extension began about 11 million years ago and continues today. The Great Basin contains more than 100 fault block valleys, bounded by more than 130 named north to northeast trending high mountain ranges, mountains, and hills. The mountain ranges are 95–190 km long and 5–24 km wide, and the valleys are commonly wider. Hundreds to thousands of meters of relief separates adjacent ranges and valleys. Bedrock in the mountain ranges consists of often steeply dipping and structurally complex layers of Precambrian metamorphic core complex rocks, Paleozoic age carbonate and fine-grained clastic rocks, and Tertiary age volcanic lava and ash flows.

With up to 400 km of east–west separation, many of the valleys became endorheic basins, filled with thousands of meters of Tertiary to Recent coarse- and fine-grained terrestrial clastic sediment shed from the surrounding ranges (Snyder 1962). In valley floors, alluvial fan sediments interfinger with fine-grained playa and lake bed sediments, and volcanic debris. Today the Great Basin is an arid expanse of about 490,000 km² of internal drainage and many of the valleys, including Pilot Valley, are endorheic (Fig. 2).

The most well-known and best-studied ancient endorheic lakes in the Great Basin are the large Pleistocene age pluvial Lakes Lahontan and Bonneville (Fig. 4). These and numerous smaller pluvial lakes flooded many of the Great Basin valleys between about 32,000 and 9,000 years ago. Today a few smaller lakes, such as the hypersaline Great Salt Lake in Utah and the freshwater Pyramid Lake in Nevada remain as shrunken remnants of the Great Basin’s past watery history. Of interest to us here is the lake history associated with Lake Bonneville and its attendant sedimentary record in Pilot Valley (Oviatt and Shroder 2016; Rey et al. 2016).

Pilot Valley was a flooded, but nearly isolated finger-shaped embayment along the western edge of Lake Bonneville for most of Bonneville time. Except for the Lake Bonneville high stand, the only connection between Pilot Valley and the larger Lake Bonneville was the narrow gap between Lemay Island and the Silver Island Range (Fig. 3). Four high-stand terraces have been identified in ancient Lake Bonneville shorelines: Stansburry ~23–20 ka at ~1,372 m above mean sea level (amsl), Bonneville ~20–16 ka at ~1,552 m amsl, Provo ~15–14 ka at 1,447 m amsl, and Gilbert ~11–10 ka at ~1,295 m (Currey et al. 1984; Miller and Phelps 2016). The salinity of Lake Bonneville varied according to water level. Both Bonneville and Provo waters were fresh, Stansbury was moderately saline, and Gilbert was saline. After the Gilbert high stand, the lake level continued to decline leaving the modern Great Salt Lake as a hypersaline remnant of the once impressive freshwater lake. The modern-day Pilot Valley salt pan, and the better-known Bonneville Salt Flats that is located in the adjacent basin to the south, are episodically flooded with hypersaline water.

Pilot Valley

The 7–15 km wide and 35 km long Pilot Valley is a northeast trending endorheic basin that is bounded by the Pilot Range to the west, the Silver Island Range to the east and southeast, Lemay Island to the north, and the Leppy Hills to the south (Fig. 3). To the northeast the valley is closed between the Lemay and Crater Island at the north end of the Silver Island Range. Except for unusual surface inflows from Pilot Creek, the valley is closed to the south (Fig. 5). The playa spill point is only about 1.5 m higher than the topographic low in the salt pan. The Pilot and Silver Island ranges rise to 3,266 and 2,305 m amsl, respectively. The Pilot Range consists of Precambrian metamorphic core complex and Paleozoic carbonate and siliceous bedrock, and the Silver Island Range consists of Paleozoic carbonate and siliceous bedrock (Fig. 5). Because the valley is a half graben, with the principal dip-slip frontal fault located at the base of the Pilot Range (Fig. 3), the playa surface slopes gently easterly (Fig. 6). The frontal fault is covered by alluvial fan sediments and the
exact location is uncertain. The valley is filled with as much as 1,600 m of alluvial fan, shoreline, lake bed, and volcanic sediments (Cook et al. 1964; Lines 1979). Coarse-grained alluvial fan sediments shed from the eroding mountain ranges, accompanying the block faulting grade into finer-grained fluvial and lacustrine sediments in the bottom of the gradually sinking valley floor.

Pilot Valley mountain-front alluvial fan/pediment surfaces typically extend 3–5 km from the mountain bedrock to the basin’s playa surface. The fan/pediment surfaces are steep with gradients averaging 0.085 and 0.051 for the Pilot and Silver Island ranges and the alluvial fans occupy about 151 and 87 km², respectively. Ephemeral stream channels that cross the fans are filled with very coarse-grained sediments, which become progressively finer-grained down gradient. Some low-elevation fan channels and pediment surfaces in the Silver Island Range are underlain by fine-grained Lake Bonneville deposits. Using high-resolution seismic reflection, South et al. (2016) found that both the Pilot Range and Silver Island Range alluvial fan sediments dip beneath the nearly horizontal playa and lacustrine sediments at the alluvial fan/playa interfaces. The angular unconformity extends as much as 1 km into the basin to a depth of 150 m below ground surface (bgs).

The 379 km² Pilot Valley playa is divided herein into three subbasins: north, central, and south (Fig. 6). A low topographic divide separates the central and south subbasins. The north subbasin is nearly flat ranging in elevation from about 1,295 to 1,293.5 m amsl, and slopes from the south, east, and north to the topographic low near the Pilot Range alluvial fan/playa interface. The average east–west gradients in the central and north subbasins are $10^{-4}$ and $10^{-5}$, respectively. Near the salt

**Fig. 5** Simplified geologic map of Pilot Valley. Modified after Stephens and Hood 1973
pan there is less than 1 mm of elevation change over a 2-km measured distance. The north subbasin contains a 26 km$^2$ salt pan. Most of the north and central subbasin surfaces are covered by mud flats containing no vegetation. The south subbasin occupies about 90 km$^2$, is a mud flat in the center and is covered by sage bush in the south.

Based on core analysis, Rey et al. (2016) identified five pre-Lake Bonneville, Lake Bonneville, and post-Lake Bonneville stratigraphic units within 4 m of the ground surface (Fig. 7). Because the depth to the base of the Lake Bonneville sediments varies, 3.8 m is considered the approximate boundary between the Lake Bonneville and earlier lake sediments. The salt pan, which overlies unit 1 in the north subbasin, is only a few cm thick. The post-Lake Bonneville silty sediments (unit I) and the Lake Bonneville marls (units II–IV) are very sticky clays that only slowly transmit measurable water into new borings. Most groundwater in unit III is transmitted in a thin oolitic sand layer that quickly fills new borings with water. The pre-Lake Bonneville oolitic sand in unit V is locally well cemented, but friable elsewhere and freely transmits groundwater. Below the unit V oolitic sand the basin sediments are grey to blue colored marl that extends to 15 m or more bgs. Only one playa well is deeper than 15 m and the well log for this 30.5 m deep well is not available.

Structure contour maps of the tops of units II, III, and IV show that the elevation of the south subbasin Lake Bonneville sediments are a few meters higher than in the north subbasin, and that the sediments in the north subbasin tend to slope westward (Fig. 8). The tilting of the pre-Lake Bonneville and Lake Bonneville sediments, the topographic divide separating the central and south subbasins, and the western tilt of modern playa surface suggest that the tilting is due to extension fault movement along the Pilot Range frontal fault during and after Lake Bonneville time.

**Climate, precipitation and water budget**

**Climate and precipitation**

Pilot Valley is located in an arid environment with hot summers and cold winters. Long-term temperature and precipitation measurements are not available for the valley. However,
data from Wendover, Utah, located 10 miles to the south, are a reasonable surrogate for the low elevation regions of the valley. The Wendover maximum average monthly precipitation is only about 20 mm and precipitation peaks in the spring and fall. Average monthly temperature is near freezing in the winter and peaks to about 30 °C in the summer. Monthly spring, summer, and early fall pan evaporation rates are greater than 200 mm (Lines 1979).

Stephens and Hood (1973) estimated the total annual Pilot Valley basin precipitation as $227 \times 10^6$ m$^3$ and groundwater recharge as $4.19 \times 10^6$ m$^3$. Based on PRISM 30-year 800-m grid normalized data, the total annual Pilot Valley basin precipitation is about $159.67 \times 10^6$ m$^3$ with about equal amounts falling on the mountain bedrock, mountain front alluvial fans, and the playa (Fig. 9; Table 1). Precipitation rates are geographic and elevation dependent, and the distribution and fate of the precipitation in the mountain blocks are asymmetrical (Fig. 9a). Even though the bedrock portions of the Pilot and Silver Island Ranges are about the same size, the total annual precipitation and precipitation intensity in the Pilot Range are about 100 and 40% greater, respectively, than in the Silver Island Range. This difference is largely due to the higher elevation orographic advantage of the Pilot Range. The total precipitation falling on the Pilot Range alluvial fan is also about twice as great as the precipitation falling on the Silver Island alluvial fan due to the larger surface area of the Pilot Range fan.

Tipping bucket measurements of precipitation on Silver Island alluvial fans provide insight into the intensity of storm events (Fig. 10). Data from 160 storm events over a 5-year period for locations on the alluvial fan and bedrock show that most storms are short duration, low precipitation events. However, long duration and high intensity storms are not uncommon and monthly precipitation totals can exceed 3 cm in the spring. The upper elevations of the Pilot Range develop a winter snowpack and during the spring snowmelt Pilot Range surface flows occasionally reach the distal end of the alluvial fan. The lower elevation Silver Island range rarely develops a snow pack. Pilot Range surface flows readily infiltrate into the alluvial fan stream channels (personal observations of the authors; Stephens and Hood 1973) and are manifested as springs that cluster at the distal end of major alluvial fan stream channels.

What is particularly interesting about the fate of precipitation is the fact that, except for possibly unusual events, Pilot Range streams do not flood the playa surface, although surface flows and playa flooding are annual events associated with prolonged Silver Island storm events. Based on 25 plus years of observation and an examination of historical Google Earth images, it has never been observed that a Pilot Range stream reaches the playa surface, but surface flooding of the playa from the Silver Island Range has been observed tens of times. Silver Island Range flooding events spread out across and flood the playa surface in the vicinity of the salt pan to a depth of a few cm each year. Some flooding events do not reach the salt pan and during extremely wet seasons, such as 2019, flooding may extend to the 1,294-m elevation contour in the central subbasin (Fig. 6). Extensive sheet flows have been observed crossing the surface in the north subbasin. There is also playa surface evidence that playa flooding is sometimes associated with a single Silver Island Range channel due to locally isolated storm cells.

**Water budget**

A water budget has been developed for Pilot Valley (Table 1). Groundwater recharge was calculated using PRISM precipitation data and Maxey-Eakin (1949) recharge coefficients. Maxey-Eakin coefficients are widely used for the Great Basin assessments. Due to the steepness of the bedrock terrain it was assumed that most bedrock groundwater reports to the alluvial fans as shallow underflow. The total alluvial fan underflow was then adjusted for discharge to springs, water piped to nearby Wendover, Nevada, and groundwater used locally for irrigation. Although there is considerable accumulation of surface water on the playa due to direct precipitation ($55.8 \times 10^6$ m$^3$) and surface runoff from the Silver Island
Range (0.66 × 10^6 m³), this water is largely consumed by evaporation on the playa. Surface runoff was calculated by assuming that all runoff accumulates in the salt pan lake and the depth of the annual lake is about 0.025 m. Years of personal observation and the spatial distribution of the salt pan make the dimension of the salt pan a reasonable surrogate for the surface area of the annual lake. Inflow from Pilot Creek is considered negligible, as there has never been evidence of surface flows into the valley and the 30-m deep Pilot Creek alluvial well has been dry since it was first measured in 1991.

Except for about 35 × 10^3 m³ of water piped annually from five springs in the Pilot Range to Wendover, Utah (G. Wadsworth, City of Wendover (Utah), personal communication, 2018), the total annual 159.67 × 10^6 m³ of precipitation is consumed by evapotranspiration (Table 1). The 55.8 × 10^6 m³ of precipitation that falls on the playa constitutes about 93% of the total playa water budget. The remaining 7% is from alluvial fan underflow and surface flow from the Silver Island Range. The total alluvial fan underflow to the playa is only 3.31 × 10^6 m³. Infiltration of direct precipitation and surface runoff from the Silver Island Range to pre-Lake Bonneville sediments have not been estimated but are likely small. Uncertainties in the water budget are due to the fact that the quantity of alluvial fan groundwater underflow and surface flows from the Silver Island Range cannot be directly

Fig. 8 Structure contour maps of the top of (a) unit II, (b) unit III and (c) unit V. Measurement locations are shown with filled squares.
measured. Additionally, the amount of direct surface water infiltration on the playa surface is uncertain.

**Infiltration, dilution, and slug testing**

Infiltration rates in mountain front alluvium, mountain front-playa interfaces, and playa surfaces were measured at 45 locations in the Silver Island Range and 38 locations in the Pilot Range (Fig. 11). Locations include: (1) upper elevation (1,650–1,450 m) alluvial fan, pediment, and ephemeral stream channels, (2) mid elevation (1,450–1,350 m) alluvial fan, pediment, and ephemeral stream channels, (3) low elevation (1,350–1,295 m) alluvial fan/playa interfaces, and (4) near fan playa surfaces. Ephemeral stream channels are filled with very coarse-grained cobble-sandy sediments that become progressively finer-grained downstream. Some low elevation fan stream channel and pediment surfaces in the Silver Island Range...
Range are underlain by fine-grained Lake Bonneville deposits. Near the Silver Island Range the Lake Bonneville alluvial fan/playa interface deposits are covered by a layer of post Lake Bonneville wind-blown silt and sand, whereas Lake Bonneville sediments are exposed at the playa surface near the Pilot Range alluvial fan/playa interface.

Field saturated hydraulic conductivity was not calculated from the infiltrometer data as the tests were only undertaken to evaluate the relative differences in the potential for groundwater recharge. Total infiltration vs. time for the playa, alluvial fan and pediment, and stream channel locations are shown in Fig. 12. On the playa, the total measured infiltration was minimal (<8 mm) during the first 4–6 min and was generally followed by stabilized water levels (Fig. 12a). Silver Island Range desert pavement surfaces underlain by Lake Bonneville sediments had similar infiltration characteristics as the Silver Island Range playa sediments with an initial infiltration surge (up to 12 mm/min) followed by a stabilized rate of 0 mm/min.

Pilot Range fan-pediment surfaces typically have greater total infiltration capacity than Silver Island Range surfaces (Fig. 12b). The median, minimum, and maximum total infiltration for the Pilot Range fan-pediment surfaces are 62.5, 21 and 96 mm, respectively during the 15-min tests. The median, minimum, and maximum total infiltration for the Silver Island Range fan-pediment surfaces are 26, 8 and 80 mm, respectively. When the infiltration of Silver Island stream channels is compared to Pilot Range stream channels, a pattern opposite to that in the fan-pediment surfaces emerges, in that the Silver Island Range channels have appreciably greater infiltration

### Table 1: Pilot Valley water budget. Totals are italicized

| Parameter                                      | Precipitation/runoff $10^6$ m³ | Recharge $10^6$ m³ |
|------------------------------------------------|-------------------------------|-------------------|
| Precipitation                                  |                               |                   |
| Pilot Range bedrock                            | 28.39                         | –                 |
| Pilot Range alluvial fan                       | 29.97                         | –                 |
| Silver Island Range bedrock                    | 13.69                         | –                 |
| Silver Island Range alluvial fan               | 15.71                         | –                 |
| Leppy Hills bedrock                            | 4.86                          | –                 |
| Leppy Hills alluvial fan                       | 11.47                         | –                 |
| Playa                                          | 55.58                         | –                 |
| Salt pan (4.16 × 10⁶ m³)                       |                               |                   |
| North and central playa including salt pan (42.08 × 10⁶ m³) |                  |                   |
| South playa (13.50 × 10⁶ m³)                    |                               |                   |
| Total annual precipitation                      | 159.67                        | –                 |
| Surface runoff to Playa                        |                               |                   |
| Silver Island Range surface runoff to playa    | 0.663                         | –                 |
| Groundwater recharge                            |                               |                   |
| Pilot Range                                    | –                             | –                 |
| Pilot Range bedrockb                           | –                             | 4.032             |
| Pilot Range alluvial fan                       | –                             | 0.755             |
| Pilot Range spring discharge                   | –                             | -1.742            |
| Pilot Range export to Wendover                  | –                             | -0.350            |
| Pilot Range irrigationc                        | –                             | -0.247            |
| Total Pilot Range fan underflow to the playa   | –                             | 2.448             |
| Silver Island Range                            | –                             | –                 |
| Silver Island Range bedrock                    | –                             | 0.421             |
| Silver Island Range alluvial fan               | –                             | 0.396             |
| Total Silver Island Range underflow to playa   | –                             | 0.817             |
| Leppy Hills                                    | –                             | –                 |
| Leppy Hills bedrock and alluvial fan underflow to the playa | – | 0.049 |
| Playa infiltration of direct precipitation and runoff | – | ? |

*Based on annual salt pan flooding at 0.0.254 m depth

b Calculated value likely high due to bedrock outcrops and steep slopes

c Stephens and Hood (1973)
The median, minimum, and maximum total infiltration for the Pilot Range stream channels are 65, 25 and 146 mm, respectively. The median, minimum, and maximum total infiltration for the Silver Island Range stream channels are 102, 105 and 125 mm, respectively.

The infiltration data have been plotted as box plots to better understand the importance of fan location relative to infiltration (Fig. 13). There are no statistically significant differences in the lower-elevation fan-pediment and mid-elevation streams between the Pilot Range and Silver Island Ranges at the 95% confidence level. The upper fan stream infiltration capacities are statistically different.

Pilot and Silver Island Range alluvial fan/playa interface hydraulic conductivities were evaluated by slug and dilution test methods (Fig. 14). Based on 12 slug tests conducted on the west side of the valley, the hydraulic conductivity ($K$) of the oolitic sand ranged from $2.83 \times 10^{-2}$ to $1.80 \times 10^{-2}$ m day$^{-1}$ and averaged $4.92 \times 10^{-1}$ m day$^{-1}$. The median $K$ is $6.14 \times 10^{-1}$ m day$^{-1}$. Calculated storage ($S$) ranged from $1.75 \times 10^{-2}$ to $10 \times 10^{-10}$ and averaged $1.91 \times 10^{-3}$, which is consistent with leaky confined conditions. Single-well dilution tests were conducted on 18 Silver Island alluvial fan/playa interface wells. Calculated hydraulic conductivities vary greatly between 0.4–98.9 m day$^{-1}$. The average values for the piston flow and two exponential models were 5.4, 14.7 and 20.19 m day$^{-1}$, which are in the range of the slug test results for the Pilot Range alluvial fan/playa slug tests. The average $K$ value for five Pilot Range alluvial fan/playa interface slug tests ranged from 0.37 to 5.88 m day$^{-1}$ and averaged 3.64 m day$^{-1}$. 

Fig. 10 Total monthly precipitations in Silver Island alluvial fan catchments. Precipitation was measured using recording tipping bucket and cumulative precipitation collectors. Catchment areas are shown in the subsequent figure.
Hydrogeology

Springs

Springs only occur in the Pilot Range bedrock and at the distal end of the Pilot Range alluvial fan. Eleven bedrock springs have been identified in the Pilot Range (Peterson 1993). More than 50 springs and seepage areas discharge at the distal end of the Pilot Range fan surfaces (Fig. 15). The north subbasin springs discharge above the alluvial fan/playa interface, the central subbasin springs discharge near the interface, and the south subbasin springs discharge from playa sediments below the interface. The larger springs are concentrated at the distal end of the major Pilot Range drainages. Regardless of the alluvial fan lithology (i.e., coarse aluminosilicate and carbonate gravel, fine-grained silt, and Lake Bonneville sediments) all Pilot Range alluvial fan springs discharge at the Gilbert shoreline (1,305 m amsl; Fig. 16).

Several of the springs have measurable discharge rates; however, most of the springs are seepage areas that are covered by meadow grass, dense salt grass, reed and other hydrophytes. Measured discharge rates are relatively constant over time and range from about <1 to ~30 L s$^{-1}$. The 31 measured seepage areas range in size from 2.23 to 280 × 10$^5$ m$^2$ with a median size of 8,125 m$^2$. Based on an average annual evapotranspiration rate of 1.1 m (USGS 2018) the calculated total annual discharge at the spring/seep areas is 9.31 × 10$^5$ m$^3$.

Fig. 12 Scatter plots of infiltration vs. time. Pilot Range data are open circles and Silver Island Range data are filled circles. a Playa (near fan), b Alluvial fan–alluvial pediment, c Stream channel
**Basin water levels**

Most of the groundwater in Lake Bonneville sediments is confined. Unconfined conditions are largely restricted to the southern subbasin and a few basin margin areas. In the pre-Lake Bonneville sediments, water pressure surfaces range from about 1.5 m above the top of the well screens near the base of central Silver Island Range alluvial fan to 4+ m above the top of the well screens in the western side of the basin. Average density corrected water levels in Lake Bonneville and pre-Lake Bonneville sediments indicate groundwater flow is from the basin margins toward the northern subbasin (Fig. 17). In order to more readily visualize the data, the water levels are contoured relative to an arbitrary 100 m datum. The 100 m datum is 1,293 m amsl. In the southern subbasin, groundwater flows from the north, west, and south alluvial fans toward the southern depression and then spills into the central portion of the valley. In the central and northern subbasins, groundwater flows westward from the Silver Island Range toward the Pilot Range alluvial fan and then northward to the salt pan area. Water levels that were measured during low- and high-flow season mass-measurement campaigns show that, regardless of the season and well depth, all of the contoured water levels have the same general pattern indicating time consistent groundwater flow directions.
Two years of pressure transducer data collected from nested well pairs at the north subbasin surface-water outlet between Lemay and Crater islands and in the center of the salt pan verify that Pilot Valley is a closed groundwater basin. Water levels in both pre-Lake Bonneville and Lake Bonneville sediments at the outlet ranged from ~1 to 2 m above the water level in Lake Bonneville sediments in the topographic low of the valley. Water levels in both outlet wells have considerable seasonal variability with low levels during the summer and fall months. Water level changes in the salt pan well were more seasonally subtle.

Westerly groundwater flow from the Silver Island Range alluvial fan is readily apparent in time-series water level profiles (Fig. 18). In the figures the 0 m distance is set at a location known locally as Truck Spring (Fig. 15) and water levels are
relative to the 100 m datum. The data also suggest a north-south trending trough in the water levels west of the Pilot Range alluvial fan/playa interface and a ridge near the interface (Figs. 18 and 19). The data in the time series profiles were collected monthly for one year and have been organized into the Lake Bonneville (Fig. 18a) and pre-Lake Bonneville (Fig. 18b) sediment intervals. The north profile extends eastward from the base of the Pilot Range alluvial fan to about 7,000 m onto the playa (Fig. 18c). The south profile extends from the alluvial fan, across the playa, and ends at the base of the Silver Island Range alluvial fan (Figs. 18a, b). Maximum water level changes during the 12-month period in individual wells in the south profile range from 0.23 to 1.06 m and average 0.72 m for the 62 wells. Maximum water level changes in individual wells in the north profile range from 0.09 to 0.98 m and average 0.50 m for the 16 wells.

The water level profiles confirm that, regardless of season, in the central and north subbasins, groundwater flows westward from the Silver Island Range to the Pilot Range alluvial fan/playa interface. The profiles also show that the pressure surfaces in many of the wells are sometimes above the ground surface. Above land-surface pressure levels in the shallow and intermediate depth wells correspond with spring time groundwater recharge and extend into the late summer. In the deeper wells, pressure levels above land surface commonly occur throughout the year. At about 3,000–4,000 m from Truck Spring there is an upward bulge in the time series water level contours. This bulge may represent alluvial fan underflow via an oolitic sand layer that thins further westward. Time series data also show groundwater underflow from the Pilot Range alluvial fan.

In order to visualize the Pilot Range alluvial fan/playa groundwater transition zone the average water levels for each well in the time series data have been plotted relative to the ground surface (Fig. 19). In Fig. 19, pre-Lake Bonneville sediments have been assigned to either the intermediate zone (4–6 m bgs) or a deep zone (9–12 m bgs). Elsewhere there are not sufficient data to subdivide wells in the pre-Lake Bonneville sediments. At the transition zone the collision between the easterly flowing steep gradient groundwaters in the alluvial fan and the gentler gradient westerly flowing groundwaters in the playa results in elevated water levels in each of the horizons, and there is not a smooth or regular transition between groundwater flowing eastward in the Pilot Range alluvial fan and the westward flowing groundwater in the basin sediments. The bump in interface water levels is as great as 1 m in the deeper wells and is progressively less in the shallower wells. Most transition zone wells completed in Lake Bonneville sediments and all of the wells completed in the pre-Lake Bonneville sediments are screened in confined layers. About one third of the Lake Bonneville sediment wells are unconfined and the confined wells typically have less than 2 m of confining pressure. The confining pressure in the upper portion of the pre-Lake Bonneville sediments ranges from 2 to ~5 m, and the confining pressure in the deeper pre-Lake Bonneville sediments ranges from about 8 to 13 m.
Analysis and discussion

Overall, the hydrogeology of the Pilot Valley is typical of endorheic basins in arid, block-faulted regions. Surface water and groundwater recharge from the surrounding mountains and precipitation on the valley floor flows toward the topographic low. In the topographic low, a salt pan develops when the valley floor dries out. Elsewhere the valley bottom contains calcareous mud that is locally covered with thin aeolian deposits. Although the hydrogeology of Pilot Valley has many characteristics typical of block-faulted closed basins, analysis of the 25+ years of data provides insight into surface and groundwater flow not readily apparent from short-term and limited scope investigations.

Basin margin groundwater recharge and flow

Several factors indicate that most alluvial fan groundwater recharge occurs in the stream channels: (1) the Pilot Range springs cluster at the distal ends of major drainage systems (Fig. 15), (2) there are rapid precipitation-related water-level responses in wells located at the distal end of Silver Island Range alluvial fans (Carling, 2012), (3) about 50% of the total annual precipitation in both the Pilot and Silver Island Range falls on the bedrock where runoff rapidly accumulates in stream channels and reports to and infiltrates into the alluvial fans, (4) episodic precipitation events flood the playa via ephemeral stream channels, and (5) infiltration rates in the alluvial fan stream channel sediments are appreciably greater than on the mountain front pediment surfaces (Fig. 13).

The behavior of shallow alluvial fan groundwater associated with the Pilot and the Silver Island ranges is asymmetrical in that Pilot Range groundwater both discharges from springs at the alluvial fan/playa interface and underflows to the basin, whereas all Silver Island Range groundwater underflows to basin sediments. The primary difference between the groundwater systems is the gradient of the alluvial fans. The Pilot Range fan typically has a gradient of ~0.065 near the fan/playa interface, whereas the Silver Island Range interface is considerably less steep at ~0.023. This difference means that some shallow groundwater in the Pilot Range fan intercepts the ground surface and that shallow groundwater in the Silver Island Range fan only underflows to the basin sediments. The Pilot Range interception occurs at the Gilbert shoreline break in slope, where the gradient flattens appreciably and the fan groundwater surface and ground surface intersect (Fig. 16). The absence of the Gilbert shoreline break-in-slope at the Silver Island fan/playa interface means that the shallow groundwater in the fan sediments continues to flow unobstructed into the playa/lake bed sediments. Springs do not discharge at the Leppy Hills fan/playa interface for a similar reason. The Leppy Hills fan has a gradient of only ~0.019.
The steeper gradient of the Pilot Range alluvial fan is attributed to the active mountain front fault which has tilted the basin gently westward.

Groundwater flow in the basin

Horizontal groundwater flow

The flux of alluvial fan groundwater underflow to basin sediments from the Pilot Range is about three times as great as the underflow from the Silver Island Range (Table 1). One would expect to see such a disparity in recharge to be reflected in the groundwater level contours with a water surface sloping from both the Pilot Range and Silver Island alluvial fans toward the center of the basin. Instead the water surface contour map (Fig. 17) and water level profiles (Fig. 18) depict complex groundwater flow directions that are controlled by the structure of the lake bed deposits that have been tilted westward by tectonic activity and perhaps hydrostatic rebound of the Silver

Fig. 18 Twelve-month, density corrected water level profiles across a–b south and c north profiles. Truck Spring is located near the base of the Pilot Range alluvial fan. See Fig. 6 for profile locations and Fig. 15 for the location of Truck Spring. Dates are given as mm/dd/yy

Fig. 19 Average water levels in wells near the Pilot Range alluvial fan/playa interface in the central subbasin
Island Range associated with Lake Bonneville water level declines. The shallow lake bed sedimentary layers slope from south to north and from east to west in the central subbasin (Fig. 8). The westerly movement of south and central subbasin groundwater (Fig. 18) is attributed to this western tilt of the basin as the groundwater flow follows the structure contours. In the south subbasin the water level contour map indicates groundwater flow in both pre-Lake Bonneville and Lake Bonneville sediments is from the south subbasin structural depression and then the water spills to the central subbasin (Fig. 18). In the central subbasin, groundwater flow is from the Silver Island alluvial fan to the topographic low along the western edge of the central playa and to the north playa. Easterly groundwater flow from Pilot Range alluvial fan into playa sediments is restricted to the westerly margins of the basin.

What is striking about the water level contour map is the fact that the gradients are extremely small. In the north subbasin there is less than 1 m of vertical elevation change across a distance of 13 km and in the central subbasin there is less than 2 m of vertical change across 9 km. Horizontal groundwater flow in basin sediments is largely restricted to: (1) the thin sandy layer in unit III-b observed in the core samples and during well construction, and (2) the more massive oolitic sand in unit VI (Fig. 7). Attempts to evaluate the hydraulic conductivity of the clay layers by slug testing were unsuccessful as the water level recovery rates were so slow. Many Lake Bonneville sediments monitoring wells took several hours to days for water levels to recovery after water quality sampling. During water quality sampling, wells competed in the oolitic sand recovered very quickly and there was no observable drawdown in some wells. The relatively high hydraulic conductivity of the oolitic sand is confirmed by the slug testing where the median $K$ is $6.14 \times 10^{-1} \text{ m day}^{-1}$ which is consistent with silty sand.

**Vertical groundwater flow**

Water levels in nested well pairs (Table 2) and the time-series water level contour map (Figs. 18 and 19) show upward vertical gradient from the pre-Lake Bonneville sediments to the Lake Bonneville sediment. The upward gradients are consistent with groundwater loss from evapotranspiration in the Bonneville sediments. The upward gradients mean that pre-Lake Bonneville sediment groundwater discharges to Bonneville sediments where it can be evaporated. Except for a single well pair in the central subbasin all of the calculated vertical gradients are upward. Excluding playa wells located at the fan/playa interface along the south profile, the long-term average upward gradients in the north and central subbasin are 0.0135 and 0.0139, respectively. In many instances, up to 15 years of water level measurement are included in the calculations. The average upward gradients at the Pilot Range alluvial fan/playa interface are 0.01 and ~0.067 for the fan and basin sediments, respectively. The difference in these average vertical gradients is consistent with mostly horizontal groundwater flow in the alluvial fan and upward flow in the low hydraulic conductivity basin muds at the transition zone.

Two Pilot Range transition-zone alluvial-fan/playa well pairs are particularly interesting. The deep wells in each well pair reports water pressures that are completed in sediments well below the oolitic sand in Horizon V. The average water level in the 13.32-m deep well (96–36) is 0.6 m above ground surface (ags) and the 30.5-m deep well (96–38) has an average water level of 2.43 m ags. Water levels in the two deeper wells are greater than the central and north playa surface elevations and the water levels indicate that groundwater systems in the pre-Lake Bonneville sediments are vertically stratified with increasing confining pressures with depth.

**Basin groundwater flux and playa recharge**

The extremely small low-flow season horizontal gradients of $10^{-5}$ to $10^{-2}$ in the Lake Bonneville sediments (October 2007) in much of the central and north subbasins and the abundance of clay in the sediments are consistent with a small groundwater flux. The high-flow season pre-Lake Bonneville sediment water levels (May 2014) have a gradient of about $10^{-4}$ suggesting a pressure response to alluvial fan groundwater recharge. High-flow season groundwater recharge is consistent with the spike in spring time precipitation rates, the timing of observed playa flooding, and the temporal water level changes shown in the southern profile (Fig. 18a,b). A small recharge flux is consistent with the calculated Silver Island underflow of only about $4 \times 10^{-5} \text{ m}^3 \text{ year}^{-1}$.

The idea of shallow-basin groundwater recharge from alluvial fan underflow is well established. What is less well understood is the role of playa surface recharge from direct precipitation and playa flooding. Several factors indicate that playa precipitation and infiltrated ponded surface runoff in the salt pan lake do not significantly contribute to recharge in pre-Lake Bonneville sediments: (1) there are upward gradients from the pre-Lake Bonneville sediments to the Lake Bonneville sediments, (2) the east–west time sequence water level profiles across the south profile (Fig. 18) indicate that the hydraulic heads of groundwater in pre-Lake Bonneville sediments are above the hydraulic heads in the Lake Bonneville sediments, (3) calculated vertical gradients for nested well pairs located on the playa and salt pan are upward, (4) the Lake Bonneville sediments consist of several meters of clay with very low hydraulic conductivity, (5) infiltration rates of playa sediments are small and total infiltration tends to stabilize quickly in response to applied water (Fig. 12), and (6) pre-Lake Bonneville sediment groundwater resides at least 3.8 m bgs. Additionally, much of the central and north subbasin area groundwaters in Lake Bonneville sediments and some pre-
Lake Bonneville sediments have stable isotopic compositions consistent with evaporative water (A.L. Mayo, Brigham Young University, unpublished data, 2020). Lake Bonneville sediment groundwaters transition from non-evaporative to evaporative in the north, west, and south. All the wells containing evaporated water have water levels that are <0.5 m from ground surface, which means the evaporation signatures may be the result of groundwater evaporation and/or infiltration of evaporated surface water. Infiltration cannot be the major factor in much of the central subbasin because the area of evaporated groundwater extends well beyond the salt pan where surface water accumulates annually.

Assuming the total shallow basin sediment groundwater recharge is from alluvial fan underflow the average annual recharge is only 1.8% of the total basin precipitation. When the playa surface precipitation is not considered the total annual recharge is 3.1% of the bedrock and alluvial fan precipitation.

### Alluvial fan/playa inverted salinity gradient

Water levels and salinity in the south time-series profile are particularly interesting in that there is an unusual transition in the vertical hydraulic head gradients and an inverted salinity gradient at the Pilot Range alluvial fan/playa interface. At the transition zone, about 900–1,050 m east of Truck Spring, the vertical gradient changes from upward (~0.01) to strongly upward (~0.07) (Fig. 19; Table 2). Deep groundwater upwelling at the transition zone likely extends for a considerable distance to the north and south as there is perennial surface moisture at the alluvial fan/playa interface. Due to frequent drying events and the shallowness of the monitoring wells it is not possible to confirm that a similar condition extends to the north profile.

At the alluvial fan/playa transition zone, saline groundwater overrides the less saline groundwater (Fig. 20). The inverted salinity gradient is contrary to what is expected by the density driven Ghyben-Herzberg relationship where the freshwater zone overlies the saline water zone. The groundwater pressure ridge associated with the deep (i.e., 9–12 m) monitoring wells (Fig. 19) and the inverted freshwater/brine transition zone (Fig. 20) have long been an enigmatic feature of the Pilot Valley groundwater system. It is clear that the interaction of relatively freshwater with the high-density brine (total dissolved solids (TDS) as great as 150,000 mg/L) is responsible for the pressure ridge and the inverted salinity gradient. At the transition zone the up-gradient freshwater pressure head is not adequate to cause the observed pressure ridge and the overlying confining layers would not permit rapid vertical groundwater movement. Well log data indicating continuous overlying clay layers in the basin sediments are confirmed by the high-resolution seismic reflection profile at the transition zone (South et al. 2016). It is likely that the east flowing freshwater in the deeper coarse alluvial fan sediments and oolitic sand has sufficient hydraulic head, velocity, and flux, due to the gradient and hydraulic properties of the coarse materials, to keep the west flowing brine at bay while the velocity and flux of the freshwater in the overlying clays are not sufficient to prevent the west movement of shallow brine at the transition zone. This condition would result in the inverted salinity gradients. However, such a pressure-density competition does not account for the freshwater pressure ridge at the transition zone.

### Table 2  Calculated density corrected vertical gradients for nested well pairs. Averages are italicized

| Well pair | Easting | Northing | Well depth (m) | Horizona | Gradientb |
|-----------|---------|----------|----------------|-----------|-----------|
| North playa (salt pan) | | | | | |
| 91–1 | 254084 | 4543188 | 3.06 | B | 0.0160 |
| 91–2 | 5.21 | PB | | | |
| 91–2 | 254084 | 4543188 | 5.21 | PB | 0.0041 |
| 91–3 | 11.31 | PB | | | |
| 91–17 | 254124 | 4552598 | 1.25 | B | 0.0096 |
| 91–19 | 3.30 | B | | | |
| 91–19 | 254124 | 4552598 | 3.30 | B | 0.0244 |
| 91–18 | 4.85 | PB | | | |
| Average | | | | | 0.0135 |
| Central playa | | | | | |
| 96–40 | 251492 | 4543902 | 2.27 | B | 0.0003 |
| 96–41 | 6.10 | PB | | | |
| 96–42 | 251791 | 4543807 | 2.27 | B | 0.0196 |
| 96–43 | 5.58 | PB | | | |
| 96–44 | 252600 | 4543603 | 2.85 | B | 0.0160 |
| 96–45 | 5.57 | PB | | | |
| 96–47 | 253386 | 4543383 | 2.67 | B | 0.0518 |
| 96–46 | 5.58 | PB | | | |
| Average | | | | | 0.0139 |
| Playa side south transition zone | | | | | |
| 96–34 | 251130 | 4544035 | 1.37 | B | 0.0900 |
| 96–35 | 4.46 | PB | | | |
| 96–36 | 251132 | 4544034 | 13.32 | D | 0.0650 |
| 96–36 | 251132 | 4544034 | 13.32 | D | 0.0415 |
| 96–38 | 251179 | 4544108 | 30.5 | D | 0.0708 |
| 96–38 | 251130 | 4544035 | 1.37 | B | 0.0668 |
| Average | | | | | |
| Fan side south transition zone | | | | | |
| 96–21 | 251038 | 4544121 | 3.1 | B | 0.005 |
| 96–22 | 11.91 | D | | | |
| 96–26 | 251050 | 4544101 | 1.96 | B | 0.015 |
| 96–24 | 11.94 | D | | | |
| Average | | | | | 0.0100 |

*a* Lake Bonneville sediments, *PB* pre-Lake Bonneville sediments, *D* deep  

*b* Positive = upward gradient, negative = downward gradient
To test the pressure-salinity idea as the cause of the inverted salinity condition, SUTRA (Voss 1984) was used to model the freshwater/brine interface. SUTRA was selected because it is a fluid-density-dependent finite-element model for groundwater flow that may be employed for cross-sectional modeling. Model construction was based on the Lake Bonneville and pre-Lake Bonneville sediment stratigraphy (Fig. 7) and well drilling logs in the vicinity of the transition zone. The model domain (Fig. 21) is rectangular with the dimensions $x = 400$ m (120 elements) and $y = 15$ m (15 elements). In the final model, anisotropy is two orders of magnitude, where horizontal ($K_H$) and vertical ($K_V$) hydraulic conductivities are $5 \times 10^{-17}$ and $5 \times 10^{-19}$ m$^2$ s$^{-1}$, respectively. The upper boundary is negative to be consistent with the perennial wet surface condition and to account for water loss by evaporation. A positive flux from the alluvial fan (left) is $Q = -4 \times 10^{-3}$ kg s$^{-1}$ based on the calculated gradient and the hydraulic conductivity determined from slug testing. The boundary playa boundary (right) is a specified pressure head based on fluid density and depth of the water column. Diffusivity is based on literature average Na$^+$ and Cl$^-$ diffusivity values of $168 \times 10^{-9}$ m$^2$ s$^{-1}$. SUTRA was used to successfully model the inverted salinity gradient with and without the need for thinning sand layers in the alluvial fan sediments (Fig. 21).

A plausible explanation for the freshwater pressure ridge is an osmotic effect between the deeper coarser grained layers and the overlying clay layers. Formation of an osmotic pressure ridge requires two key elements, both of which exist at the transition zone. One is that there are semi-permeable membrane conditions and the other is that there are sufficient concentration gradients to induce osmotic pressure. Oolitic sand overlain by clays with thin laminations supports the idea of vertical anisotropy and a semi-permeable membrane, and there are steep concentration gradients over very short distances. The concept of osmotic-induced pressure across a semi-permeable membrane is well established (Fig. 22a) and the likely transition-zone osmotic pressure ridge is illustrated in Fig. 22b.

Osmotic pressure, $P$ (Pa), can be calculated from a modified form of the ideal gas law (Purdue 2007):

$$PV = nRT$$

where $V$ is volume (m$^3$), $n$ is the molar concentration of dissolved species (mol), $R$ is the ideal gas constant (m$^3$·Pa/K·mol), and $T$ is the temperature (K). This may be modified to:

$$\Pi_{(m)} = M \times R \times T \times a$$

where $\Pi_{(m)}$ is the osmotic pressure in meters, and is substituted for $PV$. $M$ is molarity (mol/L), $T = 291.48$ K (18.48 °C), and the factor $a = 10.33$ (m/atm) is used to convert the pressure from atmospheres to meters of water. TDS concentration (mg/L) was converted to $M$ by assuming TDS is Na + Cl and the concentration of all other ions are negligible:

$$M = \frac{TDS}{58,440}$$

The factor 58,440 (mg/mol) is the molecular weight of NaCl. Substituting Eq. (3) in Eq. (1) yields:

$$\Pi_{(m)} = 0.00423 \times TDS$$

An alternative simplified method for calculating osmotic pressures in English units is based on the TDS relative to seawater (Reynolds and Richards 1996):

$$\Pi_{(f)} = TDS \times 0.02608 + 3.34$$

where $\Pi_{(f)}$ is the pressure in feet.

Osmotic pressure calculations using both Eqs. (4) and (5) demonstrate that there is more than sufficient osmotic pressure to explain the observed pressure ridge (Table 3). In Table 3, osmotic pressures are calculated based on the deeper freshwater well and the shallow saline-water well. The average calculated osmotic pressure is 391.7 m which is considerably greater than the average 1.5 m observed. Layered clays are nonideal membranes (Malusis and Shackelford 2001) and the sediments at the transition zone contain lenses of clay and coarser grained sediment which further reduce the membrane effect. At the transition zone the real-world osmotic pressure would only have to be about 0.4% effective to create the observed pressure ridge. The large difference between the calculated and measured hydraulic head differences is likely due to the combination of nonideal membrane condition and a small upward flux from deeper horizons.

**Conclusions**

The 828-km$^2$ endorheic Pilot Valley consists of 147 km$^2$ of bounding mountains, 302 km$^2$ of mountain front alluvial fans, and a 379-km$^2$ playa surface covering the basin sediments. A thin 26-km$^2$ salt pan has formed on the northern most playa surface, and most of the playa surface is devoid of vegetation. The bounding mountains include aluminosilicate and carbonate bedrock in the Pilot Range to the west, carbonate bedrock in the Silver Island Range to the east, and the volcanic rocks in the Leppy Hills to the south. Mountain-front alluvial fans extend 3–5 km from the mountain blocks. The basin is filled with 1.6 km of alluvial fan and lacustrine sediments. The upper most 3.8 m of the basin sediments consists of low hydraulic conductivity Pleistocene age Lake Bonneville calcareous mud with a few thin oolitic sand units. A thicker oolitic sand and pre-Lake Bonneville calcareous mud underlies the Lake Bonneville sediment.
Block fault tilting has resulted in an asymmetry in the slope of the alluvial fans, the playa surface, and the shallow basin sediments, and has had a profound effect on the shallow groundwater flow regime. Alluvial fan gradients are 0.085 on the west and 0.051 on the east side of the playa, respectively. In the south subbasin the surface drainage it toward the center of the subbasin, whereas in the central and north subbasins the topographic lows are near the Pilot Range alluvial fan/playa interface. The playa surface and underlying Lake Bonneville sediments slope gently westward and northward with gradients of only $10^{-4}$ to $10^{-5}$.

Only 1.8% of total Pilot Valley precipitation recharges the shallow basin sediments and this recharge is via alluvial fan underflow. Although about one-third of the total Pilot Valley precipitation falls on the playa, playa precipitation and annual surface flooding do not significantly contribute to groundwater recharge. When the playa precipitation is excluded, only 3.1% of the bedrock and alluvial fan precipitation recharges the shallow basin sediments via alluvial fan underflow. An additional 1.5% of mountain block and alluvial fan precipitation is lost to evapotranspiration at alluvial fan springs and groundwater exportation.

Almost all mountain-block groundwater recharge underflows to the alluvial fans. Infiltrometer data indicate that direct alluvial fan groundwater recharge is largely restricted to ephemeral stream channels. Annual playa flooding does not originate from the larger and higher Pilot Range due to the

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**Fig. 20** West–east TDS contour profile at the Pilot Range alluvial fan/playa interface showing inverted density profile with elevated TDS water overriding lower TDS water. a TDS contour profile between 350 and 1,400 m from Truck Spring, b enlarged view of inverted density profile in the critical area. Well screen locations are shown as filled circles.

**Fig. 21** Results of SUTRA freshwater/brine interface models. Low TDS contours are blue and high TDS is red. a Model with anisotropy only, b Model with anisotropy and two sand layers in the alluvial fan.
Table 3  Calculated osmotic pressures ($\Pi$) between well pairs at the Pilot Valley freshwater/saline-water interface

| Layer  | Well 1 | Well 2 | Well 1 TDS (mg/L) | Well 2 TDS (mg/L) | $\Pi_{(o)}$ Perdue, 2007 | $\Pi_{(o)}$ Reynolds, 1996 | Vertical distance (m) | Horizontal distance (m) |
|--------|--------|--------|-------------------|-------------------|--------------------------|--------------------------|------------------------|------------------------|
| Shallow| 96-6   | 96-9   | 4,500             | 48,750            | 374.3                    | 352.8                    | 6.5                    | 14.4                   |
|        | 96-10  |        | 145,760           | 1,194.8           | 123.9                    | 1123.9                   | 4.5                    | 28.7                   |
|        | 96-11  |        | 63,400            | 498.2             | 469.2                    | 469.2                    | 7.4                    | 32.6                   |
|        | 96-12  |        | 12,250            | 65.6              | 62.6                     | 62.6                     | 2.3                    | 44.0                   |
|        | 96-17  | 96-18  | 8,500             | 60,500            | 439.8                    | 414.4                    | 1.2                    | 1.3                    |
|        | 96-19  |        | 70,900            | 527.8             | 497                      | 497                      | 0.1                    | 1.7                    |
|        | 96-22  | 96-25  | 1,400             | 28,667            | 230.6                    | 217.8                    | 2.7                    | 9.2                    |
|        | 96-24  |        | 14,233            | 108.5             | 103                      | 103                      | 1.4                    | 15.2                   |
|        | 96-26  | 97-3   | 2,400             | 49,200            | 396.7                    | 373.8                    | 1.0                    | 5.8                    |
| Deep   | 96-13  | 96-14  | 5,750             | 12,700            | 58.8                     | 56.3                     | 25.8                   | 11.7                   |
|        | 96-15  |        | 25,300            | 165.4             | 156.4                    | 156.4                    | 28.3                   | 11.9                   |
|        | 96-16  |        | 23,920            | 153.7             | 145.5                    | 145.5                    | 1.4                    | 15.2                   |
|        | 96-20  |        | 68,000            | 526.5             | 495.9                    | 495.9                    | 28.5                   | 17.8                   |
|        | 97-4   |        | 35,467            | 251.4             | 237.2                    | 237.2                    | 17.8                   | 44.3                   |
|        | 96-27  |        | 130,800           | 1,057.7           | 995.1                    | 995.1                    | 25.7                   | 77.7                   |
western tilt of the basin. Instead all annual flooding events originate in the Silver Island Range. Ephemeral Pilot Range stream flows are lost to alluvial fan infiltration or infiltration into Lake Bonneville shoreline sands near the alluvial fan/playa interface. The asymmetry of alluvial fan gradients results in more than 50 springs and seeps at the distal end of the steeper Pilot Range alluvial fan. These springs and seeps discharge at the Lake Bonneville Gilbert shoreline break in slope near the alluvial fan/playa interface. The westward basin tilt also restricts the movement of Pilot Range alluvial fan underflow to the extreme western side of the basin. There are no Silver Island alluvial fan springs and only Silver Island Range alluvial fan groundwater recharges the basin sediments.

Basin groundwater flow mostly occurs in Lake Bonneville sediments within 3.8 m of land surface, although the deep upward gradients at the Pilot Range alluvial fan/playa interface suggest some deeper groundwater flow. Horizontal groundwater gradients are only $10^{-4}$ to $10^{-5}$. Long-term manual and pressure transducer density corrected water level measurements demonstrate upward gradients from pre-Lake Bonneville sediments to Lake Bonneville sediments and upward gradients in Lake Bonneville sediments. The entire $3.4 \times 10^6$ m$^3$ of basin groundwater recharge is lost to evaporation in the northern portion of the basin where the groundwater surface is <0.5 m bgs.

Along the Pilot Range alluvial fan/playa interface in the central portion of the basin there is an inverted salinity gradient that is contrary to what is expected by the density driven Ghyben-Herzberg relationship. Here saline water overlies freshwater. In addition to the inverted salinity gradient there is a freshwater pressure ridge beneath the brine at the fresh/brine interface. The groundwater pressure ridge associated with the deep (i.e., 9–12 m) monitoring wells and the inverted freshwater/brine transition zone have long been an enigmatic feature of the Pilot Valley groundwater system. The east flowing freshwater from the Pilot Range alluvial fan in the deeper coarse alluvial fan sediments and oolitic sand has sufficient hydraulic head, velocity, and flux, due to the gradient and hydraulic properties of the coarse materials, to keep the west-flowing basin brine at bay, while the velocity and flux of the freshwater in the overlying clays are not sufficient to prevent the west movement of shallow brine at the transition zone. The pressure-salinity idea as the cause of the inverted salinity condition was modeled using the computer code SUTRA.

A plausible explanation for the freshwater pressure ridge is the osmotic effect between the deeper coarser grained layers and the overlying clay layers. Formation of an osmotic-induced pressure ridge requires two key elements, both of which exist at the transition zone. One is that there are semi-permeable membrane conditions and the other is that there are sufficient concentration gradients to induce osmotic pressure. Oolitic sand overlain by clays with thin laminations supports the idea of vertical anisotropy and a semi-permeable membrane, and there are steep concentration gradients over very short distances. Osmotic pressure calculations demonstrate that there is more than sufficient osmotic pressure to explain the observed pressure ridge.

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