GROUNDWATER QUALITY CLASSIFICATION FOR DISCHARGE ZONE OF THE SHALLOW, UNCONFINED BASIN-FILL AQUIFER, EAST SHORE AREA, DAVIS COUNTY, UTAH

Prepared for FRIENDS of Great Salt Lake

by

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&

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INTRODUCTION

This is a formal petition to the Utah Water Quality Board (Board) submitted by Dr. Greg Carling (Brigham Young University) and Janae Wallace (Utah Geological Survey) on behalf of FRIENDS of Great Salt Lake to classify groundwater quality in the discharge zone of the shallow, unconfined aquifer in the east shore area, Davis County, Utah, pursuant to Utah Administrative Code R317-6-5, Ground Water Classification for Aquifers as Class IC or Ecologically Important Groundwater. A map of the area to be protected is provided in Plate 1.

Davis County has the third largest county population in Utah, estimated at 367,285 in 2021 (https://www.census.gov/quickfacts/daviscountyutah). In 2021, Davis County residents made up 11% of Utah's total population of 3,337,975 (https://www.census.gov/quickfacts/UT). Based on projections made in 2015, the population of Davis County is expected to increase to 544,958 by 2065, an increase of 62% over the period 2015–2065 (Perlich et al., 2017).

The principal basin-fill aquifer underlying Davis County is currently protected for drinking water quality as part of an existing aquifer classification (Plate 2). However, the existing protections do not apply to all groundwater in Davis County. As stated in the existing aquifer petition document, "This classification does not apply to the shallow unconfined aquifer, which overlies the principal aquifer in much of the study area" (Wallace et al., 2011). The shallow aquifers (shallow unconfined and shallow confined) underlying Davis County contribute water to Great Salt Lake and perimeter freshwater wetlands, and thus groundwater discharge from these aquifers is important to the continued support of the lake's designated beneficial uses. We therefore petition the Board to classify the discharge zone of the shallow unconfined aquifer beneath Davis County as Class IC groundwater or Ecologically Important Groundwater.

FACTUAL DATA

Sufficient information is available to classify groundwater quality in the discharge zone of the shallow, unconfined aquifer system, located in the southern part of the east shore area of Davis County, Utah. Data required to formally petition the Board were obtained from previously published studies. The information required for classification is contained in maps submitted with this report and in Plate 1.

In addition, the following previously released publications contain valuable information about the Davis County part of the east shore area of the Great Salt Lake aquifer systems. Copies of these reports are available upon request or online:

- Clark, D.W., Appel, C.L., Lambert, P.M., Puryear, R.L., 1990. Ground-water resources and simulated effects of withdrawals in the east shore area of Great Salt Lake, Utah. Utah Department of Natural Resources Technical Publication No. 93:150. https://waterrights.utah.gov/cgi-bin/docview.exe?Folder=TP20-6-330&Title=Technical+Publication+93

- Kirby, S.M., Inkenbrandt, P.C., Rupke, A., 2019. Mapping groundwater quality and chemistry adjacent to Great Salt Lake, Utah. Utah Geological Survey Open-File Report 699. https://ugspub.nr.utah.gov/publications/open_file_reports/ofr-699/ofr-699.pdf

- Wallace, J., Inkenbrandt, P., Lowe, M., 2011. Ground-water quality classification for the principal basin-fill aquifer, East Shore area, Davis County, Utah. Utah Geological Survey Open-File Report 592. https://ugspub.nr.utah.gov/publications/open_file_reports/OFR-592.pdf

GEOLOGIC SETTING

The study area is the southern part of the east shore area of Great Salt Lake in Davis County, Utah, east of Farmington Bay (Figure 1). The study area was the subject of a previous groundwater classification petition for the principal basin-fill aquifer (Wallace et al., 2011). The current groundwater petition seeks protection for the shallow, unconfined aquifer overlying the principal basin-fill aquifer.

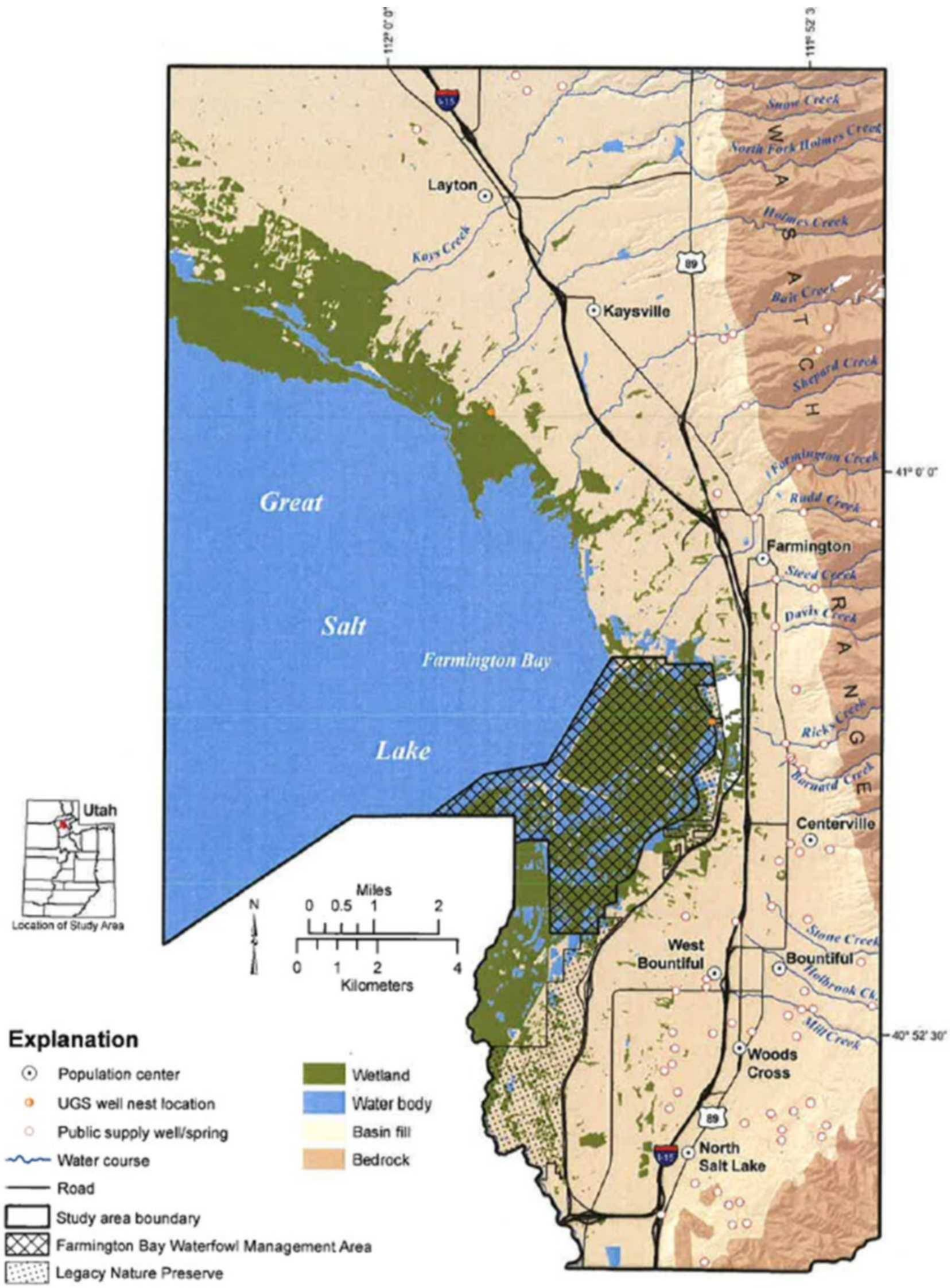

Figure 1. Study area map of the southern part of the east shore of Great Salt Lake in Davis County, east of Farmington Bay. Figure from Wallace et al. (2011).

The east shore area is defined as the area extending from North Salt Lake to the town of Willard in Box Elder County, and from the eastern shore of Great Salt Lake to the western margin of the Wasatch Range (Clark et al., 1990). The area considered for groundwater classification covers the Davis County portion of the east shore area. The description of the geologic setting includes information about the larger east shore area because it is a connected hydrologic system.

Elevation across the east shore area ranges from over 9000 feet in the Wasatch Range to about 4190 feet at the shore of Great Salt Lake. The Weber and Ogden Rivers in Weber County are the largest streams in the east shore area, accounting for 90% of surface water flow (Clark et al., 1990). Davis County streams include Holmes, Farmington, Parrish, Centerville, Stone, and Mill Creeks (Figure 1), with dozens of other perennial, intermittent, and ephemeral streams that flow westward from the Wasatch Range into the east shore area (Clark et al., 1990).

The geology of the east shore area was described in the previous aquifer classification petition by Wallace et al. (2011). Here we provide a brief overview of the geology. Rocks in the Farmington area of the Wasatch Range include the Precambrian Farmington Canyon Complex metamorphic and igneous basement rocks overlain by Paleozoic metasedimentary and sedimentary rocks, Tertiary sedimentary rocks, and Quaternary surficial deposits (Hintze and Kowallis, 2009). The rocks have been deformed and fractured by late Mesozoic to early Cenozoic thrust faulting and Miocene to Quaternary normal faulting along the Wasatch fault (Hintze and Kowallis, 2009).

The east shore area of Great Salt Lake is a structural graben that started to develop during the Tertiary with basin and range normal faulting. The active Wasatch fault is at the base of the Wasatch Range, the eastern margin of the graben. The graben, or basin, has accumulated large amounts of sediment shed from the uplifting Wasatch Range. The basin fill consists mainly of the Salt Lake Formation, with a maximum thickness of 14,000 feet beneath Great Salt Lake (Hintze and Kowallis, 2009).

The graben is located within the hydrologically closed Bonneville basin, with water draining towards Great Salt Lake and leaving only by evapotranspiration. The basin has been internally drained for much of the past 15 million years, having lakes of various sizes during much of that time. Four major lake cycles occurred during the last 780,000 years (Oviatt et al., 1999). Lake Bonneville was the last major lake cycle in the basin, existing from 30 ka to 13 ka, with modern Great Salt Lake as a remnant of the larger lake (Oviatt, 2015). With a history of deep lake cycles interspersed with periods of small lakes or nonexistent lakes, the basin-fill deposits in the east shore area contain interfingering gravel, sand, silt, and clay deposited in lacustrine and fluvial environments (Sprinkel, 1993).

GROUNDWATER CONDITIONS

The groundwater system of the central east shore area was described in detail by Feth et al. (1966). Groundwater in the east shore area occurs under both confined and unconfined conditions in the basin-fill sediments to depths of at least 3000 feet. The major artesian aquifers are the Delta aquifer, which is located about 500–700 feet below ground surface and is primarily 50–150 feet thick, and the Sunset aquifer, which is located about 200–400 feet below ground surface and is 50–250 feet thick. The deeper Delta aquifer is more productive with wells of large yield, whereas the shallower Sunset aquifer is less permeable with wells of small yield. The shallow aquifer supplies water to wells in Roy and Syracuse. In the Roy area, the shallow aquifer yields water from depths between 50 and 150 feet below ground surface. In the Syracuse area, the shallow aquifer yields water in wells less than 250 feet deep. The water table contours in the shallow aquifer create a sloping surface from the Wasatch Range to Great Salt Lake, paralleling the shoreline of the wetlands.

Additional characterization of the east shore aquifers, including the Bountiful area, was provided by Clark et al. (1990). The groundwater flow direction is primarily from the mountain block and mountain front towards Great Salt Lake (Figure 2). The east shore aquifer system was defined by Clark et al. (1990) as the saturated sediments in the valley fill between the Wasatch Range and Great Salt Lake, including the Sunset and Delta aquifers, but not including the shallow unconfined aquifers in the study area (Figure 3). A shallow unconfined aquifer commonly exists above the upper confining beds within the Quaternary surficial deposits. Unconfined groundwater is generally located along stream channels, in perched aquifers on the bench areas, and throughout the valley lowlands within a few feet of the surface. The shallow water table zone receives large amounts of seepage from irrigation and infiltration of urban runoff. A geologic profile of the Delta and Sunset aquifers in the Weber Delta part of the east shore area was provided by Hurlow et al. (2011); modified after Feth et al. (1966) (Figure 4). A conceptual model of groundwater flow in the east shore area (Figure 5) shows groundwater discharge from deep and shallow aquifers to Great Salt Lake and perimeter wetlands (Kirby et al., 2019). Discharge from the east shore aquifer system includes water withdrawal from wells and flow into the shallow unconfined aquifer (Clark et al., 1990). The shallow unconfined aquifer discharges to the surface through springs and gaining stretches of streams, evapotranspiration of shallow groundwater, and diffuse shallow groundwater flow to Great Salt Lake (Clark et al., 1990).

Groundwater in the east shore area occurs in unconsolidated basin-fill deposits under both water table (unconfined) and artesian (confined) conditions, but most of the water withdrawn by wells is from the artesian aquifers and is used for public supply (Smith et al., 2019). Total estimated withdrawal from the east shore area in 2017 was 38,200 acre-feet, which is about 11,000 acre-feet less than the average annual withdrawal for the period of 2007–2016 (Smith et al., 2019). Of the total withdrawal in 2017, 30,900 acre-feet was for public supply, 3,600 acre-feet for irrigation, and 2,600 acre-feet for industrial use (Smith et al., 2019). Water levels have generally declined since the mid-1980s in wells south of Kaysville and have generally declined since the mid-1950s in wells north of Kaysville (Smith et al., 2019).

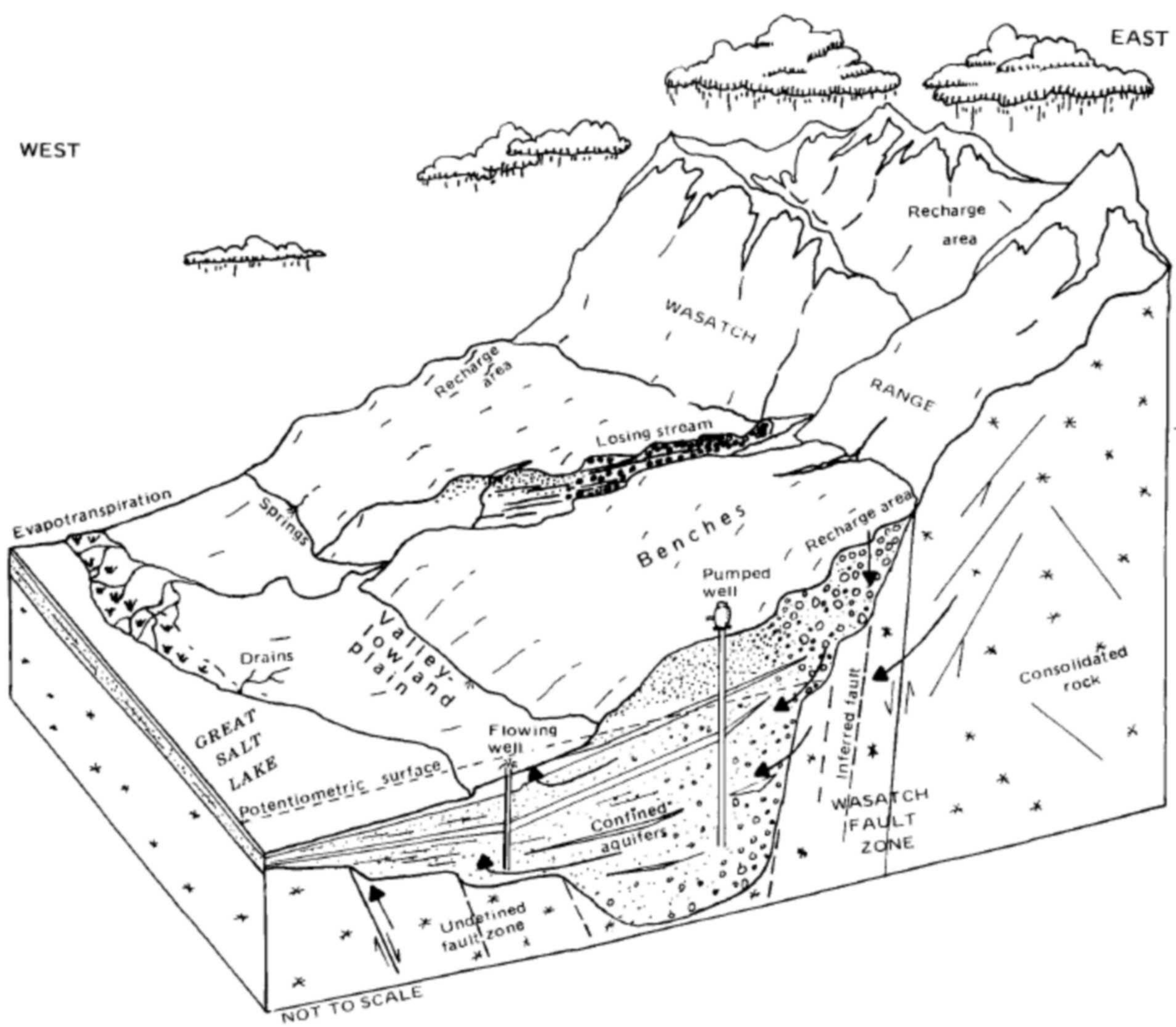

Figure 2. Generalized block diagram showing the aquifer systems, probable directions of groundwater movement, and recharge and discharge areas. Figure from Clark et al. (1990).

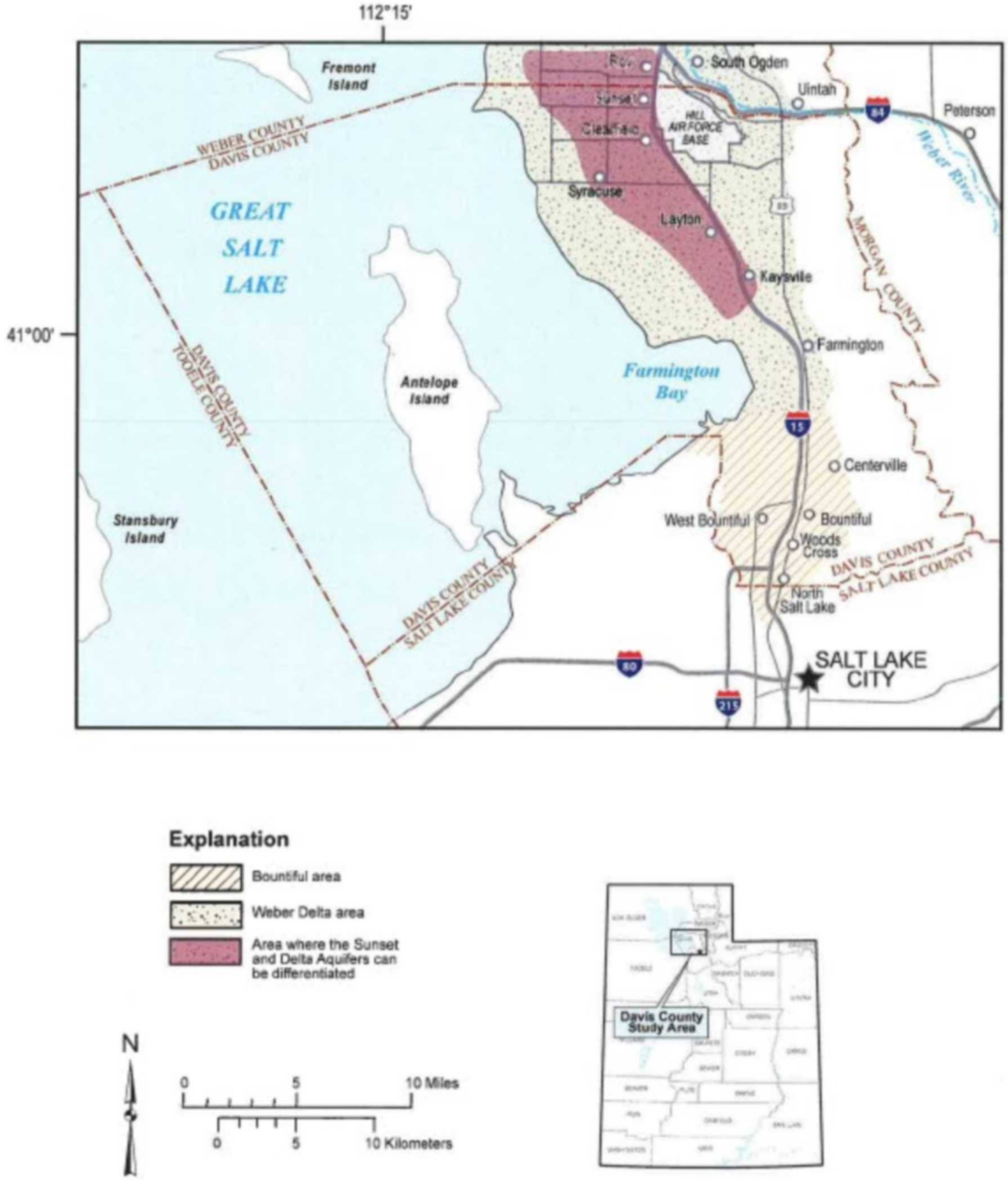

Figure 3. Map of the Sunset and Delta aquifers in Davis County, including the Bountiful and Weber Delta areas. Figure from Wallace et al. (2011); modified after Clark et al. (1990).

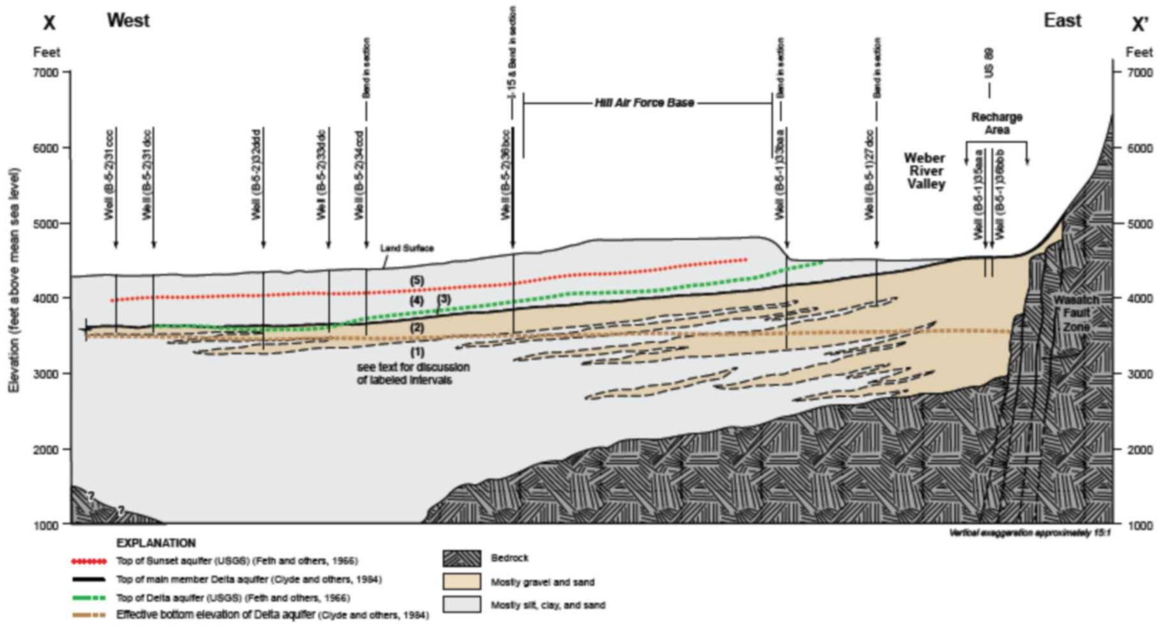

Figure 4. Geologic profile of the Sunset and Delta aquifers in the Weber Delta portion of the east shore area. Figure from Hurlow et al. (2011; modified after Feth and others [1966]).

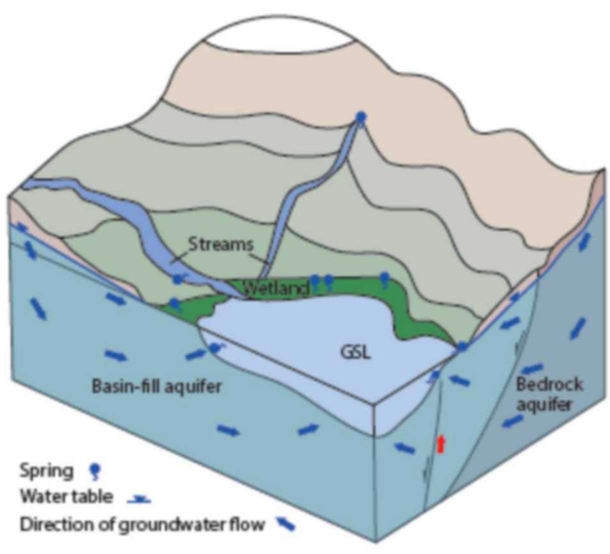

Figure 5. Conceptual model of groundwater flow to Great Salt Lake and perimeter wetlands. Figure from Kirby et al. (2019). The lake is the discharge area for groundwater and surface water in the watershed. The red arrow indicates potential input of hydrothermal water.

PREVIOUS STUDIES

Previous studies in the east shore area have primarily focused on the deep principal aquifers. These studies are described in Wallace et al. (2011). Only a few studies have focused on the shallow aquifer system. Yidana et al. (2010) investigated the connections between deep confined aquifers and shallow unconfined aquifers. The purpose of their study was to determine whether groundwater pumping from the principal aquifer caused a significant decrease in groundwater discharged from the deep aquifer to the shallow aquifer. In Salt Lake Valley, the shallow unconfined aquifer overlies confining beds above the principal aquifer system and provides water to approximately 58,000 acres of wetlands in groundwater discharge areas. Yidana et al. (2010) installed shallow monitoring wells in Salt Lake Valley wetlands on the fringe of Great Salt Lake to determine the hydraulic gradient and water quality conditions. Through a MODFLOW model, the study showed that development of the principal aquifer could dramatically decrease the amount of water that the wetlands receive. Carling et al. (2013) investigated the impacts of shallow groundwater discharge on water chemistry and ecology of wetlands on the east side of Great Salt Lake. Kirby et al. (2019) compiled existing groundwater chemistry data adjacent to Great Salt Lake. Their study focused primarily on deep groundwater but also included a comparison with chemistry of wetlands adjacent to the lake.

GROUNDWATER QUALITY FROM PREVIOUS STUDIES

Groundwater quality is generally good in the east shore aquifer system, though most work focused on the confined aquifers (Wallace et al., 2011). A recent comprehensive study investigated all available groundwater chemistry data adjacent to Great Salt Lake, including the east shore area (Kirby et al., 2019). The major ion water type for groundwater in the east shore area of Davis County is mainly calcium-bicarbonate waters with some sodium-bicarbonate waters near the shore of Great Salt Lake (Figure 6). Total-dissolved-solids (TDS) concentrations are generally low (<500 mg/L) in confined aquifers of the east shore area (Figure 7). Groundwater with TDS concentrations higher than 500 mg/L is found in isolated locations in the confined aquifers of the east shore area, with some samples falling in the 500 to 1000 mg/L and 1000 to 2500 mg/L categories, reflecting some local variability (Figure 7). The map in Figure 7 shows samples from confined aquifers and limited data are available for TDS for unconfined aquifers in the east shore area. In certain locations, the deep groundwater system may act as a source of water having TDS concentrations >500 mg/L to the shallow groundwater system.

In the unconfined aquifer, former hazardous waste disposal sites at Hill Air Force Base located on the Weber Delta in northern Davis County have contaminated the shallow perched groundwater with halogenated organic compounds (solvents such as trichloroethylene, TCE) and heavy metals (including cadmium and chromium) and is under remediation (Dalpias et al., 1989). Hill Air Force Base overlies three aquifers: an unnamed unconfined aquifer and the confined Sunset and Delta Aquifers, with groundwater contamination in the top 100 feet of the unconfined aquifer (Figure 8) (EA-Engineering, 2015). Contamination plumes are located in multiple locations on and off the base (Figure 9), with cleanup expected to continue for decades (EA-Engineering, 2015). Ongoing efforts are remediating the groundwater contamination using monitored natural attenuation, enhanced bioremediation, and institutional controls (EA-Engineering, 2015).

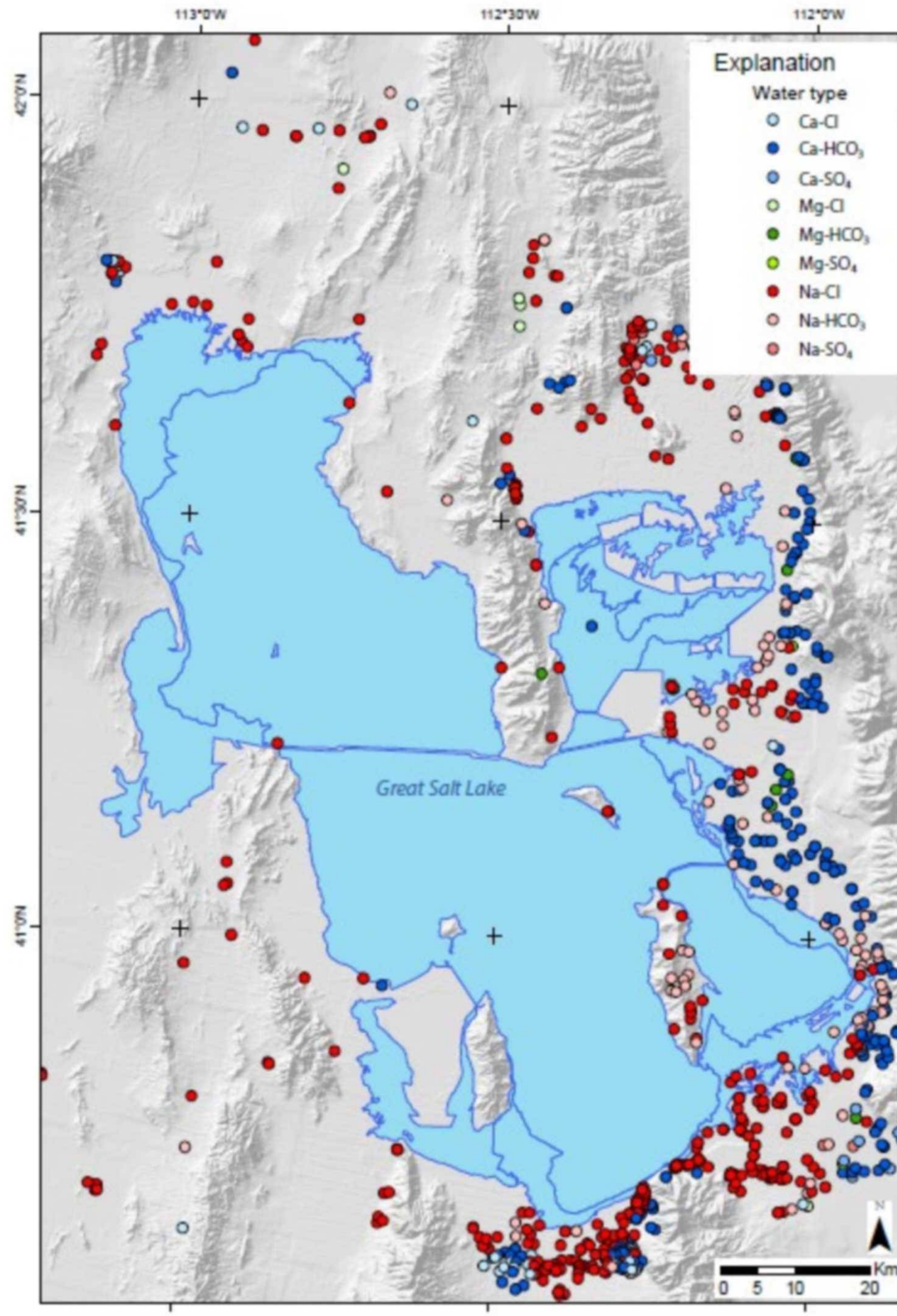

Figure 6. Major ion water type for groundwater samples collected adjacent to Great Salt Lake. Figure from Kirby et al. (2019). The blue lines in the lake indicate bathymetry and the locations of causeways.

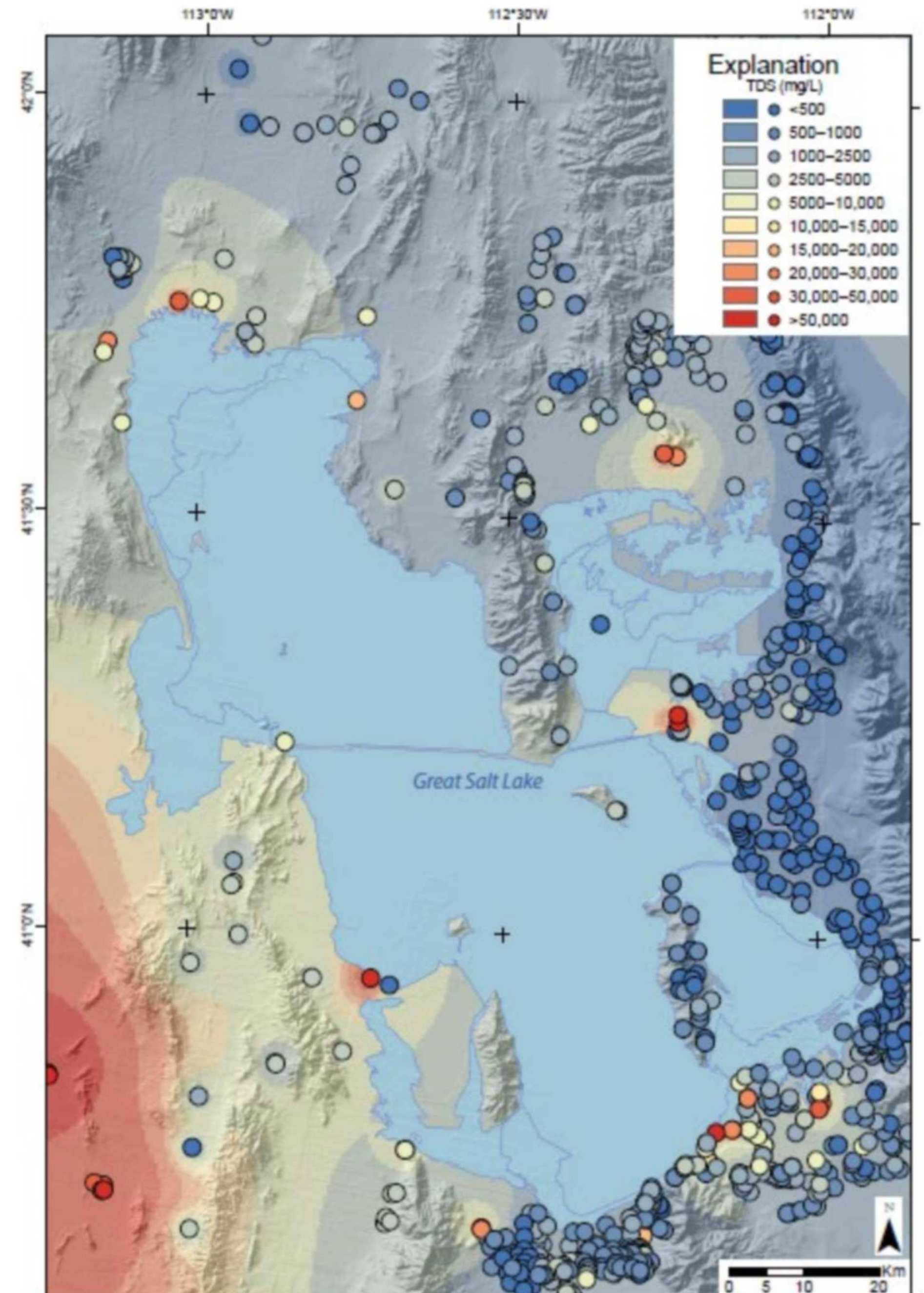

Figure 7. Interpolated total-dissolved-solids concentrations for groundwater samples collected adjacent to Great Salt Lake. Figure from Kirby et al. (2019). The blue lines in the lake indicate bathymetry and the locations of causeways.

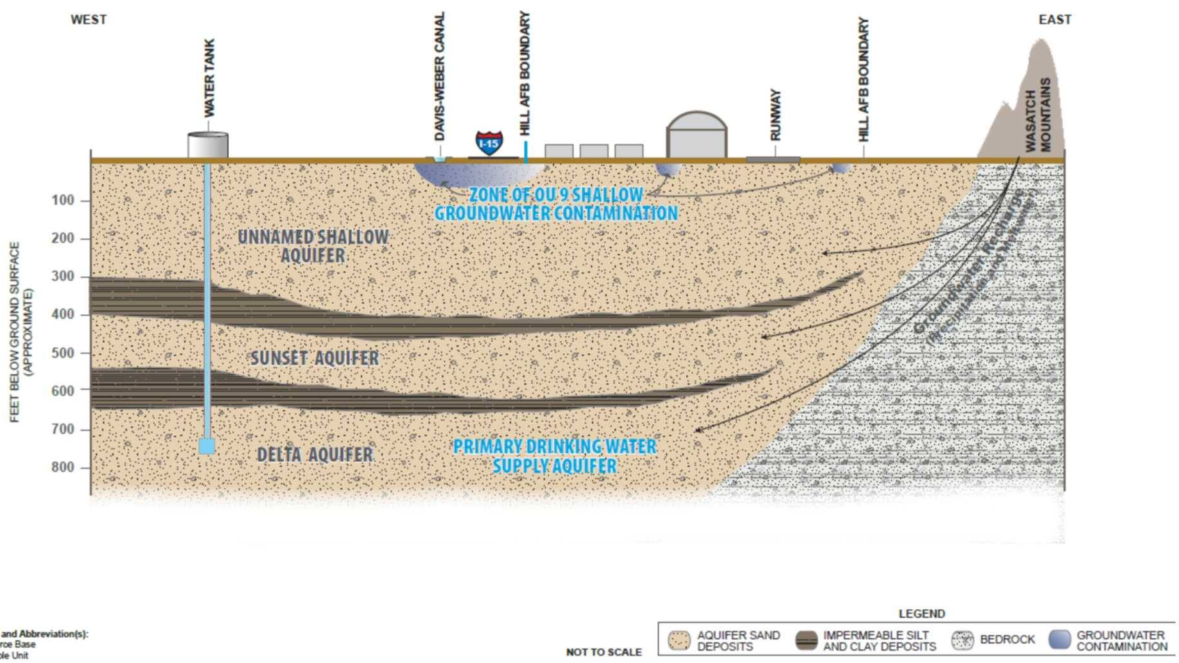

Figure 8. Conceptual geologic cross section beneath Hill Air Force Base showing the three aquifer systems and location of shallow groundwater contamination. Figure from EA-Engineering (2015).

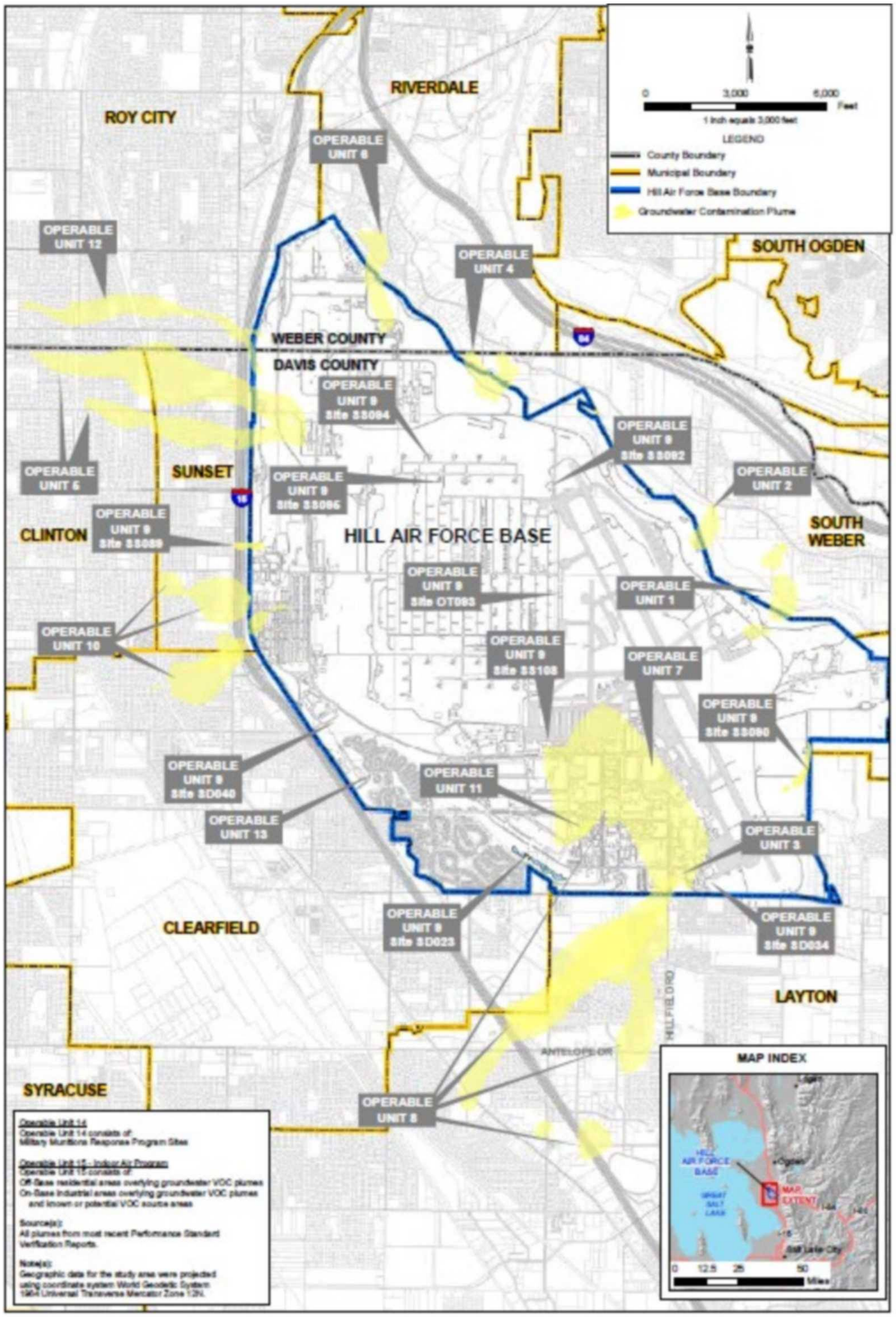

Figure 9. Map of groundwater contamination plumes on and around Hill Air Force Base. Figure from EA-Engineering (2015).

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PROPOSED CLASSIFICATION

This petition seeks to classify the discharge zone of the shallow, unconfined aquifer in the east shore area of Davis County as Class IC groundwater. Class IC groundwater is considered ecologically important groundwater and is a source of groundwater discharge that is important to the continued survival of an existing wildlife habitat. Limits on increases of total dissolved solids and organic and inorganic compounds are determined to meet applicable surface water standards (https://deq.utah.gov/water-quality/classes-utah-ground-water-quality-protection-program).

FRIENDS of Great Salt Lake is petitioning the Utah Water Quality Board to classify the discharge zone of the shallow, unconfined aquifer in the east shore area of Davis County as Class IC, Ecologically Important Groundwater. Specifically, the area includes the shallow, unconfined aquifer overlying the discharge zone (but not the primary or secondary recharge zones) as mapped by Anderson et al. (1994) and shown in Figure 10. The confined aquifers that comprise the principal drinking-water aquifer are currently classified as Class IA, Pristine, or Class IB, Drinking Water Quality (Plate 2), but the overlying unconfined aquifers have no protection. Here, we define the shallow, unconfined aquifer as groundwater at a maximum of 300 feet below ground surface, residing above a confining layer of variable depth. The shallow groundwater system overlies the deep aquifer system with a similar footprint as the deep confined aquifers (compare Plate 2 and Figure 10). For example, in the Weber Delta area, the shallow groundwater system resides above the Sunset Aquifer and ranges from approximately 300 feet deep at Hill Air Force Base to 100 feet deep at the edge of Great Salt Lake (Figures 4 and 8). Farther south in the Farmington and Bountiful areas, the unconfined aquifer is approximately 100 feet deep (Clark et al., 1990).

The shallow unconfined and deep confined aquifers are directly connected to the wetlands on the east side of Great Salt Lake. Water in the confined shallow aquifer contributes to groundwater upwelling in freshwater wetlands and seeps in the lakebed of Great Salt Lake (Yidana et al., 2010). Protecting the shallow unconfined aquifers also provides further protection for the deep principal water-supply aquifers in the east shore area where the confining layer that separates the two aquifers is thin or absent and/or where vertical hydraulic gradients are not strongly upward.

The petition to classify the principal drinking-water aquifers in Davis County noted that "this classification does not apply to the shallow unconfined aquifer, which overlies the principal aquifer in much of the study area. This is technically justified by the presence of low-permeability confining layers between the shallow unconfined and deep aquifers, which act as an aquitard to protect the deep aquifer from surface contamination, and the upward vertical hydraulic gradient in ground-water discharge areas underlying much of the area where a shallow unconfined aquifer exists" (Wallace et al., 2011). This statement describes the footprint of the shallow unconfined aquifer as overlying the principal aquifer and that groundwater in the east shore area has a generally upward gradient, where groundwater contributes to surface water wetlands, streams, and Great Salt Lake.

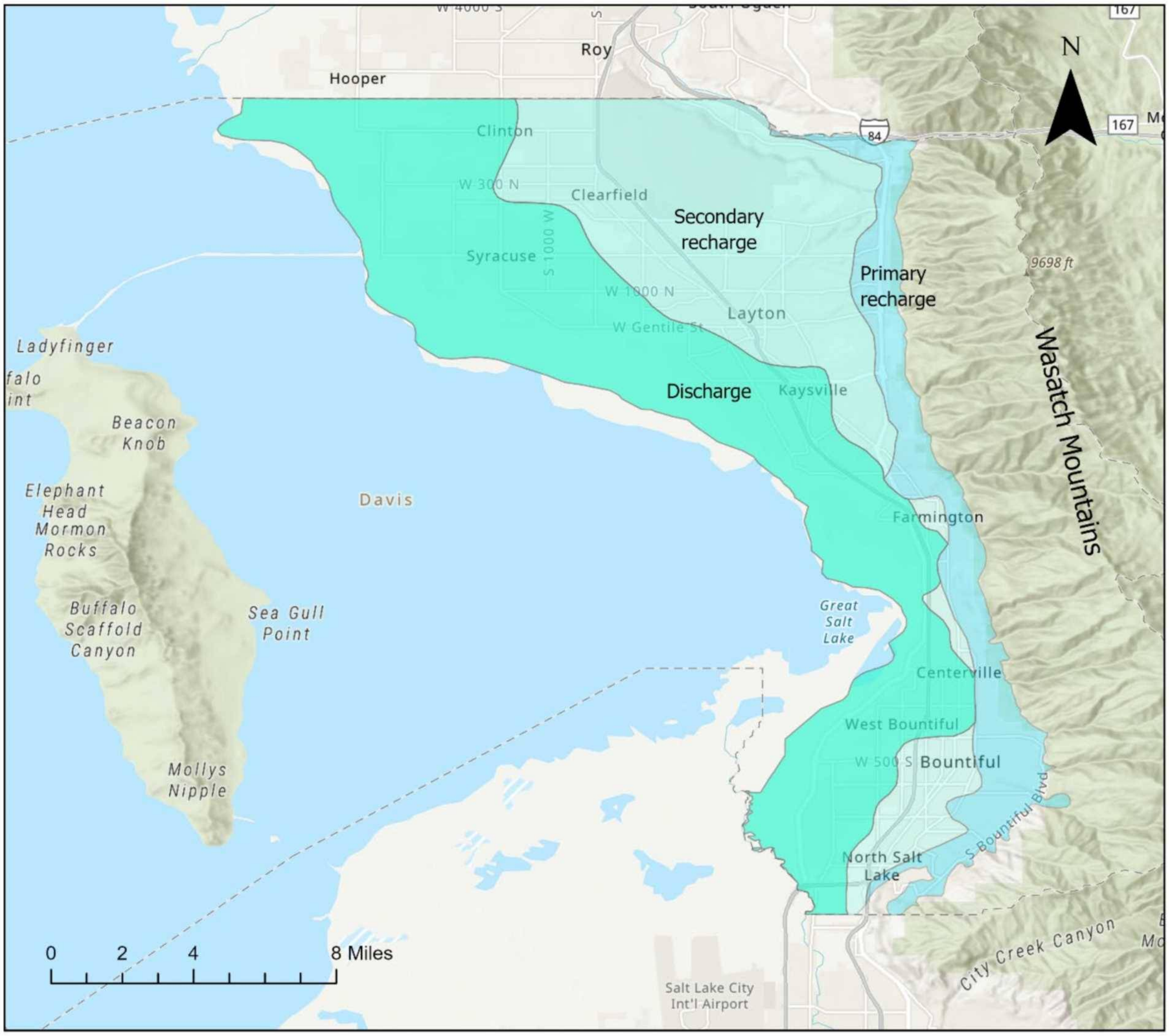

Figure 10. Map of primary recharge, secondary recharge, and discharge zones in the principal aquifer underlying the east shore of Davis County. The shallow aquifer overlying the discharge zone is the area that will be protected as part of the current petition. The recharge and discharge zones were mapped by Anderson et al. (1994).

CURRENT BENEFICIAL USES

In Davis County, groundwater from the shallow unconfined aquifer is an important source of water for the wetlands on the east side of Great Salt Lake and for diffuse seepage to Great Salt Lake. Great Salt Lake and its perimeter wetlands were declared a bird habitat of hemispheric importance by the Western Hemisphere Shorebird Reserve Network (https://whsrn.org/whsrn_sites/great-salt-lake/). Recent estimates suggest that groundwater contributes 10%–12% of all inflow to Great Salt Lake (Bunce et al., 2022).

Groundwater discharge from the shallow aquifer to Great Salt Lake and its perimeter wetlands primarily impacts Farmington Bay, which is classified as Class 5D, and Gilbert Bay, which is classified as Class 5A in the beneficial use classification scheme. Both Farmington and Gilbert Bay have similar designated beneficial uses and both bays are protected for "waterfowl, shore birds and other water-oriented wildlife including their necessary food chain" under Utah Administrative Code R317-2-6.5. The classification systems for surface water and groundwater used by DWQ differ in that surface water classifications are primarily broken out based on how the water is used (e.g., Class 1 – Protected for use as a raw water source for domestic water systems. *See generally* R317-2-6), whereas groundwater classifications are generally broken out based on the level of TDS contained in the water (i.e., Class II groundwater has TDS levels greater than 500 mg/L but less than 3000 mg/L. *See generally* R317-6-3). An exception to the TDS level classification is Class IC – Ecologically Important Groundwater which "is a source of ground water discharge important to the continued existence of wildlife habitat" (R317-6-3.4).

WATER SUPPLY WELLS

The shallow unconfined aquifer is an important source of water, likely for agricultural and industrial use, but it is not clear to what extent water from the shallow aquifer is used for municipal water. A map of existing wells, including shallow wells, is provided in Figure 11. This petition does not seek to classify specific shallow wells in Davis County. Rather, the petition seeks to protect shallow groundwater that flows to Great Salt Lake, where it is considered ecologically important.

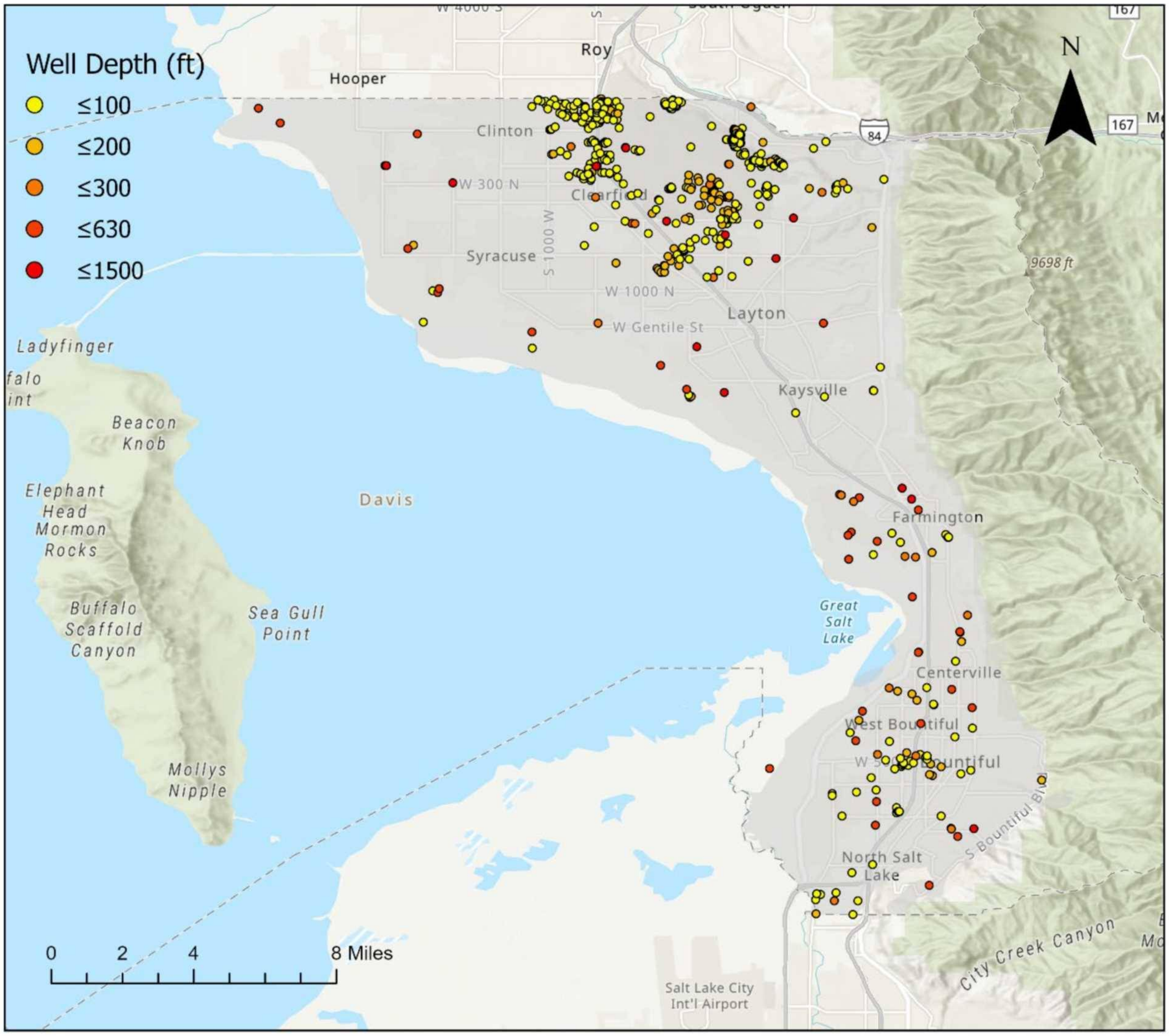

Figure 11. Map of existing wells in Davis County color-coded by depth (ft) below ground surface. Well locations and depths obtained from the Utah Division of Water Rights database (www.waterrights.utah.gov).

POTENTIAL CONTAMINANT SOURCES

Potential contaminant sources in the Davis County portion of the east shore aquifer system were described in detail in the previous groundwater petition (Wallace et al., 2011). Wallace et al. mapped 1798 potential contaminant sources including facilities related to mining, agriculture, industry, fuel storage, and junkyard/salvage areas. Additionally, there are 257 private septic systems (as of 2010) that may potentially pollute groundwater. Changes to potential contaminant sources since 2011 consist primarily of the transition of open, agricultural areas to subdivisions and the accompanying infrastructure, especially in the northwestern part of the county. The increase in population in the Davis County area has also resulted in the addition of numerous roads, including the West Davis Corridor which is located to the east of Great Salt Lake wetlands.

To update the list of potential contaminant sources for this petition, we obtained records for all drinking water source protection plans since 2011 associated with wells in the mapped discharge zone of Davis County. The request generated 76 source protection plans for the area of interest. Each source protection plan listed numerous potential contaminant sources. The compiled list includes 1411 potential contaminant sources, and is included as Table 1.

EXISTING POLLUTION SOURCES

Existing pollution sources include contaminants that have been documented and/or are currently being treated. As described in Wallace et al. (2011), known sources of pollution exist in the Davis County part of the east shore aquifer system. In northern Davis County, groundwater contamination plumes with concentrations of organic solvents such as tetrachloroethylene (PCE) and trichloroethylene (TCE) exceeding drinking water quality standards (EPA, 2022) have been identified in the shallow unconfined aquifer in and around Hill Air Force Base with ongoing remediation (Dalpias et al., 1989; EA-Engineering, 2015). In southern Davis County, a groundwater contamination plume of PCE exists in the Five Points area of Woods Cross and is currently undergoing remediation (https://cumulis.epa.gov/supercpad/SiteProfiles/index.cfm?fuseaction=second.Cleanup&id=0802654#bkground).

GROUNDWATER FLOW DIRECTION

Groundwater flow in the east shore area is generally westward from the Wasatch Range towards Great Salt Lake (Clark et al., 1990), as shown in Figure 12.

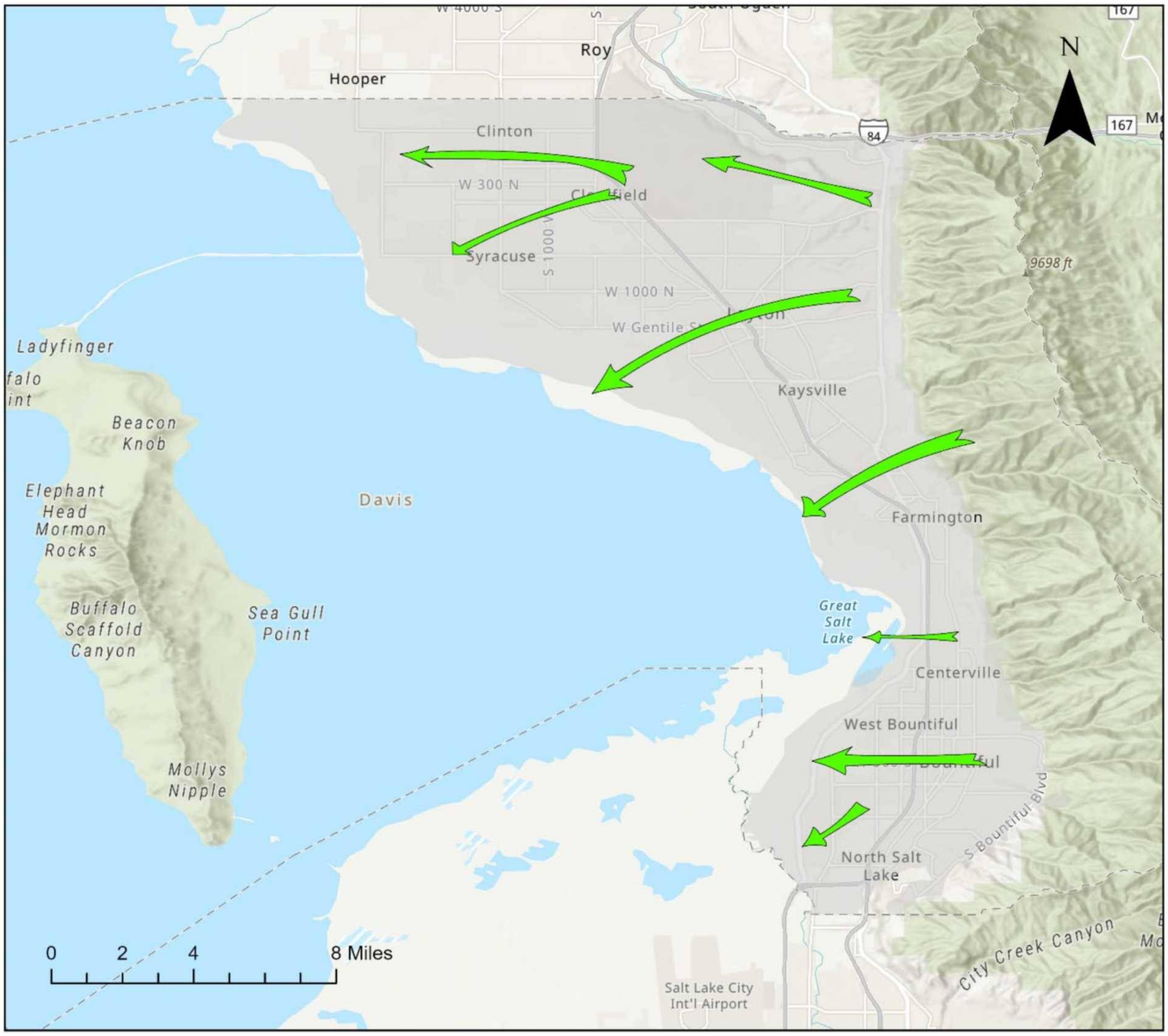

Figure 12. Map of groundwater flow direction in the shallow aquifer underlying Davis County, based on data in Clark et al. (1990).

CONCLUSIONS

The shallow unconfined aquifer system in the east shore area of Davis County provides critical water flow to bird habitats in Great Salt Lake and adjacent wetlands. Groundwater classification is a tool that may be used to manage potential groundwater contamination sources and protect the quality of groundwater resources in Utah. The deep confined aquifer in the east shore of Davis County contains groundwater with generally low total-dissolved-solids concentrations (<500 mg/L) with isolated areas having elevated total-dissolved-solids concentrations (>500 mg/L) that may contribute salts to the shallow aquifer. The shallow aquifer at Hill Air Force Base is contaminated with an organic solvent plume exceeding drinking water standards that is currently undergoing remediation and would not have an effect on the waters to be classified in this petition. Classifying the discharge zone of the shallow, unconfined aquifer as IC, Ecologically Important Groundwater, would provide tools for protecting this groundwater resource for wildlife habitat and would also further protect the deep underlying principal drinking water aquifer.

REFERENCES

Anderson, P.B., Susong D.D., Wold S.R., Heilweil V.M., Baskin R.L., 1994. Hydrogeology of recharge areas and water quality of the principal aquifers along the Wasatch Front and adjacent areas, Utah. U.S. Geological Survey Water-Resources Investigations Report 93-4221: 74.

Bunce, L., Lowenstein, T.K., Jagniecki, E., 2022. Significance of spring inflow to Great Salt Lake. Great Salt Lake Issues Forum Poster.

Carling, G.T., et al., 2013. Relationships of surface water, pore water, and sediment chemistry in wetlands adjacent to Great Salt Lake, Utah, and potential impacts on plant community health. Science of the Total Environment, 443(0): 798–811.

Clark, D.W., Appel, C.L., Lambert, P.M., Puryear, R.L., 1990. Ground-water resources and simulated effects of withdrawals in the east shore area of Great Salt Lake, Utah. Utah Department of Natural Resources Technical Publication No. 93: 150.

Dalpias, E.A., Heyse, E., James, W.R., 1989. Overview of contaminated sites at Hill Air Force Base, Utah, and Case History of Actions Taken at Landfills No. 3 and 4, Chem Pits 1 and 2, in Cordy, G.E., editor, Geology and hydrology of hazardous-waste, mining-waste, and repository sites in Utah. Utah Geological Association: 59–67.

EA-Engineering, 2015. Operable Unit 9 Record of Decision, Hill Air Force Base, Utah.

EPA, 2022. National Primary Drinking Water Regulations. URL: https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations. Accessed 7 June 2023.

Feth, J.H.F., Barker, D.A., Moore, L.G., Brown, R.J., Veirs, C.E., 1966. Lake Bonneville: Geology and hydrology of the Weber Delta district, including Ogden, Utah. 518, Washington, D.C.

Hintze, L., Kowallis, B., 2009. Geologic History of Utah. Brigham Young University Geology Studies Special Publication 9: 225 p.

Hurlow, H., Lowe, M., Matyjasik, M., Gettings, P., 2011. The Weber River Basin aquifer storage and recovery pilot project. Utah Geological Survey Special Study 136: 135 p.

Kirby, S.M., Inkenbrandt, P.C., Rupke, A., 2019. Mapping groundwater quality and chemistry adjacent to Great Salt Lake, Utah. Utah Geological Survey Open File Report, 699: 19.

Oviatt, C.G., 2015. Chronology of Lake Bonneville, 30,000 to 10,000 yr B.P. Quaternary Science Reviews, 110: 166–171.

Oviatt, C.G., Thompson, R.S., Kaufman, D.S., Bright, J., Forester, R.M., 1999. Reinterpretation of the Burmester Core, Bonneville Basin, Utah. Quaternary Research, 52(2): 180–184.

Perlich, P.S., Hollinghaus, M., Harris, R., Tennert, J., Hoque, M.T., 2017. Utah's long-term demographic and economic projections summary. Research Brief, Kem C. Gardner Policy Institute, The University of Utah: 32 p.

Smith, L. et al., 2019. Groundwater conditions in Utah, Spring of 2018, USGS Utah Water Science Center.

Sprinkel, D.A., 1993. Amoco's advanced drilling technology retrieves a deep core from Lake Bonneville sediments, Davis County. Utah Geological Survey Survey Notes, 26.

Wallace, J., Inkenbrandt, P., Lowe, M., 2011. Ground-water quality classification for the principal basin-fill aquifer, East Shore area, Davis County, Utah. Utah Geological survey.

Yidana, S.M., Lowe, M., Emerson, R.L., 2010. Wetlands in northern Salt Lake Valley, Salt Lake County, Utah—An evaluation of threats posed by ground-water development and drought. Utah Geological Survey Report of Investigation 268: 38.