Characterization of Groundwater Quality in Wasatch County, Utah, with Recommendations for Septic System Development Regulations

SEPTEMBER 2020

PREPARED FOR

Wasatch County Health Department

PREPARED BY

SWCA Environmental Consultants

CHARACTERIZATION OF GROUNDWATER QUALITY IN WASATCH COUNTY, UTAH, WITH RECOMMENDATIONS FOR SEPTIC SYSTEM DEVELOPMENT REGULATIONS

Prepared for

Wasatch County Health Department
55 South 500 East
Heber City, Utah 84032
Attn: Tracy Richardson

Prepared by

SWCA Environmental Consultants
257 East 200 South, Suite 200
Salt Lake City, Utah 84111
(801) 322-4307
www.swca.com

SWCA Project No. 50345

September 2020

EXECUTIVE SUMMARY

Wasatch County is one of the fastest growing counties in the state of Utah. Rapid development and population growth have taken place in the county over the past few decades and are projected to continue through 2050 (MAG 2020; University of Utah 2020). This historically agricultural area has seen a conversion of agricultural lands to residential development, most of which uses on-site small wastewater disposal (septic) systems. Although the proportion of the development connected to centralized wastewater treatment systems (via sanitary sewers) continues to increase, a large proportion of the county continues to depend on septic systems for wastewater disposal. Concern that groundwater resources that provide the county's drinking water could be susceptible to contamination from wastewater systems and higher density residential development has led the Wasatch County Health Department (WCHD) to investigate the potential impacts of wastewater contamination to groundwater quality and to implement regulations to limit potential contamination groundwater.

WCHD engaged SWCA Environmental Consultants (SWCA) to implement an updated groundwater study of the groundwater resources of the Heber and Round Valleys of Wasatch County (see report Figure 1) . A previous study was conducted approximately 25 years ago by Hansen, Allen & Luce (HAL); the 1994 HAL study recommends a septic system density of one septic system per 5 acres of land based on the allowable nitrate degradation (as determined by the WCHD) of 1 milligram per liter (mg/L). Phase 1 of the SWCA study identified data gaps related to the aquifers and data gaps water quality in the project area. This report, titled *Characterization of Groundwater Quality in Wasatch County, Utah, with Recommendations For Septic System Development Regulations*, describes Phase 2 of the study. The objectives of Phase 2 are as follows:

- Collect new data to characterize the water quality of the Heber and Round Valley aquifers and evaluate changes in water quality over the past 25 years, including evaluating the effectiveness of the measures implemented following the 1994 HAL study and setting a baseline for groundwater conditions as part of a future monitoring program.
- Attempt to link any degradation of water quality with specific activities within the study area.
- Model the effect of future population growth on water quality of the aquifers.
- Make recommendations to the WCHD related to regulations on development of small wastewater disposal systems within Wasatch County to inform their future planning decisions.

Groundwater and Surface Water Quality Sampling and Trends (report Sections 3 and 4)

SWCA conducted four groundwater sampling events between fall 2018 and spring 2020 and combined these data with historic data, largely from U.S. Geological Survey (USGS) monitoring. A core group of parameters were consistently analyzed (total dissolved solids [TDS], total suspended solids, nitrate, total phosphorus, and chloride), and other suites of parameters were analyzed in a more limited fashion for specific screening purposes, including volatile organic compounds, pesticides and herbicides, metals, anthropogenic markers (i.e., personal care/pharmaceutical products), and major cation/anions. These parameters are discussed below.

- **Total dissolved solids**: The aquifers of Wasatch County are classified as Class 1A (found throughout most of the county) and Class 2 (found near Midway). Class 1A and Class 2 aquifers are both considered drinking water quality and State of Utah code specifies that they should be protected as drinking water. Class IA groundwater, also called "pristine groundwater," has concentrations of TDS below 500 mg/L, and Class 2 groundwater has TDS concentrations between 500 and 3,000 mg/L. The average TDS concentration in wells within the Class 1A aquifer is 325 mg/L. The areas of highest TDS concentrations are in Lake Creek/Center Creek,

South Fields/Charleston, and the Swiss Alpine areas, with some wells consistently exceeding 500 mg/L. TDS concentrations are generally greater at shallower depths, but overall TDS concentration and well depth are poorly correlated. We identified statistically significant upward trends in TDS in four wells consistently sampled by the USGS and for the aquifer as a whole.

- **Nitrate:** In 1994, HAL recommended that nitrogen in the form of nitrate be used as a groundwater quality management indicator in Wasatch County. In 2020, nitrate continues to be one of the primary indicators of pollution from septic systems and is consistently used as the best indicator for allowable septic system density recommendations in the state of Utah. The overall average nitrate value measured across all groundwater sites in the study area was 1.92 mg/L and includes data from wells in Round Valley, Timberlakes, Woodland, and Brighton Estates. The average nitrate concentration in the Heber Valley aquifer was approximately 2.4 mg/L. The highest nitrate values were observed in the Lake Creek planning area. Nitrate concentrations are generally greater at shallower depths, but overall nitrate concentration and well depth are poorly correlated. We identified statistically significant upward trends in nitrate in three wells consistently sampled by the USGS and for the aquifer as a whole. We also reviewed nitrate concentrations for public drinking water systems and found that concentrations generally remain low and do not appear to be increasing rapidly.

- **Phosphorus**: Total phosphorus was identified as a core parameter in the study primarily because of the potential impact nutrient-rich groundwater can have on surface water resources in the study area, particularly Deer Creek Reservoir. The average measured value of total phosphorus in the Heber Valley Class 1A aquifer is 0.06 mg/L, which is above the phosphorus pollution indicator for rivers and streams of 0.05 mg/L. Phosphorus concentrations in the Lake Creek planning area have consistently exceeded the pollution indicator threshold since 1998. We identified statistically significant upwards trends in phosphorus in five wells consistently sampled by the USGS, but not for the aquifer as a whole.

- **Chloride**: The most common sources of elevated chloride levels in groundwater are road salting and discharge of water softeners to septic systems. The average chloride concentration in the Heber Valley aquifer is approximately 29 mg/L, well below the U.S. Environmental Protection Agency (EPA) secondary standard of 250 mg/L. The highest chloride concentrations are observed in the South Fields area where land application of treated wastewater occurs directly upgradient from the well. The conclusion that the land application may have an effect on water quality is also supported by elevated chloride-to-bromide ratios. Chloride in surface water samples was also generally low, with the exception of Daniels Creek. Road salts are assumed to be the primary cause of elevated chloride concentrations in Daniels Creek and the nearby Daniel #1 well. We identified statistically significant upward trends in chloride in six wells consistently sampled by the USGS, and for the aquifer as a whole.

- **Volatile organic compounds**: We screened for VOCs and trace metals in groundwater wells that were downgradient of high-intensity (urban) development to identify potential threats to water quality, including leaking underground storage tanks, industrial activities, and stormwater runoff from impervious surfaces. VOCs were not present in concentrations above the detection limits for all water samples.

- **Pesticides and herbicides**: We screened for pesticides and herbicides at wells where agriculture was the predominant land use and where groundwater was determined to be highly sensitive to groundwater contamination. Concentrations of pesticides and herbicides were not present in concentrations above the detection limits for all water samples.

- **Metals:** We compared analytical test results of metals testing to State of Utah drinking water standards. Two locations exceeded the drinking water standard for arsenic (0.010 mg/L): Heber Lagoons West (Fish Hatchery) at 0.0111 mg/L and Charleston #1 at 0.0137 mg/L. No other locations exceeded the drinking water standard for arsenic.

- **Anthropogenic markers**: Personal care products and pharmaceutical compounds are a class of groundwater contaminants of growing concern and are considered anthropogenic markers because they are not naturally occurring in the environment. To identify sources of elevated nitrate, in spring 2020, we sampled for a suite of pharmaceutical compounds at nine wells throughout the study area that showed diminished groundwater quality. Two wells had measurable concentrations of compounds but did not indicate clear contamination from any given source.

- **Cations/anions**: Major cations and anions were sampled to evaluate the ionic composition of water samples from different sections of the study area. Patterns and commonalities in major ion chemistry provide evidence for the fundamental flow patterns and water sources in the aquifer. Overall, we found relatively little differentiation anywhere in the aquifer: geographically, between wells completed in bedrock versus alluvium, or between surface water samples and groundwater samples. This is consistent with the conceptual model that the basin water balance is dominated by precipitation, whether through runoff or mountain-front recharge, and that both alluvial and bedrock units are productive parts of the aquifer with groundwater moving freely between them. Cation/anion signatures suggest that runoff from road salt (elevated sodium chloride) may be contributing to higher TDS, including in the Daniels Creek area, South Fields area, and Wallsburg area. Two areas with elevated nitrate—Lake Creek and South Fields—are notable because they have both high nitrate values and elevated sodium-chloride signatures. This suggests that these wells may be influenced by surface runoff or shallow groundwater, possibly through poor surface construction or a nearby recharge source.

Surface water quality data collection and analysis efforts in the study were limited. The greatest focus was on the Timberlakes development, which provides a unique opportunity to evaluate the impact from septic tank development on water quality. Concentrations in surface water are higher below the Timberlakes development than they are above it and indicate that surface water quality degradation below the Timberlakes development is likely the result of wastewater from septic systems and of runoff from impervious surfaces, disturbed areas (construction sites and roads), and residential properties. The same trends were not readily evident for groundwater samples, however, and additional data are needed to strengthen the conclusion.

Groundwater Budget and Groundwater Model (report Sections 5 and 6)

A water budget was created for the Heber Valley and subsequently informed the preparation of a numeric groundwater model. Sources of recharge include infiltration from precipitation, outflow from “losing” stream reaches, unconsumed irrigation water, mountain-front recharge, and wastewater infiltration. Sources of discharge are assumed to be evapotranspiration, leakage to Deer Creek Reservoir, seepage to surface water, springs and seeps, consumptive use of potable water, and subsurface outflow to consolidated rocks.

SWCA used the FREEWAT—an open-source and public domain GIS integrated modelling environment used to simulate water quantity and quality in surface water and groundwater—to create a MODFLOW model for the Heber Valley, excluding Round Valley (titled the 2020 Heber Valley Groundwater Model or “HVGM2020”). We chose to create a steady-state model, which means that the model runs until it reaches an equilibrium between water sources and sinks in the aquifer. Specific inputs into the model included hydraulic conductivity, groundwater levels, and basin geometry (bedrock depths).

- To evaluate hydraulic conductivity for specific portions of the aquifer, we used drinking water well delineation reports provided by the Utah Division of Drinking Water. These data were derived from controlled aquifer tests and are more accurate than previous estimates for the Heber Valley based largely on specific capacity values.
- We performed an independent analysis of groundwater levels to develop a new groundwater contour map (potentiometric surface map) and to estimate hydraulic gradients throughout the Heber Valley aquifer. Although the contours and flow directions that we developed are likely more accurate, they do not differ dramatically from those developed by earlier studies.
- Analysis of aquifer tests and drillers' logs shows that there are productive wells in the Heber Valley that intersect both alluvial and bedrock layers. The depths of these two aquifer layers and the portion that is saturated have not been well defined for the Heber Valley. We estimated the thickness of alluvial materials from interpretation of 35 drillers' logs that appear to show evidence of a contact between unconsolidated and consolidated materials. Alluvial materials are thin toward the edges of the basin and are thickest toward the southern portion of the basin.

In all, we ran 21 calibration runs, varying hydraulic conductivity values in four separate zones (east, north, west, central), evaluating differences between Layer 1 and Layer 2 hydraulic conductivity, varying river conductivity values, and varying mountain front recharge amounts. The final best-calibrated steady-state model yielded a successful calibration statistic (RMSE/Range) of 9%. The fit of the calibration varies across the aquifer. The model is most closely calibrated to observed water levels in the central/lower basin (RMSE/Range of 4%), and less well calibrated in the eastern basin (RMSE/Range of 11%).

The model successfully replicates the general aquifer dynamics and flow paths. Qualitative comparison of secondary calibration targets (water budget components, see Section 5) indicates that simulation of the gain/loss of the Provo River in the model may not accurately reflect real-world conditions, and that discharge to springs/seeps in the lower basin is largely unaccounted for except as discharge through Deer Creek Reservoir. Based on the results, we estimate that groundwater travel time through the aquifer can range as high as 24 feet per day, with a best-controlled estimate (based on the eastern basin) of roughly 3 feet per day.

Impacts from Wastewater and Future Growth Scenarios (report Sections 7 and 8)

We modeled impacts from current and future septic systems using a mass-balance model of nitrogen loading. The mass-balance model estimates potential water quality degradation as a function of nitrogen load from current and future septic systems and includes dilution both from groundwater flow and from the septic tanks themselves. The mass-balance model of nitrogen loading has been widely (and successfully) implemented by the Utah Geological Survey since the late 1990s in places such as Round Valley, Tooele Valley, Sanpete Valley, Cache Valley, and Cedar Valley and by other municipalities managing sole-source aquifers in other regions around the country. A mass-balance model was implemented in the HAL 1994 study to develop the recommendation for a septic system density of approximately 5 acres per system.

We chose to focus the mass-balance model on the Lake Creek planning area in the eastern basin. Most of this area is within the Heber Valley alluvial basin, but we extended it to include the Timberlakes development as well because it is a significant source of nitrogen loading to the aquifer. Existing nitrate concentration in the Lake Creek planning area was calculated to be 3.19 mg/L, and groundwater flow available for mixing was estimated to be 20.6 cfs. We conducted modeling for several scenarios:

- To account for uncertainties in inputs, we modeled projected nitrate using a baseline scenario as well as best- and worst-case scenarios that reflect 20% uncertainties in aquifer flows and nitrogen inputs from septic systems.
- To account for different allowable levels of degradation, we compared modeling results to 1-mg/L allowable degradation and to 2-mg/L allowable degradation.
- To account for future sewer development, four scenarios of land acreage were considered based on the percentage of land in the Lake Creek planning area on sewer network (0%, 30%, 50%, and 90% sewer connection).

The modeling yielded the predicted number of septic tanks and the resulting anticipated water quality; these results were then converted into septic tank density (acres/tank) (see report Figure 36). As an example of the results, for the baseline scenario, a lot size of 3.6 acres per septic system may result in a 1-mg/L increase in the Lake Creek planning area. If 30% of the land in the Lake Creek planning area is on sewer, a septic system density of 2.94 acres/septic system may increase nitrate by 1 mg/L. If 90% of the land in the Lake Creek planning area is on sewer, a septic system density of 1.72 acres per septic system may increase nitrate by 1 mg/L.

Similar calculations were done for the entire Heber Valley. We estimate that nitrate concentration in the Heber Valley aquifer could increase by 1 mg/L if 5,200 septic tanks are added to the valley. We estimate that nitrate from septic systems may stay below 3.0 mg/L if lot sizes are 5 acres each per septic system. Accounting for model uncertainties, the range of the projected nitrate concentration at 5 acres per septic system in the Heber Valley aquifer is calculated to be between 2.71 and 3.31 mg/L.

We also applied our mass-balance model to recreate the HAL 1994 calculations for the Charleston to Lake Creek transect. We estimate that 374 septic tanks are currently in this area. At 374 septic tanks, the 1994 HAL model predicts nitrate concentration in the Charleston to Lake Creek transect to be between 2.20 and 2.53 mg/L with a best estimate of 2.27 mg/L. In reality, the current nitrate concentration in the area is 2.82 mg/L, which the 1994 HAL prediction suggests would not have been reached until 718 to 723 septic tanks exist (nearly double the current number). In other words, the 1994 HAL model underestimates the impact on nitrate levels from septic tanks, with a number of possible explanations including the lack of inclusion of inputs from the Timberlakes development in the 1994 HAL model. Overall, though, the 1994 HAL recommendation of a minimum lot size of 5 acres per septic system appears to be effective at managing nitrogen load from septic systems for the valley as a whole.

We estimated the amount of nitrogen that is removed by wastewater treatment and land application and found that more than 70% of nitrogen compared to septic tanks may be removed from the system. WCHD estimates that as much as 85% of the Heber Valley may ultimately be on sewer. Mathematically, removal of this nitrogen load through treatment suggests that a high density of septic tanks could be placed in the remaining area while still maintaining water quality. High-density septic tank development violates several assumptions of the mass-balance model and should be assessed with care.

We estimate under our baseline model that average concentrations of nitrate in the Heber Valley aquifer will not increase by an additional 1 mg/L until 5,200 new septic systems are added to the valley; however, local increases would be expected depending on where septic systems are added. For one growth scenario, assuming 40% of the additional population is on septic, we estimate that it would not be until the year 2065 when this level of development would be reached.

Discussion and Recommendations (report Section 9)

The tools developed during the study have a common goal: to estimate anticipated changes in aquifer water quality from the addition of nitrogen from wastewater. A variety of regulatory approaches could be implemented to manage aquifer water quality using these tools. We explore the advantages and disadvantages of four possible management approaches:

1. Management by monitoring nitrate concentration, in which a limit would be set on the average nitrate concentration allowable in the aquifer, with a robust monitoring plan focused on a suite of sentinel wells. Development could occur unrestricted until concentrations exceeded an action level.
2. Management by limiting septic system density, as is currently in place.
3. Management by limiting nitrate load, which is similar to limiting density, but would allow for the possibility for nitrate removal.
4. A hybrid approach with management by limiting septic system density, as is currently in place, but allowing site-specific exceptions if they can be demonstrated to maintain similar loads.

We also make recommendations for future monitoring, building from the baseline monitoring conducted for the study.

CONTENTS

1 Introduction and Background 1
1.1 Study Objectives 1
1.2 Aquifer Classification and Protection 2
2 Results of Phase 1 of the Study 4
2.1 Areas of Concern 4
2.2 Data Gaps 5
2.3 Groundwater Sensitivity and Vulnerability Mapping 6
2.4 Sampling Approach and Methodology 13
2.4.1 Sampling Locations 13
2.4.2 Parameters 15
3 Groundwater Quality 16
3.1 Field Parameters 16
3.2 Total Dissolved Solids 18
3.2.1 Comparison to Historical Data 21
3.3 Nitrate 23
3.3.1 Comparison to Historical Data 26
3.4 Total Phosphorus 31
3.4.1 Comparison to Historical Data 34
3.5 Chloride 36
3.5.1 Comparison to Historical Data 39
3.6 Pesticides, Volatile Organic Compounds, and Metals 41
3.7 Personal Care Products and Pharmaceutical Compounds 43
3.8 Major Ions 46
3.8.1 Overall Aquifer Dynamics 46
3.8.2 Areas of Elevated TDS 47
4 Surface Water Quality 51
4.1 Existing Surface Water Quality 51
4.2 Land Uses and Pollutants of Concern 54
4.3 Monitoring Results 55
4.3.1 Timberlakes Development 56
4.3.2 Comparison to Groundwater Data 60
4.4 Surface Water and Groundwater Interactions 61
5 Groundwater Budget 63
5.1 Recharge 64
5.1.1 Precipitation 64
5.1.2 Surface Streams 65
5.1.3 Unconsumed Irrigation Water 65
5.1.4 Mountain-Front Recharge 66
5.1.5 Recharge from Wastewater 67
5.2 Discharge 67
5.2.1 Evapotranspiration 67
5.2.2 Leakage to Deer Creek Reservoir 69
5.2.3 Seepage to Surface Streams 69
5.2.4 Springs and Seeps 70

5.2.5 Potable Water Use from Wells and Springs 70
5.2.6 Subsurface Outflow to Consolidated Rocks 70
5.3 Areas of Uncertainty 71
5.3.1 Results from Groundwater Modeling 73
6 Groundwater Model Development 74
6.1 Background and Evaluation 74
6.2 Updated Understanding of Aquifer Characteristics 75
6.2.1 Model Development 78
6.2.2 Layer Conceptualization and Discretization 80
6.2.3 Model Calibration 80
6.2.4 Model Validation 81
6.3 Model Assumptions and Limitations 81
6.4 Groundwater Model of the Round Valley Aquifer 82
7 Impacts from Wastewater 82
7.1 The Mass-Balance Approach to Model Impact from Septic Systems 83
7.1.1 General Methods and Assumptions of the Mass-Balance Approach 84
7.1.2 Limitations of the Mass-Balance Approach and Estimates of Uncertainties 85
7.1.3 Lake Creek Septic System Density Evaluation 88
7.1.4 Heber Valley–Wide Septic System Density Evaluation 93
7.1.5 Round Valley Septic Density Evaluation 94
7.1.6 Re-Creation of 1994 HAL Model 96
7.2 Centralized Wastewater Treatment Plant Effluent 98
8 Future Growth 99
8.1 Implications of the Increase in Residential Development Connected to the Sewer System 100
9 Discussion and Recommendations 101
9.1 Potential Methods of Managing or Regulating Aquifer Water Quality 101
9.1.1 Management by Monitoring Nitrate Concentration 101
9.1.2 Management by Limiting Septic System Density 102
9.1.3 Management by Limiting Nitrate Load 102
9.1.4 Hybrid Approach: Management by Limiting Septic System Density, but Allowing Site-Specific Load Exceptions 103
9.2 Septic System Development and Maintenance Recommendations 103
9.3 Continued Groundwater Quality Monitoring 104
10 Summary and Conclusions 105
11 Literature Cited 107

Appendices

Appendix A. SWCA Environmental Consultants Field Data Measurements
Appendix B. Detailed Documentation for the 2020 Heber Valley Groundwater Model (HVGM2020)

Figures

Figure 1. Study area. 3
Figure 2. Sensitivity of the study area to groundwater contamination based on the spatial model. 10
Figure 3. Vulnerability of the study area to groundwater contamination based on the spatial model. 11
Figure 4. Study area, sampling locations (groundwater wells and river/stream sampling), and the combined sensitivity and vulnerability to potential groundwater contamination. 12
Figure 5. Linear regression analysis between individual paired TDS and specific conductance measurements (left) and paired average values (among all visits to each site) for each well (right). 17
Figure 6. Average TDS values at SWCA sampling locations (2018 to 2020). 19
Figure 7. TDS concentration versus well intake depth and well formation. 19
Figure 8. Average TDS values at SWCA sampling locations (2018 to 2020). 20
Figure 9. TDS concentrations at USGS wells in Heber Valley between 1998 and 2019. 22
Figure 10. TDS values from 1998 to 2020 at USGS wells in the Heber Valley. 22
Figure 11. Average nitrate concentrations at SWCA sampling locations (2018 to 2020). 24
Figure 12. SWCA sampling locations and average nitrate concentrations measured between 2018 and 2020. 25
Figure 13. Nitrate concentration versus well intake depth and well formation. 26
Figure 14. Time series graphs of nitrate concentrations between 1998 and 2019 at USGS wells in Heber Valley. 27
Figure 15. Boxplots of USGS nitrate concentrations in Heber Valley from 1998 to 2020. 28
Figure 16. Yearly average nitrate concentrations at community drinking water systems in the study area from 1994 to 2018. 30
Figure 17. Bar chart of average total phosphorus values at SWCA sampling locations (2018 to 2020). 32
Figure 18. Average total phosphorus values at SWCA sampling locations (2018 to 2020). 33
Figure 19. Time series graphs of phosphorus concentrations at nine USGS wells in the Heber Valley 35
Figure 20. Boxplot of total phosphorus concentrations at USGS wells in the Heber Valley from 1998 to 2020. 35
Figure 21. Average chloride concentration at SWCA sampling locations between 2018 and 2020. 36
Figure 22. Average chloride values at SWCA sampling locations (2018 to 2020). 37
Figure 23. Time-series graphs of chloride concentrations at USGS wells in the Heber Valley. 40
Figure 24. Boxplot of chloride concentrations at USGS wells in the Heber Valley from 1998 to 2020. 40
Figure 25. Piper diagram of water chemistry. 49
Figure 26. Study area showing stiff diagrams for ion concentrations in surface and groundwater samples. Label number refers to site name (see Table 13). 50
Figure 27. DWQ assessment units in the study area with 2016 Integrated Report assessment categories (Source: UDEQ 2019). 53
Figure 28. Timberlakes surface water sampling locations, NHD streams, and septic systems. 59
Figure 29. Average parameter concentrations from surface streams above and below the Timberlakes development. 60
Figure 30. Average parameter concentrations for groundwater samples above and below the Timberlakes development. 61
Figure 31. Potentiometric surface contours. 77
Figure 32. Cross sections of the Heber Valley aquifer. 78

Figure 33. The HVGM2020 model grid. 79
Figure 34. Lake Creek TAZ zones. 90
Figure 35. Projected nitrate in groundwater underlying the Lake Creek planning area. 92
Figure 36. Modeled relationship between septic system density and projected nitrate concentration under four scenarios of sewer expansion in the Lake Creek planning area. 93
Figure 37. Modeled relationship between number of septic tanks and projected nitrate concentration in the Round Valley aquifer (A.), and septic tank density and projected nitrate concentration (B.) (Inkenbrandt 2019). 95
Figure 37. Digitization of HAL (1994) Lake Creek to Charleston Transect. 96
Figure 38. HAL 1994 model of nitrate concentration versus septic system density in the Charleston to Lake Creek transect. 97

Tables

Table 1. Past, Current, or Future Threats to Groundwater Resources in the Study Area 4
Table 2. Discussion of Data Gaps Related to Groundwater Resources in the Study Area 6
Table 3. Natural Factors (Sensitivity) 8
Table 4. Anthropogenic Activities (Vulnerability) 8
Table 5. Attributes of Water Quality Sampling Locations 14
Table 6. Water Quality Parameters for Which Samples Were Analyzed During the Study 15
Table 7. Sources of Groundwater Pollution and the Associated Chloride-to-Bromide Mass Ratio Ranges 38
Table 8. Chloride-to-Bromide Ratios at SWCA sampling locations 38
Table 9. Sampling Locations for Volatile Organic Compounds, Pesticides, Herbicides, and Metals 42
Table 10. List of Pesticides and Herbicides Tested in the Spring 2019 Sampling Event 43
Table 11. Personal Care Product and Pharmaceutical Sampling Results 44
Table 12. Compounds Present in the PPCP Sampling Suite 45
Table 13. Concentrations of Cations and Anions Sampled during the Fall 2019 Sampling Event 48
Table 14. Surface Water Assessment Determinations from DWQ 2016 Integrated Report 51
Table 15. Land Use in the Study Area and the Associated Pollutants of Concern as Well as Their fate and Transport in Surface and Groundwater 54
Table 16. Surface Water Quality Monitoring Results 56
Table 17. Groundwater Budget Summary and Comparison to Previous Studies for Groundwater Budget Estimates 63
Table 18. Discussion of Level of Uncertainty and Potential Effect for Each Water Budget Component 71
Table 19. 5-year Average Nitrate Concentrations at Individual Wells Located in the Heber Valley Aquifer 85
Table 20. Discussion of the Level of Uncertainty and Potential Effect for Each Mass-Balance Model Component 87

1 INTRODUCTION AND BACKGROUND

Wasatch County is one of the fastest growing counties in the state of Utah. Rapid development and population growth have taken place in the county over the past few decades and are projected to continue through 2050 (MAG 2020; University of Utah 2020). This historically agricultural area has seen a conversion of agricultural lands to residential development, most of which uses on-site small wastewater disposal (septic) systems. Although the proportion of the development connected to centralized wastewater treatment systems (via sanitary sewers) continues to increase, a large proportion of the county continues to depend on septic systems for wastewater disposal. Concern that groundwater resources that provide the county's drinking water could be susceptible to contamination from wastewater systems and higher density residential development has led the Wasatch County Health Department (WCHD) to investigate the potential impacts of wastewater contamination to groundwater quality and to implement regulations to limit potential contamination groundwater.

In 1994, WCHD commissioned a study to evaluate existing Wasatch County water quality protection measures and to prepare or strengthen guidelines for drinking water source protection, septic system development, and surface water protection (Hansen, Allen & Luce [HAL] 1994). Recommendations from the HAL study with regard to the septic system management practices included the following: 1) require that septic system plans be prepared and filed with the local health department, 2) initiate a maintenance permit program that would require annual inspections for septic tank system owners, and 3) create districts for septic system management. HAL estimated that the average nitrate concentration in the Heber Valley aquifer was approximately 2 milligrams per liter (mg/L). HAL recommended a septic system density of one septic system per 5 acres of land based on the allowable nitrate degradation (determined by the WCHD) of 1 mg/L. HAL also provided septic system regulation recommendations for site evaluation, locational standards, design criteria, and management practices. The septic system density recommendation resulted in a county-wide regulation that limits new development (to 1 system per every 5 acres) in portions of the county that do not have access to the sewer network. The WCHD did not implement the recommendations to initiate a septic maintenance program or to create districts for septic system management.

Approximately 25 years after HAL's study, WCHD engaged SWCA Environmental Consultants (SWCA) to implement an updated groundwater study to evaluate the condition of groundwater resources in Heber and Round Valleys, evaluate the effectiveness of measures implemented following the HAL study, to set a baseline for groundwater conditions as part of a future groundwater monitoring program, and to make recommendations for future monitoring and management of the groundwater aquifer. This report summarizes Phase 2 of the groundwater study building off of the information gathered during Phase 1 of the groundwater study, which included a literature review and summary of existing information, a geographic information system (GIS) study, and a preliminary assessment of general groundwater quality conditions within the county.

1.1 Study Objectives

The purpose of this report is to describe the body of knowledge gathered by SWCA related to the groundwater resources of the Heber and Round Valleys of Wasatch County (study area shown in Figure 1). During Phase 1 of the study, SWCA identified data gaps related to the Heber and Round Valley aquifers and the quality of the water within both. In this report, SWCA presents and discusses research, sampling, and modeling efforts that were developed to address data gaps identified in the Phase 1 report.

The objectives of Phase 2 of the WCHD groundwater study are to 1) collect new data to characterize the water quality of the Heber and Round Valley aquifers and evaluate changes in water quality over the past

25 years, 2) attempt to link any degradation of water quality with specific activities within the study area, 3) model the effect of future population growth on water quality of the aquifers, and 4) make recommendations to the WCHD related to regulations on development of small wastewater disposal systems within Wasatch County to inform WCHD's future planning decisions. The findings of Phase 2 of the study and future monitoring will help WCHD evaluate current and future county regulations as they may influence groundwater quality.

1.2 Aquifer Classification and Protection

Most of the aquifers of Wasatch County are classified as Class 1A with some near Midway classified as Class II. Class 1A and Class II aquifers are both considered drinking water quality, and State of Utah code specifies that they should be protected as drinking water:

> Class 1A ground water will be protected to the maximum extent feasible from degradation due to facilities that discharge or would probably discharge to ground water. The following protection levels will apply: 1) Total dissolved solids may not exceed the greater of 1.25 times the background or background plus two standard deviations. 2) When a contaminant is not present in a detectable amount as a background concentration, the concentration of the pollutant may not exceed the greater of 0.1 times the ground water quality standard value, or the limit of detection. 3) When a contaminant is present in a detectable amount as a background concentration, the concentration of the pollutant may not exceed the greater of 1.25 times the background concentration, 0.25 times the ground water quality standard, or background plus two standard deviations; however, in no case will the concentration of a pollutant be allowed to exceed the ground water quality standard. (Utah Administrative Code [UAC] R317-6-4)

In the code, "background concentration" means the concentration of a pollutant in groundwater upgradient or lateral hydraulically equivalent point from a facility, practice, or activity that has not been affected by that facility, practice, or activity.

For Class II aquifers, the code specifies that Class II groundwater will be protected for use as drinking water or other similar beneficial use with conventional treatment prior to use. The three protection levels that apply to Class II aquifers are the same as those specified for Class 1A.

Based on the monitoring of groundwater quality, background concentrations of total dissolved solids (TDS) are roughly 210 mg/L) for the Class 1A aquifer and 611.5 mg/L for the Class II aquifer[1]. Based on the guidance from the state code, increases in TDS of up to 260 mg/L would be allowed from discharges into the aquifer. However, "Ground water classifications are intended to be used as a planning tool by local governmental agencies. Ground water classifications do not mandate any specific actions for local planning and zoning, nor obligate local governments to perform any technical assessments or monitoring, nor restrict existing or future land use."

[1] Total dissolved solids (TDS) is a water quality measurement conducted in the laboratory that relates the mass of dissolved constituents in a given quantity of water. TDS is typically measured in units of milligrams per liter. Specific conductance is a measurement typically made in the field using a handheld meter. Specific conductance measures how readily an electrical current travels through a water sample. Because the amount of dissolved solids generally increases the conductance of a liquid, specific conductance is a useful proxy for TDS. The exact conversion factor can vary; a site-specific conversion factor for the Heber Valley is calculated in Section 3 of this report.

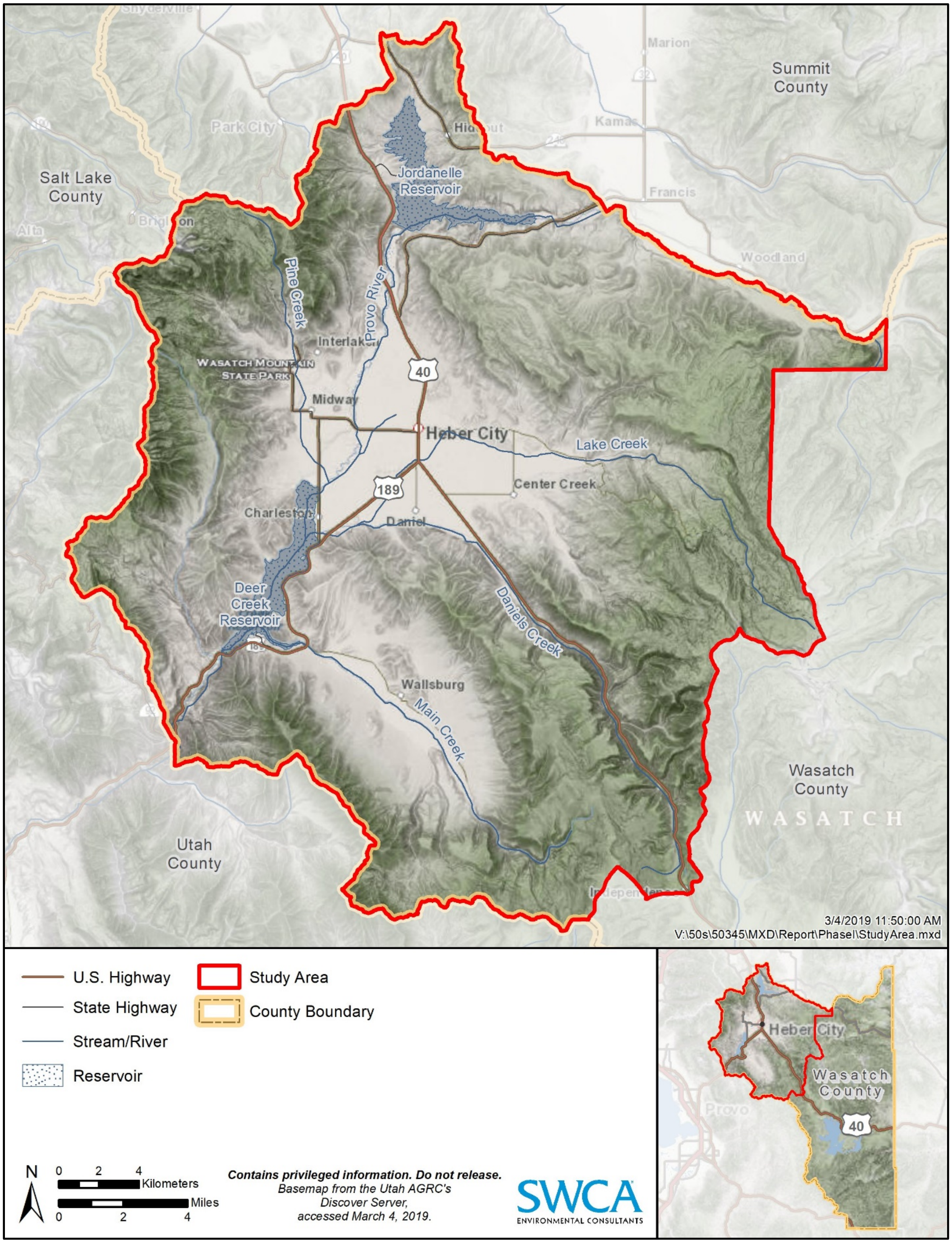


Figure 1. Study area.

2 RESULTS OF PHASE 1 OF THE STUDY

In Phase 1 of the study, SWCA compiled relevant studies and information completed to date for the study area. The main hydrogeologic investigations were completed more than 25 years ago, and subsequent water quality monitoring has been sparse. The available information indicates that groundwater in Heber and Round Valleys is of high quality and is meeting State of Utah groundwater standards based on current aquifer classification. However, groundwater degradation from anthropogenic activities is possible, especially given increasing development of the area and the physical properties of the aquifers in the study area. In addition, groundwater water quality monitoring done by the U.S. Geological Survey (USGS) has indicated concentrations above background levels for certain contaminants.

2.1 Areas of Concern

The Phase 1 report (SWCA 2019a) identifies a list of past, current, and future threats to the groundwater resources of the study area. The items included in the list were identified from previous studies and from an analysis of activities and land uses in the study area that pose a threat of contamination to groundwater resources (Table 1). Acknowledging the list of threats, a separate list of perceived data gaps and potential approaches for filling each of these gaps was developed at the end of Phase 1 (Table 2). Phase 2 of the study was designed to address many of the data gaps identified in Phase 1 and to assess the severity of some of the main threats as they relate to the data gaps.

Table 1. Past, Current, or Future Threats to Groundwater Resources in the Study Area

Contaminant or Area of Concern	Discussion
Pesticides	The 2003 Utah Geological Survey (UGS) pesticide sensitivity and vulnerability study (Lowe et al. 2003) reveals that although pesticides did not pose a serious threat to groundwater at the time, continued monitoring is warranted because of high pesticide sensitivity and vulnerability. Aquifers in Heber and Round Valleys are not protected by impermeable clay layers, and soils are highly conductive. The State of Utah has adopted groundwater numeric criteria for 28 pesticides and polychlorinated biphenyls (PCBs).
Groundwater in fractured rocks	Groundwater in fractured rocks (as is found in upland areas surrounding Heber and Round Valleys) is highly susceptible to pollution because there is little soil cover and therefore little capacity for filtration (Lowe 1995). However, terrain that is rocky and steep is generally not suitable for waste disposal operations such as landfills or septic tanks.
Increasing nitrate in USGS groundwater monitoring wells/increasing background concentrations	The Provo River Watershed Council's *2015 Water Quality Implementation Report* identified USGS wells with increasing nitrate concentration. "Concentrations of nitrates are continuing to increase along the southeastern and south side of the valley. The reasons that these increases are occurring has not been identified" (Desert Rose Environmental 2016:9–4). The USGS wells identified in the report were (D-4-4) 12dcc-1, (D-4-5) 3dcc-1, and (D-4-5) 4ccb-1. USGS monitoring indicates the average nitrate concentration at USGS well (D-4-5) 3dcc-1 located in the Lake Creek planning area is 6.25 mg/L, more than three times the background nitrate concentration in the Heber Valley aquifer. USGS wells in the Lake Creek planning area also have the highest seasonal water level fluctuations.
Leaking underground storage tanks	Approximately 48 separate incidents of leaking underground storage tanks in Wasatch County were reported to the Utah Division of Environmental Response and Remediation (DERR) between 1988 and 2019 (DERR 2019). DERR regulates underground storage tanks with a minimum capacity of 110 gallons that hold either petroleum products or certain hazardous chemicals.

Contaminant or Area of Concern	Discussion
Volatile organic compounds (VOCs)	All groundwater samples collected by SWCA in fall 2019 and analyzed for VOCs had results below the detection limit; however, continued monitoring for these chemicals is warranted. The State of Utah has adopted groundwater numeric criteria for 28 different VOCs. The USGS conducted a national assessment of 55 VOCs in groundwater in 2006. VOCs were detected at low levels in many aquifers across the country. Trihalomethanes (THMs), which may come from chlorine disinfection of drinking water, were the most commonly detected VOC in groundwater (Zogorski et al. 2006). “The widespread occurrence of VOCs indicates the ubiquitous nature of VOC sources and the vulnerability of many of the Nation’s aquifers to low level VOC contamination” (Zogorski et al. 2006:3).
Contaminants of emerging concern (CECs)	CECs are a wide class of chemicals that include pharmaceuticals and personal care products. The U.S. Environmental Protection Agency (EPA) is currently investigating CECs to develop numeric criteria for aquatic life. Continued monitoring of CECs is warranted given the research demonstrating the toxicity of CECs to human and aquatic life and the persistence of these chemicals in the environment.
Septic system density and waste load	A mass-balance model using population density was used during Phase I of the study to estimate nitrogen loading due to septic systems. Although no areas appear to exceed the drinking water standard of 10 parts per million (ppm) of nitrate, several areas of concern were identified where USGS data are not provided. These include 1) several areas in Charleston proximal and upgradient of Deer Creek Reservoir and the Provo River; 2) development in the uplands west of Midway along Swiss Alpine Road, Lime Canyon Road, and Snake Creek Road; 3) the Pine Canyon Road area west of the Jordanelle Reservoir; 4) Deer Mountain north and upgradient of Jordanelle Reservoir; 5) west and downgradient of Timber Lakes; 6) Woodland adjacent to the upper Provo River; and 7) downgradient and within Wallsburg. HAL provided a density recommendation of one septic system per 5 acres of land in order to meet the recommended allowable nitrate concentration degradation of 1 mg/L (HAL 1994).
Stormwater runoff	Nutrients (agricultural), pesticides (agricultural), chloride (road salt), and other contaminants may be transported into groundwater during unsaturated surface conditions (EPA 2019).
Long-term trends in groundwater levels	A trend analysis of groundwater levels with a 95% confidence interval indicates that groundwater levels are declining at 11 out of 22 USGS wells examined in Heber Valley. In these cases, groundwater levels show a significant downward trend after removing the effect of antecedent precipitation. At the remaining 11 wells, the evidence was insufficient to conclude that a trend in either direction existed. None of the wells showed a positive trend in groundwater levels (SWCA 2019b).
Phosphorus levels in groundwater	As noted in the Deer Creek Reservoir total maximum daily load report (PSOMAS 2002), phosphorus loading from groundwater accounts for 18% of the annual total phosphorus load to the reservoir. According to HAL (1994), “the absorption and precipitation capabilities of the Heber Valley aquifer for phosphorous removal are not known” (HAL 1994:III-9). Continued monitoring of background phosphorus levels is warranted given the lack of information regarding the long-term phosphorus absorption capacity of the aquifers in the study area.

2.2 Data Gaps

The review of existing information completed during Phase 1 of the study exposed several data gaps related to the aquifers and the potential for water quality degradation. Table 2 summarizes data gaps identified during the review of existing information in addition to an approach for filling them during Phase 2. Not all data gaps identified in Phase 1 were addressed during Phase 2 of the study.

Table 2. Discussion of Data Gaps Related to Groundwater Resources in the Study Area

Data Gap	Approach to "Filling" the Gap
Groundwater quality data: The USGS collects samples on an annual basis from a small group of wells within Heber Valley and has them analyzed for a suite of parameters. However, there are no data available outside of the summer months or for a large portion of the study area (including Round Valley). Also, no data are available for emerging contaminants	SWCA developed sampling and analysis plans (SAP) to guide the collection of groundwater quality samples in spring 2019, fall 2019, and spring 2020. The SAPs include additional sampling locations (beyond the list sampled by USGS) and parameters for analysis beyond what USGS has traditionally sampled for.
Stormwater data: Information regarding the flow and chemical composition of stormwater within the study area is generally lacking.	SWCA did not collect stormwater samples as part of this project; however, SWCA made assumptions about stormwater pollutant constituents and loading based on stormwater data collected in similar watersheds in Utah.
Aquifer testing: For the water budget and to understand groundwater flow, aquifer tests are valuable compared to the specific capacity estimates used for the transmissivity estimates. Currently the models predict much higher transmissivity values than suggested by the well capacity tests and the one aquifer test that has been discussed (Inkenbrandt 2019)	SWCA conducted reviews of the drinking water source protection reports for aquifer test information in addition to well drilling logs.
Aquifer properties	Aquifer characteristics such as transmissivity, hydraulic conductivity, aquifer thickness, and water storage were estimated in previous hydrologic studies by examining specific capacity from well drillers' logs. SWCA made updated estimates of transmissivity and hydraulic conductivity from groundwater protection zone delineation reports, drillers' logs, and groundwater modeling.
Literature review outside the study area	SWCA's literature review was expanded outside the study area to evaluate other relevant studies to provide insight on groundwater modeling efforts or future sampling efforts.
Climate change	The effects of climate change on the water resources in the study area is not well documented or understood, although SWCA considered the potential impacts of climate change when developing the water budget. Robust and long-term datasets for many individual parameters are generally needed to model climate change effects. Additional data will likely be required.
Consolidated rock aquifers: Roark et al. (1991) stated that several public water supply systems obtain drinking water that comes from springs discharging from consolidated rock aquifers; however. the primary focus of the investigation was related to groundwater in the unconsolidated valley-fill deposits.	As part of a groundwater budget, SWCA estimated rates of recharge, rates of discharge, and groundwater movement.
Groundwater contamination from leaking underground storage tanks (LUSTs)	LUSTs in California were evaluated in a 1998 study conducted by D.W. Rice and W.W. McNab (Rice and McNab 1998) that looked at LUST sites in California and determined that rarely do they contaminate groundwater farther than a few hundred feet. A literature review should be conducted to see if similar studies have been undertaken in Utah.
Private drinking water supply wells: Information is generally not available about groundwater quality or about the consumptive use rate of groundwater pumped from private wells.	SWCA's groundwater monitoring included collection of groundwater quality samples from numerous private wells within the study area.

2.3 Groundwater Sensitivity and Vulnerability Mapping

SWCA completed a spatial analysis of the study area using geographic information system (GIS) to evaluate the sensitivity and vulnerability of groundwater resources to contamination from anthropogenic activities. These analyses were meant to 1) help inform the details of SWCA's sampling and analysis plans (SAPs) and 2) be used as a resource for WCHD to assist in evaluating locations of future development. Groundwater sensitivity was evaluated using natural factors that describe physical attributes favorable to the transport of pollutants either spilled at the ground surface or delivered subsurface. Hydrogeologic setting (areas of recharge or discharge), hydraulic conductivity of soils, depth to restrictive or impermeable layer, and depth to water table were the primary factors analyzed in determining groundwater sensitivity.

Groundwater vulnerability was determined by evaluating anthropogenic activities occurring in the study area that have potential to impact groundwater quality. Predicted nitrate concentration in groundwater (based on census data for portions of the study area on septic systems [SWCA 2019a]), land use (residential, agricultural, or open space), the proximity to point sources (such as groundwater discharge permits, underground injection, underground storage tanks, hazardous waste facilities, etc.), and Utah Division of Drinking Water (DDW) groundwater protection zones were the primary factors used in determining groundwater vulnerability.

For both the sensitivity and vulnerability analyses, once input layers were identified, corresponding GIS data were obtained and added to the study database. Attributes of each input layer were ranked based on potential for impacting groundwater quality (from low to high). A raster layer was then created for each input layer, and each raster cell (10 × 10 meters [m]) was assigned a rank based on the attributes within that cell. Cumulative assessment involved totaling the scores for each raster cell.

As shown in Table 3, the attributes of the data within each input layer to the sensitivity map were reclassified and assigned a rank between 0 and 3 depending on the potential to impact groundwater resources (0 having the lowest potential, 3 having the highest potential). Each raster cell (10 × 10 m) for each input layer was assigned a score. The final sensitivity map (Figure 2) was produced by overlaying the sensitivity input layers (hydrogeologic setting, hydraulic conductivity of soils, depth to restrictive layer, and depth to water table) and summing the scores in each raster cell using the weighted sum analyst tool in ArcGIS, with all layers having equal weight. For example, if a given location was in a secondary recharge zone (score of 2), was classified as hydrologic soil group D (score of 3), had 100 centimeters (cm) to restrictive layer (score of 3), and 50 cm to water table (score of 3), the total sensitivity score would be 2 + 3 + 3 + 3 = 11. Sensitivity scores for each cell are depicted by a color shading scheme in Figure 2.

The same process was repeated to develop the groundwater vulnerability map. Spatial datasets for predicted nitrate concentration in groundwater (based on census data for portions of the study area on septic systems), land use (undeveloped, agricultural, or developed), the proximity to point sources (such as groundwater discharge permits, underground injection, underground storage tanks, etc.), and DDW groundwater protection zones were combined into a single map. Following the same methodology described above for the sensitivity analysis, each input layer was given a series of rankings (between 0 and 3) for each of its value classes based on the potential to impact groundwater quality (Table 4). Using the weighted sum analyst tool in GIS and giving each parameter equal weight, the scores in each raster layer were summed for each cell on the map. Groundwater vulnerability was based on the sum of scores for each input layer. Figure 3 depicts the vulnerability of the study area to groundwater contamination.

The sensitivity and vulnerability spatial models were overlaid on top of each other to evaluate the alignment of the “hot spots” from each analysis. The resulting map was used as one of the tools to identify sampling locations for groundwater quality modeling. Existing private and community wells located as close to the sampling locations as possible were selected for sampling, and access to the wells was coordinated with well owners. The combined sensitivity and vulnerability map with the sampling locations overlain is shown as Figure 4. Specific land uses and point sources in proximity to each of the sampling locations from the vulnerability mapping exercise informed the list of parameters for analysis at each site (described in more detail in Sections 2.4 and 3.5).

Table 3. Natural Factors (Sensitivity)

Input Layer	Description	Value Range	Rank	Discussion
Hydrogeologic setting	(Groundwater recharge zone: primary, secondary, etc.)	Categorical	0: Discharge 2: Secondary recharge 3: Primary recharge	For areas with no data, SWCA reclassified the following areas: U.S. Forest Service land above Heber Valley = primary recharge valley uplands. Wallsburg: Used hydrologic unit code (HUC) 12 boundary. Area near Main Creek = primary recharge valley upland. Area above Deer Creek = not a recharge zone. Above Deer Creek Reservoir = not a recharge zone (HUC 12). Above Midway = Midway area recharge.
Hydrologic soil group	A–D (A has high permeability/low runoff potential; D has low permeability/high runoff potential.)	Categorical	3: ≥ 1 inch per hour 3: No data 1: < 1 inch per hour	Used methodology from Lowe and Butler (2003:10): "For GIS analysis, we divided soil units into two hydraulic conductivity ranges: greater than or equal to, and less than, 1 inch (2.5 cm) per hour. We chose 1 inch (2.5 cm) per hour because it corresponds to the minimum allowable percolation rate permitting septic tanks under Utah Division of Water Quality administrative rules. For areas having no hydraulic conductivity data, we applied the greater than or equal to 1 inch (2.5 cm) per minute … to be protective of ground-water quality."
Depth to any restrictive layer	Soil Survey Geographic database soils (Natural Resources Conservation Service 2017)	25–201 cm	1: 0–40 2: 41–75 3: 76–201	–
Depth to water table	Soil Survey Geographic database soils (Natural Resources Conservation Service 2017)	46–201 cm	1: > 200 2: 91–200 3: 0–90	–

Note: Spatial information about the aquifer type (consolidated rock aquifer versus valley-fill) is not available. SWCA identified consolidated rock aquifers as an area of concern during Phase 1.

Table 4. Anthropogenic Activities (Vulnerability)

Input Layer	Description	Category	Value Range	Rank	Discussion
Predicted nitrate concentration	SWCA nitrate model output (SWCA 2019a)	Nonpoint source	3–40 mg/L	0: < 1 mg/L 1: 1–2 mg/L 2: 2–5 mg/L 3: > 5 mg/L	Removed areas with sewer. Used parcel data and sewer line data. Where sewer and septic overlap, septic overrules sewer to be conservative.
Land Use (National Land Cover Database 2011)	Land use categories	Nonpoint source	Categorical	0: all other categories 1: undeveloped 3: agriculture, high-intensity development, medium-density development	Municipal boundaries: reclassified as 3 (high-intensity developed) Subdivision layer: reclassified as 3 (low-intensity development Manually reclassified Timber Lakes development as 3 (high-intensity development)

Input Layer	Description	Category	Value Range	Rank	Discussion
Utah Department of Environmental Quality (UDEQ) point sources (UDEQ 2019)	Known point sources of potential groundwater contaminants	Point source	Density value (no units) assigned from Kernal density analysis output.	Density Value 1: 0.0–1.5 2: 1.5–5.0 3: > 5	Kernal density tool, 0.5-mile radius was the threshold for running the analysis.
Groundwater protection zone (UDEQ 2019)	Zones 1–4	Receptor	Categorical	1: Zone 3/4 2: Zone 2 3: Zone 1	Where polygons overlap, lower numbered zones take precedence over higher numbered zones (assumption to be more conservative/protective to groundwater).

Under this model, aquifer vulnerability has likely increased over time as septic development and Utah Department of Environmental Quality (UDEQ) point sources have increased. General growth within Wasatch County has likely resulted in increased potential for contamination of the groundwater aquifer. Shallow groundwater is more vulnerable to anthropogenic contamination because there is a smaller unsaturated buffer between surface activities and groundwater. Sensitivity due to shallow groundwater levels (depth to water table; see Table 3) likely has not changed dramatically over time. Although water levels are declining at some wells in the Heber Valley aquifer, the volume of groundwater recharge and flow has not changed dramatically and remains significant (SWCA 2019b). Groundwater levels are further discussed in Section 5. Recharge of clean water and movement of groundwater through the aquifer provide dilution to protect the aquifer from contamination.

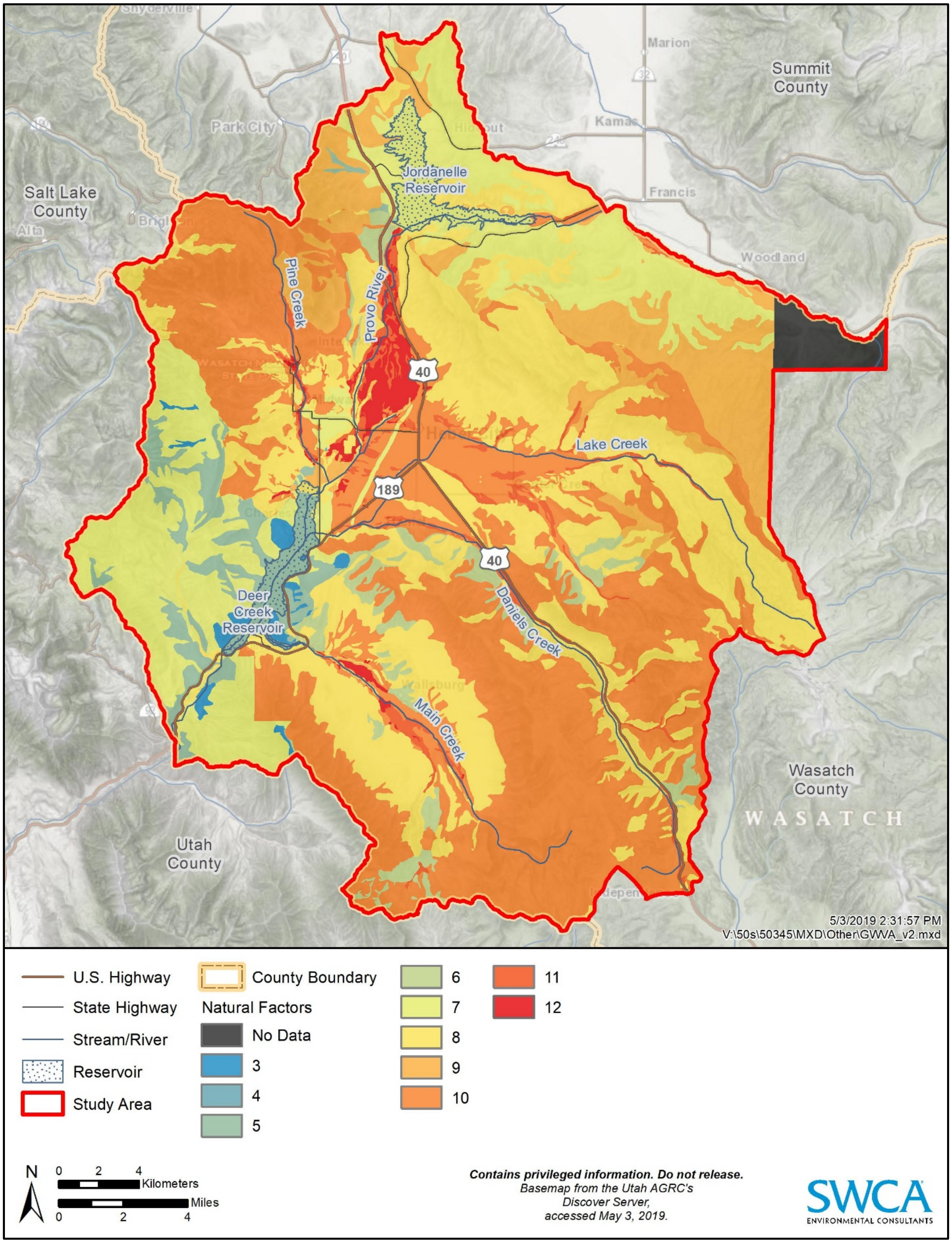


Figure 2. Sensitivity of the study area to groundwater contamination based on the spatial model.

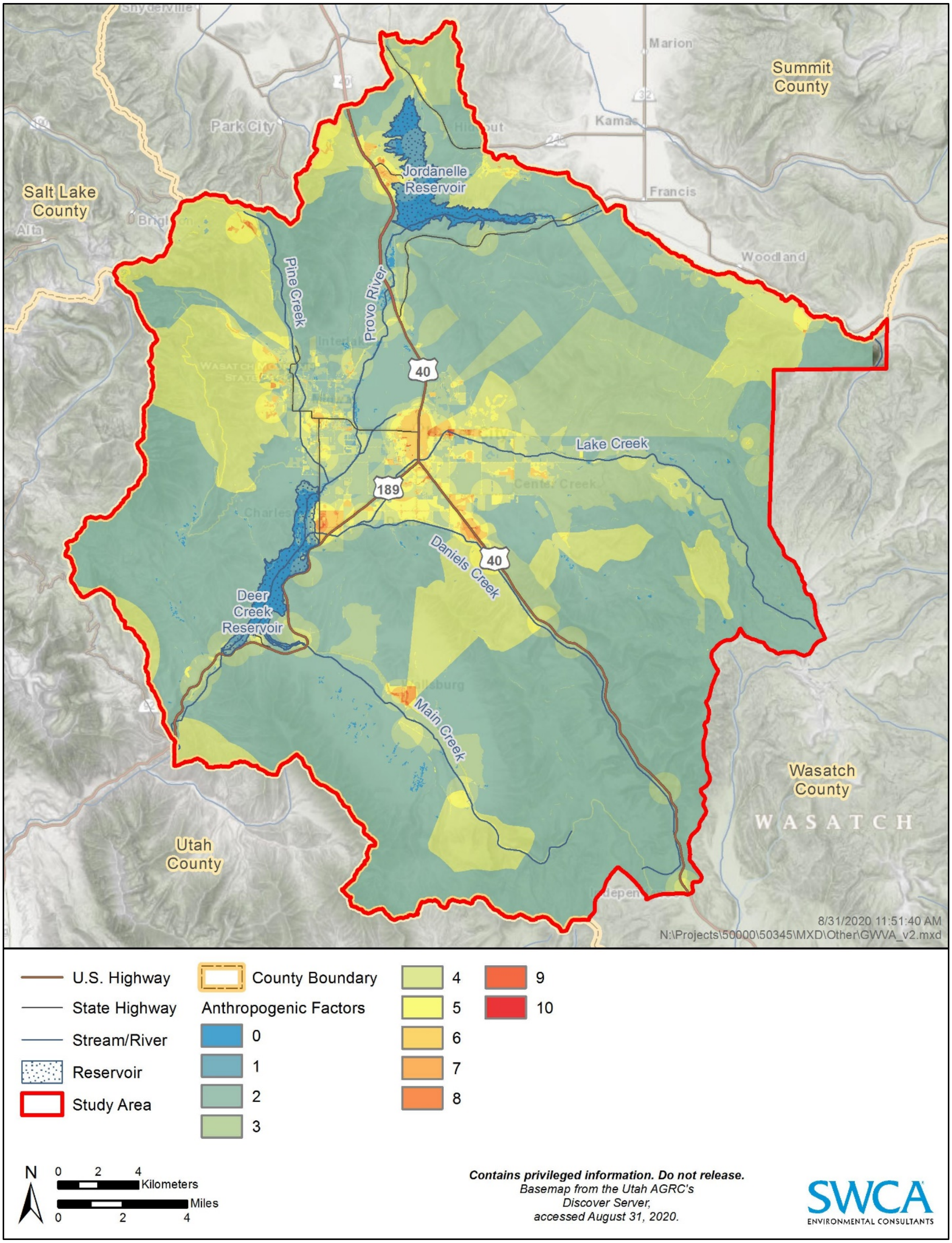


Figure 3. Vulnerability of the study area to groundwater contamination based on the spatial model.

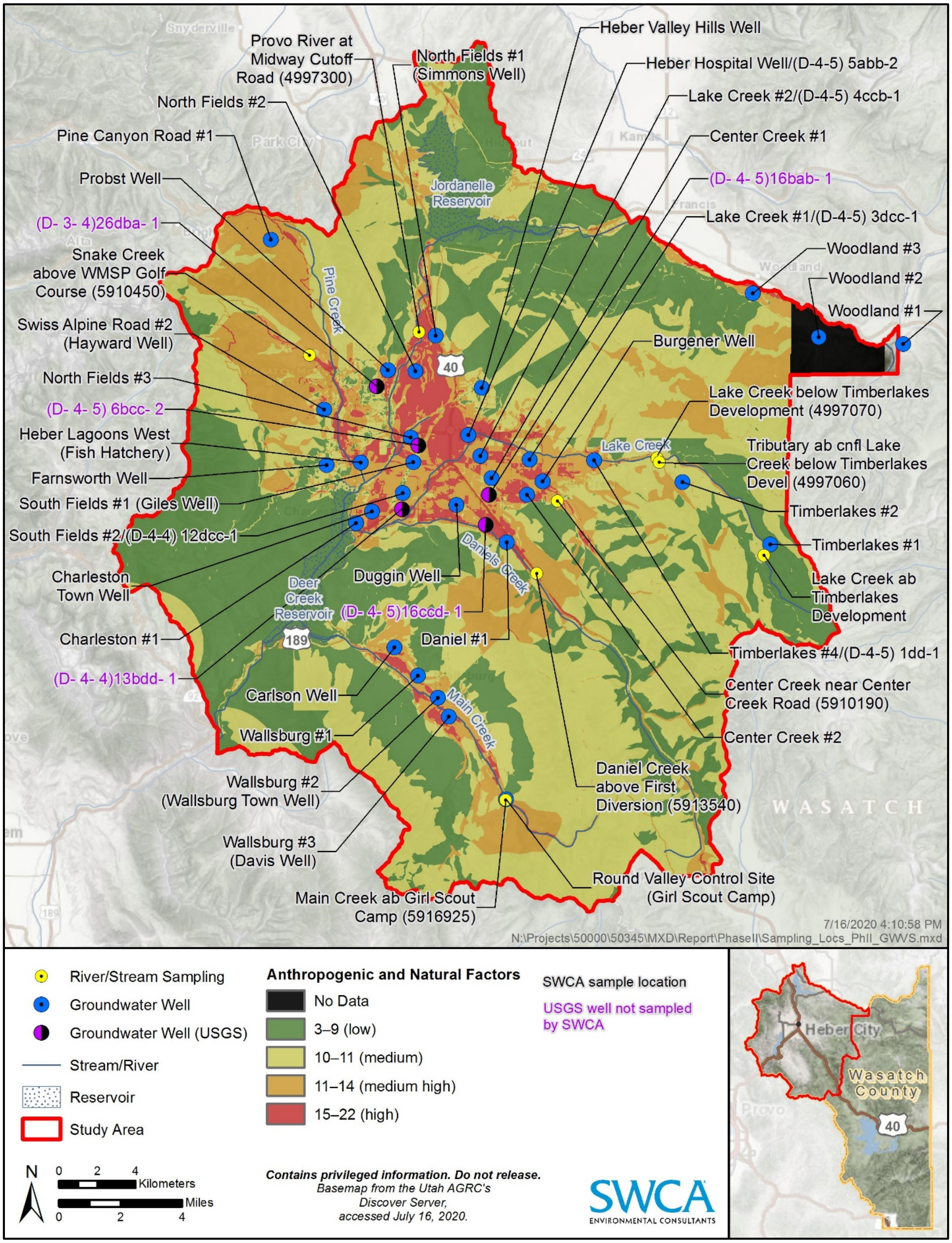


Figure 4. Study area, sampling locations (groundwater wells and river/stream sampling), and the combined sensitivity and vulnerability to potential groundwater contamination.

2.4 Sampling Approach and Methodology

One of the main objectives of the study is to investigate groundwater quality in the Heber and Round Valleys to provide additional resolution to existing data or to establish baseline conditions for future monitoring and management activities. The 1994 HAL study references data collected by the USGS and establishes 2 mg/L as a background concentration for nitrate; however, no comprehensive analysis of groundwater quality had been done to date. SWCA's investigation of groundwater quality included analysis of both existing data (from the USGS and DDW) and additional samples to be collected by SWCA. The SWCA sampling was designed to supplement the USGS dataset and establish a more robust baseline dataset for future reference.

Although the USGS maintains approximately 11 active groundwater monitoring wells in the Heber Valley, there are no active USGS wells in developments or townships such as Woodland, Timberlakes, or Brighton Estates. Additionally, there are no active USGS monitoring wells in Round Valley. The USGS defines an active site as having time series data collected in the past 6 months, or discrete data collected within the last 13 months. Therefore, the water quality data collected by SWCA in this hydrologic investigation will serve as important baseline data to which future groundwater quality data can be compared, especially in developments that are not routinely monitored by the USGS.

The approach and methodology for sampling was based on information gathered in the Phase 1 of the study to address the identified data gaps. Because of the historic drought conditions of fall 2018 and an interest in documenting the potential impact of the drought on water quality, SWCA worked with the WCHD to develop an abbreviated SAP and collect groundwater samples from a series of wells prior to winter. Access to the wells was coordinated by WCHD, and the list of parameters for analysis was developed by SWCA and WCHD. Following the collection of samples in November 2018 (the first sampling event), SWCA performed a comprehensive analysis of existing information aimed at informing the SAPs for three subsequent sampling events: spring 2019, fall 2019, and spring 2020.

Using the results of the groundwater sensitivity and vulnerability analysis (see Section 2.3, Figure 4), SWCA identified areas of greatest sensitivity and vulnerability to groundwater contamination and attempted to locate (both private and public) wells in those areas. SWCA worked with the WCHD to contact the owners of wells to obtain permission to visit wells and collect water samples. Once permission was obtained from well owners, a list of parameters for analysis was developed for each well based on anthropogenic activities proximal to, and immediately "upstream" of, the well. For example, wells within the North and South Fields areas were screened for common herbicides and pesticides because of the current and historic agriculture use of those areas.

2.4.1 *Sampling Locations*

Table 5 and Figure 4 include the groundwater and surface water locations sampled during the study. Additionally, Figure 4 includes USGS wells that were included in the data analysis but not sampled by SWCA personnel. Because of access and permission limitations, not all locations were sampled during each sampling event. Furthermore, modifications to goals and objectives lead to certain sites being removed from the SAP after a single sample event. The water right number, aquifer formation[2], and water intake depth for each well were obtained from drilling logs obtained from the Utah Division of Water Rights (DWRi) database area included in Table 5. Where possible, SWCA selected sampling locations

[2] The two aquifer formations in the study area are discussed in greater detail in Section 6. These two aquifer formations are referred to as alluvium (which is unconsolidated material) and bedrock (which is consolidated material). The alluvial aquifer is underlain by the bedrock aquifer within the Heber Valley basin. Generally speaking, groundwater is derived from the pore spaces within the alluvium and from fractures within the bedrock.

that coincided with existing sampling locations visited by the USGS (groundwater) or Utah Division of Water Quality (DWQ) (surface water).

Table 5. Attributes of Water Quality Sampling Locations

Sampling Location Name	Type	Water Right Number	Intake Formation	Intake Depth (feet)
Burgener Well	Well	55-6508	Alluvium	Missing
Carlson Well	Well	55-4658	Alluvium	97
Center Creek #1	Well	55-7012	Alluvium	Missing
Center Creek #2	Well	55-7109	Alluvium	175
Charleston #1	Well	55-2542	Alluvium	298
Charleston Town Well	Well	55-4581	Alluvium	120
Daniel #1	Well	55-6654	Bedrock	75[*]
Duggin Well	Well	55-11990	Alluvium	245
Farnsworth Well	Well	55-9684	Bedrock	160
Heber Hospital Well/(D-4-5) 5abb-2[^]	Well	55-3346	Bedrock	142
Heber Lagoons West (Fish Hatchery)	Well	55-9602	Bedrock	145
Heber Valley Hills Well	Well	55-5780	Bedrock	230
Lake Creek #1/(D-4-5) 3dcc-1[^]	Well	55-7995	Alluvium	Missing
Lake Creek #2/(D-4-5) 4ccb-1[^]	Well	55-5397	Alluvium	150
North Fields #1 (Simmons Well)	Well	55-5423	Alluvium	222
North Fields #2	Well	55-9696	Alluvium	130
North Fields #3	Well	55-9112	Alluvium	160
Pine Canyon Road #1	Well	55-12551	Bedrock	205
Probst Well	Well	55-9199	Bedrock	136
Round Valley Control Site (Girl Scout Camp)	Well	55-4745	Bedrock	140
South Fields #1 (Giles Well)	Well	55-12470	Alluvium	74
South Fields #2/(D-4-4) 12dcc-1[^]	Well	55-888	Alluvium	75
Swiss Alpine Road #2 (Hayward Well)	Well	55-8019	Alluvium	134
Timberlakes #1	Well	55-12720	Bedrock	370
Timberlakes #2	Well	55-12229	Alluvium	95
Timberlakes #4/(D-4-5) 1dd-1	Well	Missing	Bedrock	Missing
Wallsburg #1	Well	55-9205	Alluvium	145
Wallsburg #2 (Wallsburg Town Well)	Well	55-1389	Bedrock	247
Wallsburg #3 (Davis Well)	Well	55-5648	Alluvium	80
Woodland #1	Well	55-8120	Bedrock	160
Woodland #2	Well	55-4609	Bedrock	120
Woodland #3	Well	55-6846	Alluvium	127
Center Creek near Center Creek Road (5910190)[+]	River/stream	–	–	–
Daniels Creek above First Diversion (5913540)[+]	River/stream	–	–	–

Sampling Location Name	Type	Water Right Number	Intake Formation	Intake Depth (feet)
Lake Creek ab Timberlakes Development	River/stream	–	–	–
Lake Creek below Timberlakes Development (4997070)	River/stream	–	–	–
Main Creek ab Girl Scout Camp (5916925)+	River/stream	–	–	–
Provo River at Midway Cutoff Road (4997300)+	River/stream	–	–	–
Snake Creek above WMSP Golf Course (5910450)+	River/stream	–	–	–
Tributary ab cnfl Lake Creek below Timberlakes Devel (4997060)	River/stream	–	–	–

* Well log indicates intake depth ranges from 60 to 90 feet. Assumed 75 feet for data analysis.
^ SWCA sample location coincides with existing USGS groundwater monitoring well. Both SWCA and USGS site descriptions are provided.
+ SWCA sample location coincides with existing DWQ monitoring location ID (MLID). The DWQ MLID is provided in parentheses.

2.4.2 *Parameters*

SWCA collected water quality samples and submitted them to analytical laboratories for analysis. In coordination with the WCHD, the suite of parameters each specific sample was analyzed for was determined prior to sampling in each of the SAPs. Table 6 summarizes the water quality parameters that were analyzed during the study along with the parameter sources and implications. Parameters such as pesticides/herbicides, VOCs, and dissolved metals were analyzed at certain wells based on a screening strategy during spring 2019. These analyses were pursued for the locations where the vulnerability analysis indicated that nearby land uses could serve as a source of a specific type of contaminant. Given that the results were non-detect at most locations, these analyses were not pursued again at most locations in subsequent sampling events. Personal care products were screened during the spring 2020 sampling event at several locations that were deemed likely to receive wastewater inputs from nearby septic systems or exhibited elevated concentrations of parameters indicative of wastewater impact from septic systems. A core group of water quality parameters were identified for analysis at all sampling locations during each of the sampling events. These core parameters (TDS, total suspended solids (TSS), chloride, nitrate, and phosphorus) were chosen for consistency and continuity with previous sampling efforts and because they are low-cost, proven indicators of contamination.

Table 6. Water Quality Parameters for Which Samples Were Analyzed During the Study

Parameter Name	Parameter Description	Implications	Sources
TDS	The sum of all dissolved matter in a sample of water	High TDS values negatively affect suitability of groundwater for drinking water and agricultural uses.	Dissolution of natural materials such as rock, soil, and organic material
TSS (surface water only)	A measure of the weight of all particulate matter suspended in the water column	TSS affects water clarity, a water's suitability for irrigation and drinking, and aquatic life; high TSS typically indicates sediment from streambank erosion; particles can carry other pollutants.	Streambank erosion, stormwater runoff, decaying plant and animal matter, and sewage
Chloride	Chlorine ion	Salty taste in drinking water, harmful to aquatic life	Natural weathering of natural materials, road salts, wastewater, agriculture, and landfills
Bromide	Bromine ion	Chloride-to-bromide ratio can help distinguish between sources of nitrate (human versus livestock).	Septic systems, agriculture, and livestock

Parameter Name	Parameter Description	Implications	Sources
Nitrate + nitrite	Sum of nitrate plus nitrite: the oxidized and partially oxidized forms of nitrogen (N)	Adverse health and ecological effects	Major sources are fertilizer and sewage
Total nitrogen (surface water only)	The sum of all forms of N in a water sample	Adverse health and ecological effects	Wastewater, runoff from fertilized lawns and fields, and runoff from animal feedlots and manure storage areas
Total phosphorus	A measure of the total phosphorus in aquatic systems	No drinking water standard; adverse ecological affects (eutrophication of aquatic ecosystems)	Fertilizer, manure, sewage, and erosion of natural deposits
VOCs	Types of organic compounds with shared characteristics of volatilization	Human health concerns, persistent in groundwater (little degradation)	Sources of VOCs in groundwater are chemicals associated with industrial, residential, and commercial land uses. A broad VOC screen will identify issues for future sampling efforts.
Pesticides and herbicides	Classes of chemicals used to protect agricultural crops from pests and weeds	Human health concerns	Agricultural activities
Arsenic, aluminum, cadmium, chromium, copper, iron, lead, selenium, and zinc	Dissolved metals	Adverse health and ecological effects	Historic mining activity, natural sources, some sources are unknown
Personal care products and pharmaceuticals	Suite of parameters	Major ion compositions can be compared between water samples to identify groundwater flow paths and sources of pollution.	Combination of natural and anthropogenic sources

3 GROUNDWATER QUALITY

As described above in Section 2.4.2, SWCA analyzed all groundwater samples collected during the four sampling events (between fall 2018 and spring 2020) for the following four parameters: TDS, nitrate, total phosphorus, and chloride. Discussions of each parameter and the sampling results are included in Sections 3.2 through 3.5. Supplemental parameters such as pesticides, VOCs, metals, personal care products and pharmaceuticals, and major ion composition were sampled at least once at specific sites during the study to help identify sources of degraded water quality, establish baseline conditions where no data previously existed, or to further characterize the hydrologic system. Supplemental parameters are discussed in Sections 3.6, 3.7, and 3.8.

3.1 Field Parameters

In addition to laboratory measured parameters, SWCA also measured temperature, pH, and specific conductance in the field in accordance with the standard operating procedure for collection of drinking water samples that was followed for the study (EPA 2016). Prior to water sample collection, field measured parameters were monitored at least three times at each well to determine if the well had been sufficiently purged. Purging, or flushing, removes stagnant water from the well and causes groundwater representative of aquifer conditions to take its place. Wells were purged for a minimum of 10 minutes, or until repeated measurements of temperature, pH, and specific conductance were within 5% of each other. Laboratory samples were collected after field parameters had stabilized.

Groundwater pH ranged from 6.68 at North Fields #2 to 9.02 at Timberlakes #1. The average pH measured in groundwater samples from the Heber Valley aquifer was 7.24. Specific conductance ranged from 192 µS/cm at Pine Canyon Road #1 to 963 µS/cm at Swiss Alpine Road #2 (Hayward Well). Average specific conductance in the Heber Valley aquifer was approximately 500 µS/cm. A regression analysis of paired TDS and specific conductance measurements indicates a moderate positive relationship ($R^2 = 0.52$), which is affected by potential outlier data. Linear regression using the average at each site yielded a tighter correlation ($R^2 = 0.83$), indicating that field measurement of specific conductance could be used as a proxy for TDS in groundwater (Figure 5). Based on these linear regressions, the site-specific factor in the Heber Valley between TDS and specific conductance would range from 0.69 to 0.77 (TDS = specific conductance × conversion factor).

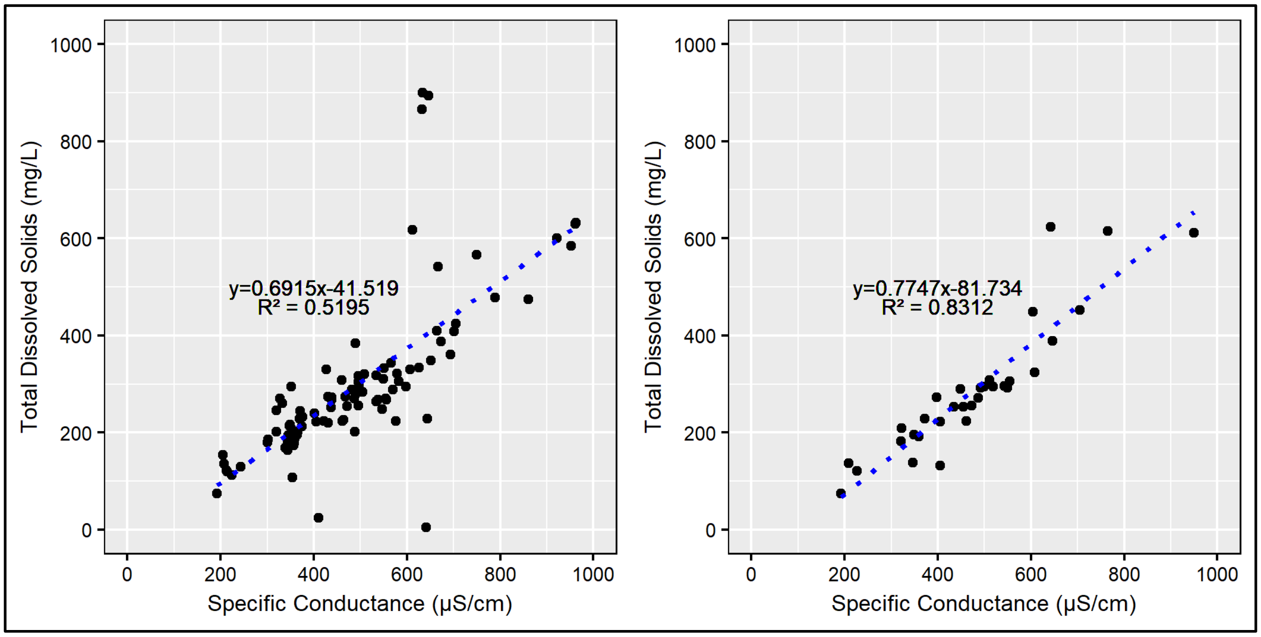


Figure 5. Linear regression analysis between individual paired TDS and specific conductance measurements (left) and paired average values (among all visits to each site) for each well (right).

Dissolved oxygen was not collected during the first sampling event in 2018 because it is not a required parameter in the standard operating procedure for collection of drinking water samples (U.S. Environmental Protection Agency [EPA] 2016). However, dissolved oxygen measurements were collected at all sites in subsequent sample events. Two wells had dissolved oxygen concentrations less than 3.0 mg/L: Lake Creek #1/(D-4-5) 3dcc-1 and North Fields #2, with most groundwater wells averaging between 5 and 10 mg/L. Temperature measurements were averaged to account for seasonal variability. Groundwater from the Pine Canyon Road #1 well had the lowest average temperature (5.9 degrees Celsius [°C]). Water from the Heber Hospital Well was warmest with all measurements > 13°C, with an average measurement of 13.73°C. Further analysis and discussion of field data are not included in this report; however, the field data are summarized in Appendix A.

Many water samples collected during the study had parameter concentrations below laboratory method reporting limits. In such cases, a value of one-half the reporting limit was used in the data analysis. Using values of half the reporting limit is common practice because values of zero may underestimate the true concentration, whereas values of the reporting limit itself may overestimate the true concentration. The results of water quality analysis are described by parameter below.

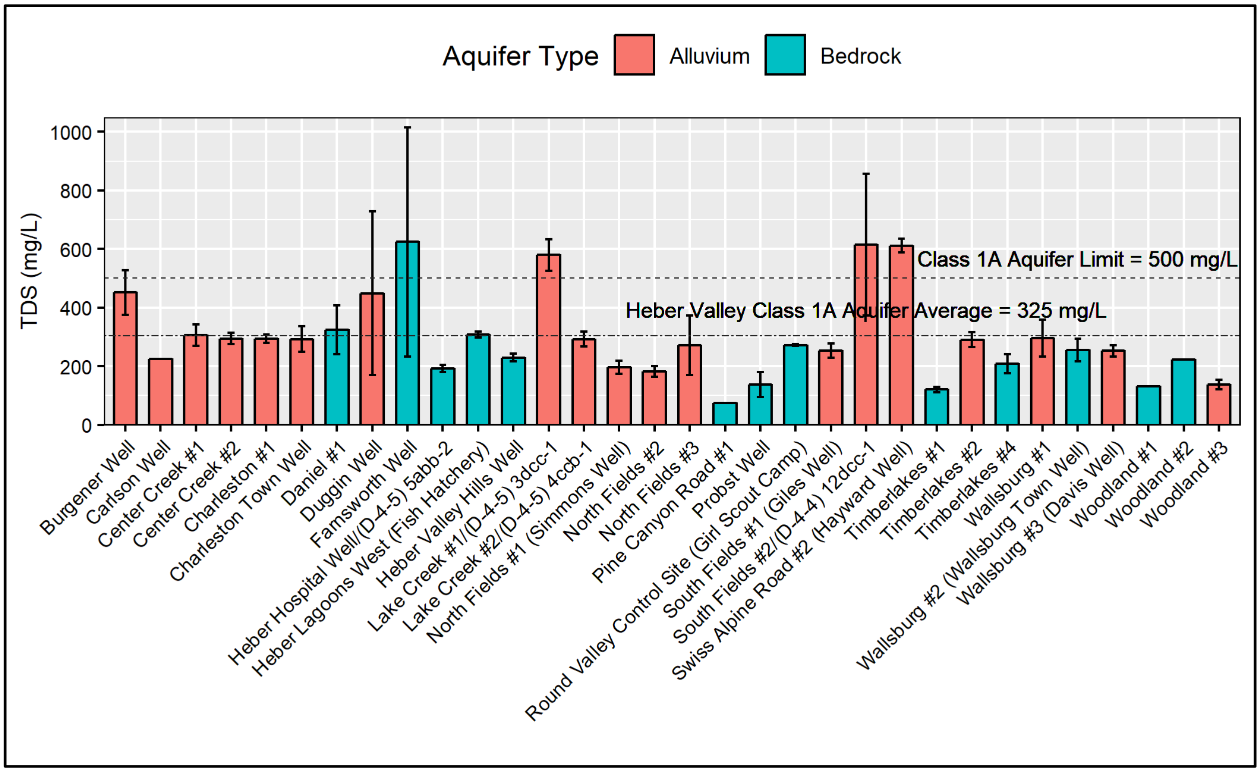
3.2 Total Dissolved Solids

TDS is a measure of all the dissolved constituents in water and includes organic compounds as well as inorganic minerals, salts, nutrients, and trace metals. Water becomes saline at high TDS concentrations and becomes less suitable for drinking water and agricultural uses. TDS is a useful indicator of overall water quality because it comprises all the dissolved constituents in water from natural and anthropogenic sources.

Groundwater in the unconsolidated valley-fill deposits in Heber and Round Valleys was classified as Class IA by the Utah Water Quality Board in 1995 (Lowe 1995). Class IA groundwater, also called pristine groundwater, has concentrations of TDS below 500 mg/L, and contaminant concentrations less than groundwater quality standards as written in UAC R317-6-2. The code states that “Class IA ground water will be protected to the maximum extent feasible from degradation due to facilities that discharge or would probably discharge to ground water.” Groundwater near Midway was classified as Class II by the Utah Water Quality Board because of TDS concentrations exceeding the 500-mg/L threshold. Higher TDS concentrations in this area are the result of tufa deposits from geothermal springs. Class II groundwater, also referred to as drinking water quality groundwater, has TDS concentrations between 500 and 3,000 mg/L and contaminant concentrations less than groundwater quality standards in UAC R317-6. UAC R317-6-2 states that “Class II ground water will be protected for use as drinking water or other similar beneficial use with conventional treatment prior to use.”

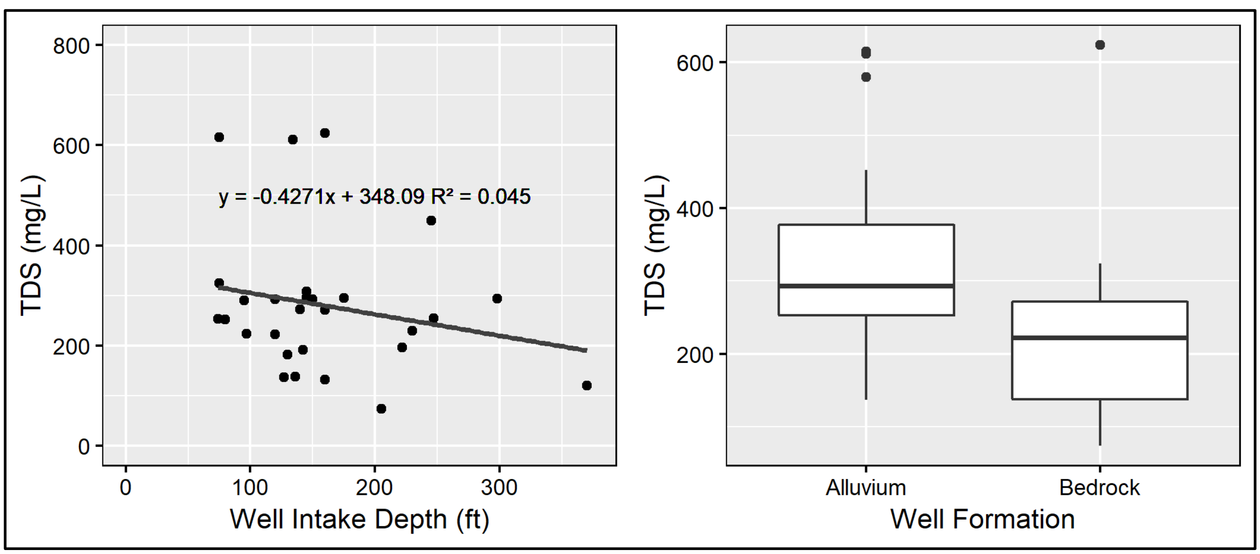
SWCA analyzed TDS at all sampling locations during each of the four sampling events from fall 2018 to spring 2020. Figure 6 shows average TDS concentration at each well and includes error bars representing the mean plus and minus the standard deviation of the sample set. For reference, the average TDS concentration in wells within the Heber Valley aquifer (325 mg/L) is included in Figure 6. TDS values from the Swiss Alpine Road #2 Well (located in the Class II aquifer where allowable TDS limits extend to 3,000 mg/L) are not included in the Heber Valley average.

Several wells in the Class 1A aquifer had individual water samples with TDS concentrations exceeding the 500-mg/L limit, although only Lake Creek #1/(D-4-5) 3dcc-1, South Fields #2/(D-4-4) 12dcc-1, and the Farnsworth Well had average TDS sample values (from all SWCA sampling events) exceeding 500 mg/L. The Farnsworth well (located in the Class 1A aquifer) had the highest average TDS concentration at 624 mg/L, although the average is elevated considerably by the most recent sample in April 2020 with TDS at 900 mg/L. TDS did not vary considerably between summer and fall sampling events as a whole, although some sites like the Farnsworth well, South Fields #2/(D-4-4) 12dcc-1, and the Duggin Well had significantly different TDS values between sample events. Variability in TDS concentrations is illustrated by the error bars at each sampling location. In general, shallower wells had higher TDS concentrations as did wells screened in the alluvial material (Figure 7). The graph on the left side of Figure 7 illustrates that TDS concentration and well depth are poorly correlated except that shallower wells drawing water at depths less than 200 feet have the highest TDS concentrations. Average TDS concentrations for all wells are depicted spatially in Figure 8, which shows the areas of highest TDS concentrations in Lake Creek/Center Creek, South Fields/Charleston, and the Swiss Alpine areas.



Note: Error bars are defined as the mean plus and minus the standard deviation. Wells without error bars were only sampled once.

Figure 6. Average TDS values at SWCA sampling locations (2018 to 2020).



Note: In many cases wells were screened over intervals rather than at a discrete depth. In these cases, SWCA used one half the well screen interval as the well intake depth for data analysis.

Figure 7. TDS concentration versus well intake depth and well formation.

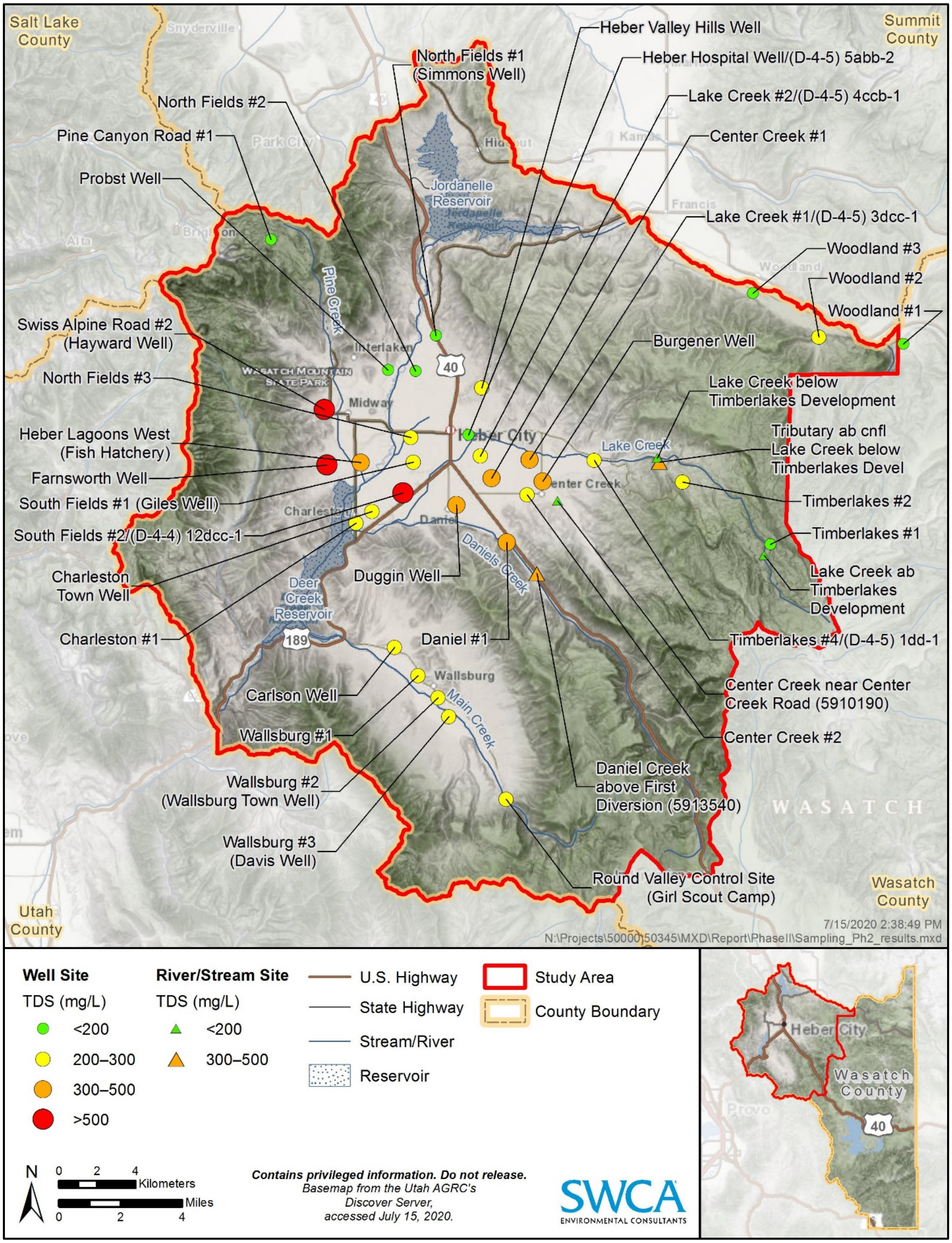


Figure 8. Average TDS values at SWCA sampling locations (2018 to 2020).

3.2.1 *Comparison to Historical Data*

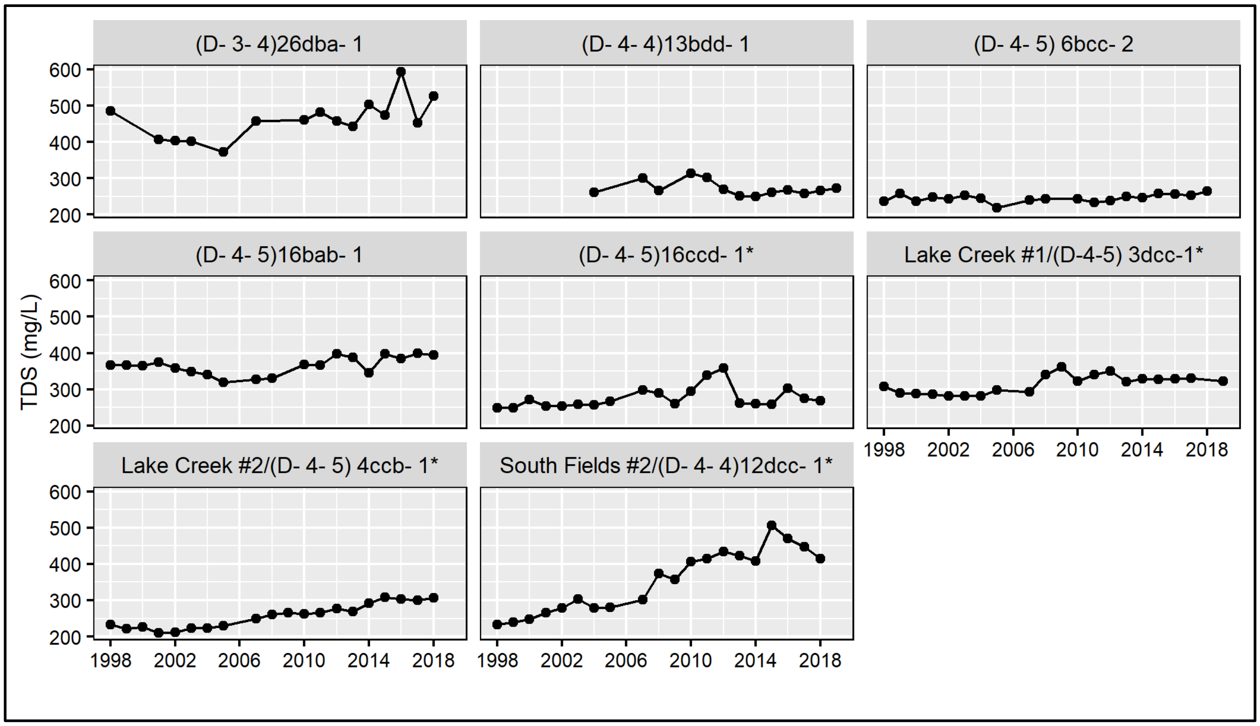
SWCA obtained water quality data from the USGS National Water Information System (NWIS) database to examine if and how TDS concentrations have changed in groundwater since the last significant hydrologic investigations in the late 1990s. Figure 9 displays individual time-series plots of TDS concentrations for USGS wells with 10 or more observations in the last 20 years. To examine trends over time, SWCA ran the Mann-Kendall test with a 95% confidence interval on time series data from 1998 to 2019 for each of the eight USGS wells. The Mann-Kendall test is a nonparametric statistical test commonly used in environmental time-series data to determine whether a significant upward or downward trend has occurred over the period of record analyzed (Helsel and Hirsch 2002).

Results of the Mann-Kendall test for trends indicate there is strong evidence ($p < 0.05$) to reject the null hypothesis of no significant trend in favor of the alternative hypothesis (that a significant trend exists) at four out of eight USGS wells, three of which coincide with SWCA sampling locations:

- South Fields #2/(D-4-4) 12dcc-1
- Lake Creek #1/(D-4-5) 3dcc-1
- Lake Creek #2/(D-4-5) 4ccb-1
- (D-4-5) 16ccd-1

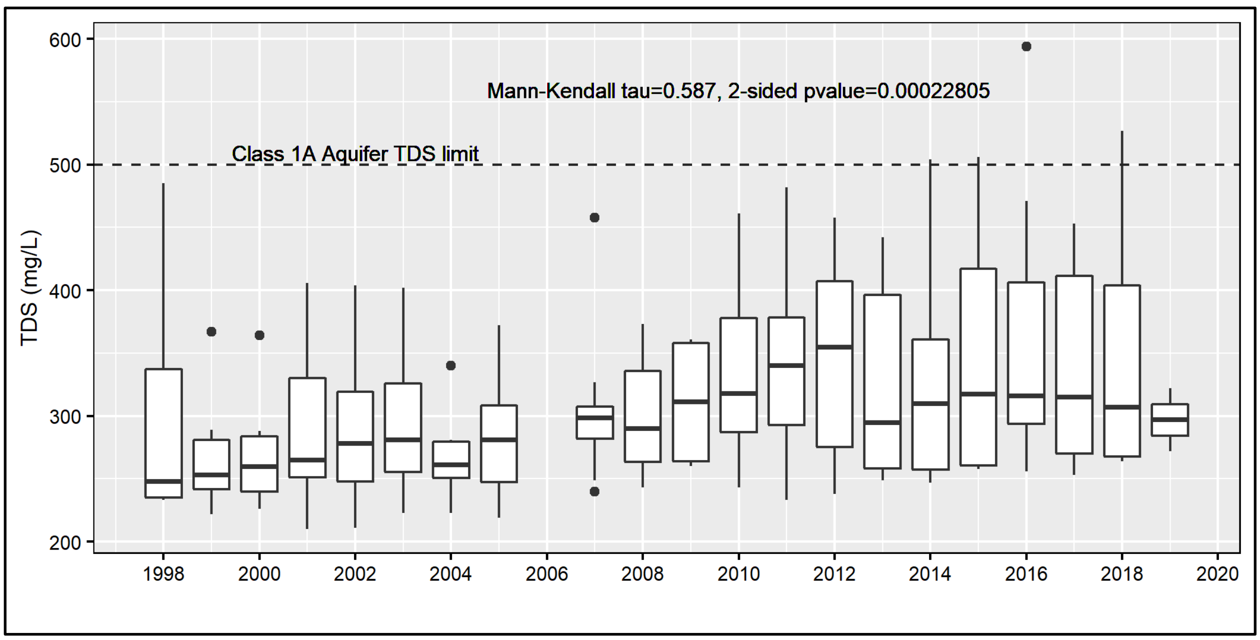
A positive tau sign indicates increasing TDS at all four wells with statistically significant trends (see Figure 9). South Fields #2/(D-4-4) 12dcc-1 is located at the southern edge of the agricultural fields where treated wastewater from the Heber Valley Special Service District is applied. Well (D-3-4) 26dba-1 in northwestern Heber Valley consistently has the highest TDS concentrations and more variability in recent years, although no trend was detected using the Mann-Kendall test ($p > 0.05$). Review of USGS data and SWCA data indicates the Lake Creek #1/(D-4-5) 3dcc-1 and Lake Creek #2/(D-4-5) 4ccb-1 wells have elevated concentrations of the core indicator parameters identified in the study (TDS, nitrate, total phosphorus, and chloride), although sources have yet to be identified. The Lake Creek wells are discussed in greater detail in subsequent sections of this report.

USGS data from the same eight wells summarized in Figure 9 were aggregated by year to evaluate how conditions in the aquifer have changed between 1998 and 2019 (Figure 10). SWCA tested for a significant monotonic TDS trend in the Heber Valley aquifer using the Mann-Kendall test because assumptions for linear regression were not met due to non-normal distribution of data. Median TDS concentrations were aggregated by year for the Mann-Kendall test. Results indicate a statistically significant upward trend in TDS concentrations in the Heber Valley aquifer ($p = 0.0002$).



* Results of the Mann-Kendall test indicate increasing linear trend over time ($p < 0.05$).

Figure 9. TDS concentrations at USGS wells in Heber Valley between 1998 and 2019.



Note: The size of each boxplot corresponds to the interquartile range of the data, described as the distance between the 25th and 75th percentile or first and third quartiles. The horizontal line in each box plot represents the median, or 50th percentile. Whiskers extend from the box to the highest and lowest value, at most 1.5 times the interquartile range. Data beyond the whiskers are considered outliers and are plotted individually.

Figure 10. TDS values from 1998 to 2020 at USGS wells in the Heber Valley.

3.3 Nitrate

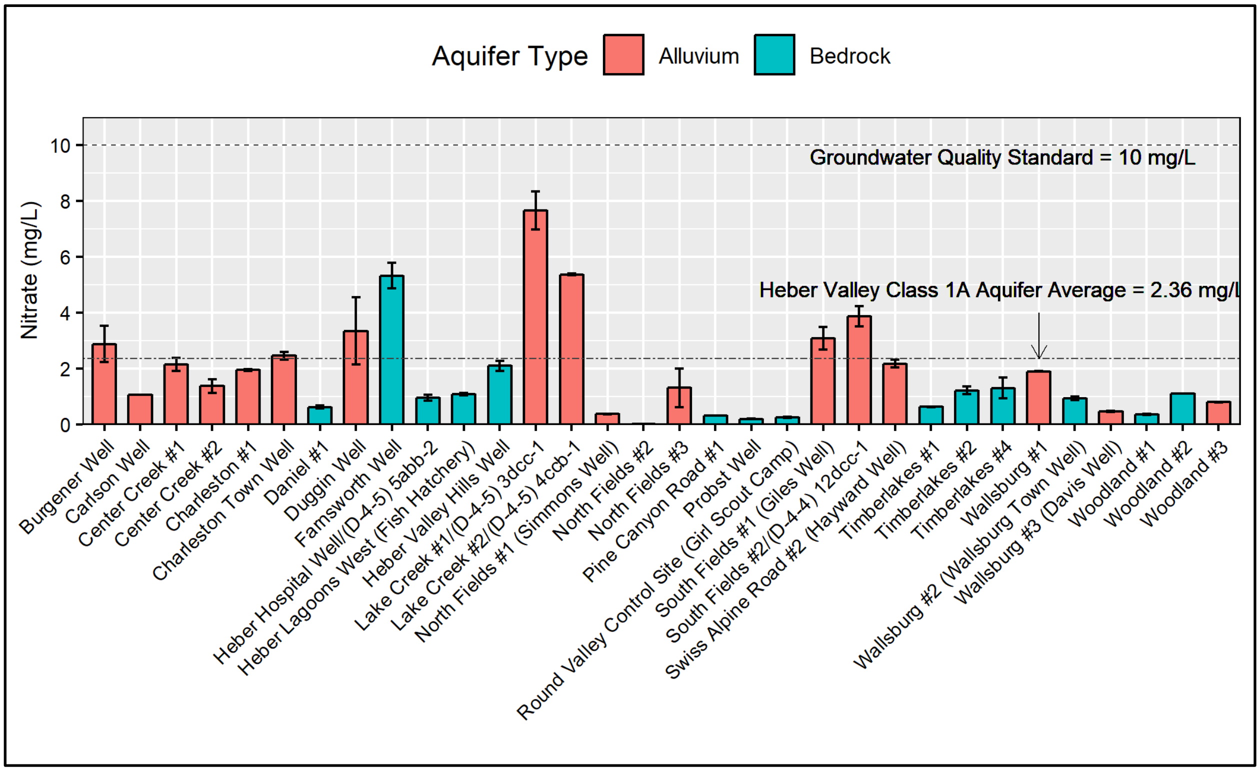
In 1994, HAL recommended that nitrogen in the form of nitrate be used as a groundwater quality management indicator in Wasatch County. In 2020, nitrate continues to be one of the primary indicators of pollution from septic systems and is consistently used as the best indicator for allowable septic system density recommendations in the state of Utah (Bishop et al. 2007a, 2007b; Inkenbrandt 2019; Lowe et al. 2010; Wallace and Lowe 1998).

Nitrogen from human waste is converted to nitrate in the septic system leach field and readily passes through the soil to become mobile in groundwater. Additionally, nitrogen (as ammonia) from fertilizers and animal waste is converted to nitrate under aerobic conditions. High nitrate concentrations in drinking water poses a public health concern, especially for infants (it can cause blue baby syndrome). Elevated levels of nitrate in surface waters can also contribute to eutrophic conditions and subsequent depletion of dissolved oxygen. When nitrate infiltrates the subsurface it can potentially be removed by plant uptake in the presence of a shallow root system or by denitrification in anoxic conditions, although the denitrification capacity of the Heber Valley aquifer is negligible, and plant uptake only occurs in shallow aquifer areas (Jeppson et al. 1991). Denitrification is the process by which nitrate is converted back into nitrogen gas by denitrifying bacteria.

HAL (1994) assumed the ambient nitrate concentration in the Heber Valley aquifer was 2 mg/L. The presence of nitrate in the aquifer was assumed to be from natural sources, agricultural practices, and septic systems. Through discussions with WCHD, HAL recommended an allowable degradation of 1.0 mg/L nitrate as a management goal. The State of Utah groundwater quality standard for nitrate in Utah is 10 mg/L (UAC R317-6). A recent study in Utah by the USGS assumed that nitrate levels exceeding 2.0 mg/L in groundwater are indicative of contamination by human activities (Jordan 2017). SWCA measured nitrate at all sampling locations between 2018 and 2020 with an aim to evaluate current nitrate conditions in the aquifer, provide additional resolution to USGS monitoring data, and provide baseline data where none exist.

Figure 11 and Figure 12 show average nitrate concentration at each well monitored by SWCA between 2018 and 2020. The overall average nitrate value measured across all groundwater sites in the study area was 1.92 mg/L and includes data from wells in Round Valley, Timberlakes, Woodland, and Brighton Estates. The average nitrate concentration in the Heber Valley aquifer was approximately 2.4 mg/L. The highest nitrate values were observed in the Lake Creek planning area at Lake Creek #1/(D-4-5) 3dcc-1 and Lake Creek #2/(D-4-5) 4ccb-1 wells; all three groundwater samples from each well had nitrate concentrations > 5 mg/L.

In general, shallower wells had higher nitrate concentrations as did wells screened in the alluvial material (Figure 13). The graph on the left side of Figure 13 illustrates that nitrate concentration and well depth are poorly correlated except that shallower wells drawing water at depths less than 200 feet have the highest nitrate concentrations. In many cases, wells were screened over an interval rather than at a discrete depth. In these cases, the well screen interval was divided in half for data analysis.



Note: Error bars are defined as the mean plus and minus the standard deviation. Wells without error bars were only sampled once.

Figure 11. Average nitrate concentrations at SWCA sampling locations (2018 to 2020).

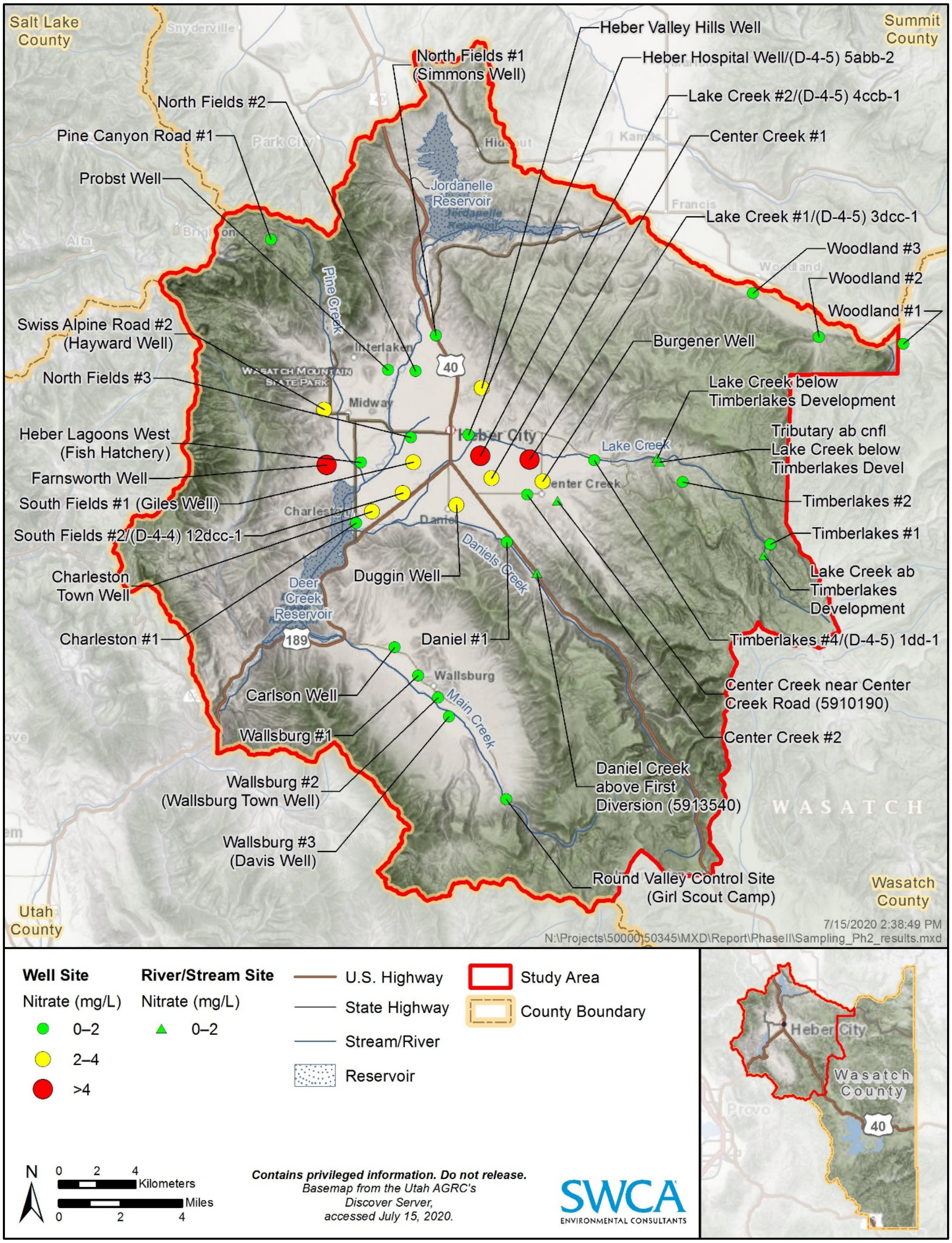
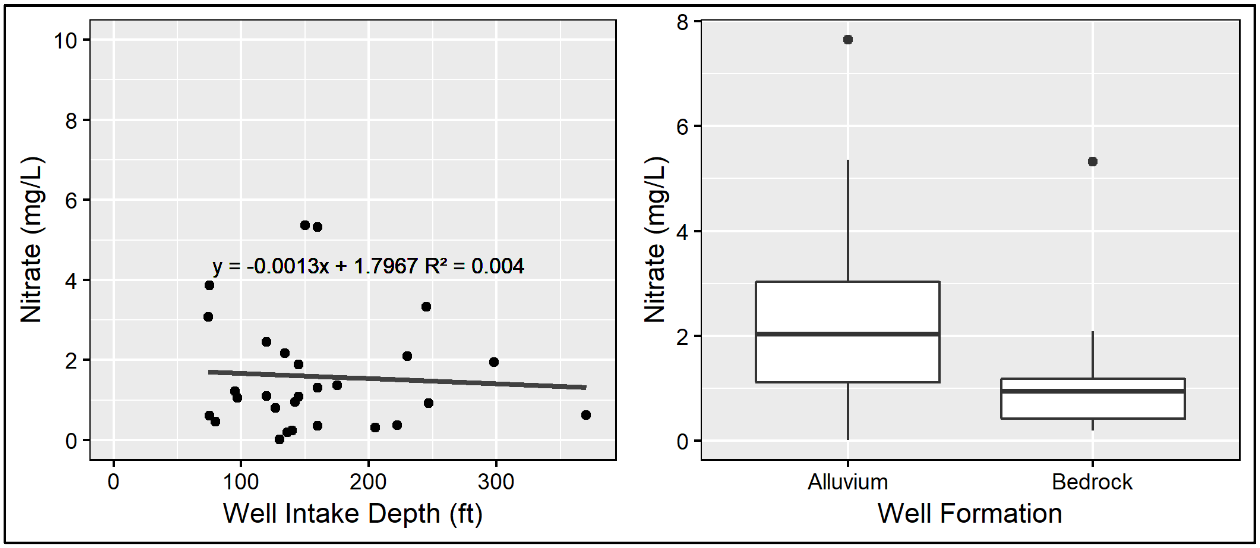


Figure 12. SWCA sampling locations and average nitrate concentrations measured between 2018 and 2020.



Note: In many cases wells were screened over intervals rather than at a discrete depth. In these cases, the well screen interval was divided in half for data analysis.

Figure 13. Nitrate concentration versus well intake depth and well formation.

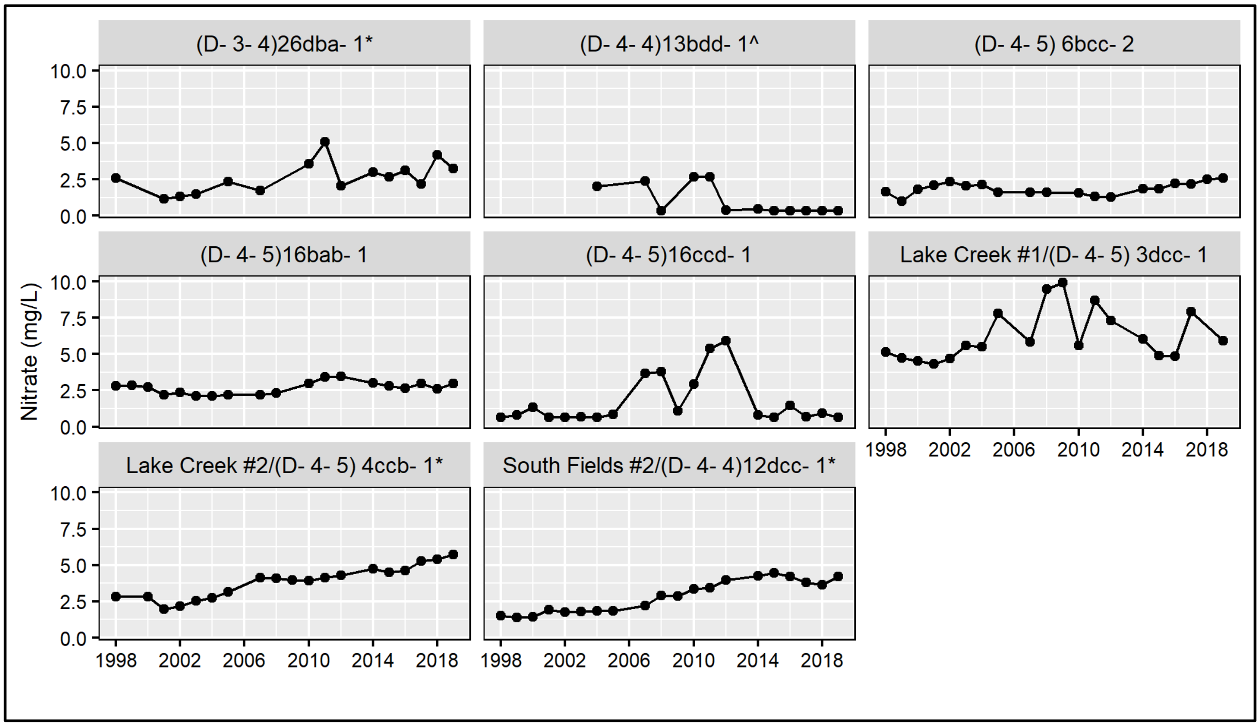
3.3.1 *Comparison to Historical Data*

Nitrate data from the USGS NWIS database were plotted to evaluate how nitrate concentrations have changed over time in the Heber Valley. Figure 14 shows individual time-series graphs of nitrate concentrations at nine USGS wells in Heber Valley from 1998 to 2019. The non-parametric Mann-Kendall test with a 95% confidence interval was used to detect trends in nitrate concentrations at each USGS well from 1998 to 2019.

Results indicate that three out of eight USGS wells show a statistically significant ($p < 0.05$) upward trend in nitrate over time:

- South Fields #2/(D-4-4) 12dcc-1
- Lake Creek #2/(D-4-5) 4ccb-1
- (D-3-4) 26dba-1

Increasing nitrate at South Fields #2/(D-4-4) 12dcc-1 may be attributed to land application of treated wastewater in fields upgradient from the well, although further investigation is needed to conclusively identify sources. These findings parallel the TDS results discussed in Section 3.2.1. A spike of nitrate was observed in USGS well (D-4-5) 16ccd-1 near U.S. Route 40 in the Daniel area, peaking at 5.4 mg/L in 2011. However, nitrate levels at this USGS well are significantly lower in recent years with all measurements since 2011 less than 1.5 mg/L. Because the Heber Valley aquifer has limited capacity for denitrification, SWCA assumes the decreases in nitrate at individual wells can be attributed to increased flow through the aquifer, or modifications to site-specific activities resulting in reductions in load of nitrogen to the aquifer. Well (D-4-4) 13bdd-1 between Daniel and Charleston had a weak decreasing trend, although still significant.



* Mann-Kendall test using a 95% confidence interval indicates a statistically significant upward trend in nitrate over time.
^ Mann-Kendall test using a 95% confidence interval indicates a statistically significant decreasing trend in nitrate over time.

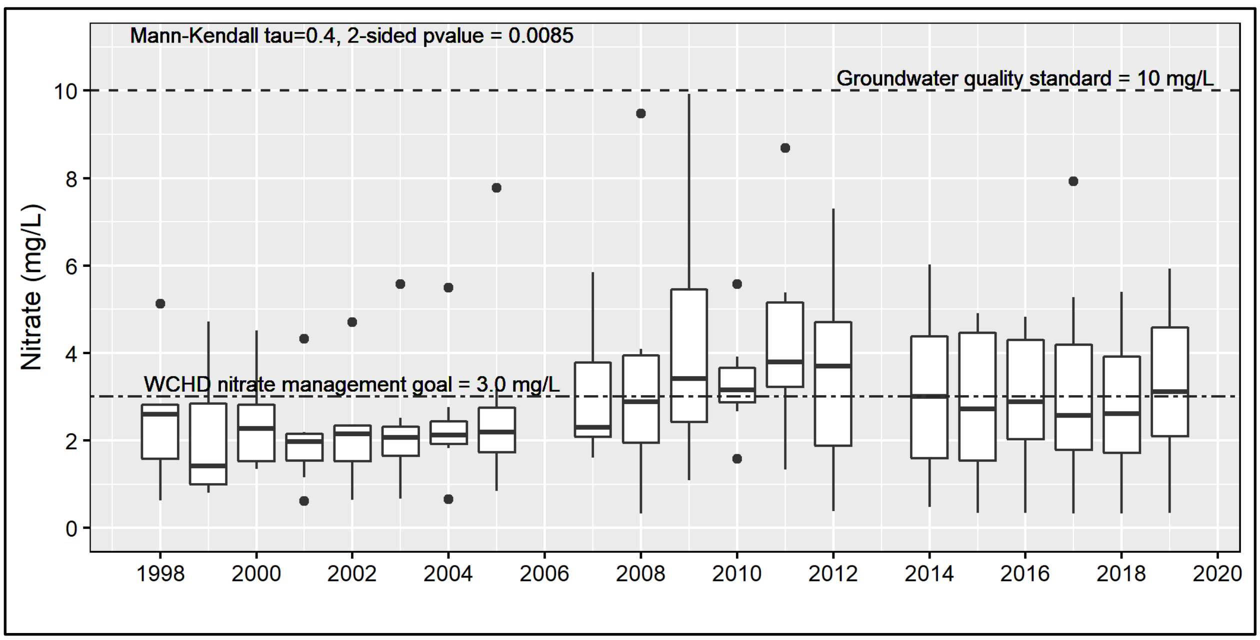
Figure 14. Time series graphs of nitrate concentrations between 1998 and 2019 at USGS wells in Heber Valley.

Lake Creek #1/(D-4-5) 3dcc-1 on the eastern side of Heber Valley in the Lake Creek drainage had the highest nitrate with a maximum concentration of 9.92 mg/L in 2009, close to Utah's groundwater quality standard for nitrate of 10.0 mg/L. The time series plot at this site (see Figure 14) indicates nitrate concentrations are variable from year to year, and recent data indicate concentrations are somewhat lower than they were between 2008 and 2011. However, nitrate concentrations are well above average for the Heber Valley, and recent nitrate concentrations from water samples collected by SWCA at Lake Creek #1/(D-4-5) 3dcc-1 ranged from 5.93 to 6.98 mg/L. According to the *2015 Water Quality Implementation Report* for the 2014 Water Year, nitrate concentrations at this site and two others in the Lake Creek drainage area of the Heber Valley are increasing for reasons that remain to be identified (Desert Rose Environmental 2016). SWCA notes that Lake Creek #1/(D-4-5) 3dcc-1 well appears to be located proximal to a historic farm operation so an on-site agricultural source may be responsible for the high nitrate concentrations. SWCA tested for a suite of pesticides (see Section 3.6) and anthropogenic markers (see Section 3.7) in an effort to determine the likely source of nitrate at Lake Creek #1/(D-4-5) 3dcc-1 and Lake Creek #2/(D-4-5) 4ccb-1. Pesticides and pharmaceutical compounds were not present in measurable concentrations at the Lake Creek wells. A positive test result for anthropogenic markers or pesticides could indicate that the source of elevated nitrate in the well is from wastewater from septic systems (anthropogenic markers) or agricultural activity (pesticides). Conversely, negative test results for pesticides and anthropogenic markers are not deterministic of nitrate source identification for the following reasons:

- As discussed in Lowe 1995, pesticides have relatively short half-lives and are known to attenuate in the soil. Therefore, local fertilizer application may be contributing to elevated nitrate in the well, but pesticides would not be detected.
- Pesticides may not be applied in large enough quantities in this area to reach the aquifer.

- Anthropogenic markers might be present but are being diluted by large amounts of groundwater flow and are not detected at measurable concentrations.
- Groundwater flow from the Timberlakes development may be delivering nitrate from septic systems into the Heber Valley aquifer. However, anthropogenic markers and pesticides may not be present at high enough concentrations to detect because of the long distance between the Timberlakes subdivision and the Lake Creek wells and the long travel time (see Section 4.2 for further discussion on the Timberlakes subdivision).
- Livestock manure leachate may be contributing to elevated nitrate at Lake Creek #1/(D-4-5) 3dcc-1 and Lake Creek #2/(D-4-5) 4ccb-1.

Time series graphs provide a way to examine how nitrate concentrations are changing at individual wells over time, and boxplots of all USGS data by year provide a way to visualize how nitrate concentrations are changing in the Heber Valley as a whole. Nitrate data from the USGS wells were aggregated by year to evaluate how conditions in the aquifer have changed between 1998 and 2020. (Figure 15). Nitrate concentrations are more variable after 2007, and no measurements were collected in 2006 and 2013. For reference, the WCHD groundwater quality management goal of 3.0 mg/L nitrate and the State of Utah groundwater quality standard of 10.0 mg/L are included as horizontal lines in Figure 15. SWCA tested for a significant monotonic trend in nitrate concentration using the Mann-Kendall test because assumptions for linear regression were not met because of the non-normal distribution of data. Results indicate a statistically significant upward trend in nitrate concentrations in the Heber Valley aquifer ($p = 0.0085$).



Note: The size of each boxplot corresponds to the interquartile range of the data, described as the distance between the 25th and 75th percentile or first and third quartiles. The horizontal line in each box plot represents the median, or 50th percentile. Whiskers extend from the box to the highest and lowest value, at most 1.5 times the interquartile range. Data beyond the whiskers are considered outliers and are plotted individually. Mann-Kendall test for trend using a 95% confidence interval indicates an increasing trend in nitrate.

Figure 15. Boxplots of USGS nitrate concentrations in Heber Valley from 1998 to 2020.

SWCA also obtained water chemistry reports from DDW's WaterLink Database for the 22 community drinking water systems in the study area to examine if and how nitrate levels have changed in drinking water supply systems since the last significant hydrologic investigations in the 1990s (HAL 1994; Roark et al. 1991). Each drinking water system can contain multiple facilities with varying source water types, such as springs, wells, or water intakes from surface water. For example, the Heber City Water System comprises the Broadhead Spring, the Murdock Spring, the Heber Valley Hills Well, the Hospital Well, and the Broadhead Well. Each facility is potentially sampled multiple times within 1 year. Well attributes such as intake depth, total well depth, or well intake screened formation were not available in the DDW WaterLink Database but are available in groundwater protection zone delineation reports. SWCA obtained groundwater protection zone delineation reports from DDW in 2019.

Nitrate data were aggregated by system and by year and plotted so that long-term trends could be visualized (Figure 16). The only water systems for which yearly average nitrate levels appear to be increasing over time are the Charleston Water Conservancy District (WCD) system and the Woodland Mutual Water Company, although statistical trend tests were not conducted. The Charleston WCD system comprises the Charleston Town Well and Charleston Park well, which were both sampled by SWCA, as well as the Charleston upper and lower springs located on the hillslope west of Deer Creek Reservoir. The Jordanelle Special Services District (JSSD) had the highest maximum nitrate concentration in the Deer Crest Well above Jordanelle Reservoir in 2004 at 4.40 mg/L. Nitrate data are not available at the Deer Crest well beyond 2004. Well logs for this well indicate the total well depth is approximately 740 feet, although aquifer formation type (alluvium or consolidated rock) is unknown. The Jordan Valley WCD and Metropolitan Water District systems are included in Figure 16 because they are within the study area (near the outlet of Deer Creek Reservoir), although these systems likely serve populations in Utah County as opposed to Wasatch County. Nitrate concentrations at the Country Estates Mobile Home Park range from 1.39 to 2.69 mg/L and are some of the highest observed in community drinking water systems within the county. The Country Estates Mobile Home Park system is located along U.S. Route 40 near the mouth of Daniels Canyon. In general, the concentrations of nitrate in community drinking water systems remain low and do not appear to be increasing rapidly.

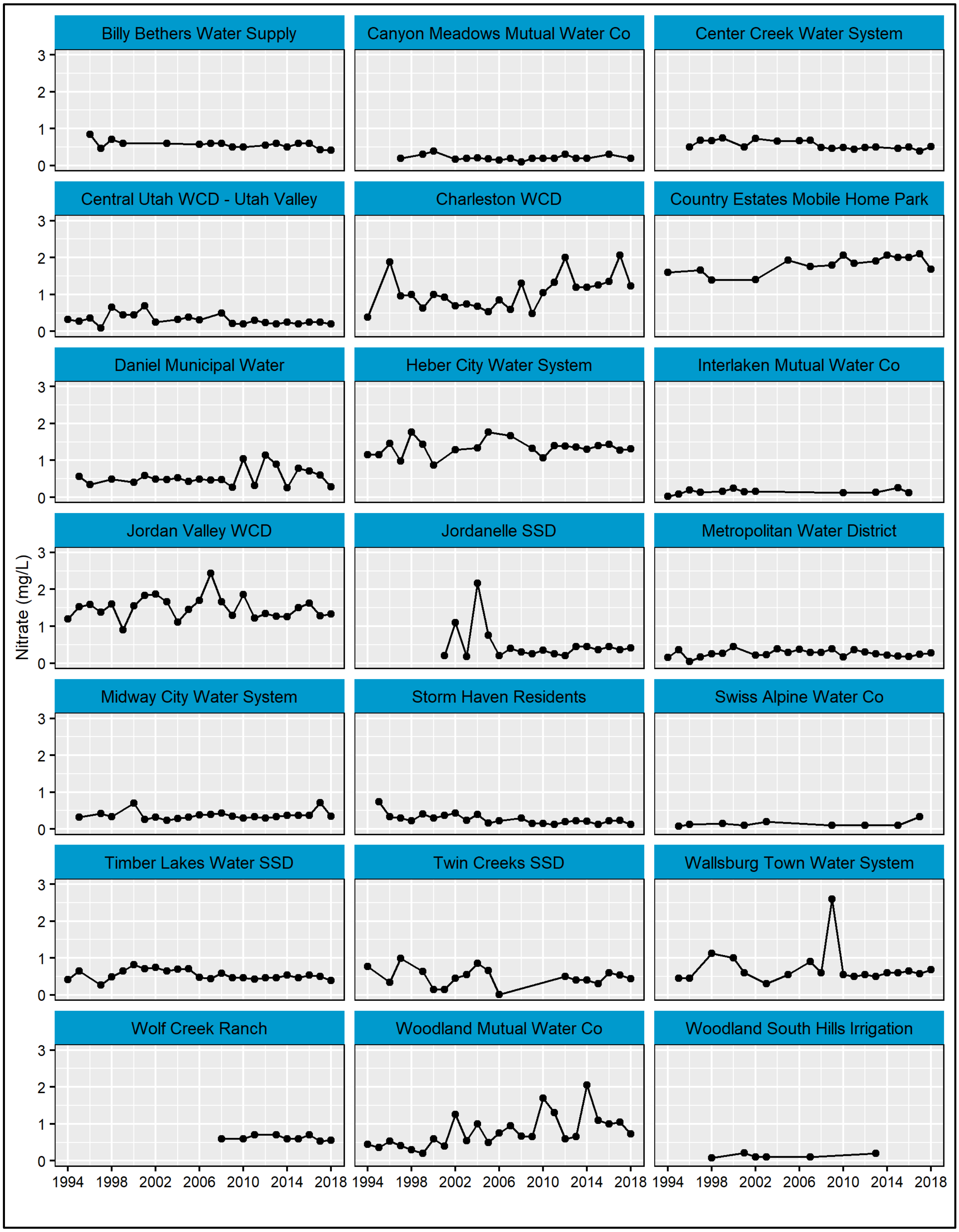


Figure 16. Yearly average nitrate concentrations at community drinking water systems in the study area from 1994 to 2018.

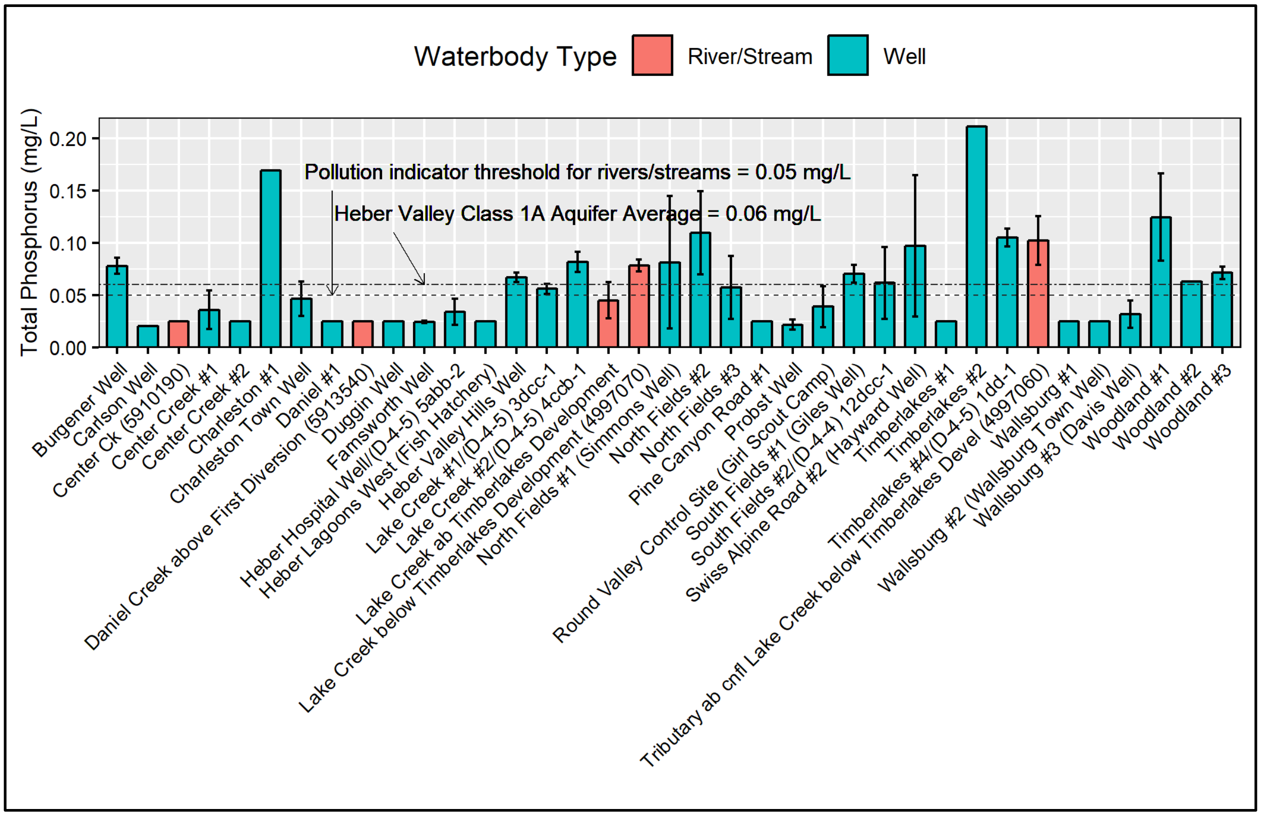
3.4 Total Phosphorus

In collaboration with WCHD, total phosphorus was identified as a core parameter in the study, primarily because of the potential impact nutrient-rich groundwater can have on surface water resources in the study area. Neither the EPA or State of Utah has groundwater quality or drinking water quality standards for phosphorus, but excess phosphorous in surface waters can lead to eutrophic conditions, which contribute to nuisance algae blooms, toxic algae blooms, low dissolved oxygen, and fish kills. In surface waters, total phosphorus is identified as a pollution indicator as opposed to a water quality standard, with a threshold of 0.05 mg/L for rivers and streams and 0.025 mg/L for lakes and reservoirs (UAC R317-2). In addition, algal blooms can potentially violate narrative standards as written in UAC R317-2. Sources of phosphorus in groundwater include natural sources like the dissolution of soils and rocks, and anthropogenic sources like agricultural fertilizer, animal waste, infiltration of wastewater, and septic systems.

The reduction of nutrient loading to Deer Creek Reservoir, especially phosphorous loading, has been an ongoing focus in the watershed since 2000 when DWQ assessed Deer Creek Reservoir and determined the reservoir was not meeting the 3A (cold-water fishery) beneficial use because of low dissolved oxygen levels and high levels of phosphorus. The major sources of phosphorus identified in the subsequent 2002 Deer Creek Reservoir total maximum daily load (TMDL) report were non-point source agricultural activities in the watershed and background phosphorus levels, including the Jordanelle Reservoir discharge (PSOMAS 2002). The phosphorus load to Deer Creek Reservoir from groundwater was estimated at 2,725 kilograms (kg) of total phosphorus per year, representing approximately 18% of the annual phosphorus load to Deer Creek Reservoir (PSOMAS 2002). Therefore, monitoring total phosphorus in groundwater as well as surface water is an important element in watershed management plans.

Phosphorus has a high affinity for minerals in the soil and is largely retained in the soil by adsorption. For this reason, properly functioning septic systems are 75% to 80% effective at reducing the influent load of phosphorus (HAL 1994). Phosphorus movement in the soil is minimal until the capacity of the soil is reached, after which phosphorus becomes more mobile and is transported to the underlying aquifer and to surface waters (USGS 2012). The long-term phosphorous adsorption capacity of the Heber Valley aquifer is not well understood. For this reason, as well as the concern about impacts to surface waters, phosphorus was included as a core parameter at all SWCA sampling locations during the study.

SWCA compared the average concentration of total phosphorous at each site sampled by SWCA to the pollution indicator threshold for rivers and streams (Figure 17) in the absence of a groundwater-specific standard. The highest concentration of total phosphorus was observed at the Timberlakes #2 site in July 2019. The reported value of 0.77 mg/L, more than twice the concentration of the next highest measurement, was not included in this figure because including the result in the figure would make it difficult to visualize the variability in the locations with lower concentrations. In June 2020, the total phosphorus concentration at Timberlakes #2 had significantly decreased to 0.21 mg/L. Charleston #1 also had higher than average total phosphorus concentrations. Average total phosphorus concentrations are displayed spatially in Figure 18. The phosphorus pollution indicator for rivers and streams (0.05 mg/L) and the average measured value (0.06 mg/L) for all wells in the Heber Valley Class 1A aquifer are shown as horizontal lines in the figure.



Note: Error bars represent the mean plus and minus the standard deviation. Locations that do not have error bars were only visited once. A total phosphorus concentration of 0.768 mg/L at Timberlakes #2 was not included in the figure because including the result in the figure would make it difficult to visualize the variability in the locations with lower concentrations.

Figure 17. Bar chart of average total phosphorus values at SWCA sampling locations (2018 to 2020).

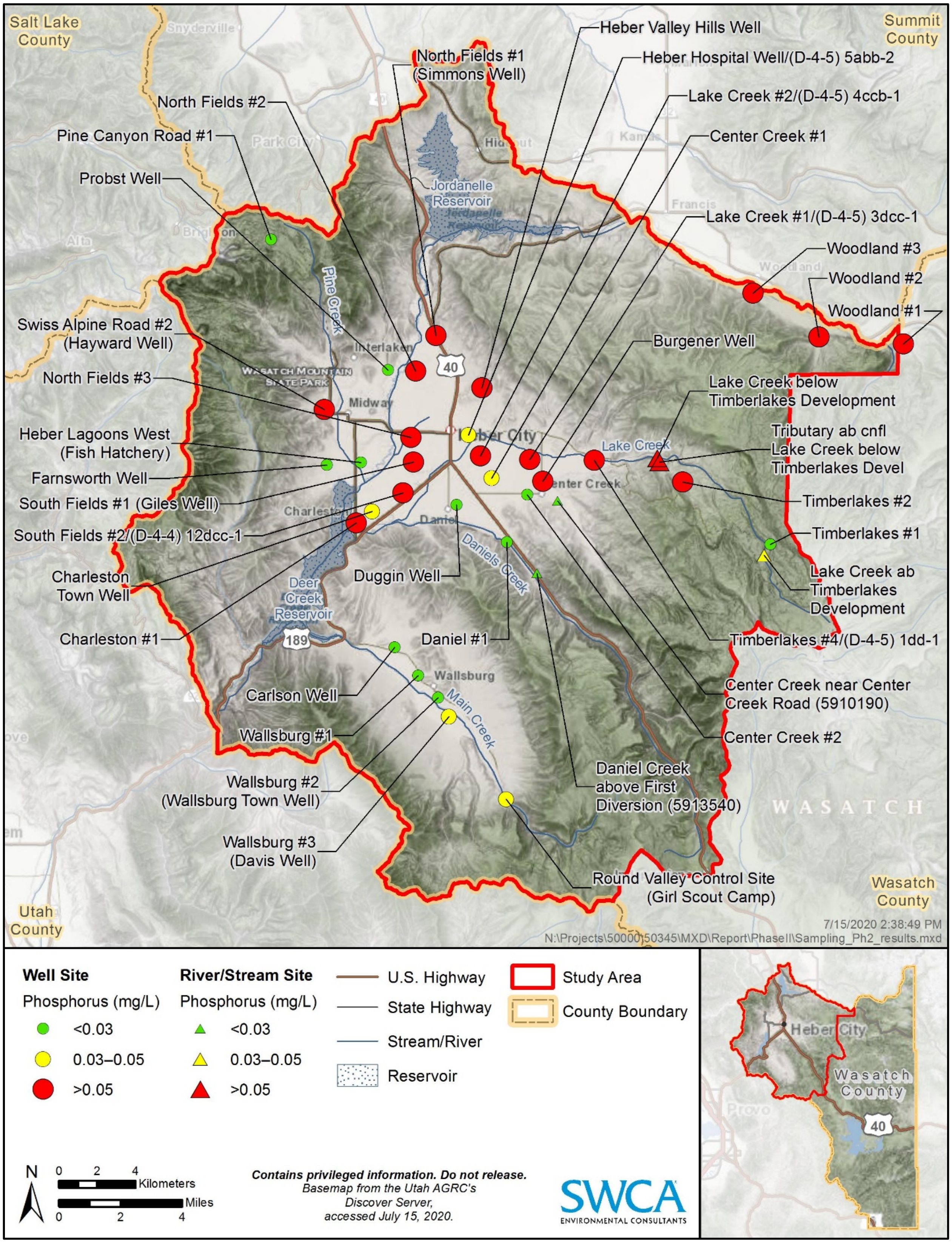


Figure 18. Average total phosphorus values at SWCA sampling locations (2018 to 2020).

3.4.1 *Comparison to Historical Data*

SWCA plotted total phosphorous concentrations obtained from the USGS NWIS database to evaluate how phosphorus concentrations have changed over time in the Heber Valley. Phosphorus concentrations were obtained by retrieving data for USGS parameter codes P00666: Phosphorus, water, filtered, milligrams per liter as phosphorus and P00671: Orthophosphate, water, filtered, milligrams per liter as phosphorus. In 2013, the USGS began reporting phosphorus concentrations as orthophosphate and discontinued parameter code P00666. Orthophosphate is the form of phosphorus that is biologically available for plant uptake.

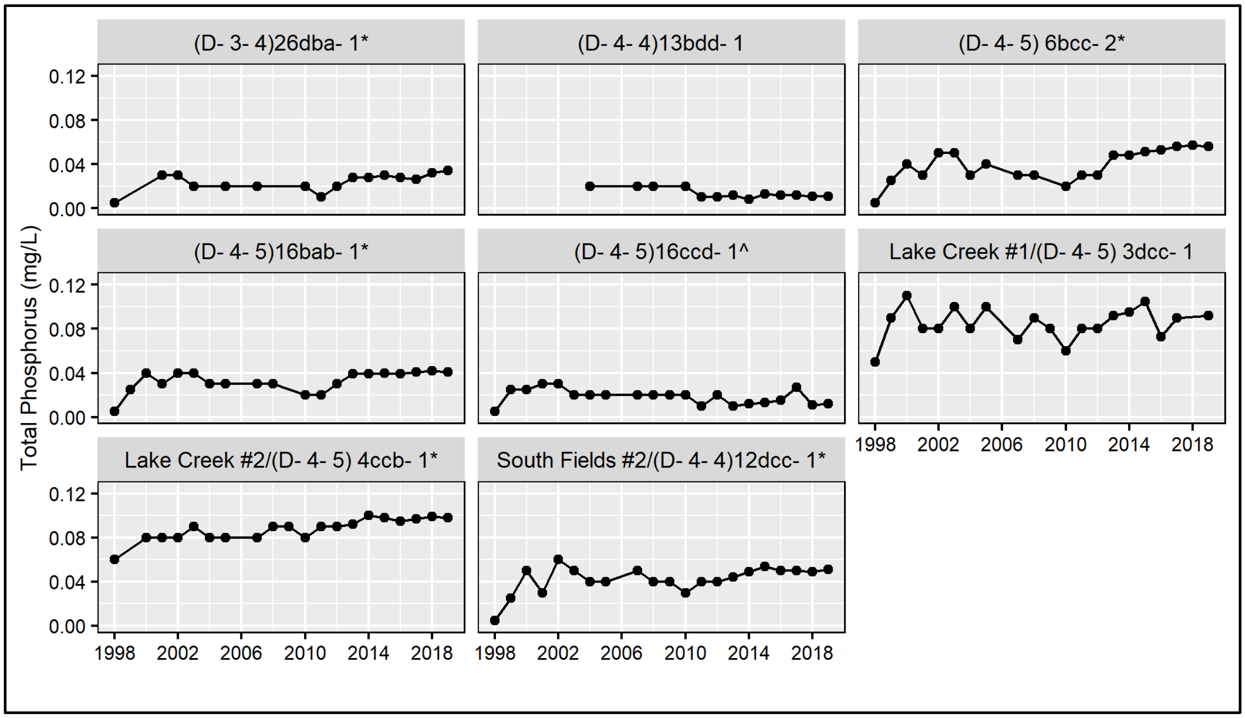
Following consultation with American West Analytical Laboratory (AWAL), data for both parameter codes were combined to form a continuous dataset from 1998 to 2019. Orthophosphate is a component of total phosphorus and is assumed to be the most predominant form of phosphorous in groundwater because it is the most stable form of kind of phosphate. Therefore, SWCA assumed the orthophosphate test results would be comparable to total phosphorus test results.

Figure 19 shows individual time-series graphs of phosphorus concentrations at eight USGS wells in Heber Valley from 1998 to 2019. Following the same methodology applied for evaluating TDS and nitrate trends, SWCA used the nonparametric Mann-Kendall test for trend with a 95% confidence interval on timeseries total phosphorus data. These wells are annotated with an asterisk in Figure 20. Well (D-4-5) 16ccd-1 had a statistically significant decreasing trend.

Five out of eight USGS wells with long-term data showed statistically significant upward trends ($p < 0.05$):

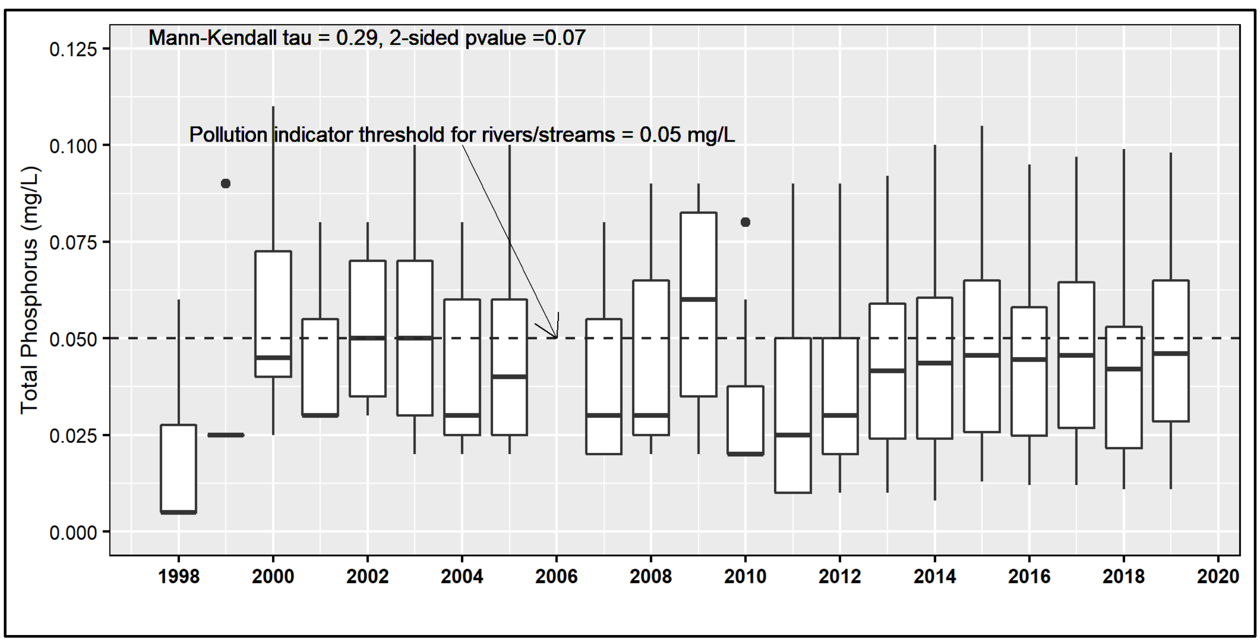
- (D-4-5) 16bab-1 (located in the Center Creek area of the valley)
- South Fields #2/(D-4-4) 12dcc-1
- Lake Creek #2/(D-4-5) 4ccb-1
- (D-4-5) 6bcc-2
- (D-4-5) 26dba-1

Phosphorus concentrations are variable at Lake Creek #1/(D-4-5) 3ddc-1 and have exceeded pollution indicator threshold for rivers and streams of 0.05 mg/L since 1998, although a upward trend in phosphorus was not detected using the Mann-Kendall test. Phosphorus levels at USGS well (D-4-4) 13bdd-1 in Charleston has changed very little in the past 20 years. Boxplots of total phosphorus concentration by year are displayed in Figure 19. The Mann-Kendall test for trend did not reveal a significantly increasing or decreasing trend in phosphorus concentrations in the Heber Valley aquifer over time ($p > 0.05$). Continued evaluation of USGS data is warranted to examine changes in phosphorus concentrations over time.



Note: USGS parameter codes P00666 and P00671 were combined to form a continuous a dataset.
* Mann-Kendall test using a 95% confidence interval indicates a statistically significant upward trend in nitrate over time.
^ Mann-Kendall test using a 95% confidence interval indicates a statistically significant decreasing trend in nitrate over time.

Figure 19. Time series graphs of phosphorus concentrations at nine USGS wells in the Heber Valley



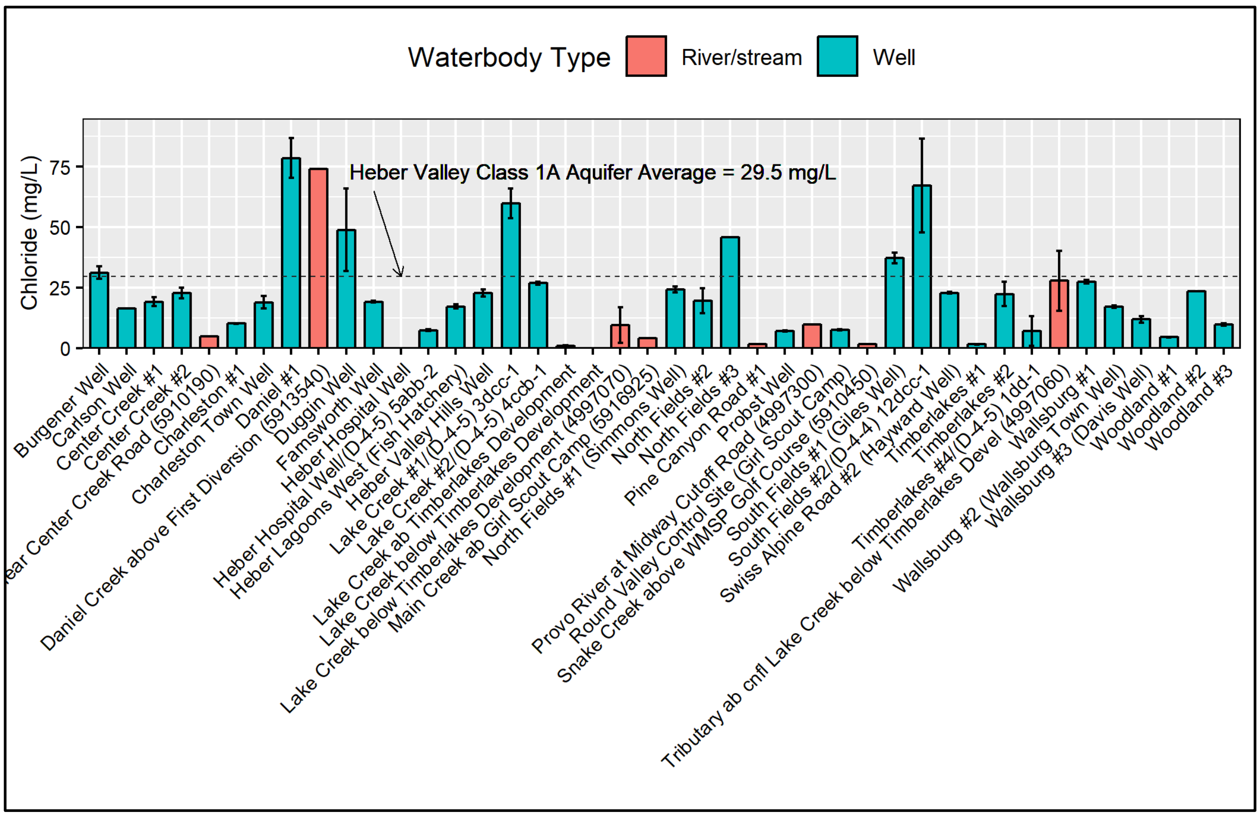
Note: USGS parameter codes P00666 and P00671 were combined to form a continuous a dataset. The size of each boxplot corresponds to the interquartile range of the data, described as the distance between the 25th and 75th percentile or first and third quartiles. The horizontal line in each box plot represents the median, or 50th percentile. Whiskers extend from the box to the highest and lowest value, at most 1.5 times the interquartile range. Data beyond the whiskers are considered outliers and are plotted individually. No significant trend in either direction was detected with the Mann-Kendall test using a 95% confidence interval.

Figure 20. Boxplot of total phosphorus concentrations at USGS wells in the Heber Valley from 1998 to 2020.

3.5 Chloride

Sources of chloride in drinking water are both natural and anthropogenic, although natural concentrations in surface and groundwater are expected to be low. Chlorides are often used as an indicator of contamination of groundwater by wastewater because human waste is high in chloride. The most common sources of elevated chloride levels in groundwater are road salting and discharge of water softeners to septic systems (Rayne et al. 2018). The EPA has set a secondary maximum contaminant level of 250 mg/L for chloride in drinking water (EPA 2009).

Along with TDS, nitrate, and total phosphorus, we tested for chloride in all water samples collected during the study to supplement existing datasets, to gather baseline data where none existed, and to identify elevated sources of nitrate throughout the aquifer. Chloride values ranged from 1.1 mg/L at Timberlakes #4, to 99 mg/L at North Fields #3, with an average chloride concentration in the Heber Valley aquifer of approximately 29 mg/L. Figure 21 summarizes the average chloride concentration at each sampling location from 2018 to 2020. Average chloride concentrations are displayed spatially in Figure 22. Wells with above-average chloride were Burgener Well, Daniel #1, Duggin Well, Lake Creek #1/(D-4-5) 3dcc-1, North Fields #3, South Fields #1 (Giles Well), and South Fields #2/(D-4-4) 12dcc-1. Chloride in surface water samples was generally low, with the exception of Daniels Creek. Road salts are assumed to be the primary cause of elevated chloride concentrations in Daniels Creek and the nearby Daniel #1 well (see Section 3.5.1 for further discussion of the Daniel #1 well).



Note: Error bars represent the mean plus and minus the standard deviation. Locations that do not have error bars were only visited once.

Figure 21. Average chloride concentration at SWCA sampling locations between 2018 and 2020.

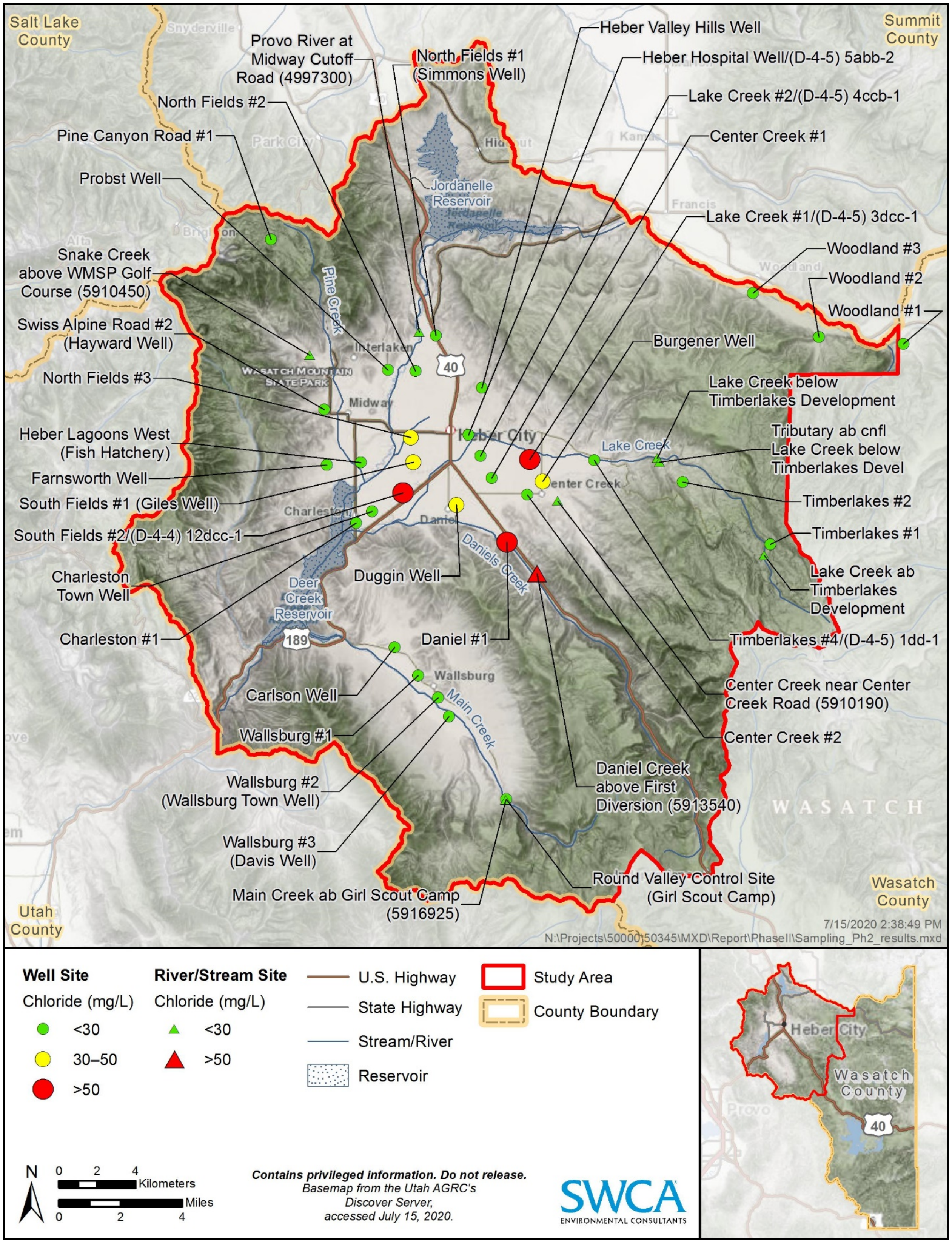


Figure 22. Average chloride values at SWCA sampling locations (2018 to 2020).

SWCA also tested for bromide with the aim of using the chloride-to-bromide ratio in contaminant source identification. The chloride-to-bromide ratio has been used to differentiate between sources of groundwater contamination because different sources have been documented to have distinctive elemental ratios (Davis et al. 1998; Jordan 2017; Katz et al. 2011; Panno et al. 2006). The chloride-to-bromide mass ratio of a water sample is calculated by dividing the concentration of chloride by the concentration of bromide in equal units. Table 7 shows the typical ranges of chloride-to-bromide ratios associated with groundwater human and agricultural sources, as well as ranges typically seen in precipitation and fresh groundwater (Katz et al. 2011).

Table 7. Sources of Groundwater Pollution and the Associated Chloride-to-Bromide Mass Ratio Ranges

Water Source	Chloride-to-Bromide Mass Ratio Range
Precipitation	30–120
Cattle manure leachate	65–167
Fresh and brackish subsurface groundwater	82–164
Sewer or septic tank effluent	544–1,150
Animal waste	1,245–1,654

Source: Katz et al. (2011)

Although the chloride-to-bromide ratio can be used to help differentiate between human and livestock sources of contamination, the technique is not always definitive because of the similarities in ranges of chloride-to-bromide ratios (Panno et al. 2006). For example, "livestock manure leachate has Cl:Br [chloride-to-bromide ratio] similar to fresh groundwater; therefore, groundwater contaminated from feedlots and dairies may have high chloride and other TDS, but the Cl:Br would not be distinguishable from uncontaminated groundwater" (Jordan 2017:39). Bromide concentrations measured in 2019 ranged from 0.02 to 0.05 mg/L, consistent with natural levels of bromide in fresh groundwater, which typically range from 0.0032 to 0.058 mg/L (VanBriesen 2014). Water samples from 30 locations were tested for Bromide in 2019; however, only nine wells had concentrations greater than method reporting limit of 0.02 mg/L. Table 8 summarizes these data as well as the chloride-to-bromide ratio for each well. Most wells with measurable concentrations of bromide had chloride-to-bromide ratios in the range indicative of sewer or septic effluent; however, the results are not deterministic as previously mentioned. Furthermore, most of the wells sampled had lower than average nitrate concentrations, indicating the groundwater quality was not likely degraded from septic influence. The chloride-to-bromide ratio analysis was supplemented with the collection of additional parameters to characterize sources of groundwater pollution in the study area. Supplemental parameters such as pesticides and pharmaceutical compounds are discussed in Sections 3.6 and 3.7.

Table 8. Chloride-to-Bromide Ratios at SWCA sampling locations

Sampling Location Name	Sample Date	Chloride (mg/L)	Bromide (mg/L)	Chloride-to-Bromide Ratio	Nitrate* (mg/L)
Wallsburg #2 (Wallsburg Town Well)	11/13/2019	17.3	0.033	524.2	0.93
Wallsburg #3 (Davis Well)	11/13/2019	13.5	0.023	587.0	0.45
Burgener Well	11/18/2019	34.1	0.056	608.9	2.86
Heber Valley Hills Well	11/18/2019	25.0	0.038	657.9	0.95
Heber Lagoons West (Fish Hatchery)	11/18/2019	18.1	0.027	670.4	1.10

Sampling Location Name	Sample Date	Chloride (mg/L)	Bromide (mg/L)	Chloride-to-Bromide Ratio	Nitrate* (mg/L)
Center Creek #1	11/13/2019	17.8	0.025	712.0	2.10
Wallsburg #1	11/13/2019	27.3	0.036	758.3	1.89
Swiss Alpine Road #2 (Hayward Well)	11/18/2019	22.4	0.020	1,120.0	2.17
South Fields #2/(D-4-4) 12dcc-1	11/14/2019	80.3	0.031	2,590.3	3.86

* Value is an average of nitrate concentrations in water samples collected at the site from 2018 to 2020.

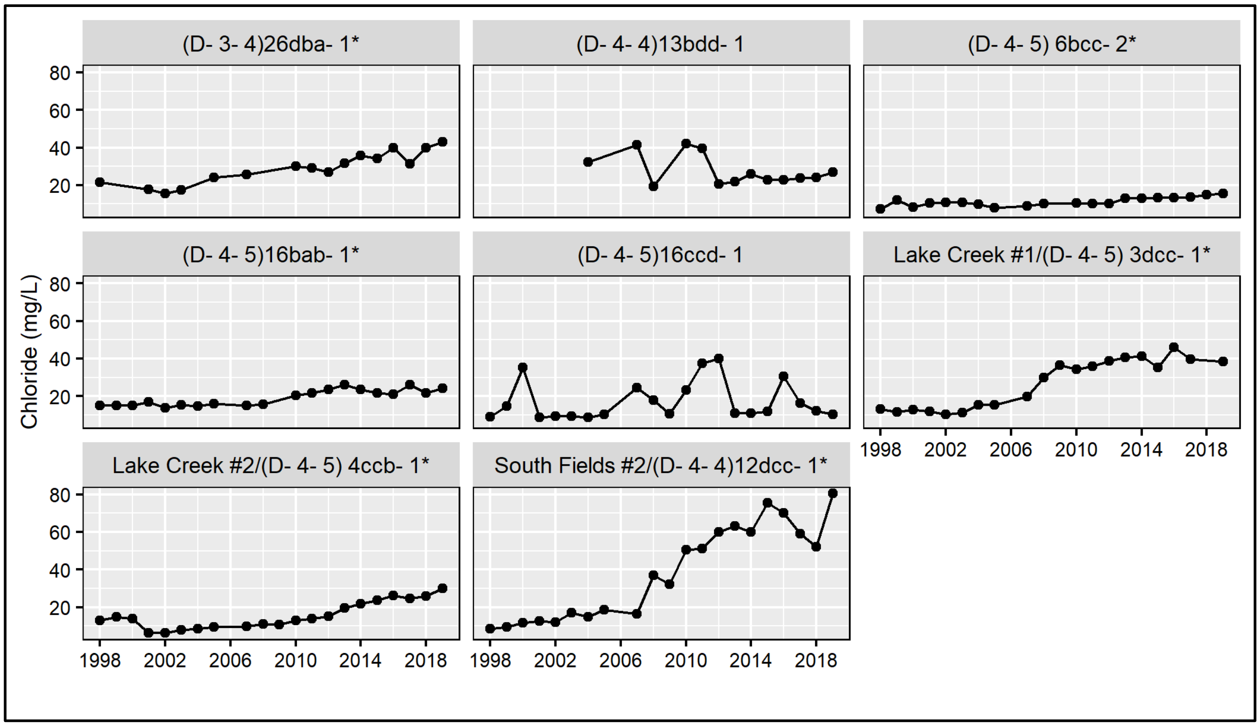
3.5.1 *Comparison to Historical Data*

SWCA obtained data from the USGS NWIS database to evaluate if and how chloride concentrations are changing over time in the study area. Eight wells in the Heber Valley were selected for further review because they have at least 10 samples collected in the last 20 years. Figure 23 shows time-series graphs of chloride concentrations for each USGS well from 1998 to 2020. The Mann-Kendall test for trend using a 95% confidence interval suggests that chloride concentrations are increasing at six out of eight USGS wells. The USGS wells with statistically increasing chloride trends were as follows:

- (D- 4- 5) 16bab- 1
- South Fields#2/(D-4-4) 12dcc- 1
- Lake Creek #1/(D- 4- 5) 3dcc- 1
- Lake Creek #2/(D- 4- 5) 4ccb- 1
- (D- 4- 5) 6bcc- 2
- (D- 3- 4) 26dba- 1

The highest chloride concentrations are observed at South Fields #2/(D-4-4) 12dcc-1 where land application of treated wastewater (which is assumed to be high in chloride) occurs directly upgradient from the well. Water is applied through sprinkler heads on these fields where evaporation further concentrates chloride concentrations in the soil where it can be transported into the groundwater.

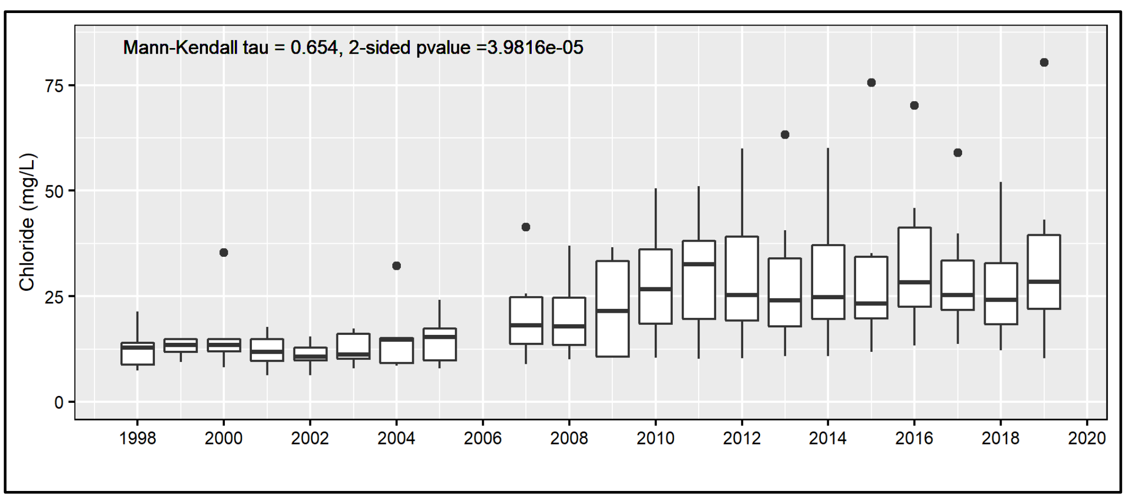
The two wells that did not exhibit an upward trend in chloride were (D-4-4) 13bdd-1 and (D-4-5) 16 ccd-1, located in Charleston to the east of highway 189, and near the mouth of Daniels Canyon, respectively. Chloride concentrations at well (D-4-5) 16ccd-1 at the mouth of Daniels Canyon are variable and range from 8.6 to 40.1 mg/L. Water samples are collected annually in August at this well. Given SWCA's understanding of the hydrologic system, the pollutant sources in the area (road salts), and higher than average chloride concentrations at the nearby Daniel #1 well, SWCA may have expected chloride concentrations to be higher at this well. The well driller's log obtained from DWRi indicates that the Daniel #1 well is drilled to a depth of approximately 75 feet below ground surface and draws water from the fractured bedrock aquifer formation. The nearby USGS well with lower chloride concentrations is screened in the unconsolidated fill material at approximately 150 feet below ground surface. Groundwater from higher elevation areas may be moving along fractures and fissure openings downgradient into the source water for the Daniel #1 well. Groundwater in fractured rocks (as is found in upland areas surrounding Heber and Round Valleys) is highly susceptible to pollution because there is little soil cover and therefore little capacity for filtration (Lowe 1995).



* Mann-Kendall test using a 95% confidence interval indicates a statistically significant upward trend in nitrate over time.

Figure 23. Time-series graphs of chloride concentrations at USGS wells in the Heber Valley.

Data from the same eight USGS wells were aggregated by year from 1998 to 2020 using the median value for each year (Figure 24). SWCA tested for a significant monotonic chloride trend in the Heber Valley aquifer using the Mann-Kendall test because assumptions for linear regression were not met because of the non-normal distribution of the data. Results indicate a statistically significant upward trend in chloride concentrations in the Heber Valley aquifer ($p < 0.05$). Outliers in Figure 24 are greater than 1.5 times the interquartile range and are plotted individually. Outliers in recent years are from well South Fields #2/(D-4-4) 12dcc-1.



Note: The size of each boxplot corresponds to the interquartile range of the data, described as the distance between the 25th and 75th percentile or first and third quartiles. The horizontal line in each box plot represents the median, or 50th percentile. Whiskers extend from the box to the highest and lowest value, at most 1.5 times the interquartile range. Data beyond the whiskers are considered outliers and are plotted individually. The secondary drinking water standard for chloride of 250 mg/L is not shown in this figure.

Figure 24. Boxplot of chloride concentrations at USGS wells in the Heber Valley from 1998 to 2020.

3.6 Pesticides, Volatile Organic Compounds, and Metals

The 2003 Utah Geological Survey (UGS) pesticide sensitivity and vulnerability study (Lowe et al. 2003) revealed that although pesticides did not pose a serious threat to groundwater at the time, continued monitoring is warranted because of high pesticide sensitivity and vulnerability. Lowe et al. (2003) concluded that pesticides may not be reaching the groundwater because of long travel times in the vadose zone and short half-lives in the environment; however, aquifers in Heber and Round Valleys are not protected by impermeable clay layers, and the soils are highly conductive.

SWCA screened for pesticides and herbicides at wells where agriculture was the predominant land use and where groundwater was determined to be highly sensitive to groundwater contamination based on the groundwater sensitivity and vulnerability analysis (Table 9). Table 10 contains a complete list of the pesticides and herbicides that were screened. Concentrations of pesticides and herbicides were not present in concentrations above the detection limits for all water samples.

Volatile organic compounds (VOCs) are a wide class of chemicals that evaporate easily into air and water. VOCs are commonly found in industrial and commercial products, including solvents, paint, gasoline, cleaners, pesticides, and degreasers. VOC use is more common in urban areas than in areas of other land use. VOCs can easily enter the groundwater through spills and through wastewater from septic tanks, and small amounts can contaminate large quantities of groundwater. Appendix A of the spring 2019 SAP contains a list of analytes captured by EPA Method 8260 for analyzing VOCs.

During the spring 2019 sampling event, SWCA screened for VOCs and trace metals in groundwater wells that were downgradient of high-intensity (urban) development to identify potential threats to water quality from this type of land use including leaking underground storage tanks, industrial activities, and stormwater runoff from impervious surfaces. The VOC screen at various wells in the study area also serves to establish baseline conditions where data were limited or nonexistent. Table 9 only summarizes the wells that were sampled in spring 2019 for pesticides, herbicides, VOCs, and metals, and does not include the surface water locations or groundwater wells that were targeted for the core parameters sampled at all locations during each sampling event. The core parameters targeted at all locations are nitrate, total phosphorous, TDS, chloride, and field-measured parameters such as pH and specific conductance. For example, the sites in Timberlakes and Woodland are not included in Table 9 because the primary groundwater quality concern is nitrate, and the mechanism of pollution is septic tanks.

The occurrence of VOCs in groundwater depends on multiple factors, including the following (USGS 2006):

- Geographic and temporal extent of production and use of VOCs in industry, commerce, and household products
- Types and locations of VOC sources relative to sampled wells
- Extent of urban land use near the well
- Chemical and physical characteristics of the compounds themselves, such as their mobility and persistence
- Aquifer characteristics, including the presence or absence of dissolved oxygen, hydrogeology, and water-table depth
- Pumping stress on the aquifer
- Soil characteristics and climate
- Timing and amount of recharge to the groundwater system
- Timing of VOC releases to the environment and the age of groundwater

For all water samples, VOCs were not present in concentrations above the detection limits. It is important to note that although pesticides and VOCs were not present in measurable concentrations at the wells targeted by SWCA in the spring 2019, continued monitoring of VOCs is warranted, especially in areas of shallow groundwater. Shallow groundwater can "move downward into deeper aquifers used for drinking-water supply. Because ground-water movement is usually slow, contamination may take many years to disperse" (USGS 2006:4).

SWCA compared analytical test results of metals testing to State of Utah drinking water standards as written in UAC R309-200. The comparison revealed that two locations exceeded the drinking water standard for arsenic (0.010 mg/L): Heber Lagoons West (Fish Hatchery) at 0.0111 mg/L and Charleston #1 at 0.0137 mg/L. Ten of the sites sampled for arsenic were found to be below the method detection limit, and the two sites mentioned above were found to have concentrations just above the method detection limit. There were no other exceedances of drinking water quality standards for arsenic or other metals. Elevated concentrations of dissolved phase arsenic could be the result of anoxic or low pH chemical conditions, which transfer naturally occurring metals in soil/rock to a dissolved phase.

Table 9. Sampling Locations for Volatile Organic Compounds, Pesticides, Herbicides, and Metals

Sampling Location Name	Supplemental Parameter Summary*	Concern
Center Creek #1	Pesticides and herbicides	High sensitivity, baseline conditions, agriculture
Center Creek #2	Pesticides and herbicides	High sensitivity, baseline conditions, agriculture
Burgener Well	Pesticides and herbicides	High sensitivity, baseline conditions, agriculture
Charleston #1	VOCs, pesticides, herbicides, As, Al, Cd, Cr, Cu, Fe, Pb, Se, Zn	Septic contamination, aquifer terminus
Charleston Town Well	VOCs, pesticides, herbicides, As	Septic contamination, aquifer terminus
Heber City #1	VOCs, As, Al, Cd, Cr, Cu, Fe, Pb, Se, Zn	High-intensity urban development
Heber Hospital Well	VOCs, As, Al, Cd, Cr, Cu, Fe, Pb, Se, Zn	High-intensity urban development
Heber Lagoons West	VOCs, As, Al, Cd, Cr, Cu, Fe, Pb, Se, Zn	Wastewater, downgradient of high-intensity development
North Fields #1	Pesticides, herbicides, As	High sensitivity, baseline conditions, agriculture
North Fields #2	Pesticides, herbicides, As	High sensitivity, baseline conditions, agriculture
North Fields #3	Pesticides, herbicides, As	High sensitivity, baseline conditions, agriculture
South Fields #1 (Giles Well)	VOCs, As, Al, Cd, Cr, Cu, Fe, Pb, Se, Zn	Downgradient of high-intensity development
South Fields #2/(D-4-4) 12dcc-1	VOCs, As, Al, Cd, Cr, Cu, Fe, Pb, Se, Zn	Downgradient of high-intensity development
Wallsburg #1	Pesticides and herbicides	Septic contamination, agriculture
Wallsburg #2	Pesticides and herbicides	Septic contamination, agriculture
Wallsburg #3	Pesticides and herbicides	Septic contamination, agriculture
Heber Valley Hills Well	VOCs, As, Al, Cd, Cr, Cu, Fe, Pb, Se, Zn	Control site
Round Valley Control Site (Girl Scout Camp)	VOCs, pesticides, herbicides, As	Control site

Note: Core parameters were also sampled at all wells. Core parameters are nitrate, total phosphorous, TDS, chloride, and field parameters.

* As = arsenic, Al = aluminum, Cd = cadmium, Cr = chromium, Cu = copper, Fe = iron, Pb = lead, Se = selenium, and Zn = zinc.

Table 10. List of Pesticides and Herbicides Tested in the Spring 2019 Sampling Event

Full Pesticide List (American West Analytical Laboratories)	Targeted Herbicide List (Utah Department of Agriculture and Food)
4,4´-DDD	Atrazine
4,4´-DDE	Metolachlor
4,4´-DDT	Simazine
Aldrin	Cyanazine
alpha-BHC	Zeta-cypermethrin
beta-BHC	–
Chlordane, total	–
cis-Chlordane	–
delta-BHC	–
Dieldrin	–
Endosulfan I	–
Endosulfan II	–
Endosulfan sulfate	–
Endrin	–
Endrin aldehyde	–
Endrin ketone	–
gamma-BHC	–
Heptachlor	–
Heptachlor epoxide	–
Methoxychlor	–
Toxaphene	–
trans-Chlordane	–
2,4 D	–

3.7 Personal Care Products and Pharmaceutical Compounds

Groundwater chemistry data collected in 2018 and 2019 suggest that although groundwater quality in the study area is generally quite high, certain wells show diminished groundwater quality, which is evident by elevated concentrations of nitrate, phosphorous, chloride, and TDS. Identifying specific sources of nitrate and chloride can be difficult because numerous sources of each parameter exist within the study area. For example, elevated nitrate in a well can be the result of wastewater from a septic system but can also be attributed to the use of fertilizers in municipal or agricultural settings. Elevated chloride can be indicative of septic waste but can also be attributed to heavy use of road salts in the groundwater recharge area. Recent groundwater studies in Utah (Jordan 2017; Inkenbrandt 2019) have successfully used anthropogenic markers alongside traditional parameters like nitrate and chloride to help differentiate between human and agricultural sources of water quality degradation.

Personal care products and pharmaceutical compounds (PPCPs) are a class of groundwater contaminants of growing concern and are considered anthropogenic markers because they are not naturally occurring in the environment. PPCPs include compounds found in classes of pharmaceuticals like antibiotics, hormones, anti-depressants, steroids, and painkillers. PPCP compounds such as caffeine, acetaminophen, and carbamazepine are persistent in groundwater (i.e., they have limited degradation in groundwater) and are therefore suitable markers (Fenech et al. 2012; Glassmeyer et al. 2015).

During the spring 2020 sampling event, SWCA sampled for a suite of pharmaceutical compounds at nine wells distributed throughout the study area showing diminished groundwater quality with an aim to identify sources of elevated nitrate, to screen for potential groundwater contaminates in the aquifer, and to gather baseline data where none existed. SWCA also sampled two wells at reference locations above the influence of any septic system wastewater plumes as quality control samples. A list of the wells targeted for PPCP sampling is provided in Table 11, and the list of compounds included in the PPCP screen is included in Table 12.

Table 11. Personal Care Product and Pharmaceutical Sampling Results

Sampling Location Name	Reason for Sampling	Sampling Result
Burgener Well	Above average nitrate, TDS, chloride, and total phosphorus (TP)	No compound detected above laboratory reporting limit
Duggin Well	Above average nitrate, TDS, and chloride	Sulfamethoxazole at 14 nanograms per liter (ng/L)*; all other compounds below laboratory reporting limits
Farnsworth Well	Above average nitrate and TDS	No compound detected above laboratory reporting limit
Lake Creek #1/(D-4-5) 3dcc-1	Above average nitrate, TDS, chloride, and TP	No compound detected above laboratory reporting limit
Lake Creek #2/(D-4-5) 4ccb-1	Above average nitrate, TDS, and chloride	No compound detected above laboratory reporting limit
Round Valley Control Site (Girl Scout Camp)	QA/QC reference location	No compound detected above laboratory reporting limit
South Fields #1	Above average nitrate, chloride, and TP	No compound detected above laboratory reporting limit
South Fields #2/(D-4-4) 12dcc-1	Above average nitrate, TDS, chloride, and TP	No compound detected above laboratory reporting limit
Heber Valley Control Site (Timberlakes #1)	QA/QC reference location	No compound detected above laboratory reporting limit
Timberlakes #2	Above average TDS, chloride, and TP	No compound detected above laboratory reporting limit
Wallsburg #1	Collect baseline information in Round Valley; screen for contaminants of emerging concern	Bisphenol A at 14 ng/L#; all other compounds below laboratory reporting limits

Note: Nitrate concentration in Heber Valley is approximately 2.2 mg/L, average TDS is 275 mg/L, average chloride is 20 mg/L, and average TP is 0.04 mg/L.

* Sulfamethoxazole is an antibiotic, and the method reporting limit for this compound is 5 ng/L.
# Bisphenol A is also known as BPA. It is an industrial chemical used in certain food grade plastics such as plastic containers and water bottles. The method reporting limit for this compound is 10 ng/L.

Table 12. Compounds Present in the PPCP Sampling Suite

Analyte	Source
Acetaminophen	Nonsteroidal anti-inflammatory
Bisphenol A	Plastic food containers
Butalbital	Pain killer
Caffeine	Food and beverages
Carbamazepine	Anticonvulsant
Cotinine	Alkaloid found in tobacco
Diazepam	Anti-anxiety medication
Diclofenac	Nonsteroidal anti-inflammatory
Erythromycin	Antibiotics
Estradiol	Estrogen derivative
Estrone	Estrogen derivative
Ethinyl estradiol-17	Estrogen derivative
Fluoxetine	Anti-depressant
Gemfibrozil	Cholesterol medication
Ibuprofen	Nonsteroidal anti-inflammatory
Naproxen	Nonsteroidal anti-inflammatory
PFOA	Industrial surfactant
Primidone	Anticonvulsant
Progesterone	Hormone
Sulfamethoxazole	Antibiotic
Testosterone	Hormone
Trimethoprim	Antibiotic

As indicated in Table 11, two wells had a measurable concentration of one of the compounds in the suite of analytes. Sulfamethoxazole, an antibiotic used to treat infections in humans and animals, was present at 14 ng/L (0.014 parts per billion) in the Duggin Well in the Daniel area, and Bisphenol A (BPA; an industrial chemical used to make plastics) was detected in the Wallsburg #1 well at 14 ng/L. Most of the PPCPs listed in Table 12 are contaminants of emerging concern and therefore do not have federal or state water quality standards. However, according to the Minnesota Department of Health (2013), sulfamethoxazole levels lower than 100 parts per billion are safe in drinking water. Given that sulfamethoxazole is used in human and veterinary applications, the results are not deterministic of septic system contamination at the Duggin Well. Furthermore, the lack of signal from all other PPCPs in the sample and the very low concentration of sulfamethoxazole do not indicate clear contamination from septic local septic tanks.

Similarly, the BPA measured in the Wallsburg #1 well is present at an extremely low concentration (0.014 parts per billion) and is significantly lower than the guidance value of 20 parts per billion implemented by the Minnesota Department of Health (2014). SWCA assumes there are no agricultural applications of BPA and therefore reasonably suggest that septic system leachate (either from the Wallsburg #1 well or from neighboring wells) may be contributing to the BPA in drinking water at the Wallsburg #1 well.

SWCA queried the USGS NWIS database for caffeine data to supplement the analysis of personal care products and pharmaceuticals in the study area. Caffeine was tested for at four USGS wells between 2009 and 2013, including USGS well South Fields #2/(D-4-4) 12dcc- 1, Lake Creek #1/(D-4-5) 3dcc- 1, and Lake Creek #2/(D-4-5) 4ccb- 1, which are known to be hot spots for nitrate, TDS, and total phosphorus. Caffeine was not detected in any sample, which indicates the source of degraded water quality at these wells could be attributed to agricultural activities or that concentrations from septic systems are too low to detect.

3.8 Major Ions

Major cations and anions were sampled during the fall 2019 sampling event to evaluate the ionic composition of water samples from different sections of the study area. Major ion concentrations were used to create Stiff and Piper diagrams that provide a way to visually compare water chemistry makeup between samples and compare ionically related waters. Additionally, Stiff diagrams can also be used to help delineate groundwater flow paths. Major ion composition is also an important baseline to which future groundwater monitoring efforts can be compared. Stiff and Piper diagrams are most useful in their ability to compare water samples and find commonalities and patterns. These patterns provide evidence for the fundamental flow patterns and water sources in the aquifer. The following conclusions are drawn from the Stiff and Piper diagrams.

3.8.1 *Overall Aquifer Dynamics*

Most water samples collected in the study can be classified as calcium bicarbonate water type, with all but two of the samples clustering closely in the Piper diagram (Figure 25). The Wallsburg #1 well, screened in the alluvial material in Round Valley (see Figure 26 for a map of sampling locations), has a very low calcium concentration compared to other water samples. For comparison, the average calcium concentration across all samples was 58.22 mg/L, and calcium concentration at the Wallsburg #1 well was 0.5 mg/L. Timberlakes #1, screened in bedrock, also has a lower than average calcium concentration at 10.8 mg/L

Overall, there is relatively little differentiation anywhere in the aquifer. Little variation is observed whether geographically, between wells completed in bedrock versus alluvium, or between surface water samples and groundwater samples. This confirms several assumptions made about the aquifer dynamics. Based on the water budget and groundwater modeling, the primary sources of water throughout the aquifer are recharge from the surrounding mountains (~64% of total recharge), agricultural return flow (~16% of total recharge), and recharge from the tributary streams (~11% of total recharge). Mountain-front recharge and tributary recharge are both derived from precipitation with relatively little opportunity to change through evaporation and account for 80% of recharge in the basin. Agricultural return flow is primarily derived from surface flow as well but has greater opportunity to pick up salt load and concentrate through evaporation. The lack of differentiation in the Stiff and Piper diagrams is consistent with the conceptual model that the basin water balance is dominated by precipitation, whether through runoff or mountain-front recharge.

The lack of differentiation between groundwater samples from wells completed in unconsolidated materials (alluvium) versus consolidated materials (bedrock) confirms the conceptual model that both units are productive parts of the aquifer, and that groundwater moves freely between these two general geologic units.

3.8.2 *Areas of Elevated TDS*

Based on groundwater sampling results shown in Table 13, six wells have elevated TDS concentrations (defined as being in the upper 20% of the 30 wells sampled):

- Burgener Well
- Daniel #1
- Daniels Creek
- South Fields #2/(D-4-4) 12dcc-1 (also statistically confirmed to have TDS concentration increases over time)
- Swiss Alpine Road #2
- Wallsburg #1

Four of these wells have a similar pattern, with sodium and chloride being elevated.[3]These wells are Daniel #1, Daniels Creek, South Fields #2/(D-4-4) 12dcc-1, and Wallsburg #1. This signature is potentially indicative that increased TDS in these wells is influenced by runoff from road salt (which generally is 95% sodium chloride, depending on source and proprietary additives). Two other wells do not exhibit elevated TDS levels, but also share the sodium/chloride signature: Lake Creek #1/(D-4-5) 3dcc-1 and Timberlakes #1. The Swiss Alpine Road #2 well has elevated TDS, but rather than this being an impact from road salt, this well appears to be impacted by naturally occurring tufa deposits ($CaCO_3$) in the Midway areas, because this well has the highest concentrations of both calcium and bicarbonate of the 30 wells in Table 13. However, the Stiff diagrams illustrate that Swiss Alpine Road #2 also shows a relatively high influence of magnesium and sulfate.

3.8.2.1 AREAS OF ELEVATED NITRATE

Stiff diagrams were prepared for four wells that were identified with the relatively high concentrations (Figure 26):

- Lake Creek #1/(D-4-5) 3dcc-1
- Lake Creek #2/(D-4-5) 4ccb-1
- South Fields #2/(D-4-4) 12dcc-1
- Duggin Well

No notable patterns stand out from the Lake Creek #2/(D-4-5) 4ccb-1 and Duggin wells. Lake Creek #1/(D-4-5) 3dcc-1 and South Fields #2/(D-4-4) 12dcc-1 are both notable for their elevated sodium-chloride concentrations, as described above. The combination of these two elevated signatures (elevated nitrate and elevated sodium-chloride) suggests that these wells may be influenced by surface runoff or shallow groundwater, possibly through poor surface construction or a nearby recharge source.

---

[3] *Elevated* was defined by first converting all concentrations to milliequivalents per liter (the metric used to create Stiff diagrams), calculating the percentage that sodium and chloride represent of the total milliequivalents, and then identifying the upper 20% of wells.

Table 13. Concentrations of Cations and Anions Sampled during the Fall 2019 Sampling Event

Sampling Location Name	Stiff Label	Ca^+	Mg^+	Na^+	K^+	CO_3^-	HCO_3^-	Cl^-	SO_4^-	TDS
Burgener Well	1	99.1	20.5	29.2	2.6	5.0	304.0	31.6	31.7	410.0
Center Creek #1	2	72.2	16.3	12.2	2.5	5.0	234.0	19.5	17.2	327.0
Center Creek #2	3	67.3	17.8	12.9	3.5	5.0	214.0	24.1	21.3	302.0
Center Creek near Center Creek Road (5910190)	4	50.9	13.4	5.1	1.1	28.0	142.0	4.8	19.3	198.0
Charleston Town Well	5	77.5	19.0	11.1	1.9	5.0	256.0	18.0	18.2	310.0
Daniel #1	6	70.6	23.9	29.6	1.6	5.0	214.0	82.8	16.4	372.0
Daniels Creek above First Diversion (5913540)	7	59.7	19.7	39.4	1.2	5.0	216.0	74.1	7.0	392.0
Duggin Well	8	69.9	24.0	14.0	1.0	5.0	232.0	36.1	15.2	306.0
Heber Hospital Well	9	50.7	10.8	7.4	1.8	5.0	168.0	7.3	11.4	188.0
Heber Lagoons West (Fish Hatchery)	10	63.9	15.6	20.7	3.8	5.0	184.0	17.7	58.9	307.0
Heber Valley Hills Well	11	50.9	10.6	13.0	3.7	5.0	146.0	22.0	11.4	228.0
Lake Creek #1/(D-4-5) 3dcc-1	12	53.1	10.9	18.1	3.4	5.0	190.0	62.5	10.1	273.5
Lake Creek #2/(D-4-5) 4ccb-1	13	72.8	12.4	5.8	2.5	5.0	176.0	26.6	15.7	304.0
Lake Creek above Timberlakes Development	14	55.6	5.7	3.4	1.2	5.0	174.0	0.9	1.3	149.0
Lake Creek below Timberlakes Development (4997070)	15	41.8	7.4	11.2	2.1	52.0	90.0	6.4	4.6	163.0
Main Creek ab Girl Scout Camp (5916925)	16	56.2	13.5	4.3	0.5	44.0	118.0	4.0	27.2	172.1
North Fields #1 (Simmons Well)	17	45.4	9.0	13.5	3.9	5.0	120.0	23.4	22.8	214.0
North Fields #2	18	34.2	8.6	7.0	0.5	5.0	112.0	19.4	14.9	172.0
North Fields #3	19	57.1	11.1	9.3	2.3	5.0	160.0	19.2	20.5	213.0
Provo River at Midway Cutoff Road (4997300)	20	25.0	5.4	4.5	0.5	14.0	51.0	9.7	17.5	129.9
Snake Creek ab WMSP Golf Course (5910450)	21	42.3	13.1	2.5	0.5	5.0	130.0	1.5	22.9	168.9
South Fields #1 (Giles Well)	22	59.4	10.1	10.0	1.8	5.0	152.0	38.4	17.6	252.0
South Fields #2/(D-4-4) 12dcc-1	23	94.2	26.3	36.9	1.8	5.0	266.0	78.2	40.2	476.0
Swiss Alpine Road #2 (Hayward Well)	24	129.0	45.0	17.3	1.0	5.0	324.0	23.0	207.0	600.0
Timberlakes #1	25	10.8	5.5	28.8	3.4	5.0	114.0	1.5	2.6	125.0
Timberlakes #4	26	42.8	5.2	6.1	2.0	5.0	140.0	3.9	5.2	216.0
Tributary above Lake Creek below Timberlakes Development (4997060)	27	90.0	13.2	8.3	3.0	5.0	180.0	22.8	6.4	238.0
Wallsburg #1	28	0.5	0.5	131.0	1.2	5.0	240.0	27.0	23.3	332.0
Wallsburg #2 (Wallsburg Town Well)	29	72.3	16.9	10.3	1.2	5.0	214.0	17.3	20.9	268.0
Wallsburg #3 (Davis Well)	30	64.4	17.5	13.8	1.7	5.0	214.0	11.9	26.4	260.0

Note: All concentrations are reported in mg/L.

Ca+ = calcium, Mg+ = magnesium, Na+ = sodium, K+ = potassium, CO_3- = carbonate, HCO_3 = bicarbonate, Cl = chloride, SO_4- = sulfate, and TDS = total dissolved solids.

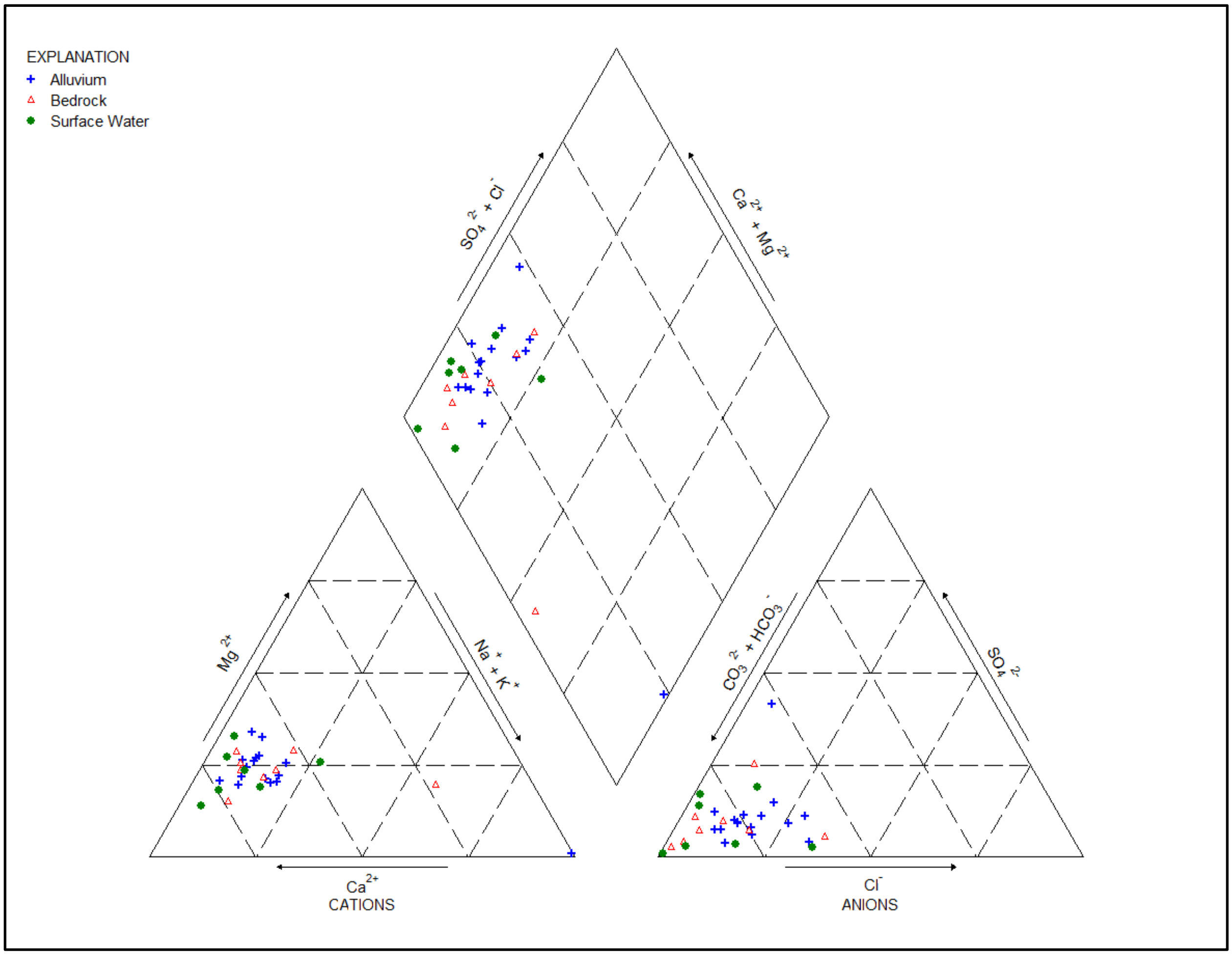


Figure 25. Piper diagram of water chemistry.

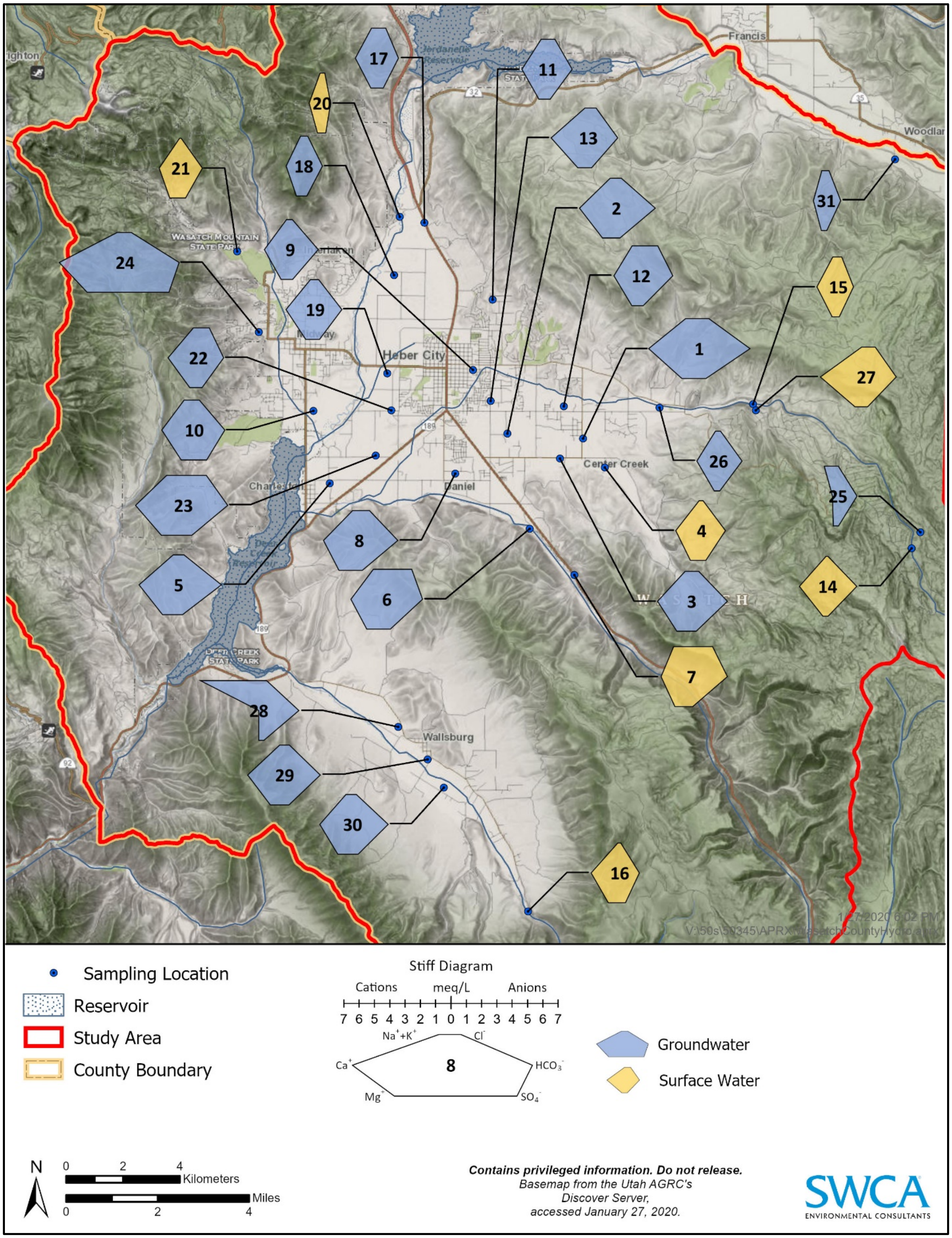


Figure 26. Study area showing stiff diagrams for ion concentrations in surface and groundwater samples. Label number refers to site name (see Table 13).

4 SURFACE WATER QUALITY

This section includes a brief discussion of the surface water quality conditions in the study area (Section 4.1); the land use activities in the study area, the associated pollutants of concern, and the fate and transport of the pollutants of concern in surface and groundwater (Section 4.2); the results of SWCA's surface water quality sampling and data analysis efforts (Section 4.3); and a discussion of the potential pathways for surface water contaminants to enter the aquifer (Section 4.4). Surface water hydrology is discussed in greater detail in SWCA's Phase 1 report and groundwater budget (SWCA 2019a; 2019b).

4.1 Existing Surface Water Quality

Surface water quality in the study area is mixed, with higher elevation sub-watersheds generally having better water quality than sub-watersheds at lower elevations that are below the influence of anthropogenic activities that typically have detrimental impacts on water quality.

Every 2 years, DWQ assesses the biological, chemical, and physical integrity of surface waters in the state of Utah and reports beneficial use attainment status in the state's integrated report. To carry out the assessment, surface waters of the state such as rivers, lakes, and streams have been separated into discrete sub-watershed units called assessment units. Assessment units are delineated by DWQ and are based on USGS 5th-level and 6th-level hydrologic unit codes. Data collected within each assessment unit are compared to state numeric and narrative criteria for each designated beneficial use, as written in UAC R317-2. Beneficial use classes and water quality standards are described in Utah Administrative Code R317-2. Surface waters failing to meet water quality standards for any designated beneficial use are listed on Utah's 303(d) list of impaired waterbodies and are subsequently prioritized for development of a TMDL study to outline the process to restore beneficial use attainment. In general, sources of pollution are not considered or identified during the assessment process but are evaluated during a subsequent TMDL process after a waterbody has been placed on Utah's 303(d) list of impaired waterbodies. Pollution sources may also be investigated as part of watershed studies or non-point source pollution monitoring efforts.

Figure 27 shows the assessment determinations of surface waters from the most recent state integrated report in Utah, and Table 14 summarizes the beneficial use categories and cause of impairment (if applicable) for each assessment unit in the study area. *Escherichia coli* (*E. coli*) and temperature are the most common impairments in the study area. The only approved TMDL in the study area is for Deer Creek Reservoir.

Table 14. Surface Water Assessment Determinations from DWQ 2016 Integrated Report

Assessment Unit Name	Designated Beneficial Uses	DWQ 2016 Assessment*	Impairment
Daniels Creek-1	1C, 2B, 3A, 4	2: Supports all assessed uses	–
Daniels Creek-2	1C, 2B, 3A, 4	2: Supports all assessed uses	–
Deer Creek Reservoir	1C, 2A, 3A, 4	5/4A: TMDL required/TMDL approved	Use Class 3A: temperature, dissolved oxygen
Heber Valley	1C, 2B, 3A, 4	5: TMDL required. 303d impaired	Use Class 3A: temperature
Jordanelle Reservoir	1C, 2A, 3A, 4	5: TMDL required. 303d impaired	Use Class 3A: pH
Lake Creek-2	1C, 2B, 3A, 4	1: Supports all designated uses	–
Little South Fork Provo	1C, 2B, 3A, 4	2: Supports all assessed uses	–

Assessment Unit Name	Designated Beneficial Uses	DWQ 2016 Assessment*	Impairment
Main Creek-1	1C, 2B, 3A, 4	5: TMDL required. 303(d) impaired	Use Class 1C: *E. coli* Use Class 2B: E. *coli* Use Class 3A: O/E bioassessment†
Main Creek-2	1C, 2B, 3A, 4	5: TMDL required. 303(d) impaired	Use Class 1C: *E. coli* Use Class 2B: *E. coli*
McHenry Creek	1C, 2B, 3A, 4	5: TMDL required. 303(d) impaired	Use Class 3A: zinc, cadmium
Provo River-4	1C, 2B, 3A, 4	5: TMDL required. 303(d) impaired	Use Class 1C: *E. coli* Use Class 2B: *E. coli*
Provo River-6	1C, 2B, 3A, 4	5: TMDL required. 303(d) impaired	Use Class 3A: aluminum, zinc
Provo Tributaries-Heber	1C, 2B, 3A, 4	3: Insufficient data	–
Provo Tributaries-Heber	1C, 2B, 3A, 4	3: Insufficient data	–
Snake Creek-1	1C, 2B, 3A, 4	5: TMDL required. 303(d) impaired	Use Class 1C: arsenic
Snake Creek-2	1C, 2B, 3A, 4	1: Supports all designated uses	–
Spring Creek-Heber	1C, 2B, 3A, 4	5: TMDL required. 303(d) impaired	Use Class 1C: *E. coli* Use Class 2B: *E. coli*

Note: An assessment unit is reported as category 2 “if there are insufficient data to assess all beneficial uses, yet those uses that have been assessed are found to be supporting designated uses” (DWQ 2016).

* Data from DWQ (2016).

† O/E bioassessment: Assessment of macroinvertebrate assemblages. O/E is a comparison of the observed taxa (O) to the list of expected taxa (E).

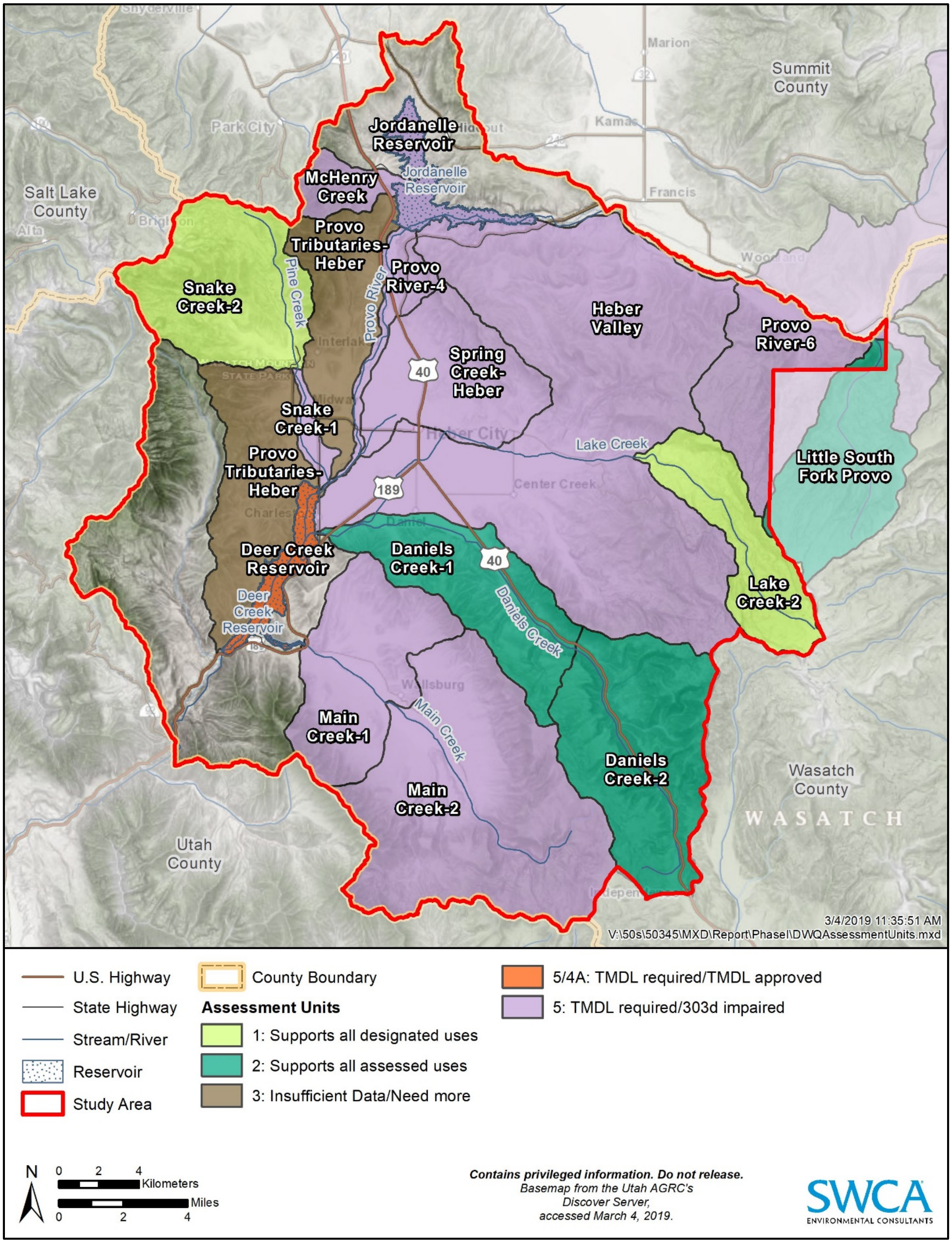


Figure 27. DWQ assessment units in the study area with 2016 Integrated Report assessment categories (Source: UDEQ 2019).

All surface waters in the study area eventually discharge to Deer Creek Reservoir, which is a major drinking water source for residents along the Wasatch Front as well as a popular recreation area. In 2000, DWQ assessed Deer Creek Reservoir and determined the reservoir was not meeting its cold-water fishery beneficial use because of low levels of dissolved oxygen and high levels of phosphorus. The major sources of phosphorus identified in the subsequent 2002 Deer Creek Reservoir TMDL report were non-point source agricultural activities in the watershed and background phosphorus levels, including the Jordanelle Reservoir discharge (PSOMAS 2002).

4.2 Land Uses and Pollutants of Concern

Land use categories in the study area are forested and undeveloped (native range), agricultural, residential, and commercial/urban. Within the study area, native range land use categories have been, and continue to be, the largest land use categories, making up more than half of the total land use (National Land Cover Database 2011). Native range land uses are generally undeveloped, but there may be impacts to surface water quality from public and private roads, limited areas of residential development, or grazing. Agricultural land use and residential land use are the next largest land use categories. The general trend in the Heber Valley has been a shift from agricultural to residential and urban areas. Many areas have mixed land use. For example, some areas may be classified as residential but have many agricultural aspects and vice-versa. Urban areas contain a mix of commercial and residential area.

Nonpoint source pollution is the primary mechanism of surface water quality degradation in the study area because there are no permitted point-source discharges to surface waters. Nonpoint source pollution is caused by runoff from snowmelt or rainfall that moves across the ground, picks up natural and anthropogenic pollutants, and finally deposits them into a waterbody. Surface water pollutant source identification is complex because of mixed land uses, multiple and diffuse sources of pollutants, and the dynamic nature of surface water. For example, increases in total suspended sediment in a stream may be attributed to crop agriculture, livestock agriculture, construction activities occurring with any land use, or naturally occurring high flow events like spring runoff. Additionally, stormwater runoff is often of short duration and is not frequently captured in monitoring efforts.

In consultation with the WCHD, SWCA established parameters of concern associated with the land uses in the study area. Table 15 summarizes these parameters as well as their fate and transport in surface water and groundwater.

Table 15. Land Use in the Study Area and the Associated Pollutants of Concern as Well as Their fate and Transport in Surface and Groundwater

Land Use	Pollutants of Concern	Fate and Transport in Surface Water	Fate and Transport in Groundwater
Native range	None	Not applicable	Not applicable
Agricultural	Pesticides and herbicides	Solubility is dependent on the pesticide. Herbicides are detected in surface water more frequently than pesticides, and detection in surface water may be a function of the amount of chemical applied (USGS 2014). "Pesticides applied to cropland can contaminate the underlying ground water and then move along ground-water flow paths to surface water" (Winter et al 1998:64).	In the pesticide sensitivity and vulnerability study completed in 2003, UGS concluded that the pesticides in question did not pose a serious threat and had high attenuation and short half-lives (Lowe et al. 2003). Pesticides adsorb to organic carbon in the soil and move slowly through the vadose zone. Additionally, the pesticides in question were found to degrade relatively quickly (Lowe et al. 2003).

Land Use	Pollutants of Concern	Fate and Transport in Surface Water	Fate and Transport in Groundwater
	Nutrients (N and P)	Highly soluble and persistent in surface water.	Highly soluble and persistent in groundwater. Nitrogen in the form of nitrate is typically more mobile in groundwater than phosphorus.
	Pathogens	Agricultural return flows and surface runoff over pasture lands can carry animal waste into rivers and streams, transporting pathogens to downstream areas.	Localized contamination may result from improperly constructed wells and septic tanks. Natural filtering occurs between surface water and groundwater; therefore, it is unlikely (although possible) that pathogens enter groundwater from surface water.
Residential	Nutrients (N and P)	Nitrogen from human and animal waste or fertilizer is conveyed to surface waters by runoff. Nitrogen in surface water can be present as ammonia, organic nitrogen, or nitrate/nitrite. Excess nutrients lead to eutrophic conditions in surface waters.	Nitrate is the predominant form of nitrogen in groundwater. Most forms of nitrogen (organic nitrogen and inorganic nitrogen including ammonia) are readily converted to nitrate in aerobic conditions. Nitrogen in the form of nitrate is typically more mobile in groundwater than phosphorus.
	PPCP	Different compounds have different patterns of persistence in surface water due to the inherent stability of the compound. Wastewater treatment plant effluent is a significant source of PPCP compounds in surface water. Not all compounds are removed during wastewater treatment.	Different compounds have different patterns of persistence in groundwater related to the inherent stability of the compound. Fenech et al. 2012 identified 30 compounds (including caffeine, acetaminophen, and ibuprofen) that are suitable markers in groundwater because they are persistent and stable in water.
Urban/commercial	Metals	Fate and transport of metals is dependent on many factors that include physical, chemical, and biological processes. Under neutral pH, many metals precipitate and settle to the bottom of a stream. Low pH contributes to the release of metals to the water column.	As designed, septic systems significantly reduce dissolved phase metals from the wastewater influent before the treated effluent discharges to groundwater. Mobility of metals in groundwater is very low; however, anoxic and low pH conditions can contribute to leaching of naturally occurring metals to groundwater.
	Organic compounds	Large areas of impervious surfaces in an urban area reduce the extent to which natural areas can absorb and filter rainfall and runoff before they enter a waterbody. Solubility and persistence are dependent on the type of compound.	Solubility and persistence is dependent on the type of compound. Gasoline and diesel range organics may be less mobile than VOCs (Rice and McNab 1998).
	Chloride	Highly soluble and mobile in surface waters.	Highly soluble and mobile in groundwater.

* Arsenic in Snake Creek may be naturally occurring.

4.3 Monitoring Results

SWCA collected major cations and anions from rivers and streams during the fall 2019 sampling event to evaluate the ionic composition of water samples from different sections of the study area (see Section 3.7 for further discussion). Additionally, SWCA collected water samples from rivers and streams to gather some limited baseline data where none existed. However, in consultation with the WCHD, most of the data collection and analysis efforts were undertaken for groundwater. Surface water quality data collection and analysis efforts in the study were limited for the following reasons:

1. Surface water quality is routinely monitored and assessed by agencies such as DWQ, Provo River Watershed Commission, and USGS.
2. The same parameters and/or parameter concentrations may be present in both surface and groundwater; however, the sources may be unrelated. Additional environmental tracer tests (beyond major ion composition analysis) such as isotope analysis were not undertaken as part of the study but may provide a way to provide additional information describing the relationship between surface and groundwater in the study area.
3. Analysis for more costly parameters like personal care products and pharmaceutical compounds (PPCPs), pesticides, herbicides, and VOCs were prioritized in groundwater to evaluate groundwater quality conditions in the study area. Pesticides, herbicides, and VOCs were not detected in groundwater. Analysis of surface water for these compounds is an area for future study.
4. Interpretation of surface water quality data, including source identification, is complicated by nonpoint source pollution, complex hydrology in the study area (surface diversions), and seasonal cycles, and dynamic flow regimes.
5. Although stormwater may transport large pollutant loads into surface waters, stormwater samples are difficult to obtain, and monitoring efforts did not capture storm events.
    a. Additionally, there may be limited potential for contamination of groundwater in Wasatch County from stormwater runoff, with most stormwater delivered to surface waters, and limited opportunity for direct discharge into groundwater.

Table 16 summarizes average concentration of surface water quality parameters collected during the study. Although major cations and anions were collected from surface waters during the fall 2019 sampling event, these results are not summarized in Table 16 because they are presented in Section 3.7, Table 13. Most surface water quality samples were collected in the Timberlakes area. Further discussion of the Timberlakes area is presented below.

Table 16. Surface Water Quality Monitoring Results

Sampling Location Name	Nitrate/nitrite (mg/L)	TN (mg/L)	TP (mg/L)	TDS (mg/L)	TSS (mg/L)
Center Creek near Center Creek Road (5910190)	0.27	0.25	0.03	198.00	1.50
Daniels Creek above First Diversion (5913540)	0.01	0.25	0.03	392.00	1.50
Lake Creek ab Timberlakes Development	0.07	0.45	0.04	144.00	6.55
Lake Creek below Timberlakes Development (4997070)	0.04	0.43	0.08	172.67	4.15
Tributary ab cnfl Lake Creek below Timberlakes Devel (4997060)	0.23	0.69	0.10	306.00	7.40

Note: Major cation and anion concentrations of surface water are summarized in Table 13 and are not included in this table.

TN = total nitrogen (as N), TP = total phosphate (as P), TDS = total dissolved solids, and TSS = total suspended solids.

4.3.1 *Timberlakes Development*

The Timberlakes subdivision above Heber City is approximately 3,600 acres and contains 916 septic systems (WCHD 2018), with an average density of approximately 3.9 acres per septic system. The Timberlakes development is in the Lake Creek subwatershed with Lake Creek on the northeastern side of the watershed and an unnamed tributary on the southwest side. Land use in the Timberlakes area is largely residential, with some livestock grazing that occurs on the national forest boundary above the development. Residential units in the Timberlakes development have mixed occupancy, with some occupied year-around some occupied only in summer. There are no agricultural, commercial, or industrial activities in the Lake Creek subwatershed. The Timberlakes development offers a unique opportunity to evaluate impacts to surface and groundwater resources from residential land use including septic systems for the following reasons:

- The Timberlakes development area is directly upgradient from the Heber Valley aquifer. and there is little opportunity for water quality to be impacted by additional pollutant sources along the transect from source to sink.
- Surface water and groundwater are contained within the Lake Creek subwatershed catchment area as is the entire Timberlakes subdivision.
- The land use is entirely residential. and all wastewater in the subwatershed is treated with septic systems.
- Septic systems occur at a higher density in the Timberlakes development than anywhere else in the study area, which would theoretically allow for a signal from wastewater (if present) to be detected in surface and groundwater.
- Lake Creek is a source of recharge for the Heber Valley aquifer. Previous hydrologic investigations indicate Lake Creek is a losing stream with 25% of annual flow contributing to groundwater recharge in the Heber Valley aquifer (Baker 1970; Roark et al. 1991).
- Groundwater underlying the Timberlakes development area is more likely to move laterally (toward the Heber Valley aquifer) than downward. This is evident by potentiometric surface maps that show there is a steeper hydrologic gradient from Lake Creek to the basin center and likely a shallower bedrock surface in this area (Roark et al. 1991). Well logs in the eastern portion of the basin at the mouth of the Lake Creek subwatershed indicate depth to consolidated rock is approximately 30 feet below ground surface.

For the reasons listed above, longitudinal changes in surface and groundwater quality from the upper watershed to lower watershed (if present) can reasonably be attributed to impacts from residential development and septic systems, which are occurring in the Timberlakes subwatershed. Although septic development is occurring in other watersheds such as the Daniel subwatershed, Snake Creek subwatershed, and Brighton estates area, these areas have additional variables such as multiple pollutant sources (Daniel), complicated hydrology with gaining and losing segments of the stream (Snake Creek), and relatively low number of septic systems (Brighton Estates).

Sampling locations at the top of the Lake Creek subwatershed are largely above the influence of anthropogenic activities and help establish background concentrations of parameters of concern against which downstream samples can be compared. Some livestock grazing and dispersed camping occur on the national forest above the Timberlakes development; however, impacts from these activities to surface water quality are expected to be negligible. Surface water grab samples were collected above and below the Timberlakes subdivision to evaluate impacts to surface waters from residential development and high-density septic systems. Surface water sampling locations were selected based on established DWQ monitoring location IDs (MLIDs) to allow for comparison between data collected by SWCA and by DWQ. Lake Creek above Timberlakes (DWQ MLID 5989270) is at the top of the watershed, upstream of all septic system wastewater influence. Lake Creek below the Timberlakes development (DWQ MLID 4997070) and Lake Creek Tributary (DWQ MLID 4997060) are below the Timberlakes subdivision. Figure 28 shows septic systems in the Timberlakes development, National Hydrography Dataset (NHD) streams in the watershed, surface water sampling locations, and groundwater sampling locations.

Surface water grab samples were collected during the fall 2018, spring 2019, and fall 2019 sampling events and were analyzed for total nitrogen, nitrate/nitrite, total phosphorus, TDS, and chloride. Total nitrogen was added to the sampling plan at surface water sites to capture organic forms of nitrogen that are more likely to be present in surface water than in groundwater. In addition, SWCA queried the DWQ database for *E. coli* data at the same sampling locations. DWQ *E. coli* data are available from grab samples collected between 2010 and 2016 at the two downstream sampling locations; however, no *E. coli data* were available at the upstream location on Lake Creek. Parameter concentrations were averaged by site and graphed to compare relative differences above and below the Timberlakes development (Figure 29).

The small tributary that runs parallel to Lake Creek through the Timberlakes development had the highest concentrations of all parameters included in this analysis. Most parameter concentrations increased from the upper Lake Creek location to the lower Lake Creek location except for nitrate and total nitrogen. Additional DWQ data were not available at the upper Lake Creek location to supplement the nitrate data collected by SWCA between 2018 and 2020. Error bars representing the mean plus and minus the standard deviation are included to illustrate the variability between grab samples. Seasonal patterns contribute to natural variations in water quality, and concentrations of most parameters are expected to be higher during the spring when snow melts over land, carrying nutrients, salts, and other constituents from soils into surface waters. Primary productivity (terrestrial and aquatic plant growth) also contributes to seasonal changes in nutrient concentrations due to uptake of biologically available nitrogen and phosphorus. Despite high variability between spring and fall sampling events at all sampling locations, mean parameter concentrations are higher below the Timberlakes development than they are above it. Statistical tests for significant differences between means (i.e., t-test for means) may not be appropriate given the large variability between samples collected between spring and fall sampling events and the small sample size. For example, only three data points were collected at each location. More data are needed during spring runoff and during base flow to determine if the sample means for each site and parameter are statistically different below the development than above the development, or if natural seasonal variability contributes to elevated parameter concentrations.

For the reasons presented at the beginning of this section, and especially given the lack of other land uses in the watershed, these results indicate that surface water quality degradation below the Timberlakes development is likely the result of wastewater from septic systems, and runoff from impervious surfaces, disturbed areas (construction sites and roads), and residential properties, although additional data are needed to strengthen the conclusion.

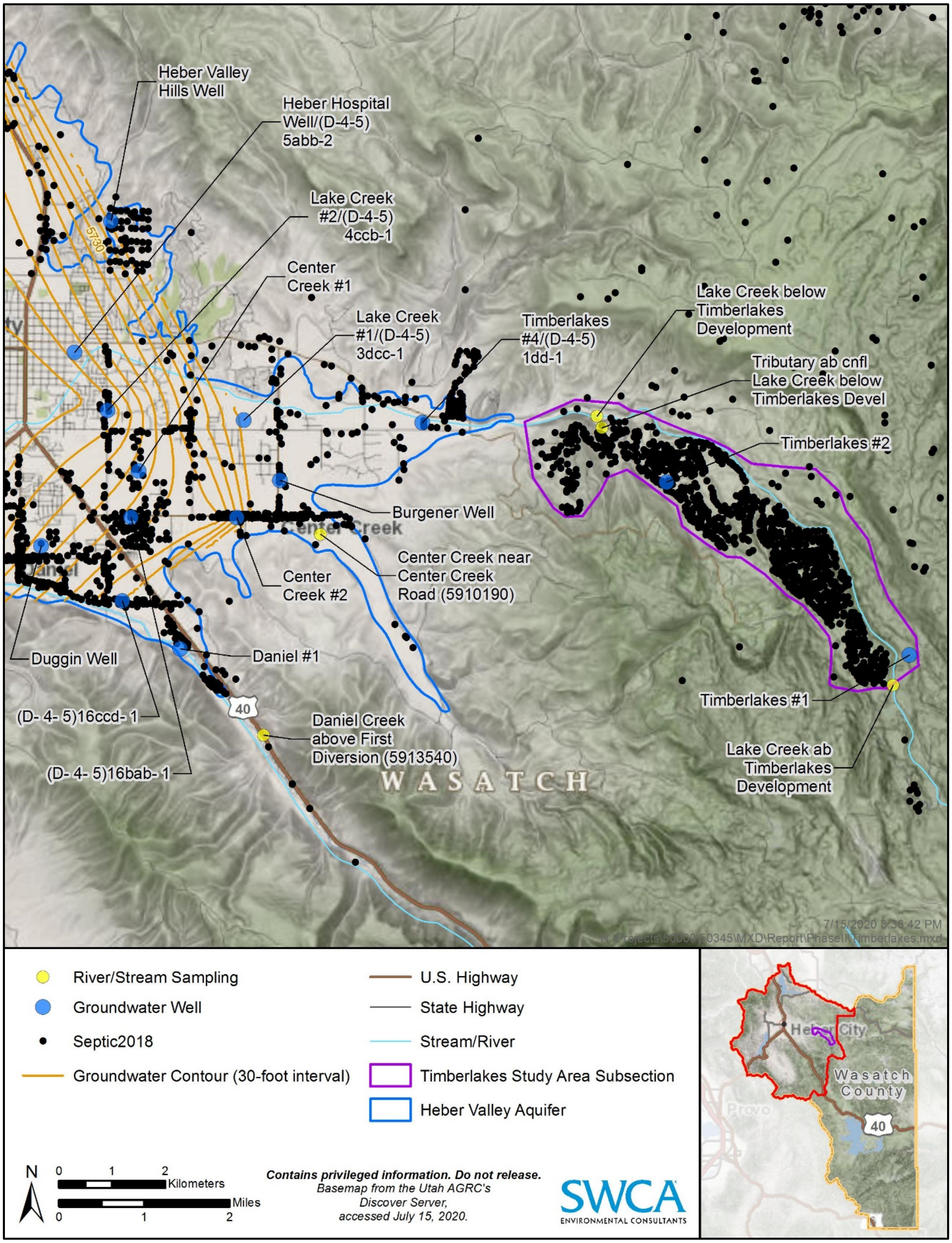
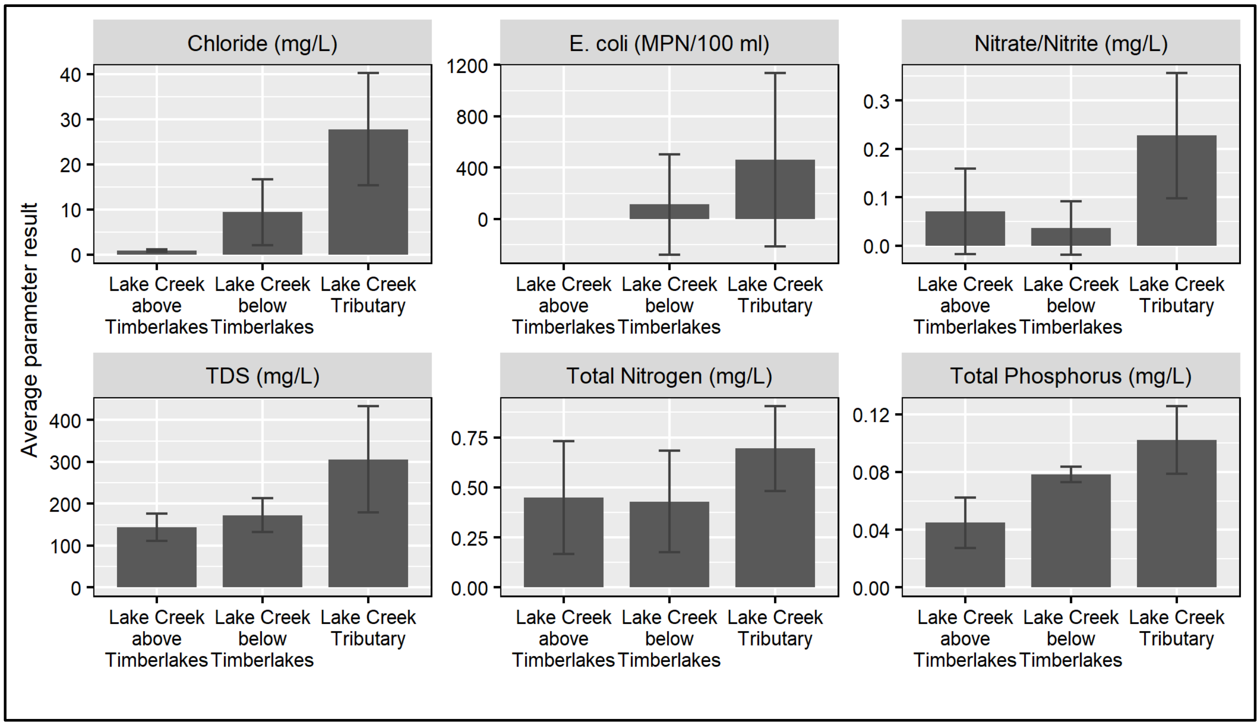


Figure 28. Timberlakes surface water sampling locations, NHD streams, and septic systems.



Note: Data summarized in this figure were collected by SWCA between 2018 and 2010 except for *E. coli* data, which were downloaded from the DWQ online public database. *E. coli* data were collected between 2010 and 2016 at the two downstream locations. Error bars represent the mean plus and minus the standard deviation of the sample set. Lake Creek below tributary coincides with DWQ MLID 4997070, and Lake Creek Tributary coincides with DWQ MLID 4997060.

Figure 29. Average parameter concentrations from surface streams above and below the Timberlakes development.

4.3.2 *Comparison to Groundwater Data*

Similar to the surface water sampling design, SWCA targeted groundwater wells above and below the Timberlakes development to evaluate impacts from septic systems and residential development. Surface and groundwater sites in the Lake Creek subwatershed were ordered from top (lowest) to bottom of the subwatershed (highest) to evaluate if and how groundwater quality changed along the longitudinal profile. For example, the Timberlakes #1 site at the top of the watershed was ordered number 1, whereas the Lake Creek #2 site at the bottom of the watershed in the Heber Valley aquifer was ordered number 5. Parameter concentrations were plotted for the five sampling locations in the Timberlakes to Lake Creek transect, with locations ordered from top of watershed to bottom (Figure 30).

Groundwater from the Timberlakes #1 well had the most pristine groundwater quality with concentrations of nitrate, chloride, TDS, and total phosphorus below the average values calculated from wells in the Heber Valley Class 1A aquifer. The Timberlakes #1 well draws water from the consolidated rock aquifer at a depth of approximately 370 feet. Water quality results from the Timberlakes #1 well serve as a baseline for comparison for downgradient groundwater samples.

The Timberlakes #2 well is located approximately two-thirds of the way down the Timberlakes development. The well is screened in unconsolidated material at approximately 95 feet below surface with a total well depth of 120 feet. Concentrations of nitrate, total phosphorus, TDS, and chloride increased between the Timberlakes #1 well and Timberlakes #2 well. Total phosphorus concentrations at Timberlakes #2 were the highest of any well in the study area, ranging from 0.21 to 0.77 mg/L. By contrast, the average concentration of total phosphorus in wells located in the Heber Valley Class 1A aquifer was 0.06 mg/L, and the average concentration of total phosphorus in surface streams below the Timberlakes development was 0.09 mg/L. A clear longitudinal increase in parameter concentrations is not readily observed upon inspection of the data (Figure 30). A statistical test for significance was not performed because of the small sample size (two or three samples at each location). Additionally, the Lake Creek wells located in the Heber Valley may be receiving additional input besides groundwater and/or surface water recharge from the Timberlakes subdivision.

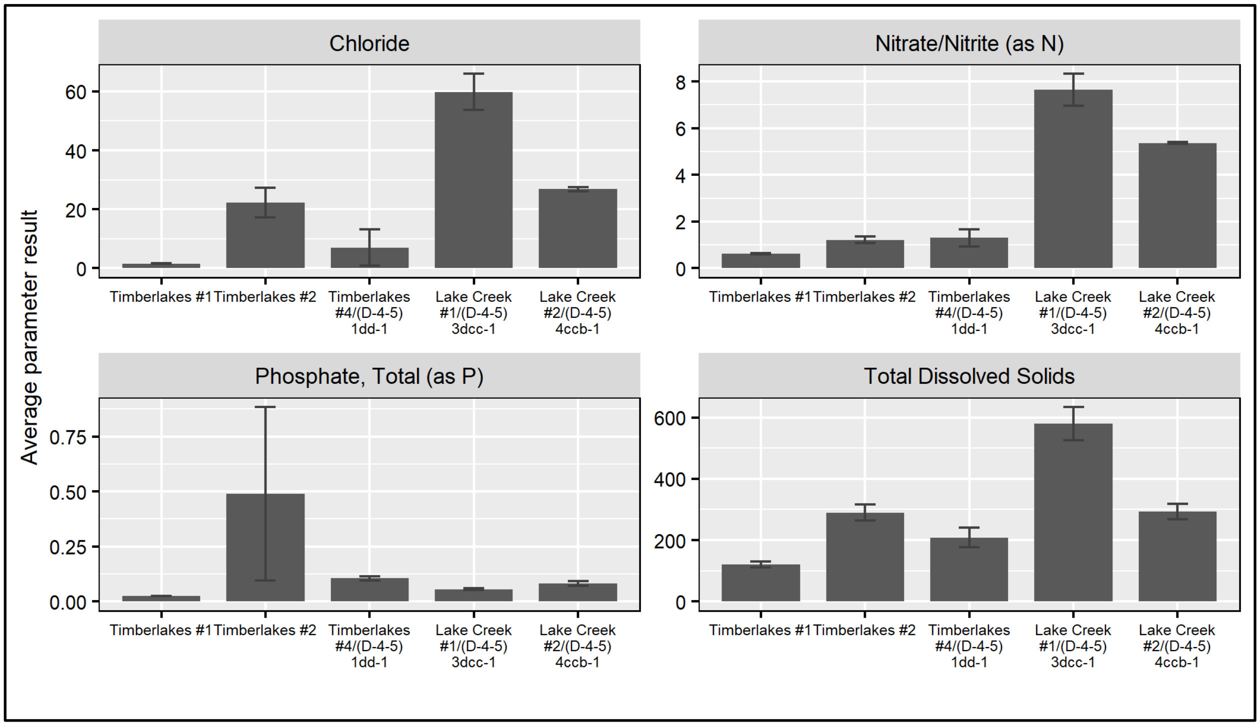


Figure 30. Average parameter concentrations for groundwater samples above and below the Timberlakes development.

Previous investigations have noted the increasing concentrations of nitrate at the Lake Creek #1/(D-4-5) 3dcc-1 and Lake Creek #2/(D-4-5) 4ccb-1 sampling locations, although reasons for increasing nitrate were not identified in the report (Desert Rose Environmental 2016). Lake Creek #1/(D-4-5) 3dcc-1 and Lake Creek #2/(D-4-5) 4ccb-1 wells are also known hotspots for chloride and TDS, although total phosphorus concentrations are near average at both wells. SWCA tested for pesticides, herbicides, and a suite of anthropogenic markers at the Lake Creek #1 and Lake Creek #2 wells to help identify sources of elevated nitrate, chloride, and TDS. Results for all supplemental parameters were non-detect. As discussed in Section 4.2, surface waters in the Lake Creek subwatershed appear to be impacted by the Timberlakes development. Because Lake Creek is known to contribute to groundwater recharge, there is the possibility that nutrients, chloride, and TDS from septic systems in the Timberlakes development are contributing to increased concentrations of these parameters in Lake Creek #1/(D-4-5) 3dcc-1 and Lake Creek #2/(D-4-5) 4ccb-1 wells. However, additional tests that are deterministic of source identification, such as stable isotope analysis, are needed to conclusively identify the cause of elevated concentrations of nitrate, chloride, total phosphorus, and TDS at the Lake Creek wells.

4.4 Surface Water and Groundwater Interactions

Previous groundwater budgets prepared for the Heber Valley aquifer have estimated that recharge from surface streams accounts for 12.5% to 17.5% of the total recharge to the aquifer and 10% to 12% of the total discharge (Roark et al. 1991; SWCA 2019b). Therefore, development or modifications to either resource have the potential to impact the quantity and quality of the other. There are multiple forms of interaction between surface and groundwater. The water budget exercise (Section 5) indicated that there are both losing and gaining reaches of the Provo River and tributary streams within the study area. This exchange of water between surface and groundwater involves the exchange of chemicals, and in losing reaches of the streams, there may be potential for delivery of contaminants from agriculture and stormwater inputs. Although monitoring data indicate elevated nutrients, TDS, and chloride in some portions of the aquifer, SWCA did not observe pesticides/herbicides or VOCs in any of the samples.

Overall, there is relatively little differentiation in major ion composition between surface and groundwater in the study area. Although this confirms the conceptual model that surface water and groundwater are in close communication, it does not provide a detailed indication of where in the aquifer groundwater may receive heavy influence from surface water. SWCA's conceptual understanding, however, is that the Provo River closer to Jordanelle Reservoir is losing surface flow to groundwater, whereas the Provo River closer to Deer Creek reservoir is gaining groundwater flow. Discharge measurements on the Provo River (USGS 10155200 Provo River at River Road) are consistently lower than releases from the Jordanelle Reservoir, even after considering agricultural diversions. Near Deer Creek Reservoir, discharge measurements from the lower gage on the Provo River (USGS 10155500 Provo River near Charleston) are consistently higher than those from the upper gage (USGS 10155200 Provo River at River Road), potentially indicating that the Provo River is gaining flow from groundwater between the two gage stations.

SWCA collected one sample on the Provo River at River Road to be analyzed for major cations and anions and did not identify any differentiation between nearby groundwater samples, although water from the Provo River at this location has less total dissolved solids than nearby groundwater. Conceptually, this sampling location is in an area where the Provo River is losing surface flow to groundwater. It is possible that nutrients and other contaminants have a pathway to enter the groundwater at this location and along this reach of the Provo River. Concentrations of total phosphorus are typically higher at the Midway bridge and above Deer Creek Reservoir than below Jordanelle (Desert Rose Environmental 2020). Increased phosphorus at the downstream sampling locations could be attributed to nonpoint source pollution input as the Provo River travels from Jordanelle to Deer Creek, or input from groundwater. The average concentration of total phosphorus measured in groundwater from the Heber Valley aquifer was 0.06 mg/L, which is above the pollution indicator threshold for rivers and streams of 0.05 mg/L total phosphorus. Phosphorus concentrations in the middle Provo River increase with distance downstream with average concentrations increasing from 0.01 mg/L below Jordanelle Dam to 0.03 mg/L at McKellar Bridge above Deer Creek Reservoir. Groundwater concentrations east of the Provo River near this stretch of the Provo River are higher than concentrations in the river itself.

Mountain-front recharge and tributary recharge are both derived from precipitation and account for 80% of recharge in the basin. During these pathways of groundwater recharge there is relatively little opportunity for change in ionic composition. The lack of differentiation in the Stiff and Piper diagrams is consistent with the conceptual model that the basin water balance is dominated by precipitation, whether entering the basin through surface runoff or mountain-front recharge.

In the Daniels Creek area, groundwater from higher elevation areas may be moving along fractures and fissure openings downgradient to the alluvial deposits at the valley margin. Road salts may be contributing to elevated concentrations of chloride in the wells near the mouth of Daniels Canyon. Typically streams moving from mountainous terrain into alluvial fans lose water as they travel across the highly permeable material (Winter et al. 1998).

5 GROUNDWATER BUDGET

Although most of the focus of the study is on water quality of the groundwater aquifers in Wasatch County, water quantity plays a key role in water quality and therefore is highly relevant to the study. Additionally, concerns from local water users regarding potential lowering of groundwater elevations led SWCA to complete a groundwater budget for the Heber Valley aquifer. Because the county has grown and continues to grow, there have been subsequent changes in activity and water use, which have the potential to impact the water budget. SWCA analyzed the main sources of recharge to, and discharge from, the Heber Valley aquifer and developed estimates of each. A summary of the groundwater budget is provided in Table 17, and descriptions of each of the individual components of the water budget are provided subsequently in this section. Additionally, Table 17 includes a summary of the groundwater budgets completed for the aquifer (Baker 1970; Roark 1991) for comparison.

There is overlap between the conceptual groundwater budget developed here and the inputs and outputs from the numerical groundwater flow model (see Section 6). A brief comparison to the modeled value is provided for each component discussed in this section. In general, the recharge components match exactly in the groundwater model, whereas the discharge components are derived after running the model. The groundwater model was calibrated to water levels, not water budget components. Therefore, in many cases, the modeled discharges vary from the conceptual groundwater budget. Major variances are discussed in Section 5.3.1.

Table 17. Groundwater Budget Summary and Comparison to Previous Studies for Groundwater Budget Estimates

Budget Element	Flow (acre-feet/year)		
	Baker 1970*	Roark et al. 1991*	SWCA
Recharge			
Precipitation	0	3,500	3,116
Infiltration from Provo River	0	14,490	1,090
Stream infiltration	0	5,068	8,760
Mountain-front recharge	N/A	N/A	50,200
Unconsumed irrigation water	56,035	70,949	12,500
Wastewater	N/A	N/A	2,973
Subsurface inflow from consolidated rocks	29,972†	17,375‡	NA§
Total recharge (rounded)	**86,152**	**111,491**	**78,639**
Discharge			
Evapotranspiration	11,004	12,308	6,906
Leakage to Deer Creek Reservoir	46,986	50,678	46,479
Seepage to surface water	11,004	13,031	9,846
Springs and seeps	0¶	34,751#	34,750
Wells	0	869	3,275
Subsurface outflow to consolidated rocks	17,013#	0**	0
Total discharge (rounded)	**86,152**	**111,491**	**101,256**

* Data from Roark et al. (1991:Table 4).
† Difference between total recharge and recharge from unconsumed irrigation water.
‡ Difference between total discharge and all other forms of recharge.

§ Included in mountain-front recharge
¶ Included in seepage to Provo River in Baker (1970:12).
[#] Difference between total recharge and all other forms of discharge.
[**]Assumed to be zero.

SWCA also evaluated long-term trends of water levels at 22 USGS wells in the Heber Valley aquifer with a mixed-method approach using antecedent precipitation as a covariate to remove the effect of climate variability in the analysis. Results of the mixed-method trend analysis with a 95% confidence interval indicates that groundwater levels are declining at 11 out of 22 USGS wells examined in Heber Valley. In these cases, groundwater levels show a significant downward trend after removing the effect of antecedent precipitation. At the remaining 11 wells, the evidence was insufficient to conclude that a trend in either direction existed. None of the wells showed a positive trend in groundwater levels (SWCA 2019b). Methods and results of the long-term trend analysis are further discussed in the water budget (SWCA 2019b).

5.1 Recharge

Sources of recharge to the Heber Valley aquifer are assumed to be infiltration from precipitation, outflow from “losing” stream reaches, unconsumed irrigation water, mountain-front recharge, and wastewater infiltration. Each of these sources of recharge is described in separate sections below.

5.1.1 *Precipitation*

For the purpose of the study, the average annual precipitation is assumed to be 16 inches based on estimates from the Parameter-elevation Relationships on Independent Slopes Model (PRISM 2019) and data from the National Oceanic and Atmospheric Administration (NOAA) weather station at the Heber Valley Russ McDonald Field Airport. This value closely aligns with previous investigations; Roark et al. (1991) estimated average annual precipitation in Heber City (1936–1988) to be 15.95 inches, and the Utah Division of Water Resources [DWRe] estimated average annual precipitation to be 15.9 inches for the 2014 *Utah Lake Basin Planning for the Future; Utah State Water Plan* (DWRe 2014).

The Maxey-Eakin method is commonly used in Utah and Nevada and “estimates recharge as a percentage of the volume of precipitation falling within specified ranges of precipitation within the study area. A higher percentage of precipitation becomes recharge in areas with higher precipitation” (Brooks and Mason 2005:18–19). Recharge from precipitation estimates obtained using the Maxey-Eakin method may be overestimates, especially in more arid climates, because the “method was developed for mountainous areas and does not account for water storage in soil moisture” (Brooks and Mason 2005:19).

Using the Maxey-Eakin method, SWCA estimate the recharge rate of the Heber Valley aquifer from precipitation to be 3,116 acre-feet/year, assuming 9% of the precipitation recharges the 25,968 acres of unconsolidated valley-fill deposits, and an average annual precipitation rate of 16 inches per year. Given the potential for the Maxey-Eakin method to produce overestimates, SWCA adjusted the percentage of rainfall contributing to recharge from 10% to 9%. SWCA’s estimate of 3,116 acre-feet/year of recharge from precipitation may be high given that a portion of the total volume of water from precipitation (during the irrigation season onto a portion of the study area) is also included in the analysis to estimate recharge from unconsumed irrigation water.

Comparison to groundwater model (Section 6): Direct recharge from precipitation was used as an input for the groundwater flow model, applied as areal recharge across the basin. The modeled precipitation recharge was 3,116 acre-feet/year applied evenly to 1,255 model cells.

5.1.2 *Surface Streams*

SWCA estimated that recharge to the alluvial groundwater is approximately 8,760 acre-feet/year assuming 25% of the average combined flow of 35,040 acre-feet/year on Lake Creek, Center Creek, and Daniels Creek. The overall contribution of surface water to the aquifer is estimated to be 9,850 acre-feet/year (infiltration from the Provo River plus infiltration of other surface streams). Snake Creek is a gaining stream (Baker 1970; Carreón-Diazconti et al. 2003) and therefore not considered to contribute to recharge to the aquifer.

Comparison to groundwater model (Section 6): Tributary recharge was used as an input for the groundwater flow model, applied as recharge along Lake Creek, Center Creek, and Daniels Creek. The modeled tributary recharge was 8,760 acre-feet/year, applied to 61 model cells and weighted by magnitude of flow in each tributary.

Recharge from the Provo River was not input directly into the model; rather, the Provo River was modeled using the River (RIV) package, which allows the river to be gaining (flow from aquifer to river) or losing (flow from river to aquifer) based on modeled groundwater levels. Recharge from the Provo River derived from running the groundwater model was much higher than estimated in the conceptual water balance, with 24,431 acre-feet/year recharging the aquifer.

5.1.3 *Unconsumed Irrigation Water*

Historically, the Heber Valley was dominated by agricultural lands, which were largely irrigated by flood irrigation. However, residential development has replaced much of the agricultural lands, and irrigation practices have largely shifted from flood to sprinkler. The north fields area remains the largest agricultural area in the valley and continues to be largely irrigated by flood irrigation.

SWCA estimated groundwater recharge from irrigation water to be 12,500 acre-feet/year based on the total volume of water diverted for irrigation (61,286 acre-feet; minus conveyance losses), the volume of precipitation reaching irrigated lands (7,267 acre-feet/year), and the volume of water consumed by crops (35,609 acre-feet/year). The recharge estimate includes recharge from canal seepage during conveyance (5%), estimated recharge from groundwater recharge ponds (780 acre-feet/year), and recharge occurring outside the irrigation season (November through March; 986 acre-feet/year). SWCA assumed that none of the water diverted from the Provo River returns to the Provo River with the exception of some flow from the Rock Ditch via Spring Creek. SWCA assumed 100% of the measured flow on Spring Creek returns to the Provo River and is not used for irrigation purposes. Although the conversion of irrigation practices from flood to sprinkler throughout the Heber Valley is assumed to decrease recharge to groundwater, the net reduction is not estimated to represent a significant portion (1%–3%) of the total recharge to the aquifer.

Groundwater recharge from surface diversions was estimated using the following formula:

$$IRR_R = \left[\left(IRR + PRECIP - CROP_{Req}\right) * RECHARGE_{ef}\right] + SEEPAGE + POND_R + WINTER_R$$

Where:

IRR_R = Estimated volume of groundwater recharge from surface diversions (acre-feet/year).

IRR = The estimated total volume of water delivered to fields during irrigation season, defined as May through September (acre-feet/year). This estimate is 90% of the gross irrigation season diversion total, assuming 10% is lost through seepage and evaporation during conveyance (Pearson 2019).

PRECIP = Estimated volume of water from precipitation during irrigation season in acre-feet/year. Calculated by multiplying the average precipitation rate from May through September (5.1 inches/year) by the area of land with sprinkler or flood irrigation (17,794 acres; Pearson 2019; DWRe 2017a). SWCA assumed 80% of the precipitation would be available for plant consumptive use (Jordan and Sabbah 2012; Stolp et al. 2017).

$CROP_{Rreq}$ = The crop requirement of plants growing in the irrigated area of land within the study area in acre-feet/year. Crop requirement is based on an average consumptive water use rate of 2.07 feet/year (Central Utah Water Conservancy District 2019) and 17,202 acres of sprinkler or flood-irrigated land (DWRe 2017a).

$RECHARGE_{ef}$ = Recharge efficiency is the fraction of supplied water that becomes recharge. SWCA assigned a recharge efficiency of 30% in areas where flood irrigation dominates, and 10% in areas where sprinkler irrigation dominates (Jordan and Sabbah 2012).

SEEPAGE = Recharge form seepage during conveyance was assumed to be 5% of the gross diversion total (Pearson 2019).

$POND_R$ = Recharge from overflow ponds at the end of the irrigation system is typically 780 acre-feet/year (Pearson 2019).

$WINTER_R$ = Groundwater recharge outside of irrigation season in acre-feet/year. Based on the gross surface diversions occurring in October through April and a recharge efficiency rate of 25%.

Previous investigations (Baker 1970; Roark et al. 1991) estimated groundwater recharge from unconsumed irrigation water to be 56,000 acre-feet/year and 70,948 acre-feet/year, respectively. Both estimates assume that recharge from unconsumed irrigation water is the quantity diverted for irrigation plus precipitation during the irrigation season, minus the crop requirement. Recharge estimates by Baker (1970) and Roark et al. (1991) assume 100% irrigation efficiency and do not consider known losses that occur in the irrigation system (evaporation, seepage, or runoff). Baker (1970) and Roark et al. (1991) also assume much larger irrigation diversions (87,000 acre-feet/year and 77,500 acre-feet/year, respectively).

Comparison to groundwater model (Section 6): Incidental agricultural recharge was used as an input for the groundwater flow model, applied as areal recharge across known agricultural lands. The modeled agricultural recharge was 12,500 acre-feet/year, applied evenly to 314 model cells.

5.1.4 *Mountain-Front Recharge*

Our approach for estimating mountain-front recharge was based on Feth et al. (1966), who analyzed the hydrology of the Weber Delta region of the Salt Lake Basin on the west slopes of the Wasatch Range, an area with similar climatology and geology to the Heber and Round Valleys. Feth et al. (1966) estimated that of the total precipitation that falls to the mountain blocks of the area, 52.9% is lost to evaporation; 25.4% leaves the mountains as surface runoff; and 21.7% is assumed to infiltrate into fractures and fault zones, eventually making its way in the subsurface as recharge to the alluvial aquifer. Additionally, 10% (2.5%) of the portion of mountain block precipitation leaving the mountains as surface runoff was estimated to recharge the aquifer immediately along the basin margins once more permeable alluvial sediments were encountered. All told, the total percentage of mountain block precipitation becoming recharge at the margins of the alluvial basin is approximately 24.2% (21.7% plus 2.5%). Using the estimate of precipitation to the mountain block for the Heber Valley (207,320 acre-feet/year), SWCA estimates that 50,200 acre-feet/year (24.2% of 207,320 acre-feet/year, rounded) enters into the alluvial aquifer as mountain-front recharge.

Comparison to groundwater model (Section 6): Mountain-front recharge was used as an input for the groundwater flow model, applied along the margins of the basin. The modeled mountain-front recharge was 50,200 acre-feet/year, applied to 165 cells at the edge of the basin. Recharge was roughly grouped into six geographic areas. Weighting of these areas was informed by the amount of upstream watershed contributing to that side of the basin, the maximum elevation of the upstream watershed, and precipitation patterns (from PRISM).

5.1.5 *Recharge from Wastewater*

Groundwater recharge from wastewater is a combined estimate of the volume of water recharging the aquifer from the Heber Valley Special Services District (HVSSD) lagoons, the rapid infiltration basin (RIB), land application of treated wastewater from the treatment lagoons, and residential septic systems. SWCA estimates that groundwater recharge from all combined wastewater sources to be approximately 2,713 acre-feet/year.

The lagoons treat approximately 2,655 acre-feet of wastewater each year. SWCA estimates that evaporation from the lagoons accounts for approximately 12% (322 acre-feet/year) of the total volume of wastewater based on the lagoon size of 115 acres and an open water evaporation rate of 2.8 feet/year. The remaining water (2,333 acre-feet/year) becomes recharge from seepage in the two southern lagoon cells (572 acre-feet/year), is consumed by crops following sprinkler irrigation (828 acre-feet/year), evaporated during sprinkler irrigation (280 acre-feet/year), recharged into the ground during sprinkler irrigation (186 acre-feet/year), or recharged into the ground via the RIB (467 acre-feet/year).

The volume of treated wastewater that is discharged to the RIB is approximately 467 acre-feet/year. This flow is assumed to either evaporate (at a rate of 2.8 feet/year) or infiltrate into the shallow aquifer. Total evaporation from the 7-acre RIB is 20 acre-feet/year (7 acres × 2.8 feet/year), which leaves 447 acre-feet/year (467 acre-feet/year minus 20 acre-feet/year) to recharge. Total recharge from the HVSSD is estimated to be 1,205 acre-feet/year (the sum of 572 acre-feet/year of seepage in the two southern lagoons, 186 acre-feet/year recharged during sprinkler irrigation, and 447 acre-feet/year recharged into the ground via the RIB).

Groundwater recharge from septic systems in the study area was estimated to be 1,488 acre-feet/year based on the number of septic systems in the study area (3,280 septic systems; WCHD 2018), the average household size (three people; U.S. Census Bureau 2019a), and the average potable water use rate (135 gallons per person per day; DWRe 2017b).

Comparison to groundwater model (Section 6): Wastewater recharge was used as an input for the groundwater flow model, applied in cells where known septic tanks occur, and in cells associated with the RIB. The modeled wastewater recharge for septic tanks was 1,488 acre-feet/year, applied to 221 cells. The modeled wastewater recharge for the RIB was 1,205 acre-feet/year, applied to nine cells.

5.2 Discharge

Sources of discharge are assumed to be evapotranspiration, leakage to Deer Creek Reservoir, seepage to surface water, springs and seeps, consumptive use of potable water, and subsurface outflow to consolidated rocks. Each of these sources of discharge is described below.

5.2.1 *Evapotranspiration*

The estimated total volume of water lost through evapotranspiration (ET_T) is a combined volume from both surface and groundwater. The estimated total volume of water discharged from the aquifer through evapotranspiration (ET_G) was obtained by multiplying each vegetation type area by the associated evapotranspiration rate (ET_T) and subtracting the total amount of available water to that area. Total evapotranspiration (ET_T) was estimated by multiplying the area of a specific water-related land use or predominant vegetation type by the associated evapotranspiration rate using similar techniques to those used in hydrologic studies throughout Utah by the USGS and UGS (Jordan and Sabbah 2012; Marston 2017; Wallace et al. 2012). Land cover and vegetation type estimates were obtained from 2017 water-related land use data from the DWRe (2017a) and from evapotranspiration rates from the Morgan Valley hydrologic study (Wallace et al. 2012) and from Hill et al. (2011. SWCA assumed evapotranspiration rates for land use categories and vegetation types in the Heber Valley to be comparable to those in the Morgan Valley (Wallace et al. 2012). The water-related land use data (DWRe 2017a) covered approximately 92% of the study area. For the remaining 8% of land in the study area, SWCA applied the "General Forest" evapotranspiration rate from the Morgan Valley hydrologic study (Wallace et al. 2012). The estimated total volume of water discharged from the aquifer through evapotranspiration (ET_G) was obtained by multiplying each vegetation type area by the associated evapotranspiration rate and subtracting the total amount of available water to that area. The remaining volume is an estimate of the groundwater discharge attributed to evapotranspiration in the shallow groundwater area in Heber Valley, approximately 6,906 acre-feet/year.

Using methods described in the 2012 hydrologic study in Cedar Valley (Jordan and Sabbah 2012), SWCA assumed plants will use water available to them (from precipitation and applied irrigation water) and will only use groundwater when other sources are not adequate. Consistent with Jordan and Sabbah (2012), SWCA chose 10 feet as the maximum depth that plants could be taking up water from the water table. SWCA examined rooting depths for pasture grasses, crops, and naturally occurring vegetation (Canadell et al. 1996) and assumed that all plants in the study area could access the water table, given that depth to water table is less than 10 feet for the entire study area (Natural Resource Conservation Service 2017). Wasatch County municipal/industrial water use data (DWRe 2017b) and agricultural water use data (DWRe 2019) were used to estimate the volume of water available to plants through septic discharge and through irrigation methods.

Evapotranspiration volumes from groundwater (ET_G) for each vegetation category in the 2017 water-related land use data were calculated using the following formula:

$$ET_G = \sum ET_T - (PRECIP + IRRIGATION)$$

Where:

ET_G = Estimated volume of groundwater discharged through evapotranspiration by plants in the study area (acre-feet/year).

ET_T = The estimated total volume of water lost from all available water sources through evapotranspiration (acre-feet/year). Calculated by multiplying area of land use or vegetation pattern by the associated evapotranspiration rate from Wallace et al. (2012).

PRECIP = Estimated volume of water from precipitation during the growing season (acre-feet/year). Calculated by multiplying the average annual precipitation rate (16 inches per year) by the area of each vegetation type in the study area. SWCA assumed 80% of the precipitation would be available for plant consumptive use (Jordan and Sabbah 2012; Stolp et al. 2017).

IRRIGATION = Volume of water available for plant use through sprinkler or flood irrigation methods (acre-feet/year). An irrigation efficiency rate of 50% was applied for areas with flood irrigation (Miller 2019; Hill and Williams 2002). An irrigation efficiency factor of 50% means that 50% of the irrigation water is available for plant use and the remaining 50% is lost through evaporation, seepage during conveyance, and recharge to the aquifer. Where sprinkler irrigation was the dominant method, SWCA applied an efficiency rate of 70% (Hill and Williams 2002).

Comparison to groundwater model (Section 6): Evapotranspiration was modeled using the evapotranspiration (EVT) package, which specifies an evapotranspiration rate, but also can modify that rate based on modeled groundwater levels. The specified rate amounted to 7,626 acre-feet/year, applied to 699 cells, which reduced slightly to 7,272 acre-feet/year when actually modeled.

5.2.2 *Leakage to Deer Creek Reservoir*

The groundwater contours for the Heber Valley suggest that the aquifer must discharge primarily at Deer Creek Reservoir. Once water budget components are estimated for surface inflow, surface outflow, change in storage, and evaporation, the remainder can be assumed to be contributed by subsurface flow from the Heber Valley aquifer into the Deer Creek Reservoir. Release, evaporation, and reservoir storage data were obtained from the U.S. Bureau of Reclamation (2012), and surface inflows were obtained from three USGS gaging stations (USGS 10155500 Provo River at Charleston, USGS 10156000 Snake Creek near Charleston, and USGS 10157500 Daniels Creek at Charleston). One additional surface input to the reservoir, Main Creek, which drains Round Valley, was estimated based on flow values contained in the *2015 Water Quality Implementation Report* (Desert Rose Environmental 2018).

Based on 12 separate years using the most current data available, the median estimate of aquifer inflow into Deer Creek Reservoir is ~47,200 acre-feet/year (65.2 cubic feet per second [cfs]). The year-to-year variation is substantial, which reflects the general uncertainty associated with this approach; however, the results are remarkably consistent with previous estimates, though calculated using completely independent datasets separated by several decades.

Comparison to groundwater model (Section 6): Leakage to Deer Creek Reservoir was modeled using constant head cells. These cells remove water from the aquifer as needed to match the elevation of the reservoir. A total of 75,851 acre-feet/year were modeled to flow out of the model at Deer Creek Reservoir.

5.2.3 *Seepage to Surface Streams*

Discharge measurements from the lower gage on the Provo River (USGS 10155500 Provo River near Charleston) are consistently higher than those from the upper gage (USGS 10155200 Provo River at River Road), potentially indicating that the Provo River is gaining flow from groundwater between the two gage stations. SWCA examined monthly flow from these gage stations between December and February from 2002 to 2018 in an attempt to isolate the groundwater contribution and exclude the influence of precipitation, evapotranspiration, and irrigation return flows. This represents a period of dormancy for most riparian vegetation; most precipitation falls as snow that does not enter the stream system until spring runoff, and agricultural diversions are not taking place. Observations of flow during this period should primarily reflect the baseline interaction between the stream and the aquifer.

For the period of record from 2002 to 2018, the average monthly flow from December to February at Charleston was 169.2 cfs, whereas average monthly flows at River Road were 142 cfs. The difference in flow between these two points for the period from December to February is 27.2 cfs. Given SWCA's understanding of the hydrologic system, SWCA assumes the 27.2 cfs (~19,690 acre-feet/year) is largely from groundwater, but also likely includes irrigation return flow from the Rock Ditch via Spring Creek and flow from Lake Creek and Center Creek. SWCA assumes these combined flows account for approximately 50% of the gain between the two gage stations, and estimate that the total annual discharge from the aquifer to surface waters is 9,846 acre-feet/year.

Comparison to groundwater model (Section 6): As with potential inflow from the Provo River, potential outflow was also modeled using the RIV package. Discharge from the aquifer to the Provo River derived from running the groundwater model was 4,897 acre-feet/year.

5.2.4 *Springs and Seeps*

Discharge measurements for springs in the Heber Valley were not available in the USGS NWIS database. The best estimate of total flow of springs discharging from the Heber Valley aquifer is found in Roark et al. (1991) where data from springs in the study area indicate that total discharge from the aquifer to springs and seeps is approximately 34,750 acre-feet/year (48 cfs). Given that SWCA was unable to estimate this portion of discharge directly and that it represents a large portion of the total estimated discharge, it is considered a major assumption of the water budget.

Comparison to groundwater model (Section 6): This component was not directly modeled; see discussion in Section 5.3.1.

5.2.5 *Potable Water Use from Wells and Springs*

Discharge from the Heber Valley aquifer from wells and springs is estimated to be approximately 3,275 acre-feet/year based on the per capita water use rate and population within the study area. According to municipal and industrial water use data reports from DWRe (2017b), the 2017 average total potable water use rate in Wasatch County was 135 gallons per capita (per person) per day. Population estimates from the U.S. Census Bureau for Heber City and Midway City were combined for a total population of 21,657 (U.S. Census Bureau 2019b). For reference, the population in Wasatch County is approximately 34,091 people (U.S. Census Bureau 2019a).

Discharge from the Heber Valley aquifer through municipal and industrial water use is a combined estimate from wells and springs. Community drinking water systems in the study area rely on water from a combination of springs and water supply wells, with approximately half of the water sources being springs and the other half wells (DDW 2019). The towns of Center Creek, Charleston, Daniel, Heber City, Midway, and Wallsburg obtain some public drinking water from wells screened in the consolidated rock aquifer, as do many water users in the hills surrounding the valley lowlands.

Comparison to groundwater model (Section 6): Well discharge was used as an input for the groundwater flow model, applied in cells representing well pumping in five water systems. The modeled well pumping was 3,275 acre-feet/year, applied to 16 cells.

5.2.6 *Subsurface Outflow to Consolidated Rocks*

SWCA assumes, similar to Roark et al. (1991), that subsurface outflow to consolidated rocks is negligible. Roark et al. (1991) concluded that there was no evidence of subsurface outflow to consolidated rocks and therefore, subsurface outflow to consolidated rocks was assumed to be zero. Given the geologic material of the mountain blocks surrounding the Heber Valley (sandstones and limestones with fractured networks), there is potential for groundwater movement between the basins; however, examination of groundwater contour maps of the study area supports the assumption that groundwater flow between the mountain blocks is negligible.

Comparison to groundwater model (Section 6): The groundwater flow model assumed no outflow from the Heber Valley basin to consolidated rocks but treated all boundaries as no-flow boundaries.

5.3 Areas of Uncertainty

The various components of the water budget are calculated using a number of independent methods, techniques, and empirical data, which means the uncertainty associated with each component varies considerably (Table 18). The following is a summary of the relative uncertainties associated with the water budget. Generally speaking, if the relative level of uncertainty is low, or the potential effect on the water budget is low, the water budget component is not of great concern. The following represent the greatest points of uncertainty in the water budget:

- Recharge: Mountain-front recharge. Although the estimate used is reasonable, this water budget component is notably hard to estimate, and it represents the single greatest source of recharge to the system.
- Recharge: Unconsumed irrigation water. SWCA relied on the best available dataset for irrigation diversions and delivery; however, numerous assumptions were made in developing the estimate of irrigation recharge, which represents the second-greatest source of recharge to the system.
- Recharge: Stream infiltration (other than Provo River). This estimate was based solely on prior work done by Roark et al. (1991), has not been independently verified with field data, and represents a significant portion of the water budget (10%).
- Discharge: Seeps and springs. This estimate was based solely on prior work done by Roark et al. (1991), has not been independently verified with field data, and represents the second greatest source of discharge from the aquifer. Given the lack of data available to SWCA and the magnitude of the estimate from Roark et al. (34,750 acre-feet/year, 34% of total discharge), SWCA questions whether this might be an overestimate of discharge.
- Discharge: Seepage to Provo River. Although based on reliable gage data over a decent period of record, the amount of surface inflow from Spring Creek or other spring discharges along the lower reach of the Provo River makes precise analysis of this reach difficult.

Table 18. Discussion of Level of Uncertainty and Potential Effect for Each Water Budget Component

Water Budget Component	Relative Level of Uncertainty and Rationale	Potential Effect on Water Budget
Recharge		
Precipitation	Low. Estimate is based on high-quality, site-specific PRISM dataset, and the well-established Maxey-Eakin method.	Low. This component only accounts for approximately 4% of the total recharge.
Infiltration from Provo River	Low. Estimate is based on high-quality datasets for the period from 2002 through 2018 that include U.S. Bureau of Reclamation Jordanelle Dam releases and USGS gaging data. Agricultural diversion data are from the Central Utah Water Conservancy District and are considered accurate. Basing this estimate on the period of November–February reduces interference from agricultural diversions, evapotranspiration, and runoff.	Low. This component only accounts for approximately 1% of the total recharge.
Mountain-front recharge	Medium. Total precipitation is based on high-quality, site-specific PRISM dataset. The method for estimating recharge is reasonable because it is based on an empirical study in the vicinity (Feth et al. 1966) and coincides with several other methods of estimation (Wilson and Guan 2004). However, estimates for this component vary widely in the literature.	High. This component currently accounts for approximately two-thirds of estimated recharge to the aquifer. A slight change in assumptions would lead to a large change in recharge volume.

Water Budget Component	Relative Level of Uncertainty and Rationale	Potential Effect on Water Budget
Stream infiltration (other than Provo River)	High. This component was estimated based on information discussed in Roark et al. (1991) because no other techniques were found to independently estimate this component.	Medium. This component currently accounts for more than 10% of total recharge.
Unconsumed irrigation water	High. The acreage of irrigated land is considered reasonably accurate, as is the consumptive water use rate. However, there is a large discrepancy between the amount of water diverted each year (61,286 acre-feet/year) versus the estimated amount of water consumed by crops (36,833 acre-feet), irrigation recharge (12,500 acre-feet), and various seepage losses (2,944 acre-feet). Recharge estimates are based on the volume of water diverted and not the volume applied to the landscape because these data are not available.	High. There is a known discrepancy in the amount of water diverted for irrigation and separate estimates of recharge, consumptive use, and seepage losses, and the residual water was assumed to be evaporation. Additional recharge in recharge ponds connected to irrigation canals beyond the 780 acre-feet/year used in the budget may occur if a portion of water diverted for irrigation is not used. Slightly higher recharge estimates could result in up to 10,000 acre-feet more recharge to the basin. Previous estimates have suggested this component is much higher, although assumptions of recharge efficiency rates do not seem realistic.
Wastewater	Medium. Estimates of RIB recharge should be reasonably accurate; estimates of septic discharge and land application of wastewater are considered approximate only.	Low. This component accounts for less than 5% of the water budget.
Subsurface inflow from consolidated rocks	Medium. Previous studies have included subsurface inflow from consolidated rocks, but the physical process being referred to was the same as the “mountain-front recharge” term being used in this water budget. For the current budget, this term refers to the inflow of groundwater from adjacent basins. It is considered negligible based on a conceptual understanding of the general geology of the area and groundwater flowpaths.	Low. Although this component could result in additional recharge, a similar change would likely occur with the discharge estimate.
Discharge		
Evapotranspiration	Medium. The acreage of various vegetation types is considered reasonably accurate, as are the consumptive water use rates. The depth to groundwater across the basin has been recently measured, and the ability of most vegetation to access water is considered reasonably certain.	Low. The assumption that all vegetation has access to groundwater could lead to an overestimate; however, this water budget component represents only approximately 6% of the water budget.
Leakage to Deer Creek Reservoir	Low. This estimate is based on high-quality data from both the U.S. Bureau of Reclamation (Deer Creek releases, evaporation, and storage) and USGS (inflows form Provo River, Daniels Creek, and Snake Creek) for the period from 2010 to 2016. The results closely align with at least two similar studies conducted decades earlier with completely independent datasets.	High. This component represents the single largest discharge in the water budget, representing approximately 45% of total discharge.
Seepage to Provo River	Medium. Based on high-quality datasets for the period from 2002 through 2018 from USGS gaging data. Basing this estimate on the period of November–−February reduces interference from agricultural diversions, evapotranspiration, and runoff. However, the estimate of return flow into this reach from Spring Creek (and other springs) is uncertain and an estimate only.	Medium. The estimate of Spring Creek return flow accounts for half of this water budget component, and it could be much larger or smaller.
Springs and seeps	High. This is based solely on an estimate included in Roark et al. (1991) and has not been independently verified because there is a lack of gage data for springs and seeps.	High. This component represents more than a quarter of the water budget, and any change would substantially change the balance.

Water Budget Component	Relative Level of Uncertainty and Rationale	Potential Effect on Water Budget
Wells	Low. Based on water use data compiled by DWRe and considered accurate.	Low. This component only represents approximately 3% of the total discharge.
Subsurface outflow to consolidated rocks	Medium. Subsurface outflow to consolidated rocks refers to the outflow of groundwater from the Heber Valley basin to adjacent basins. It is considered negligible based only on a conceptual understanding of the general geology of the area and likely flowpaths; however, the geologic units encountered (Oquirrh Formation) are sedimentary, fractured, and capable of transmitting groundwater. Groundwater-level contours do not suggest flow exists between the Heber and Round Valleys (contours are perpendicular to the mountain front).	Low. Although this component could result in additional recharge, a similar change would likely occur with the discharge estimate.

5.3.1 *Results from Groundwater Modeling*

As discussed in Section 6, the groundwater model as constructed adequately replicates the groundwater levels in the Heber Valley basin, as demonstrated through the calibration statistics. However, although modeled groundwater levels matched measured groundwater levels, some groundwater budget components were different from water budget estimates. In some cases, and because of uncertain inputs, this likely represents an inability of the model to properly replicate a physical process believed to be taking place. Examples of this are the modeled Provo River gains and losses. In other cases, discrepancies are explained by the fact that not every conceptual water budget component was directly incorporated into the model; an example of this is how seep and spring discharge is modeled. In all cases, the uncertainties described above also need to be considered.

One large component of the conceptual groundwater budget that was not modeled directly was seep and spring discharge. This is because SWCA does not have a clear understanding of a specific geographic area to model springs and seeps. Within the basin, springs generally occur where groundwater is very shallow. Shallow groundwater occurs in many places within the basin, but primarily in the lower basin and along the lower reaches of the Provo River. For this reason, although not modeled directly, the seep-spring flow is partially represented in other modeled discharges in this area, including Provo River gaining reaches and outflow from the constant head cells at the downstream edge of the basin (Deer Creek Reservoir). Total modeled outflow from these two sources (constant head cells, Provo River discharge) amounts to 80,748 acre-feet/year; this is comparable to the 91,075 acre-feet/year in the conceptual water budget (Deer Creek Reservoir discharge, seeps and spring discharge, and Provo River discharge).

Overall, modeling of the Provo River poorly matched the conceptual groundwater budget, with the groundwater model predicting much more stream losses to the aquifer than originally estimated (24,431 acre-feet/year modeled, versus 1,090 acre-feet/year estimated), and less stream gains from the aquifer than originally estimated (4,897 acre-feet/year modeled versus 9,846 acre-feet/year estimated). This difficulty is not unexpected. The RIV package relies heavily on the absolute elevation of the stream channel to determine whether the river is gaining or losing, and this is difficult to estimate from regional elevation models. A difference of a few feet can turn a losing reach to a gaining reach, and vice versa. Although the flow magnitudes were poorly matched, the geographic distribution of gains and losses matched reasonably well, with losing reaches in the upper portion of the basin and gaining reaches in the lower basin. Overall, the ramifications of this inability to fully model the Provo River does not affect the general basin flow paths, flow rates, or inputs to the water quality estimates. As a steady-state model, the overall calibration is driven primarily by hydraulic conductivity and the major sources/sinks (recharge from the basin margins, outflow to Deer Creek Reservoir). If a transient model were developed, it would be more important to accurately replicate the seasonal or annual changes that occur with flow along the Provo River.

6 GROUNDWATER MODEL DEVELOPMENT

During Phase 1 of the study, SWCA evaluated model feasibility to determine the best plan for developing a groundwater model. Importing one of the previous versions of the Heber Valley MODFLOW input files into the current version of the MODFLOW software was not feasible. FREEWAT—an open-source and public domain GIS integrated modelling environment used to simulate water quantity and quality in surface water and groundwater—was used instead (Borsi et al. 2018). FREEWAT, a composite plugin for QGIS (an open-source GIS software), was determined to be the best option for modeling groundwater. The use of the FREEWAT platform to accomplish these objectives allows for integration with GIS software and does not prohibit future use from incompatibility of software or proprietary software limitations.

The primary objectives of modeling efforts of Phase 2 are as follows:

1. Create a steady-state model of the aquifer using the conceptual water budget as a guide for model inputs (see Section 5); use the model to develop a map of groundwater elevation contours and evaluate flow paths.
2. Re-create the 1991 USGS MODFLOW for Phase 2 of the Wasatch County groundwater study model for Heber Valley using open-source pre- and post-processing software, rather than proprietary interfaces.
3. Where feasible, update model input information based on more recent and available information.

The steady-state model created by SWCA using FREEWAT, referred to here as the HVGM2020 model, was created to further investigate the water budget developed empirically by analysis of literature and real-world datasets, and in doing so reasonably replicate the observed groundwater levels in the basin. In a steady-state model, the time discretization is arbitrary, and for ease, the stress period was set as 1 year, and the time periods were set as 1 day.

6.1 Background and Evaluation

SWCA evaluated groundwater modeling software options with respect to the existing modeling efforts conducted for the study area (Inkenbrandt 2019; Roark et al. 1991). Both studies focused on assessing the hydrogeologic conditions and water quality within the Heber Valley and/or Round Valley areas within Wasatch County, followed by modeling groundwater flow to assist in fine tuning the water budget. MODFLOW was used within the Roark et al. (1991) study, which likely used one of the earliest versions of MODFLOW. Three evolutions of the original MODFLOW groundwater model (dated 1988, 2001, and 2006) have been created using the original Roark et al. (1991) study and are provided on the DWRi website (DWRi 2020).

Computerized groundwater modeling gained ground in the 1970s and 1980s with the rise of computing power. Starting ca. 1981, the USGS used its experience on developing other single-use numerical models to develop the industry-standard groundwater flow model: MODFLOW, or the USGS Modular Three-Dimensional Finite-Difference Ground-Water Flow Model, as follows:

- Modular. This means that the model is built around modules or "packages." which can be swapped in or out as needed. This creates incredible flexibility with the model and has contributed to MODFLOW's longevity.

- Three-dimensional. This means that the model is constructed of individual three-dimensional cells (each with its own length, width, and thickness), but also that there are multiple layers of these cells stacked on top of each other. This type of flexibility allows complex structures like aquitards and perched aquifers to be directly modeled.
- Finite-difference. MODFLOW calculates the incremental movement of water between each of these three-dimensional cells, based on conservation of mass. The head for every cell is calculated individually, and accounting for any water added to the cell, or water taken from the cell. The results from the first cell are used to feed the calculations for the second cell, and so on.

At its core, the MODFLOW model is open-source software. It can be downloaded from the USGS for no charge, and USGS is continually working on new versions. In practice, most users rely on proprietary pre- and post-processing software packages to access MODFLOW. These software packages typically still run the original USGS MODFLOW executable files but provide interfaces that make it easy for users to create and modify models, run the models, and then visualize the results after running them. FREEWAT is simply another pre- and post-processing software program, but has the benefit of being open-source (with no licensing costs), readily accessible, and fully integrated with GIS.

SWCA used the FREEWAT software package to create a MODFLOW model for the Heber Valley, excluding Round Valley (titled the 2020 Heber Valley Groundwater Model or the HVGM2020 model). SWCA chose to create a steady-state model, which means that the model runs until it reaches an equilibrium between water sources and sinks in the aquifer. This approach is informed by the conceptual water budget developed for the Heber Valley aquifer (see Section 5). A successfully calibrated steady-state model should reasonably replicate the observed groundwater levels in the basin.

6.2 Updated Understanding of Aquifer Characteristics

A baseline understanding of the Heber and Round Valley aquifers was developed in studies by Baker (1970), Roark (1991), HAL (1994), and Inkenbrandt (2019). Aquifer properties, such as hydraulic conductivity, depend many factors but can be generalized for different unconsolidated porous media. As for nearly all aquifers, the Heber and Round Valley aquifers are heterogeneous, meaning aquifer characteristics are spatially variable. Spatial variability within both aquifers has been characterized somewhat by the Roark et al. (1991) and Inkenbrandt (2019) studies for the Heber and Round Valley aquifers, respectively. Each study used groundwater-level data to estimate groundwater contours and hydraulic gradients and existing well and drilling information to estimate specific capacity from drillers' short-term (i.e., 2-hour) pumping tests. Hydraulic conductivity can in turn be roughly estimated from specific capacity estimates. These specific capacity estimates are considered approximate compared to aquifer test data retrieved from formal long-term pumping tests with multiple observation wells and formal quality assurance and quality control measures implemented.

The limitations of relying on drill logs for aquifer characterization and the overall limited understanding of the aquifers were recognized in these previous studies. SWCA's efforts to improve upon this baseline understanding were guided by newly available information (delineation reports) and the financial and temporal constraints of the study. Using drinking water well delineation reports provided by the DDW, SWCA obtained location-specific estimates of hydraulic conductivity for specific portions of the aquifer. These data were derived from controlled aquifer tests. SWCA considers aquifer tests obtained from delineation reports to be more accurate and reliable than specific capacity inferred from drill logs.

SWCA performed an independent analysis of groundwater levels (from USGS monitoring data) to develop a new groundwater contour map (potentiometric surface map) and to estimate hydraulic gradients throughout the Heber Valley aquifer. The updated groundwater contour map (Figure 31) allowed us to develop updated estimates of groundwater flow directions throughout the aquifer. However, although the contours and flow directions that SWCA developed are likely more accurate, they do not differ dramatically from those developed by HAL.

An understanding that local aquifers consist of both alluvial fill (unconsolidated) and bedrock (consolidated) layers has existed for many years. Analysis of aquifer tests and drillers' logs shows that there are productive wells in the Heber Valley that intersect both alluvial and bedrock layers. Flow in the bedrock is likely controlled primarily by fractures, but flow rates suggest a relatively well-connected fracture network and little separation between alluvial and bedrock units.

The depths of these two aquifer layers and the portion that is saturated have not been well defined for the Heber Valley. Baker (1970) attempted to model the depth of "low density" materials using gravity data, but SWCA's own analysis of drillers' logs suggests that this method greatly overestimates the thickness of alluvial material. Roark (1991) also compared the Baker results to drillers' logs and concluded similar results. SWCA estimated the thickness of alluvial materials from interpretation of 35 drillers' logs that appear to show evidence of a contact between unconsolidated and consolidated materials. Alluvial materials thin toward the edges of the basin and are thickest toward the southern portion of the basin, as shown in Figure 32.

Based on the information compiled for the groundwater model and calculations of flow through the aquifer, SWCA estimates that groundwater travel time through the aquifer can range as high as 24 feet per day, with a best-controlled estimate (based on the eastern basin) of roughly 3 feet per day. In general groundwater travels from zones of recharge at the mountain fronts toward Deer Creek Reservoir. Transit time for groundwater to cycle through the aquifer based on estimated flow velocity is 30 to 40 years. This is the average flow velocity along the predicted flow paths. These flow paths generally run from north to south along and from Jordanelle Reservoir, parallel with the Provo River; from northwest to southeast from the Midway area, toward the Provo River and Deer Creek Reservoir, and from east to west from the Timberlakes area, before turning toward Deer Creek Reservoir. The flow generally does not cross the valley in an east–west direction.

Previous estimates of groundwater flow velocity through the aquifer were made by HAL (1994). These velocities varied greatly across the aquifer and ranged from 50 to 7,000 feet per year (0.1 to 19 feet per day), suggesting travel times anywhere from 5 to 600 years. The difference between the HAL and SWCA estimate reflects the use of a similar approach (i.e., use of the Darcy flow equation), but with different values selected as inputs (specifically hydraulic conductivity and basin depth) based on different datasets. Overall, the ranges are consistent within the uncertainty of the approach: 3 to 24 feet per day for the SWCA estimate compared to 0.1 to 19 feet per day for the HAL estimate.

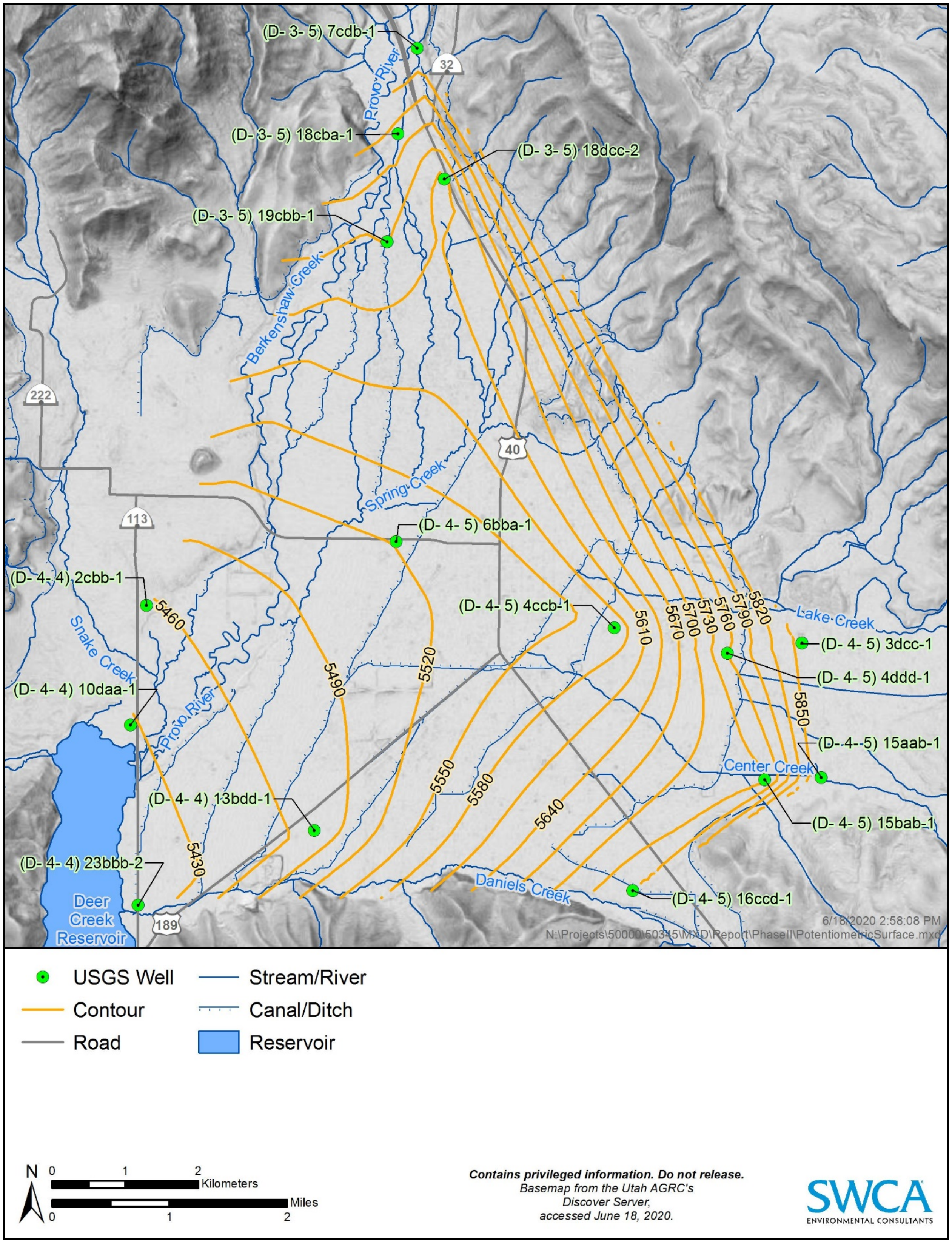


Figure 31. Potentiometric surface contours.

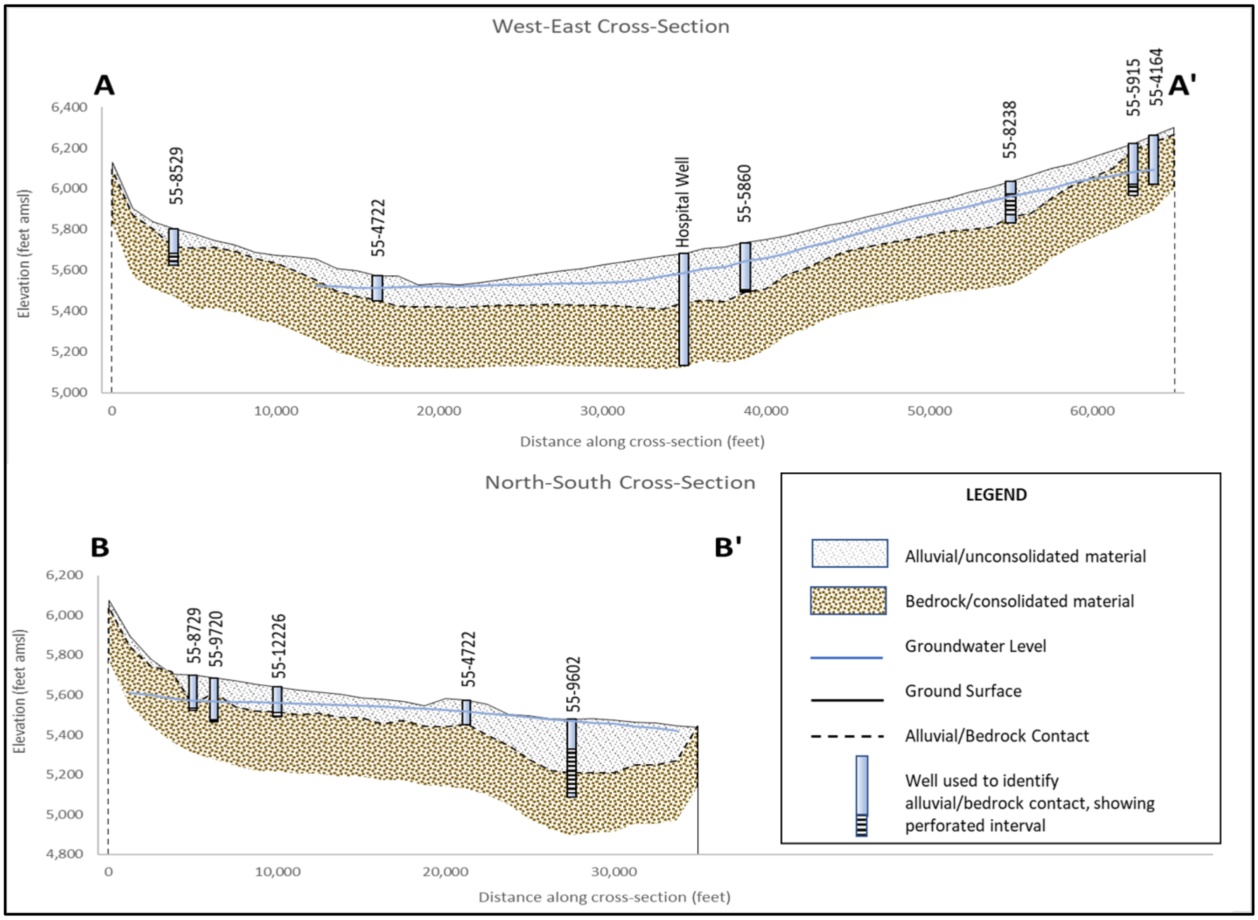


Figure 32. Cross sections of the Heber Valley aquifer.

6.2.1 *Model Development*

The full HVGM2020 model domain was set up to incorporate the watershed area for the Provo River as it flows through Heber Valley, including the contributing watersheds to Jordanelle Reservoir, the contributing watersheds to Deer Creek Reservoir (including Round Valley), and the watersheds for all tributary streams entering the Heber Valley. The model domain was discretized into 200 columns and 150 rows, for a total of 30,000 individual cells per layer. Each cell is equally sized, measuring 1,000 feet on each side. The entire model area encompasses approximately 700,000 acres.

The full model domain remains as described above. However, for the current focused modeling effort for the Heber Valley, the only active cells in the model are those that overlap the spatial extent of the basin-fill aquifer of the Heber Valley (Figure 33). The Jordanelle Reservoir lies just outside the active model domain to the north, and Deer Creek Reservoir lies just outside the active model domain to the south. All other cells—including those overlapping Jordanelle and Deer Creek Reservoirs—have been set as no-flow inactive cells. For the focused effort, the HVGM2020 model contains 1,270 active model cells

Further detail on the model assumptions and inputs can be found in Appendix B.

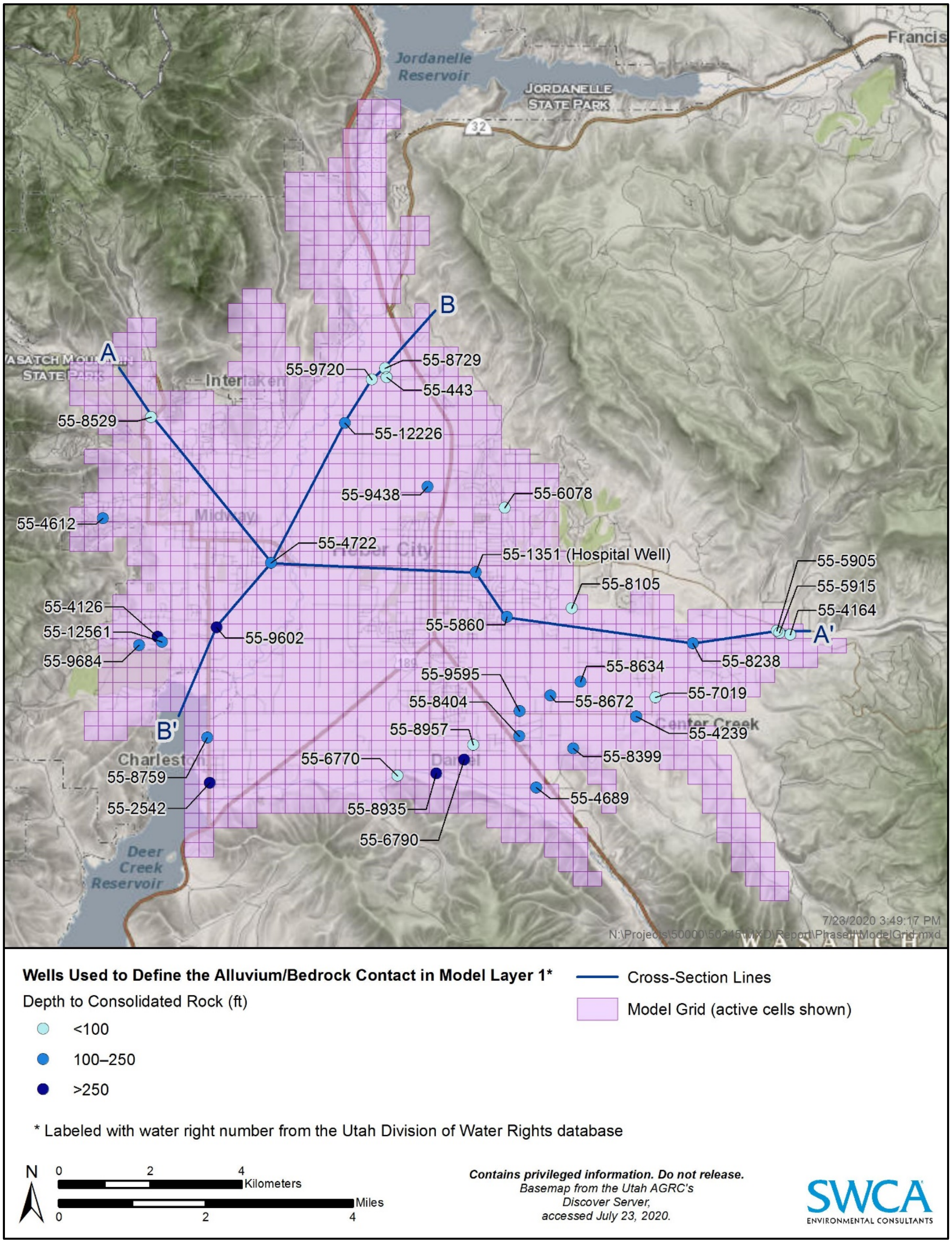


Figure 33. The HVGM2020 model grid.

6.2.2 *Layer Conceptualization and Discretization*

The HVGM2020 model uses two layers, conceptualized as follows:

- Layer 1 represents the lower-density basin-fill aquifer materials in the Heber Valley, which are assumed to be primarily unconsolidated, porous, alluvial or basin-fill materials. The top of Layer 1 is the ground surface, as measured from digital elevation models. The bottom of Layer 1 corresponds to the elevation contours derived from drillers' logs. The maximum thickness of Layer 1 (to the southern side of the basin, near Charleston) is approximately 400 feet, and the minimum depth (at the margins of the basin) is assumed to be 30 feet.
- Layer 2 represents the fractured or porous consolidated rocks that underlay the basin-fill materials. These may include fluvial and lake deposits (Uinta Formation) and conglomerate (Fowkes Formation, Knight Conglomerate). Analysis of well data suggests that in many areas these rocks can be productive as much or more so than the basin-fill deposits. Layer 2 plays an important role at the margins of the basin, where water levels fall below Layer 1, but is less important for the rest of the model area.
- The top of Layer 2 corresponds to the bottom of Layer 1. The total thickness of Layer 2 is difficult to define but is important to the model outcomes, especially because aquifer tests show consolidated materials to be as productive as unconsolidated materials. In theory, saturated fractured rock could be many hundreds of feet deep in the basin. Based on a database of drilling data for wells within the Heber Valley, the deepest productive well has been drilled to approximately 1,500 feet. However, most wells in the basin appear to use no more than 300 feet of consolidated aquifer. This value (300 feet) was used as the total thickness of Layer 2.

6.2.3 *Model Calibration*

Because the model is created to predict real-life groundwater interactions, a calibration process is needed to ensure future predictions are reliable. The calibration is based on the comparison of the real-world groundwater levels to the modeled groundwater levels.

Three primary pieces of information are obtained from each model run:

1. Steady-state water budget for the model
2. Simulated steady-state groundwater elevations in each model cell
3. Comparison of observed to simulated heads

The comparison of observed to simulated heads was the primary target used during the calibration process, though water budget comparisons were also reviewed for each model run.

In all, 21 calibration runs were conducted. In the calibration runs we varied hydraulic conductivity values in four separate zones (east, north, west, central), evaluated differences between Layer 1 and Layer 2 hydraulic conductivity, varying river conductivity values, and varied mountain-front recharge amounts. Each calibration run was evaluated using the following:

- The root mean square deviation (RMSE)/Range statistic. This is a percentage that compares the average error in the model results to the overall range of head values. Typically, a well-calibrated model would have an RMSE/Range statistic of less than 10%.
- The scatter plot of observed versus simulated head values. This tool is valuable because it shows patterns that affect the overall calibration statistic. Patterns can be observed to identify the outliers, and then the raw results can be evaluated to figure out which wells those outliers are from. This helps to determine if there is a certain geographical region of the model that is not calibrated very well, which may provide clues as to what could be changed to get a better calibration.

The final best-calibrated steady-state model yielded a RMSE/Range statistic of 9%. The fit of the calibration varies across the aquifer. The model is most closely calibrated to observed water levels in the central and lower basin (RMSE/Range of 4%), and less well calibrated in the eastern basin (RMSE/Range of 11%).

Overall, the fit of the groundwater elevations simulated with the steady-state model to real-world observed groundwater elevations indicates that the model successfully replicates the general aquifer dynamics and flow paths. Qualitative comparison of secondary calibration targets (water budget components; see Section 5) indicates that simulation of the gain/loss of the Provo River in the model may not accurately reflect real-world conditions, and that discharge to springs and seeps in the lower basin is largely unaccounted for except as discharge through Deer Creek Reservoir.

6.2.4 *Model Validation*

Most industry-standard modeling guidance suggests additional steps after calibration to ensure that the model not only simulates the calibration dataset but is also flexible enough to simulate other real-world datasets. Often referred to as validation or verification, these steps can be made immediately if another adequate dataset is available or can be made later as a post-audit comparison of predicted water levels to monitoring data. In all cases, an entirely separate dataset is needed beyond the calibration dataset. These steps are often most useful for transient models that are used to predict future scenarios.

In the case of the HVGM2020 model, a transient model was not developed, only a steady-state model, and a secondary, independent dataset was not identified beyond the groundwater levels used for calibration. Therefore, no model validation or verification was conducted[4].

As with all models, care needs to be taken not to extend the capabilities of the model beyond the proven calibration. The HVGM2020 steady-state model is adequately calibrated to reflect the general basin geometry, water budget, recharge patterns, recharge amounts, sinks, flow directions, and flow velocities. However, further work would be needed to translate this general steady-state model into a transient model capable of being used as a predictive tool.

6.3 Model Assumptions and Limitations

Because the purpose of the groundwater model is to simulate response relationships within real-world systems, and real-world systems are extremely complex, simplification through a set of assumptions is necessary. Assumptions for the HVGM2020 model are as follows:

1. All materials in the unconsolidated basin-fill aquifer in Heber Valley are assumed to form a single combined aquifer unit with similar characteristics (Layer 1).
2. The materials in the consolidated bedrock aquifer are also assumed to form a single combined aquifer unit with similar characteristics (Layer 2).

[4] Guidance exists on appropriate methods for calibration, e.g., ASTM standard D5981 – 96 (Reapproved 2008), Standard Guide for Calibrating a Ground-Water Flow Model Application (ASTM 2018). The goal of verification is to protect against a non-unique solution, which is where the model is only useful in a single situation (i.e., hardwired to produce a single result). The guidance suggests that when only a single calibration dataset (groundwater level observations) is available, it is not desirable to arbitrarily split it in order to create a verification dataset. Instead, a different approach to protect against non-uniqueness was used: "Other ways to address the uniqueness problem are to include ground-water flows with heads as calibration targets, and to use measured values of hydraulic properties as model inputs" (ASTM 2018). This was the approach in this case: calibration was made to measure groundwater heads, and the hydraulic conductivity values were informed by the available aquifer tests.

3. No vertical anisotropy was incorporated, and unimpeded hydraulic communication between the two layers was assumed.
4. The mountain-front recharge enters through fractures, faults, or infiltration from streams close to the mountain front. Recharge was allowed to enter either Layer 1 (if saturated), or Layer 2 (if Layer 1 cells were dry).
5. Other recharge components included tributary recharge from Lake Creek and Center Creek, agricultural incidental recharge, precipitation recharge, and wastewater recharge.
6. Outflow from the aquifer at Deer Creek Reservoir was modeled using constant-head cells, set to the average elevation of the reservoir surface.
7. Other discharge components included evapotranspiration and well pumping.
8. The RIV package was used to simulate the Provo River, with gain/loss occurring based solely on the simulated groundwater elevations.

6.4 Groundwater Model of the Round Valley Aquifer

Paul Inkenbrandt of the UGS developed an analytical element model of the Round Valley aquifer in 2018 to estimate hydraulic conductivity of the system and improve the understanding of the groundwater system (Inkenbrandt 2019). The specific modeling tools used by Inkenbrandt differ from the MODFLOW model developed by SWCA, but the conceptual model of the Round Valley aquifer is similar. Similar to the SWCA model of the Heber Valley, the Round Valley model consists of two layers, unconsolidated material and bedrock, which differ in hydraulic conductivity. Inkenbrandt also developed a potentiometric surface map for the aquifer and derived gradients from this map. Similar to the model SWCA developed, the Inkenbrandt model assumed constant head at Deer Creek Reservoir. Some of the components and findings of the Round Valley model were used by Inkenbrandt to develop a mass-balance model of septic nitrate loading. The findings of this mass-balance model are described in Section 7.1.4.

7 IMPACTS FROM WASTEWATER

In 1994, HAL recommended nitrate as a groundwater quality management indicator in Wasatch County. In 2020, nitrogen in the form of nitrate continues to be one of the primary indicators of pollution from septic systems and is consistently used as the best indicator for allowable septic system density recommendations in the state of Utah (Bishop et al. 2007a, 2007b; Inkenbrandt 2019; Lowe et al. 2010; Wallace and Lowe 1998). SWCA considers nitrate to be the key contaminant for use in developing a septic system management recommendation in Heber Valley and in monitoring the general impacts of wastewater management on groundwater quality.

In previous wastewater disposal publications in Utah, nitrate is the groundwater contaminant of interest because it is relatively inexpensive to analyze and is commonly associated with wastewater from septic systems. And, although the denitrification process can occur in aquifers, nitrate is generally assumed to not attenuate in groundwater except by dilution. The Heber Valley aquifer has a negligible capacity for denitrification, and plant uptake only occurs in shallow aquifer areas (Jeppson et al. 1991). Denitrification is the process by which nitrate is converted back into nitrogen gas by denitrifying bacteria.

7.1 The Mass-Balance Approach to Model Impact from Septic Systems

The mass-balance model estimates potential water quality degradation as a function of nitrogen load from current and future septic systems and includes dilution both from groundwater flow and from the septic tanks themselves. The mass-balance model also uses variables obtained during the hydrogeologic characterization and subsequent modeling of the Heber Valley aquifer such as groundwater flow rate through the aquifer or area of interest and existing nitrate concentration in the aquifer or area of interest.

The mass-balance model of nitrogen loading has been widely (and successfully) implemented by the UGS since the late 1990s in places such as Round Valley, Tooele Valley, Sanpete Valley, Cache Valley, and Cedar Valley (Bishop et al. 2007a, 2007b; Inkenbrandt 2019; Lowe et al. 2010; Wallace and Lowe 1998) and by other municipalities managing sole-source aquifers in other regions around the country. Additionally, a mass-balance model was implemented by HAL (1994) during the previous significant hydrologic investigation undertaken in Heber Valley to recommend a septic system density of approximately 5 acres per system.

SWCA modeled impacts from current and future septic systems using a mass-balance model of nitrogen loading. SWCA chose to apply the mass-balance model for the following reasons:

1. The mass-balance model is a peer-reviewed and valid approach for water resource management and land use planning that has been successfully applied numerous times throughout the state of Utah by researchers and local planning departments.
2. By using the mass-balance model, SWCA compared site-specific assumptions and calculations for the Heber Valley aquifer against site-specific assumptions and calculations for other aquifers in the state of Utah. SWCA validated the mass balance model by comparing results obtained in the Heber Valley to those obtained in other watersheds and aquifer systems.
3. Planning officials in Wasatch County can compare recommendations to other local health departments that have used the mass-balance model to develop septic system density recommendations.
4. The mass-balance model allows calculations completed by HAL to be re-created to evaluate the effectiveness of the 1994 HAL recommendations and to compare 2020 septic system density recommendations to those from the HAL study (see Section 7.1.5).
5. The mass-balance model methodology is clear and easy to follow, making it easier to defend and demonstrate to the public.
6. The mass-balance model is a mathematical model that is easy to modify based on varying the input parameters; therefore, multiple scenarios can be quantified that SWCA deems appropriate given the potential level of uncertainty associated with some input variables.

7.1.1 General Methods and Assumptions of the Mass-Balance Approach

The following mathematical model (equation) was used to calculate projected nitrate concentration in groundwater (Bishop et al. 2007a, 2007b; HAL 1994; Inkenbrandt 2019; Lowe et al. 2000, 2010):

$$Np = \frac{\left[[STt - STc]Qst * NL\right] + \left[Na\left(Qm + (STt * Qst)\right)\right]}{[(STt * Qst) + Qm]}$$

Where:

Np = projected nitrate concentration (mg/L)

STt = total number of septic tanks in the system (variable, unitless)

STc = current number of septic tanks (constant, unitless)

Qst = flow from each septic tank (L/s)

NL = estimated average nitrate concentration from each septic tank (mg/L)

Na = ambient (background) nitrate concentration (mg/L)

Qm = groundwater flow through the area of interest (L/s)

For the calculations, SWCA assumed nitrogen output is 17 grams (g) per person per day, 15% of which was assumed to be ammonia that is retained in the septic system or in the leach field (Bishop et al. 2007a, 2007b; Inkenbrandt 2019; Kaplan 1988; Lowe et al. 2010, 2000). Indoor water use was assumed to be 60 gallons per person per day (DWRe 2009), and average household size was assumed to be 3.5 people (U.S. Census Bureau 2019b). Under this scenario, nitrate concentration for each septic tank was 63.6 mg/L. This concentration, although greater than the HAL (1994) best estimate of 40 mg/L nitrate, is close to Bauman and Shafer's (1985) septic tank effluent concentration of 62 ± 21 mg/L nitrate and is also within HAL's (1994) high and low estimate of septic system effluent concentration of 80 mg/L and 30 mg/L, respectively. The EPA (2002) estimates that typical nitrate concentrations for domestic wastewater system effluent range from 21 to 108 mg/L.

Nitrate concentration was obtained by dividing the load per person by the indoor water use per person (i.e., the flow). It is important to note that HAL (1994) assumed per capita water use was 100 gallons per day, contributing to a lower septic system nitrate concentration estimate. A more recent study by DWRe indicates indoor water use (per person) is 60 gallons per day (DWRe 2009). SWCA and HAL both assumed that a load of 17 grams (g) of nitrogen per person per day and differences in nitrate concentration are the result of changing assumptions in indoor water use. A higher indoor water use results in a decreased nitrate concentration, whereas a lower indoor water use results in a decreased nitrate concentration. However, the load per person is assumed to be the same.

Existing nitrate concentrations were calculated by combining nitrate data collected by USGS between 2015 and 2020 (USGS 2020) and nitrate data collected by SWCA from 2018 to 2020. As discussed in Section 3, some SWCA wells coincide with USGS wells. In these instances, the SWCA data were combined with USGS data during the 6-year period from 2015 to 2020. An average nitrate value was calculated for each well. Next, the wells were geolocated on a map containing the areas of interest such as the Lake Creek planning area and the Heber Valley aquifer (see Sections 7.1.2 and 7.1.3) and a mean of means was calculated using the appropriate wells. Average nitrate concentration for all wells located in the Heber Valley aquifer are summarized in in Table 19.

Table 19. 5-year Average Nitrate Concentrations at Individual Wells Located in the Heber Valley Aquifer

Well Designation	Sampling Agency	Average Nitrate Value	Record Count from 2015 to 2020
(D- 3- 4)26dba- 1	USGS	3.08	5
(D- 4- 4)13bdd- 1	USGS	0.34	5
(D- 4- 5) 6bcc- 2	USGS	2.26	5
(D- 4- 5)16bab- 1	USGS	2.80	5
(D- 4- 5)16ccd- 1	USGS	0.87	5
Burgener Well	SWCA	2.87	5
Center Creek #1	SWCA	2.13	3
Center Creek #2	SWCA	1.37	3
Charleston #1	SWCA	1.94	2
Charleston Town Well	SWCA	2.45	4
Daniel #1	SWCA	0.62	3
Duggin Well	SWCA	3.34	5
Farnsworth Well	SWCA	5.32	2
Heber Hospital Well/(D- 4- 5) 5abb- 2	USGS/SWCA	0.94	5
Heber Lagoons West (Fish Hatchery)	SWCA	1.08	3
Heber Valley Hills Well	SWCA	2.09	4
Lake Creek #1/(D- 4- 5) 3dcc- 1	USGS/SWCA	6.65	7
Lake Creek #2/(D- 4- 5) 4ccb- 1	USGS/SWCA	5.20	8
North Fields #1 (Simmons Well)	SWCA	0.37	4
North Fields #2	SWCA	0.01	3
North Fields #3	SWCA	1.31	3
Probst Well	SWCA	0.19	2
South Fields #1 (Giles Well)	SWCA	3.08	4
South Fields #2/(D- 4- 4)12dcc- 1	USGS/SWCA	3.99	8
Swiss Alpine Road #2 (Hayward Well)	SWCA	2.17	4
Timberlakes #4	SWCA	1.30	3

Note: This table summarizes available nitrate data obtained through USGS and/or SWCA field collection efforts between 2015 to 2020. All wells are located within the Heber Valley aquifer boundary.

7.1.2 *Limitations of the Mass-Balance Approach and Estimates of Uncertainties*

Although the mass-balance approach is considered an effective planning tool that provides a general basis for septic system lot size recommendations, there are several known limitations associated with the technique. The limitations of the mass-balance approach identified by the UGS and summarized in Lowe et al. (2000) are included in the list below, along with a brief discussion of the SWCA approach to mitigating impacts (if applicable).

1. Calculations are typically based on a short-term hydrologic budget, single aquifer test, and limited water-gradient data.
    a. During Phase I of the study, SWCA assembled a robust and comprehensive dataset from which assumptions and calculations are based.
2. The background nitrate concentration is attributed to natural and anthropogenic sources, agricultural practices, and use of septic systems, but projected increases in nitrate concentrations are based on septic-tank systems only and do not include nitrate from other sources.
3. Calculations do not account for localized, high-concentration nitrate plumes associated with individual or clustered septic-tank systems, and also assume that the septic tank effluent from existing homes is in a steady-state condition with the aquifer.
4. The approach assumes negligible denitrification.
    a. Limited data suggest that the Heber Valley aquifer has limited capacity for denitrification (Jepson et al. 1991).
5. The approach assumes uniform, instantaneous groundwater mixing for the entire aquifer or entire mixing zone below the site.
6. Calculations do not account for changes in groundwater conditions from groundwater withdrawal from wells.
7. Calculations are based on aquifer parameters that must be extrapolated to larger areas where they may not be entirely representative. Calculations may be based on existing data that do not represent the entire valley.
    a. SWCA applied the mass-balance model to a smaller area using site-specific data as well as the Heber Valley aquifer area.

The overall septic system density calculation is sensitive to the acreage that is considered in the analysis as well as groundwater flow available for mixing. Like the Lake Creek planning area, expansion of the sewer network is projected to occur in the Heber Valley aquifer. WCHD estimates that as much as 85% of households in the Heber Valley could eventually become connected to the sewer network.

Sewer connections effectively prevent nitrogen from reaching the aquifer, except at controlled outfall locations after treatment. Conceptually, the same nitrogen load (and thus the same number of septic tanks) is allowable to reach the chosen degradation threshold, but the amount of available land for septic systems to be built is reduced. Mathematically this leads to a higher allowable density of septic systems (fewer acres per septic system).

However, septic systems occurring at high densities may violate certain assumptions of the mass-balance model listed above. First, the mass-balance model assumes complete mixing of septic tank effluent with the groundwater. Septic systems occurring at high densities can lead to local hot spots of nitrate and other pollutants where complete mixing with the aquifer is not facilitated. Second, the mass-balance model does not incorporate nitrogen loading from sources besides septic system wastewater. Other sources of nitrogen are assumed to be in steady-state condition with the aquifer and are therefore captured in the existing nitrate concentration. Septic systems at high densities (small lot size) do not provide a margin of error to account for other known sources of nitrogen such as recharge from rivers and streams, stormwater or agricultural recharge. Finally, although sewer systems remove the nitrogen from interacting with the aquifer in most of the valley, there still is an eventual discharge of treated effluent. The mass-balance model does not incorporate nitrogen from wastewater in the sewer system, which SWCA understands to contribute to overall nitrogen loading in the Heber Valley aquifer as a whole, albeit at a different location than the source of wastewater. Calculated lot sizes that factor in a percentage of land on sewer are not conservative in that they contribute to higher density developments, which do not meet assumptions of the mass-balance model, and they do not allow a margin of error for other known sources of nitrogen loading. Care should be taken when assuming high percentages of sewer hookups allow for denser septic tank development.

The various components of the mass-balance model were calculated using a number of independent methods, techniques, and empirical data, which means the uncertainty associated with each component can vary considerably. Table 20 summarizes the relative uncertainties associated with each mass-balance model component.

Table 20. Discussion of the Level of Uncertainty and Potential Effect for Each Mass-Balance Model Component

Mass-Balance Equation Component	Relative Level of Uncertainty and Rationale	Potential Effect on Density Recommendation
Projected nitrate concentration in the aquifer in mg/L (Np)	Low to medium. In Section 7.4 the HAL (1994) model is evaluated in its ability to predict real-world nitrate concentrations in 2020. The HAL model underpredicted actual nitrate values measured in the field in the Charleston to Lake Creek transect. The model would have been more accurate if HAL had included the septic tanks in the Timberlakes subdivision and would have modeled measured nitrate values within 10%. Because SWCA's approach and assumptions do not diverge wildly from HAL's, SWCA assumes the level of uncertainty associated with the overall model to be low to medium.	High. The projected nitrate concentration is the basis from which allowable septic system density is calculated.
Estimated average nitrate concentration from each septic tank in mg/L (NL)	High. Like other septic system wastewater impact studies in Utah, SWCA assumed an average loading of 17 g of nitrogen per person per day. The number is based on a study completed in the late 1980s in Michigan (Kaplan 1988) as opposed to recent field data collected in similar climates and geologic conditions as those found in Heber Valley aquifer.	Medium. SWCA's approach mitigates the potential impact of variability because SWCA has included multiple scenarios associated with a 20% margin of error in this variable. Although the estimate of 17 g of nitrogen per capita is outdated, it appears to be the industry standard and is consistently used in most UGS septic system wastewater impact studies.
Existing nitrate concentration in mg/L (Na)	Low. Estimate is based on high-quality, recent data collected by USGS and SWCA.	Medium. The existing nitrate concentration is where the linear model begins.
Total (future) number of septic tanks in the system (STt)	Low. The mass-balance model describes the linear relationship between number of septic tanks (x axis) and projected nitrate concentration (y axis).	Low. Septic system density can be calculated from any future nitrate threshold corresponding to any future number of tanks.
Current number of septic tanks in the system (STc)	Low. SWCA used a spatial dataset of septic systems provided by WCHD in 2018, which is the best,	Low. Any given number of septic tanks plus or minus 5 tanks results in the same projected nitrate concentration. Therefore, small differences (<10%) in estimates of the number of septic tanks do not significantly affect the overall estimated nitrate concentration.
Flow from each septic tank in L/s (QSt)	Low. Average flow through each septic tank is based on 2018 U.S. Census Bureau data for number of people per household, and DWRe (2009:1) indoor water use data. Variability between individual septic tanks is high but is assumed to be captured by using the average flow value calculated from high-quality datasets.	Medium. Flow from each septic tank, along with the per capita nitrogen load, is used to calculate the nitrate concentration from each septic tank. As flow goes up, the concentration goes down and vice versa. Therefore, flow through each septic tank by itself does not have a large effect on the model output.

Mass-Balance Equation Component	Relative Level of Uncertainty and Rationale	Potential Effect on Density Recommendation
Groundwater flow available for mixing in L/s (Qm)	Medium SWCA's estimate of 20.6 cfs was calculated from independent techniques (SWCA's groundwater model and the Darcy flow equation) using high-quality real-world data. However, the field data used as inputs to the groundwater model (such as hydraulic conductivity) exhibit a wide range of values, and the data are limited.	High. Although the estimate is reasonable, previous wastewater impact studies conducted by UGS have determined that the groundwater flow available for mixing is the major control when using the mass-balance approach to estimate nitrate concentration in groundwater (Lowe et al. 2000). More specifically, it is the single most important driver of the mass-balance model output.

7.1.3 *Lake Creek Septic System Density Evaluation*

Like other Utah wastewater impact studies (HAL 1994; Inkenbrandt 2019; Lowe et al. 2000), SWCA considered a smaller area for the mass-balance calculation because it may be more representative of potential development scenarios given that large areas of Heber Valley will not be used by septic systems due to zoning (sewer), land suitability, or landownership. Furthermore, using site-specific data (such as existing nitrate concentration) collected in a smaller area is more accurate than extrapolating parameters to larger areas where they may not be representative (Inkenbrandt 2019). SWCA applied the mass-balance model to the Lake Creek planning area using site-specific groundwater flow estimates and water quality data to evaluate the potential impact to groundwater quality from septic system development.

7.1.3.1 LOCATION AND AREA

SWCA delineated an area in the eastern portion of the Heber Valley (referred to as the Lake Creek planning area) using the Mountainland Association of Governments (MAG) projected population data for traffic analysis zones (TAZ) (MAG 2020). The Lake Creek planning area boundary (approximately 4,822 acres) was defined by city boundaries on the north and west sides, and by TAZ boundaries separating areas of higher population growth from areas with less population growth. SWCA also delineated an area to encompass the extent of the spatial distribution of septic points in the Timberlakes subdivision. This area was added to the Lake Creek planning area to account for nitrogen loading from the Timberlakes subdivision septic tanks. The total area considered in the mass-balance model is 8,420 acres (see Figure 34).

7.1.3.2 EXISTING AND FUTURE SEPTIC SYSTEMS

In 2018, the Lake Creek planning area contained an estimated 293 septic systems. According to WCHD (Richardson 2020), the number of septic systems in the database may not be current and there are likely more than 293 septic systems in the Lake Creek planning area. For this reason, SWCA assumed a 10% increase in the number of septic systems from the 2018 estimates in the Lake Creek planning area and Timberlakes subdivision. Additionally, SWCA assumed that septic systems from the Timberlakes subdivision are contributing a nitrogen load to the Heber Valley aquifer, given that Timberlakes is located upstream in the Lake Creek subwatershed (see Section 4.1 for further discussion), and modeling indicates that Timberlakes is connected hydrologically. SWCA added the total number of septic systems in the Timberlakes subdivision (1,008) to the 322 septic systems in the Lake Creek planning area for a total of 1,330 septic systems.

The relationship between number of septic systems and projected future nitrate concentration is predicted to be linear. Future growth scenarios (estimated number of future septic systems) can be compared to the linear model to derive septic system density. Septic system density can be calculated from any future nitrate threshold corresponding to any future number of tanks.

7.1.3.3 GROUNDWATER CONDITIONS

SWCA obtained well logs for 12 wells in the Lake Creek planning area from the DWRe interactive mapping tool to examine well construction data and lithology. Review of well logs indicated that the depth of unconsolidated material is variable, and ranges from approximately 30 feet at the eastern edge of the basin, to approximately 250 feet at the western edge of the Lake Creek planning area near the Heber City boundary. Movement of groundwater is generally east to west at a gradient of approximately 126 feet per mile (calculated from potentiometric surface contours, see Figure 31 [Section 6]). The potentiometric surface ranges from approximately 19 to 144 feet below land surface. Groundwater occurs in both the unconsolidated valley-fill deposits and consolidated rock. Groundwater flow available for mixing is estimated to be 20.6 cfs. This was calculated using the Darcy flow equation, with inputs (hydraulic gradient, hydraulic conductivity, aquifer depth) that were derived from compiled field data such as aquifer tests and well logs. These flow values were closely confirmed using output from the steady-state groundwater model, which estimated a flow of 21.7 cfs through this area.

7.1.3.4 EXISTING NITRATE CONCENTRATIONS

To calculate existing nitrate concentration, SWCA first identified SWCA and USGS wells in the Lake Creek planning area and combined the available nitrate data collected between 2015 and 2020. As previously discussed, elevated nitrate concentrations were observed at Lake Creek #1/(D-4-5) 3dcc-1 and Lake Creek #2/(D-4-5) 4ccb-1 wells, which are located within the Lake Creek planning area, with concentrations ranging from 4.5 to 8.3 mg/L in the last 5 years. Because different wells have different numbers of samples, caution was exercised to avoid any single location from overinfluencing the average nitrate concentration of the aquifer. To do this, SWCA first calculated the mean of all nitrate samples available for each individual well, resulting in a single representative nitrate concentration per well. SWCA then averaged these representative nitrate concentrations for all wells in the planning area, yielding a single average nitrate concentration for the planning area. Existing nitrate concentration in the Lake Creek planning area was calculated to be 3.19 mg/L.

Nitrate concentrations from the wells in the Timberlakes subdivision were not included in the existing nitrate concentration calculation for the following reasons. First, wells in the Timberlakes subdivision are not located within the Heber Valley aquifer where mixing of groundwater is assumed. Wells in the Timberlakes subdivision are completed in various formations and various depths that may not be representative of conditions in the Heber Valley aquifer. Second, including nitrate concentrations from wells in the Timberlake subdivision would have lowered the overall existing nitrate concentration in the aquifer, resulting in less conservative approach.

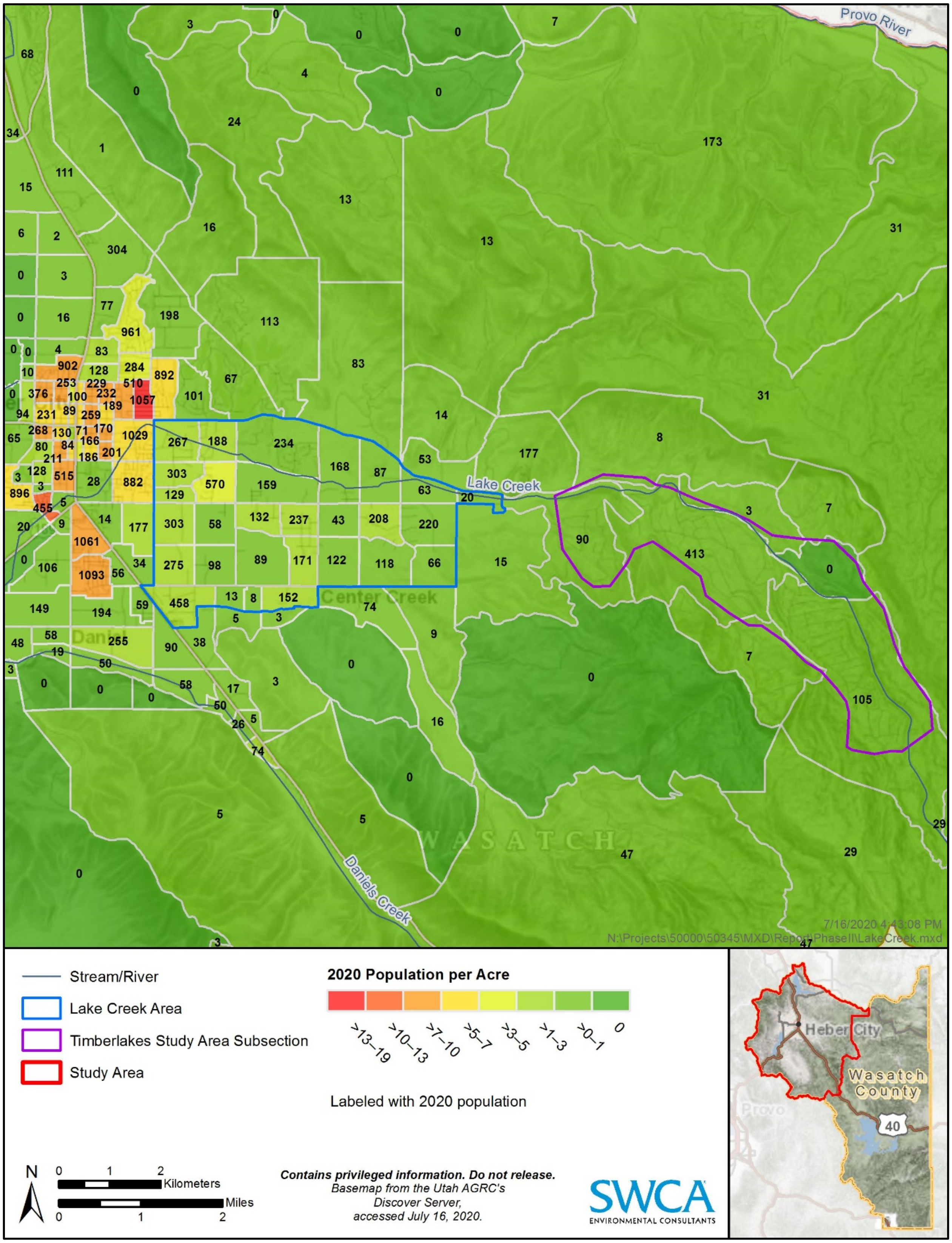


Figure 34. Lake Creek TAZ zones.

7.1.3.5 RESULTS

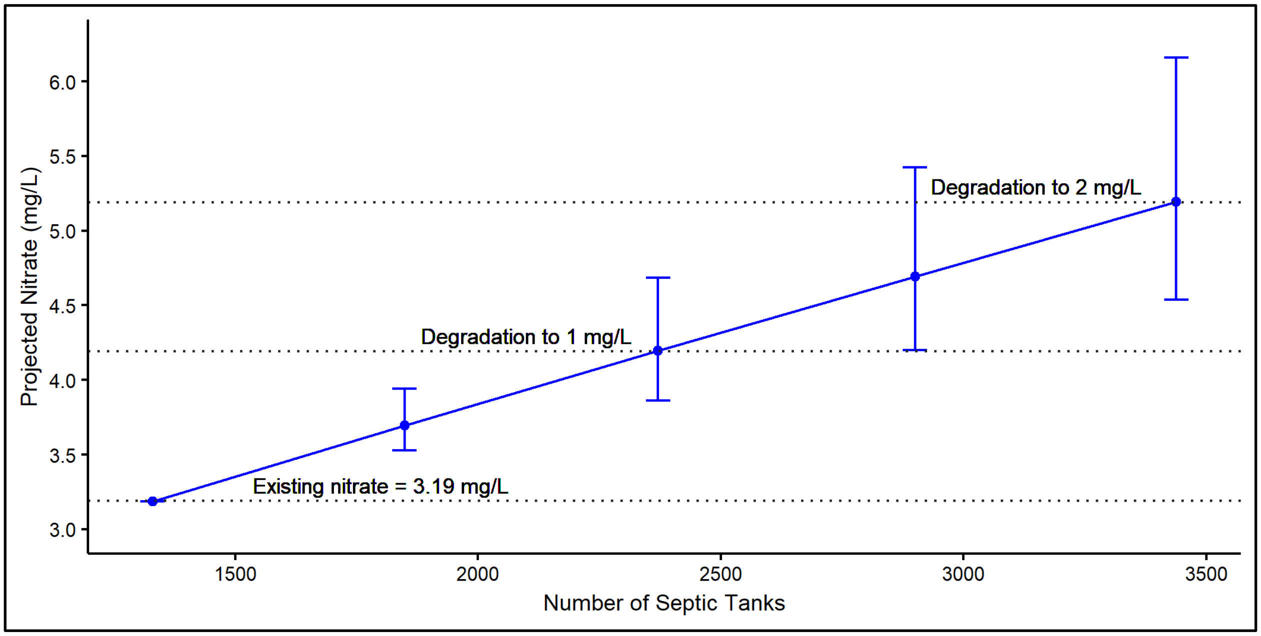
SWCA calculated the projected nitrate concentration in the aquifer based on the number of septic systems in the Lake Creek planning under three different scenarios. SWCA developed three scenarios to account for uncertainty related to estimations and to capture the natural variability that exists in the environment. For example, groundwater flow available for mixing can vary year to year and is dependent on groundwater withdrawal, recharge from mountain-front precipitation, and other sources. SWCA estimates the groundwater flow to be approximately 20.6 cfs. Previous wastewater impact studies conducted by UGS have determined that the groundwater flow available for mixing is the major control when using the mass-balance approach to estimating nitrate concentration in groundwater (Lowe et al. 2000). More specifically, groundwater flow is the single most important driver of the mass-balance model output. Therefore, SWCA modeled projected nitrate using a best- and worst-case scenario of groundwater flow using a 20% margin of error (20.6 ± 4.12 cfs). SWCA also included a margin of error of 20% in the estimate of nitrogen load per person.

The current nitrate concentration in the Lake Creek planning area is estimated to be 3.19 mg/L, which already exceeds the WCHD management threshold of 3.0 mg/L. Using the mass-balance mathematical model, no additional septic systems in the Lake Creek planning area or in the Timberlakes subdivision would be allowed to maintain the existing nitrate concentration in the groundwater underlying the Lake Creek planning area.

Initial model results indicate that the addition of approximately 1,000 septic tanks to the Lake Creek planning area would result in a 1-mg/L increase in groundwater nitrate concentrations. Activities upstream in the Lake Creek drainage are expected to impact nitrate concentrations in the Heber Valley aquifer. The lots that are already approved for septic build-out in the Timberlakes subdivision are included in the model. Therefore, additional tanks—whether they occur in the Timberlakes subdivision or in the Lake Creek planning area—are assumed to contribute the same nitrogen load to the aquifer. Under low flow conditions, the addition of approximately 694 septic systems may cause an increase of 1.0 mg/L of nitrate in groundwater. Under high flow conditions, the same increase of 1.0 mg/L of nitrate would not occur until an additional 1,560 septic systems were installed in Timberlakes or the Lake Creek planning area (Figure 35). The septic density calculation is very sensitive to the total area used in the calculation and total groundwater flow available for dilution (Inkenbrandt 2019). The total number of septic systems (existing plus new) estimated in the model can then be divided by the land area where they would be built to put the future condition in terms of septic density.

The acreage of land area where additional septic systems could be developed in the Lake Creek planning area is influenced by landownership, site suitability, and the expansion of existing sewer networks. For the Timberlakes area upgradient from the Lake Creek planning area, roughly 700 additional septic systems could be installed at a density much greater than current WCHD regulations because the subdivision was permitted prior to the development of the regulation. SWCA assumes wastewater from homes connected to the sewer does not enter the groundwater in-situ. Rather, it is transported to the Heber Valley lagoons where some nitrogen removal occurs in a series of settling ponds (lagoons) or through additional treatment. Treated wastewater is discharged to the groundwater from the RIB or through land application by sprinkler (see section 7.5 for further discussion on sewer wastewater).

In the mass-balance mathematical model discussed in Section 7.1, wastewater from homes connected to the sewer system and the area of the land on the sewer network are not factored into the equation for two reasons. First, homes on sewer do not contribute a nitrogen load to the groundwater in-situ, and second, the parcels of land currently on sewer or expected to be on sewer are not available for septic system build-out. As previously noted, the addition of approximately 1,000 septic tanks in the Lake Creek or Timberlakes areas may result in a 1-mg/L nitrate increase in groundwater. As the sewer network expands, the available land for septic system build-out decreases. Consequently, the septic system density (acres per septic system) decreases.

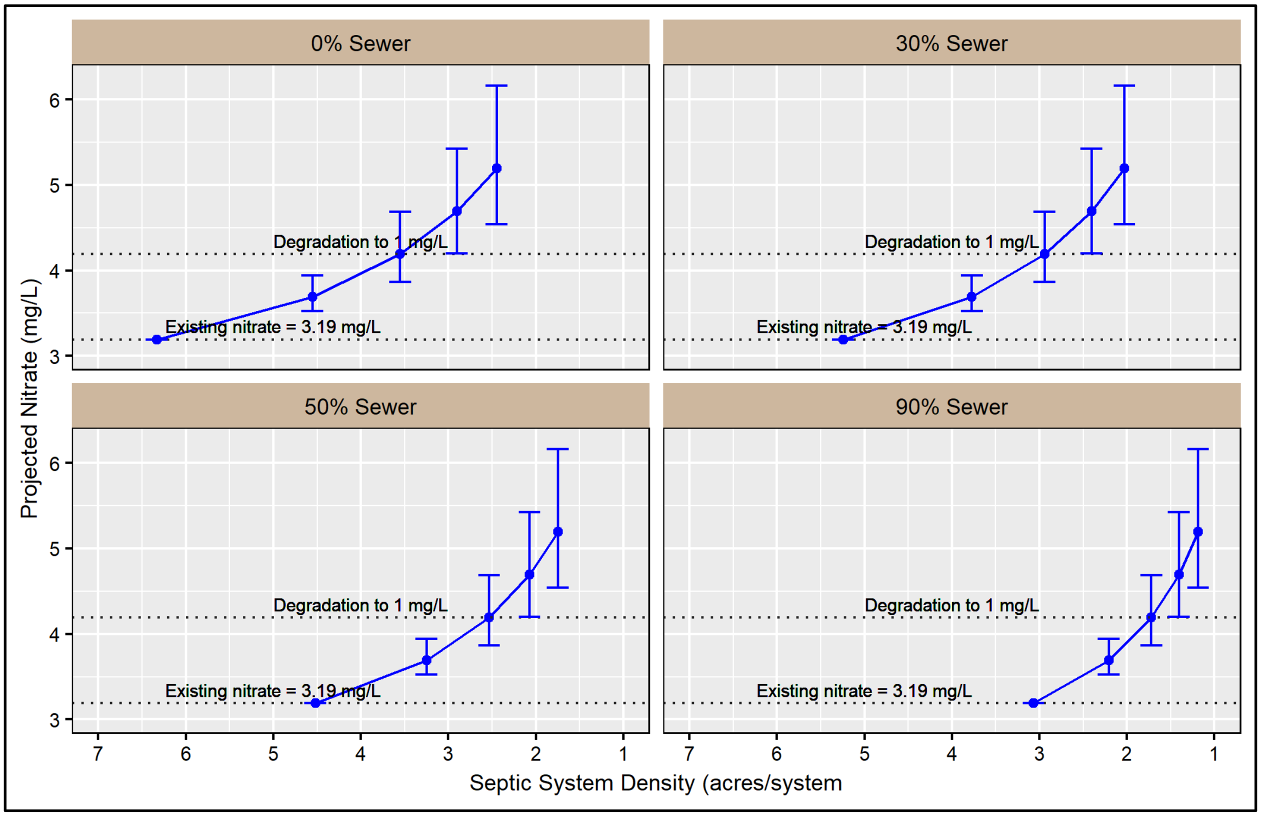


Note: Error bars represent projected nitrate concentration with adjusted parameters in the mass-balance model. A 20% reduction in groundwater flow and a 20% increase in nitrogen load per person results in higher projected nitrate (top error bar), whereas a 20% increase in groundwater flow and a 20% decrease in nitrogen load per person results in lower projected nitrate (bottom error bar).

Figure 35. Projected nitrate in groundwater underlying the Lake Creek planning area.

SWCA modeled the relationship between projected nitrate concentration in the aquifer underlying the Lake Creek planning area and septic system density (Figure 36). Four scenarios of land acreage were considered based on the percentage of land in the Lake Creek planning area on sewer network. For each scenario, SWCA adjusted the percentage of land in the Lake Creek planning area, whereas the Timberlakes area remained the same. A lot size of 3.6 acres per septic system may result in a 1-mg/L increase in the Lake Creek planning area. If 30% of the land in the Lake Creek planning area is on sewer, a septic system density of 2.94 acres/septic system may increase nitrate by 1 mg/L. If 90% of the land in the Lake Creek planning area is on sewer, a septic system density of 1.72 acres/septic system may increase nitrate by 1 mg/L. Error bars in Figure 36 represent the variability in projected nitrate concentration under best- and worst-case scenarios. Best- and worth-case scenarios were defined by adjusting groundwater flow available for mixing and the nitrogen load per person by ±20%. Higher density areas contribute to local hotspots of nitrate.

Calculated lot sizes in the three scenarios shown in Figure 36 that factor in a percentage of land on sewer are not conservative in that they contribute to higher density developments. Septic systems installed at a high density do not meet assumptions of the mass-balance model and they do not allow a margin of error for other known sources of nitrogen loading. Expected nitrate concentrations may exceed the calculated amount under scenarios where acreage of land is removed in the density calculation. Assumptions and limitations of the mass-balance approach are discussed in Section 7.1.6.



Note: Error bars represent projected nitrate concentration with adjusted parameters in the mass-balance model. A 20% reduction in groundwater flow and a 20% increase in nitrogen load per person results in higher projected nitrate (top error bar), whereas a 20% increase in groundwater flow and a 20% decrease in nitrogen load per person results in lower projected nitrate (bottom error bar).

Figure 36. Modeled relationship between septic system density and projected nitrate concentration under four scenarios of sewer expansion in the Lake Creek planning area.

7.1.4 *Heber Valley–Wide Septic System Density Evaluation*

SWCA modeled the projected nitrate concentration in the entire Heber Valley aquifer due to wastewater from septic systems using the mass-balance mathematical model described in Section 7.1. SWCA used similar baseline assumptions for the valley-wide analysis but modified the site-specific parameter values. For example, the indoor water use estimate of 60 gallons per person per day did not change, but the existing nitrate concentration changed as well as the estimate of groundwater flow available for mixing. Existing nitrate concentration in the Heber Valley aquifer is 2.22 mg/L based on a 5-year dataset from USGS and SWCA monitoring wells in the Heber Valley aquifer.

Groundwater flow available for mixing is estimated to be 105.87 cfs and was calculated using the Darcy flow equation, with inputs (hydraulic gradient, hydraulic conductivity, aquifer depth) that were derived from compiled field data such as aquifer tests and well logs. The flow value of 105.87 cfs was closely confirmed using output from the steady-state groundwater model, which modeled outward flow from Deer Creek Reservoir to be 104.8 cfs. The parameters and assumptions used in calculating valley-wide septic system density values are summarized below:

- Indoor water use was 60 gallons per person and 3.5 people per household.
- Nitrogen output was 17 g, 15% of which is retained in the septic system. SWCA included a 20% margin of error in this assumption and estimate that nitrogen output can range from 13.6 g of

nitrogen to 20.4 g nitrogen. Variability in the nitrogen load per person affects the nitrate concentration leaving the septic tank.

- Area of land was 25,968 acres. The area of land was modified to account for the percentage of households that could be connected to the sewer network.
- Groundwater flow was 105.87 cfs. SWCA included a 20% margin of error and estimates that groundwater flow could be between 84 and 127 cfs.
- Existing nitrate was 2.22 mg/L.
- Existing number of septic tanks was 1,289 (WCHD 2018) plus an additional 10% to account for increases that have occurred since 2018 for a total of 1,418 existing septic systems.
- The current septic system density is 18 acres per septic system. This is an average, gross density for the entire Heber Valley aquifer. Existing distribution of septic systems suggests that there are areas of higher density development surrounded by lower density areas.

Using these assumptions, SWCA estimates that nitrate concentration in the Heber Valley aquifer could increase by 1 mg/L if 5,200 septic tanks are added to the valley. SWCA estimates that nitrate from septic systems may stay below 3.0 mg/L if a lot size is 5 acres per septic system. If lot sizes are 5 acres per septic system, the projected nitrate concentration in the Heber Valley aquifer is calculated to be between 2.71 and 3.31 mg/L. The range in projected nitrate concentration corresponds to best- and worst-case conditions that factor in natural variability in groundwater flow and variability in nitrogen loading from individual households. A discussion of these results is included in Section 9.2

7.1.5 *Round Valley Septic Density Evaluation*

Septic system density in Round Valley was evaluated by the UGS using the mass-balance technique described in Section 7.1 (Inkenbrandt 2019). The following parameters and assumptions were used to model the relationship between projected nitrate and septic system density in Round Valley (Inkenbrandt 2019):

- Indoor water use was 60 gallons per person and 3 people per household.
- Nitrogen output was 17 g, 15% of which is retained in the septic system.
- Area of land was 1,813 acres (the area of the alluvial fill material in Round Valley).
- Groundwater flow was between 11 and 20 cfs.
- Existing nitrate was 1.6 mg/L.
- Existing number of septic tanks was 290.

Under these parameters and assumptions, Inkenbrandt (2019) estimated there could be a 1-mg/L nitrate increase in groundwater if septic system density was 2 acres per system and groundwater flow was 11 cfs. A lot size of 1.3 acres per tank may cause nitrate to increase by 1 mg/L if the groundwater flow was 20 cfs. The addition of approximately 500 septic systems to the valley would cause a 0.5-mg/L increase in nitrate. Finally, a lot size of 0.3 acre or smaller would result in nitrate exceeding the groundwater standard of 10 mg/L under both high and low groundwater flow scenarios. Figure 37 illustrates the modeled relationship between number of septic tanks and projected nitrate concentration in the Round Valley aquifer (left), and septic tank density and projected nitrate concentration (right).

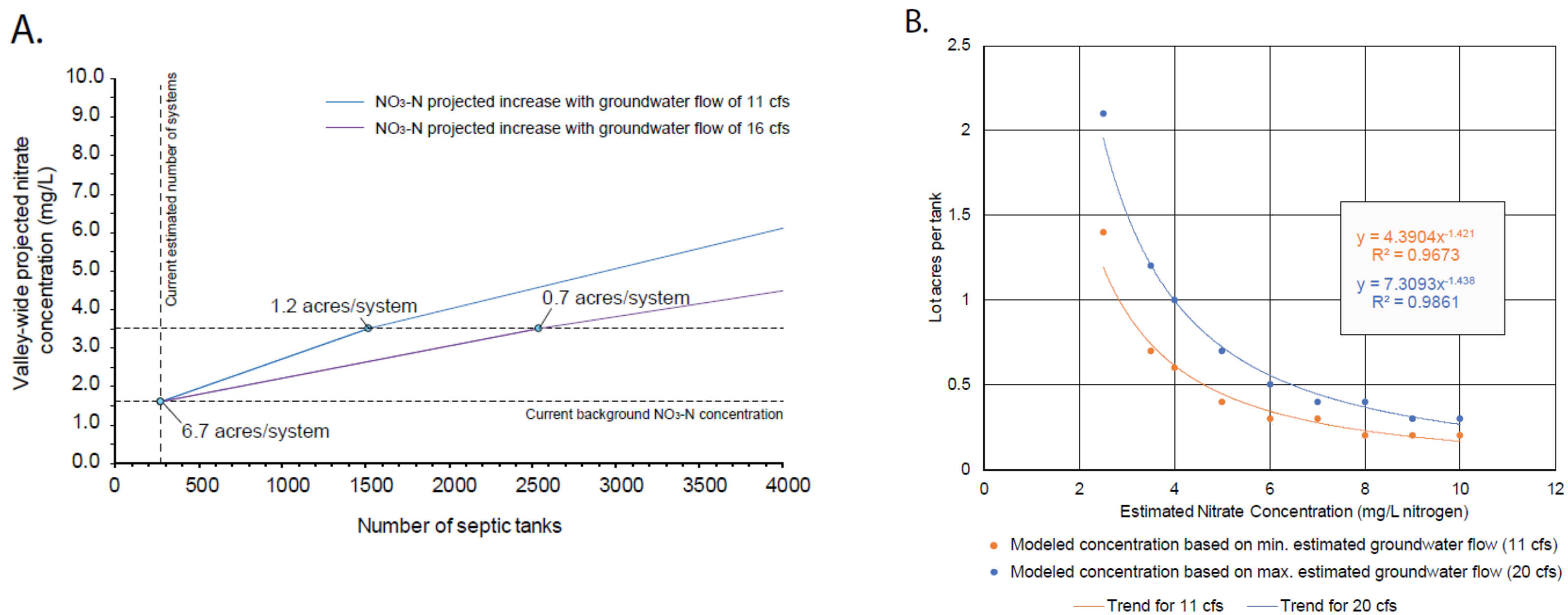


Figure 37. Modeled relationship between number of septic tanks and projected nitrate concentration in the Round Valley aquifer (A.), and septic tank density and projected nitrate concentration (B.) (Inkenbrandt 2019).

7.1.6 *Re-Creation of 1994 HAL Model*

In 1994, HAL used the mass-balance model for nitrogen loading to recommend a septic system density (lot size) in Wasatch County of 5 acres per septic system. To arrive at this recommendation, HAL developed a relationship between septic systems and expected nitrate concentration for the Heber Valley aquifer as well as for a transect in the valley from Charleston to the eastern edge of the basin near Lake Creek. The transect was constructed by delineating lines perpendicular to groundwater contours (Figure 37). HAL (1994) estimated the transect was approximately 4,300 acres with 210 septic systems, and the background nitrate concentration was assumed to be 2.0 mg/L.

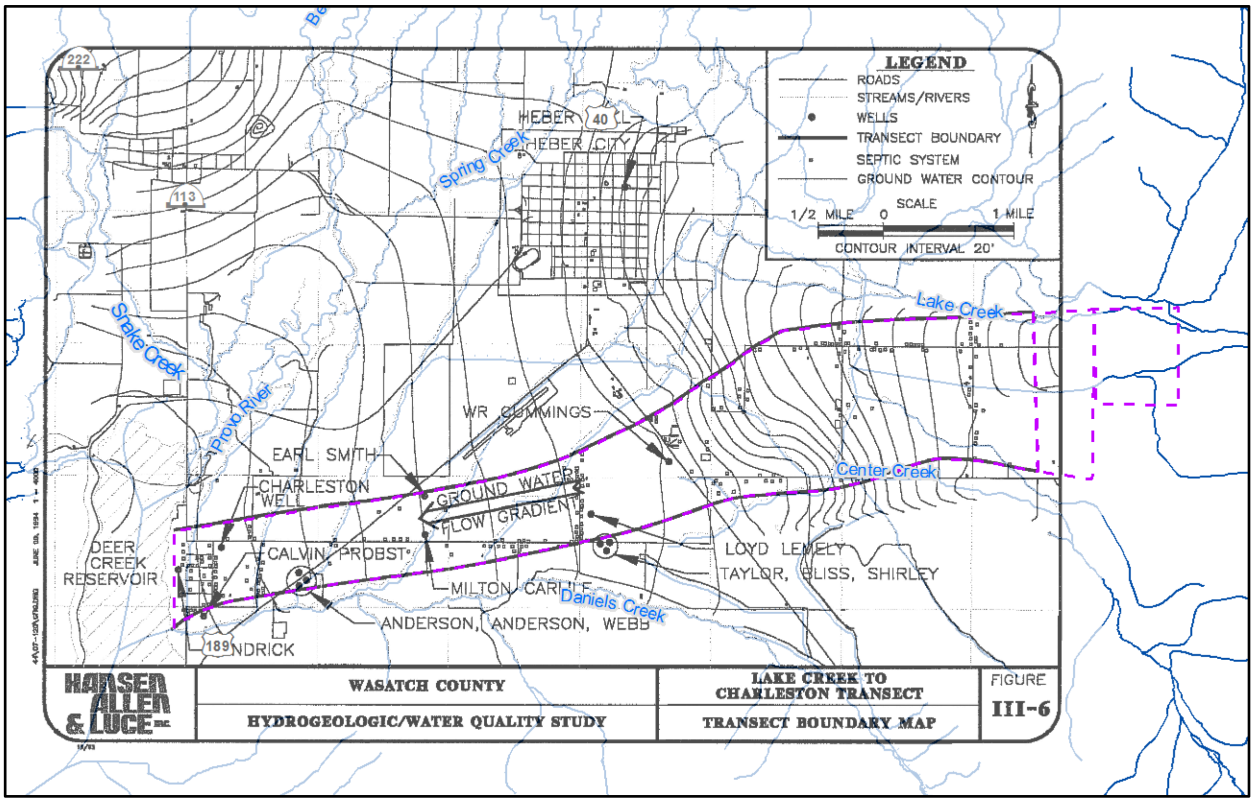


Figure 37. Digitization of HAL (1994) Lake Creek to Charleston Transect.

SWCA re-created the HAL (1994) mass-balance model in the Charleston to Lake Creek transect to determine how effective the model was at predicting ambient nitrate concentrations in 2020 given the current number of septic systems in the area. The Charleston to Lake Creek transect was digitized in GIS and overlaid with the septic system points layer (WCHD 2018) to identify the current number of septic systems in the area, as well as the groundwater wells with available nitrate data to establish the background nitrate level in the transect (see Figure 37). SWCA's GIS analysis of the transect area indicates that there are 374 septic systems in the transect area of 3,648 acres based on the 340 septic systems accounted for the in the 2018 dataset plus an assumed 10% increase between 2018 and 2020. This size estimate of the Charleston to Lake Creek transect is less than HAL's, and SWCA attributes the discrepancy in area to improvements in GIS technology since 1994. To calculate existing nitrate, SWCA first identified SWCA and USGS wells in the transect area and combined the available nitrate data collected between 2015 and 2020. SWCA used the mean of means instead of the grand mean to reduce the influence of high numbers on the overall overage. Ambient nitrate in the Charleston to Lake Creek transect in 2020 is 2.82 mg/L.

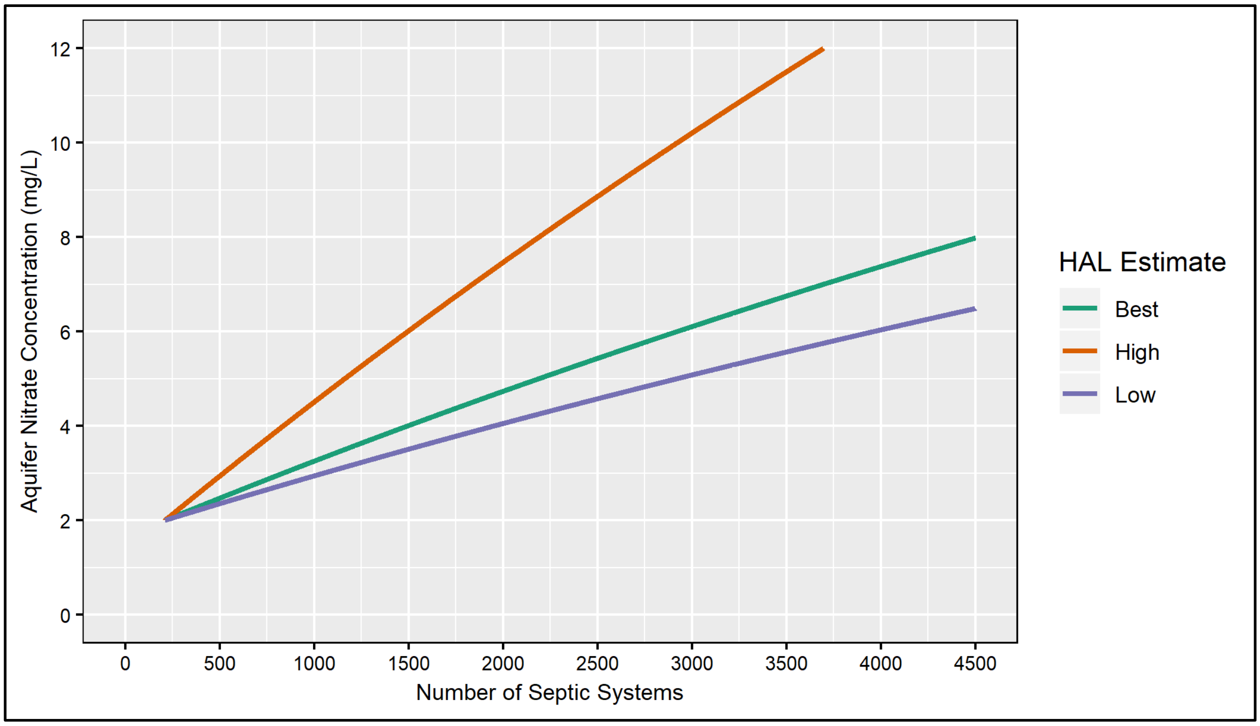


Figure 38. HAL 1994 model of nitrate concentration versus septic system density in the Charleston to Lake Creek transect.

At 374 septic tanks, the HAL model predicts nitrate concentration in the Charleston to Lake Creek transect to be between 2.20 and 2.53 mg/L with a best estimate of 2.27 mg/L (see Figure 38). The HAL model predicted nitrate would reach the current concentration of 2.82 mg/L at 718–723 septic systems, nearly double the current number of septic tanks in the Charleston to Lake Creek transect. There are several reasons why the HAL model is underestimating the current nitrate levels:

- The mass-balance model does not include nitrogen loading from additional sources. Therefore, any projected nitrate concentration from the model is assumed to underpredict actual concentrations that reflect all sources of nitrogen loading.
- HAL did not factor in the Timberlakes septic systems, which are contributing a nitrogen load to the Heber Valley aquifer, therefore impacting the background concentration. If Timberlakes septic systems had been included in the equation, the HAL model would have predicted nitrate to be between 2.84 and 4.23 mg/L at the current number of septic tanks in the HAL transect (340) plus the Timberlakes development (916). Assuming these numbers have increased by 10% since 2018, the total number of septic systems in the Lake Creek to Charleston (HAL) transect plus Timberlakes development is 1,382 septic systems.
- Local hot spots of nitrate (such as the Lake Creek #1 well) are likely elevating the background concentration of nitrate in the Charleston to Lake Creek transect.
- Groundwater flow available for mixing is the major control on nitrate concentration in the aquifer (Lowe et al. 2000); therefore, it may be more appropriate to base the high and low estimates for nitrate concentration on flow available for mixing instead of nitrate concentration from each septic tank as was done in the HAL study. Conversion of irrigation practices on agricultural lands from flood to sprinkler is not expected to significantly reduce flow available for mixing (dilution) because most flow is from precipitation and mountain front recharge (see Section 5). More recent

septic system density studies have based high and low estimates for nitrate on groundwater flow (Inkenbrandt 2019).

- It is possible that the background nitrate concentration in the Lake Creek to Charleston transect was greater than 2.0 mg/L in 1994.

SWCA's statistical test for trend in nitrate concentration indicates a statistically significant upward trend in nitrate concentrations in the Heber Valley aquifer between 1998 and 2019 ($p = 0.0085$). Local hot spots of nitrate are observed at several locations throughout the valley; however, the average concentration of nitrate is below the WCHD management goal of 3.0 mg/L. Based on available data, the HAL recommendation of a minimum lot size of 5 acres per septic system appears to be effective at managing nitrogen load from septic systems.

7.2 Centralized Wastewater Treatment Plant Effluent

All wastewater collected by the sewer network in Wasatch County has historically been (and is currently) treated at the Heber Valley Wastewater Treatment Plant operated by the HVSSD. As described in Section 5.1.5, most (approximately 80%) of the wastewater treated at the HVSSD is treated in lagoons before being discharged as irrigation water (via sprinkler) to a farm in the south fields area. A portion of the effluent in the lagoons is thought to be lost as seepage from the southern lagoons (Sunrise Engineering 2013). The other approximately 20% of the treated wastewater is discharged to a RIB (groundwater) west of the treatment lagoons. Discharge of effluent via irrigation and groundwater infiltration is designed to keep treated wastewater out of the Provo River, which has suffered water quality impairments and has a TMDL for phosphorus.

Groundwater monitoring wells installed in 2012 in the area around the RIB and treatment lagoons have been monitored quarterly ever since their installation. Monitoring results from 2018 provide further evidence of leakage from the southern lagoons with elevated concentrations of inorganic nitrogen, phosphorus, and TDS in shallow (19–25 feet) groundwater. Although the pathway into the groundwater for effluent applied via sprinkler to agricultural crops in south fields is less direct, SWCA's sample results from the South Fields #2 well (south of the irrigated field) also showed elevated concentrations of TDS, nitrate, phosphorus, and chloride.

SWCA used water use, HVSSD effluent, and population data from 2017 to generate rough estimates of wastewater loading to the aquifer. SWCA used an annual recharge of 758 acre-feet/year from the treatment lagoons (572 acre-feet/year) in seepage from the southern lagoons plus 186 acre-feet/year (excess from irrigation) and an average discharge concentration of 16 mg/L of dissolved organic nitrogen (DIN) (Gunn 2020a). Additionally, SWCA estimated that 447 acre-feet of effluent from the mechanical plant (average of 5 mg/L DIN) is recharged to the aquifer via the RIB per year. This combined 1,205 acre-feet/year of effluent from the HVSSD plant (see Section 5.1.5) is estimated to add 17,716 kg of DIN into the groundwater aquifer, most of which is assumed to end up as nitrate in the aquifer. Given that a portion of the nitrogen waste load is removed during treatment and additional effluent from the lagoons is taken up by crops, the total estimated load to the aquifer only equates to roughly 2.8 g per person per day (based on an estimated 17,309 people in 2017). This represents only 16.5% of the 17 g of nitrogen that each person is estimated to contribute to raw wastewater. The remaining 72.5% is assumed to be removed during treatment or taken up by crops during the land application of wastewater as irrigation.

For comparison, SWCA estimated the total loading to groundwater from the estimated 14,162 people (based on the estimate of 45% of the population on septic) contributing to roughly 3,280 septic systems (2018 estimate) throughout the county. Although some nitrogen (ammonia) is contained with the septic system, SWCA estimates that 116,733 kg of nitrate may be discharged into the groundwater aquifer from septic systems. This would equate to 22.5 g per person per day (based on 14,162 people in 2017), which is eight times as much as is estimated to enter per person per day from the centralized wastewater treatment facility (sewer system). SWCA recognizes that the estimated loading per person per day from septic is higher than the assumed 17 g/person/day used in the mass-balance. This estimate and the mass-balance are largely independent and rely on different water use data, yet they both resulted in similar estimates of loading per person/day. The margin of error for these calculations is likely high given the simplicity of the calculations; however, they provide compelling evidence that the centralized HVSSD facility combined with land application reduces nitrate loading to the aquifer significantly. Although SWCA was not able to obtain estimates of nitrogen removal from HVSSD, the effluent monitoring data clearly indicate nitrogen removal, which is widely documented in monitoring from other facilities and in literature (EPA 2011).

8 FUTURE GROWTH

The Wasatch County Planning Department uses the MAG projected population data for TAZs (MAG 2020) and population projections from the Ken C. Gardner Policy Institute (University of Utah 2020) to inform their planning decisions. These data predict that the population of Wasatch County will increase rapidly from 35,713 in 2020 to 48,168 in 2030 at an average rate of 3%. This growth is predicted to slow slightly to an average of 2% between 2030 and 2050 when the population is projected to be 68,904. Although MAG has attempted to allocate this growth into the various TAZs within Wasatch County, county planners are not certain as to exactly where the sewer network will expand as the growth occurs. As stated previously, WCHD estimates that as much as 85% of the development within the Wasatch County could be serviced by the sewer network, although some level of septic development is expected to continue. WCHD has authority to manage the density of septic development in the un-sewered portions of Wasatch County.

SWCA's analysis of nutrient loading to the aquifer from wastewater inputs indicates that as much as 6.5 times more nitrate may be contributed via septic systems per person than via the centralized wastewater treatment facility. The existing septic density regulation and the general pattern of septic growth have distributed this septic wastewater nutrient load over a broad area. Conversely, the existing HVSSD wastewater facility discharges treated effluent to a relatively small area in the South Fields area. As population growth occurs, HVSSD is expected to expand its capacity and aims to continue discharging treated effluent via RIB and land application (as irrigation water) in the South Fields area (Gunn 2020b). Additionally, in August 2020, the JSSD wastewater treatment plant is expected to go online and will treat a portion of the wastewater that is currently being sent to the HVSSD.

The JSSD plant is permitted to discharge primarily to the Timpanogos Canal, which delivers Provo River water to agricultural and residential water users throughout the Heber Valley. The secondary discharge location would be the Wasatch Canal and subsequently into Rock Ditch, which also convey Provo River water for secondary use within the valley. The third and fourth options for discharge would be to ditches that drain to the Provo River. Although the JSSD plant has yet to treat and discharge wastewater, the discharge permit (UPDES No. UT0021628) includes effluent limitations for phosphorus that are similar to measured concentrations of phosphorus in the Provo River. The discharge permit does not include effluent limits for nitrogen, although it does require self-monitoring of nitrite, nitrate, and ammonia. The design flow rate for the facility of 1 million gallons per day (roughly 1.85 cfs) would not be met initially and would represent a small fraction of the total flow in the Timpanogos Canal (up to 75 cfs). The potential for discharge of JSSD effluent into groundwater is via seepage loss from the canals and ditches, recharge from land application as irrigation water, and from recharge from the Provo River. Because of the low expected effluent concentrations and the small proportion of the discharge that would be expected to enter into groundwater, loading from the JSSD effluent discharge is not expected to be a significant source of nitrate to the aquifer.

The mass-balance model described in Section 7.1.3 indicates that average concentrations of nitrate in the Heber Valley aquifer will not increase by an additional 1 mg/L until 5,200 new septic systems are added to the valley. As stated in the assumptions, this does not include increases in other sources of nitrate to the aquifer, which include additional discharge from the centralized wastewater plants among other sources. Therefore, it is possible that nitrate concentrations could increase by 1 mg/L before 5,200 additional septic tanks are added. WCHD expects the proportion of future growth on the sewer network to be much greater than the portion of the growth on septic. For this projection, SWCA assumes that septic systems would represent 15% of future growth (the population in Wasatch County on septic is roughly 36%). If SWCA continues to assume an average of 3.5 individuals per household, 5,200 new septic systems would represent 18,200 individuals. In reviewing Ken C. Gardner Policy Institute's population projections through the year 2065, additional population growth (beyond the 2020 population) by 2065 would be 46,306 people. Of these 46,306 individuals, we assume that 6,946 (15%) individuals would be supported by 1,985 (based on 3.5 individuals per system) septic systems. Therefore, we would not expect to approach an increase in 1 mg/L of nitrate in groundwater due to septic discharge for at least 45 years.

8.1 Implications of the Increase in Residential Development Connected to the Sewer System

As the population of Wasatch County continues to grow, an increasing portion of the development is expected to be connected to the sewer network. In many places this development will likely consist of an increase in impervious areas and a decrease in the total area of agricultural/irrigated area. The growth of the sewer network and proportion of the county that is connected to the sewer system will dramatically change the distribution wastewater discharge throughout the county and will also affect groundwater recharge. Locally, in the immediate area of individual houses and developments (subdivisions), it is expected that the potential for contamination is reduced, with a reduction in pathways for infiltration of contaminants to groundwater. Without a septic system to deliver wastewater into the ground, the only pathways for contamination would be via infiltration through permeable areas such as lawns, landscapes, naturally vegetated areas, or nearby drainages. Therefore, potential contaminants in these localized areas may include nutrients, pesticides, and herbicides from yard care products; chloride from road salts; and oils, gas (VOCs), and other fluids from vehicles. However, the potential for contamination from these contaminants is not unique to developments connected to the sewer network. All residential developments have the potential to discharge these pollutants to groundwater, and SWCA's sampling program attempted to target and capture this contamination where it may exist. SWCA did not collect any samples that had pesticide/herbicide concentrations above the detection limit and very few samples with VOC concentrations above detection limits. SWCA did observe elevated concentrations of nutrients, chloride, and TDS in numerous locations, but are unable to attribute the sources specifically to non-septic development.

The most direct pathway of groundwater contamination from residential development is from septic systems that dispose wastewater from human waste and graywater (from sinks, washing machines, etc.) into leach fields underneath the ground surface. By delivering this wastewater to centralized facility that employs treatment processes to remove a portion of the contaminant before discharging the treated effluent, smaller loads are discharged into the environment in a specific area (as described in Section 7.2). Most of this effluent will be used as secondary water to either irrigate commercial crops (for livestock feed) or residential landscapes. Given this, there is much less potential for groundwater contamination compared to wastewater discharge via septic systems distributed throughout the county. Although effluent from HVSSD is discharged to a relatively small area compared to the wide distribution of septic systems, the treatment process and discharge via RIB and land application (for crop uptake) appear to be minimizing impacts to the South Fields and Charleston areas of the aquifer.

9 DISCUSSION AND RECOMMENDATIONS

9.1 Potential Methods of Managing or Regulating Aquifer Water Quality

The tools developed during the study have a common goal: to estimate anticipated changes in aquifer water quality due to the addition of nitrogen from wastewater and other anthropogenic sources. A variety of regulatory approaches could be implemented to manage aquifer water quality using these tools. The management approaches in this section have two aspects in common:

1. Ultimately, although the management approaches may use different metrics, all of these methods ultimately focus on managing the total amount of nitrogen in the aquifer.
2. All of the following methods require selecting a specific limit on the allowable amount of aquifer degradation, as measured by the concentration of nitrate in the aquifer (mg/L).

Hydrologic characteristics vary across the basin, as does the pattern of current and future development. All of the approaches described in this section could be applied to Wasatch County as a whole or tailored to certain areas. The study focused on two study areas to inform the analysis: Lake Creek planning area and the Heber Valley aquifer area. Other study areas could be developed in a similar manner. Whether applied to Wasatch County as a whole or tailored to certain areas, the approaches here are based on average conditions. Site-specific conditions could still lead to localized areas of increased nitrate, which would not be depicted by these approaches. This potential is mitigated by well construction and spacing requirements, and by minimum requirements for septic tank construction.

SWCA has identified the following four potential approaches to managing septic development in Wasatch County as it impacts groundwater quality, and each is described in more detail below.

1. Management by monitoring nitrate concentration
2. Management by limiting septic system density
3. Management by limiting nitrate load
4. Hybrid approach: management by limiting septic system density, but allowing site-specific load exceptions

9.1.1 *Management by Monitoring Nitrate Concentration*

9.1.1.1 BASIC APPROACH

Under this management approach, a limit would be set on the average nitrate concentration allowable in the aquifer. A robust monitoring plan would need to be developed to consistently sample a suite of sentinel wells. Development could occur unrestricted until concentrations exceeded an action level.

9.1.1.2 ADVANTAGES

- Development would be unhindered until actual impacts seen.

9.1.1.3 DISADVANTAGES

- Ongoing cost of monitoring
- Delay in response
- Potential for natural variation to cause confusion

9.1.2 *Management by Limiting Septic System Density*

9.1.2.1 BASIC APPROACH

Under this management approach, an acceptable limit of degradation (i.e., the concentration of nitrate in the aquifer) would be selected, the allowable number of septic systems within Wasatch County to stay below this concentration would be calculated, and the average density of non-sewered development (acres/septic system) would be calculated. No development could occur at a higher density than this limit. This approach is similar to the approach currently in place.

9.1.2.2 ADVANTAGES

- It is not a significant departure from existing lot size requirements in the county (5 acres per septic system).
- It does not take into account sewered development or other land uses with little potential to discharge nitrogen to groundwater (such as parking lots or open space), so it would be a conservative approach (i.e., in general overestimating the load, not underestimating it).
- Sewered development and other land uses with the potential to discharge nitrogen to groundwater (such as agriculture) could be added into the mass-balance model. This would be most important on a basin-wide scale. The use of sewer and wastewater treatment is a mechanism that removes substantial amounts nitrogen from the overall system, greatly reducing the nitrogen load available to enter the environment via surface water or groundwater discharge of wastewater. At the same time, however, the remaining nitrogen is concentrated at the point of discharge. This concentrated load is not an issue for most of the land in the Heber Valley, but still contributes to the basin-wide nitrogen balance.

9.1.2.3 DISADVANTAGES

- Lack of flexibility in development, no mechanism for exceptions.
- Portions of Wasatch County (such as the Timberlakes subdivision) would not follow the density recommendation because they were permitted before density regulations were developed.

9.1.3 *Management by Limiting Nitrate Load*

9.1.3.1 BASIC APPROACH

Under this management approach, an acceptable limit of degradation (i.e., the concentration of nitrate in the aquifer) would be selected, the allowable load of nitrate within the aquifer to stay below this calculation would be calculated, and the typical nitrate load from a septic system would be calculated. The health department would then be able to approve lot development as long as sufficient load remained available.

9.1.3.2 ADVANTAGES

- Because it is based on load, this approach also allows different nitrogen-reduction or removal technologies to be considered.
- New septic systems could be approved at higher densities as long as their cumulative nitrate load into the planning area is not exceeded.
  - o This would better take into account areas such as Timberlakes that will add new septic systems at a pre-permitted density.

9.1.3.3 DISADVANTAGES

- Requires detailed tracking by the health department against the total aquifer load
- Leads to a first-come, first-serve mentality
- Could lead to areas of high-density septic systems with localized high concentration plumes of nitrate and other pollutants from wastewater (hot spots)

9.1.4 *Hybrid Approach: Management by Limiting Septic System Density, but Allowing Site-Specific Load Exceptions*

9.1.4.1 BASIC APPROACH

Under this management approach, an acceptable limit of degradation (i.e., the concentration of nitrate in the aquifer) would be selected, the allowable number of septic systems within Wasatch County to stay below this concentration would be calculated, and the average density of non-sewered development (acres/septic system) would be calculated. This is a hybrid approach in that instead of having a blanket limit on development at a higher density than the established limit, procedures could be put in place for a site-specific evaluation of nitrogen load. To obtain an exception, a permittee would need to submit a site-specific analysis to demonstrate that the overall nitrogen load would remain equal to or less than that from septic systems at average density.

9.1.4.2 ADVANTAGES

- Minimum lot size would be calculated based on the total area and not just the acreage of land available for septic system build-out, so this approach would be conservative (i.e., always overestimating the load, not underestimating it).
- By allowing for exceptions based on load calculations, flexibility is introduced, and nitrate reduction or removal technologies are encouraged.
- An automatic reduction can also be built in—i.e., the load has to be no more than 90% of that from septic systems at average density. This provides a basic mechanism to give a margin of error.

9.1.4.3 DISADVANTAGES

- Requires human power to define requirements of and review site-specific studies

9.2 Septic System Development and Maintenance Recommendations

Density recommendation should be implemented with different consideration of the various portions of the aquifer and background nitrate concentrations. For example, background concentrations in the Lake Creek planning area are significantly higher than average concentrations throughout the valley. SWCA suggests that continuing to follow the general density recommendation of 5 acres per septic system should preserve the overall concentration of nitrate in the Heber Valley aquifer below 3 mg/L. However, background concentrations of nitrate in some locations of the aquifer (such as Lake Creek) are already above 3 mg/L and therefore septic development may need to be curtailed if additional degradation beyond 3 mg/L is not deemed acceptable by WCHD and the WCHD Board of Health.

Although properly constructed on-site wastewater disposal systems generally do not require significant upkeep, they do require periodic maintenance to keep them functioning properly. The1994 HAL report recommends that WCHD initiate a maintenance permit program that would require annual inspections be performed for septic tank system owners. To SWCA's knowledge, no such permit program was implemented by WCHD, and greater than expected loading of contaminants to groundwater may be caused by old and improperly functioning septic systems.

SWCA suggests that WCHD implement regulations for septic systems to be inspected annually and pumped every 3 years to ensure that wastewater is being treated and disposed properly. This is particularly important for the existing septic systems in Wasatch County, some of which may be old and beyond their expected lifespan or occurring a higher density such as in the Timberlakes area. It is possible that some of the elevated concentrations of contaminants observed in SWCA's sampling efforts are a result of improperly functioning septic systems, and regular inspections and maintenance would help to minimize loading to the aquifer.

9.3 Continued Groundwater Quality Monitoring

One of WCHD's main objectives in completing the study was to conduct groundwater monitoring to establish a baseline dataset for future monitoring. As the population increases, development continues in Wasatch County, and particularly if WCHD decides to modify their septic density regulations, SWCA recommends continued monitoring to ensure that potential unanticipated changes to water quality do not go unnoticed. With up-to-date water quality information, WCHD will be able to confidently make management decisions that would not compromise the water quality of groundwater.

The study has identified areas of concern with respect to groundwater quality degradation. Additionally, it is important to continue to monitor wells that may represent background concentrations in the aquifer to measure the rate of change for water quality. SWCA recommends that these wells be monitored at least every 3 to 5 years (with seasonal or duplicate samples) moving forward. Additionally, as new wells are developed within the study area, they may present opportunities for monitoring in locations that were not available for the study. WCHD may also consider developing shallow groundwater monitoring wells to investigate the contamination pathway from septic and surface activities to deeper portions of the aquifer. Data from the study may indicate a relationship between depth and concentration of contaminants, and SWCA was unable to identify shallow monitoring wells to sample. Potential locations for shallow monitoring wells might be in the Lake Creek planning area in the area between the Lake Creek #2 and #1 wells, and in the South Fields area to the east or north of the South Fields #2 well. These monitoring wells could be developed as nested wells with multiple screened depths between roughly 15 and 100 feet below ground surface. Additionally, WCHD may consider identifying other private wells for monitoring near areas considered to be potential contamination hotspots, such as Lake Creek and South Fields.

SWCA has developed a suggested list of potential wells for continued monitoring, which include wells that are sampled by USGS. At these wells (indicated with a cadastral name in addition to the SWCA site description), USGS collects water level measurements and conventional parameters on an annual basis. Additionally, USGS has periodically assessed non-conventional water quality parameters such as pesticides or personal care product and pharmaceutical compounds, although the frequency of collection of these parameters is not apparent. Suggested wells for future monitoring are as follows:

- Lake Creek #1/(D-4-5) 3dcc-1
- Lake Creek #2/(D-4-5) 4ccb-1
- Duggin Well

- South Fields #1 (Giles Well)
- South Fields #2/(D-4-4) 12dcc-1
- Carlson Well
- North Fields #1
- North Fields #2
- Charleston Town Well

Future groundwater monitoring should take an approach to identifying parameters for analysis similar to the study. SWCA recommends continuing to monitor the four core parameters (TDS, nitrate, phosphorus, and chloride) so that comparison to baseline conditions established during the study can be performed.

In addition, SWCA suggests periodically including a screening-level assessment of additional parameters linked to specific sources. Although SWCA did not discover contamination from the screening of VOCs and personal care products, this screening effort should be repeated roughly every 5 years. Screening for additional and/or non-conventional parameters such as major cations and anions, pesticides, VOCs, or metals should be executed at wells that were not targeted during this investigation. A probabilistic design for future groundwater screening efforts may be more beneficial than a targeted approach because it would ensure an unbiased assessment of changing conditions across a large area (Dressing et al. 2016). A probabilistic design means the wells targeted for screening would be randomly selected. A probabilistic (random) screening approach would be especially important in screening for compounds that were not detected during SWCA sampling efforts (compounds such as pesticides, VOCs, and personal care products and pharmaceuticals). As discussed in Section 3.7, negative test results for these compounds may not be deterministic for reasons such as sample location bias. Periodically collecting samples from random wells throughout the Heber Valley aquifer and screening samples for compounds like pesticides, VOCs, and personal care products and pharmaceuticals may mitigate sample location bias and add additional support to SWCA's findings about these classes of compounds.

10 SUMMARY AND CONCLUSIONS

As part of Phase 2 of the Wasatch County groundwater study, SWCA documented current water quality conditions of the Heber and Round Valley aquifers and analyzed trends over the past approximately 20 years. The areas of elevated concentrations of common groundwater contaminants were found to be the Lake Creek and Center Creek area, in addition to the South Fields and Charleston area. Concentrations were generally greater at shallower depths in the alluvial aquifer, but the correlation between concentration and depth was not strong. Statistically significant upward trends were found for TDS, nitrate, phosphorus, and chloride at wells that have been consistently sampled by the USGS since ca. 1998. Elevated concentrations of pesticides, VOCs, and anthropogenic markers were not found most wells. An analysis of major ions did not indicate significant differentiation in water types geographically throughout the study area, between wells constructed in the alluvium versus bedrock, or between surface water and groundwater samples. Two areas with elevated nitrate—Lake Creek and South Fields—are notable that they have both high nitrate values and elevated sodium-chloride signatures. This suggests that these wells may be influenced by surface runoff or shallow groundwater, possibly through poor surface construction or a nearby recharge source.

SWCA used the FREEWAT software package to create a MODFLOW model for the Heber Valley, excluding Round Valley (titled the 2020 Heber Valley Groundwater Model or the HVGM2020 model). The model is most closely calibrated to observed water levels in the central and lower basin

(RMSE/Range of 4%), and less well calibrated eastern basin (RMSE/Range of 11%). The model successfully replicates the general aquifer dynamics and flow paths but does not adequately replicate some water budget components.

Based on the results, SWCA estimates that groundwater travel time through the aquifer can range as high as 24 feet per day, with a best-controlled estimate (based on the eastern basin) of roughly 3 feet per day. SWCA used mass-balance modeling to estimate the allowable number of septic systems in the study area, focusing on the Lake Creek planning area and then the entire aquifer. The results for the analysis conducted for the Lake Creek planning area are listed here:

- For the baseline scenario, a lot size of 3.6 acres per septic system may result in a 1-mg/L increase in nitrate concentration.
- If 30% of the land in the Lake Creek planning area is on sewer, a septic system density of 2.94 acres/septic system may increase nitrate by 1 mg/L
- If 90% of the land in the Lake Creek planning area is on sewer, a septic system density of 1.72 acres/septic system may increase nitrate by 1 mg/L.

For the entire Heber Valley, SWCA estimates that nitrate concentration could increase by 1 mg/L if 5,200 septic tanks are added to the valley. SWCA estimates that nitrate from septic systems may stay below 3.0 mg/L if lot sizes are 5 acres per septic system. SWCA estimated the amount of nitrogen that is removed by wastewater treatment and land application and found that more than 70% of nitrogen compared to septic tanks may be removed from the system. Mathematically, removal of this nitrogen load through treatment suggests a high density of septic tanks could be placed in the remaining area while still maintaining water quality. High-density septic tank development violates several assumptions of the mass-balance model and should be assessed with care.

The tools developed during the study have a common goal: to estimate anticipated changes in aquifer water quality due to the addition of nitrogen from wastewater. A variety of regulatory approaches could be implemented to manage aquifer water quality using these tools. SWCA presented several potential management approaches for consideration by WCHD including 1) management by nitrate concentration, 2) management by limiting septic system density, 3) management by limiting nitrate load, 4) a hybrid approach with management by limiting septic system density but allowing site-specific exceptions. The data, model predictions, and recommendations provided in this report are meant to serve as a resource for WCHD as they manage the groundwater aquifer into the future.

11 LITERATURE CITED

ASTM. 2018. ASTM D5981 / D5981M-18, Standard Guide for Calibrating a Groundwater Flow Model Application. West Conshohocken, Pennsylvania: ASTM International. Available at: www.astm.org.

Baker, C.H., Jr., 1970. *Water resources of the Heber-Kamas-Park City area, north-central Utah.* Technical Publication No. 27. Utah Department of Natural Resources.

Bauman, B.J., and W.M. Schafer. 1985. Estimating groundwater quality impacts from on-site sewage treatment systems. In *On-Site Wastewater Treatment: Proceedings of the Seventh International Symposium on Individual and Small Community Sewage Systems*, pp. 285–294. American Society of Agricultural Engineers Publication 07-85. St. Joseph, Michigan: American Society of Agricultural Engineers.

Bishop, C.E., J. Wallace, and M. Lowe. 2007a. *Recommended Septic Tank Soil-Absorption System Densities for the Principal Valley-Fill Aquifer, Sanpete Valley, Sanpete County, Utah Geological Survey*. Report of Investigation 259. Available at: https://ugspub.nr.utah.gov/publications/reports_of_investigations/ri-259.pdf. Accessed July 9, 2020.

———. 2007b. *Recommended Septic Tank Soil-Absorption System Densities for the Shallow Unconfined Aquifer in Cache Valley, Cache County, Utah*. Utah Geological Survey. Report of Investigation 257. Available at: https://ugspub.nr.utah.gov/publications/reports_of_investigations/ri-257.pdf. Accessed July 9, 2020.

Borsi, I, L. Foglia, M. Cannata, E. Vazquez-Sune, S. Mehl, G. De Filippis, R. Criollo, M. Ghetta, M. Cardoso, V. Velasco, J. Neumann, A. Toegl, A. Serrano, C. Riera, and R. Rossetto. *FREEWAT User Manual – Volume 0: Reference Manual*. Version 1.1.1. November 30, 2018.

Brooks, L.E., and J.L. Mason. 2005. *Hydrology and Simulation of Groundwater Flow in Cedar Valley, Iron County, Utah*. Scientific Investigations Report 2005-5170. Salt Lake City, Utah: U.S. Geological Survey. Available at: https://pubs.usgs.gov/sir/2005/5170/PDF/SIR2005_5170.pdf. Accessed January 15, 2019.

Canadell, J., R.B. Jackson, J.R. Ehleringer, H.A. Mooney, O.E. Sala, and E.-D. Schulze. 1996. Maximum Rooting Depth of Vegetation Types at the Global Scale. *Oecologia* 108:583–595.

Carreón-Diazconti, C., S. Nelson, A.L. Mayo, D.G. Tingey, and M. Smith. 2003. *A Mixed Groundwater System at Midway, UT: Discriminating Superimposed Local and Regional Discharge.* Journal of Hydrology. 273. 119-138. 10.1016/S0022-1694(02)00359-1. Available at: https://www.researchgate.net/publication/223370102_A_Mixed_Groundwater_System_at_Midway_UT_Discriminating_Superimposed_Local_and_Regional_Discharge. Accessed January 15, 2019.

Central Utah Water Conservancy District. 2019. Diversions from the Provo River, 2004-2019. Excel file Received from Central Utah Water Conservancy District on September 9, 2019. Available on file at SWCA, Salt Lake City, Utah.

Davis, S.N., D.O. Whittemore, and J. Fabryka-Martin. 1998. *Uses of Chloride/Bromide Ratios in Studies of Potable Water. Groundwater, Volume 36, No. 2. March-April 1998.* Available at: http://riogrande.ees.nmt.edu/outside/courses/hyd558/downloads/Set_20_Cl-Br/Davis1998.pdf. Accessed July 29, 2020.

Desert Rose Environmental. 2016. *2015 Water Quality Implementation Report*. Park City, Utah. Available at: https://www.provoriverwatershed.org/reporting.html. Accessed January 15, 2019.

———.2018. *2018 Water Quality Implementation Report for the 2017 Water Year. Prepared for Wasatch County and Provo River Watershed Council*. Available at: https://www.provoriverwatershed.org/uploads/4/4/8/0/44802125/2018_water_quality_implementation_report.pdf. Accessed October 21, 2019.

———.2020. *2020 Water Quality Implementation Report for the 2019 Water Year*. Prepared for Wasatch County and Provo River Watershed Council. Available at: https://www.provoriverwatershed.org/uploads/4/4/8/0/44802125/2020_wq_implementation_report_draft.pdf. Accessed July 21, 2020.

Dressing, S.A., D.W. Meals, J.B. Harcum, J. Spooner, J.B. Stribling, R.P. Richards, C.J. Millard, S.A. Lanberg, and J.G. O'Donnell. 2016. *Monitoring and Evaluating Nonpoint Source Watershed Projects*. Washington, DC: U.S. Environmental Protection Agency, Office of Water Nonpoint Source Control Branch. Available at: https://www.epa.gov/sites/production/files/2016-06/documents/nps_monitoring_guide_may_2016-combined_plain.pdf. Accessed July 20, 2020.

Fenech, C., L. Rock, K. Nolan, J. Tobin, A. Morrissey. 2012. The Potential for a Suite of Isotope and Chemical Markers to Differentiate Sources of Nitrate Contamination: A Review. *Journal of Water Research* 46:2023–2041. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0043135412000760. Accessed July 29, 2020.

Feth, J.H., D.A. Barker, L.G. Moore, R.J. Brown, and C.E. Veirs. 1966. *Lake Bonneville: Geology and Hydrology of the Weber Delta District, Including Ogden, Utah.* Geological Survey Professional Paper 518. Prepared cooperatively by the U.S. Geological Survey and the U.S. Bureau of Reclamation with the cooperation of the Utah State Engineer. Available at: https://pubs.usgs.gov/pp/0518/report.pdf. Accessed October 1, 2019.

Glassmeyer, S.T., E.T. Furlong, D.W. Kolpin, A.L. Batt, R. Benson, J.S. Boone, O. Conerly, M.J. Donohue, D.N. King, M.S. Kostich, H.E. Mash, S.L. Pfaller, K.M. Schenck, J.E. Simmons, E.A. Varughese, S.J. Vesper, E.N. Villegas, and V.S. Wilson. 2015. Nationwide reconnaissance of contaminants of emerging concern in source and treated drinking waters of the United States. Elsevier. *Science of the Total Environment* 581–582:909–922. Available at: https://ac.els-cdn.com/S0048969716326894/1-s2.0-S0048969716326894-main.pdf?_tid=3a278c11-4bb0-4456-a887-9370acfbd5eb&acdnat=1551374342_223b57d2bd1b983f7e0cb6ef366c42fa. Accessed January 15, 2019.

Gunn, D. 2020a. District Manager. Heber Valley Special Services District (HVSSD). Operating Reports: 2016–2020. Personal communication, July 17, 2020.

———. 2020b. District Manager. Heber Valley Special Services District (HVSSD). Plans for future growth. Personal communication, July 17, 2020.

Hansen, Allen & Luce, Inc. (HAL). 1994. *Hydrogeologic/Water Quality Study, Wasatch County, Utah.* Midvale, Utah: Salt Lake Area Office.

Helsel, D.R., and R.M. Hirsch. 2002. *Statistical Methods in Water Resources.* Techniques of Water Resources Investigations of the United States Geological Survey. Book 4, Hydrologic Analysis and Interpretation. U.S. Geologic Survey. Available at: https://pubs.usgs.gov/twri/twri4a3/pdf/twri4a3-new.pdf. Accessed January 15, 2019.

Hill, R.W., and S. Williams. 2002. *Sprinklers, Crop Water Use, and Irrigation Time Rich County*. Utah State University Extension Electronic Publishing. Available at: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1175&context=extension_histall. Accessed September 24, 2019.

Hill, R.W., J. Burdette Barker, and C.S. Lewis. 2011. *Crop and Wetland Consumptive Use and Open Water Surface Evaporation for Utah*. Utah State University. Available at: https://extension.usu.edu/irrigation/ou-files/ez-plug/uploads/Crop_and_Wetland_Water_Use_Hill_Baker_Lewis.pdf. Accessed September 25, 2019.

Inkenbrandt, P. 2019. *Hydrogeology of Round Valley, Wasatch County, Utah*. Utah Geologic Survey. Report of Investigation 279. Available at: https://ugspub.nr.utah.gov/publications/reports_of_investigations/ri-279.pdf. Accessed July 22, 2020.

Jeppson, R.W., J. Maclean, C.G. Clyde, S. Korom. 1991. *Studies Related to Nutrients Entering Groundwater From the Heber Valley Sewer Farm and Dairies.* Utah Water Research Laboratory. Utah State University. Available at: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1290&context=water_rep. Accessed January 15, 2019.

Jordan, J.L. 2017. *Groundwater Conditions and Water Quality Degradation near Monroe City, Utah.* Utah Geological Survey. Prepared for Central Utah Public Health Department.

Jordan, L.J., and W.W. Sabbah. 2012. *Hydrogeology and Simulation of Groundwater Flow in Cedar Valley, Utah County, Utah.* Special Study 145. Utah Geological Survey. Available on file at SWCA Environmental Consultants.

Kaplan, O.B. 1988, Septic systems handbook: Chelsea, Michigan, Lewis Publishers, Inc., 290 p.

Katz, B.G., S.M. Eberts, and L.J. Kauffman. 2011. Using Cl/Br Ratios and Other Indicators to Assess Potential Impacts on Groundwater Quality from Sewer Systems: A Review and Examples from Principal Aquifers in the United States. *Journal of Hydrology* 397(3–4):151–166. Available at: https://www.sciencedirect.com/science/article/pii/S0022169410007134. Accessed July 29, 2020.

Lowe, M. 1995. *Hydrogeology of Western Wasatch County, Utah, with Emphasis on Recharge-area Mapping for the Principal Valley-Fill Aquifers in Heber and Round Valleys.* Environmental and Engineering Geology of the Wasatch Front Region. Utah Geologic Survey. Publication 24.

Lowe, M., and M. Butler. 2003. *Groundwater Sensitivity and Vulnerability to Pesticides, Heber and Round Valleys, Wasatch County, Utah.* Utah Geologic Survey. In cooperation with Utah Department of Agriculture and Food. Available at https://ugspub.nr.utah.gov/publications/misc_pubs/mp-03-5.pdf. Accessed January 15, 2019.

Lowe, M., J. Wallace, and C.E. Bishop. 2000. *Analysis of Septic Tank Density for Three Areas in Cedar Valley, Iron County, Utah. A Case Study for Evaluations of Proposed Subdivisions in Cedar Valley*. Utah Geological Survey. Water Resources Bulletin 27. Available at: https://ugspub.nr.utah.gov/publications/water_resources_bulletins/wrb-27.pdf. Accessed July 9, 2020.

Lowe, M., J. Wallace, and W. Sabbah. 2010. *Science-Based Land-Use Planning Tools To Help Protect Ground-Water Quality, Cedar Valley, Iron County, Utah.* Utah Geological Survey. Special Study 134. Available at: https://ugspub.nr.utah.gov/publications/special_studies/ss-134.pdf. Accessed July 24, 2020.

Marston, T. 2017. *Water Resources of Parowan Valley, Iron County, Utah.* U.S. Geological Survey. Scientific Investigations Report 2017-5033. Available at: https://pubs.usgs.gov/sir/2017/5033/sir20175033.pdf. Accessed January 15, 2019.

McDonald, M.G., and A.W. Harbaugh. 1988. *A Modular Three-Dimensional Finite-Difference Groundwater Flow Model.* Techniques of Water Resource Investigations of the U.S. Geological Survey, Chapter A1. Available at: https://pubs.usgs.gov/twri/twri6a1/pdf/TWRI_6-A1.pdf. Accessed January 15, 2019.

Miller, C. 2019. State of Utah water use data. Utah Division of Water Resources. Personal communication (email), February 11, 2019.

Minnesota Department of Health. 2013. Sulfonamide Antibiotics in Drinking Water. Environmental Health Division, St. Paul Minnesota. Available at: https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/sulfamethinfosht.pdf. Accessed July 14, 2020.

———.2014. Bisphenol A in Drinking Water. Environmental Health Division. St. Paul, Minnesota. Available at: https://www.health.state.mn.us/communities/environment/risk/docs/guidance/gw/bpainfosheet.pdf. Accessed July 14, 2020.

Mountainland Association of Governments (MAG). 2020. Wasatch County Socioeconomics. Available at:https://mountainland.maps.arcgis.com/apps/MapSeries/index.html?appid=086c48901e00469d85f58887d2c07bf5. Accessed July 9, 2020.

National Land Cover Database. 2011. *NLCD 2011 Land Cover Conterminous United States.* U.S. Geological Survey. Available at: https://catalog.data.gov/dataset/nlcd-2011-land-cover-conterminous-united-states. Accessed January 15, 2019.

Natural Resources Conservation Service. 2017. Web Soil Survey. Available at: https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx. Accessed October 28, 2018.

Panno, S.V., K.C. Hackley, H.H. Hwang, S.E. Greenberg, I.G. Krapac, S. Landsberger, and D.J. O'Kelly. 2006. Characterization and Identification of Na-Cl Sources in Ground Water. *Groundwater* 44(2):176–187. Available at: https://ngwa.onlinelibrary.wiley.com/doi/abs/10.1111/j.1745-6584.2005.00127.x. Accessed July 29, 2020.

Pearson, R. 2019. Staff engineer, Central Utah Water Conservancy District. Personal communication (telephone call) regarding the diversion and use of irrigation water in the Heber Valley. August 13 and October 21, 2019.

PRISM Climate Group. 2019. PRISM Precipitation Data, Time Series for Individual Locations in Heber Valley, 1990 to 2018. Available at: http://www.prism.oregonstate.edu/. Accessed August 9, 2019.

PSOMAS. 2002. *Deer Creek Reservoir Drainage TMDL Study.* Prepared for Utah Division of Water Quality. Available at: https://digitallibrary.utah.gov/awweb/awarchive?type=file&item=21686. Accessed January 15, 2019.

Rayne, T.W., K.R. Bradbury, and J.K. Krause. 2018. Impacts of Rural Subdivision on Groundwater Quality: Results of Long-Term Monitoring. Groundwater. Available at: https://doi.org/10.1111/gwat.12666. Accessed January 15, 2019.

Rice, D.W., and W.W. McNab. 1998. Natural Biodegration of Organic Contaminants in Groundwater. Paper presented at the 23rd Session of the International Seminar on Planetary Emergencies, Erice, Italy, August 19–24, 1998. Available at: https://e-reports-ext.llnl.gov/pdf/234361.pdf. Accessed January 15, 2019.

Richardson, T. 2020. Wasatch County Health Department. July 2020. Personal communications (telephone call).

Roark, D.M., W.F. Holmes, and H.K. Shlosar. 1991. *Hydrology of Heber and Round Valleys, Wasatch County, Utah, with Emphasis on Simulation of Groundwater Flow in Heber Valley.* Technical Publication No. 101. U.S. Geologic Survey in cooperation with Utah Department of Natural Resources. Available at: https://waterrights.utah.gov/docSys/v920/y920/y9200009.pdf. Accessed January 15, 2019.

Stolp, B.J., L.E. Brooks, and J.E. Solder. 2017. *Hydrology and Numerical Simulation of Groundwater Flow and Streamflow Depletion by Well Withdrawals in the Malad-Lower Bear River Area, Box Elder County, Utah.* Scientific Investigations Report 2017-5011. U.S. Geological Survey. Reston, Virginia. Available at: https://pubs.usgs.gov/sir/2017/5011/sir20175011.pdf. Accessed January 15, 2019.

Sunrise Engineering, Inc. 2013. *Hydrologic Site Characterization and Groundwater Monitoring Proposed Rapid Infiltration Basins.* UDWQ EDOCS No. DWQ-2013-007361. Prepared for Heber Valley Special Services District.

SWCA Environmental Consultants (SWCA). 2019a. *Review of Background Information Related to Groundwater Quality in Wasatch County, Utah.* Prepared for Wasatch County Health Department. P#50345.

———. 2019b. *Groundwater Budget for the Heber Valley Aquifer*. Prepared for Wasatch County Water Committee. P#50345.

University of Utah. 2020. Kem C. Gardner Policy Institute: State and County Projections. Available at: https://gardner.utah.edu/demographics/population-projections/. Accessed July 20, 2020.

U.S. Bureau of Reclamation. 2012. *Jordanelle Reservoir Resource Management Plan.* U.S. Department of the Interior. Available at: https://www.usbr.gov/uc/envdocs/ea/jordanelle/Final-Jordanelle-RMP.pdf. Accessed January 15, 2019.

U.S. Census Bureau. 2019a. Quick Facts for Wasatch County, Utah. Available at: https://www.census.gov/quickfacts/wasatchcountyutah. Accessed 24, 2020.

———. 2019b. Quick Facts for Heber City, Utah. Available at: https://www.census.gov/quickfacts/fact/table/hebercityutah#. Accessed July 9, 2020.

U.S. Environmental Protection Agency (EPA). 2009. National Primary Drinking Water Regulations. EPA 816-F-09-004. Available at: https://www.epa.gov/sites/production/files/2016-06/documents/npwdr_complete_table.pdf. Accessed July 31, 2020.

———. 2002. *Onsite Wastewater Treatment Systems Manual*. EPA/625/R-00/008. https://www.epa.gov/sites/production/files/2015-06/documents/2004_07_07_septics_septic_2002_osdm_all.pdf. Accessed February 15, 2019

———. 2011. *Principles of Design and Operations of Wastewater Treatment Pond Systems for Plant Operators, Engineers, and Managers*. EPA/600/R-11/088, August 2011. Available at: https://www.epa.gov/sites/production/files/2014-09/documents/lagoon-pond-treatment-2011.pdf, accessed on July 23, 2020

———. 2016. *Quick Guide to Drinking Water Sample Collection.* Second Edition, Update. Region 8 Laboratory. September 2016. Available at: https://www.epa.gov/sites/production/files/2015-11/documents/drinking_water_sample_collection.pdf. Accessed July 23, 2020.

———. 2019. Basic Information About Nonpoint Source (NPS) Pollution. Available at: https://www.epa.gov/nps/basic-information-about-nonpoint-source-nps-pollution. Accessed January 15, 2019.

U.S. Geological Survey (USGS). 2006. *Volatile Organic Compounds in the Nation's Groundwater and Drinking Water Supply Wells - A Summary.* Fact Sheet 2006-3048. April 2006. Available at: https://pubs.usgs.gov/fs/2006/3048/pdf/fs2006-3048.pdf. Accessed January 15, 2019.

———. 2012. *Phosphorus and Groundwater: Establishing Links Between Agricultural Use and Transport to Streams.* Fact Sheet 2012–3004. Available at: https://pubs.usgs.gov/fs/2012/3004/pdf/fs20123004.pdf. Accessed January 15, 2019.

———. 2014. *Pesticides Found in Surface Waters.* Pesticide National Synthesis Project. U.S. Geological Survey Fact Sheet FS-039-97. Available at: https://water.usgs.gov/nawqa/pnsp/pubs/fs97039/sw4.html. Accessed July 21, 2020.

———. 2020. Groundwater Quality Data for USGS Wells in the Study Area. National Water Information System (NWIS). U.S. Geological Survey. Available at: https://waterdata.usgs.gov/nwis. Accessed April 7, 2020.

Utah Division of Drinking Water (DDW). 2019. Public Water System Water Monitoring Report query. Available at: https://waterlink.utah.gov/deqWater/. Accessed January 15, 2019.

Utah Department of Environmental Quality (UDEQ). 2019. Utah Environmental Interactive Map. Available at: https://enviro.deq.utah.gov/. Accessed January 15, 2019.

Utah Division of Environmental Response and Remediation. 2019. *Leaking Underground Storage Tank (LUST) Sites in Utah.* Excel file updated daily. Report retrieved on February 26, 2019. Available at: https://deq.utah.gov/environmental-response-and-remediation/lists-underground-storage-tanks-branch. Accessed February 26, 2019.

Utah Division of Water Quality (DWQ). 2016. *Utah's Final 2016 Integrated Report.* Available at: https://documents.deq.utah.gov/water-quality/monitoring-reporting/integrated-report/DWQ-2017-004941.pdf. Accessed January 15, 2019.

Utah Division of Water Resources (DWRe). 2009. 2009 Residential Water Use. Survey Results and Analysis of Residential Water Use for Seventeen Communities in Utah. Available at: https://conservewater.utah.gov/pdf/MaterialsResources/Brochures/Residential%20Water%20Use%20Brochure.pdf. Accessed July 9, 2020.

———. 2014. *Utah Lake Basin Planning for the Future; Utah State Water Plan*. Available at: https://water.utah.gov/wp-content/uploads/2019/03/UtahLake06302014A1.pdf. Accessed June 12, 2019.

———. 2017a. Water Related Land Use Statewide. 2017. Features. Available at: http://dwre-utahdnr.opendata.arcgis.com/datasets/water-related-land-use-statewide-2017-features/data. Accessed September 9, 2019.

———. 2017b. MnIReport2017 Counties. Water use and supply data for 2017 joined to spatial boundaries. 2017. Available at: http://dwre-utahdnr.opendata.arcgis.com/datasets/47afe20ccf834b07ae8a17847fde4cf2_1. Accessed September 24, 2019.

———. 2019. Historic agricultural water use data in Heber and Round Valley. Received by SWCA on February 23, 2019, by email from Utah Division of Water Resources.

Utah Division of Water Rights (DWRi). 2020. Groundwater Models. Heber Valley. Available at: https://waterrights.utah.gov/groundwater/gwmodelsview.asp#Heber. Accessed July 29, 2020.

VanBriesen, J.M., 2014. *Potential Drinking Water Effects of Bromide Discharged from Coal-Fired Electric Power Plants*. Available at: https://www3.epa.gov/region1/npdes/merrimackstation/pdfs/Comments2RevisedDraftPermit/VanBriesenReport.pdf. Accessed July 3, 2020.

Wallace, J. and M. Lowe. 1998. *The Potential Impact of Septic Tanks Soil Absorption Systems on Water Quality in the Principal Valley-Fill Aquifer, Cedar Valley, Iron County, Utah Assessment and Guidelines*. Utah Geological Survey Report of Investigation 239. Available at: https://ugspub.nr.utah.gov/publications/reports_of_investigations/ri-239.pdf. Accessed July 24, 2020.

Wallace, J., M. Lowe, J.K. King, W. Sabbah, and K. Thomas. 2012. *Hydrogeology of Morgan Valley, Morgan County, Utah.* Special Study 129. Utah Geological Survey. Utah Department of Natural Resources. Available at: https://digitallibrary.utah.gov/awweb/awarchive?type=file&item=50672. Accessed October 1, 2019.

Wasatch County Health Department (WCHD). 2018. Spatial Distribution of Septic Systems in Wasatch County, Utah. Esri ArcGIS Shapefile. Received February 22, 2019.

Wilson, J.L., and H. Guan. 2004. Mountain-Block Hydrology and Mountain-Front Recharge. Preprint of paper to be published in *Groundwater Recharge in A Desert Environment: The Southwestern United States*, edited by Fred M. Phillips, James Hogan, and Bridget Scanlon. Washington, DC: AGU.

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. 1998. *Ground Water and Surface Water, A Single Resource.* U.S. Geological Survey Circular 1139. Available at: https://pubs.usgs.gov/circ/circ1139/pdf/circ1139.pdf. Accessed July 29, 2020.

Zogorski, J.S., J.M. Carter, T. Ivahnenko, W.W. Lapham, M.J. Moran, B.L. Rowe, P.J. Squillace, and P.L. Toccalino. 2006. *Volatile Organic Compounds in the Nation's Groundwater and Drinking Water Supply Wells.* U.S. Geological Survey. Available at: https://pubs.usgs.gov/circ/circ1292/pdf/circular1292.pdf. Accessed February 15, 2019.

This page intentionally left blank.

APPENDIX A

SWCA Environmental Consultants
Field Data Measurements

Table A-1. SWCA Environmental Consultants Field Data Measurements

Sampling Location Name	Sample Date	Temperature (°C)	Specific Conductance (µS/cm)	Dissolved Oxygen (mg/L)	pH (S.U.)
Burgener Well	11/29/2018	10.46	664.00	N/A	7.39
Burgener Well	6/4/2019	10.49	701.00	5.62	7.43
Burgener Well	11/18/2019	10.48	705.00	10.51	7.34
Burgener Well	4/2/2020	9.86	749.00	14.21	7.20
Carlson Well	11/21/2018	12.22	461.00	N/A	7.70
Center Creek #1	6/12/2019	10.87	550.00	0.80	7.83
Center Creek #1	11/13/2019	10.26	578.00	5.47	7.21
Center Creek #1	4/6/2020	10.14	534.00	15.27	7.13
Center Creek #2	7/11/2019	9.42	495.00	N/A	7.20
Center Creek #2	11/13/2019	9.24	569.00	5.74	7.46
Center Creek #2	4/2/2020	8.04	490.00	17.85	7.05
Center Creek near Center Creek Road (5910190)*	11/18/2019	4.48	333.00	12.50	8.67
Charleston #1	7/11/2019	10.83	495.00	N/A	7.48
Charleston #1	4/2/2020	10.35	504.00	15.86	7.39
Charleston Town Well	11/21/2018	10.25	538.00	N/A	7.50
Charleston Town Well	6/4/2019	10.88	549.00	5.61	7.50
Charleston Town Well	11/14/2019	10.70	566.00	5.48	7.29
Charleston Town Well	4/2/2020	10.97	546.00	19.02	7.33
Daniel #1	6/12/2019	11.03	489.00	1.73	7.58
Daniel #1	11/19/2019	10.86	693.00	8.17	7.49
Daniel #1	4/2/2020	9.12	643.00	9.97	7.63
Daniel Creek above First Diversion (5913540)*	11/19/2019	4.80	629.00	10.78	8.26
Duggin Well	11/29/2018	10.54	582.00	N/A	7.17
Duggin Well	6/5/2019	10.89	597.00	4.58	7.23
Duggin Well	11/14/2019	10.92	606.00	5.74	7.07
Duggin Well	4/2/2020	10.06	632.00	15.17	7.10

Sampling Location Name	Sample Date	Temperature (°C)	Specific Conductance (µS/cm)	Dissolved Oxygen (mg/L)	pH (S.U.)
Farnsworth Well	11/21/2018	10.60	651.00	N/A	7.37
Farnsworth Well	4/2/2020	10.46	633.00	17.39	7.23
Heber Hospital Well/(D-4-5) 5abb-2	11/21/2018	13.84	359.00	N/A	7.67
Heber Hospital Well/(D-4-5) 5abb-2	6/5/2019	13.45	364.00	3.90	7.71
Heber Hospital Well/(D-4-5) 5abb-2	11/18/2019	13.74	358.00	10.07	7.68
Heber Hospital Well/(D-4-5) 5abb-2	4/6/2020	13.87	353.00	9.96	7.48
Heber Lagoons West (Fish Hatchery)	6/5/2019	13.25	534.00	3.42	7.50
Heber Lagoons West (Fish Hatchery)	11/18/2019	12.72	497.00	7.92	7.64
Heber Lagoons West (Fish Hatchery)	4/3/2020	12.84	500.00	6.86	7.57
Heber Valley Hills Well	11/21/2018	12.69	369.00	N/A	7.37
Heber Valley Hills Well	6/5/2019	12.79	374.00	4.47	7.47
Heber Valley Hills Well	11/18/2019	12.59	376.00	11.59	7.35
Heber Valley Hills Well	4/6/2020	12.55	370.00	10.94	7.29
Lake Creek #1/(D-4-5) 3dcc-1	6/12/2019	11.80	666.00	1.48	7.00
Lake Creek #1/(D-4-5) 3dcc-1	6/12/2019	11.80	666.00	1.48	7.00
Lake Creek #1/(D-4-5) 3dcc-1	11/13/2019	11.40	641.00	6.27	7.60
Lake Creek #1/(D-4-5) 3dcc-1	4/3/2020	10.64	611.00	7.32	7.02
Lake Creek #2/(D-4-5) 4ccb-1	6/5/2019	11.25	481.00	3.89	6.89
Lake Creek #2/(D-4-5) 4ccb-1	11/14/2019	11.04	508.00	6.42	6.83
Lake Creek #2/(D-4-5) 4ccb-1	4/6/2020	10.97	487.00	10.82	6.75
Lake Creek ab Timberlakes Development*	6/12/2019	7.83	173.00	9.32	8.60
Lake Creek ab Timberlakes Development*	11/13/2019	0.50	365.00	7.23	8.71
Lake Creek ab Timberlakes Development*	6/2/2020	12.50	216.00	9.50	8.60
Lake Creek below Timberlakes Development (4997070)*	6/12/2019	10.49	186.00	9.25	8.51
Lake Creek below Timberlakes Development (4997070)*	11/13/2019	2.53	11580.00	7.35	9.47
Lake Creek below Timberlakes Development (4997070)*	4/6/2020	3.67	336.00	13.76	8.50
Main Creek ab Girl Scout Camp (5916925)*	11/18/2019	3.02	349.00	12.15	8.78

Sampling Location Name	Sample Date	Temperature (°C)	Specific Conductance (µS/cm)	Dissolved Oxygen (mg/L)	pH (S.U.)
North Fields #1 (Simmons Well)	11/21/2018	12.15	344.00	N/A	7.05
North Fields #1 (Simmons Well)	6/4/2019	12.13	349.00	4.33	7.11
North Fields #1 (Simmons Well)	11/18/2019	12.00	347.00	9.35	7.27
North Fields #1 (Simmons Well)	4/3/2020	12.60	357.00	6.64	7.07
North Fields #2	6/4/2019	8.49	344.00	1.17	6.69
North Fields #2	11/14/2019	8.52	301.00	3.71	6.90
North Fields #2	4/2/2020	4.16	319.00	10.25	6.68
North Fields #3	6/4/2019	12.39	422.00	4.31	7.16
North Fields #3	11/18/2019	12.22	365.00	10.24	7.59
North Fields #3	4/3/2020	10.59	673.00	10.93	6.80
Pine Canyon Road #1	7/11/2019	5.90	192.00	N/A	8.99
Probst Well	11/21/2018	11.04	339.00	N/A	7.86
Probst Well	4/3/2020	10.10	354.00	7.11	7.91
Provo River at Midway Cutoff Road (4997300)*	11/18/2019	8.49	21.00	11.69	9.13
Round Valley Control Site (Girl Scout Camp)	6/12/2019	9.79	327.00	2.10	7.29
Round Valley Control Site (Girl Scout Camp)	6/2/2020	9.38	467.00	9.62	7.20
Snake Creek above WMSP Golf Course (5910450)*	11/18/2019	7.61	280.00	11.53	8.42
South Fields #1 (Giles Well)	11/21/2018	11.34	430.00	N/A	6.84
South Fields #1 (Giles Well)	6/4/2019	11.62	437.00	5.00	6.87
South Fields #1 (Giles Well)	11/18/2019	11.40	438.00	10.43	6.82
South Fields #1 (Giles Well)	4/6/2020	11.24	430.00	10.08	6.75
South Fields #2/(D-4-4) 12dcc-1	6/4/2019	12.06	789.00	3.26	6.84
South Fields #2/(D-4-4) 12dcc-1	11/14/2019	11.11	861.00	5.96	6.98
South Fields #2/(D-4-4) 12dcc-1	4/2/2020	11.07	646.00	14.15	6.85
Swiss Alpine Road #2 (Hayward Well)	11/21/2018	10.52	952.00	N/A	7.36
Swiss Alpine Road #2 (Hayward Well)	6/5/2019	10.77	963.00	3.57	7.34
Swiss Alpine Road #2 (Hayward Well)	11/18/2019	10.72	921.00	10.46	7.39

Sampling Location Name	Sample Date	Temperature (°C)	Specific Conductance (µS/cm)	Dissolved Oxygen (mg/L)	pH (S.U.)
Swiss Alpine Road #2 (Hayward Well)	4/3/2020	10.81	961.00	13.26	7.34
Timberlakes #1	6/12/2019	7.15	214.00	0.67	8.47
Timberlakes #1	11/13/2019	6.36	243.00	3.04	9.02
Timberlakes #1	6/2/2020	7.18	224.00	8.09	8.44
Timberlakes #2	7/11/2019	7.82	460.00	N/A	7.11
Timberlakes #2	6/2/2020	8.07	438.00	10.73	7.06
Timberlakes #4/(D-4-5) 1dd-1	8/22/2019	9.20	319.00	N/A	6.90
Timberlakes #4/(D-4-5) 1dd-1	11/19/2019	8.83	302.00	7.89	7.16
Timberlakes #4/(D-4-5) 1dd-1	4/6/2020	9.03	345.00	7.45	6.96
Tributary ab cnfl Lake Creek below Timberlakes Devel (4997060)*	6/12/2019	15.36	275.00	6.55	8.37
Tributary ab cnfl Lake Creek below Timberlakes Devel (4997060)*	11/13/2019	2.63	516.00	7.11	8.92
Tributary ab cnfl Lake Creek below Timberlakes Devel (4997060)*	4/6/2020	3.40	383.00	12.72	8.11
Wallsburg #1	6/12/2019	12.18	427.00	3.59	7.31
Wallsburg #1	11/13/2019	11.43	626.00	4.72	7.85
Wallsburg #1	4/6/2020	11.31	576.00	8.43	7.44
Wallsburg #2 (Wallsburg Town Well)	11/21/2018	10.46	495.00	N/A	7.64
Wallsburg #2 (Wallsburg Town Well)	6/12/2019	10.54	351.00	4.25	7.69
Wallsburg #2 (Wallsburg Town Well)	11/13/2019	10.39	555.00	4.67	8.03
Wallsburg #2 (Wallsburg Town Well)	4/2/2020	10.39	488.00	7.44	7.51
Wallsburg #3 (Davis Well)	11/29/2018	9.71	471.00	N/A	7.07
Wallsburg #3 (Davis Well)	6/12/2019	10.06	332.00	2.56	7.46
Wallsburg #3 (Davis Well)	11/13/2019	9.95	554.00	3.54	7.53
Wallsburg #3 (Davis Well)	4/2/2020	9.29	464.00	10.47	7.07
Woodland #1	7/11/2019	10.70	401.00	N/A	7.54
Woodland #1	4/3/2020	7.89	410.00	13.18	7.73
Woodland #2	6/4/2019	8.00	405.00	6.22	7.71
Woodland #3	6/4/2019	8.71	207.00	6.75	7.15

Sampling Location Name	Sample Date	Temperature (°C)	Specific Conductance (µS/cm)	Dissolved Oxygen (mg/L)	pH (S.U.)
Woodland #3	11/19/2019	8.37	205.00	8.78	7.34
Woodland #3	4/3/2020	8.55	212.00	9.61	7.25

Notes: °C = degree Celsius, µS/cm = microsiemens per centimeter, mg/L = milligrams per liter, S.U. = standard units.

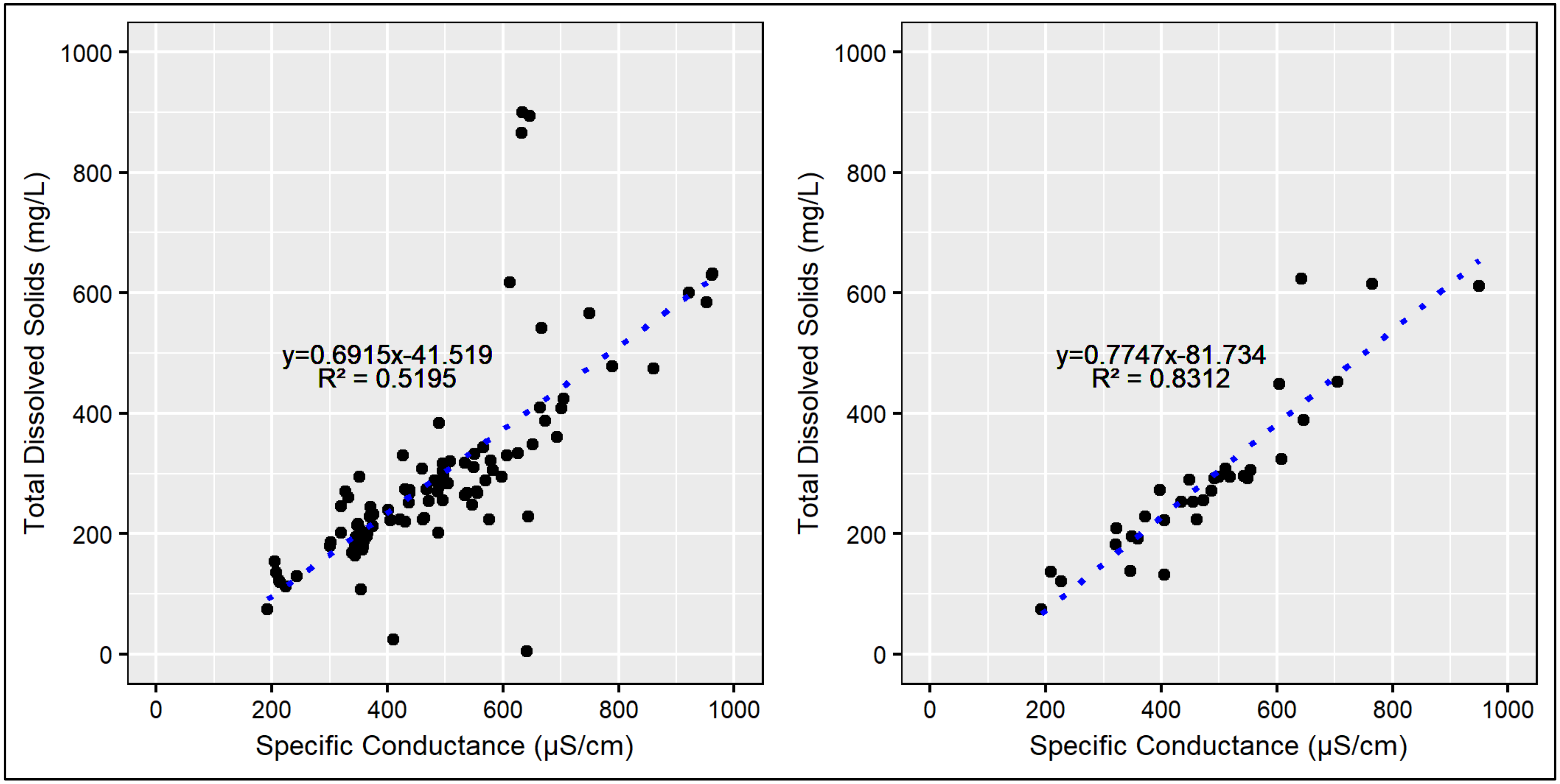


Figure A-1. Linear regression analysis between individual paired TDS and specific conductance measurements (left) and paired average values (among all visits to each site) for each well (right).

This page intentionally left blank.

APPENDIX B

Detailed Documentation for the 2020 Heber Valley Groundwater Model

CONTENTS

Model Purpose and Objectives B-1
Software Selection........ B-1
Model Domain and Discretization........ B-2
Global Approach........ B-2
Focused Effort on Heber Valley Aquifer........ B-2
Layer Conceptualization and Discretization........ B-3
Layer 1—Unconsolidated Aquifer Materials........ B-3
Layer 2—Consolidated Aquifer Materials........ B-5
Modeling Approach........ B-5
Modeling Units B-5
Boundary Conditions (Outflows)—Deer Creek Reservoir........ B-7
Boundary Conditions (Inflows)—Mountain-Front Recharge........ B-8
Boundary Conditions (Inflows)—Tributary Stream Recharge........ B-10
Boundary Conditions (Inflows)—Agricultural Recharge........ B-11
Boundary Conditions (Inflows)—Wastewater Recharge B-11
Boundary Condition (Inflows)—Precipitation Recharge B-13
Boundary Conditions (Inflows/Outflows)—Provo River........ B-13
Boundary Conditions (Outflows)—Evapotranspiration B-15
Boundary Conditions (Outflows)—Wells B-16
Special Note—Spring and Seep Discharge B-17
Head Observations B-18
Model Calibration........ B-20
Assessment of Calibration Results........ B-20
Hydraulic Conductivity Calibration—Initial Values B-21
Hydraulic Conductivity Calibration—Varying Values by Region B-21
Variation of River Conductance and Mountain-Front Recharge B-23
Final Variation of Hydraulic Conductivity Values B-23
Overall Acceptability of Calibration........ B-24

Figures

Figure B-1. Entire model domain, with focused Heber Valley modeling area. B-2
Figure B-2. Elevation of bottom of Layer 1, primarily interpolated from drillers' logs. B-4
Figure B-3. Thickness of Layer 1 (ground surface minus elevation of bottom of Layer 1). B-4
Figure B-4. Distribution of hydraulic conductivity estimates from aquifer tests B-7
Figure B-5. Constant-head boundary cells used to simulate Deer Creek Reservoir groundwater level control. B-8
Figure B-6. Recharge cells used to simulate mountain-front recharge. B-9
Figure B-7. Recharge cells used to simulate tributary stream recharge. B-10
Figure B-8. Recharge cells used to simulate agricultural incidental recharge. B-11
Figure B-9. Recharge cells used to simulate wastewater recharge (Rapid Infiltration Basin, land application, and septic systems). B-12
Figure B-10. River package cells used to simulate aquifer gains from and losses to the Provo River. .. B-14
Figure B-11. Evapotranspiration package cells used to simulate evapotranspiration from general forest/dry land (green) and from riparian, open water, and idle pasture (blue). B-16
Figure B-12. Well package cells used to simulate municipal wells and springs. B-17
Figure B-13. Head observation locations within the model. B-20
Figure B-14. Scatter plot for best and final calibration (Model Run K18). B-24

Tables

Table B-1. Number of Model Test Runs for Hydraulic Conductivity in Both Valley Fill and Bedrock Portions of the Aquifer B-6
Table B-2. Calculation of Mountain-Front Recharge Values Used in HVGM2020 Recharge Package B-9
Table B-3. Calculation of Tributary Stream Recharge Values Used in HVGM2020 Recharge Package B-10
Table B-4. Calculation of Agricultural Incidental Recharge Values Used in HVGM2020 Recharge Package B-11
Table B-5. Calculation of Wastewater Recharge Values Used in HVGM2020 Recharge Package B-12
Table B-6. Calculation of Precipitation Recharge Values Used in HVGM2020 Recharge Package B-13
Table B-7. Calculation of Evapotranspiration Values Used in HVGM2020 Evapotranspiration Package B-16
Table B-8. Calculation of Pumping Values Used in HVGM2020 Well Package B-17
Table B-9. Head Observations Used for Calibrating HVGM2020 .... B-19
Table B-10. Starting Hydraulic Conductivity Values, based on Aquifer Tests B-21
Table B-11. Results of All Calibration Runs B-24

MODEL PURPOSE AND OBJECTIVES

The 2020 Heber Valley Groundwater Model (HVGM2020) was created as part of an ongoing multiphased study to investigate the management of aquifer water quality for the Wasatch County Health Department (WCHD) and to make recommendations for regulating septic tanks. Ultimately, this effort requires calculating the nitrogen load in the aquifer under different scenarios. The model is one tool to help estimate these loads.

The specific objectives of the HVGM2020 are as follows:

- Incorporate the understanding of the aquifer dynamics of the Heber Valley that was explored in order to prepare an overall water budget for the basin (Phase 1 of the WCHD study).
- Incorporate data developed from new investigations into hydraulic conductivity and thicknesses of unconsolidated and consolidated aquifer units.
- Adequately replicate real-world groundwater elevations and flow directions in the Heber Valley.
- Derive flow rates through specific portions of the aquifer, to inform the loading calculations.
- Derive travel time estimates for the aquifer.

Software Selection

During Phase 1 of the project, SWCA Environmental Consultants (SWCA) conducted a model feasibility evaluation to determine the best plan for developing a groundwater model. It was determined that importing one of the previous versions of the Heber Valley MODFLOW input files into the current version of the MODFLOW software was not feasible. FREEWAT, an open-source and public-domain geographic information system (GIS)–integrated modeling environment used to simulate water quantity and quality in surface water and groundwater, was used instead (Borsi et al. 2018).

FREEWAT is a composite plugin for QGIS, an open-source GIS software. The use of the FREEWAT platform to accomplish these objectives allows for integration with GIS software and does not prohibit future use due to incompatibility of software or proprietary software limitations.

Previous modeling studies conducted for the study area have used three-dimensional finite-difference models like MODFLOW (Roark et al. 1991) or analytic element models (Inkenbrandt 2019). Those studies focused on assessing the hydrogeologic conditions and water quality within the Heber Valley and/or Round Valley areas within Wasatch County, followed by modeling groundwater flow to assist in fine-tuning the water budget. SWCA determined that MODFLOW was the appropriate underlying model tool to use for the current modeling effort, primarily because of the flexibility for modeling complex geometries.

At its core, the MODFLOW model is open-source software. It can be downloaded from the U.S. Geological Survey (USGS) for free—and USGS is continually working on new versions. In practice, most users rely on proprietary pre- and post-processing software packages to access MODFLOW. These software packages typically still run the original USGS MODFLOW executable files but provide interfaces that make it easy for users to create and modify models, run the models, and then visualize the results after running them. FREEWAT is simply another pre- and post-processing software program, but it has the benefit of being open source, readily accessible, and fully integrated with GIS.

Model Domain and Discretization

Global Approach

The HVGM2020 was set up to incorporate the watershed area for the Provo River as it flows through Heber Valley, including the contributing watersheds to Jordanelle Reservoir, the contributing watersheds to Deer Creek Reservoir (including Round Valley), and the watersheds for all tributary streams entering the Heber Valley.

The model domain was discretized into 200 columns and 150 rows, for a total of 30,000 individual cells per layer; the model uses two layers (Figure B-1). Each cell is equally sized, measuring 1,000 feet on each side. The entire model area encompasses approximately 700,000 acres.

The larger model domain is not actively being used, but it allows for future expansion to explore other aspects, such as the hydrology of the mountain blocks or Round Valley.

Focused Effort on Heber Valley Aquifer

For the current focused modeling effort for the Heber Valley, the only active cells in the model are those that overlap the spatial extent of the basin-fill aquifer of the Heber Valley. All other cells in the overall model domain—including those overlapping Jordanelle and Deer Creek Reservoirs—have been set as no-flow inactive cells.

For the focused effort, the HVGM2020 contains 1,270 active model cells.

Figure B-1. Entire model domain, with focused Heber Valley modeling area.

Layer Conceptualization and Discretization

The two layers are conceptualized below.[1]

Layer 1—Unconsolidated Aquifer Materials

Layer 1 represents the lower-density basin-fill aquifer materials in the Heber Valley. Baker (1970) used an analysis of gravity data to map out the thickness of these "low-density rocks." The Baker contours represent the boundary "between the low density material underlying the valleys and the more dense pre-Tertiary rocks in the bordering mountains" (Baker 1970:57). The Baker contours indicate that these materials have a thickness greater than 800 feet in some parts of the basin.

SWCA interprets Layer 1 as consisting of unconsolidated alluvial and basin-fill materials. The original geometry of the model was based on the Baker contours. Unfortunately, original interpretation and analysis of drillers' logs in the basin suggests that the Baker contours likely overestimate the thickness of the valley fill materials. This is similar to what Roark et al. (1991:18) found:

> On the basis of geophysical data, Baker (1970, fig. 22) interpreted the maximum thickness of low-density rock (assumed to be unconsolidated valley fill) in Heber Valley to be greater than 800 feet. Test drilling by the Utah Geological and Mineral Survey (Kehler, 1979) indicated that the thickness of unconsolidated valley-fill deposits is less than one-fourth of the thickness of low-density rock as interpreted by Baker. Data reported in drillers' logs were used to estimate the thickness of the unconsolidated valley-fill deposits rather than using the contours of thickness interpreted by Baker. Wells in Heber Valley have penetrated unconsolidated valley-fill deposits to depths of as much as 375 feet.

SWCA conducted an independent review of drillers' logs in the Heber Valley. A total of 35 logs appear to show the contact between unconsolidated and consolidated material. The minimum thickness of unconsolidated identified was 30 feet, and the maximum thickness of alluvium identified was 360 feet. The median thickness was 140 feet, but the thickness varied across the basin, as would be anticipated.

These thicknesses were interpolated into a three-dimensional surface and imported into the model to define the bottom of Layer 1/top of Layer 2 (Figure B-2). Many areas around the fringes of the basin fall outside the area for which drillers' logs are available and interpolated, and other areas generate conflicts between ground surface elevations (from the digital elevation model) and the Layer 1/Layer 2 boundary. To remedy these areas, all points beyond the area of interpolation, or with thicknesses less than 10 meters [m], were set to a standard 10-m thickness—these represent about one-third of active model cells:

- The top of Layer 1 is the ground surface, as measured from digital elevation models.
- The bottom of Layer 1 corresponds to the Layer 1/Layer 2 boundary as interpolated from drillers' logs. The maximum interpolated thickness of Layer 1 (in the central part of the basin, near Heber City) is about 600 feet (184 m). Near Deer Creek Reservoir and Daniels Creek the thickness is approximately 300 feet (90 m), and the minimum depth (at the margins of the basin) is approximately 30 feet (10 m) (Figure B-3).

[1] The Phase 2 report and this appendix use various shorthand terms to describe these two aquifer units: Layer 1 is often referred to as "alluvium" or "unconsolidated," and Layer 2 is often referred to as "bedrock" or "consolidated."

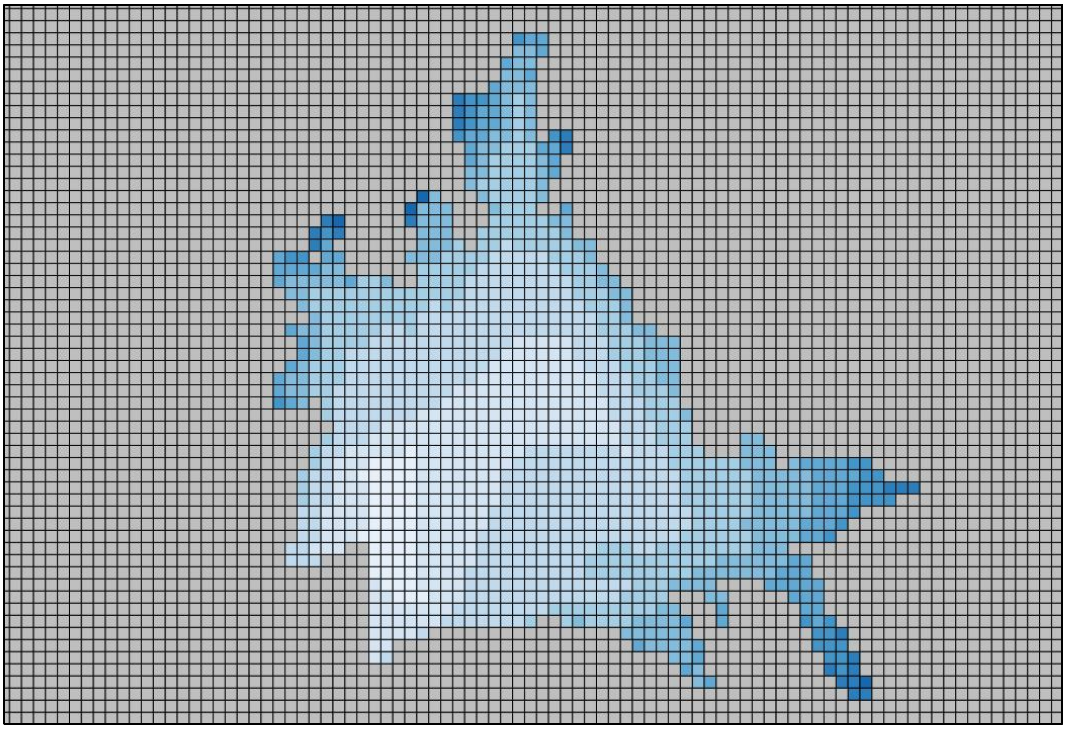


Figure B-2. Elevation of bottom of Layer 1, primarily interpolated from drillers' logs.

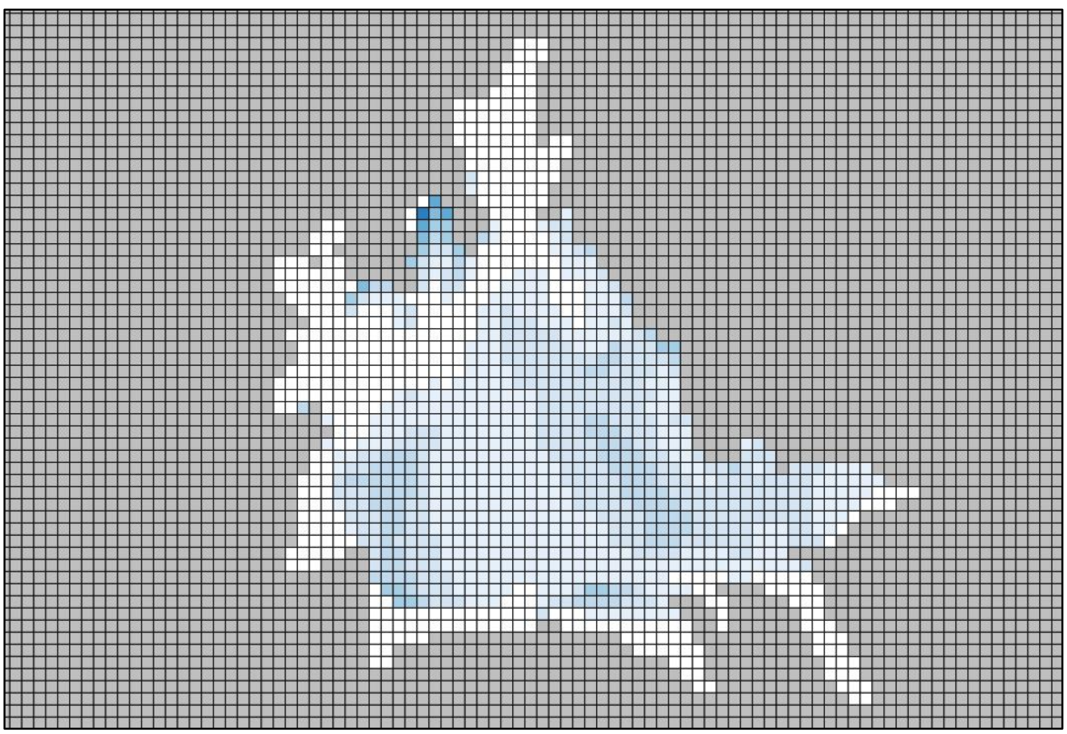


Figure B-3. Thickness of Layer 1 (ground surface minus elevation of bottom of Layer 1).

Layer 2—Consolidated Aquifer Materials

Layer 2 represents the fractured or porous consolidated rocks that underlie the basin-fill materials. Baker's "pre-Tertiary rocks" consist of a variety of units, including fluvial and lake deposits (Uinta Formation) and conglomerate (Fowkes Formation, Knight Conglomerate). All of these materials are assumed to form a single combined aquifer unit with similar characteristics for the purposes of modeling. Analysis of well data suggests that in many areas these rocks can be as productive as, or more productive than, the basin-fill deposits. Layer 2 plays an important role at the margins of the basin, where water levels fall below Layer 1. In the rest of the basin, the total productive thickness of Layer 2 is important because it affects both groundwater levels and the calibration of hydraulic conductivity (K) values:

- The top of Layer 2 corresponds to the bottom of Layer 1.
- In theory, saturated fractured rock could be many hundreds of feet deep in the basin. According to a database of drilling data for wells within the Heber Valley, the deepest productive well has been drilled to approximately 1,500 feet. However, most wells in the basin appear to use no more than 300 feet (90 m) of consolidated aquifer. This value (300 feet [90 m]) was used as the total thickness of Layer 2.

Modeling Approach

The HVGM2020 is a steady-state model.

Sources and sinks within the aquifer were conceptualized in a water budget report prepared by SWCA for Phase 1 of the WCHD study (SWCA 2019b). These water budget components were translated into various sources and sinks within the HVGM2020; the intent of the steady-state model is to roughly replicate the water budget developed empirically by analyzing literature and real-world datasets and, in doing so, to reasonably replicate the observed groundwater levels in the basin.

Because this is a steady-state model, the time discretization is arbitrary. For ease, the stress period was set as 1 year, and the time periods were set as 1 day.

Modeling Units

For HVGM2020, the Universal Transverse Mercator (UTM) coordinate system—using meters—was selected during model construction. Difficulties were encountered mixing units within FREEWAT and QGIS, so all units were converted to metric to correspond with the UTM coordinate system. Meters instead of feet were used for the top and bottom elevations for cells, K values, and starting water levels.

The modeling units used for the HVGM2020 are "meters" and "days".

HYDRAULIC CONDUCTIVITY

While working on the groundwater model, it became evident that one of the most critical parameters for calibrating the model and replicating real-world water levels is the K value assigned to both Layer 1 and Layer 2.

Estimates of hydraulic conductivity form aquifer tests conducted in the Heber Valley were reviewed to assign hydraulic conductivity estimates to Layers 1 and 2. SWCA's efforts to improve upon this baseline understanding were guided by newly available information (delineation reports). Using drinking water well delineation reports provided by the Utah Division of Drinking Water, SWCA obtained location-specific estimates of hydraulic conductivity for specific portions of the aquifer. These data were derived from controlled aquifer tests. SWCA considers aquifer tests obtained from delineation reports to be more accurate and reliable than specific capacity inferred from drillers' logs, which has been used in previous modeling efforts.

Initial Approach for Hydraulic Conductivity

Initial calibration efforts focused on assigning a single K value each to Layers 1 and 2. The K value selected represented the mean of logs from estimates from aquifer tests conducted in the Heber Valley, with no vertical or horizontal anisotropy.

- A total of six tests were available purporting to represent valley fill material:
  - Range: 1.2 to 15 feet/day
  - Mean: 6.4 feet/day
  - Mean of logs: 5.0 feet/day (1.5 m/day)
- A total of 19 tests were available purporting to represent bedrock material:
  - Range: 0.8 to 178 feet/day
  - Mean: 28.8 feet/day
  - Mean of logs: 8.5 feet/day (2.6 m/day)

This initial approach to assigning K values was unsuccessful in replicating groundwater levels in the eastern part of the basin or the northern part of the basin. This poor fit with real-world groundwater levels was reflected in the measurement of error for the model,[2] which was unable to reach anything better than about 14%.

Revised Approach to Hydraulic Conductivity

Previous modeling efforts by Roark et al. (1991) resulted in variation of hydraulic conductivity across the basin, and informal model test runs (shown in Table B-1) suggested that varying K values spatially may be able to better calibrate the model.

The dataset of K values obtained from aquifer tests was revisited and reviewed with respect to rough geographic areas. The 25 tests previously reviewed were distributed as shown in Figure B-4.

Table B-1. Number of Model Test Runs for Hydraulic Conductivity in Both Valley Fill and Bedrock Portions of the Aquifer

General Geographic Area	Number of Tests—Valley Fill	Number of Tests—Bedrock Material
Eastern basin/Daniels Creek	1	7
Central basin	3	3
Western basin	1	3
Outside margins of basin	1	6

[2] The "measurement of error for the model" is specifically the root mean square error (RMSE) divided by the range of water levels in the calibration data set (see the Model Calibration section for more detail). Most model guidance suggests that this measurement of error should be less than 10%.

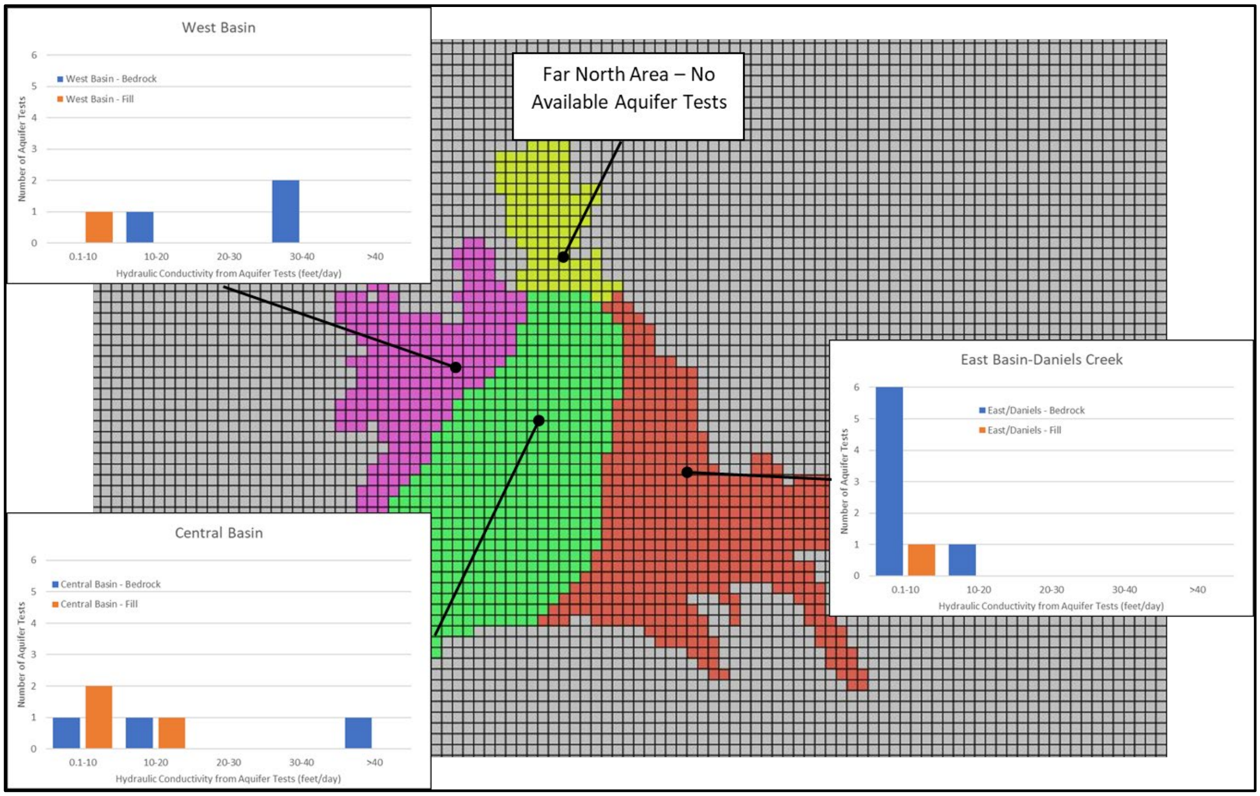


Figure B-4. Distribution of hydraulic conductivity estimates from aquifer tests.

Once the hydraulic conductivity dataset was divided by geographic area, the number of data points became too small to draw hard conclusions about hydraulic conductivity. Instead, the following approach was taken for the calibration, described later in this appendix:

- The available data—though limited—support the hypothesis that there is a geographic variation in K values across the basin, as was assumed in previous modeling efforts by Roark et al. (1991).
- Given the paucity of real-world field data, SWCA recognizes that the calibration of the model will ultimately drive the geographic distribution of K values. However, if possible, the best calibrated model should conform with available real-world data in order to keep final values within the range of observed K values.

Boundary Conditions (Outflows)—Deer Creek Reservoir

Deer Creek Reservoir is modeled as a series of 15 constant-head cells located around the upper edge of the reservoir. The constant-head cells were set to an average reservoir surface elevation of 5,419 feet above mean sea level (amsl), which was obtained by analyzing Bureau of Reclamation operational records for the reservoir (Figure B-5).

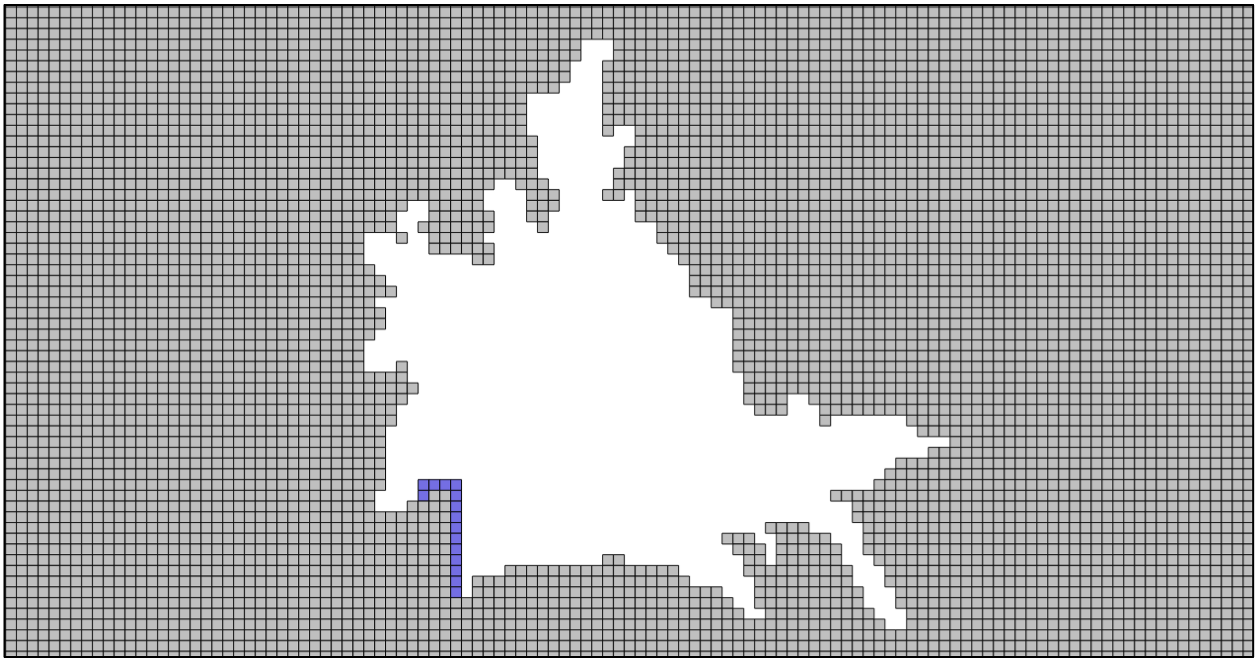


Figure B-5. Constant-head boundary cells used to simulate Deer Creek Reservoir groundwater level control.

Boundary Conditions (Inflows)—Mountain-Front Recharge

The SWCA water budget estimated mountain-front recharge entering the aquifer as 50,200 acre-feet per year. This recharge is assumed to enter the aquifer subsurface through fractures or faults, or by infiltration from streams very close to the mountain front.

The mountain-front recharge was modeled using recharge cells (Table B-2).[3] The recharge is applied to cells at the margin of the basin and is roughly weighted by the size of the contributing watershed (Figure B-6). The maximum elevation of most of the watersheds was similar, about (9,000–10,000 feet

[3] In QGIS, additional columns may be added to the model shapefiles without interfering with FREEWAT, as long as the original fields and field headers are not modified. Because there are multiple types of recharge incorporated into a single recharge shapefile, an additional column was added to the recharge model shapefile to provide an easy method for sorting and modifying rates. The different sources are coded by three-digit integers, as shown below.

Code	Represents	Code	Represents
100	Precipitation recharge (PR) only	113	MFR, Lake Creek; plus PR
101	Agricultural incidental recharge; plus PR	114	MFR, Spring Creek; plus PR
102	Wastewater recharge (Rapid Infiltration Basin, land application); plus PR	115	MFR, Center Creek; plus PR
103	Wastewater recharge (septic system); plus PR	015	MFR, Center Creek only
003	Wastewater recharge (septic system) only	116	MFR, Daniels Creek; plus PR
111	Mountain-front recharge (MFR), Snake Creek; plus PR	121	Tributary stream recharge (TSR), Lake Creek; plus PR
011	MFR, Snake Creek only	122	TSR, Center Creek; plus PR
112	MFR, Cottonwood Canyon; plus PR	123	TSR, Daniels Creek; plus PR

amsl). Snake Creek was increased somewhat to reflect the relatively high elevation of this watershed (10,500 feet amsl), and Lake Creek was reduced by the same amount to reflect the relatively low elevation of the watershed (7,500 feet amsl). The values used are as follows:

Table B-2. Calculation of Mountain-Front Recharge Values Used in HVGM2020 Recharge Package

Contributing Watershed	Rough Percentage of MFR, based on Contributing Watershed Area	Rough Percentage of MFR, Adjusted for Elevation	MFR Amount to Model (acre-feet/year)	Number of Cells	Amount of Recharge per Cell (acre-feet/year)	Amount per Cell (cubic meters/day)	Recharge Applied to Model Cells (meters/day)*
Snake Creek	17%	22%	11,070	35	316.3	1,050.4	0.0104
Cottonwood Canyon	10%	10%	5,020	49	102.4	340.1	0.0034
Lake Creek	21%	16%	8,000	35	228.6	759.2	0.0075
Spring Creek	12%	12%	6,020	11	547.3	1,817.5	0.0181
Center Creek	15%	15%	7,530	16	470.6	1,562.8	0.0155
Daniels Creek	25%	25%	12,550	19	660.5	2,193.5	0.0218
Total for model	**100%**	**100%**	**50,190**	**165**	**N/A**	**N/A**	**N/A**

Note: MFR = mountain-front recharge, N/A = not applicable.

* Model cells are ideally 303 × 303 m; it has been noted that FREEWAT coordinate system conversion when the MODFLOW input files are created changes this slightly to 315 × 319 m.

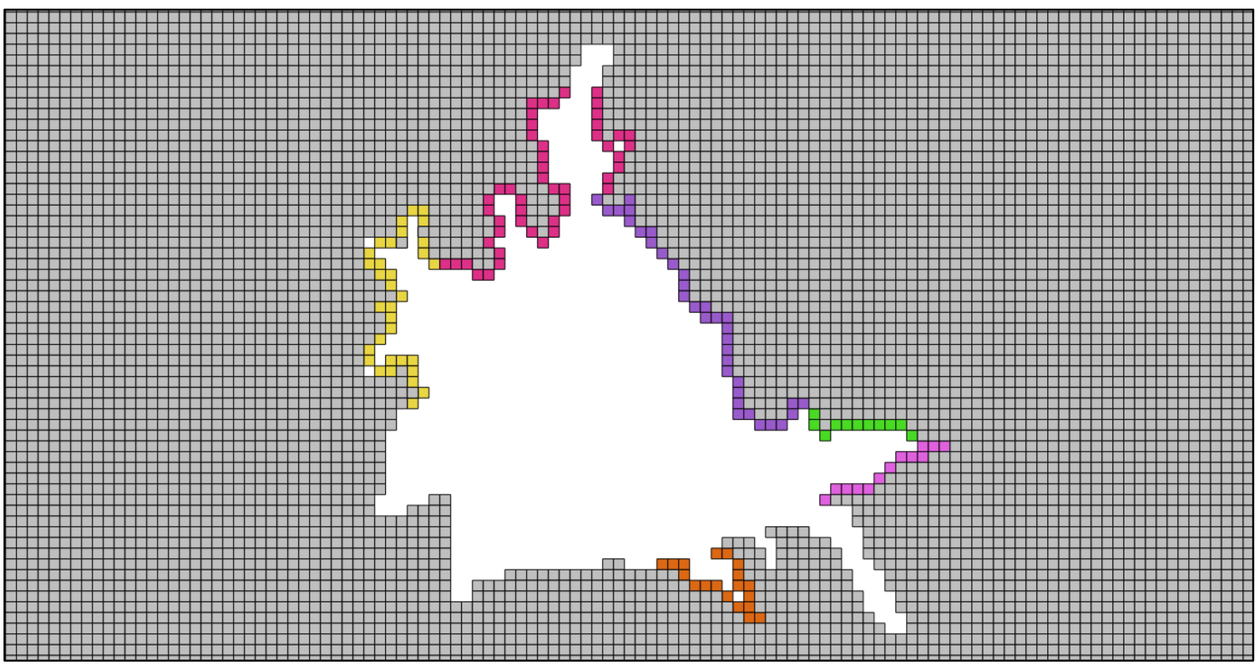


Figure B-6. Recharge cells used to simulate mountain-front recharge.

Boundary Conditions (Inflows)—Tributary Stream Recharge

The SWCA water budget estimated that most tributary streams entering the Heber Valley lose water to the aquifer, at a rate of 8,760 acre-feet per year (Table B-3).

Three tributary streams were modeled using the Recharge package, weighted roughly by their approximate flow rates (Figure B-7).

Where cells associated with these tributary streams overlapped cells where mountain-front recharge was already being modeled, these cells were not included in the calculations. In other words, any given cell contains only mountain-front recharge or tributary stream recharge, but not both.

Table B-3. Calculation of Tributary Stream Recharge Values Used in HVGM2020 Recharge Package

Tributary Stream	Approximate Flow Rate from Available Records (cubic feet/second)	Percentage of Stream Recharge	Stream Recharge Amount to Model (acre-feet/year)	Number of Cells	Amount of Recharge per Cell (acre-feet/year)	Amount per Cell (cubic meters/day)	Recharge Applied to Model Cells (meters/day)
Lake Creek	10.9	33%	2,891	22	131.4	436.4	0.0043
Center Creek	6.5	20%	1,752	20	87.6	290.9	0.0029
Daniels Creek	15.6	47%	4,117	19	216.7	719.6	0.0072
Total for model	**33.0**	**100%**	**8,760**	**61**	**N/A**	**N/A**	**N/A**

Note: N/A = not applicable.

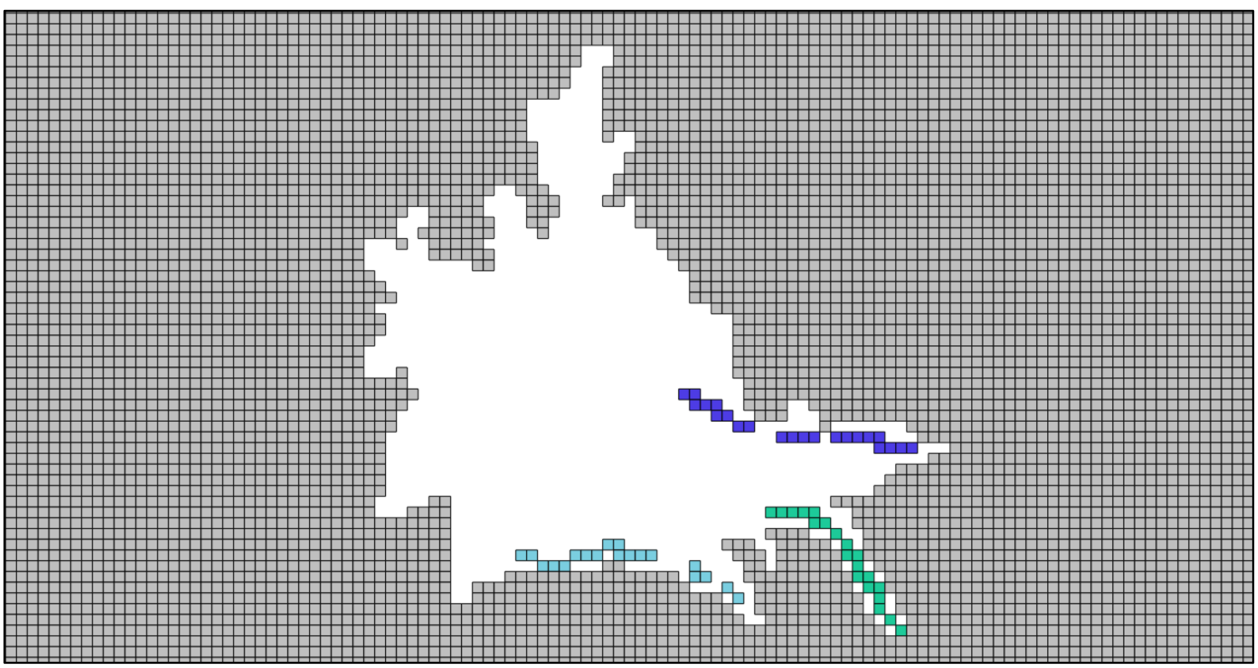


Figure B-7. Recharge cells used to simulate tributary stream recharge.

Boundary Conditions (Inflows)—Agricultural Recharge

The SWCA water budget estimated that incidental aquifer recharge occurs from agriculture in Heber Valley at a rate of 12,500 acre-feet per year (Table B-4). Agricultural areas were roughly defined using aerial photographs, and an agricultural recharge rate was assigned to those cells (Figure B-8).

Table B-4. Calculation of Agricultural Incidental Recharge Values Used in HVGM2020 Recharge Package

Total Agricultural Recharge (acre-feet/year)	Number of Cells	Amount of Recharge per Cell (acre-feet/year)	Amount per Cell (cubic meters/day)	Recharge Applied to Model Cells (meters/day)
12,500	314	39.8	132.2	0.0014

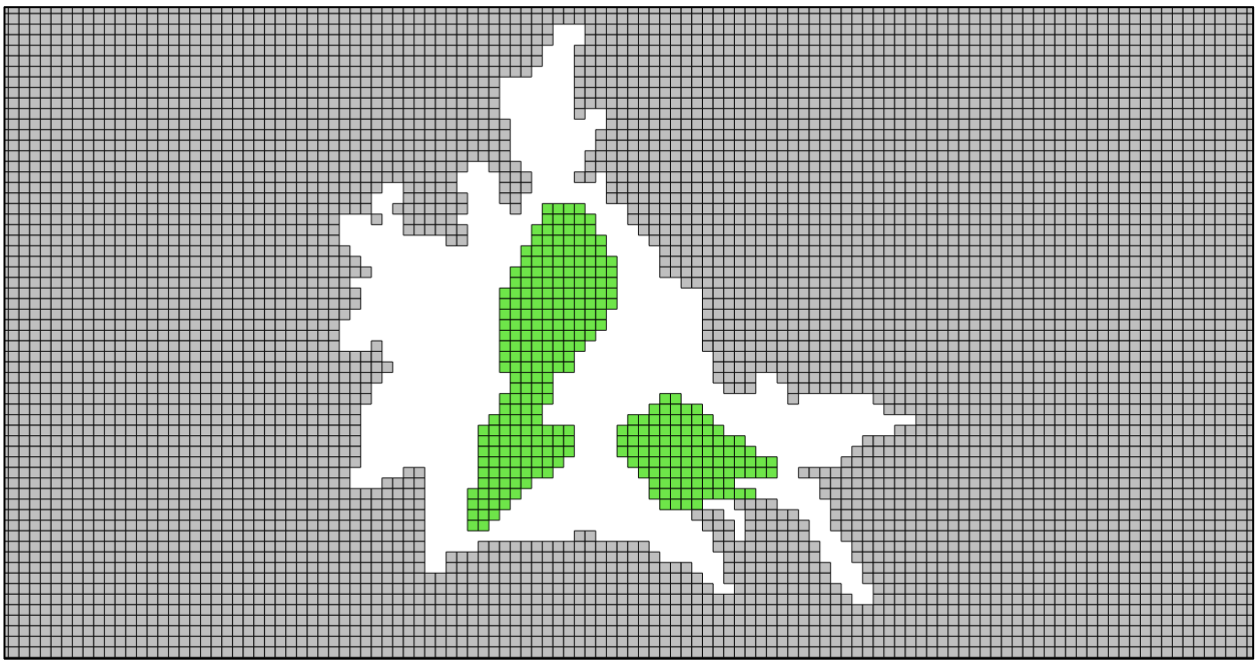


Figure B-8. Recharge cells used to simulate agricultural incidental recharge.

Boundary Conditions (Inflows)—Wastewater Recharge

The SWCA water budget estimated that wastewater recharge occurs in the Heber Valley at a rate of 2,693 acre-feet per year (Table B-5). This recharge comprises three different components:

- Infiltration of wastewater from the Rapid Infiltration Basin, located on the west side of the Provo River, near Midway, or other lagoons. This recharge is estimated at 447 acre-feet per year (Rapid Infiltration Basin) and 572 acre-feet per year (lagoons).
- Wastewater is also applied directly to land in the vicinity of the Rapid Infiltration Basin. This recharge is estimated at 186 acre-feet per year.
- Recharge also occurs from septic systems distributed throughout the Heber Valley, estimated at a rate of 1,488 acre-feet per year.

The first two categories of recharge were applied to cells in the immediate vicinity of the Rapid Infiltration Basin (Figure B-9). Septic system recharge was applied in a distributed manner, using shapefiles provided by the WCHD. The septic system partly overlaps with areas with other recharge, most notably agricultural recharge. Septic recharge was only applied to those cells that had not already been assigned a recharge value.[4]

Table B-5. Calculation of Wastewater Recharge Values Used in HVGM2020 Recharge Package

Wastewater Recharge Component	Recharge Amount to Model (acre-feet/year)	Number of Cells	Amount of Recharge per Cell (acre-feet/year)	Amount per Cell (cubic meters/day)	Recharge Applied to Model Cells (meters/day)
Rapid Infiltration Basin and land application	1,225	9	136.1	451.9	0.0044
Septic systems	1,488	221	6.7	22.2	0.0002
Total for model	**2,713**	**230**	**N/A**	**N/A**	**N/A**

Note: N/A = not applicable.

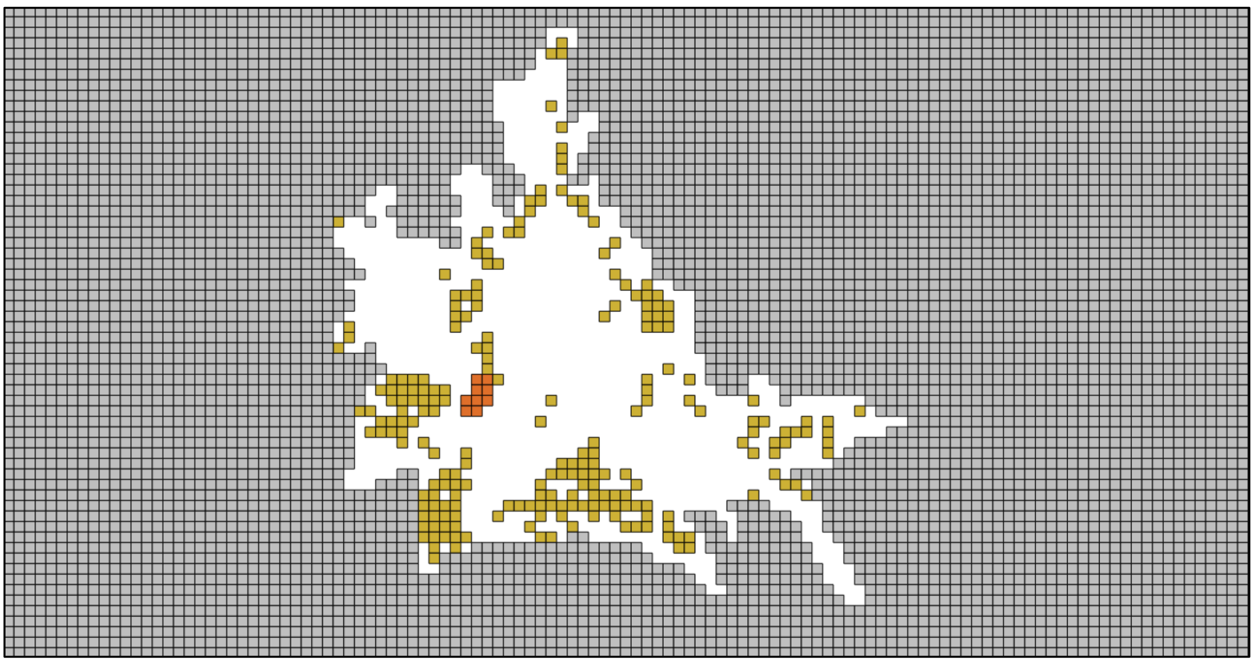


Figure B-9. Recharge cells used to simulate wastewater recharge (Rapid Infiltration Basin, land application, and septic systems).

[4] For simplicity, ease of modification, and to preserve the ability to understand how different components affect the model, only a single type of recharge (with the exception of precipitation) was applied to any given cell. Because most recharge is distributed over a wide area, and given the relatively coarse grid of the model, this simplification is not expected to cause any more uncertainty than already exists in the recharge estimates. The order in which recharge values were assigned is as follows:

1. Mountain-front recharge (MFR).
2. Tributary stream recharge (TSR). There was some overlap with MFR cells; these cells were excluded from TSR calculations.
3. Agricultural incidental recharge. There was no overlap with either MFR or TSR cells.
4. Wastewater recharge—Rapid Infiltration Basin and land application. There was no overlap with MFR, TSR, or agricultural recharge cells.
5. Wastewater recharge—septic systems. There was overlap with all previous recharge types; these cells were excluded from septic system recharge calculations.
6. Precipitation recharge was added cumulatively to all active cells, regardless of prior recharge components.

Boundary Condition (Inflows)—Precipitation Recharge

The SWCA water budget estimated that precipitation recharge occurs in the Heber Valley at a rate of 3,116 acre-feet per year (Table B-6). This recharge was applied evenly to all active model cells (i.e., the entire surface of the Heber Valley), in addition to recharge already applied.

Table B-6. Calculation of Precipitation Recharge Values Used in HVGM2020 Recharge Package

Recharge Amount to Model (acre-feet/year)	Number of Cells	Amount of Recharge per Cell (acre-feet/year)	Amount per Cell (cubic meters/day)	Recharge Applied to Model Cells, in addition to Existing Recharge Amounts (meters/day)
3,116	1,255	2.5	8.3	0.0001

Boundary Conditions (Inflows/Outflows)—Provo River

Using empirical streamflow data from available gages, the SWCA water budget estimated that the Provo River loses water to the aquifer in the reaches immediately downstream of Jordanelle Dam (estimated at 1,090 acre-feet/year) and gains water from the aquifer in the reaches at the lower end of Heber Valley (estimated at 9,846 acre-feet/year).

There is substantial uncertainty in these estimates. While the streamflow records are of high quality and have useful periods of record, there is substantial uncertainty associated with agricultural diversions. These diversion rates have been estimated, but only annually. In addition, more focused site-specific work near the Rapid Infiltration Basin suggests that this particular reach is a losing aquifer reach, not a gaining reach, which is a level of detail that could not be obtained through the analysis of streamflow records.

Multiple modeling choices were available to model the Provo River:

- For the losing reaches immediately downstream from Jordanelle Dam, the discharge from Jordanelle Dam could be handled as a constant-head boundary, under the assumption that groundwater levels are likely maintained close to the dam because of the constant discharge of water to the river.
- Alternatively, these losing reaches could be handled as recharge cells, similar to how the tributary streams were handled.
- The gain of water in the lower valley could be handled as drain cells, which pull water from the aquifer, on the basis of modeled aquifer levels.

All of the above choices are based on the certainty of knowing where the Provo River is a gaining or losing stream. Given the uncertainty, one useful application of the HVGM2020 is to determine through modeling how the Provo River is reacting to modeled aquifer water levels, without making any predetermined assumptions.

To do this, SWCA used the River (RIV) package. This package allows water to be added to the aquifer or removed from the aquifer, depending on the modeled groundwater levels compared with the specified river water level.[5]

[5] The Stream package is similar to the RIV package, except that it incorporates a surface water routing function. For the HVGM2020, SWCA focused on the aquifer itself rather than on the exact nature of the surface flows in the Provo River, except as a conduit that adds or removes water from the aquifer. For this reason, SWCA chose to use the simpler RIV package.

The RIV package makes use of three values for each cell:

1. Stage in the river (elevation). The stage in the river was set to be 3 m (10 feet) below the top of Layer 1 for each cell. The stage has critical influence on the change of the river from gaining to losing in any given cell.
2. Bottom of the river (elevation). Relatively little detail is available on the geometry of the channel. On the basis of available information from some USGS gages, the bottom of the river was assumed to be 16 feet (5 m) below the stage. The bottom of the river has little influence on the change from gaining to losing but affects the overall amount of water movement.
3. River conductance.

The river conductance value is a calculation that involves several other assumptions. The formula is as follows:

$C_{RIV} = K * L * W / M$

Where:
C_{RIV} = Conductance of riverbed (square meters/day)
K = Hydraulic conductivity of the riverbed material (meters/day)
L = Length of the river segment in the cell (meters). This is a GIS calculation conducted by FREEWAT when creating the river model shapefile.
W = Width of the river (meters).
M = Thickness of the riverbed (meters).

For the initial river conductance values, the following values were used:
K = 0.1 m/day (assumes riverbed conductivity is lower than surrounding material)
M = 1 m (arbitrary; no available data)
Width = 18.2 m, which corresponds to 60 feet. This width was measured from aerial photographs.

Note that the conductance value is relatively uncertain overall and therefore is one focus of calibration efforts.

A total of 58 cells represent the Provo River, using the RIV package (Figure B-10).

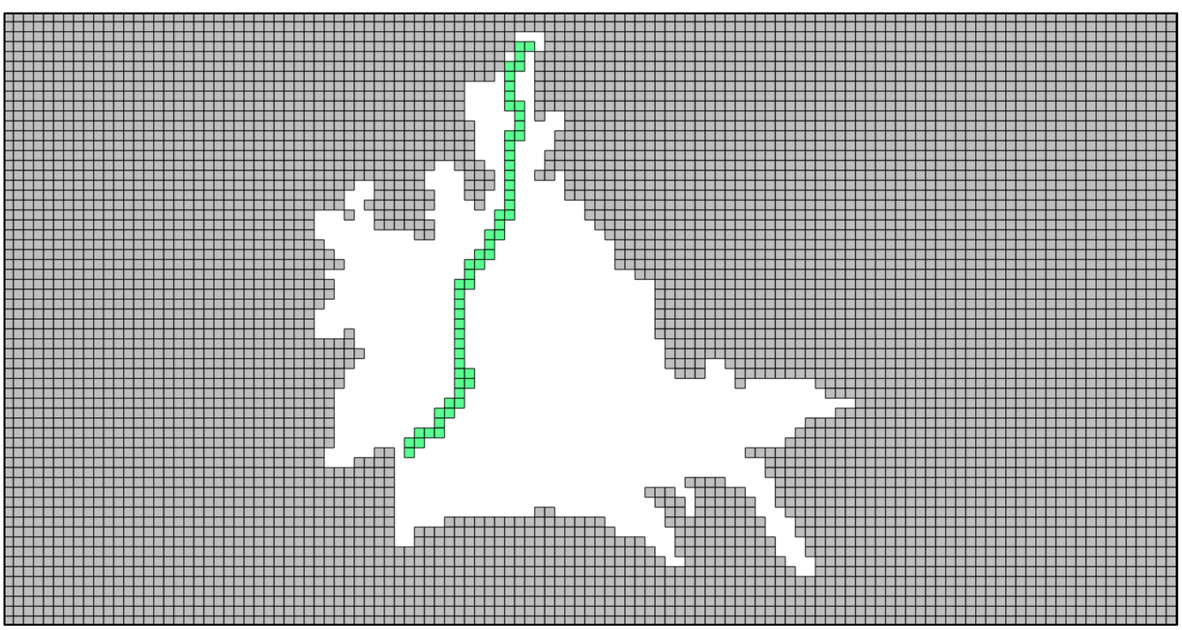


Figure B-10. River package cells used to simulate aquifer gains from and losses to the Provo River.

Boundary Conditions (Outflows)—Evapotranspiration

The SWCA water budget estimates net evapotranspiration based on different land cover types across the entire Heber Valley. Some land covers result in net recharge to the aquifer—notably agricultural land cover. Other land types result in net evapotranspiration (Figure B-11), including the following:

- Dry land/other (3,180 acre-feet/year)
- General forest (2,191 acre-feet/year)
- Idle pasture (835 acre-feet/year)
- Riparian (701 acre-feet/year)
- Open water (719 acre-feet/year)

These land uses were developed using GIS coverages, and the specific areas of land use are distributed over much of the Heber Valley. However, a review of data coverages upon which the estimates were based suggests that most of the amount is centered in several distinct geographic areas (see SWCA 2019b:Figure 11).

1. One distinct area is along the Provo River corridor, consisting of not only riparian vegetation but also idle pasturelands and open water.
2. Another distinct area is on the mountain flanks northwest and northeast of the Heber Valley, consisting of dry land/other and general forest land types.[6]

The most appropriate modeling approach used to estimate evapotranspiration is the Evapotranspiration package. This package identifies a maximum evapotranspiration rate, as well as an extinction depth below which evapotranspiration ceases.[7]

For the HVGM2020, the areas on the mountain flanks are almost perfectly coincident with portions of Layer 1 that tend to dry up during model runs. MODFLOW allows for this, with an option for applying evapotranspiration (like recharge) to the highest active layer. However, the extinction depth in this situation becomes relatively meaningless.

To ensure the removal of water through evapotranspiration, the extinction depth was set to the bottom of Layer 2 for all evapotranspiration areas. In other words, evapotranspiration will never shut off and should remain relatively close to the maximum evapotranspiration rates. Estimates of evapotranspiration for the various land coverages are provided in Table B-7.

---

[6] The GIS land use coverage does not actually include "general forest." This is a designation assigned by SWCA to incorporate any areas not specifically designated for a land use. Similar to the mountain-front recharge modeling, a field was added to the evapotranspiration modeling shapefile to indicate the land use, using the following codes:

Code	Represents	Code	Represents
1	Dry land/other	4	Riparian
2	General forest	5	Open water (includes sewage lagoon)
3	Idle pasture		

[7] Because Layer 1 cells tend to dry up at the margins of the basin, the extinction depth was set very deep (bottom of Layer 2), in order to not curtail evapotranspiration.

Table B-7. Calculation of Evapotranspiration Values Used in HVGM2020 Evapotranspiration Package

Land Use Type	ET Amount from Model (acre-feet/year)	Number of Cells	Amount of ET per Cell (acre-feet/year)	Amount per Cell (cubic meters/day)	ET Applied to Model Cells (meters/day)
Dry land/other; general forest	5,371	314	17.1	56.8	0.0006
Idle pasture; riparian; open water	2,255	385	5.8	19.3	0.0002
Total for model	**7,626**	**699**	**N/A**	**N/A**	**N/A**

Note: ET = evapotranspiration, N/A = not applicable.

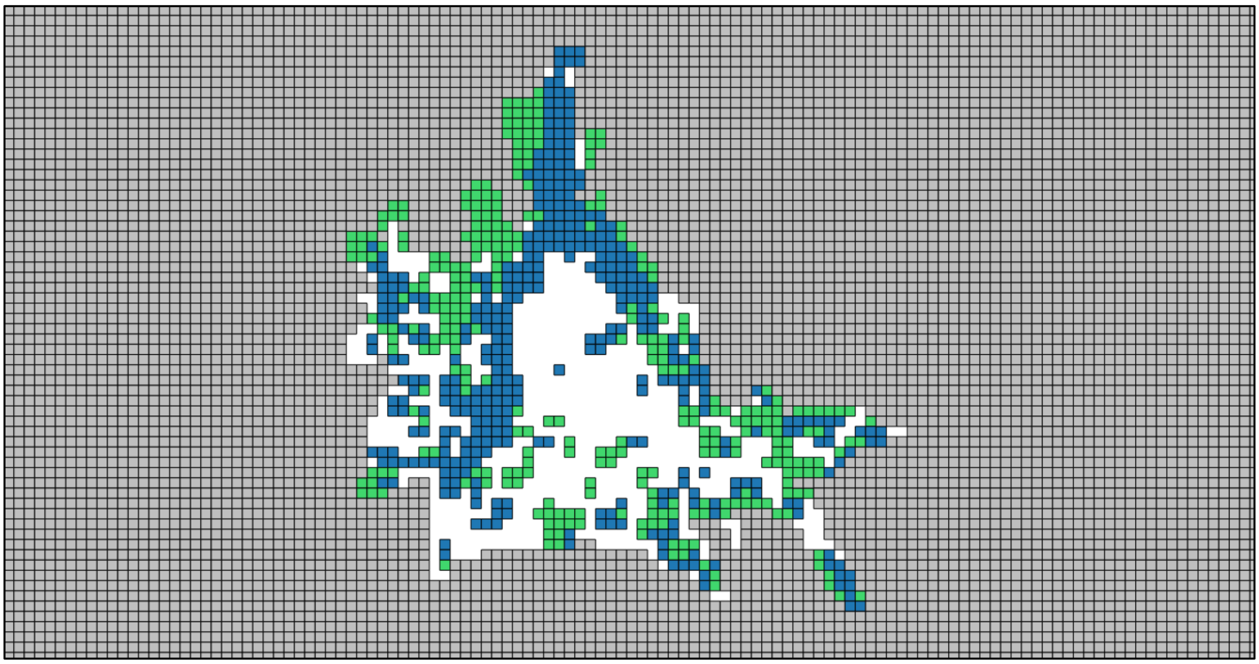


Figure B-11. Evapotranspiration package cells used to simulate evapotranspiration from general forest/dry land (green) and from riparian, open water, and idle pasture (blue).

Boundary Conditions (Outflows)—Wells

The SWCA water budget estimated that municipal supply withdrawn from wells and springs occurs in the Heber Valley at a rate of 3,275 acre-feet per year, primarily from five municipal systems (Table B-8).[8] Pumping was assigned to model Layer 2 at each well location (Figure B-12).

[8] Similar to mountain-front recharge and evapotranspiration modeling, a field was added to the well modeling shapefile to indicate the municipal system, using the following codes:

Code	Represents	Code	Represents
1	Center Creek	4	Heber City
2	Daniel	5	Midway
3	Charleston		

Table B-8. Calculation of Pumping Values Used in HVGM2020 Well Package

Municipal System	Population Served by Wells and Springs	Percentage of Population	Pumping Amount from Model (acre-feet/year)	Number of Cells	Amount of Pumping per Cell (acre-feet/year)	Amount per Cell (cubic meters/day)
Center Creek	200	1.0%	32.8	2	16.4	54.5
Daniel	499	2.3%	75.3	2	37.7	125.2
Midway	5,200	24.4%	799.1	4	199.8	663.5
Heber City	14,969	70.1%	2,295.8	4	574.0	1,906.2
Charleston	480	2.2%	72.1	2	36.1	119.9
Total for model	**21,348**	**100%**	**3,275.1**	**14**	**N/A**	**N/A**

Note: N/A = not applicable.

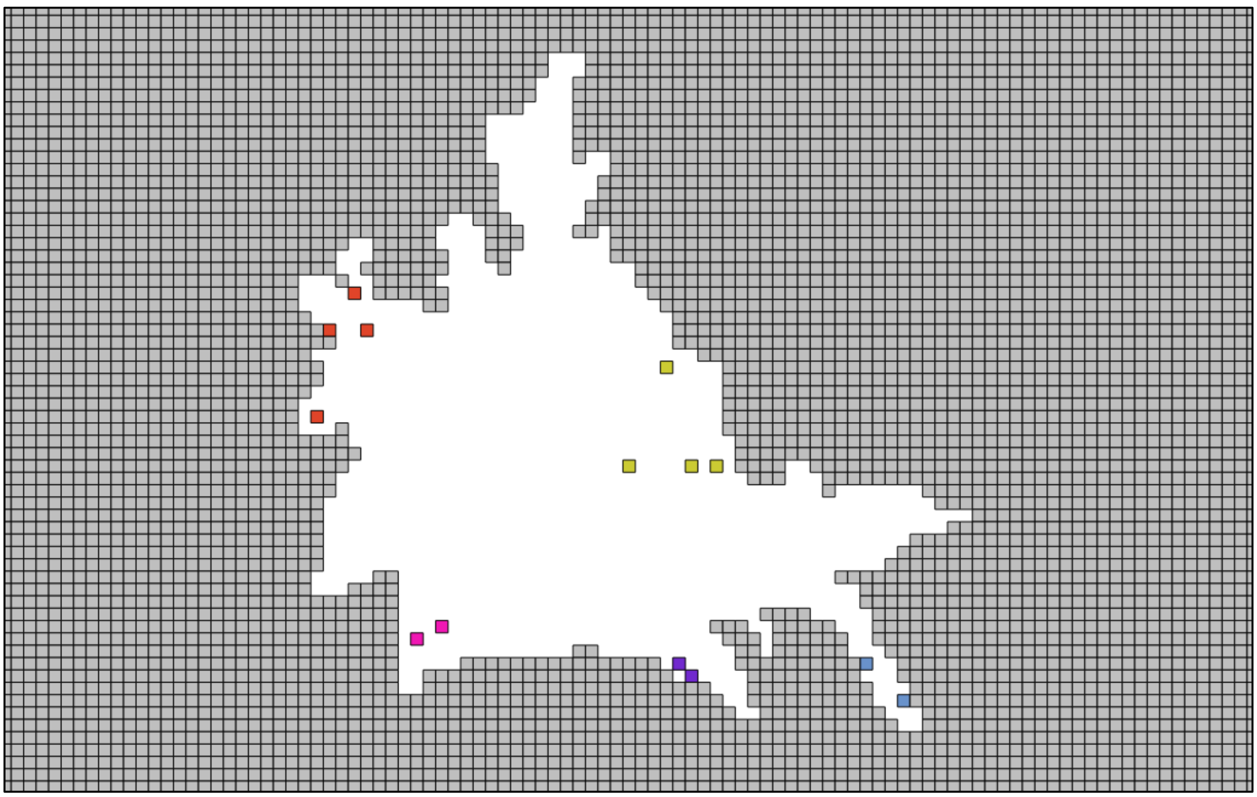


Figure B-12. Well package cells used to simulate municipal wells and springs.

Special Note—Spring and Seep Discharge

One component in the SWCA water budget has little additional empirical support—discharge from seeps and springs. The amount of discharge (34,750 acre-feet/year) was taken from Roark et al. (1991).

No geographical location is assigned to this discharge; therefore, it has not been added explicitly to the HVGM2020. However, it is believed that some springs are located along the floodplain of the Provo River in the lower part of the Heber Valley, where groundwater is close to the surface. The RIV package for the Provo River in part simulates removal of water from the aquifer in this area based on groundwater levels, and the constant-head cells at Deer Creek Reservoir also act to remove water from the aquifer.

For the purposes of assessing the model, the RIV package output can probably be interpreted partially as gaining flows in the Provo River and partially as discharge of water from the aquifer through springs, and the constant-head cells can probably be interpreted partially as underflow to Deer Creek Reservoir and partially as discharge of water from the aquifer through springs.

Head Observations

Head observations are real-world groundwater levels as measured in the field. If used during a model run, MODFLOW outputs a comparison of the head observations with simulated groundwater levels from the model (Figure B-13). This provides the fundamental basis for the calibration.

A suite of 20 water levels, obtained from the USGS National Water Information System well inventory, were used for calibration purposes (Table B-9).

Table B-9. Head Observations Used for Calibrating HVGM2020

USGS Site ID	Site Name	Row	Column	Well Depth (feet)	USGS Aquifer ID*	Count of Water Level Records	Date Range Used for Calibration Water Levels	Range of Depth-to-Water Measurements (feet below ground surface)	Well Altitude (feet above sea level)	Median Groundwater Altitude (feet above sea level)
403403111253501	(D- 3- 5) 7cdb- 1	46	60	88	VF	12	1994–2005	2.2–5.1	5,759	5754.3
403325111254601	(D- 3- 5)18cba- 1	49	59	140	VF	12	1994–2005	14.1–20.3	5,700	5684.2
403305111251901	(D- 3- 5)18dcc- 2	51	61	243	VF	12	1994–2005	94.0–99.8	5,695	5599.3
403243111252701	(D- 3- 5)19bdd- 2	53	61	120	–	12	1993–2005	14.6–25.6	5,654	5634.0
403237111255201	(D- 3- 5)19cbb- 1	54	59	Unknown	–	31	1993–1996	7.5–10.3	5,650	5641.2
403146111272701	(D- 3- 4)26dba- 1	59	52	19	–	5	2015–2019	13.2–13.9	5,580	5566.3
403127111240301	(D- 3- 5)29cac- 1	60	68	15	–	4	2016–2019	10.3–12.3	5,608	5595.9
403024111254601	(D- 4- 5) 6bba- 1	67	59	11	–	7	1990–1998	0.9–6.9	5,526	5521.0
402955111281101	(D- 4- 4) 2cbb- 1	69	49	158	–	15	1994–1995	20.1–25.4	5,480	5456.2
403003111255801	(D- 4- 5) 6bcc- 2	69	59	Unknown	–	4	2016–2019	31.2–37.1	5,530	5495.0
402946111233901	(D- 4- 5) 4ccb- 1	70	69	217	VF	5	2015–2019	142.0–146.4	5,700	5554.5
402937111214901	(D- 4- 5) 3dcc- 1	71	77	75	VF	5	2015–2019	17.0–21.9	5,880	5861.7
402842111223601	(D- 4- 5) 4ddd- 1	72	74	56	–	5	2015–2019	22.9–43.8	5,798	5763.0
402902111282001	(D- 4- 4)10daa- 1	75	48	65	VF	5	2015–2019	2.2–3.4	5,430	5427.0
402842111263101	(D- 4- 4)12dcc- 1	77	56	Unknown	VF	5	2015–2019	63.8–69.1	5,545	5477.4
402839111221101	(D- 4- 5)15bab- 1	77	75	165	–	11	1994–2005	128.6–133.7	5,850	5720.2
402840111213801	(D- 4- 5)15aab- 1	77	78	150	–	12	1994–2005	17.1–21.4	5,900	5881.1
402810111263601	(D- 4- 4)13bdd- 1	79	56	Unknown	–	5	2015–2019	79.7–83.9	5,550	5467.6
402742111281501	(D- 4- 4)23bbb- 2	82	48	26.5	VF	11	1994–2005	15.4–23.7	5,426	5407.5
402750111232701	(D- 4- 5)16ccd- 1	82	70	150	VF	5	2015–2019	88.0–92.6	5,850	5758.9

* VF = valley fill; dash indicates that no information is available in the USGS National Water Information System database for the well.

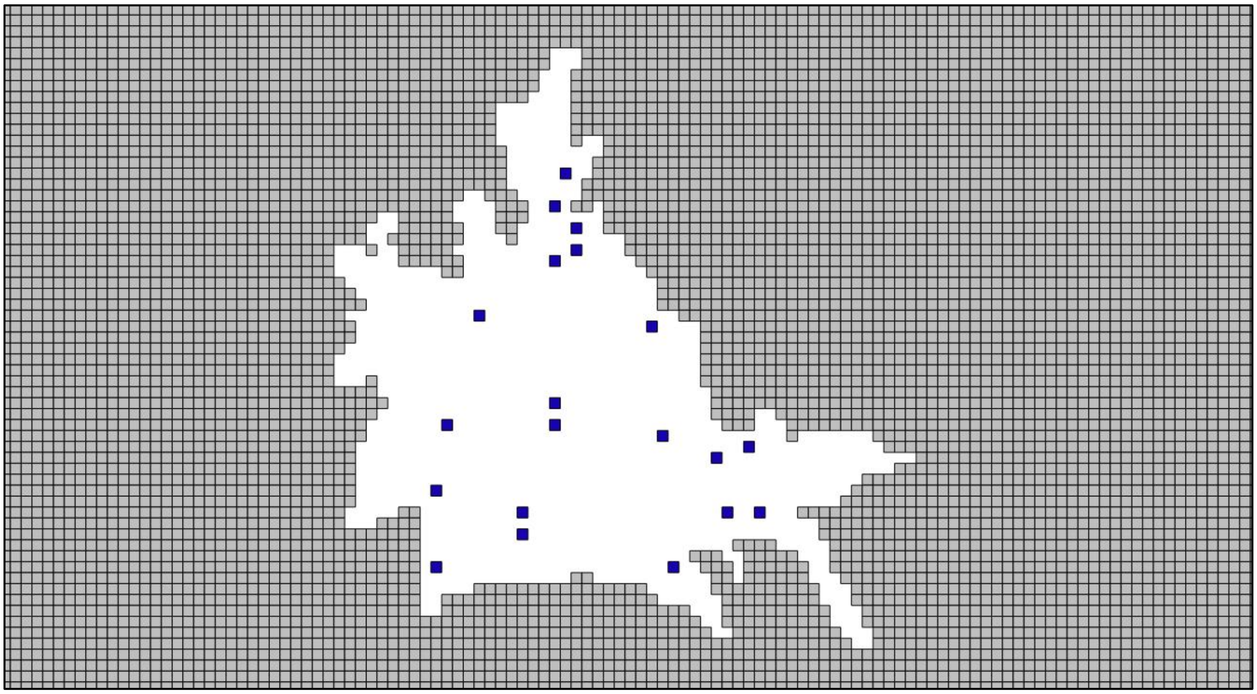


Figure B-13. Head observation locations within the model.

Model Calibration

Assessment of Calibration Results

Three metrics were used to assess the results of each calibration run.

The root mean squared error (RMSE)/Range statistic. This is a commonly used percentage that compares the magnitude of the average error in the model results with the overall range of head values. The raw input for this statistic is the head residuals (observed calibration water levels minus simulated water levels). Typically, a well-calibrated model should have an RMSE/Range statistic of less than 10%.

Scatter plots of observed versus simulated head values. Graphical representations are valuable because they shows patterns that affect the overall calibration statistic. Typically, each calibration run involves observing the pattern, identifying the outliers, and then reviewing the raw results to determine which wells those outliers are from and what might be affecting those water levels. The calibration scatter plots for the HVGM2020 were grouped into these categories:

3. Far north wells: (D-3-5)7cdb-1; (D-3-5)18cba
4. North wells: (D-3-5)18dcc; (D-3-5)19bdd; (D-3-5)19cbb
5. West well: (D-3-4)26dba
6. Northeast well: (D-3-5)29cac
7. Center wells: (D-4-5)6bba-1; (D-4-4)2cbb-1; (D-4-5)6bcc-2; (D-4-4)12dcc; (D-4-4)13bdd
8. Reservoir wells: (D-4-4)10daa; (D-4-4)23bbb
9. East wells: (D-4-5)4ccb-1; (D-4-5)3dcc-1; (D-4-5)4ddd-1; (D-4-5)15bab; (D-4-5)15aab; (D-4-5)16ccd

Water budget. The water budget for the Heber Valley was defined in the Phase 1 report. This is not a quantitative calibration target, because there is no expectation that the percentages or the proportions of different inputs/outputs will be exact. Rather, these values and proportions are considered as a qualitative measure to distinguish between different calibration runs that otherwise have acceptable calibration statistics.

Hydraulic Conductivity Calibration—Initial Values

There were insufficient aquifer tests to differentiate between valley fill and bedrock, except perhaps in the central part of the basin. For the first calibration run, all aquifer tests were considered together, regardless of the geologic unit they represented. The mean of the log values was used as a starting point, since hydraulic conductivity often has a lognormal distribution (although insufficient data exist here to check the distribution of this particular dataset). The hydraulic conductivity values used to start the calibration are provided in Table B-10.

No data exist for the northern basin. Given the similarity in geography (at the margins of the basins), it was initially assumed to be similar to the eastern basin.

Table B-10. Starting Hydraulic Conductivity Values, based on Aquifer Tests

	Western Basin	Central Basin	Eastern Basin/ Daniels Creek Area	Northern Basin
Minimum (feet/day)	3.9	0.9	0.8	0.8
Mean of log values (feet/day)	15.6	10.5	2.9	2.9
Maximum (feet/day)	37.2	178	15	15
Minimum (meters/day)	1.2	0.3	0.2	0.2
Mean of log values (meters/day)	4.7	3.2	0.9	0.9
Maximum (meters/day)	11.3	53.9	4.5	4.5

10. Model Run K1.
    a. *Approach:* Use the mean of log values, all areas.
    b. *Outcome:* These calibration results for the central basin were extremely poor (216% error for the whole basin).

Hydraulic Conductivity Calibration—Varying Values by Region

The central part of the basin was suspected to have the greatest influence on the results, so this was calibrated first, followed by the eastern, northern, and then western portions. Table B-11 shows the results for all the calibration runs.

11. Model Runs K2 and K3.
    a. *Approach:* Use the mean of log values for north, central, and east; vary central basin between minimum and maximum K values.
    b. *Outcome:* The calibration results for the minimum K values were extremely poor (351% error for the central basin). The calibration results for the maximum K values were acceptable (4% error for the central basin).

12. Model Run K4.
    a. *Approach:* Use the mean of log values for north, central, and east; informed by results from Runs K2 and K3, attempt to vary the K values for Layers 1 and 2 in the central basin.
    b. *Outcome:* Given the strength of the central basin calibration using the maximum values of K, the separate maximum values of K for Layer 1 (4.5 m/day) and Layer 2 (53.9 m/day) were used. The calibration results were acceptable (7% error for the central basin) but worse than using the single maximum K value (53.9 m/day) for both layers. The single maximum K value (53.9 m/day) was selected as the best estimate for the central basin for the remainder of the calibration runs.
13. Model Runs K5 and K6.
    a. *Approach:* Keep the best calibrated value for the central basin (53.9 m/day); use the mean log values for the north and west; vary the K values for the eastern basin between minimum and maximum values.
    b. *Outcome:* The calibration results for the minimum K values were extremely poor (1,372% error for the eastern basin). The calibration results for the maximum K values were also poor (27% error for the eastern basin).
14. Model Runs K7 and K8-A through K8-D.
    a. *Approach:* At this point, it was clear that the eastern basin would not calibrate with K values based on the available data; to match real-world water levels, the K value would need to be greater than the eastern basin range. Given the general paucity of the hydraulic conductivity dataset, the decision was made to increase the K value beyond the range of the observations in the eastern basin but to keep it within the range observed for the basin as a whole. The starting point was the maximum value for the entire basin (53.9 m/day), and this was refined downward, ultimately ending at 8 m/day. The central basin was held at the best estimate of 53.9 m/day, and the mean log values were used for the northern and western basins.
    b. *Outcome:* The calibration at the initial 53.9 m/day (Run K7) was poor (41% error for the eastern basin). The K value was gradually reduced from 30 m/day (Run K8-A) to 15 m/day (Run K8-B) to 10 m/day (Run K8-C) to 8 m/day (Run K8-D). At 8 m/day, the calibration was marginally acceptable (10% error for the eastern basin), as well as acceptable for the overall model (9% error). This value (8 m/day) was selected as the best estimate for the central basin for the remainder of the calibration runs.
15. Model Run K9.
    a. *Approach:* Keep the best calibrated value for the central basin (53.9 m/day) and eastern basin (8 m/day); use the mean log values for western basin; vary the K values for the northern basin between minimum and maximum values.
    b. *Outcome:* This model run failed to converge when using the minimum K value, even with loosened solver criteria.
16. Model Runs K10 and K11.
    a. *Approach:* The best calibrated values were kept for the central basin (53.9 m/day) and eastern basin (8 m/day). Several variations of K values were used for the western and northern basins simultaneously, with the expectation that they may be interrelated.
    b. *Outcome:* These results were varied, ranging from 9% to 19% error for the entire model, with the error driven almost entirely by the western basin.

17. Model Run K12.
    a. *Approach:* This model run represents the best estimate of calibrated K values based on the previous runs: west (1.5 m/day), central (53.9 m/day), east (8 m/day), and north (4.5 m/day).
    b. *Outcome:* This run has all regions of the basin acceptably calibrated, with the overall calibration at 8% error.

Variation of River Conductance and Mountain-Front Recharge

Once the K values were calibrated by region, the calibration was focused on several components of the water budget with relatively high uncertainty: the Provo River and the mountain-front recharge.

18. Model Runs K13 and K14.
    a. *Approach:* The calculated river conductance values were changed higher and lower by a factor of two for each run.
    b. *Outcome:* The calibration results were mixed. With increased river conductance, the overall basin calibration did not change (8% error), but the northern basin calibration improved from 10% error to 8% error.
19. Model Runs K15 and K16.
    a. *Approach:* The mountain-front recharge values were changed higher and lower by a factor of 20% for each run.
    b. *Outcome:* The calibration results were mixed. With decreased mountain-front recharge, the eastern and central basin calibrations both improved.

20. Model Run K17.
    a. *Approach:* This run attempted to get the benefits of both the river conductance and mountain-front recharge changes. River conductance was increased by a factor of two, and mountain-front recharge was decreased by 20%.
    b. *Outcome:* The resulting calibration was acceptable overall (9% error), and all regions except the eastern basin were acceptably calibrated. The eastern basin had an error of 12%. Though the calibration statistics based on groundwater levels was slightly poorer than Model Run K12, the total flow values more closely matched those developed for the basin, and Model Run K17 was selected as an improvement.

Final Variation of Hydraulic Conductivity Values

Recognizing that there is complex interplay between all the model components, one final model run was conducted to fine-tune the K values.

21. Model Run K18.
    a. *Approach:* The mountain-front recharge was kept with the 20% decrease, and the river conductance was kept with the increase by a factor of two. The K values were moderated using professional judgment on the basis of the scatter plots. The only change that made an improvement was to reduce the eastern basin from 8 m/day to 6 m/day.
    b. *Outcome:* The resulting calibration was acceptable overall (9% error), and all regions except the eastern basin were acceptably calibrated. The eastern basin improved slightly to an error of 11%. This model was selected as using parameters that best match real-world groundwater elevations while also most closely replicating water budget components.

The scatter plot for the final model run (K18) is shown in Figure B-14.

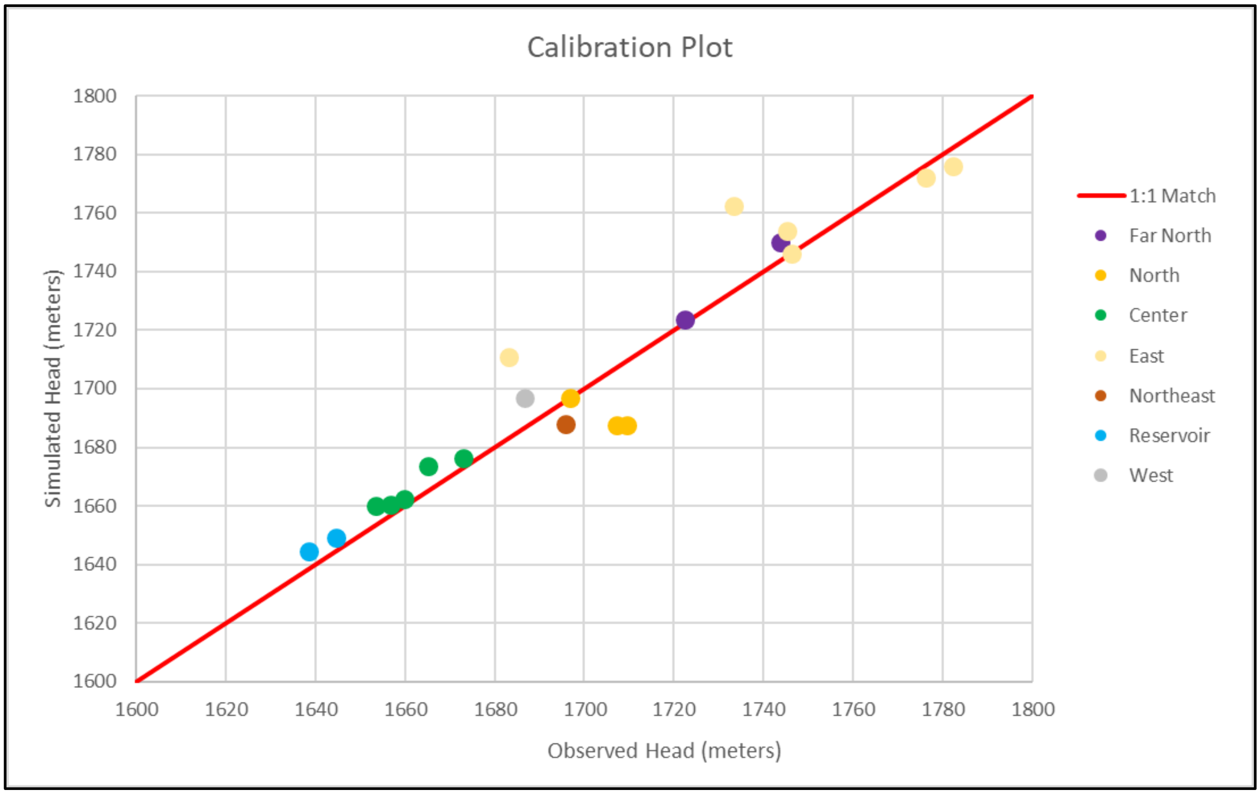


Figure B-14. Scatter plot for best and final calibration (Model Run K18).

Overall Acceptability of Calibration

Overall, the fit of the groundwater elevations simulated with the steady-state HVGM2020 to real-world observed groundwater elevations indicates that the model successfully replicates the general aquifer dynamics and flow paths.

Qualitative comparison of secondary calibration targets (water budget components) indicates that simulation of the gain/loss of the Provo River in the model may not accurately reflect real-world conditions and that discharge to springs/seeps in the lower basin is largely unaccounted for, except as discharge through Deer Creek Reservoir.

Table B-11. Results of All Calibration Runs

Model Run	Selected Parameters (K value in meters/day)				Error of Model (RMSE/Range)†				
	West (Zone3)	Central (Zone2)	East (Zone1)	North (Zone4)	All Wells	North Wells	East Wells	Central Wells	West Wells
K1	4.7 (mean)	3.2 (mean)	0.9 (mean)	0.9 (mean)	216%	25%	362%	48%	30%
K2	4.7 (mean)	0.3 (min)	0.9 (mean)	0.9 (mean)	650%	73%	1,039%	351%	51%
K3	4.7 (mean)	53.9 (max)	0.9 (mean)	0.9 (mean)	162%	10%	273%	4%	16%
K4	4.7 (mean)	4.5 (Level 1) 53.9 (Level 2)	0.9 (mean)	0.9 (mean)	164%	6%	278%	7%	19%
K5	4.7 (mean)	53.9 (best)	0.2 (min)	0.9 (mean)	812%	9%	1,372%	4%	16%

Model Run	Selected Parameters (K value in meters/day)				Error of Model (RMSE/Range)†				
	West (Zone3)	Central (Zone2)	East (Zone1)	North (Zone4)	All Wells	North Wells	East Wells	Central Wells	West Wells
K6	4.7 (mean)	53.9 (best)	4.5 (max)	0.9 (mean)	17%	9%	27%	4%	17%
K7	4.7 (mean)	53.9 (best)	53.9 (all max)	0.9 (mean)	25%	11%	41%	4%	16%
K8-A	4.7 (mean)	53.9 (best)	30 (est. best)	0.9 (mean)	21%	10%	34%	4%	16%
K8-B	4.7 (mean)	53.9 (best)	15 (est. best)	0.9 (mean)	14%	9%	21%	4%	17%
K8-C	4.7 (mean)	53.9 (best)	10 (est. best)	0.9 (mean)	10%	10%	13%	4%	16%
K8-D	4.7 (mean)	53.9 (best)	8 (est. best)	0.9 (mean)	9%	9%	10%	4%	17%
K9	4.7 (mean)	53.9 (best)	8 (est. best)	0.2 (min)	DNC				
K10	1.2 (min)	53.9 (best)	8 (est. best)	4.5 (max)	9%	10%	10%	4%	12%
K11	0.2 (min all)	53.9 (best)	8 (est. best)	3.5 (best)	19%	10%	10%	4%	74%
K12	1.5 (best)	53.9 (best)	8 (best)	4.5 (best)	8%	10%	10%	4%	9%
K13	RIVx2				8%	8%	10%	5%	11%
K14	RIVx0.5				11%	18%	10%	3%	3%
K15	MFR * 0.8				10%	12%	12%	3%	2%
K16	MR * 1.2				10%	8%	13%	5%	13%
K17	RIVx2; MFR * 0.8				9%	9%	12%	4%	7%
K18	RIVx2; MFR * 0.8				9%	9%	11%	4%	7%
	1.5 (best)	53.9 (best)	6 (best)	4.5 (best)					

Note: DNC = Did not converge. This means that the solver package for the model was unable to reach a solution that met the acceptable error limits for head and flow differences.

† For the purposes of calibration statistics, “North Wells” includes the north and far north categories, “East Wells” includes the east and northeast categories, “Central Wells” includes the central and reservoir categories, and “West Wells” includes the sole western well.

This page intentionally left blank.