DEPARTMENT OF NATURAL RESOURCES

Groundwater Flow and Groundwater / Stream Interaction in the Little Rock Creek Area

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PROFESSIONAL GEOLOGIST

I hereby certify that this plan, document, or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Geologist under the Laws of the State of Minnesota

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Acknowledgements

The models were developed by DNR staff as a sub-project of the Little Rock Creek Sustainable Groundwater Use Plan project. A Technical Advisory Team (TAT) was assembled to engage interested experts during development of the models. The team were asked to comment on the DNR's approach, provide advice, and give feedback on the model's fitness for purpose. The TAT members were:

- Kelton Barr, retired
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Executive Summary

The Little Rock Creek Area (LRCA) is one of several locations across the state where groundwater use is concentrated and has been increasing over the last several decades. The Minnesota Department of Natural Resources (DNR) is responsible by state law for issuing permits to appropriate water, provided they meet the criteria established in law. Although current groundwater uses in the LRCA are not expected to exceed the capacity of the aquifer system to supply water, the DNR is concerned that cumulatively, the currently permitted groundwater use in the LRCA might be having a negative impact on Little Rock Creek by reducing streamflow. Groundwater pumping can reduce streamflow by decreasing groundwater discharge to streams and, in some cases, by inducing or increasing seepage out of streams.

In November 2015, the DNR initiated a project to develop a five-year action plan to ensure that groundwater use in the LRCA is sustainable and meets the requirements of state law. Key tasks in the action plan include: 1) establishing a protected flow for Little Rock Creek, 2) establishing a corresponding sustainable diversion limit, and 3) determining whether collective groundwater use is reducing streamflow by more than the sustainable diversion limit. The DNR has recommended setting streamflow diversion limits relative to the median August base flow.

In the LRCA, groundwater is the water source for public water supplies, private domestic supplies, non-crop agricultural uses, and nearly all agricultural irrigation in the area. Agricultural irrigation is the largest category of water use in the LRCA. Groundwater use for crop irrigation began in the late 1960s, and the number of water appropriation permits in the area has increased steadily for four decades. Little Rock Creek and its tributary Bunker Hill Creek are designated trout streams that are particularly dependent on a steady supply of groundwater. Streams are particularly sensitive to diversion of base flow during summer periods with low flows. Base flow is the part of total streamflow that is sustained in the absence of direct runoff, and it is sustained largely by groundwater discharges.

Hydrological Investigation and Modeling

This report describes DNR's hydrological investigation in support of the action plan. DNR reviewed previous studies in the area and compiled, reviewed, and analyzed available data on geology, climate, hydrology, soils, and land use. A key component of the DNR's study was the development, construction, and use of a hydrological model.

Streamflow diversion caused by groundwater use cannot be directly measured because it is the difference between flows that have been affected by groundwater use, and a hypothetical reference condition without groundwater use (no use). Diversions must be separated from variations in streamflow caused by climate-driven changes in recharge, evapotranspiration by riparian vegetation, runoff and other factors.

Although statistical and empirical methods can provide insight into hydrological impacts, assessing streamflow diversions in real-world, complex hydrological systems requires the application of numerical models. Numerical hydrological models can represent important geological and hydrological features of the system while also applying basic physical principles such as maintaining the water balance. Models are also needed to represent the hypothetical, no-use condition or to evaluate hypothetical management scenarios. Hydrological modeling tied to real-world data is the standard approach applied worldwide for providing science-based guidance for basin or watershed-scale water-management decisions.

The LRCA hydrological model (the model) consists of two parts run in sequence, a surface-water and soils focused watershed model and a multi-layer groundwater-flow model. The surface-water and soils focused model uses GSSHA, developed by the U.S. Army Corps of Engineers. This model computed net recharge as input to the groundwater-flow model. The groundwater-flow model uses MODFLOW, developed by the U.S. Geological Survey. The model built upon previous data collection and studies conducted in the area.

The model computes groundwater levels and stream base flows for water years 2006 through 2018 (a water year is from October of the previous year through September) with water year 2005 used as a warm-up period. DNR selected this period based on the availability of streamflow data, although some discontinuous periods of streamflow data are available prior to 2006. Model development began in late 2015, and the model period ran through water year 2014. The model period was extended through water year 2018 in spring 2020 using available climate, water use, and land cover inputs.

DNR developed the model as a tool for use in evaluating the potential impacts of changes in groundwater use and other management actions on monthly base flow in Little Rock Creek. This applies directly to tasks 1) and 3) (listed above) and also to evaluating the potential effects on Little Rock Creek base flow of other scenarios being explored during plan implementation. The model may also be used for preliminary evaluation of impacts of management actions on base flow in other streams in the LRCA. Finally, the model can be updated to test model results against new data and/or to extend the computation period. The DNR continues to collect data from stream-gaging stations on Little Rock Creek and from observation wells in the LRCA.

The model incorporates a variety of data and key hydrological features and processes, and it reasonably matches observed monthly base flows outside of winter/ice-affected periods, particularly during summer low-flows. The model represents a practical and effective application of available data and analysis methods. Like all models of complex natural systems, however, it has unavoidable data and model limitations. Therefore, there is some uncertainty in model-computed base-flow diversions. The stream base-flow diversion analysis considers the implications of these limitations and uncertainties.

DNR engaged a Technical Advisory Team (TAT) of interested experts during development of the models. Team members commented on the DNR's approach, provided advice, and gave feedback on the model's fitness for purpose. The team met with DNR in April, August, and December 2016. DNR provided the team with a draft model report in December 2018 and met with the team again in January 2019.

Stream Base-Flow Diversion Analysis

The DNR used the model to evaluate:

- The monthly rate of streamflow diversions due to groundwater use and

- The August median base flow for a reference condition (no use).

The streamflow diversions were calculated as the differences between computed base flows (computed groundwater-sourced discharge) in Little Rock Creek during the modeling period versus computed base flows in a hypothetical, no-use scenario for the same period.

To calculate the median August base flow for the reference condition, DNR combined model results (computed base-flow diversions) with base flows derived directly from streamflow measurements. This approach is more accurate than simply using base flow computed in the no-use model scenario to represent the reference-condition base flow. The reference-condition base flow was calculated as the sum of the computed base-flow diversion and the base flow estimated directly from streamflow measurements. DNR staff separated base flow from total, measured streamflow using a filtering algorithm (Eckhardt, 2005) implemented in the Web-based Hydrograph Analysis Tool (WHAT) developed at Purdue University.

DNR uses the median value of base flow as an index because it is representative of typical flows. Infrequent, high flows skew the arithmetic average to a relatively large value. For example, measured August streamflow was less than the arithmetic average approximately 75 percent of the time. Base-flow diversion is of greater risk to aquatic life under typical to low-flow conditions.

For the initial 8 years with concurrent August streamflow measurements and model-computed base flows at the long-term gaging station (2006 and 2008 through 2012), the median August base flow was 4.6 cfs. The corresponding median August base flow calculated for the reference condition was 5.5 cfs. The computed median monthly base-flow diversion (1.3 cfs) and maximum monthly base-flow diversion (1.9 cfs) were 24 percent and 35 percent, respectively, of the calculated August median base flow for the reference condition. Extended to 12 analysis years (through 2018), the median August base flow was 6.8 cfs, and the median August base flow calculated for the reference condition was 7.2 cfs. The computed median base-flow diversion (0.77 cfs) and maximum monthly base-flow diversion (1.9 cfs) were 11 percent and 27 percent, respectively, of the calculated August median base flow for the reference condition.

The DNR also conducted an inter-watershed comparison as a separate check on base-flow differences related to contrasting groundwater-use rates. DNR staff compared measured streamflow in Little Rock Creek to measured streamflow in a similar, nearby watershed (Rice Creek) where there is substantially less groundwater use. This analysis provided an independent line of evidence that the model-computed base-flow diversions are reasonable (See Appendix B).

In addition to groundwater pumping, the DNR had to consider land use in the no-use scenario representing the reference condition. Land use affects the amount and timing of groundwater recharge, which, in turn, affects groundwater discharge to streams. Therefore, the computed base flow for the no-use scenario and the corresponding, calculated base-flow diversions are sensitive to the representation of land uses.

More than 95 percent of the groundwater use in the area is for crop irrigation. Irrigation with groundwater affects the hydrologic system through groundwater pumping and through the effects of irrigation applications and crop water use on groundwater recharge and surface runoff. Although other land-uses that are not directly related to groundwater use also affect Little Rock Creek, the purpose of the analysis was to isolate the impacts of permitted groundwater pumping and use on base flow. Therefore, for the no-use scenario used as a reference condition, DNR modified the land use representation in the model only in irrigated areas.

In the no-use scenario, there was no high-volume groundwater pumping, and irrigated crops were replaced with non-irrigated alfalfa. DNR selected alfalfa as a representative crop to replace irrigated crops in the no-use scenario because water use by non-irrigated alfalfa is at the high end of the range for non-irrigated, agricultural land uses in Central Minnesota (i.e., row crops, other hay crops, small grains, and pasture) and because alfalfa is more drought tolerant than many row crops.

Selecting a different land cover that uses less water than alfalfa in place of irrigated crops results in larger computed base flows in the no-use scenario and corresponding larger calculated base-flow diversions. As an example, DNR also tested a no-use scenario in which non-irrigated row crops were represented in the model in place of irrigated row crops. Using this alternative no-use scenario as a reference condition, the calculated median August base flow diversion was 3 cfs (2006, 2008-14), and the calculated August median base flow was 8 cfs. This latter scenario is a less appropriate representation of a non-irrigated agricultural landscape (i.e., reference condition) than the selected no-use scenario, but it demonstrates how the modeled land use can affect the analysis results.

DNR evaluated the range of possible groundwater diversions and reference August base flow considering data and model uncertainties and limitations. One important source of uncertainty in the model inputs is the reported monthly pumping volumes. DNR metered nine irrigation systems offered by volunteers in the LRCA during the 2018 and 2019 seasons. The data from these nine systems suggested that over-reporting of irrigation volumes may be much more common than under-reporting. The differences between metered and reported use varied widely, but the average percent difference was about 20 percent more reported than measured.

To evaluate the effect of a potential systematic bias in reported pumping, DNR developed a simplified model scenario in which all groundwater use was multiplied by 80 percent. For this scenario, the computed median monthly base-flow diversion (0.52 cfs) and maximum monthly base-flow diversion (1.5 cfs) were 7.4 percent and 21 percent, respectively, of the calculated August median base flow for the reference condition (7.0 cfs).

Considering model and data uncertainties, it is unlikely that monthly groundwater-discharge diversions did not exceed 1 cfs at the long-term station in some years. Maximum-monthly diversions in excess of 2.5 cfs are plausible. The reference August median base flow is sensitive to the period of record examined, but it is relatively insensitive to model uncertainties. For the selected reference condition, the August median base flow (2006, 2008-18) is close to 7 cfs.

1. Introduction

This report describes available hydrological and geological data and characterizes the hydrogeological system surrounding Little Rock Creek. Using these data and analyses, the Minnesota Department of Natural Resources (DNR) developed a hydrological model as a tool to support groundwater-appropriations management. The hydrological model consists of two parts run in sequence, a surface-water and soils focused watershed model and a multi-layer groundwater-flow model.

1.1. Background and Purpose

The Little Rock Creek area (LRCA) has been identified by the DNR as an area where groundwater use is concentrated and at increased risk of overuse and contamination. Groundwater is the source for public water supplies, private domestic supplies, non-crop agricultural uses, and nearly all agricultural irrigation in the area. Agricultural irrigation is the largest category of water use in the LRCA. Groundwater use for crop irrigation began in the area in the late 1960s, and the number of water appropriation permits in the area has increased steadily for four decades.

The Little Rock Creek Area Sustainable Groundwater Use Planning Project was launched to ensure that beneficial use of groundwater continues while remaining sustainable. Minnesota Statute 103G.287, Subd. 5 states that permitted water use must be sustainable and not “harm ecosystems, degrade water, or reduce water levels beyond the reach of public water supply and domestic wells.” This report describes hydrologic analyses performed in support of this planning project.

The sustainability of groundwater uses in the area, particularly with regard to impacts to surface waters, must be determined. Little Rock Creek and its tributary Bunker Hill Creek are designated trout streams that are particularly dependent on a steady supply of groundwater. Groundwater withdrawals divert groundwater discharge to streams. While some diversion of stream discharge is an expected consequence of consumptive groundwater use, the net or cumulative rate of these diversions must remain below sustainable limits.

Historically water-appropriation applications were reviewed individually with evaluations focused on impacts to features near the point of appropriation (e.g. well). A numerical hydrological model is needed to account for the complex hydrological system as a whole and the cumulative effects of all permitted appropriations on groundwater levels and streamflow.

DNR used the model described in this report to calculate cumulative diversions of base flow at selected gaging locations on Little Rock Creek. Together with the available streamflow data, the calculated base-flow diversions were then used to estimate potential base flow (reference base flow) that may have occurred without the effects of groundwater withdrawals and use.

The model was also developed as a tool to inform development of and evaluate alternative water-use-management scenarios. The model has capabilities needed to compute estimates of the potential impacts of changes in groundwater withdrawals and irrigation, land cover, and/or augmentation of streamflow on base flow in Little Rock Creek at the monthly time scale. The model can also be used for preliminary, screening-level evaluation of impacts of groundwater use on other streams in the LRCA.

1.2. Study Area

Little Rock Creek is located north of St. Cloud, in Morrison and Benton counties. The study area is bounded by adjacent watershed divides to the east and south, the Skunk River to the North, and the Mississippi River to the west (Figure 1). The area of focus is Little Rock Creek and the portion of the groundwater flow system where groundwater withdrawals may affect base flow in Little Rock Creek.

Based on the elevations of surface-water features and water levels reported in well records, the groundwater-flow divide to the east approximately corresponds to the topographic watershed divides. The groundwater-drainage divide likely does not correspond to the topographic divide on the north and west sides of the watershed.

1.3. Previous Studies

Previous work reviewed for this study included reports published by the U.S. Geological Survey (USGS), Minnesota Geological Survey (MGS), DNR, and Minnesota Pollution Control Agency (MPCA) and unpublished reports and additional documents produced for water-appropriation permit evaluations and wellhead protection studies. Table C-1 in Appendix C summarizes the previous reports.

2. Data Review

This section describes the data that were used to characterize the hydrogeology of the LRCA.

2.1. Climate

Average annual precipitation (1981-2010) for the area is approximately 29 inches per year (State Climatology Office). Annual average May through October free water surface potential evaporation is approximately 29 inches based on data from 1956-1970 (Farnsworth et al. 1982). Average potential evapotranspiration approximately equal to average annual precipitation places the area in the transition zone between moist and semi-arid climates (State Climatology Office). Mean annual snow fall at the St. Cloud municipal airport is 47 inches with an average of 105 days per year with snow depth of at least one inch (National Climatic Data Center). Soil at the St. Cloud airport is frozen from mid-November to early-December through early March to mid-April (U.S. Army Corps of Engineers). Other information summarizing the climate and climate-change trends is provided in Appendix B.

Precipitation, temperature, humidity, cloud cover, and wind-speed data were compiled and processed for development of the surface-water-focused watershed model (GSSHA model) described in Appendix A.

2.2. Geology and Geomorphology

Geological data sources including well boring records, borehole geophysical logs, geotechnical and other borings, cores, near surface samples, and seismic soundings were compiled for the Geologic Atlas of Benton County (MGS 2010) and the Geologic Atlas of Morrison County (MGS 2014). A series of east-west geological cross sections at one kilometer (km) spacing of the Quaternary deposits and Quaternary stratigraphic and sand body surface grids were produced for the atlases to interpret subsurface Quaternary geology.

For the Morrison County Part B atlas DNR staff updated/corrected the coordinates for several wells that were included in the data set used for the Part A atlas (MGS, 2014). The changes to the data set included wells constructed after the Part A atlas data collection and corrections to the locations of irrigation wells based on information available in the MPARS database. The most up-to-date coordinates were used in the geological data analysis and interpretation described in the Geological Mapping section.

The Little Rock Creek study area straddles the boundary between two geomorphic zones defined by the underlying geology (Figure 2). The western part of the study area includes river terraces and sandy glacial outwash. This area is characterized by mostly droughty upland sandy soils, except in floodplains and depressions (Soil Survey Staff, NRCS).

The eastern part of the study area is characterized by drumlinized ground moraine formed by the Superior lobe ice sheet. Surficial geological materials are sandy loam till (MGS 2010b). The depressions between drumlin ridges contain peatlands with shallow organic material. The dense till impedes water movement through the soil profile. The drainage network is young and undeveloped, with extensive areas of wetlands present, although many wetlands are affected by artificial drainage. Some tributaries in the upper watershed have been ditched and straightened.

Bedrock in the area consists of crystalline, igneous and metamorphic rocks of Paleoproterozoic and Archean age (Jirsa and Chandler, 2010; Boerboom, 2014). Bedrock units generally have low permeability, although these rocks yield small quantities of water to low capacity wells where no other aquifer is available (Jirsa and Chandler, 2010). Depth to bedrock or weathered bedrock residuum varies from approximately 40 feet to approximately 300 feet (Jirsa and Chandler, 2010; Boerboom, 2014). A bedrock valley trends from north to south through the middle of the area.

Bedrock in the area is overlain by unconsolidated sediments deposited in association with multiple Quaternary continental glacial episodes. Most of the western part of the area is covered at the surface by glacio-fluvial sand and gravel deposits associated with an early stage of the Mississippi River and other drainage ways from the last glacial retreat (Setterholm, 2010; Lusardi, 2014). Sandy loam till deposited by the northeastern Provenance, Superior ice lobe covers most of the area to the east of the outwash and an area east of Royalton. Subsurface unconsolidated materials consist of complex deposits of diamicton (till), glacio-fluvial sand and gravel, and lake sand, silt, and clay.

The sand and gravel deposits and intervening lower permeability materials such as till act as a complexly inter-connected groundwater-flow system. The sand and gravel deposits behave as aquifers, but finer grained deposits such as till that act as aquitards are also permeable and allow leakage of water between aquifers as well as lateral groundwater flow.

2.3. Land Cover, Soils, and Topography

Land cover and soils data were compiled and processed for development of the GSSHA model described separately in Appendix A. Digital aerial imagery from the National Agricultural Imagery Program of the USDA Farm Service Agency and the U.S. Geological Survey were useful references for identifying features on the landscape. The DNR developed 1 meter (m), 3 m, and 30 m digital elevation models and 2-ft contours from LiDAR data state wide (Minnesota Geospatial Information Office). LiDAR flights in the Little Rock area occurred on April 29 and May 11, 2011.

The surface watershed of Little Rock Creek (Figure 1) is more than 90 percent rural with approximately 60 percent of the land area in agricultural uses (Benton SWCD 2010). Based on satellite derived crop estimates in the Cropland Data Layer, the largest crop areas were planted in corn, soybeans, and alfalfa (USDA, NASS 2009-13). Irrigated acreage is concentrated in the western part of the study area.

2.4. Streamflow

The USGS, DNR, and Minnesota Pollution Control Agency (PCA) have collected streamflow data in the Little Rock Creek watershed, and lake levels are measured in Little Rock Lake as part of the DNR's volunteer lake monitoring program. Streamflow measurement stations on Little Rock Creek and Bunker Hill Creek are shown in Figure 3. The most continuous data is available for station 15029001, with periods of continuous data dating to 1998.

Through 2014, the time period with the most continuously gaged flow data was 2008 through 2011 (at two stations on Little Rock and two stations on Bunker Hill Creek), although winter data were only collected at station 15029001. DNR has collected continuous data at three stations on Little Rock Creek since July 2014 and re-established continuous data collection at the fourth, downstream gage in June 2017.

Standard USGS methods were used to categorize the quality attributed to the records. Most of the records were categorized as "fair" (95 percent of the daily records are expected to be within 15 percent of the actual streamflow) or "poor" (records do not meet the criteria to categorize the accuracy). Details about the available stream-flow records are provided in Table C-2 in Appendix C.

In addition to stream-flow measurements and continuous gaging, DNR staff noted the presence or absence of flow at several Little Rock Creek tributaries and upstream locations on Little Rock Creek and Bunker Hill Creek during flow-measurement field visits in 2015 and 2016 (Figure 3).

2.5. Groundwater Levels

Groundwater level data were compiled from several sources. DNR observation wells located within the Little Rock Creek study area are shown in Figure 4. Most of the wells were constructed by the USGS for the water-table aquifer assessments reported in Helgesen (1973) and Lindholm (1980). Two wells (5006 and 5007) were installed to monitor water levels for a specific irrigation permit. Two single observation wells and a nested pair of observation wells were added in 2011 and 2012, and two new observation-well nest s were added in 2016. Data loggers were installed in most of the active observation wells in 2012. Several of the older wells have been replaced due to poor hydraulic connection or other problems. Details about the observation wells are provided in Table C-3 in Appendix C.

DNR surveyed elevations and measured water levels of private wells and DNR observation wells in and near the Little Rock watershed in April, July, and September of 2010 for the Benton County Part B Atlas. A total of 34 wells were measured during these “synoptic” measurements. Most of the wells are screened in one or more of the buried Quaternary aquifers. DNR and Benton SWCD staff repeated the synoptic measurements in March and August 2012 with some additions and substitutions to the wells that were measured. DNR also measured water levels in domestic wells sampled for the Part B Morrison County geologic atlas in the summer of 2016. Four of these wells were in the Little Rock Creek study area east of the Platte River.

A number of observation wells have been installed by permittees in the study area. Most recently, observation wells were installed in 2015 and 2016 by the applicants to support nine water-appropriation permit applications. These observation wells were utilized during aquifer testing of the production wells and have been monitored using data loggers.

2.6. Aquifer Tests

In addition to the summary information on pumping tests provided in Helgesen (1973) and Lindholm (1980), pumping-test data and analyses are also available in DNR permit files and Minnesota Department of Health (MDH) records. Pumping tests, including aquifer tests with observation wells and single well tests are listed in Table C-4 in Appendix C. Longer duration tests that include observation wells provide the best information to estimate hydraulic properties. The locations of the pumped wells are shown in Figure 5.

2.7. Groundwater Use

There are 212 active water appropriation permits covering 260 withdrawal installations in the part of the study area east of the Platte River. The best available information was used to generate an updated set of well location data for the study area.

Permit holders report annual-total and monthly water use to the DNR annually. Reported use data from 1988 through 2019 are recorded in the Minnesota Permitting and Reporting System (MPARS) data base. Water use reported prior to 1988 is in paper files. Permit holders are required to report water used within an accuracy of 10 percent. DNR has authorized a variety of methods for calculating annual water use. Most major crop-irrigation permit holders calculate monthly flow volumes by multiplying hours of operation (obtained from a timing devise and/or power bill) by the system’s nominal pumping rate.

DNR staff deployed acoustic flow meters that attach to the outside of a pipe on nine irrigation systems offered by volunteers during the 2018 and 2019 irrigation seasons. The data allowed for comparing metered versus reported average pumping rates for both seasons and total seasonal volumes for 2019 (DNR, 2021a). DNR developed the LRCA model prior to this metering study. Therefore, the study results were not available during model development. DNR later used the model to test the potential implications of the study results (See 8.3.1 Reduced Pumping).

The average/effective pumping rates applied for water-use reporting were more than 10 percent greater than the metered pumping rate for four systems and more than 10 percent less for one system. Metered pumping rates were consistent between 2018 and 2019.

In 2019, total reported volumes were more than 10 percent greater than metered volumes for 5 systems and more than 10 percent less than the metered volume for 1 system. For one system, both a larger-than-metered pumping rate and number of hours combined to push the volume difference over 10 percent. The reported pumping rate was close to the metered rate for one system, but the number of hours implicit in the reported volume was more than 20 percent less than metered hours. For one system, opposing differences in pumping rate and number of hours largely offset, resulting in a sufficiently accurate reported volume.

If the results generally indicate tendencies in reporting accuracy for the LRCA, under-reporting of irrigation volume by more than 10 percent may be rare. It is possible that the one case of under-reporting, which was due to under-reported hours of operation, was due to a reporting error, and may not be representative of other years. The results also suggest that it may be common to report irrigation volumes that are more than 10 percent greater than actual pumping volumes, mostly due to assuming larger than actual pumping rates.

Water withdrawals from private domestic wells or other sources that are pumped less than ten-thousand gallons per day or one-million gallons per year do not require a water appropriation permit, and water use is not reported. Across most of the area, the density of domestic wells is low, and domestic water use is a small fraction of total use. In areas served by subsurface sewage treatment systems (SSTS or septic systems) most of the water withdrawn from domestic wells infiltrates through the SSTS drain field and percolates to the water table. A portion of domestic irrigation water also percolates below the root zone and recharges the water table (irrigation return flow). Thus, for most domestic wells, the net withdrawal from the groundwater system is a fraction of the water pumped from the well.

2.8. Groundwater Isotopes and Chemistry

Groundwater isotope data and chemical indicators of anthropogenic influence help to define and validate the conceptual model of the groundwater-flow system. Groundwater sample analyses for major ions, tritium (^{3}H) and carbon-14 (^{14}C) were available for the area (Rivord, 2012; Minnesota Department of Health).

3. Geological and Hydrological Data Analysis and Discussion

This section describes subsurface geological mapping and hydrological data analyses completed to characterize the hydrogeology of the study area.

3.1. Geological Mapping

Because the Benton and Morrison County geological atlases (Setterholm, 2010 and Lusardi, 2014) were completed at different times as separate projects, there are differences in the geological interpretations and nomenclature in the two atlases. There were also new data available from well and boring records and updated information on well locations from permit files and DNR surveys.

To develop a consistent and updated geological interpretation, DNR staff re-interpreted geological mapping in the study area using updated well and boring records. This work included modifying the bedrock topographic surface (Figure 6), re-interpretation of the Quaternary stratigraphic surfaces within the Benton County portion of the area to match the Morrison County atlas, and modifications to the Quaternary surfaces within the Morrison County portion of the study area (See Appendix D for method details).

The stratigraphy of the Morrison County atlas (Lusardi, 2014) was adopted for the combined Quaternary geology of the LRCA. Within the LRCA, this framework includes 9 formations/members and 19 mapping units (Figure 7 and Table 2). These mapping units are associated with two provenances or geographic origins: the north-northwestern, Winnipeg provenance and the northeastern, Superior provenance. It is possible that deposits belonging to other formations are present in the study area, but these are expected to be thin and/or limited in extent. Similar methods to those used to develop the Quaternary unit surfaces for the published atlases were applied to the re-interpretations. Sand thickness grids are shown in Figures 8a through 8g.

MGS geologists reviewed the modified till-unit surfaces and sand-thickness grids for consistency with the geological framework. They concluded that the till surfaces appear to be consistent with the Morrison atlas surfaces; the sand thicknesses appear to be consistent with the atlas sand maps; and the stratigraphy applied to Benton County is consistent with currently available well records (Robert Tipping, pers. comm.).

There is a relatively high density of wells across the area of interest, generally allowing for major features such as extensive sand and till bodies to be identified and mapped in the sub-surface at the 1 to 100,000 scale of the atlases. In general, the number of available geological logs diminishes with depth. As a result, the MGS did not assign the deepest Quaternary units to any mapping unit in many areas, which were designated as undifferentiated.

Table 1 Quaternary geological units (derived from Lusardi, 2014)

Unit Code	Brief Description	Provenance
pgs	Sandy surface sediments, post glacial	Post-glacial
ms	Sand and gravel associated with the Mille Lacs Member of the Cromwell Formation	Northeastern (Superior)
ou	Sand and gravel above Cromwell Formation tills	Mixed northeastern (Superior) and north-northeastern (Rainy)
cst	Surficial sand and gravel (ice contact), and till above unit ct1	Northeastern (Superior)
ct1	Till of the Cromwell Formation above unit ct2	Northeastern (Superior)
cs2	Sand and gravel above unit ct2	Northeastern (Superior)
ct2	Till of the Cromwell Formation above unit ct3	Northeastern (Superior)
cs3	Sand and gravel above unit ct3	Northeastern (Superior)
ct3	Lower most till of the Cromwell Formation	Northeastern (Superior)
mls	Sand and gravel above unit mlt	Northwestern (Winnipeg)
mlt	Till of the Meyer Lake Member of the Lake Henry Formation	Northwestern (Winnipeg)
ebs	Sand and gravel above unit ebt	Northwestern (Winnipeg)
ebt	Till of the Eagle Bend Formation	Northwestern (Winnipeg)
es	Sand and gravel above unit et	Northwestern (Winnipeg)
et	Till of the Elmdale Formation	Northwestern (Winnipeg)
vs	Sand and gravel above unit et	Northwestern (Winnipeg)
vt	Unnamed till	Northwestern (Winnipeg)
suu	Sand and gravel within otherwise undifferentiated sediments	Unknown or mixed
Ups	Undifferentiated Pleistocene sediment	Unknown or mixed

For the portion of the study area in Benton County where the surfaces were entirely remapped, the entire Quaternary volume was assigned to stratigraphic units. Areas of undifferentiated sediments (not assigned to an stratigraphic unit) remained in the Morrison County portion of the model. When delineating the lateral extent of sand units, MGS geologists generally did not correlate (i.e. connect) sand bodies across more than one intervening cross section without boring data. Therefore, areas extending across more than one cross section without boring data for a stratigraphic interval were mapped by default as till or as undifferentiated deposits if at the base of the Quaternary. For the re-interpretation of Benton County, apparently thick and extensive sands, particularly in the bedrock valley, were extrapolated farther based upon geological judgement. These mapping preferences should be considered when interpreting the possible hydrogeological properties of areas with gaps in boring-log data.

3.2. Irrigated Areas

Irrigated agriculture is the largest category of groundwater appropriation in the area. DNR staff delineated irrigated crop areas within the part of the study area east of the Platte River using information in the DNR permits database (MPARS) and natural and color-infrared digital aerial photographs from 2003, 2008, 2010, 2013, and 2015 (Figure 9). DNR delineated newly permitted areas in 2019 using 2017 aerial photography and permit files. Reported irrigated acres were considered in the interpretation of aerial photographs because the boundary between irrigated and non-irrigated parts of a field is open to interpretation. Nevertheless, the delineated irrigated acreage is less than the permitted acreage for some permits (i.e., it appears that less acreage is irrigated than is allowed under the permit).

Irrigation is concentrated in the central and western portion of the area, where soils were mostly formed in sand with low water holding capacity. Some areas with sandy loam and loam textured soils underlain by till are also irrigated, such as in the moraine area east and northeast of Royalton (Figure 2).

3.3. Groundwater Heads

Evaluation of observation-well data included review of previously conducted trend analyses and characterization of vertical head differences at nested observation-well sites.

3.3.1. Trends

Trends in groundwater levels can be indicators of the effects of groundwater withdrawals on aquifer storage, although the influence of variation in recharge must simultaneously be considered.

Analysis of observation-well data for the period 1993 through 2012 did not indicate substantial trends in annual minimum or maximum water levels in the LRCA (Clean Water Fund Performance Report, 2014; Minnesota’s Clean Water Roadmap, 2014). This finding does not mean that groundwater use has not had an overall or long-term effect on groundwater storage. The lack of significant trends in water levels during the analyzed period suggests that influences of increasing groundwater appropriations on groundwater storage over this time period are variable and not distinguishable from climatic effects in this type of analysis. The lack of strong, long-term trends also allows for using a reasonable approximation of average conditions to initialize hydrological models rather than having to start with a pre-pumping condition.

The results support focusing sustainability evaluation on seasonal and inter-annual impacts to surface waters rather than risks of long-term aquifer depletion.

3.3.2. Vertical Head Differences

Water levels measured in observation well nests are local indicators of vertical head differences. Vertical head differences along with variations in the timing of water-level fluctuations are indicators of hydraulic resistance to vertical seepage in the area around the nest. Smaller head differences coupled with highly coincident head fluctuations suggest a stronger vertical hydraulic connection in the vicinity of the nested wells. Vertical head differences between aquifers indicate the direction of the vertical component of flow within the intervening aquitard. In addition to vertical head difference, the magnitude of vertical seepage also depends on the variable thickness and hydraulic properties of the aquifers and aquitards. Vertical head relationships at nested observation wells are summarized in Table 2 (See Figure 4 for locations).

These data reveal some of the variability in heads and vertical relationships. Vertical head differences at the nested well sites were less than or equal to 4 feet, except during pumping periods, and less than 1 foot at several locations. Vertical head gradients between the water table and buried aquifers are downward or close to zero at most locations but upward at the nest locations near Little Rock Creek. The vertical gradient between a shallower (cs3) and deeper (vs) buried aquifer was upward during non-pumping periods at two nest locations. Analyses of aquifer tests showed that the sand units screened by the permitted wells receive substantial leakage from vertically adjacent aquifers, and drawdowns propagate to the shallowest aquifer within hours to days (DNR permit files).

Table 2 Vertical head relationships at nested observation wells

Observation Wells (DNR observation well number or well unique number)	Screened Geological Mapping Units	Winter Head Difference (shallower minus deeper), ft	Maximum Summer Head Difference, ft	Distance to Nearest High Capacity Well, ft
49033, 49034	es, ou	3	> 10	2,680
49038, 49039, 49040	suu, vs, ou	-0.4 to -0.2	0	2,020
05013, 05014	vs, ou	-2 to -1	2 +	1,240
816443, 816444	es, ou	0 to 0.5	9	560
816439, 816440	mls, ou/ct1	-0.5 to 1.5	3	200
816441, 816442	mlt, ou	0 to 1	7	270
811555, 811556	vs, cs3	0.7 to 1	22	105
814736, 814737	vs, cs3	-1 to -0.1	16+	315
814763, 814762	vs, cs3	-4 to -3	49	130
811553, 811554	mls, cs3	1.5 to 2	14	815
811560, 811559	vs, ou	0.6 to 0.7	4	500
811558, 811557	vs/es, ou	0 to 0.2	8	50

3.4. Stream Base Flow

DNR estimated stream base flow from streamflow records, and stream-reach gains were characterized using field measurements of streamflow at multiple measurement stations.

3.4.1. Hydrograph Separation

Hydrograph analysis is a standard approach to separation of streamflow hydrographs into base flow and quick flow components (Barlow et al., 2014). Automated hydrograph separation provides reproducible estimates of base flow using standardized methods and available daily streamflow records. DNR staff completed hydrograph separations on the daily stream gaging records using several methods in the USGS Groundwater Toolbox (Barlow et al., 2014) and the Web-Based Hydrograph Analysis Tool (or WHAT) (Lim et al., 2005).

The base-flow results from the different methods were similar during low-flow periods but ranged more widely during higher flow periods. DNR staff selected the WHAT results for further application and analysis, which were close to the middle of the range of the base-flow estimates. The WHAT hydrograph separation method applies a two-parameter digital filter to daily flow data (Eckhardt, 2005). For Little Rock Creek, DNR staff applied the default parameters for a perennial stream with porous aquifers.

Year-round streamflow data and base-flow estimates (some missing data in 2012 and 2015) are available for stream gage 15029001 for the twelve-year period 2008-2019. Over this period, the average WHAT base flow was 17 cfs (cubic feet per second) or 5.5 inches per year over the 42.6 mi^2 surface-water drainage area. Eighteen years of streamflow record, from 1998 through 2019, were available for the month of August. Based on the daily August data from these 18 years, the August median base flow was calculated to be 4.9 cfs. The streamflow analysis completed by the DNR is further described in a separate report provided in Appendix B.

Appropriate interpretation of the WHAT hydrograph separation results under varying streamflow conditions and how WHAT base flow relates to groundwater discharge are important considerations when applying the results. The limits and potential biases of hydrograph separation should be considered when evaluating the groundwater-discharge component of streamflow during higher flow and snowmelt periods. The WHAT base flow may include other, “slower” flow sources in addition to just groundwater during and after runoff events (such as release from streambank storage, wetland discharge, tile drainage, and gradual snowmelt). WHAT base flow is expected to closely represent groundwater discharge during extended periods with limited, runoff-producing rainfall or snowmelt, such as low flow periods during the summer. Therefore, the WHAT base flow may be directly applied to represent groundwater discharge under these flow conditions.

Under flow conditions that may include a greater proportion of stormflow, snowmelt runoff, or return of bank storage, the proportion of streamflow derived from groundwater discharge is less certain. Groundwater discharge estimated using methods that include additional data, such as the chemical mass balance (CMB), can differ substantially from base flow derived from hydrograph separation methods (Arnold and Allen, 1999; Halford and Meyer, 2000; Stewart et al., 2007; Gonzales et al., 2009; Kronholm and Capel, 2014; Miller et al., 2015).

The filter that was applied in the WHAT hydrograph separation typically extracts larger average base-flow than does the CMB method, primarily due to higher flow periods (Lott and Stewart, 2016). The shape/timing of base-flow hydrographs derived from digital filter and CMB methods also differ during hydrograph rise and recession periods (e.g., Gonzales et al., 2009; Zhang et al., 2013; Cartwright et al., 2014). The base flow derived using the CMB method may itself be larger than the head-driven or Darcian groundwater discharge due to diffusion and mixing between groundwater and surface water at/near the streambed (Jones et al., 2006; McCallum et al., 2010; Park et al., 2011; Liggett et al., 2014). The head-driven component of groundwater-stream exchange is the net flux that affects streamflow rates and groundwater levels. Therefore, the WHAT base flow likely is larger than the flow attributable to groundwater discharge during higher flow periods.

3.4.2. Stream Reach Gains

Seepage runs (flow measurements at multiple locations along a stream network in one day) and continuous stream gaging data at more than one gage can show net gains or losses along whole stream reaches. The streamflow measurements made by the DNR and MPCA include multiple seepage runs per year at six gaging locations on Little Rock Creek and one location on Bunker Hill Creek in 2008 and each year since 2010 (Figure 3). Periods with minimal recent rainfall in which the WHAT base flow was equal to or nearly equal to the total flow at continuously gaged station 15029001 were used to identify seepage-run events representative of base-flow conditions. Continuous stream gaging data are available for two or three gaging stations on Little Rock Creek for different time periods, with some overlapping data from one station on Bunker Hill Creek.

Generally, under base-flow conditions, all reaches between stream measurement locations showed streamflow gains. Two typical examples under base-flow conditions in 2013 are given in Table 3. In July and September 2008, measured streamflow decreased for single reaches. For the period of continuous stream gaging at the three active, continuous stations (H15029003, H15029001, and H15029002) beginning in July 2014, however, there are no periods during which the data indicate a clear base-flow loss between gaging stations.

Rates of gain in base flow generally increase downstream, with the lowest gains in the upper-most Little Rock reach (above H15029005) and in Bunker Hill Creek, and the highest gains in the Little Rock Creek reach below Bunker Hill Creek. This pattern is most apparent when scaling the base-flow gains between measurement stations to the local drainage area between stations.

Additionally, DNR staff visually checked flow conditions approximately monthly at ungagged field-observation locations on Little Rock Creek and Bunker Hill Creek and at five tributary streams/ditch locations in 2015 and 2016 (Figure 3). Flow was observed in all of the tributaries except for dry locations observed during two of the visits (August 17, 2015 and September 21, 2015). Note that 2015 and 2016 were both relatively wet years.

Table 3 Examples of stream-flow reach gains along Little Rock Creek under base-flow conditions

Stream Gaging Stations Upstream to Downstream	Stream	8/29/13 Stream-flow (cfs)	8/29/13 Stream-flow Gain (cfs)	8/29/13 Stream-flow Gain / DA* (cfs/mi^2)	11/13/13 Stream-flow (cfs)	11/13/13 Stream-flow Gain (cfs)	11/13/13 Stream-flow Gain/DA* (cfs/mi^2)
15029005	Little Rock Cr.	0.95	0.95	0.07	1.84	1.84	0.14
15029004	Little Rock Cr.	3.37	2.42	0.35	5.26	3.42	0.49
15029003	Little Rock Cr.	5.35	1.98	0.13	7.43	2.17	0.15
15029001	Little Rock Cr.	7.70	2.35	0.32	11.7	4.2	0.57
15029002	Little Rock Cr.	11.00	3.30	1.16	14.4	2.8	0.96
15028002	Bunker Hill Cr.	0.75	0.75	0.04	2.12	2.12	0.13
15031001	Little Rock Cr.	19.60	7.85	1.57	22.2	5.7	1.13

* DA is drainage area in square miles.

3.5. Hydraulic Properties

A summary of estimated hydraulic properties derived from the aquifer tests and single-well pumping tests (listed in Table C-3) is provided in Table 4. The preferred property sets provided in the source materials were applied to the summaries in Table 5.The estimated hydraulic conductivity and specific storage values fall within the range of literature values for glacial materials (e.g. Heath, 1983) and other aquifer-test-analysis results from central Minnesota (Helgesen, 1973; Lindholm, 1980; Delin, 1990; Delin, 1995). Note that the aquifer horizontal hydraulic conductivity estimates span almost two orders of magnitude, and the aquitard vertical hydraulic conductivity estimates span more than two orders of magnitude. A wider range in aquitard hydraulic conductivity is expected, although aquitard hydraulic properties are generally less tightly constrained by aquifer-test analysis.

Table 4 Summary of hydraulic properties estimated from aquifer tests

Unit Type	Number of Tests	Horizontal Hydraulic Conductivity Range (Geometric Mean), ft/d	Vertical Hydraulic Conductivity Range (Geometric Mean), ft/d	Specific Yield Range (Mean)	Specific Storage Range (Geometric Mean), ft^{-1}
Water-Table Aquifers	6	150 – 580 (250)	[1] 4 – 8 (--)	[2] 0.05 – 0.21 (0.16)	--
Buried Aquifers	14	12 – 730 (110)	--	--	$1.9\text{x}10^{-6}$ -$1.2\text{x}10^{-4}$ ($9\text{x}10^{-6}$)
Aquitards	8	--	0.004 – 1 (0.04)	--	[3] $1.2\text{x}10^{-7}$ -$2.1\text{x}10^{-5}$ ($2\text{x}10^{-6}$)

[1] Estimated for two tests

[2] Minimum based on analysis of observation well screened in “clay and sand” beneath sand aquifer

[3] Estimated for four tests

The analytical methods applied to these tests assume that aquifer and aquitard (if included) thickness and properties can be treated as homogenous within the area of pumping influence during the test. Strict concordance to these assumptions is not always necessary for judicious application of analytical methods to lead to representative transmissivity estimates in the vicinity of the pumping well (e.g. Butler, 2009), but in complex settings the data often do not constrain the analysis to a single set of hydraulic properties.

The aquifer-test analyses show that hydraulic behavior in the LRCA groundwater system is not generally well represented by the uniform, “layer-cake” assumptions behind the analytical models. A single set of aquifer and aquitard property values typically did not result in a close fit to all of the observations. The aquifer-test analyses show that aquifer and aquitard properties and geometry are variable, not just between test locations but within the areas sampled by the aquifer tests, which spanned from tens to several thousands of feet.

The relatively large number of aquifer tests in the study area provide a solid base of information on the range of hydraulic properties, but they may not precisely represent the statistical variation of these properties across the area. For example, when constructing a high capacity well, drillers generally try to screen wells across a depth interval expected to have high transmissivity and avoid thin or likely lower transmissivity aquifers if possible.

The aquifer-test data provide direct evidence that hydraulic signals propagate relatively quickly through aquitards. Observation wells screened in the water-table or shallowest buried aquifer (where the water table occurs in a surficial aquitard) and a deeper buried aquifer were measured in 10 of the pumping tests. Drawdown was detected during the pumping period in the shallowest observation wells in all 10 of those tests. Drawdown was also detected in wells screened in sand bodies deeper than the pumped interval in several of the tests.

There is significant overlap in the hydraulic conductivity estimates for the different buried sand units. The hydraulic conductivity estimates for five of seven tests in the deeper, vs and suu units were less than the geometric mean for all buried aquifer values, however. This may be an indication that relatively lower hydraulic conductivity is more common in the deeper units but may simply be an artifact of test locations.

Well records typically record "static" and pumping water levels along with a pumping rate. These values can be used to calculate a well's specific capacity (pumping rate divided by pumping drawdown), which has been used to derive an approximate value of aquifer transmissivity in some studies. To test the potential utility of the specific capacity information in well records, transmissivities estimated from aquifer tests were compared to transmissivities estimated from the specific capacity for the same well. There was some correlation between the two estimates, but the discrepancies were generally large. Therefore, the specific capacity values were not further investigated.

4. Hydrogeological System

This section characterizes the hydrogeological system in terms of the hydrostratigraphic framework, groundwater residence times, the regional groundwater-flow field, and hydrological processes affecting groundwater flow and groundwater/surface-water interaction.

4.1. Hydrostratigraphic Framework

The sand and gravel deposits behave as aquifers, and lower permeability deposits such as till act as aquitards. Partial (or locally complete) erosion of the aquitards and their moderate permeability make the groundwater-flow system highly interconnected. Nevertheless, the Quaternary stratigraphy provides a useful reference frame for the hydrostratigraphic framework.

Several of the till deposits appear to be laterally extensive across much of the area (vt, et, mlt, ct3, and ct1 and 2). Subsurface Quaternary mapping relied primarily on sand intervals recorded in well records to distinguish stratigraphic units. Where sand units were not encountered, boundaries of till-dominated units were laterally extrapolated. The vertical boundaries between different till units is less hydrogeologically important than the lateral and vertical connections of sand units. Where sand bodies of different stratigraphic units (deposited at different times) overlap vertically, the boundary between units is not distinguishable from available data, but the position of such boundaries is also of less importance.

The Quaternary system may be divided into hydrogeological groupings based on the laterally extensive Quaternary formations/members. This provides a useful geological framework for describing the hydrogeological system in three dimensions. Each grouping includes a sand unit and the underlying till unit of the same formation/member. There is expected to be substantial overlap in the range of hydraulic properties of the several aquifer and aquitard units.

4.2. Groundwater Residence Times

Rivord (2012) reports the results of groundwater chemistry and isotope analyses for well samples from Benton County, and Baratta (2019) reports these analyses for Morrison County. Tritium concentrations were used to categorize samples as recent (recharged after 1950), mixed, or vintage age (recharge before 1950), and chloride-bromide (Cl/Br) ratios and nitrate-nitrogen concentrations were considered as indicators of anthropogenic influence.

In the Little Rock Creek area, most of the samples from wells screened in buried sand aquifers were categorized as mixed age, and samples having elevated Cl/Br ratios were common. Samples from six of 37 wells screened in buried sand aquifers in the LRCA east of the Platte River indicated recent age, and nitrate-nitrogen was greater than 10 mg/L in one of these samples. Samples from eight wells indicated vintage age.

The isotope and chemistry data indicate that groundwater residence times are relatively short across most of the system. Groundwater flows quickly (years to decades) from the water table aquifer to buried sand units, particularly where aquitards are discontinuous or thin, such as several areas between Little Rock Creek and the Platte/Mississippi Rivers in Benton County. Travel times to some, mostly deeper parts of the system are many decades to centuries, however.

4.3. Groundwater Flow System

The eastern groundwater-flow divide approximately corresponds to the topographical watershed boundaries (Rivord, 2012), which were used to define the eastern boundary of the study area (Figure 1). The topography of the eastern part of the study area is dissected into approximately east-west, elongated hills (drumlins) and adjacent lowlands. The natural drainage is poorly developed in this area, but the many of the low areas are partially drained by ditches. Although some shallow groundwater follows short flow paths to discharge in wetlands and ditches near where it was recharged, groundwater also seeps to the regional flow system. Regional groundwater flow is generally from east to west toward Little Rock Creek/Lake and streams to the north. Potentiometric heads indicate that groundwater in buried aquifers flows beneath Zuleger Creek toward Little Rock Creek (Rivord, 2012).

Buried sands are thinner and less laterally extensive in this area east of the outwash plain. Lateral groundwater flow may be focused in buried sands but flow through aquitard materials likely has a lateral component, especially between sand bodies.

Potentiometric surface contours in the buried aquifer system “bend” around Little Rock Creek where it crosses the outwash/river terrace plain, indicating that Little Rock Creek/Lake is a major discharge feature in this area (Rivord, 2012). The vertical component of flow is generally downward across most of the area but is directed upward beneath major discharge features such as Little Rock Creek based on potentiometric surface contours (Rivord, 2012) and measurements at observation-well nests. The Skunk River appears to be a major discharge feature where it crosses the outwash plain.

The relatively flat topography, permeable soils, and underlying water-table aquifer influence hydrological processes in the outwash plain and river terrace areas. Several wetland complexes occupy low areas, but most of the area is well drained by the highly permeable soils. Streams, ditches, and wetlands in this area appear to be well connected to the water-table aquifer.

To the west of Little Rock Creek, the groundwater flow divide is less well defined, and it may vary in location with depth. Beneath the headwaters of the tributary ditches on the west side of the creek, groundwater in buried aquifers may flow across the watershed divide and toward the Platte River (See Figure 1 for watershed divide and ditch locations). South of these ditches, groundwater flow is generally southward and crosses the watershed boundary. South to the City of Rice, the western groundwater-flow divide is nearly one mile west of the surface-watershed divide (Haglund, 2005).

The Platte River also appears to be a major discharge feature, but flow in buried aquifers may flow beneath the river in and south of Royalton (MDH, 2005). Analysis of a pumping test on a buried-aquifer well in Royalton indicated a very leaky response to pumping (MDH, undated). The drinking water supply management area for the City of Royalton is rated as vulnerable, indicating that, although the aquifers screened by the city’s wells are semi-confined, they are hydrologically connected to the surface. The Mississippi River is the regional discharge boundary for the system. Beneath/near the river, aquitards were completely or mostly eroded (Setterholm, 2010; Lusardi, 2014).

4.4. Groundwater-Surface-Water Interactions

The base-flow and seepage-run data indicate that all measured reaches of Little Rock creek are gaining reaches, although temporary periods of net loss may occur along some reaches. The rate of base-flow gain is generally greater where streams and tributaries cross the outwash plain/river terrace and is greatest in the downstream reaches. Large base-flow gains are consistent with the groundwater-flow pattern described above in which groundwater flows across the surface-watershed divides toward the lower reaches of Little Rock Creek.

The Little Rock Creek channel is highly meandered beginning about two miles, as the crow flies, upstream of stream station 15029005 (Figure 3). The floodplain includes shrub and wooded swamp wetlands, cut-off channels, and oxbow lakes. Some segments of the stream include two or more channels that carry flow, at least during higher flows. The riparian wetlands and side channels temporarily store flood water but act as groundwater discharge zones under most flow conditions, via direct discharges and evapotranspiration from the water table/capillary fringe. Direct transpiration of groundwater is also expected to occur in wetlands along tributary streams and ditches.

5. Model Construction

To be fit for purpose, the model had to represent groundwater-flow through the complex, three-dimensional hydrogeological system and interactions between saturated groundwater and the unsaturated soil and surface waters. Computer codes for modeling three-dimensional groundwater systems generally require that groundwater recharge be provided as an input and do not simulate unsaturated soil and surface-runoff processes.

To address these needs, the DNR developed separate models to represent surface (land surface and shallow vadose) processes and saturated groundwater-flow processes, which is a commonly used approach (Barnett et al., 2012). This entailed developing a watershed model (the GSSHA model) to compute water-table fluxes that were routed as net recharge to a three-dimensional groundwater-flow and stream base-flow model (the MODFLOW model). The MODFLOW model depended directly on outputs from the GSSHA model and computed the heads and flows of interest to the modeling objectives. Therefore, throughout the remainder of the report the MODFLOW model is referred to simply as “the model” unless a distinction is needed for clarity.

5.1. Scale

The groundwater-flow system in the LRCA is complex and heterogeneous. Determining the appropriate scale of representation of the properties and processes of the system is an important task in model development. The apparent, bulk hydraulic conductivity typically increases with the spatial extent of measurements from small to local scales but plateaus at the scale of aquifer tests in most aquifers (e.g. Bradbury and Muldoon, 1990; Rovey and Cherkauer, 1995). It is generally assumed that a groundwater-flow model can calculate reasonably accurate heads and fluxes, averaged over appropriately large areas, using representative parameters. This approach is backed by theory as well as successful model applications (e.g. Anderson and Woessner, 1992).

Representative head distributions and boundary fluxes at the resolved scale can be produced if regions having significant, large-scale trends or juxtapositions in hydraulic conductivity are not lumped (e.g. Beckie et al., 1994; Zhang et al., 2006). The major features that determine the distribution of hydraulic properties are the sand bodies (aquifers) and lower permeability till and lake deposits (aquitards). Based on the available aquifer-test data, hydraulic-property variation within aquifers in the LRCA may be primarily at the local scale. These local-scale variations cannot practically be resolved throughout the area of interest, but reasonable model results can be achieved at the scale larger scale affecting multi-mile stream reaches.

5.2. Model Codes

The model codes applied in this study were Gridded Surface Subsurface Hydrologic Analysis (GSSHA) (Downer et al., 2008), custom programs written in FORTRAN 90 to process input and output data, and MODFLOW-USG version 1.3.00 (Panday et al., 2013, 2015). The role of each modeling code is described below.

5.2.1. GSSHA

GSSHA is a distributed (gridded), physics-based hydrologic (and sediment and chemical fate and transport) model (Downer et al., 2008). Process components include precipitation distribution, snow accounting, frozen ground, evapotranspiration, one-dimensional (1-D) infiltration and soil moisture accounting, 2-D overland flow, 2-D groundwater flow, and 1-D streamflow with coupling between the flow domains. Model computations are performed on a regular 2-D grid. Some of the limitations of not fully coupling the MODFLOW model to the GSSHA model are alleviated by the fact that GSSHA includes two-dimensional groundwater flow. The gridded discretization of GSSHA also provides more spatial and process detail than semi-distributed watershed models. The GSSHA model development and results are described in Appendix A.

The GSSHA model computes cumulative percolation below the root zone at specified time steps for each cell, but the lag and attenuation from the base of the root zone to the water table is not represented. DNR staff wrote a computer program to read in cumulative percolation values for each GSSHA model cell, route the water to the water table, and write recharge input for MODFLOW-USG (the MODFLOW model). The routing process is described further under Recharge in the Sources and Sinks Section below.

5.2.2. MODFLOW-USG

MODFLOW-USG (Panday et al., 2013) is a member of the MODFLOW family of computer programs developed and supported by the U.S. Geological Survey for simulation of three-dimensional, steady-state and transient groundwater flow. “MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater/surface-water interactions” [https://water.usgs.gov/ogw/modflow/].

Whereas other versions of MODFLOW (Harbaugh, 2005; Niswonger et al., 2011) use the finite-difference method to solve the groundwater-flow equation on a rectangular grid, MODFLOW-USG uses a control volume finite difference (CVFD) formulation that allows unstructured grid types. This formulation allows for flexibility in the grid design, for example to focus resolution in areas of interest or where higher spatial accuracy is required. The code uses a modular design in which specific aspects of the flow system are represented using components called “Packages.” Applications of specific packages are described in the appropriate sections below.

5.3. Model Domain and Discretization

The GSSHA and MODFLOW models share a rectangular model domain of 36,200 meters (m) by 34,200 m (22.5 by 21.25 mi). Only the portion of the grid within the study area was included in the active flow domain (approximately 291 mi^2) for both models. The flow domain was discretized into a horizontal grid and vertically into layers for the MODFLOW model. Cells were inactivated where bedrock extended upward into model layers. This resulted in a MODFLOW model domain with 139,727 active model cells. There is no flow across the perimeter of the active flow domain.

5.3.1. Lateral Discretization

The model area was discretized into a base grid of 171 rows and 181 columns with a uniform 200-m spacing. Columns were oriented north-south (i.e. no rotation). This grid was used in the GSSHA model and was the “base” grid for the MODFLOW model.

The primary purpose of the model is to evaluate the impact of groundwater use on groundwater-stream interactions. Refinement of the grid near streams where they may experience groundwater diversions increases the precision of the location of stream channels and wells near the streams. Finer grid spacing also increases the accuracy of calculated hydraulic gradients and flows near the streams.

The lateral grid for the MODFLOW model was refined in selected areas using a smooth quadtree structure (Figure 10). The graphical user interface Groundwater Vistas, Version 6 (Rumbaugh and Rumbaugh, 2011) was used to generate the smoothed quadtree grid and assign node numbers to each cell. Ghost nodes were generated using the program GRIDGEN (Lien et al., 2015) to ensure accurate calculation of heads and flows between adjacent cells with different sizes (Dickenson, 2007; Panday et al., 2013). The grid was refined to 100-m spacing along rivers, streams, and lakes within the sandplain area east of the Platte River and further refined to 50-m spacing along Little Rock Creek and Bunker Hill Creek. An envelope of 100-m cells surrounds the 50-m cells. The area of 100-m cells was extended to include locations where pumping wells are separated from these streams by less than two base grid (200-m) cells to ensure that pumping wells near these streams are within the zone of refined grid cells.

5.3.2. Vertical Discretization

The geological mapping units were generally grouped into pairs with an aquifer unit overlying an associated aquitard unit for translation to six numerical model layers (Table 5). The shallowest buried sand unit (cs2) was included in layer 1 because it is the shallowest aquifer where it is mapped, and the water table occurs within it in some areas. The Meyer Lake member units (mls and mlt) were grouped with the Eagle Bend formation units (ebs and ebt) because the Eagle Bend formation is generally thin and of limited extent in the study area.

The 30-m grids of mapping-unit base elevations were interpolated to the model grid nodes. Cells were deactivated where the top of bedrock equaled layer top elevations. In several areas, model layers did not correspond to the hydrostratigraphic layer groups, however, to avoid excessively thick model layers and sharp changes in layer elevation between laterally adjacent cells (Figure 11).

In the northeastern part of the active model domain, the total saturated thickness of the combined ct1 and ct2 tills is mostly greater than 70 ft (20 m). There are expected to be significant vertical head differences between the water table and the base of unit ct2 in this area due to the thickness of these aquitards. By default, both of these units would be assigned to layer 1 (Table 5), but the model cannot resolve head differences within a single model cell. Computed heads within this thick interval would not be representative of either the water table or potentiometric heads at depth if represented with a single model layer.

To better represent the water table and vertical head differences in this area, the base of layer 1 was set to the base of ct1 instead of ct2, and the ct2/cs2 units were put in layer 2 (Figure 11). The hydrogeological properties of these units were expected to be similar to the properties of the underlying ct3/cs3 units in this area. The base of layer 1 transitioned to the base of ct2 around the inside perimeter of this area.

Table 5 Hydrostratigraphic unit groupings

Geological Mapping Unit	Aquifer / Aquitard	Group / Model Layer	Provenance
Qtu/pgs	Aquifer	1	Post-glacial
Qo/ou,	Aquifer	1	Mixed northeastern (Superior) and north-northeastern (Rainy)
Qci, cs2	Aquifer	1	Northeastern (Superior)
ct1, ct2	Aquitard	1	Northeastern (Superior)
cs3, ou	Aquifer	2	Northeastern (Superior)
ct3	Aquitard	2	Northeastern (Superior)
mls, ebs	Aquifer	3	Northwestern (Winnipeg)
mlt, ebt	Aquitard	3	Northwestern (Winnipeg)
es	Aquifer	4	Northwestern (Winnipeg)
et	Aquitard	4	Northwestern (Winnipeg)
vs	Aquifer	5	Northwestern (Winnipeg)
vt	Aquitard	5	Northwestern (Winnipeg)
suu	Aquifer	6	Unknown, mixed
ups	Aquifer/Aquitard	6	Unknown, mixed

In several areas near the Mississippi River and Little Rock Creek/Lake, the base of the surficial sand unit (ou) is deeply incised, and this unit is much thicker than the stack of units making up layer 1 in the immediately adjacent areas. In these areas of thick and deeply incised surficial sand, the base of layer 1 was smoothed, cutting across the ou unit (Figure 11). This transferred a portion of the thickness of the ou sand unit into layer 2. In these areas, hydraulic properties of the ou/surficial sand unit were assigned to the aquifer in layer 2 as well as in layer 1 (See 5.5 Hydrogeological Properties).

To represent the effect of the aquitard on the vertical leakance (resistance) in cells containing an aquifer overlain by an aquitard, quasi-three dimensional layers (McDonald and Harbaugh, 1988) were added beneath model layers 2-5. The quasi-3D layers add an extra term to the calculation of vertical conductance between cells, which can represent the vertical resistance to flow through an aquitard. The quasi-3D layers are represented in the model grid as an "empty space" between layers of grid cells. The thicknesses of the quasi-3D layers did not represent the actual thickness of the aquitards, but were made uniformly 0.1 m. This was accomplished by moving the layer bases up 0.1 m. The aquitard thickness was accounted for in the hydraulic conductivity assigned to the quasi-3D layers (See 5.5 Hydrogeological Properties).

In MODFLOW, model layers have to be laterally continuous. To accommodate this requirement in the MODFLOW model where hydrostratigraphic groups had zero thickness, a minimum layer thickness of 0.1 m was enforced, and the properties of the overlying layer were assigned. Model layer top and bottom elevations were adjusted accordingly.

Layer 1 of the model is unconfined, and the computed water-table is the top of the model domain of the MODFLOW model. A representative water-table surface was needed as input to define the depth to the water table for routing recharge and to assign hydraulic properties consistent with the saturated thickness of different material types within layer 1. The routing depths and saturated material thicknesses were estimated and were a fixed input. The representative water-table surface, therefore, effectively further discretized model layer 1 for those specific components of the model.

To generate this surface, a population of points representing the water-table was generated from well measurements and the LiDAR-based DEM. A 30-m gridded surface was interpolated from the points using the ArcGIS Topo to Raster tool. Raster cells that were above the 30-m DEM surface were then set to the DEM elevation to ensure that the water-table surface was at or below the land surface. Finally, the 30-m water-table grid was then interpolated to the model grid nodes.

5.3.3. Time Discretization

MODFLOW discretizes time into periods with uniform stresses (recharge, pumping, etc.) called stress periods that may be divided into any number of calculation time steps using a fully implicit solution method. The MODFLOW model was run using monthly stress periods. Final model runs divided the stress periods into daily time steps for numerical accuracy and for convenient analysis of model outputs.

The GSSHA model uses automated, variable time steps to efficiently maintain computational accuracy. Cumulative recharge (net percolation below the root zone) was computed at five-day intervals to be routed and aggregated to monthly recharge values for the MODFLOW model.

5.4. Sources and Sinks

Sources of water to the groundwater-flow system include precipitation and irrigation recharge and leakage out of surface waters. Sinks (loss) of water from the groundwater-flow system include evapotranspiration, discharge to surface waters, and withdrawals from wells and dug pits.

5.4.1. Recharge and Evapotranspiration

The net percolation/evapotranspiration from the root zone calculated by the GSSHA model was routed to a fixed, representative water-table, and applied to the MODFLOW model using the Recharge Package. Water year (October through September) totals for recharge, groundwater evapotranspiration, and net recharge are plotted in Figure 12. Inputs to the GSSHA model were soil and land cover properties; precipitation, humidity and temperature time series; irrigation time series; and groundwater pumping time series. See Appendix A for more details on the GSSHA model.

Input stresses were held constant over monthly time intervals (stress periods) in the groundwater-flow model (MODFLOW model), which smooths/disperses the timing of recharge. Therefore, the mode of routing recharge to the water table was not important where transit time from the base of the root zone is relatively rapid. For deeper water-table settings, the lag and attenuation of flow through the unsaturated zone to the water table had to be represented. At the monthly time scale, a detailed representation of unsaturated flow was not necessary. Instead, net percolation below the root zone computed by the GSSHA model (output as cumulative values over five-day time intervals) was routed using a simple function that varied the timing of recharge with depth to the water table. This vertically routed recharge was then aggregated to the monthly stress periods (See Appendix E).

5.4.2. Irrigation

Irrigation water is applied progressively across/around a field over a period of hours to days, with application to any given point over a period of minutes. This level of detail could not be included in the GSSHA model, and the details of application times, rates, and starting/ending points are not known. The modeled irrigation inputs were designed to reasonably approximate the effects of irrigation water on infiltration, soil moisture, and evapotranspiration.

For each irrigation event on a given field, water was applied to the land surface of all cells representing the field over a period of six hours to avoid extensive surface runoff while also accounting for the relatively rapid rate of irrigation application. The effects of drift, evaporation of droplets in the air, and evaporation from plant surfaces during water application could not be accounted for in the GSSHA model. Therefore, the amount of irrigation water applied was multiplied by 0.92 to represent the losses not explicitly modeled, resulting in a reasonable net irrigation efficiency (Yonts et al., 2007). Details on how monthly irrigation volumes for each permit were partitioned into irrigation-application time series for input to the GSSHA model are provided in Appendix D.

5.4.3. Groundwater Withdrawals

Withdrawals from wells, dug pits, and ponds were included in the model as monthly averaged rates based on monthly reported volumes for each pumping installation. Well locations and screened model layers are shown in Figure 13 and annual total withdrawals are plotted in Figure 14. The Well Package was used to extract pumped water in the MODFLOW model.

Eight irrigation permits had more than one active pumping installation but reported only the total withdrawals without separate volumes for each installation. Such multiple installations covered under one permit are typically run simultaneously to supply a single irrigation system. For these eight permits, reported pumping volume for each permit was apportioned to each installation based on the ratios of the pumping capacities for each installation, which were determined from information in the permit files.

The model cell(s) that correspond to the screened interval for each well were determined by comparing the screen top and bottom elevations with layer top and bottom elevations at the well locations. Where a well screen was in more than one layer, the pumping rate in each cell was apportioned by layer thickness. Accurate apportioning of fluxes to each layer for multi-layer wells was not important because of the low vertical resistance between layers at these locations (i.e. sand in both layers at the layer interface).

5.4.4. Surface-Water Network

Surface waters in the study area include ephemeral/intermittent streams and ditches, perennial streams and rivers, lakes, and ponded and intermittently flooded wetlands. Surface waters act as boundaries to the groundwater-flow system, where water is recharged or discharged. The representation of surface-water features in the GSSHA model is described in Appendix A. Rivers, streams, ditches, and lakes were represented in the MODFLOW model using several boundary condition packages (Figure 13).

The Mississippi River was represented as constant-in-time fixed heads in the top layer of cells using the Time-Variant Specified Head (CHD) package. Water elevations were taken from the LiDAR-based DEM (NAVD 88 datum).

The Skunk and Platte rivers and lakes (Skunk, Rick, Little Rock, and Mayhew) were represented with the River (RIV) package (Harbaugh, 2005). The RIV package employs a head-dependent flux boundary in which the flow between the surface water and the groundwater system within the same model cell is controlled by the head difference and a conductance term. RIV cell conductance was specified by multiplying the surface area of the water feature within a cell by a leakance parameter. Water elevations for all of these features except Little Rock Lake were taken from the LIDAR-based DEM and not varied in time. The elevation of Little Rock Lake was specified as the average measured water elevation, converted to the NAVD 88 datum.

Streams and rivers outside of the Little Rock Creek watershed and in headwater areas of Buckman Creek were represented using the Drain (DRN) package (Harbaugh, 2005). This package is similar to the RIV package except that flux is only allowed into the boundary feature, and there is no water exchange if the groundwater head is below the specified drain elevation. This allows for a reasonable representation of the effect of ephemeral/intermittent features.

The Buckman Creek, Little Rock Creek, and Zuleger Creek networks were represented using the Stream-Flow Routing (SFR) package (Prudic et al., 2004; Niswonger and Prudic, 2005). The SFR package employs a head-dependent-flux boundary condition, but the head in the stream is iteratively calculated, accounting for stream-groundwater exchange and steady-flow routing downstream. Stream properties, including beginning and ending bottom elevation, width, bottom thickness, and bed-sediment hydraulic conductivity are specified for stream lengths called segments.

Streams were manually digitized using digital aerial photographs and the 1-m, LiDAR-based DEM in ArcMap. The stream channel-bottom elevation was set at segment end points based on the DEM. The DEM overestimates the elevation of the channel bottom. Stream-flow measurement profiles tied to surveyed benchmarks were used to determine how much to adjust stream bottom elevations for Little Rock and Bunker Hill creeks. For smaller channels, the stream bottom was assumed to be 0.3 to 0.5 m lower than the 1-m DEM elevation. Streams were divided into segments having relatively uniform slope, width, and underlying surficial geology. Segment boundaries were also placed at grid-spacing transitions.

Several methods are available to calculate stream depth and width in any given segment. For Buckman Creek, Bunker Hill Creek, other tributaries to Little Rock Creek, and Zuleger Creek, for which representative channel cross section data were not available, Manning's equation for a wide rectangular channel was used. Manning's n values from 0.04 to 0.1 were assigned based on stream sinuousity, width, and slope characteristics. Stream widths were estimated considering aerial photos, the 1-m DEM, and typical channel widths.

For Little Rock Creek and Bunker Hill Creek segments that included streamflow measurement stations, information about stream cross-sectional area, width, and flow from stream-flow measurements were incorporated through use of power functions to dynamically calculate stream depth and width in each SFR cell (Leopold and Maddock, 1953):

$$w = aQ^b$$

$$d = cQ^f$$

where

w = width (m)

d = mean depth (m)

Q = discharge (m^3/d)

a, b, c, and *f* are numerical constants.

These flow versus width and depth relationships are not the same as the rating curves used to calculate streamflow at a gaging station. They were applied to employ reasonable depth-width-flow relationships for a whole stream segment based on information from the stream. The constants were estimated from scatter plots of measurements of width and depth versus flow for gaging stations H15029005, H15029003, H15029001, H15028002, and H15031001. Most measurement cross sections at gaging stations H15029004 and H15029002 did not appear to be at locations representative of the natural channel (e.g. in the culvert). The resulting power equations were applied in the SFR package in the segments containing the gages and adjacent segments. The constants are given in Table 6.

Table 6 Power equation coefficients used to calculate width and depth in the SFR Package

Gaging Station	a	b	c	f
H15029005	0.074	0.44	0.00153	0.542
H15029003	1.82	0.12	0.0026	0.41
H15029001	0.20	0.35	0.0079	0.34
H15028002	0.59	0.21	0.083	0.093
H15031001	1.22	0.184	0.0045	0.585

5.5. Hydrogeological Properties

In a numerical groundwater-flow model, hydraulic conductivity (horizontal and vertical) and storage properties (specific storage and specific yield) must be assigned to each grid cell or element. Properties controlling the conductance between the groundwater-flow system and surface waters also have to be assigned. These properties vary between different geological material types and also vary within each geological material type. Effective properties also vary with scale (the size of the area represented by a property value).

Model layer bottoms were generally aligned with bases of geological formations or members that included both aquifer and aquitard materials. This approach aligned the model layering with geological features, but necessitated allowing model cells to contain more than one geological unit. Therefore, hydraulic properties were assigned to each model cell as effective properties based on the distribution of hydrostratigraphic units within the cell (in most cases one or two units). The aquifer-test derived estimates for these properties (See 3.5 Hydraulic Properties) were used as a guide to the range of expected values during the model history-matching process.

5.5.1. Hydraulic Conductivity

5.5.1.1 Hydrostratigraphic Units and Zones

Hydraulic conductivity was assumed to be vertically anisotropic but isotropic in the horizontal direction at the scale of interest. Effective hydraulic conductivities were assigned based on the distribution and thickness of hydrostratigraphic units in each model cell, except where special hydraulic conductivity zones were assigned in layers 5 and 6 (Figures 15a – 15f).

Aquifer units in layer 1 included the pgs, ou, and cs2 sand units. The upper part of the surficial outwash (ou) is typically fine-grained sand, but the unit includes layered medium sands and gravelly sand. Aquifer-test analyses also suggest that the surficial outwash may commonly have relatively high hydraulic conductivity. Therefore, thicker sequences of surficial outwash are likely to have high bulk hydraulic conductivity, but the upper part of the outwash likely has relatively lower hydraulic conductivity. To address this in the model, areas with surficial sand greater than 10 feet (3 m) in thickness were assigned to a different hydraulic conductivity zone than sands/aquifers elsewhere in layer 1 (Figure 15a). Where surficial sand extended into layer 2, layer 2 was assigned the same zonal properties as layer 1.

As noted in Part 1 (Geological Mapping), buried sand units were not extrapolated beyond areas of nearby well control in Morrison County, leading to areas without nearby well control being mapped as till by default or as undifferentiated sediment. Laterally extensive sands (units vs and suu) were mapped overlying the bedrock valley in Benton County for this study (Figure 8). In some areas to the north in Morrison County, the deepest sediments were mapped by default as not sand by Lusardi (2014). Hydraulic conductivity zones were added to these potential unmapped aquifer areas in layers 5 and 6 (Figures 15e and 15f). During history matching these zones were allowed to take on properties that differ from the properties assigned to their mapped geological material types.

5.5.1.2 Effective Hydraulic Conductivities

Because model cells could contain more than one hydrostratigraphic unit, effective properties had to be assigned to those cells. For layered materials, the effective hydraulic conductivity is the arithmetic mean in the direction parallel to the layers and the harmonic mean in the direction perpendicular to bedding, weighted by the thickness of each layer. The harmonic mean (H) of a set of *n* numbers x_i (where *i*=1, …, *n*) is defined by:

$$H = \frac{n}{\sum_{i=1}^{n} \frac{1}{x_i}}$$

These relationships were the basis for assigning hydraulic conductivity to each model cell based on the distribution of hydrostratigraphic units in the cell. The procedures for determining these distributions are described below. First, we describe how the effective properties were calculated. The fraction of a cell occupied by each hydrostratigraphic unit was used to calculate the arithmetic mean. For a cell containing an aquifer and an aquitard, the effective horizontal hydraulic conductivity (effective HK) is:

$$(aquifer\ fraction\ \times aquifer\ HK) + \ (aquitard\ fraction\ \times aquitard\ HK)$$

As mentioned above under Discretization, quasi-3D layers were used to represent the effective leakance (hydraulic conductivity / thickness) of aquitards in cells that also include an aquifer. The quasi-3D layers were assigned a uniform thickness of 0.1 meter. To attain the correct leakance for the aquitard, the vertical hydraulic conductivity (VK) of the quasi-3D layer is:

$$\frac{aquitard\ VK\ \times 0.1}{aquitard\ thickness}$$

Because in layer 1, only the vertical hydraulic conductivity of the bottom half of the cell factors into calculation of the vertical conductance (i.e. there is no vertical conductance with a cell above), layer 1 was not given a quasi-3D layer. Instead a separate aquitard fraction for the bottom half of cells in layer 1 was calculated similarly to aquitard fraction for whole cells used to calculate effective HK. Then the vertical hydraulic conductivity of a model cell in layer 1 was calculated as:

$$\frac{aquitard\ VK}{bottom\ half\ aquitard\ fraction}$$

To implement the effective hydraulic conductivities, the effective values had to be calculated and then applied to the numerical solution. Rather than calculate the effective values externally and then provide the values as input, the effective hydraulic conductivities were calculated within MODFLOW using the additive parameters feature with zone and multiplier arrays (Harbaugh, 2005, pp. 8-2 to 8.7). This feature allows multiple parameters (in this case hydraulic conductivity of each hydrostratigraphic unit) to be applied to each cell using multiplier arrays assigned to cells by zone arrays. The multiplier and zone arrays were derived from the 30-m stratigraphic model grids as described in Appendix D.

5.5.2. Stream/Lake-Bed Conductance

The conductance is a lumped parameter representing the overall head loss in surface-groundwater exchange at the scale of the model grid cell, incorporating the effects of hydrogeological properties of the aquifer or aquitard and the stream/lake bed, area of the surface water within the cell, and cell size (Mehl and Hill, 2010; Morel-Seytoux et al., 2014). Conductance was calculated using a leakance parameter (units of day^{-1}) and area of the feature within the cell.

Surface-water leakance was parameterized into groups based on surficial geological material and feature types (Figure 16): streams/ditches overlying till; streams/ditches overlying sand; Little Rock Creek overlying sand above Bunker Hill Creek; Bunker Hill Creek overlying sand; lower Little Rock Creek; peripheral/”far field” drains; lakes and ponded stream segments; and rivers.

Published streambed leakance values in modeling studies of streams in glaciated terrain in Minnesota and Wisconsin are typically in the range of 0.01 to 30 d^{-1} (Table 7) (Stark et al., 1994, Lindgren and Landon, 2000; Lindgren, 2002; Feinstein et al., 2012; Hunt et al., 2013; Hunt et al., 2016; Bradbury et al., 2017). These leakance values overlap the corresponding ranges of hydraulic conductivity, assuming a 1-m thickness, for the sediment types in the stream beds and surrounding surficial geological materials (Heath, 1983). Heterogeneous streambed materials may lead to preferential, local discharges that affect the reach-scale, effective streambed leakance, but these local-scale details could only be resolved with intensive, local-scale field investigations.

Table 7 Streambed leakance from modeling studies of glaciated terrain in Minnesota and Wisconsin

Geologic Setting	Range of Streambed Leakance (day^{-1})
Glacio-fluvial	1 to 30
Till or wetland	0.01 to 1

5.5.3. Storage Properties

Two specific storage parameters were assigned, one for aquifers and one for aquitards. For model cells with more than one material type, the effective specific storage for the cell was calculated as the arithmetic mean as in Anderman and Hill (2000). This approach to representing the overall storage of the aquifer and aquitard in a model cell is appropriate at the spatial and time scales applied in the model. Three specific yield parameters were assigned for each of the following conditions: water table in sand, water table in an aquitard (till, clay, silt), and water table in a wetland over till (Figure 17).

6. History Matching and Sensitivity Analysis

History matching is the process of estimating parameter values and testing alternative conceptualizations or parameterization of features to achieve an acceptable fit of model outputs to observations. Model revisions are constrained by information in the available field data and professional experience and judgement.

History matching for the GSSHA model was carried out through a manual history-matching process. GSSHA model development is described in Appendix A.

The steady-state model used average net recharge and reported pumpage from 2008 through 2012. The transient model used the steady-state model output as initial conditions for monthly stress periods from January 2005 through September 2014. The modeled time periods were selected based on data availability at the time of model development and practical run times. Because the steady-state model is an approximation of initial conditions, transient model results from January 2005 through February 2006 were ignored to allow for model initialization or spin up.

6.1. History Matching Criteria

The adequacy of model results was gaged using several data-fit statistics; plots of model residuals; visual inspection of base-flow and observation-well hydrographs; and maps of model residuals. These measures were selected to evaluate the fit to heads and flows, overall bias, spatial distribution of residuals, qualitative aspects of system behavior, and congruence with the conceptual model (Anderson and Woessner, 1992; Reilly and Harbaugh, 2004; Barnett et al., 2012). Criteria that reflect overall or spatially averaged fit were emphasized in accordance with the scale of the model and its purpose. History matching goals are listed in Table 8 and were selected from recommendations in Anderson and Woessner (1992), Moriasi et al. (2007), and Crooks et al. (2012).

The Nash-Sutcliffe efficiency (NSE) is a normalized statistic commonly used as an indicator of the fit of modeled to observed-flow variations. It ranges between $-\infty$ and one (1), with NSE = 1 indicating a perfect fit. The NSE is sensitive to outliers, however, and a relatively small NSE value may result from a few large residuals. Percent bias (PBIAS) indicates the tendency of computed values to be larger or smaller than the observations with optimal PBIAS = 0. PBIAS is an indicator of overall volume errors when calculated from flows. Mean error (ME) provides similar information in the units of measurements. Root mean square error (RMSE) is a commonly used index of the magnitude of model residuals. The RMSE can be standardized or scaled to give a relative value. The RMSE-observations standard deviation ratio (RSR) is calculated as the ratio of RMSE and standard deviation of observations, with RSR = 0 indicating a perfect fit. $RMSE_n$ is the RMSE scaled to the range of observations and is commonly used as an indicator of the relative amount of head error in a groundwater flow model. Formal definitions for these are provided in Appendix E.

Table 8 History matching criteria and goals.

Feature	Statistic / Measure
Base flow	Monthly NSE > 0.5
Base flow	-15 < PBIAS < 15
Base flow	Seasonal minimum month
Base flow	RSR ≤ 0.7
Base flow	Presence/absence of base flow
Groundwater head	$RMSE_n < 0.05$
Groundwater head	-1.5 ft < ME < 1.5 ft
Groundwater head	Long-term amplitude similar in most wells
Groundwater head	Timing of maxima and minima
Groundwater head	No systematic spatial bias

6.2. Model Revisions and Steady-State Parameter Estimation

Model revisions during the history matching process included exploring different degrees of parameterization and simplification and revisions to the representation of the stream network. The process for selecting the final parameter set is described below. Initial model testing indicated that, based on the distribution of recharge and groundwater discharges calculated by the GSSHA model, many of the small ditches and streams in the eastern part of the model domain received groundwater discharge. As a result, the initial number of streams and ditches that were represented with boundary packages in the MODFLOW model were expanded.

6.2.1. Parameter Estimation Strategy

The model was initially constructed with a limited number of parameters as recommended by Hill (2006) to test the conceptual model and data support for more complex/detailed parameterization. This parameter set included three material types: 1) sand and gravel aquifers, 2) northeast provenance aquitards, and 3) northwest provenance aquitards. After initial testing with this simple parameterization, the number of aquifer, aquitard, and stream-bed hydraulic conductivity parameters were expanded to test different parameterization schemes. Parameters that were less sensitive or were not well constrained by the available data were then fixed or lumped into a smaller set of estimated parameters to determine the final set of estimated parameters (Tables 9-11).

This approach balanced improved data fit against the risk of over fitting model parameters (Reilly and Harbaugh, 2004). Over-fitting of model parameters involves improving the fit of model outputs to data by applying parameter values that are likely not the most realistic representation of a specific feature of the system to compensate for structural or data limitations (Vrugt et al., 2005; Doherty and Welter, 2010). The "wrong" parameter value may force a better model-to-observation fit but may not be the most suitable value for making predictions (Doherty and Welter, 2010; White et al., 2014). During automated parameter estimation, if parameters took on values outside of the expected range or relationship to other parameters (e.g. hydraulic conductivity of till higher than of sand) or there were large changes to relatively insensitive parameters, these were taken as indicators of over fitting.

The aquifer-test analysis results and geological interpretations were used to set bounds on the ranges of potential parameter values. The aquifer-test results suggested that the hydraulic conductivity of the water-table aquifer(s) may tend to be higher than the buried aquifers. The test results also suggested that the effective hydraulic conductivity of the deeper units (vs and suu) may, on average, be lower than the other buried units. Additionally, it is possible that the sub-surface geological mapping over-extrapolated the thickness and lateral extent of the deepest units in some areas. Few wells were drilled through the bottom of these units and fewer wells were drilled to the depth of these units compared to shallower units.

Table 9 Hydraulic conductivity parameters.

Horizontal Hydraulic Conductivity Parameter	Lower bound ft/d (m/d)	Upper bound ft/d (m/d)
khss (ou/pgs)	66 (20)	330 (100)
khcs (cs2, cs3)	66 (20)	330 (100)
khmls (mls), tied to khcs	66 (20)	330 (100)
khes (es)	59 (18)	330 (100)
khvs (vs, layer 5 zone), tied to khes	49 (15)	330 (100)
khds (suu, layer 6 zones), tied to khes	49 (15)	160 (50)
khupsu (ups)	0.33 (0.1)	16 (5)
khc1 (ct1, ct2 in layer 1)	0.33 (0.1)	9.8 (3)
khc (ct2, ct3 in layer 2)	0.33 (0.1)	4.9 (1.5)
kht (mlt, et, vt), tied to khc	0.033 (0.01)	3.3 (1)
Vertical Hydraulic Conductivity Parameter	**Lower bound ft/d (m/d)**	**Upper bound ft/d (m/d)**
kvs (all sand units, layer 5 zone)	3.3 (1)	33 (10)
kvc1 (ct1, ct2 in layer 1)	0.013 (0.004)	0.066 (0.02)
kvc (ct2, ct3 in layer 2)	0.013 (0.004)	0.066 (0.02)
kvt (mlt, et, vt, ups)	0.0066 (0.002)	0.05 (0.015)

Table 10 Surface-water leakance parameters.

Parameter	Lower bound (day^{-1})	Upper bound (day^{-1})
sc2 (streams and drains overlying till)	0.01	0.25
sc (streams overlying water-table aquifer)	0.5	5
sc1 (Little Rock Cr. on sand plain above Bunker Hill Cr. and lower Bunker Hill Cr.)	0.5	10
sc3 (Lower Little Rock Cr.)	0.5	7
rivriv (rivers, fixed)	1.0	1.0
rivlk (lakes, stream impoundments, fixed)	0.1	0.1
drnbc (peripheral drains, fixed)	0.5	0.5

Table 11 Storage parameters

Parameter	Lower bound	Upper bound
sys (specific yield sand)	0.15	0.2
syt (specific yield till)	0.05	0.15
syw (specific yield wetland over till)	0.05	0.2
sss (aquifer) , ft^{-1} (m^{-1})	1.5×10^{-6} (5×10^{-6})	1.5×10^{-5}(5×10^{-5})
sst (aquitard) , ft^{-1} (m^{-1})	3×10^{-5} (1×10^{-5})	5×10^{-4} (1.5×10^{-4})

Separate hydraulic conductivity parameters were initially assigned to each aquifer unit; each aquitard type (surficial northeast provenance, northeast provenance, and northwest provenance); the separate zones assigned in layers 5 and 6; and the unmapped (undifferentiated) sediments in layer 6. Only one vertical hydraulic conductivity was estimated for the aquifers, however, because it was not a sensitive parameter.

The effective conductance of stream beds was parameterized by assigning leakance parameters to groups of boundary condition cells/stream segments. After initial testing, leakance values for lake beds and the rivers represented using the River Package were fixed because these features are more distant from the focal area of the model. Next, eight stream-bed hydraulic conductivity parameters were allowed to vary: Drain Package cells, stream segments underlain by till, streams and tributaries underlain by sand, five Little Rock Creek segments on the sand plain, and Bunker Hill Creek on the sand plain.

This expanded set of parameters was reduced to the final set listed in Table 9. The distribution and types of target data were considered in deciding the final level of parameter simplification. Vertical head differences between model layers were relatively small compared to the overall variation of heads across the model domain. Head targets at any given location, particularly in the buried aquifers, are strongly influenced by hydraulic properties throughout the whole thickness of the model domain.

Therefore, although it is known that properties vary spatially within hydrostratigraphic units, the available data did not provide strong support for delineating spatial variations of hydraulic properties within individual hydrostratigraphic units. Estimated values for different units were also cross-correlated.

PEST outputs were reviewed and considered in aggregate before selecting final parameter values. After two to four iterations of the parameter estimation process, the reduction in the objective function was typically very small. During the later iterations, some parameters that had been within the assigned bounds were pushed to a substantially different value. Also some parameters that had started at the same value and had continued to have very similar values diverged in later iterations. These later iterations did not significantly improve the fit and were regarded as over fitting.

To reduce over-fitting during the later stages of the estimation process, the last iteration with an objective function value within two percent of the final value was used as the basis for the final parameters. Also, parameter values were rounded to two significant digits. Finally, parameters that PEST assigned very similar values (e.g. the horizontal hydraulic conductivity of buried sand units es, vs, and suu) were assigned the same value. The objective function of this final parameter set was then calculated to ensure that it fell within two percent of the range of objective function values from the later PEST iterations. This resulted in a better constrained parameter set with reduced risk of excessive over-fitting.

Following this process, the separate hydraulic conductivity zones in layers 5 and 6 were merged with the parameters defining aquifer properties for these two layers. Parameter estimation results indicated that these zones were better represented with the relatively high hydraulic conductivity of aquifers. Late parameter estimation iterations pushed the hydraulic conductivities of these zones much higher than the adjacent aquifers with minimal reduction of the objective function. Since there were no head targets within these zones, the very high conductivities were interpreted as over fitting.

The recharge input derived from the GSSHA model was not further subjected to parameter estimation during the history matching process for the MODFLOW model. The net recharge values were internally consistent and dependent on the complex processes modeled with the GSSHA model. Adjusting the GSSHA computed recharge, for example through the use of one or more multipliers, could result in water-balance disparities, such as irrigation-return flows not consistent with reported irrigation amounts. Parameter estimation for the GSSHA model is described in Appendix A.

6.2.2. Steady-State Data Targets

History matching of the steady-state model focused on comparison of modeled to measured groundwater heads. Stream base-flow estimates were initially included in the parameter estimation process but later removed as explained below.

Five sources of water elevations representing groundwater heads were used for history matching: DNR observation-well measurements, 2010 and 2012 synoptic event measurements from private water wells, privately owned observation-well measurements, Morrison County geologic atlas well-sample measurements, and LiDAR-based DEM pond elevations. The head difference between the water table and buried aquifer (es) wells at one observation-well nest (49033 and 49034) were also used as a separate head target. Most Well and Boring Records include “static” depth-to-water measurements made at the time of well construction. Groundwater heads based on these records are less accurate and/or not representative of average heads during the steady-state modeled period and were, therefore, not used directly in the history matching process.

To gauge whether the average of synoptic measurements were representative of average levels over the 2008-2012 steady-state modeling period, average water elevations in observation wells were compared to the averages for the synoptic events. The synoptic averages were all within 0.4 foot (0.1 meter) of the averages of all data, which is small relative to the range of measurements and expected model fit at any given point. Some of the wells were measured in only one year. Nevertheless, there were multiple, accurate measurements made at each well. For the other measured data sets (private observation wells, county geologic atlas well samples, and pond elevations), the differences between the measured values used and the 2008-2012 average are also expected to be relatively small.

Base-flow estimates offer a data target tied to groundwater fluxes. Streamflow data were available from station H15029001 for the entire 2008-2012 period with the exception of March and April 2012. Streamflow data were not available from station H15031001 during winter (generally December through March) or for 2012. To estimate the 2008-2012 average base flow, streamflow during periods of missing record was estimated using a previously developed regression relationship with station H15029001. The combined measured and regressed flows were then processed by the WHAT tool.

Computed base flow in the steady-state model was primarily controlled by the distribution of net recharge derived from the GSSHA model and was relatively insensitive to parameter changes within the MODFLOW model. Including observations that are not sensitive to parameter adjustments can interfere with the parameter estimation process rather than enhance it; therefore the base-flow estimates were removed from steady-state parameter estimation. Transient model results were compared to monthly WHAT base flow at the same gage (See 6.3 Transient Parameter Estimation below).

Base-flows were not targets during parameter estimation for the MODFLOW model because of uncertainty in the average groundwater discharge over the steady-state model period. The relative amount of base-flow gain along each stream reach between seepage run sites was compared to measurements, however, as a qualitative check on model fit after parameter estimation. This was accomplished by comparing the relative magnitudes of computed base-flow gains for different stream reaches to reach gains measured during seepage runs under base-flow conditions. For example, measured base-flow gains in the lowest reach (above gage 15031001) were typically about double the gain between the long-term gage (15029001) and the next downstream gage (15029002).

In addition to measured streamflow, the qualitative streamflow observations at ungagged sites suggested that tributary ditches and streams supply some base flow to Little Rock Creek most of the time. Steady-state model outputs were checked for the presence of computed base flow at the observed locations, particularly those locations where flow was observed at all field visits in 2015-2016.

6.2.3. Target Weighting

Target weights are used to scale how much each data target influences the objective function (the sum of weighted squared residuals) that is minimized during parameter estimation. Weights are based on the importance of the target data set to the model predictions of interest and structural limitations and measurement uncertainties that affect the potential for model to data fit.

The observation-well and other synoptic well measurements were the most representative of heads at their respective locations, but the component of model residuals caused by model structural uncertainty was expected to be relatively large compared to head-measurement uncertainties. Therefore, most of the head targets were given a weight of one (1). Head residuals for two target wells (243629 and 493489) were consistently larger than residuals for other wells. To prevent local errors at these locations from skewing the parameter estimates throughout the model domain, these observations were assigned a weight of 0.7, resulting in a squared weight of approximately 0.5.

Pond elevations derived from LiDAR were expected to be potentially less indicative of groundwater heads than well measurements. Therefore, the pond elevations were also assigned a weight of 0.7. Finally, to ensure that the one vertical head-difference data point (the DNR observation-well nest that was available during the steady-state model period) influenced the parameter estimation process, it was given a weight of 2.25, resulting in a squared weight of approximately 5.

6.3. Transient Parameter Estimation

Transient model runs require input of storage properties: specific yield representing draining or saturation of pores at the water table and specific storage representing water released due to elastic compression or expansion of porous, saturated materials. Specific yield and specific storage values were assigned based on two basic material types (predominantly sand aquifer or predominantly till aquitard).

The history-matching strategy for transient modeling was to perform a limited number of model runs to estimate the storage parameters. Transient modeling also tests the parameters and model structure developed in the steady-state history-matching process against an expanded set of head and flow data.

Specific yield values of 0.15 and 0.2 for sand were tested for effects on base-flow statistics and hydrographs and observation-well hydrographs. Specific yield represents the unsaturated-zone processes of non-instantaneous drainage and re-saturation at the water table and generally increases with time. It can be underestimated by fitting analytical solutions to aquifer-test data (Nwankwor et al., 1984; Nwankwor, 1992; Moench, 1995). Therefore, a value at the higher end of the range of aquifer-test estimates is appropriate, particularly at the time scale of monthly stress periods.

Monthly base flow and observation-well hydrographs were not very sensitive to changes in the specific storage values, but aquifer-test maximum drawdowns were. Specific storage values were adjusted down from the initial values to more closely match maximum aquifer-test drawdowns.

6.3.1. Transient Data Targets

6.3.1.1 Stream Base Flow

The structure and parameters of the groundwater-flow model affect transient computation of groundwater discharge to streams. The model was developed primarily to evaluate groundwater diversions under low-flow conditions, with particular emphasis on summer periods. Monthly base-flow targets were developed to compare with monthly computed base flows.

As explained in Section 3.4.1 Hydrograph Separation, the base-flow estimates derived from streamflow measurements using the WHAT tool (WHAT base flow) was the most reliable during low-flow periods. The WHAT base flow for continuous stations 15029001 and 15031001 were filtered to identify periods most likely to be representative of groundwater-derived discharge as explained below.

Base flow computed by the MODFLOW model was substantially lower than the WHAT base flow during higher flow periods, even when the total streamflow computed by the GSSHA model was close to the total measured streamflow. Because the recharge for the MODFLOW model came from the GSSHA model, this suggests that the physically-based GSSHA model calculated a lower proportion of groundwater discharge than the base-flow proportion calculated by the WHAT digital filter. That is qualitatively consistent with the expectation that WHAT base flow tends to exceed net groundwater discharge during higher flow periods (Section 3.4.1 Hydrograph Separation). The proportion of streamflow actually derived from groundwater discharge is uncertain during these higher flow periods.

To develop base-flow targets, therefore, the range of flow conditions appropriate for comparing the MODFLOW base flow (i.e., computed groundwater discharge) to the WHAT base flow had to be identified. To do this, the GSSHA results were analyzed to select a maximum WHAT base flow that could be used as base-flow targets representative of groundwater discharge and above which WHAT base flow would not be used.

The total streamflow computed by GSSHA was entered into the WHAT tool using the same parameters used for the gaged streamflow. As with the WHAT base flow derived from gaged streamflow, the WHAT base flow filtered from GSSHA-computed streamflow also exceeded MODFLOW groundwater discharge during higher flows. Monthly WHAT-filtered GSSHA flows were compared to the monthly MODFLOW base flows to identify the maximum flow rates for which the values were similar, focusing on months in which the GSSHA-computed total flow volume was close to the measured streamflow volume. For both stations H15029001 and H15031001 the maximum comparable base flow was approximately equal to the 75th percentile of the available WHAT base flows. Therefore, these were used as cut-off values to filter out high WHAT base flows that may not represent groundwater discharge: 22 cfs for 15029001 and 40 cfs for 15031001. Monthly WHAT base flows less than or equal to these cut-off values were retained as base-flow targets.

6.3.1.2 Observation-Well Water Levels

Water levels in observation wells were measured approximately monthly from April through October or November. DNR installed data-recording transducers in most of the observation wells in 2012, recording water elevations hourly. The hourly data were aggregated to monthly averages to compare with monthly averaged computed heads at the observation-well locations.

6.3.1.3 Aquifer-Test Data

The spatial discretization of the model is too coarse to compute accurate drawdown patterns in observation wells close to pumping wells during aquifer tests. For the aquifer tests conducted in the LRCA, most of the observation wells that were measured are too close to the pumping well for the model to compute drawdown accurately. Nevertheless, some of the aquifer-test data could be evaluated as a check on model behavior. Five aquifer tests were selected for which observation wells were measured that were laterally separated from the pumping well by at least three model grid cells. The maximum drawdown observed at these locations was compared to model computed drawdown at the same pumping time as a general check on model performance.

6.4. History Matching Results

This section describes the history-matching performance for the steady-state and transient models and the final model parameters. As explained above in Section 6.3, transient history matching covered the period March 2006 through September 2014. The latest model runs extend through water year 2018. This section describes data-fit for the history-matching period and the corresponding model parameters. Section 6.6 describes model fit to observations for the extended model runs that included the later years not included during model development and history matching.

6.4.1. Steady-State

Based on the goals given in Table 8, the steady-state model adequately matched groundwater head observations over the range of the observations (Figures 18 and 19); history-matching statistics are listed in Table 12. Head residuals were calculated as observed minus computed. Positive and negative residuals are generally distributed across the study area and any clustering of positive or negative residuals appears to be localized.

As explained under 6.2.2 Steady-State Data Targets above, base-flow targets were not evaluated during steady-state parameter estimation. Based on the discrepancies between MODFLOW-computed, groundwater-sourced flows and WHAT base flows (See 6.3.1 Transient Data Targets), steady-state computed base flows were not expected to closely match average WHAT base flows. Qualitative aspects of the spatial distribution of base flows were checked to better understand model behavior in relation to observations, however.

Computed base flow was much higher than WHAT base flow in Bunker Hill Creek. Most of the computed base flow originates in the moraine area upstream of 15th Ave NE (See Figure 3). This also occurs in the GSSHA model and is the dominant cause for the discrepancy. It appears that recharge was overestimated in the headwaters area for Bunker Hill Creek where the water-table generally occurs in till.

Computed base-flow gains were qualitatively similar to relative gains measured during low flow seepage runs. (Table 13). Computed base-flow gain was largest in the lower reach of Little Rock Creek (15031001), below Bunker Hill Creek, which is consistent with seepage-run measurements. The next largest computed base-flow gain was in the in the reach above station 15029003. The reach above station 15029003 includes tributaries draining the uplands to the east, where the computed recharge may be too high similar to Bunker Hill Creek. The computed flow in Little Rock Creek at the flow observation location on 250th Ave, above the upper-most measurement station (15029005), may also be too high, based on flow measurements at station 15029005. Relative gains were qualitatively similar to seepage runs for the other reaches, however, with computed local-reach gains similar at 1529004 and 1529001 and slightly greater at 15029002. See Figure 3 for streamflow measurement locations.

Table 12 Steady-state model head matching statistics. Residuals are calculated as observed minus computed.

Head Statistics (ft)	Well Targets Only (45 targets)	All Head Targets (52 targets)
Mean residual (ME)	0.50	0.38
Absolute mean residual	3.7	3.4
Root mean squared residual (RMSE)	5.0	4.8
Minimum residual	-15.6	-15.6
Maximum residual	10.5	10.5
Range of observations	254.4	254.4
Scaled RMSE ($RMSE_n$), d'less	0.020	0.019

Table 13 Computed base-flow gains in the steady-state model.

Stream Measurement Station	Stream	Computed Base-Flow Gain for Reach (cfs)
250th Ave	Little Rock	0.88
15029005	Little Rock	1.3
15029004	Little Rock	2.5
15029003	Little Rock	3.7
15029001	Little Rock	2.1
15029002	Little Rock	3.4
15th Ave NE	Bunker Hill	3.2
15028001	Bunker Hill	0.81
15028002	Bunker Hill	-0.24
15031001	Little Rock	6.9

Non-zero base flow was computed in all of the Little Rock Creek tributary locations that were field checked in 2015 and 2016 except for one location: the western tributary upstream of gaging station 15029001 at 25th Ave NW / CSAH 21 (Figure 3). Non-zero base flow was computed in this tributary less than 0.5 mile downstream from the checked location. No flow was observed during one field visit to this site (September 9, 2015), but, on average, there was likely some base flow at this location during the steady-state model period. Computed heads appear to be slightly below the average actual heads in this area based on the nearest observation wells, resulting in computed initiation of base flow farther downstream than observed. The water table occurs within the surficial till in the area upstream (west) of this site.

6.4.2. Transient

Transient history matching focused on measures of fit to WHAT base flows for the period March 2006 through September 2014. See Figure 3 for measurement station locations. As noted above under Transient Data Targets (Section 6.3.1), WHAT base flows above the 75th percentile (22 cfs for station 15029001 and 40 cfs for station 15031001) were not considered directly comparable to the groundwater-derived base flow computed by the MODFLOW model.

Hydrographs of computed versus WHAT base flow are shown in Figures 20 through 22, and statistics are listed in Table 14. History matching statistics for the selected WHAT base flows are listed in Table 15. As explained above, computed base flow was only compared to WHAT base flow during months in which the average WHAT base flow was less than or equal to a maximum value at each station (values listed in Table 14). The history-matching statistics goals for base flows were met for the compared months at station 15029001 (WHAT base flows less than 22 cfs) for the history-matching period. For the months compared, computed base flows were, on average, higher than filtered base flows as indicated by the PBIAS of -12.8 percent. At least some of the slight bias toward higher computed base flow is likely attributable to over-simulation of groundwater discharge in the upland area in the eastern part of the watershed that was discussed above.

Computed winter base flows were mostly higher than WHAT base flows. This discrepancy typically begins immediately following late autumn/early winter precipitation events with excess groundwater discharge to streams continuing throughout the winter. Excluding January and February data, the PBIAS became -2.6 percent with a NSE of 0.69. Fluctuations in the daily stage and streamflow record during the winter caused the WHAT base flow to be less than the total streamflow during periods that likely did not have any runoff, contributing to the winter bias to a lesser degree. One characteristic of measured flows during winter was a very gradual to nearly flat recession after the last runoff event. Although computed base flow after these events was too high in a number of years, the simulations did mimic the nearly flat nature of the winter hydrograph.

Computed base flow was much higher than WHAT base flow at station 15028001 on Bunker Hill Creek (Figure 22). The excess computed base flow derives mostly from the upstream moraine area, as indicated by the computed base flow at 15th Ave (Figure 22). Subtracting the computed base flow at 15th Ave from the computed base flow at station 15028001 shows that there is little computed gain in base flow along that reach, and computed gain along just that reach more closely matches WHAT base flows during low flow periods.

For the compared months at station 15031001 (WHAT base flows less than 40 cfs) the NSE and RSR goals were met, but the PBIAS was less than the minimum goal of -15 percent with a mean error (ME) of -3.1 cfs. Most of the average volume error reflected in the PBIAS at station 15031001 can be attributed to the over-simulation of base flow in the upper reaches of Bunker Hill Creek. The average computed flow at Bunker Hill station 15028001 for the months evaluated at station 15031001 was 3.6 cfs.

Measurement data are not available at station 15028001 for all of the same comparison months, but, for the months with data from each station during 2006 through 2009, the ME for station 15028001 was -2.3 cfs.

Table 14 WHAT and computed base-flow statistics for comparison months, 2006-2014

Statistic	15029001 WHAT	15029001 Model	15031001 WHAT	15031001 Model
Maximum base flow for comparison (cfs)	22	--	40	--
Number months compared	66	--	36	--
Total number of months with streamflow data	88	--	49	--
Mean, compared months(cfs)	7.9	8.9	15.3	18.4
Median, compared months (cfs)	6.0	8.9	13.1	19.5

Table 15 Model base-flow-fit statistics for comparison months, 2006-2014

Statistic	15029001	15031001
ME (cfs)	-1.0	-3.1
MAE (cfs)	2.7	4.5
MARE	0.47	0.42
PBIAS	-12.8%	-20.1%
NSE	0.56	0.59
RMSE (cfs)	3.5	5.8
RSR	0.66	0.64

In addition to the statistics assigned performance goals, the mean absolute relative error (MARE) was also calculated (Dawson et al, 2007; Reusser et al., 2009). Although the fit was satisfactory based on commonly used standards, the MARE values indicate that base-flow residuals were typically a significant percentage of the observations. The residuals were relatively lower during August, however, which is a month of particular interest. For the 8 Augusts with WHAT base flow less than 22 cfs at station 15029001, the MARE was 0.15 and the RMSE was 0.31 cfs.

Hydrographs of monthly computed base flows and field measurements of streamflow at the stations without continuous data during the history-matching period are shown in Figures 23 through 27.

Individual streamflow measurements differ from monthly base flow, but these hydrographs allow for a qualitative, visual check on computed base flows during low flow periods. Computed base flow appears to be biased high at the most upstream station (15029005) with the excess mostly derived from the moraine area as for Bunker Hill Creek. Computed, summer base flows appear to be reasonable at the other stations.

Hydrographs of monthly average computed heads and water elevations measured in observation wells are shown in Figures 28 through 36 (See Figure 4 for locations). To compare changes in computed and observed heads over time more easily, some of the plots also include computed heads shifted by a constant amount. The timing of computed, seasonal and multi-year maximum and minimum levels was similar to observations for most of the observation wells. The magnitude of computed seasonal and multi-year variations did not match observations closely for all observation wells and time periods, but the differences varied, including computed head fluctuations that were both too large and too small. The differences are likely partially attributable to local heterogeneity not resolved in the model.

At the 49033-49034 nest, the magnitude and seasonal timing of water-table fluctuations (49034) were similar to observations (Figure 28). Computed summer head declines in the buried *es* sand unit (49033) were larger than observations, but off-season heads tracked more closely (Figure 29). Computed heads varied over a larger range than measurements in observation well 49000 (Figure 32). Observation well 49000 (and its nearby replacement well 49035, installed in late 2014) is screened in a very shallow buried aquifer that fluctuates between being semi-confined and unconfined. Simulated summer head declines were less than observed at observation well 05008 in 2013 but closer to observed in 2014 (Figure 34). Observation-well 05008 is screened in a sand unit (*mls*) that is locally unconfined/minimally confined but that is overlain by an aquitard nearby.

As mentioned above, the specific storage parameters were lowered during history matching because the initially tested values resulted in under-simulation of pumping-test drawdowns at “distant” observation wells. The selected specific storage values remained within the range estimated from aquifer-test analyses and resulted in a mix of computed aquifer-test drawdown residuals (Figure 37).

6.4.3. Final Model Parameters

The final parameter values are listed in Table 16 through Table 18. These values were derived using the procedures described above. The parameterization was simplified where contrasting parameters did not substantially improve the data fit. Parameters with the same values were combined through this process, such as the horizontal hydraulic conductivity of buried aquifers in layers 1, 2, and 3 (khcs and khmls) (Table 16).

Overall, the history-matching process indicated that the fit to observed heads was not very sensitive to moderate changes to the hydraulic-conductivity parameter structure (i.e., combining or separating the parameters that were ultimately tied). The horizontal hydraulic conductivity parameters for the buried tills (khc and kht) were relatively insensitive. They were maintained as estimable parameters, but the values were tied, meaning that they were adjusted by the same multiplier rather than independently, thus maintaining the same ratio to each other. With the exception of streams overlying till (sc2), the surface-water conductance values were relatively insensitive and were fixed after initial estimation runs.

When the horizontal hydraulic conductivity of the es aquifer (khes) in layer 4 was unbounded, this caused excessive drawdown and partial draining of some model cells containing high capacity wells in model layer 4. Enforcing the model bounds served to balance the potential for a slightly lower objective function against over-fitting of parameters. After initial parameter-estimation runs, the horizontal hydraulic conductivities of the deeper aquifers in layers 5 and 6 (khvs, khds, and khus) were tied to have the same value as khes.

Table 16 Final model hydraulic conductivity parameter values

Horizontal Hydraulic Conductivity Parameter	Value, ft/d (m/d)
khss (thick ou/pgs)	220 (68)
khcs (thin ou/pgs, cs2, cs3)	102 (31)
khmls (mls), tied to khcs	102 (31)
khes (es)	*59 (18)
khvs (vs, layer 5 zone), tied to khes	59 (18)
khds (suu, layer 6 zones), tied to khes	59 (18)
khupsu (ups), tied to khes	15 (4.6)
khc1 (ct1, ct2 in layer 1)	5.9 (1.8)
khc (ct2, ct3 in layer 2)	0.59 (0.18)
kht (mlt, et, vt), tied to khc	0.29 (0.088)
Vertical Hydraulic Conductivity Parameter	
kvs (pgs, ou, cs2, cs3, mls, es, vs, suu, layers 5 and 6 zones)	16 (5.0)
kvc1 (ct1, ct2 in layer 1)	0.049 (0.015)
kvc (ct2, ct3 in layer 2)	0.049 (0.015)
kvt (mlt, et, vt, ups)	0.026 (0.008)

* Final value at lower bound set in PEST parameter estimation.

Table 17 Final surface-water leakance parameter values

Parameter	Leakance (day^{-1})
sc2 (streams and drains overlying till)	0.038
sc (streams overlying water-table aquifer, fixed)	2.0
sc29 (Little Rock Cr. on sand plain above Bunker Hill Cr. and Bunker Hill Cr. on sand plain, fixed)	5.0
sc31 (Little Rock Creek below Bunker Hill Cr., fixed)	1.0
rivriv (rivers, fixed)	1.0
rivlk (lakes, stream impoundments, fixed)	0.1
drnbc (peripheral drains, fixed)	0.5

Table 18 Final storage parameter values

Parameter	Value
sys (specific yield sand)	0.2
syt (specific yield till)	0.1
ss (aquifers), ft^{-1} (m^{-1})	3×10^{-6} (1×10^{-5})
sst (aquitards), ft^{-1} (m^{-1})	9×10^{-6} (3×10^{-5})

6.5. Sensitivity Analysis

The PEST software computes composite scaled sensitivities (CSS) of the objective function to each parameter, which were available for the steady-state model. These sensitivity values indicate how the overall fit to the observations is affected by an incremental change to each individual parameter while holding other parameter values. Higher CSS values indicate that, as a whole, computed equivalents to the observations are more sensitive to a parameter. The composite sensitivity values only represent the effects of each parameter in isolation near its final assigned value. Parameter sensitivities would differ somewhat for different sets of parameter values.

All of the parameter types were somewhat sensitive, but the aquifer horizontal hydraulic conductivity values are most sensitive (Table 19). The least sensitive parameters are the streambed leakance and horizontal hydraulic conductivities of the subsurface aquitards and the undifferentiated deposits. This is not surprising given that flow through the aquitards is primarily in the vertical direction. The horizontal hydraulic conductivity of the surficial aquitard was somewhat sensitive. The most sensitive vertical hydraulic conductivity was the northwest provenance aquitard parameter (kvt).

Table 19 Percentages of composite scaled sensitivity of parameter groups.

Parameter group	Percent of total composite scaled sensitivity (%)
Aquifer horizontal hydraulic conductivity	56
Aquitard horizontal hydraulic conductivity	17
Vertical hydraulic conductivity	18
Streambed leakance	10

The model runs performed during transient history matching provide insight into the sensitivity of simulated base flows and heads to the storage parameters and streambed leakance. Changing the specific yield of surficial sand and lowering the streambed leakance where streams cross the sand plain had relatively small but consistent effects on computed monthly base flow, but changes to the specific storage affected base flow minimally.

Specific yield affects the rate of movement to and from storage. Therefore, decreasing the specific yield slightly increased the seasonal amplitude of base-flow fluctuations. Lowering the specific yield of surficial sand from 0.2 to 0.15 had a small effect on overall base-flow statistics (e.g. NSE = 0.58 and PBIAS = -11% for 15029001). This resulted in a low bias in minimum summer base flow (from July through September), however. For example, selecting the minimum summer base-flow month from each year, the PBIAS for these months increased from 2 percent to 8% for 15029001 (positive PBIAS indicates average under-simulation). The change in specific yield had a small effect on simulated observation-well hydrographs, with mixed results on visual match to observations. Since the focus of model application was low summer flows, the specific yield was left at the initial value of 0.2.

Changes in leakance for stream segments on the sand plain also affected the timing of groundwater discharge but had a small effect on overall base-flow statistics. For example, reducing the leakance for stream segments from 5 or 2 day^{-1} to 1 day^{-1} resulted in NSE = 0.56 and PBIAS = -15.5% for station 15029001. This change resulted in a bias toward summer base flow being too high, opposite the effect of decreasing specific yield. Minimum summer base-flow month PBIAS increased from 2 percent to -11%. Note that stream leakance was estimated during steady-state parameter estimation, and these results did not prompt any changes to those values.

Specific storage affects shorter-term responses to hydraulic stresses, but computed monthly base flows and aquifer heads were affected minimally by changes in the specific storage parameters. Computed aquifer-test drawdowns were affected by the specific storage parameters; the initial, higher values resulted in simulated aquifer-test drawdowns that were too small. After adjusting the specific storage values to better match maximum drawdowns during aquifer tests, there were no further sensitivity tests of specific storage.

Groundwater wells and associated irrigation west of the Platte River were not included in the model. The Platte River limits the propagation of drawdown, and wells to the west of the Platte River are also relatively distant from Little Rock Creek. To test the assumption that groundwater use to the west of the

Platte River could be discounted without affecting the model predictions of interest in and near Little Rock Creek, the steady-state model was run with wells west of the Platte River pumping at their average reported volumes. This exaggerated the net effect of these wells because irrigation return flows were not included in this simulation. Despite the exaggerated effect of this test, adding these wells had a negligible effect on simulated base flow in Little Rock Creek (less than 0.2 percent) or on groundwater heads near the creek (less than 0.02 ft or 0.005 m). This test result supported leaving out pumping and irrigation to the west of the Platte River.

Because the primary purpose of the LRCA model is to estimate base-flow (groundwater-discharge) diversions from Little Rock Creek, we are particularly interested in the sensitivity of calculated diversions to model parameters and assumptions. One calculates base-flow diversions as the differences in computed base flows between a reference scenario, representing no groundwater use, and the baseline model. The computed diversions can be sensitive to different or additional factors than are the target observations described here. Chapter 8 describes the base-flow diversion analysis and further discusses the potential effects of model assumptions and parameters on calculated diversions.

6.6. Model Fit to Water Years 2015-18 and to the Whole Model Period

Extending the model runs through water year 2018 allows for comparing transient model fit to data beyond the history-matching period. The add-on period (water years 2015 through 2018) is half the length of the history-matching period (2006, 2008 through water year 2014), making base-flow fit statistics for the add-on period more sensitive to errors in a particular year and to outliers. The overall fit of the model to all available data is of most interest, but reviewing the fit to data outside of the history-matching period adds perspective on model performance. Therefore, this section includes fit statistics for both the add-on period and for the entire period of data and model overlap.

Hydrographs of computed versus WHAT base flow for water years 2015 through 2018 at the active stream gaging stations are included in Figures 20, 21, 25, and 26. Table 20 provides summary statistics and Table 21 provides model-fit statistics for this period.

Table 20 WHAT and computed base-flow statistics for comparison months, water years 2015 through 2018

Statistic	15029001 WHAT	15029001 Model	15031001* WHAT	15031001 Model	15029003 WHAT	15029003 Model	15029002 WHAT	15029002 Model
Maximum compared (cfs)	22	--	40	--	17	--	25	--
Number months compared	31	--	11	--	37	--	37	--
Total number of months with data	43	--	15	--	48	--	48	--
Mean, compared months (cfs)	12	15	24	31	9.1	11	15	18
Median, compared months (cfs)	13	16	26	30	8.6	12	15	19

* Station 15031001 has no record from September 26, 2011 to June 20, 2017

Table 21 Model base-flow-fit statistics for comparison months, water years 2015 through 2018

Statistic	15029001	15031001*	15029003	15029002
ME (cfs)	-2.5	-6.5	-2.1	-2.5
MAE (cfs)	4.8	10.1	4.0	4.7
MARE	0.51	0.54	0.62	0.39
PBIAS (%)	-19.9	-26.8	-23.1	-16.9
NSE	-1.1	-2.0	-1.28	-0.92
RMSE (cfs)	6.2	14	5.4	6.6
RSR	1.5	1.7	1.5	1.4

* Station 15031001 has no record from September 26, 2011 to June 20, 2017

The fit statistics do not meet the goals for the add-on period. As for the history-matching period, the poorest fit was generally during the winter, ice-affected months. Table 22 and Table 23 provide the same statistics, excluding all January and February and any other months that were mostly ice affected.

The base-flow statistics improve when excluding winter, ice-affected periods. As explained above in 6.4.2, the majority of the winter error appears to be due to recharge errors during late fall and winter, although there are larger measurement uncertainties during ice-affected periods. Note that the base-flow fit during this period met goals for non-winter periods at station H15031001, and was close to goals for stations 15029003 and 15029002. The better fit at station 15031001 was because these statistics only include data from July 2017 through September 2018, during which the fits of the GSSHA model to total flow and the fit of the MODFLOW model to base flow were better.

Table 22 WHAT and computed base-flow statistics for comparison months, water years 2015 through 2018, excluding ice-affected periods

Statistic	15029001 WHAT	15029001 Model	15031001* WHAT	15031001 Model	15029003 WHAT	15029003 Model	15029002 WHAT	15029002 Model
Maximum compared (cfs)	22	--	40	--	17	--		
Number months compared	16	--	7	--	22	--	22	--
Total number of months with data	43	--	15		48	--	48	--
Mean, compared months (cfs)	13	12	28	25	9.9	8.7	15	14
Median, compared months (cfs)	13	12	27	26	10.4	9.3	16	15

* Station 15031001 has no record from September 26, 2011 to June 20, 2017

Table 23 Model base-flow-fit statistics for comparison months, water years 2015 through 2018, excluding ice-affected periods

Statistic	15029001	15031001	15029003	15029002
ME (cfs)	1.5	2.6	1.2	1.1
MAE (cfs)	2.2	3.0	2.0	2.3
MARE	0.16	0.09	0.19	0.14
PBIAS (%)	11	9.4	12	7.2
NSE	0.33	0.86	0.42	0.46
RMSE (cfs)	2.9	4.7	2.7	3.3
RSR	0.82	0.38	0.76	0.73

The base-flow statistics for the entire model period are of greater interest because the groundwater-discharge diversion and habitat analyses apply the entire available period. Table 24 and Table 25 show these statistics. Stations 15029003 and 15029002 are not included here because data are not available before July 2014.

The base-flow fit goals were not all met for the entire model period. Including water years 2015 through 2018 degraded the fit statistics somewhat compared to the history-matching period of March 2006 through September 2014. History matching may partially explain the better fit to the initial model period, but weather conditions and input data during the add-on period are also likely important factors. The model fit is generally better under lower flow conditions (flows were higher on average in water years 2015 through 2018), and the maximum WHAT flow cutoff values do not perfectly account for uncertainties in the groundwater-derived component of WHAT base flow. Finally, the fit to winter data is poor during most years.

Although the goals for base-flow fit were not met for all compared data, the base-flow fit goals were met for the non-winter periods at both stations. The statistics for data excluding all January, February, and any other mostly ice-affected months are shown in Table 26 and Table 27. This points to the limitations of the model during winter periods but supports applying the model to analyze non-winter base flows.

Table 24 WHAT and computed base-flow statistics for all comparison months, March 2006 through September 2018

Statistic	15029001 WHAT	15029001 Model	15031001* WHAT	15031001 Model
Maximum base flow for comparison (cfs)	22	--	40	--
Number months compared	98	--	51	--
Total number of months with streamflow data	131	--	67	
Mean, compared months(cfs)	9.3	10.8	18	22
Median, compared months (cfs)	8.3	10.4	16	21

* Station 15031001 has no record from September 26, 2011 to June 20, 2017

Table 25 Model base-flow-fit statistics for all comparison months, March 2006 through September 2018

Statistic	15029001	15031001*
ME (cfs)	-1.4	-3.8
MAE (cfs)	3.4	6.4
MARE	0.48	0.50
PBIAS (%)	-15.2	-21.3
NSE	0.29	0.17
RMSE (cfs)	4.5	9.5
RSR	0.85	0.91

* Station 15031001 has no record from September 26, 2011 to June 20, 2017

Table 26 WHAT and computed base-flow statistics for March 2006 through September 2018, excluding ice-affected periods

Statistic	15029001 WHAT	15029001 Model	15031001* WHAT	15031001 Model
Maximum base flow for comparison (cfs)	22	--	40	--
Number months compared	65	--	44	--
Total number of months with streamflow data	131	--	67	--
Mean, compared months(cfs)	10.0	9.45	18	20
Median, compared months (cfs)	10.1	9.4	16	20

Table 27 Model base-flow-fit statistics for all comparison months, March 2006 through September 2018, excluding ice-affected periods

Statistic	15029001	15031001*
ME (cfs)	0.56	-2.1
MAE (cfs)	2.2	5.0
MARE	0.30	0.30
PBIAS (%)	5.6	-11.8
NSE	0.74	0.55
RMSE (cfs)	2.9	7.3
RSR	0.51	0.67

* Station 15031001 has no record from September 26, 2011 to June 20, 2017

Hydrographs of monthly average computed heads and water elevations measured in observation wells are included in Figures 28 through 36 (See also 6.4.2 above and Figure 4 for locations). Figures 38 and 39 show plots for additional wells that were constructed after water year 2014. For the observation wells with data prior to water year 2015, the fit to data during water years 2015 through 2018 was generally comparable to the history-matching period (2006 through water year 2014).

Errors in computed heads do not remain entirely consistent through time, however. Water-table observation well 49034 (Figure 28) provides a good example of how poor representation of a single, large recharge event can have a persistent effect on computed heads. Computed heads tracked fairly closely to measured heads from summer 2012 through mid-summer 2014. There was a large rise in observed heads in September 2014 that was not matched by the model at this location. Variations in computed heads tracked fairly closely to variations in observed heads from the following winter through the end of the simulation. But, the difference between computed heads (consistently larger than observed) dropped in September 2014 and generally remained smaller through the end of the simulation. This type of shift in model errors is largely removed when subtracting two different model runs.

DNR installed two observation-well nests near Little Rock Creek after water year 2014: 49038 (suu aquifer), 49039 (es aquifer), and 49040 (water-table aquifer) near stream station H15029003; and 05013 (es aquifer) and 05014 (water-table aquifer) near stream station H15029001. The computed water table at the more northern nest (49040) tracks reasonably well with observations, although the computed heads are about 1.5 feet lower than observed (Figure 38). The observed heads in the southern water-table well (05014) are more variable than the computed range (Figure 39). This observation well nest is just 54 meters (177 feet) from Little Rock Creek, and both wells appear to respond to rises in stream stage during runoff events, which the MODFLOW model does not simulate.

Computed summer head declines in the buried aquifers are larger than observed at these two observation-well nests. The model correctly computed that non-summer heads in the buried aquifers were above heads in the water table at the nest locations, but the computed vertical-head differences are larger than observed throughout the year. These characteristics of the computed heads may be due to local heterogeneities that are not represented in the model, as was the case for model fit to maximum drawdown during pumping tests shown in Figure 37. For example, aquitards near these locations may be leakier than represented in the model (due to thickness and/or hydraulic conductivity distribution). Greater aquitard leakance in these areas could simultaneously reduce both vertical head differences and seasonal drawdowns.

One cannot infer the three-dimensional, spatial distribution of hydraulic conductivity and aquitard leakance from data collected at a single observation-well nest or from a small number of observation wells, even at the local scale. It may be possible, however, to improve local modeled head predictions near these nests via selected, local modifications to the geological model and/or to the distribution of hydraulic conductivity. These types of local-scale modifications may be considered during future model updates.

7. Model Summary and Potential Future Work

A soil/surface-water-focused model (GSSHA model) and a six-layer, saturated groundwater-flow model (MODFLOW model) were developed and run in series to construct a transient groundwater/surface-water flow model for the Little Rock Creek area (the model). The GSSHA model computed net recharge/groundwater evapotranspiration input for the MODFLOW model. The model satisfactorily fit stream base flow and groundwater head observations for 2006 through 2014. The model was developed to calculate net base-flow diversions from Little Rock Creek due to permitted groundwater appropriations.

Like all hydrological models, the model results have inherent uncertainties due to intrinsic data limitations and necessary simplifications. Numerical modeling, however, is the only means of evaluating streamflow diversions for complex (i.e. real) systems at the watershed scale (Barlow and Leake, 2012).

7.1. Computed Hydrologic Budget

The MODFLOW-computed water budget averaged over water years (October through September) 2007 through 2014 is shown in Table 28. Note that MODFLOW includes releases from storage as inflows (to groundwater) and additions to storage as outflows (from groundwater) to view total inflows and outflows in the context of a balanced water budget. Changes in storage represent a significant proportion of the inflows and outflows. The computed net increase in storage over this time period was 5 percent of total inflows or outflows, resulting from dry conditions at the beginning of water year 2007 and wet conditions in water year 2014, as indicated by stream flows and observation-well heads.

Areal recharge was the principal source of groundwater followed by releases from storage. Surface waters contributed minor amounts, and losses from SFR stream cells were ultimately sourced from areal recharge that discharged to upstream SFR reaches. Gains in storage and groundwater discharge to surface waters were the largest fluxes out of the groundwater system.

Average groundwater evapotranspiration (negative recharge routed from GSSHA) was 20 percent of total groundwater outflows and 36 percent as large as average recharge. Other hydrologic studies in glaciated settings in the north-central U.S. have also found that groundwater evapotranspiration is a significant component of total groundwater discharges (Tornes et al., 1994; Lindgren and Landon, 2000; Lindgren, 2002; Cohen et al., 2006; Yeh and Famiglietti, 2009; Hunt et al., 2013).

There were substantial year-to-year variations in recharge and groundwater evapotranspiration (Figure 12). Water-year (October through September) recharge varied from 3.9 inches in 2007 to 16.5 inches in 2014. Water-year groundwater evapotranspiration varied from 2.0 inches in 2010 to 5.0 inches in 2012. Net water-year recharge varied from 0.18 inches in 2007 to 13.4 inches in 2014.

Table 28 Average computed water budget for the entire model domain, water years 2007 through 2014.

Budget Component	Inflows (cfs)	Inflows (in/yr)	Percent of Total	Percent of Areal Recharge
Release from storage	121	5.6	35	57
Areal recharge (RCH)	213	9.9	62	100
Seepage from surface waters	10.9	0.51	3.2	5.1
Streams (SFR)	4.2	0.19	1.2	2.0
Rivers and lakes (RIV)	3.0	0.14	0.9	1.4
Mississippi River (CHD)	3.7	0.17	1.1	1.8
Total	345	16.0	100.0	162
Budget Component	**Outflows (cfs)**	**Outflows (in/yr)**	**Percent of Total**	**Percent of Areal Recharge**
Addition to storage	138	6.4	40	65
Evapotranspiration (RCH)	76	3.5	22	36
Discharge to surface waters	113	5.2	33	53
Streams (SFR)	44	2.1	13	21
Other streams and ditches (DRN)	7.3	0.34	2.1	3.4
Rivers and lakes (RIV)	33	1.5	9.5	15.3
Mississippi River (CHD)	28	1.3	8.2	13.3
Wells	18	0.83	5.2	8.4
Total	345	16.0	100	162
Budget Component	**Net (cfs)**	**Net (in/yr)**	**Percent of Total**	**Percent of Areal Recharge**
Net gain in storage	17	0.79	4.9	8.0
Net areal recharge	137	6.3	40	64
Net discharge to surface waters	101	4.7	30	48

Groundwater withdrawals averaged just over five percent of total groundwater outflows and eight percent of recharge for the whole model domain. Note that withdrawal wells and irrigation west of the Platte River were not included in the model, but that area is included in the model domain. Irrigated water that returned to the water table/increased precipitation recharge was included in the areal recharge east of the Platte River. Irrigation systems increase the flux of water through the groundwater system through the combination of withdrawals and increased recharge. Groundwater withdrawals included in the model varied from 2,605 million gallons (MG) in calendar year 2011 (27.0 thousand m^3/d) to 5,712 MG in 2013 (59.2 thousand m^3/d) (Figure 14).

For comparison, the water budget for the added water years (2015 through 2018) and for water years 2007 through 2018 are shown in Table 29. The average net recharge rate was slightly smaller for water years 2015 through 2018 compared to water years 2007 through 2014. Nevertheless, the average, net discharge rate to surface waters was larger for water years 2015 through 2018. The larger groundwater discharge despite slightly smaller net recharge during the latter period resulted from a net loss in storage compared to a net gain in storage during water years 2007 through 2014.

For the entire water years 2007 through 2018 period, the average net recharge rate was slightly smaller than for the water years 2007 through 2014 portion, but the average net discharge rate to surface waters was slightly larger for the whole period. There was a small net gain in storage during water years 2007 through 2018.

Table 29 Average computed water budget for the entire model domain, water years 2015 through 2018 and 2007 through 2018.

Budget Component	Inflows (cfs)		Inflows (in/yr)		Percent of Total		Percent of Rech.	
	15-18	07-18	15-18	07-18	15-18	07-18	15-18	07-18
Release from storage	102	115	4.7	5.3	1.6	35	52	55
Areal recharge (RCH)	198	208	9.2	9.6		62	100	100
Seepage from surface waters	8.7	10	0.40	0.47		3.1	4.4	4.9
Streams (SFR)	3.3	3.9	0.15	0.18		1.2	1.7	1.9
Rivers and lakes (RIV)	2.1	2.7	0.10	0.13		0.8	1.1	1.3
Miss. River (CHD)	3.2	3.5	0.15	0.16		1.1	1.6	1.7
Total	309	333	14.3	15.4		100.0	156	160
Budget Component	**Outflows (cfs)**		**Outflows (in/yr)**		**Percent of Total**		**Percent of Rech.**	
	15-18	**07-18**	**15-18**	**07-18**	**15-18**	**07-18**	**15-18**	**07-18**
Addition to storage	90	122	4.1	5.7		59	45	55
Evapotranspiration (RCH)	65	72	3.0	3.4		22	33	35
Discharge to surface waters	137	121	6.4	5.6		36	69	58
Streams (SFR)	55	48	2.6	2.2		14	28	23
Other (DRN)	9.6	8.1	0.44	0.37		2.4	4.8	3.9
Rivers and lakes (RIV)	39	35	1.8	1.6		10	20	17
Miss. River (CHD)	33	30	1.5	1.4		9.0	17	14
Wells	17	18	0.79	0.82		5.3	8.6	8.5
Total	309	333	14.3	15.4		100	156	160
Budget Component	**Net (cfs)**		**Net (in/yr)**		**Percent of Total**		**Percent of Rech.**	
	15-18	**07-18**	**15-18**	**07-18**	**15-18**	**07-18**	**15-18**	**07-18**
Net gain in storage	-13	7.3	-0.59	0.33	-4.1	2.1	-6.4	3.4
Net areal recharge	133	135	6.3	6.3	43	41	67	65
Net discharge to SW	129	111	6.0	5.1	42	33	65	53

7.2. Model Uncertainty and Limitations

Numerical modeling is the only means of evaluating streamflow diversions for complex (i.e., real) systems at the watershed scale (Barlow and Leake, 2012). Like all hydrological models, however, the model has some inherent limitations due to unavoidable uncertainties and necessary simplifications.

7.2.1. Model Uncertainty

Uncertainties in model predictions are unavoidable in models of complex natural systems (US EPA, 2009; Barnett et al., 2012). Sources of uncertainty can be divided into random variation, such as some measurement errors, and structural uncertainties that arise from imperfect knowledge of and necessary simplifications to the real system.

Field observations have inherent measurement error. Although there are computational limitations to how much detail can be included in a numerical groundwater model, knowledge of the spatial and temporal distribution of hydrogeological properties (e.g., hydraulic conductivity) and forcing data (e.g., precipitation and evapotranspiration) is generally more limiting (Barnett et al., 2012). These factors are related because uncertainties or biases in the forcing data, such as distribution of precipitation from point measurements, limit the certainty in model structure and parameters (Renard et al., 2010; Beven, 2016). Finally, necessary simplifications or approximations of the hydrological processes such as infiltration, overland flow, and ET contribute to structural uncertainty.

The available groundwater-level and streamflow data during the modeled period encompass a wide range of hydrological conditions. Therefore, the available data provide a reasonably comprehensive view of hydrologic conditions and model performance over a range of conditions. There are 12 years of overlapping model outputs and streamflow records. This is a useful record, but flow statistics, such as the August median flow and base flow, will likely continue to change with added years of record.

The distribution of model hydrogeological properties is controlled by the geological model and parameterization of the properties within geological units. Sand bodies vary in thickness and have irregular shapes. Although there was a relatively high density of well and boring record data for the LRCA, there is some uncertainty in the sub-surface distribution of geological materials, particularly at greater depths (i.e., the data do not define a unique geological model).

The geological information that one may interpret from well and boring records is generally limited to major texture types (sand/gravel vs. sediments containing clay). The aquifer-test analyses indicated that the hydraulic conductivities of materials that are typically indistinguishable in their boring-log descriptions (e.g., “sand” or “clay”) vary over a wide range across distances of tens to a few thousand feet. Stream base flows at the evaluated stream gages are affected by groundwater flows across a multi-mile area, which limits the importance of local-scale heterogeneity on computed base flows at the gage locations.

Model results were not highly sensitive to moderate changes to the hydraulic-conductivity parameter structure that were tested during history matching. Computed base flow was also relatively insensitive to moderate changes to stream leakance, and a large reduction in stream leakance was ruled out because that resulted in computed low summer base flows that were too high. The unavoidable limits on knowledge of and representation of hydrogeological properties contribute to some uncertainty in model predictions.

Compared to the geological data, there is more information on the spatial distribution of soil texture types, crops, and other land covers from soil maps and satellite-derived land-cover data. Like aquifer and aquitard hydraulic properties, the hydrologic properties of soils and crops are heterogeneous. The satellite-derived land-cover data include errors. Unresolved heterogeneity, parameter uncertainty, and necessary process simplifications in the GSSHA model also contribute to potential model errors and uncertainty.

For the LRCA model, the focus was on estimating the net base-flow diversions in recent years that are attributable to groundwater use. One may then compare computed groundwater diversions to a negative-impact threshold. Section 8.3 describes tests of several alternative model scenarios and assumptions relevant to base-flow diversions. Section 8.4 further discusses the potential effects of model assumptions and uncertainties on computed base-flow diversions, specifically.

7.2.2. Applicability and Limitations

The LRCA model spans multiple watersheds and, although some uncertainty in model predictions is unavoidable, it is suited for “watershed-scale” analyses. The primary purpose of the model was to evaluate net base-flow diversions at a limited number of stream-gaging locations representing multi-mile reaches of Little Rock Creek. The model construction and history-matching process could not resolve physical property distributions that represent actual conditions at the local scale, but modeled heads and groundwater discharges to streams were reasonably modeled at the scale of the area of interest.

The model should not be used to quantitatively assess localized effects such as the effect of a single pumping well on a short stream reach. The model could be used for preliminary screening of the potential for base-flow diversions from adjacent streams (Buckman Cr. and Zuleger Cr.) or upstream gaging locations on Little Rock Creek, but there would be less confidence in those predictions. The model could also be used as a tool to identify areas where further evaluation of drawdown impacts to local features, such as wetlands, may be warranted.

7.3. Future Work

7.3.1. Scenario Development

Model computations described in this report were for historical conditions from 2006-2018 (baseline) and a no-use scenario for the same time period (See 8. Base-Flow Diversion Analysis below). Alternative groundwater-use and other management scenarios could be tested with the model to evaluate their expected impacts on stream base flow. Additional model analyses that could inform the development of alternative scenarios could also be explored.

7.3.2. Data Collection and Analysis

Data collection is on-going at the long-term, streamflow gaging station (15029001), the two, more recently installed gaging stations (15029003 and 15029002), and the re-established, downstream station (15031001). Most of the observation wells in the area have hourly-recorded data beginning during or after 2012. Ongoing collection of continuous data will increase the period of record and allow for further analysis of streamflow and groundwater dynamics.

Two areas of data uncertainty that might improve with additional data-collection are groundwater contributions to streamflow and more testing/verification of reported water use.

Groundwater contribution to streamflow during snowmelt and periods of high or extended runoff is uncertain because of the limitations of hydrograph separation methods. The conductivity mass balance (CMB) is a method that might provide alternative estimates for comparison. One significant limitation to this method, however, is that it cannot be applied to periods during which stream water conductivity is affected by road-salt runoff in the winter and spring. Nevertheless, the feasibility of collecting the necessary conductivity data and applying the CMB method to Little Rock Creek could be evaluated as a way to reduce uncertainty in groundwater contributions to streamflow.

For the baseline model, it was assumed that errors in reported water use were generally small and balanced out among different water users and reporting periods. For a small number of permits, water use was estimated after the fact, possibly without written records. Some other reported values appeared to be erroneous/unrealistic, likely the result of reporting or record-keeping mistakes. Few of the permitted systems are fitted with flow meters.

The 2018-19 metering study provided some new information on irrigation water-use reporting (MNDNR, 2021a). In 2019, reported seasonal water-use volumes for six of nine measured systems differed from metered volumes by more than 10 percent. Reported volume was less than metered volume for only one of these systems. These results suggest that reporting errors may be generally larger than previously assumed and over-reporting use may be much more common than under-reporting use for irrigation systems in the LRCA. It is not clear however, if or how one may confidently extrapolate the limited data from the metering study to other systems in the LRCA. There remains an opportunity to improve understanding of past water-use reporting and to improve the accuracy of future reporting.

7.3.3. Model Updates

The LRC model should continue to be run in the future to test its performance against new data and extend the period of analysis. These future model runs and data comparisons may reveal areas for revision/improvement of the model.

8. Base-Flow Diversion Analysis

Groundwater withdrawals and uses change the inflows to and outflows from the groundwater system. Groundwater irrigation removes groundwater but also changes the timing and amount of groundwater recharge relative to a non-irrigated scenario. These changes in groundwater inflows and outflows affect groundwater discharges to streams.

Except in simple hydrogeological settings or for preliminary approximations, numerical modeling is needed to analyze these changes in streamflow (Barlow and Leake, 2012). Streamflow diversions due to groundwater withdrawals and uses (i.e. base-flow diversions) are calculated as the computed base flow without groundwater use (no-use scenario) minus the computed base flow with groundwater use (baseline scenario). Therefore, a model simulation for a no-use scenario is required to compare to the baseline simulation described in the previous sections.

8.1. No-Use Scenario

For the no-use scenario, pumping from all wells and dug pits and irrigation applications were removed from both the GSSHA and MODFLOW models. In addition, irrigated row crops were changed to non-irrigated alfalfa (Scenario 2 in Appendix A). This land cover change was chosen to represent non-irrigated conditions to isolate the net effects of groundwater-supplied irrigation and was not designed to replicate any specific, historical condition. The selected land cover affects computed evapotranspiration (ET) and groundwater recharge, which in turn affects computed base flow.

DNR selected alfalfa as the land cover to replace irrigated crops because ET from alfalfa is near the upper end of the range for non-irrigated crops and grasses in this setting. Row crops (corn, soybeans, and dry beans), rye, and other small grains are examples of other crops currently grown without irrigation in fields with the same mapped soil types as currently irrigated fields. Although row crops are grown in some locations in the LRCA that have sandy soils, they may not be as viable without irrigation. Land cover/plant community effects on soil-water balance and recharge are discussed further in Appendix A.

8.2. Calculated Base-Flow Diversions and August Reference Base Flow

The model-computed base flows for the baseline and no-use scenarios are shown in Figure 40 for stations 15029003, 15029001, and 15031001 (See Figure 3 for station locations). The differences in computed base flows vary seasonally and from year to year. Computed base flows for the baseline scenario are generally lower during low-flow summer and early autumn months but are generally higher during other times of the year. This pattern results from the net impacts of pumping, irrigation, and land cover on computed base flows.

Most groundwater use in the area is for crop irrigation, and withdrawals for other uses are typically greatest during the summer. Pumping drawdowns propagate to the streams and reduce base flows, particularly during and immediately following the irrigation season.

Greater recharge and lower annual ET under the baseline condition partially offset the pumping impacts and result in the relatively higher computed base flows for the no-use scenario during the rest of the year. During months with little or no irrigation, computed ET from irrigated row crops in the baseline scenario is lower than computed ET from the same fields for the no-use scenario. Pumping-induced drawdown of the water table can also reduce direct ET from the shallow water table such as in wetlands and riparian areas. Irrigation water increases soil moisture and groundwater recharge, although the increased recharge occurs both during and after the irrigation season.

The month of August typically has relatively low streamflow and is an important part of the growing season for crops and fish and wildlife. Figure 41 shows the differences between the computed monthly August base flows for the no-use and baseline models at stations 15029003 and 15029001. These represent the monthly August base-flow diversions, which varied from -0.6 cfs (2011) to 1.4 cfs (2013) at station 15029003 and from -0.7 (2011) to 1.9 cfs (2006 and 2013) at station 15029001.

Although there is variability in the relationship, August base-flow diversions (Figure 41) were generally correlated with annual water use (i.e., August base-flow diversions tended to be larger in years with larger groundwater use) (Figure 14), except in 2007. In the summer of 2007, computed base flow was very low under the no-use scenario (0.2 cfs and 0.5 cfs at 15029003 and 15029001, respectively), limiting the amount of potential base-flow diversion. The negative calculated diversions in 2011 resulted from wet conditions and low groundwater use. Conditions were also wet in August 2017.

The DNR has recommended that diversion limits for streams be set relative to the median August base flow (DNR, 2016). The relevant August base flows represent the reference condition (i.e., with no groundwater use) rather than observed conditions. August base flow for the reference condition at station 15029001 was calculated as the WHAT base flow plus the calculated base-flow diversion. This provides more accurate estimates of the reference-condition base flows than do the computed base flows for the no-use scenario. Reference August streamflow for the no-use scenario was calculated similarly (i.e. by adding the calculated base-flow diversion to gaged streamflow) for comparison.

Table 30 lists statistics of the computed diversions and August flows for the initially analyzed years (2006 and 2008 through 2014). Table 31 lists the values for the entire, extended model period (2006 and 2008 through 2018). Note that August 2015 flows were estimated using station 15029003 data because continuous gaging data were missing for much of 2015 at station 15029001.

Using the USGS PHABSIM model, DNR conducted a habitat availability analysis on an approximately 1,000-foot reach immediately downstream of station 1502003 (DNR, 2021b). The analysis focused on differences in habitat availability between the reference condition and actual history. Continuous streamflow records for station 15029003 begin in July 2014. To develop reference-condition flows for the same analysis period as applied at station 15029001, the flow record at station 15029003 had to be extended to include estimated values prior to July 2014.

There are five-plus years of overlapping measured flows (2014-2019) at stations 15029001 and 15029003. In addition, DNR made same-day field measurements at both stations beginning in 2010. For estimating reference streamflow and base-flow statistics, DNR extended the 15029003 record using the "Maintenance of Variance – Extension" or MOVE method (Hirsch, 1982; Helsel et al., 2020) back to

March 2006. This approach assumes that there is a constant relationship over time between flows at the two stations. Table 32 provides August flow and diversion statistics using the extended record at station 15029003. Uncertainty in the estimated flows during the record-extension period is larger than uncertainty in measured flows, but as explained above, relative differences are less sensitive to variability than are the absolute flow values.

Table 30 August base-flow, streamflow, and diversion statistics for station 15029001 on Little Rock Creek for 2006 and 2008 through 2014.

Statistic	Base Flow (cfs)	Streamflow (cfs)
Median WHAT Base Flow or Gaged Streamflow	4.6	5.3
Median Computed Diversion	1.3	1.3
Median Calculated Reference Base Flow or Streamflow	5.5	6.2
Median Computed Diversion / Median Calculate Potential	24%	22%
Monthly Maximum Computed Diversion	1.9	1.9
Monthly Maximum Computed Diversion / Median Calculated Reference	35%	31%

Table 31 August base-flow, streamflow, and diversion statistics for station 15029001 on Little Rock Creek for 2006 and 2008 through 2018.

Statistic	Base Flow (cfs)	Streamflow (cfs)
Median WHAT Base Flow or Gaged Streamflow	6.8	8.05
Median Computed Diversion	0.77	0.77
Median Calculated Reference Base Flow or Streamflow	7.2	8.8
Median Computed Diversion / Median Calculated Reference	11%	9%
Monthly Maximum Computed Diversion	1.9	1.9
Monthly Maximum Computed Diversion / Median Calculated Reference	27%	22%

Table 32 August base-flow, streamflow, and diversion statistics for station 15029003 on Little Rock Creek for 2006 and 2008 through 2018.

Statistic	Base Flow (cfs)	Streamflow (cfs)
Median WHAT Base Flow or Gaged/Estimated Streamflow	4.9	6.2
Median Computed Diversion	0.64	0.64
Median Calculated Reference Base Flow or Streamflow	5.5	6.6
Median Computed Diversion / Median Calculated Reference	12%	10%
Monthly Maximum Computed Diversion	1.4	1.4
Monthly Maximum Computed Diversion / Median Calculated Reference	25%	21%

8.3. Alternative Model and Scenario Tests

This section describes several model tests that changed key model inputs and/or parameters. The test results provide insights into how model uncertainties, design, and assumptions affect calculated base-flow diversions, which in turn provides perspective for applying analysis results to management decisions. For convenience, Table * summarizes all of the model runs described in this report.

Table 33 Summary of model scenarios/runs

Scenario Name	Description
Baseline	Represents observed conditions
No Use (Scenario 2)	Represents no groundwater use with irrigated crops replaced by non-irrigated alfalfa
No Use Scenario 1	Represents no groundwater use with irrigated row crops replaced by non-irrigated row crops
80% Pumping	All groundwater withdrawals multiplied by 0.8, with resultant decreases in irrigation
Preliminary	A preliminary version of the model with different GSSHA parameterization and different GSSHA and MODFLOW parameter values. There were baseline and no use (most comparable to Scenario 1) runs of the preliminary model.

8.3.1. Reduced Pumping

The pumping and irrigation inputs in the baseline model directly affect the computed base-flow diversions. The accuracy of reported pumping volumes for crop irrigation systems is uncertain. The 2018-19 metering study (See 2.7 Groundwater Use) suggested that over-reporting of irrigation volumes may be much more common than under-reporting. For the nine-metered systems, the average of the differences between measured and reported pumping was about 20 percent more reported than measured.

As a simplified but informative example, DNR staff developed a model run with groundwater uses reduced to 80 percent of the reported volumes. Figure 42 plots computed monthly base flows at station 15029001 for this “80% pumping” scenario and for the baseline model. Table 34 lists the August base-flow statistics for both the baseline and 80% pumping scenarios.

Table 34 August base-flow and diversion statistics for station 15029001 on Little Rock Creek for 2006 and 2008 through 2018, baseline and 80% pumping scenarios.

Statistic	Baseline (cfs)	80% Pumping (cfs)
Median WHAT Base Flow	6.8	6.8
Median Computed Diversion	0.77	0.50
Median Calculated Potential Base Flow	7.2	7.0
Median Computed Diversion / Median Calculate Potential	11%	7.4%
Monthly Maximum Computed Diversion	1.9	1.5
Monthly Maximum Computed Diversion / Median Calculated Potential	27%	21%

8.3.2. Reference Condition for Irrigated Fields

In addition to the selected No-Use scenario (Scenario 2), a second no-use scenario was run for comparison. Unlike Scenario 2, land-use remained unchanged in the "default" Scenario 1. Scenario 1 did apply increased canopy stomatal resistance values for non-irrigated crops, which decreases ET compared to the values applied to irrigated crops (See Appendix A).

This scenario provides an informative and useful example of the effects that reference land-use choices have on model results. There are contrasts in computed ET between irrigated crops, non-irrigated alfalfa, and non-irrigated crops. Further, there are examples in the LRCA of non-irrigated row-crops planted in the mapped soil types that are commonly irrigated (e.g., soils with loamy sand and loamy fine sand surface textures), making Scenario 1 a relevant, although perhaps extreme example.

Computed base flows for the baseline scenario are generally lower than computed base flows for Scenario 1 throughout the year, except for a few high-flow periods. The calculated, August monthly flow diversions at station 15029001 vary from 1.1 cfs (2007) to 3.4 cfs (2013). Table 35 lists the August flow statistics for station 15029001 using the Scenario 1 reference condition (2006 and 2008 through 2014). Scenario 1 was not extended beyond water year 2014. One may compare these statistics with Table 30. See Appendix A for a comparison of the GSSHA-model water budgets for all three model scenarios.

Table 35 August base-flow, streamflow, and diversion statistics for station 15029001 on Little Rock Creek Using the Scenario 1 Reference Condition (2006 and 2008 through 2014).

Statistic	Base Flow (cfs)	Streamflow (cfs)
Median WHAT Base Flow or Gaged Streamflow	4.6	5.3
Median Computed Diversion	3.0	3.0
Median Calculated Potential Base Flow or Streamflow	7.3	8.0
Median Computed Diversion / Median Calculate Potential	40%	37%
Monthly Maximum Computed Diversion	3.4	3.4
Monthly Maximum Computed Diversion / Median Calculated Potential	46%	42%

8.3.3. Preliminary Model

Several assumptions and parameterization approaches differed for the preliminary version of the GSSHA model. The preliminary LRCA model (GSSHA and MODFLOW-USG models) produced a reasonable fit to the observed streamflow data, but the final version is expected be more realistic and reliable for the LRCA model objectives (See Appendix A for further explanation). The preliminary model, however, presents an opportunity to compare the final model to an alternative, "calibrated" model. Comparing base-flow diversions calculated using the two model versions provides some quantitative information on the sensitivity of the analysis results to the selected model assumptions and parameters.

The GSSHA model developer initially focused on overall ET totals to better match streamflow, making some simplifying assumptions. The initial model version did not apply different ET parameters (canopy stomatal resistance) for irrigated versus non-irrigated crops. In the GSSHA model, actual ET decreases with decreasing soil moisture, but the model does not account for the effect of water stress on plant-potential ET. Potential ET depends on meteorological conditions and plant size, density, and properties. In addition, the relative relationships of canopy stomatal resistance among different land covers differed for the preliminary model. Finally, the preliminary model applied a slightly different seasonal adjustment for PET.

These differences in the parameterization of ET resulted in different parameter estimates for other hydrologic parameters in the GSSHA and MODFLOW models, through the history-matching process.

8.4. Discussion

This section discusses key results from the baseline model and test scenarios and then develops an aggregate view of the hydrologic information available to support setting (a) protective flow(s) and (a) sustainable diversion limit(s). The model analysis makes reasonable use of the available data and information. The calculated groundwater diversions are useful but should be viewed in the context of data and model uncertainties, model limitations, and analysis assumptions.

8.4.1. Base-Flow Diversions Calculated Using the Baseline Model

The computed monthly August base-flow diversions were over 20 percent of the calculated median potential base flow (2006 and 2008 through 2018) in 2006, 2008, 2012, and 2013 (stations 15029003 and 15029001); and they were over 10 percent of the median potential base flow in 2009, 2014, and 2018.

The computed diversion rates are small or even negative compared to potential base flow and streamflow under higher flow conditions (August 2010, 2011, 2016, and 2017), but they are relatively larger compared to low flows. For example, at station 15029001, the calculated monthly diversion was over 45 percent of the monthly reference-condition base flow for August 2006 and August 2008. The calculated diversions were 1 percent and -1 percent of the reference-condition base flows in 2010 and 2011, respectively, although the monthly WHAT base flows were greater than the 75th percentile (22 cfs) in those months.

8.4.2. Sensitivity to Reference Condition and Model Parameterization

The calculated base-flow diversions were highly sensitive to differences in land-cover parameters between the baseline and no-use scenarios that control infiltration, ET, and recharge in irrigated areas. For example, setting the land cover in currently irrigated areas to represent non-irrigated row crops rather than alfalfa in the no-use scenario (Scenario 1 in Appendix A) results in substantially larger computed groundwater-discharge diversions.

Examining the results of the preliminary model revealed that calculated groundwater diversions are less sensitive to the approach to parameterizing ET and the corresponding differences in other estimated model parameters. The median and maximum of August monthly base-flow diversions were 15 percent and 10 percent larger, respectively, in the revised model versus the preliminary model. These differences in calculated base-flow diversions have a small effect on the calculated reference, August median base flow (1 percent larger) and the maximum monthly diversion as a percentage of August median base flow (3.6 percent larger). These differences give a sense of the relative magnitude of variability in model-analysis results due to uncertainty in model parameters.

8.4.3. Sensitivity to Uncertain Pumping Volumes

The pumping and irrigation inputs affect the calculated groundwater-discharge diversions because they directly affect the differences between the existing conditions and no-use scenarios. For the 80% pumping model test, the monthly August base-flow diversions at station 15029001 varied from 10 to 160 percent smaller than those calculated using the baseline model. The maximum monthly flow diversion was 24 percent smaller.

The absolute effects of reduced pumping on computed heads and base flows were relatively small compared to variability in the observations and baseline-model residuals. The statistics of fit to observations were comparable for the 80%-pumping and baseline scenarios.

The differences between the model scenarios were smaller relative to potential base flow because smaller calculated diversions lead directly to smaller calculated, reference-condition base flows. The maximum monthly diversion at station 15029001 was 27 percent of the potential August median base flow for the baseline model compared to 21 percent for the 80%-pumping scenario. The monthly August diversion was greater than or equal to 20 percent of the calculated median potential base flow in two years (2006 and 2013) compared to four years for the baseline scenario (2006, 2008, 2012, and 2013).

The accuracy and potential biases in reported pumping volumes should be considered when applying the model results. There are several other factors to consider when evaluating the potential impacts of permitted groundwater use, however. A number of crop irrigation systems were permitted and/or their reporting records begin after the start of the model-analysis period, but the maximum calculated diversion at station 15029001 was in August 2006 (although similar in August 2013). Some of these systems may contribute significantly to groundwater discharge diversions (the spatial distribution of impacts is yet to be assessed). In addition, future crop-rotation choices and irrigation demands are uncertain. Therefore, it is possible that groundwater-discharge diversions in a future year, with the existing permits, could exceed the diversions in 2006 and 2013.

8.4.4. Range of Possible Groundwater Diversions and Reference Base Flows

Model inputs and processes were at an appropriate scale for estimating the base-flow diversions reported here. The model reasonably matched observed monthly base flows, particularly during summer low-flow periods. As discussed under 7.2 Model Uncertainty and Limitations, however, the complexity of the hydrologic system precludes determining a perfect or unique hydrological model. Some uncertainty in the computed groundwater-discharge diversions is therefore unavoidable. The following paragraphs examine the range of possible groundwater-discharge diversions and reference base flows.

Although groundwater-discharge diversion cannot be directly measured, Barnett et al. (2012, p. 98) point out that there is “less uncertainty when a prediction can be formulated as a subtraction of two model results (because focusing on output change largely removes model bias).” Streamflow diversion due to groundwater use is the difference between the base flows computed in the no-use and baseline models. This means that the component of computed base-flow residuals caused by errors in the recharge input that are common to both model scenarios are largely removed when calculating groundwater diversions from streamflow/base flow.

As explained above, computed groundwater-discharge diversions are sensitive to differences in land-cover properties between the no-use and baseline models and to errors in reported pumping. Therefore, any relative biases between the baseline and no-use inputs (i.e., in pumping volumes or land-use properties on irrigated fields) could contribute to model prediction uncertainty.

We consider several factors here to support a general estimate of the overall “predictive” uncertainty. A formal, statistical assessment of the accuracy and precision of the calculated groundwater diversions, such as the methods suggested by Barnett et al. (2012), was not computationally feasible. Any such analysis is itself a mathematical/computational model, limited by its assumptions and by the range of outcomes that the model structure and algorithms can produce. Therefore, uncertainty assessment always entails judgement, and it should consider multiple lines of evidence.

Base-flow diversions are usually largest in August, and August is the reference period for base flow. Therefore, model errors are particularly important in August. At station 15029001, there were eight years during the model period in which WHAT base flow (estimated from a nearby station for 2015) was less than or equal to the threshold for comparison to model-computed groundwater discharge (22 cfs). The model fit to base flow was close for those months (Table 36).

Table 36 Model base-flow-fit statistics at station 15029001 for the month of August, 2006 through 2018 (for months less than the comparison threshold of 22 cfs)

Statistic	Value
Mean WHAT base flow (cfs)	4.9
Median WHAT base flow (cfs)	3.9
ME (cfs)	0.4
Number of months compared	8
MAE (cfs)	0.9
MARE	0.17
PBIAS (%)	7.7
NSE	0.77
RSR	0.48
Minimum relative error (%)	-18
Maximum relative error (%)	41

Because an appreciable part of the error cancels when subtracting two model runs, one expects errors in the calculated base-flow diversions to be typically smaller than errors in computed base flow. There are sources of model uncertainty that differ between the baseline and no-use scenarios, however, that do not cancel out in the subtraction. Examples are errors in the pumping input, errors in the groundwater-recharge contrast between the scenarios, or deficiencies in the hydraulic property distribution that affect the propagation of pumping drawdowns in the baseline scenario. Nevertheless, it is unlikely that all of the sources of predictive uncertainty are systematically biased in the same direction.

The 80%-pumping scenario provides an example of a model with a systematic bias in one key input compared to the baseline model. The maximum monthly diversion for the 80%-pumping scenario at station 15029001 was 24 percent smaller, but the median reference August base flow was only 3 percent smaller. This shifted the maximum monthly diversion as a percentage of the August median base flow from 27% to 21%. During the August with the maximum diversion (2006), the diversion was 44 percent of the reference-condition base flow for that month compared to 51 percent for the baseline model.

The preliminary model provides an example of how model results can differ due to different choices in model assumptions and parameterization. For comparable model scenarios, the maximum August monthly diversion was 10 percent larger and the calculated potential August median base flow was 1 percent larger for the final model than for the preliminary model.

Considering the variability due to parameter uncertainty, the non-uniqueness of the model, and the model fit to data, a reasonable estimate is that the calculated August groundwater-discharge diversions are mostly within about 30 percent of the most representative values for a selected reference condition. One cannot rule out a difference of more than +/- 30 percent for individual months. Model predictive errors in this range have a relatively small effect on the potential August median base flow, but there is uncertainty in, for example, the maximum monthly groundwater-discharge diversion. Nevertheless, it is unlikely that groundwater-discharge diversions, relative to the selected reference condition, did not exceed 1 cfs at station 15029001 in some years, and a maximum-monthly diversions in excess of 2.5 cfs is also plausible.

The habitat analysis for the approximately 1,000-foot reach below station 15029003 assessed how the amounts of habitat for several species/life stages differed between the reference-condition flows and the gaged (and extrapolated) August flows, focusing on the relative “shift” in available habitat. Therefore, that analysis was sensitive to variability in the calculated reference-condition flows at station 15029003. Because the total streamflow (and WHAT base flow) was nearly always larger than the calculated diversions, variability/uncertainty in the calculated diversions has a smaller relative effect on the calculated potential streamflow and potential base flow.

The other source of variability in the potential flow (base flow) is the streamflow record. Streamflow records contain measurement error. Records may contain bias for some time intervals due to the inherent accuracy of field measurements and rating-curve shifts. Streamflow records are not expected to be systematically biased, however. Similar to uncertainty in the diversions, measurement error has a lesser effect on relative differences in the potential and observed streamflow.

The period of record used in the analysis affects the range of flows and flow statistics. The relative differences between reference-condition and observed flows tend to be larger at lower flows. The model analysis period (2006 through 2018) included a range of conditions that included summers with low flows and with large irrigation demands and wet years with high flows and lower irrigation demands.

Extending the end of the analysis period from 2014 to 2018 resulted in generally larger values for the August exceedance-flow statistics, especially in the normal (intermediate) range, because August flows were mostly larger than the median from 2015 through 2018. Measured August daily flows in the 25 to 75 percent exceeds range increased by 28 to 70 percent at station 15029001. August groundwater-discharge diversions were below average from 2015 through 2018, and there were no daily streamflow values less than the 25th percentile. Therefore, extending the analysis period had a relatively small effect on the low-flow statistics for both the reference-condition and observed flows.

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