THESIS

ASSESSING GROUNDWATER STORAGE AND GROUNDWATER LEVEL FLUCTUATIONS IN THE AREA OF FORT COLLINS, COLORADO

Submitted by

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ABSTRACT

ASSESSING GROUNDWATER STORAGE AND GROUNDWATER LEVEL FLUCTUATIONS IN THE AREA OF FORT COLLINS, COLORADO

Although groundwater is the main water supply for many municipalities worldwide, shallow groundwater can adversely affect urban areas via soil waterlogging and impacts on building foundations and general city infrastructure. A quantitative assessment of groundwater levels and temporal fluctuations is needed to determine the extent to which groundwater should be managed to prevent these adverse conditions. This thesis assesses past and current groundwater storage and groundwater levels in the city limits of Fort Collins, Colorado, a moderate-sized municipality situated in the Front Range of the Rocky Mountains in the western United States. Currently, Fort Collins uses only surface water for its water supply, with the underlying unconfined alluvial aquifer mostly unused and close to ground surface. The assessment includes developing quantitative groundwater maps (depth to water table, water table elevation, and saturated thickness), estimating groundwater recharge and change in storage during large rainfall events, and defining areas with risk of high groundwater level. Observed depth to water table data from various sources was collected for two-time frames (1959-1979 and 2000-2017). The Stanford Geostatistical Modeling Software (SGeMS) was used to interpolate soil and groundwater data, and a Geographic Information System (GIS) was used to develop maps, estimate the storage, and define areas with potential risk of high groundwater level. Also, the Natural Resources Conservation Service's (NRCS) curve number method was performed to quantify recharge from high-intensity rainfall events. NRCS curve number method is a widely used method to quantify the amount of runoff due to a rainfall event. Comparing results from the two-time frames, the depth to water table in the study area has increased slightly (0.32 m) with a 3.9 m current average depth to the water table. Storage has decreased from 126.8 million m^3 to 122 million m^3, largely due to pumping groundwater for irrigation in the northeast area of the city limits. Approximately 10% of parcels in the Fort Collins area are at risk of high groundwater level. Most parcels along the Cache La Poudre River have problems with high groundwater level. The amount of recharge to the shallow aquifer in the Fort Collins area due to 10 and 100-year return-period storms is approximately equal to 1.9 million m^3 and 3.3 million m^3, respectively. Also, the percentage of the parcels at risk of high groundwater table will increase to 11% and 12%, respectively. The resulting groundwater maps, and the response of water table to rainfall events, can assist city water managers with identifying areas of potential risk to shallow groundwater conditions. In addition, the methods applied in this thesis can be used for other urban areas containing a shallow alluvial aquifer.

ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION

1.1 High groundwater levels in Urban Areas

1.1.1 Causes

Hibbs and Sharp (2012) claim that the majority of the world population (over 50%) live in urban areas and the growth of the world population will mostly occur in urban areas. These factors have caused significant hydrogeologic changes at both local and regional scales, with the groundwater system often being affected by urbanization both in terms of quantity and quality. Physical changes to the groundwater system generally include an increase in groundwater recharge (Garcia-Fresca, and Sharp, 2005; Hibbs and Sharp, 2012). Direct groundwater recharge from precipitation commonly decreases with the increase of impervious cover, so the classical view is that recharge is reduced as a result of urbanization, as direct runoff increases (Douglas, 1983; Lerner, 1990). Also, with urbanization the evapotranspiration will be reduced due to the reduction in vegetation cover and the recharge will be higher than without urbanization (Lerner, 1990). Now hydrologists know the impact of the water supply and drainage infrastructure leakage which provides large amount of non-direct recharge. Therefore, urbanization increases the overall recharge in nearly all environments (Lerner, 2002), resulting in more recharge in urban than rural areas (Lerner, 1990).

Leakage from water supply in in Lima, Peru provides 30% of the aquifer recharge (Lerner, 1986a). A 5 m groundwater level rise was observed in Kuwait City over the period 1961-1985 due to leakage from water distribution and sewer systems, return flow from irrigation, and seepage from septic tanks (Hamdan and Mukhopadhyay, 1991). Vázquez-Suñé, Carrera, Tubau, Sánchez-Vila, and Soler (2010) found that the sources and the contribution of each source for recharge in the Barcelona City aquifer are sewage network losses (30%), water supply network losses (22%), run-off infiltration (20%), rainfall in the non-urbanized areas (17%), and the Besos River (11%). However, not all leaked water recharges the groundwater, but instead drains away through the stormwater (or wastewater) systems or is intercepted by vegetation (Mitchell, Mein, and McMahon, 2001). Foster, Morris, & Lawrence (1994) suggests that the change of groundwater level due to urbanization-increased subsurface infiltration rates depends upon whether horizontal flow or vertical recharge will be dominant. Moreover, the change depends upon if the aquifer will be exploited and used for water supply, and the vertical permeability of the aquifer. Al-Sefry and Sen (2006) claim that other potential causes of groundwater table rise in urban areas are precipitation, deep percolation from irrigation, subsurface inflow from streams, canals, and lakes, and losses from septic tanks. Learner and Barrett (1996) point out that one of the main causes of groundwater table rise in the United Kingdom is the reduction in pumping groundwater due to the fact that it is either at risk of pollution or polluted while the recharge increases due to urbanization.

1.1.2 Quantifying groundwater recharge in urban areas

A few studies have been conducted in quantifying the recharge and developing its methodology for urban areas due to the complexities of land use and cover (Lener, 1990, 2002; Vázquez-Suñé et al., 2010). Taking into account precipitation as a source makes it harder to quantify recharge in urban areas. In addition, the large amount of data required to determine all of the recharge sources will aggravate the complexity of estimating recharge (Lerner, 2002). Yang, Lerner, Barrett, and Tellam (1999) shows that a combination of water balance with groundwater modelling is considered to be a traditional approach in quantifying groundwater recharge in urban areas. However, these approaches use precipitation and water supply leakages as the only sources for recharge. Sewer leakage can be added as a source using groundwater flow models and three solutes (Cl, SO_4, and total N) (Yang et al., 1999).

1.1.3 The Natural Resources Conservation Service's curve number method

The Natural Resources Conservation Service's (NRCS) curve number is a practical method in quantifying the amount of surface runoff and infiltrated water of a given amount of rainfall and uses more complex models' core components (Harbor, 1994). According to Cronshey (1986), in the United States it is the most widely used hydrologic abstraction technique, a technique used to quantify the amount of runoff of a given rainfall event. The Natural Resources Conservation Service's curve number method is used in both simple and highly sophisticated hydrologic models (Cronshey, 1986). This method was originally designed for small agricultural watersheds, then it was adjusted to urban catchments (Chin, 2013). The runoff depth is predicted using the curve number (CN) and the amount of rainfall. CN is an overall rating of the site and depends on the landuse and soil type. This analysis can be performed ideally using geo-processing in the Geographic Information Systems (GIS) (Harbor, 1994). However, this method ignores the fact that snowfall is a form of precipitation due to its simplicity and accessibility (Harbor, 1994) (see Section 2.3.4).

For this thesis, the precipitation was used for the source of recharge and curve number method was used in quantifying the recharge. Analysis was performed using the Geographic Information Systems (GIS).

1.1.4 Damages

Foster et al. (1994) claims that the presence of high groundwater level has negative effects on the integrity, stability, and functionality of subsurface engineering installations and structures. The consequences include:

1- Damages or flooding of tunnels or residential buildings. The side effects vary depending on whether or not the water is contaminated. Also, if the water enters the building the type of damages will be different than if the water does not enter the building (Kreibich and Thieken, 2008). When water enters the building through permeable basement walls/floors/ or openings for service pipes, it may stay for several weeks if the water level does not lower. As a result, damages will even occur to wall areas above the groundwater level due to capillary rise (Kelman and Spence, 2004). Furthermore, contaminated groundwater results in the corrosion of foundation materials or walls (Al-Sefry and Sen, 2006). Basement contents could be damaged and the most common form of damages to the building contents in Australia due to the 1998 flood was to the floor coverings, like linoleum and carpet (King, 1998). Moreover, the losses depend mostly on the use of the basement since the basement is the only part of the building that is affected by high groundwater. For example, it is essential whether or not the building services and heating are in the basement and water-proofed (FEMA, 1999). Even if water does not enter the building, structural damages such as base-plate or foundation demolition and destabilization and destruction of the building may occur (Kreibich and Thieken, 2008). The risk of high groundwater table was neglected in the design of buildings in Riyadh, Saudi Arabia in the mid-1980s. Consequently, the basements flooded (Rushton and Al-Othman, 1993).

2- Compromising the stability of buildings as the pore pressure increases which lead to a reduction in the bearing capacity and settlement of foundations (Morrison and Taylor, 1994).

3- Physical damages to collector sewers where they intersect with the water table resulting in major seepage.

1.2 Overview of previous research on Fort Collins groundwater

Two surface water sources are being used by the City of Fort Collins for its drinking water, the Upper Cache La Poudre River and Horsetooth Reservoir (Mihelich, Oropeza, and Heath, 2016). Groundwater has not been used yet for water supply, so there is a lack in research. The U.S. Geological Survey in cooperation with the Colorado Department of Natural Resources, Division of Water Resources, and the Colorado Water Conservation Board published "Geohydrology of the shallow aquifers in the Fort Collins-Loveland area, Colorado" in the year 2000. The publication includes but not limited to the following maps:

- The water table altitude (Figure A1 in Appendix).
- The Saturated Thickness of the aquifers (Figure A2 in Appendix).
- Depth to the water table (Figure A3 in Appendix).

These maps, however, are based on data from the 1950s through 1970s, and thus there is a need to update groundwater quantity and levels in the Fort Collins area and provide a comparison with previous data. In addition, groundwater levels have not been related to the city infrastructure, e.g. basements and building foundations.

1.3 Study objectives

To gain a better understanding of the current situation of shallow groundwater in the Fort Collins, Colorado area, this thesis aims to achieve the following objectives:

1- Collecting comprehensive data about the depth to water table in the Fort Collins Area using two different time frames (1959-1979 and 2000-2017) from multiple sources and, gathering about shallow aquifer soil type.

2- Developing quantitative groundwater maps (depth to water table, water table elevation, and saturated thickness) using a soil type map for shallow aquifer soil.

3- Estimating the amount of groundwater storage that can be used for water supply, and quantifying the change of the amount of water stored between the two time frames.

4- Identifying the areas with the risk of high groundwater levels in the Fort Collins Area.

5- Estimating the amount of groundwater recharge based on different rainfall scenarios and then defining the new areas with a high level of groundwater due to water level rise.

CHAPTER 2: METHODOLOGY

2.1 Overview of the Fort Collins Area and study area

Fort Collins is one of the cities in Larimer County, Colorado, United States. It is located 65 miles (105 km) north of the Colorado State Capitol in Denver. The GIS polygon shapefile of the land area annexed by the city of Fort Collins and the water features were obtained from the city of Fort Collins website (https://www.fcgov.com/gis/downloadable-data.php). The Wyoming, Nebraska, Kansas, Oklahoma, Texas, New Mexico, Arizona, Utah, Colorado, and the city of Denver GIS polygon shapefiles were obtained from the United States Census Bureau website (https://www.census.gov/geo/maps-data/data/tiger-cart-boundary.html). The land cover map was obtained from the USGS national map website (https://viewer.nationalmap.gov/basic/#productSearch).

Due to the availability of data beyond the city limit, the study area was extended beyond the Fort Collins area (Fig. 1). The study area was defined by the bedrock GIS polygon shapefile (Fig. 2). The bedrock GIS polygon shapefile was obtained from the USGS website (https://pubs.usgs.gov/ds/2006/193/downloads/Downloadable%20GIS%20Data/). The study area is the area where groundwater exists.

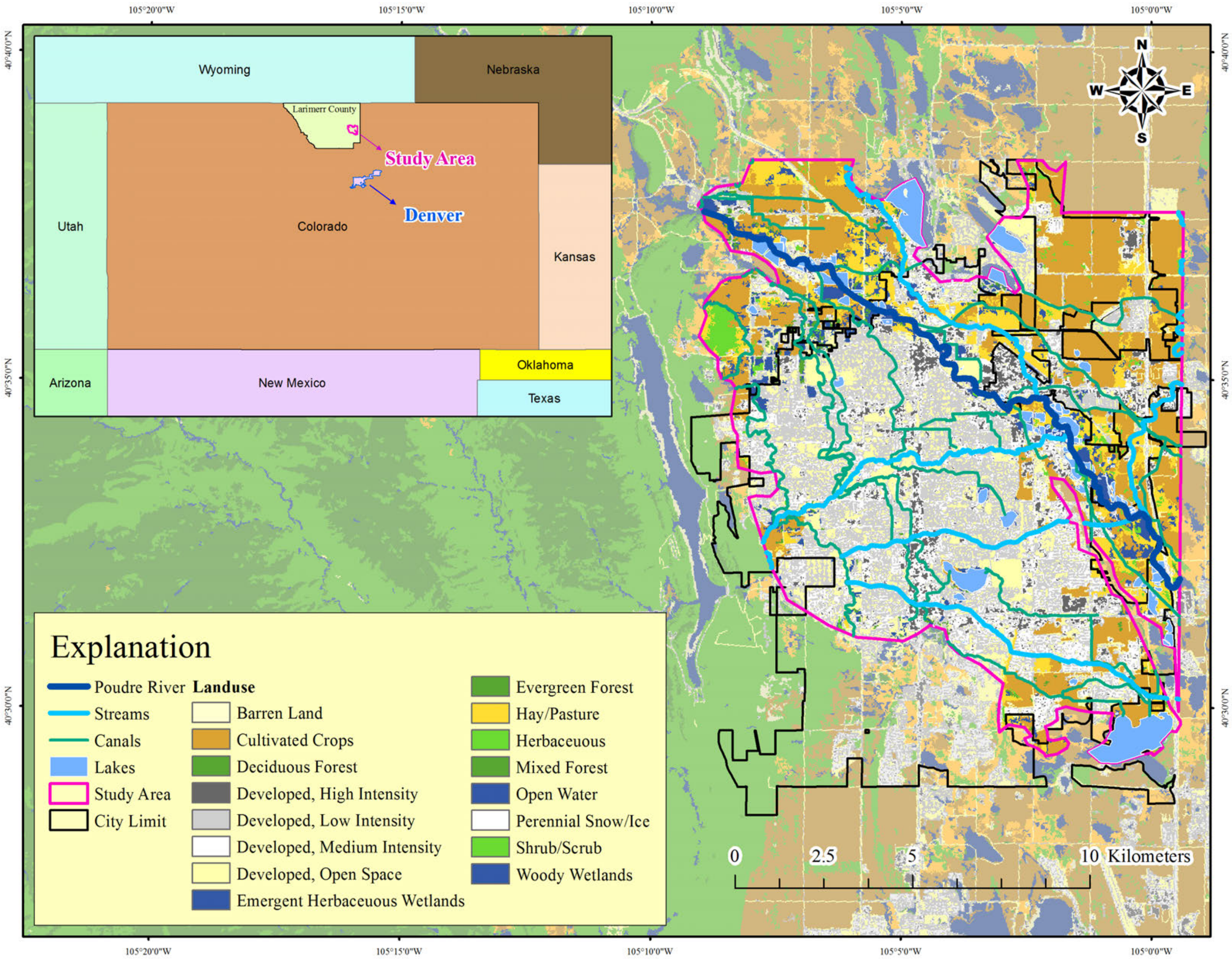

Figure 1 Study area

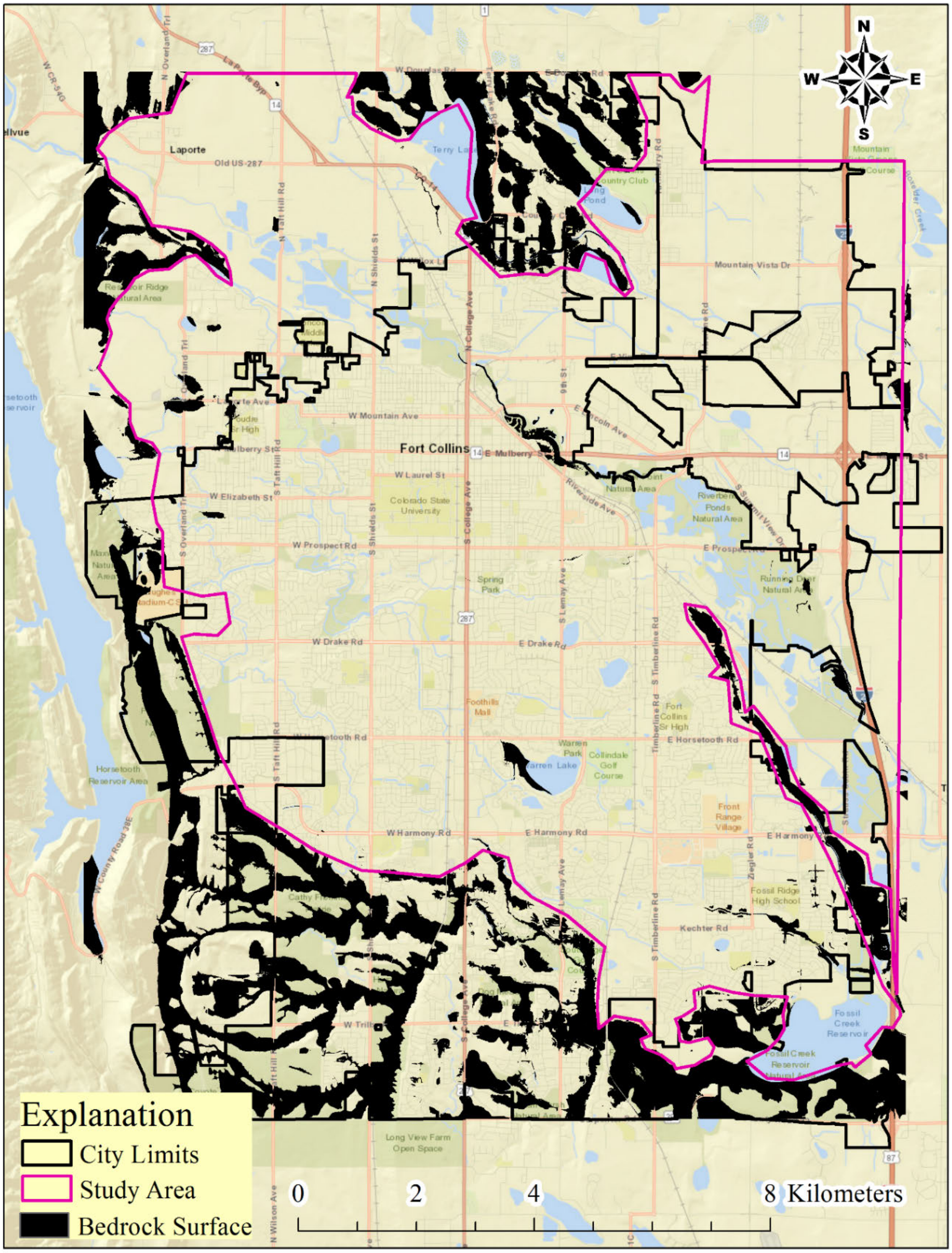

Figure 2 the Fort Collins city limit and the study area

2.2 Data Acquisition

The data provided in this section is required to perform the study and is summarized in Table 1.

Table 1 Data type and use

Data (type)	Use
Depth to water table (point shapefile)	To develop depth to water and saturated thickness maps and to determine the groundwater storage
Digital Elevation Model (raster)	To develop depth to water and saturated thickness maps
Parcels (polygon shapefile) and Foundation and basement depth (number)	To determine areas with risk of high groundwater
Water features and pumping well locations (point, line, and polygon shapefiles)	General hydrology information
Bedrock elevation contours (line shapefile)	To develop depth to water table maps
Aquifer type (point shapefile)	To determine the groundwater storage
Land use (polygon shapefile), Top layer soil type (polygon shapefile), and Precipitation Intensity-Duration-Frequency Curve (graph)	To perform the Curve Number method

2.2.1 Depth to Water Table

- Old (1959-1979) data

The depth to water table data were obtained from the Wells with Water Levels shapefile offered by the Colorado’s Decision Support Systems website (http://cdss.state.co.us/GIS/Pages/AllGISData.aspx). A total of 179 locations with measured depth to water table were obtained from the shapefile. The depth to water table data from 1959 to 1979 was used for the study. The smallest and the largest depth to water table are 0.79 m and 12.59 m, respectively (Fig. 3).

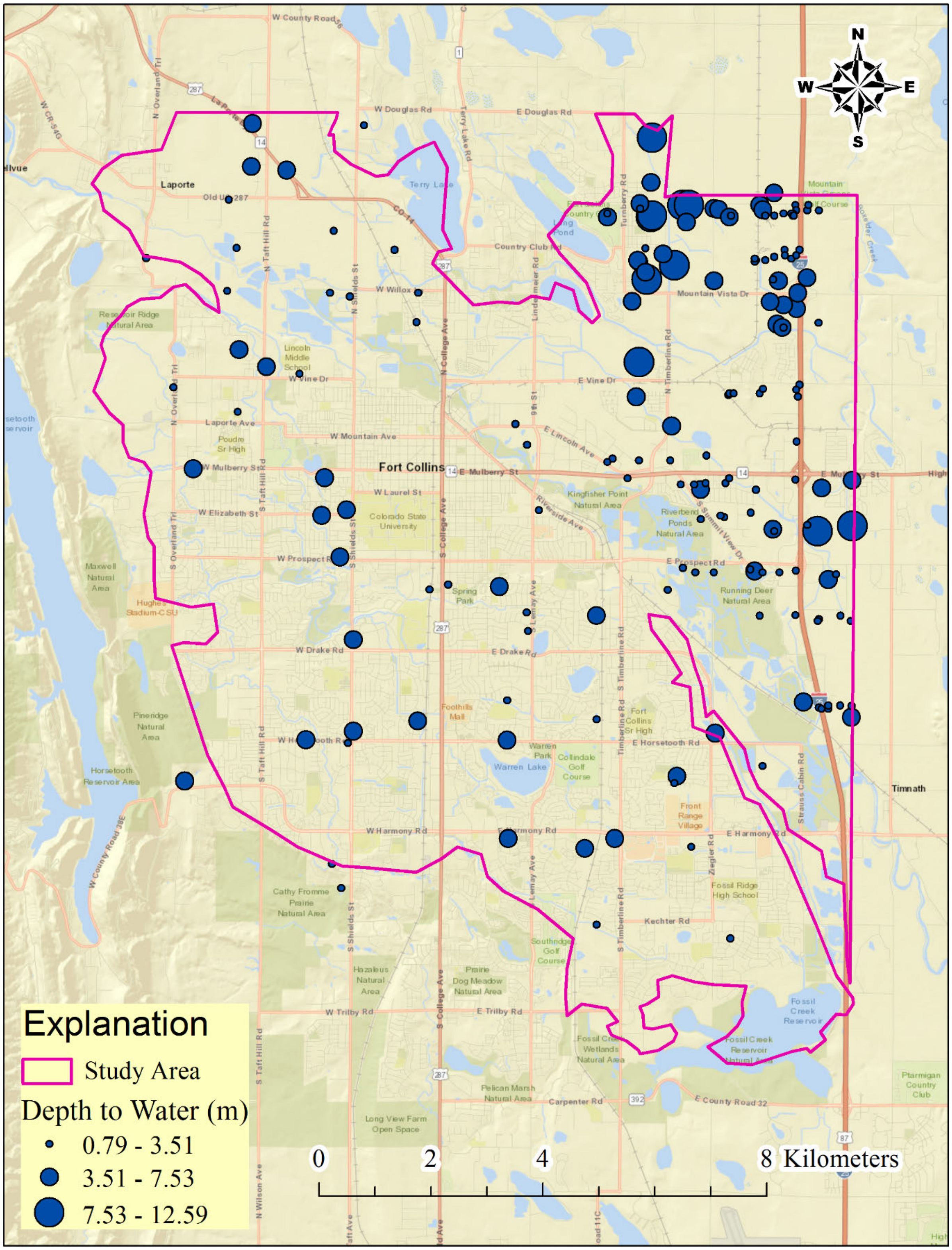

Figure 3 Locations of old (1959-1979) measured depth to water table data

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-NEW (2000-2017) data

The depth to water table data were collected from 81 construction geotechnical reports offered by the City of Fort Collins Public Records website (http://citydocs.fcgov.com/?vid=185&cmd=search&scope=doctype&dt=SUBMITTAL+DOCUMENTS&dn=Current+Planning&q=soil). A total of 286 borehole logs with data regarding water table elevation were reviewed to obtain the depth to water table, the borehole locations, and the drilling dates. These boreholes were drilled between 2004 and 2013. 381 well permits from 2000 to 2017 in the Fort Collins area were retrieved and reviewed from the Colorado Division of Water Resources has a Colorado’s Well Permit Search (http://www.dwr.state.co.us/wellpermitsearch/) which provides information about all the permits that have been processed in the state, to obtain the depth to water data. This data were combined and the result is a total of 667 locations in the Fort Collins area where the depth to water table was measured. The smallest and the largest depth to water table are 0.44 m and 24.38 m, respectively (Fig. 4).

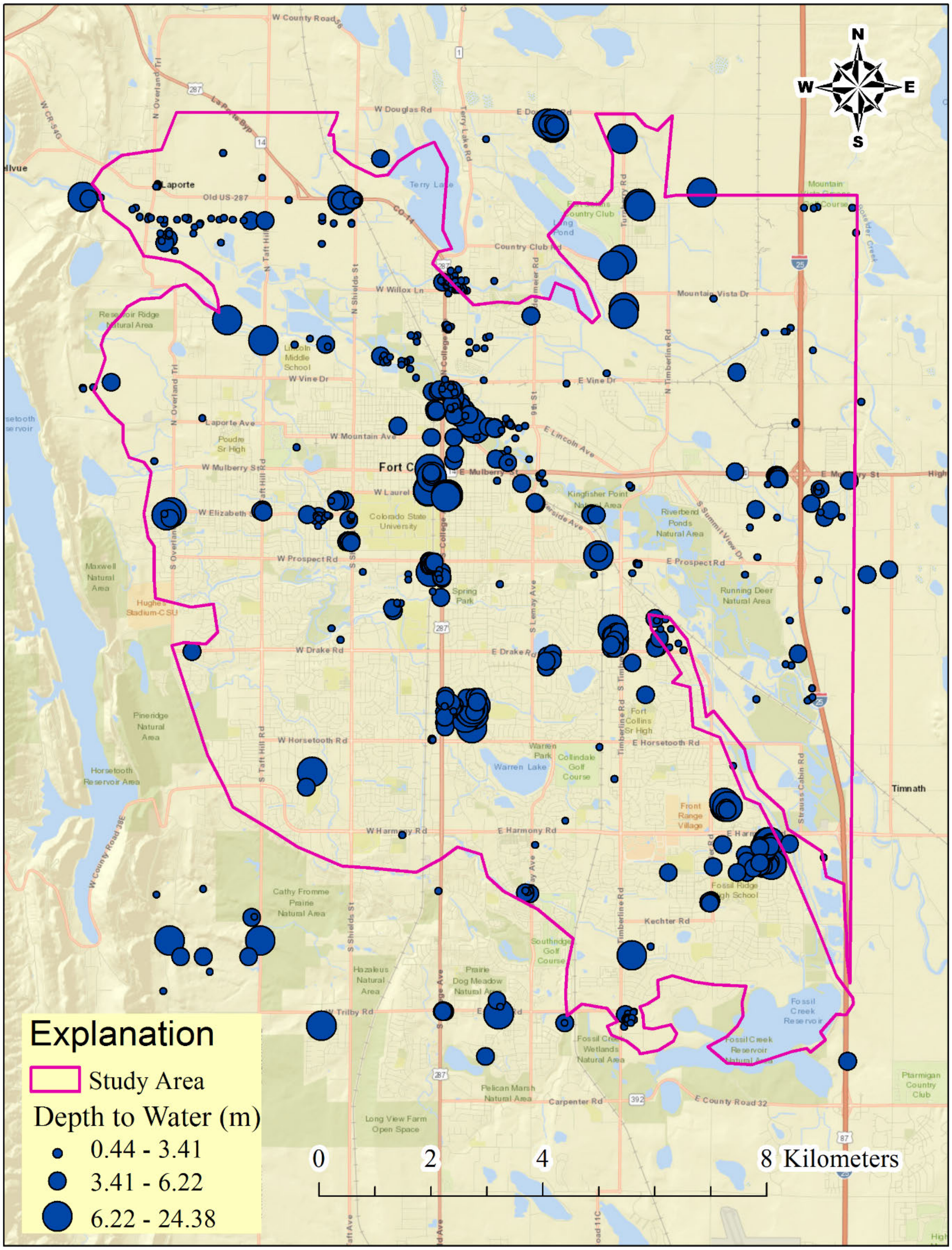


Figure 4 Locations of new (2000-2017) measured depth to water table data

2.2.2 GIS Coverages

The Digital Elevation Model (DEM) dataset was obtained from the City of Fort Collins administrative staff while the parcels, landuse, and water features were obtained from the City of Fort Collins website (https://www.fcgov.com/gis/downloadable-data.php). The bedrock elevation contours layer was obtained from the USGS website (https://pubs.usgs.gov/ds/2006/193/downloads/Downloadable%20GIS%20Data/).

2.2.3 Soil Type and specific yield (Sy)

- Top layer:

The USDA Geospatial Data Gateway was used to obtain the soil map (STATSGO2) (https://datagateway.nrcs.usda.gov/GDGOrder.aspx). The Description of Natural Resources Conservation Service (NRCS) Soil Groups table by David Chin (2000) was used to assign the soil group to each soil type (Table 2) (Fig. 5).

Table 2 Description of NRCS Soil Groups (Chin, 2000)

Group	Description	Minimum infiltration rate	
		(mm/h)	(in/h)
A	Deep sand; deep loess; aggregated silts	> 7.6	> 0.30
B	Shallow loess; sandy loam	3.8-7.6	0.15-0.30
C	Clay loams; shallow sandy loam; soils low in organic content; soils usually high in clay	1.3-3.8	0.05-0.15
D	Soils that swell significantly when wet; heavy plastic clays; certain saline soils	0.0-1.3	0.00-0.05

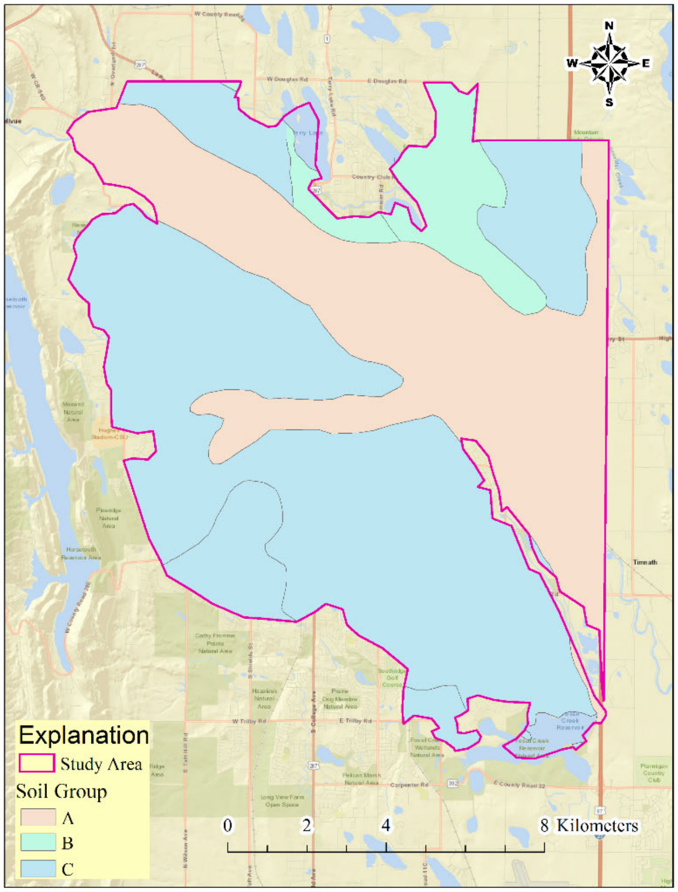


Figure 5 Top layer soil

- Shallow aquifer:

The soil type was obtained from the boring logs from both the construction geotechnical reports and the well permit documents at the 40 different locations (Fig. 7). Soil type changes with depth, but the soil where water is present was used to represent the aquifer. At some locations, there were different soil types present, so the specific yield (Sy) value of each soil type was considered in assigning the Sy value of the aquifer. The soil triangle (Fig. 6) provided by the United States Department of Agriculture website (https://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/?cid=nrcs142p2_054167) was used as a guide.

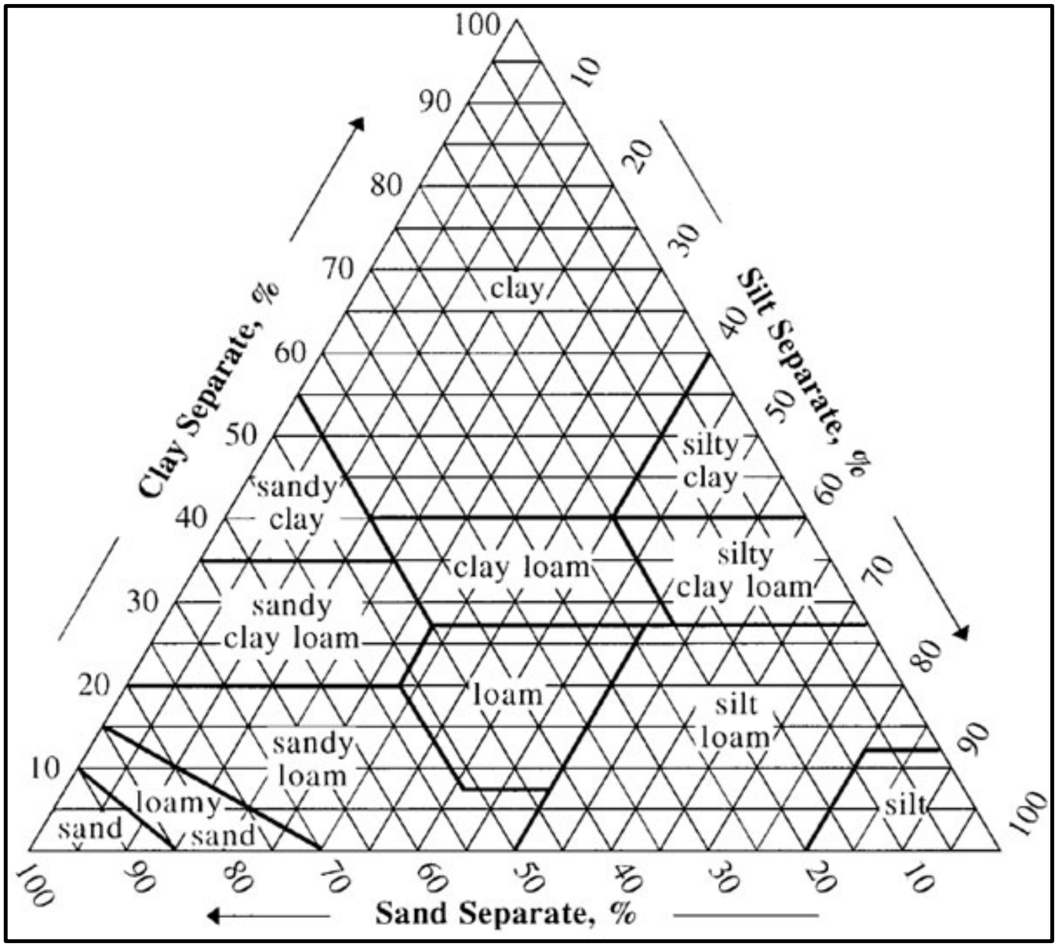


Figure 6 Soil triangle, from the United States Department of Agriculture

The typical values of Sy table by Morris and Johnson (1967) was used as a reference (Table 3). Average Sy value was calculated as the mean of the range. Then, the average Sy value was used for each soil type (Table 4), and those values were used for the study.

Table 3 Typical values of Sy (Morris and Johnson, 1967)

Material	No. of analyses	Range	Arithmetic mean
Sedimentary materials			
Sandstone (fine)	47	0.02-0.40	0.21
Sandstone (medium)	10	0.12-0.41	0.27
Siltstone	13	0.01-0.33	0.12

Sand (fine)	287	0.01-0.46	0.33
Sand (medium)	297	0.16-0.46	0.32
Sand (coarse)	143	0.18-0.43	0.3
Gravel (fine)	33	0.13-0.40	0.28
Gravel (medium)	13	0.17-0.44	0.24
Gravel (coarse)	9	0.13-0.25	0.21
Silt	299	0.01-0.39	0.2
Clay	27	0.01-0.18	0.06
Limestone	32	0-0.36	0.14
Wind-laid materials			
Loess	5	0.14-0.22	0.18
Eolian sand	14	0.32-0.47	0.38
Rock			
Schist	11	0.22-0.33	0.26
Tuff	90	0.02-0.47	0.21

Table 4 Calculated average Sy values for each soil type

Material	Range	Average
Clay	0.010-0.180	0.095
Clay & Sand	0.117-0.357	0.237
Clay, Sand & Gravel	0.130-0.360	0.245
ClayLoam	0.095-0.305	0.2
Gravel	0.150-0.363	0.257
Gravel (medium & coarse)	0.150-0.34	0.248
Gravel (small, medium, & large)	0.150-0.363	0.257
LoamySand	0.085-0.425	0.255
Sand	0.117-0.445	0.281
Sand & Gravel	0.130-0.396	0.263
Sandstone (Clayey)	0.050-0.330	0.19
SandyClay	0.085-0.320	0.203
SandyClayLoam	0.085-0.320	0.203
SandyLoam	0.160-0.460	0.31
SiltyClay	0.010-0.285	0.148

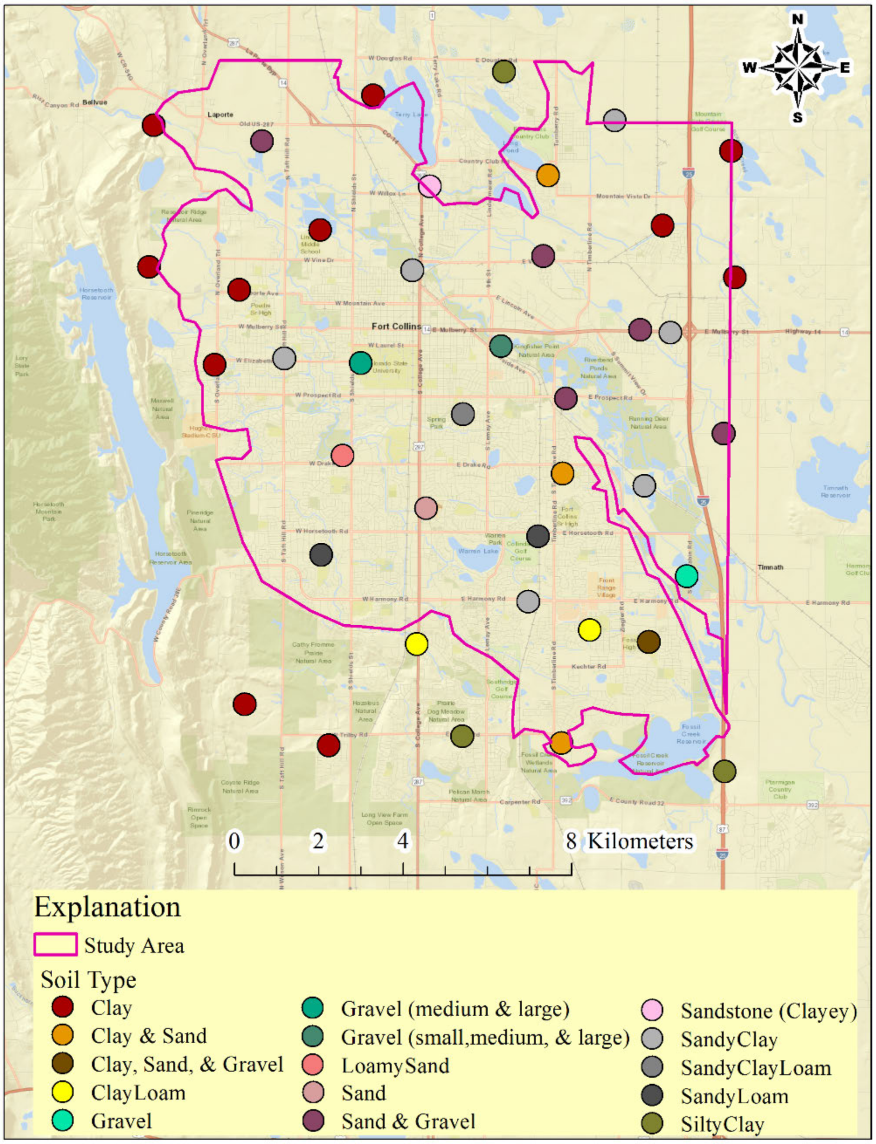


Figure 7 Shallow aquifer soil type based on data from boring logs

2.2.4 Foundation and Basement Depth

The data were obtained from the building inspection department at the City of Fort Collins (personal communication). The typical foundation depths are from 42” (frost depth) to 10 ft, and the average basement ranges from 9 to 10ft.

2.2.5 Precipitation Intensity-Duration-Frequency

The following curve was obtained from the Fort Collins Stormwater Criteria Manual (https://www.fcgov.com/utilities/business/builders-and-developers/development-forms-guidelines-regulations/stormwater-criteria). It was used to perform the NRCS curve-number method.

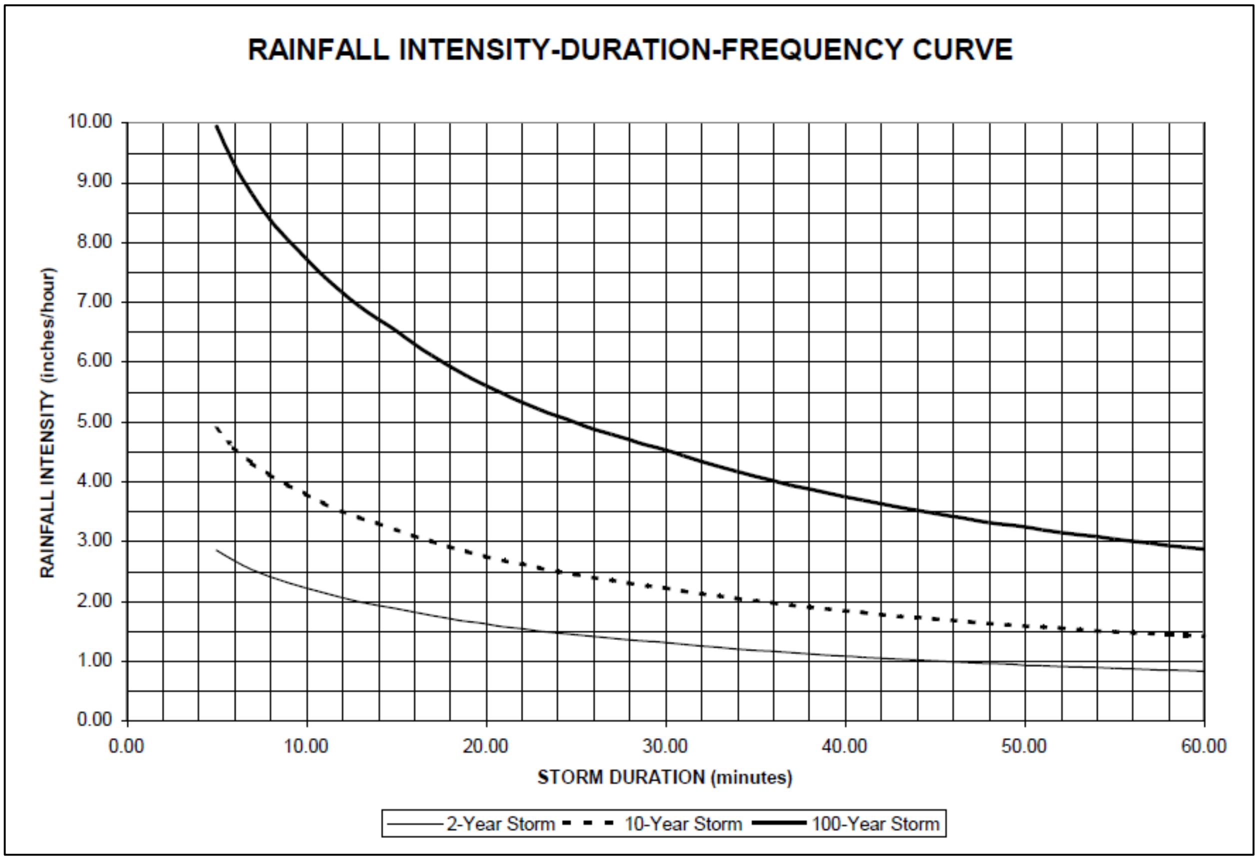


Figure 8 City of Fort Collins Rainfall Intensity-Duration-Frequency Curves

2.3 Data Analysis

2.3.1 Interpolating Depth to Water and Specific Yield Using SGeMS

2.3.1.1 Geostatistics applications in hydrogeology

Due to aspects of time, cost and safety, data monitoring or collecting field data (i.e., water levels, hydraulic conductivity, and water qualities) is conducted at a limited number of sites. Consequently, the use of an interpolation method has been invaluable to estimate values at those locations where no samples or measurements are taken (Kitanidis, 1997).

In a regular statistical approach, a histogram is used to classify the grades of samples. In this approach, the location of samples is neglected. In hydrogeology, values of quantities (hydraulic head, conductivity, etc.) vary in space. Geostatistics is a method that was developed for the estimation of quantities that vary in space (Matheron, 1963). The theory of regionalized variables is the basis of geostatistics where its applications cover nearly all areas of hydrogeology from parameter estimation at unmeasured locations to groundwater predictive modeling (Ahmed, 2001). “Geostatistics offers a way of describing the spatial continuity of natural phenomena and provides adaptations of classical regression techniques to take advantage of this continuity.” (Isaaks and Srivastava, 1989).

In the 1970s, geostatistics was popular in mining engineering; however, it is commonly used today in all fields of engineering and earth science (Kitanidis, 1997). The first application of geostatistics on groundwater hydrology was by Delhomme (1974). Then, a large number of studies have been performed in the field of hydrology, such as Delhomme (1978), Gambolati and Volpi (1979), Mizell (1980), Darricau-Beucher (1981), Neuman (1984), and Roth, Chiles, and

Fouquet (1996) (Ahmed, 2007). Variogram analysis, kriging cross-validation and mapping are the components of geostatistics (Kolsi, Bouri, Hachicha, and Dhia, 2013).

2.3.1.2 SGeMS

The Stanford Geostatistical Modeling Software (SGeMS), an open-source computer package used to solve spatially related variable problems (Remy, Boucher, & Wu, 2009), was used to interpolate the depth to water table and the specific yield. SGeMS uses the basic components of geostatistics, variogram model, and kriging, to interpolate the data. These two components are sometimes called the two stages of geostatistical estimation where constructing variogram graphs is the first stage, and developing the corresponding kriging method is the second (Clark, Place, & Oen, 1986). Variogram analysis is required to assess the spatial correlation of the data because geostatistics deals with spatially autocorrelated data. Also, a variogram model is required to perform kriging analysis (Bohling, 2005).

2.3.1.3 Variogram

The variogram is a diagram on which $\gamma(h)$ is plotted on the y-axis versus h where $\gamma(h)$ is half of the variance of the difference between the variables, and h is the distance between the variables. The function which gives the best reasonable fit determines the variogram model where a fitted curve reaches a constant value of $\gamma(h)$ at a certain value of h. In this case, $\gamma(h)$ and h are called the range and the sill, respectively (Fig. 9) (Nikroo, Kompani-Zare, Sepaskhah, & Shamsi, 2009). SGeMS has three different kinds of functions: Spherical, Exponential, and Gaussian (Fig. 10). The Spherical and Gaussian variogram models were the best fits for the depth to water and specific yield data. After interpolating the two datasets, crossvalidation analysis was performed (See Section 2.3.2). (Table 5) (Fig. 11).

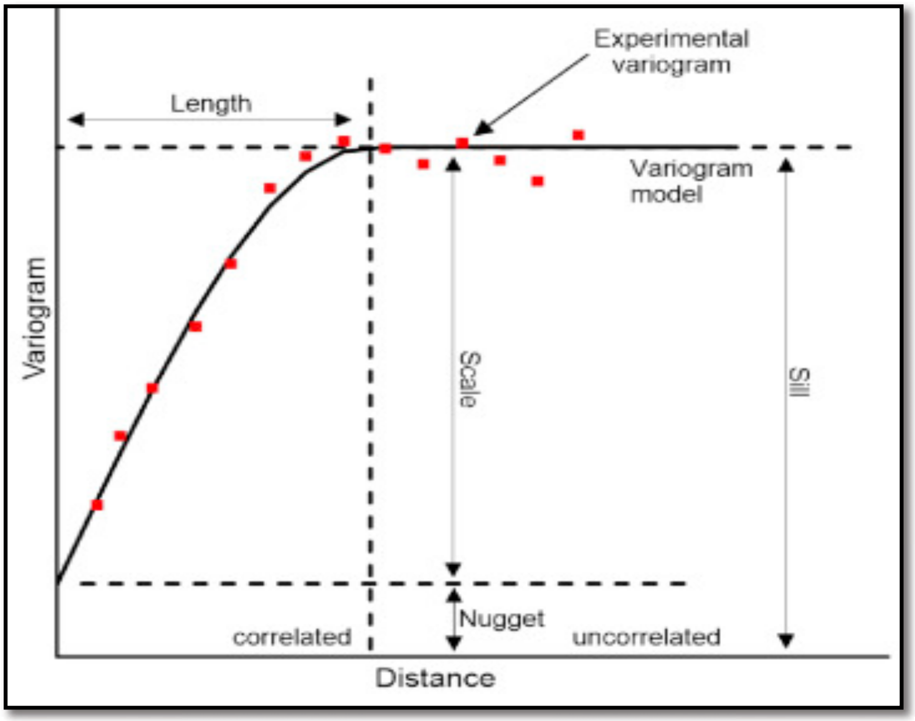


Figure 9 Experimental variogram and variogram model (Barca, Porcu, Bruno, & Passarella, 2017), used with permission from Elsevier

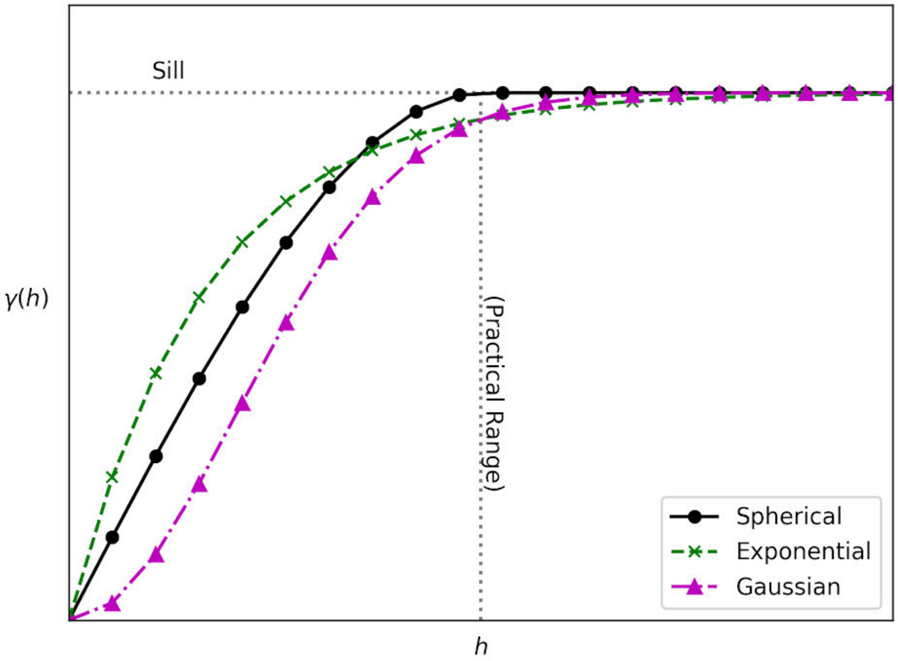


Figure 10 Different variogram model functions

Table 5 Best fit variogram model function for the data

Data	Best fit function
Depth to water table (1959-1979)	Gaussian
Depth to water table (2000-2017)	Spherical
Specific Yield	Gaussian

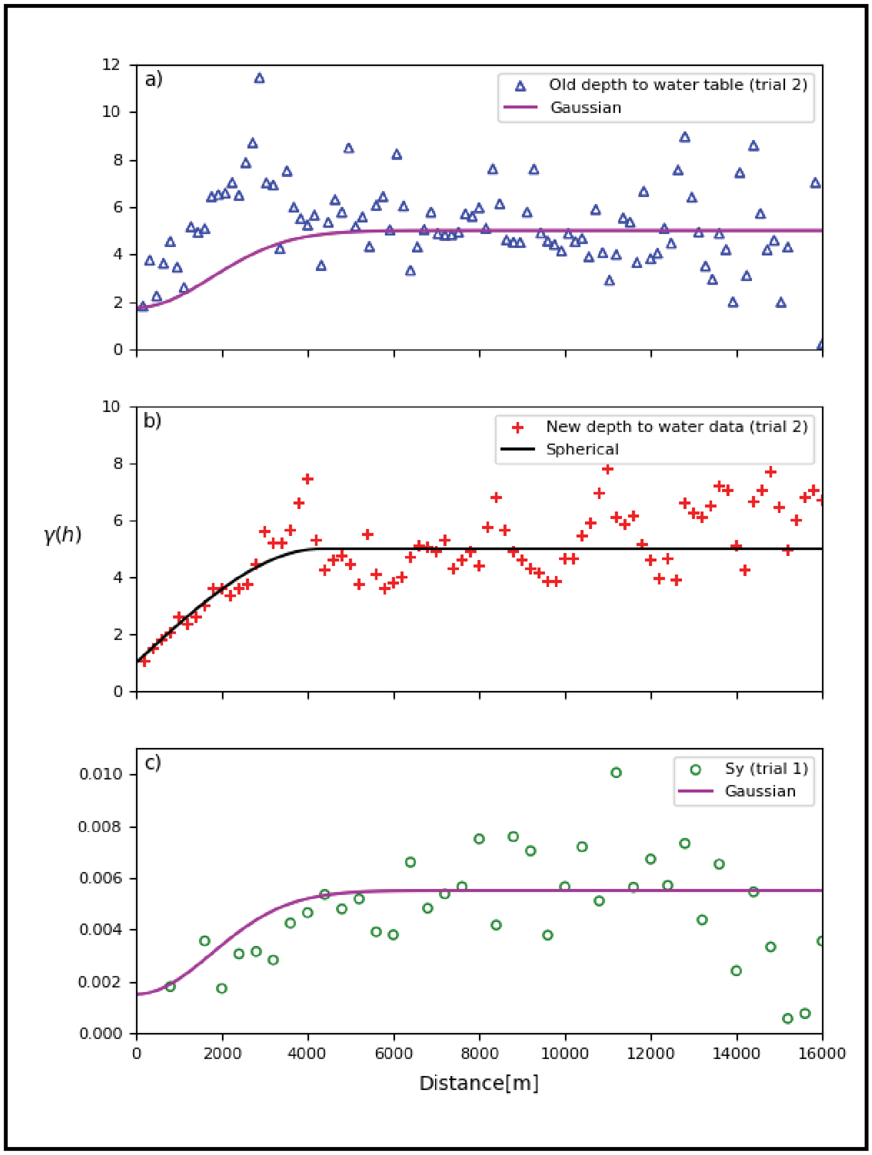


Figure 11 Best fit variogram model function for the data

2.3.1.4 Kriging

Kriging is a sophisticated approach that is used in hydrology to interpolate observation data. It was developed by Matheron (1969, 1970) and then used in the field systematically by the Ecole des Mines de Paris (Gambolati and Volpi, 1979). It is one of the most powerful and exact interpolation methods because it is based on geostatistics (Isaaks and Srivastava, 1989). Kriging is common in interpolating depth to groundwater or water table elevation (Ahmadi and Sedghamiz, 2007). Stationary and homogeneous spatially distributed data give the best kriging result (Knotters and Bierkens, 2001). Ordinary and simple kriging methods were used in this study, and SGeMS was used to perform the interpolation. The study area was divided into small cells, and each cell is 100 m^2. Therefore, the interpolated data result is for every 100 m^2. The best method for each dataset was decided after performing the crossvalidation for two trials (Section 2.3.2) (Table 6).

Table 6 Best kriging method for the data

Data	Best kriging method
Depth to water table (1959-1979)	Simple
Depth to water table (2000-2017)	Ordinary
Specific Yield	Ordinary

- Ordinary Kriging

Ordinary kriging assumes that the mean of the data is unknown, and it is simple and widely used (Nikroo et al. 2009). This method gave the best interpolated specific yield and new (2000-2017) depth to water data (Fig. 12&13). The best result was decided based on crossvalidation (Section 2.3.2).

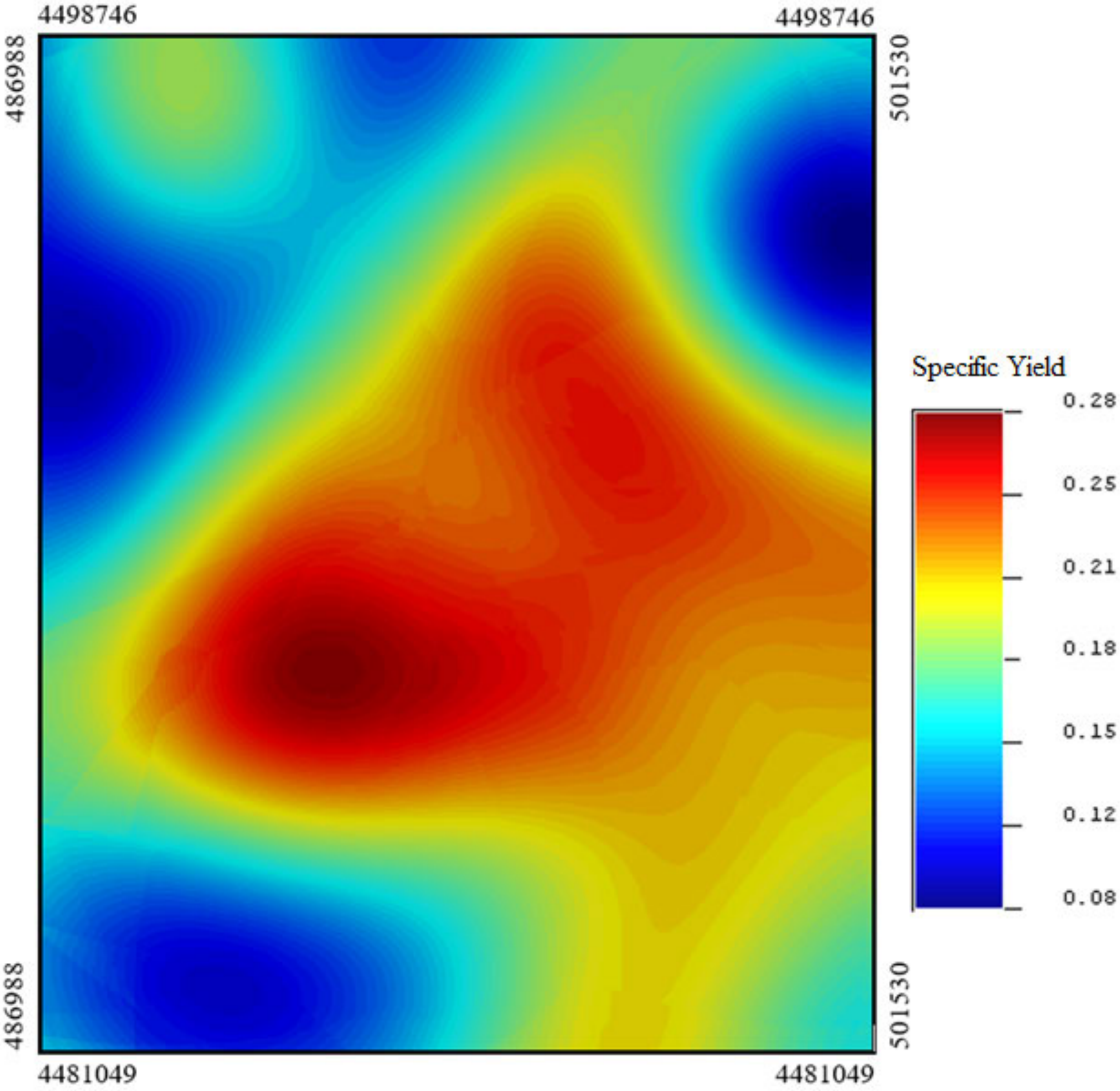


Figure 12 Interpolated specific yield data for study area using SGeMS (NAD 1983 UTM Zone 13N Meter)

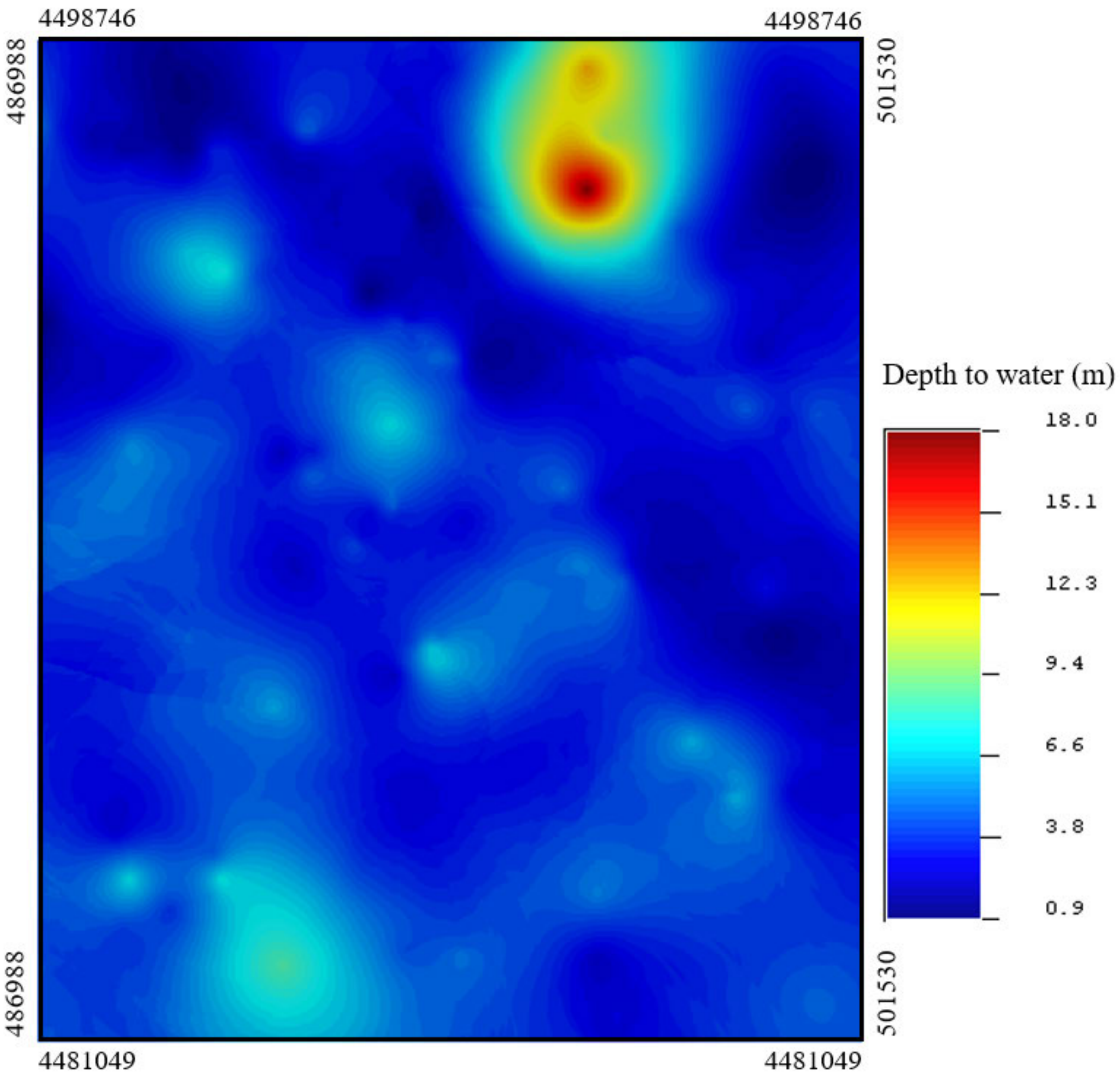


Figure 13 Interpolated new (2000-2017) depth to water data for study area using SGeMS (NAD 1983 UTM Zone 13N Meter)

- Simple Kriging

Simple kriging assumes that the mean of the data is known, and it is equal to their average (Nikroo et al. 2009). This method gave the best result for old (1959-1979) depth to water data (Fig. 14), and that was decided after performing crossvalidation (Section 2.3.2). Due to lack of data, SGeMS assigned an average value to an area where there were not enough data to do interpolation. Therefore, these areas were ignored in the analysis.

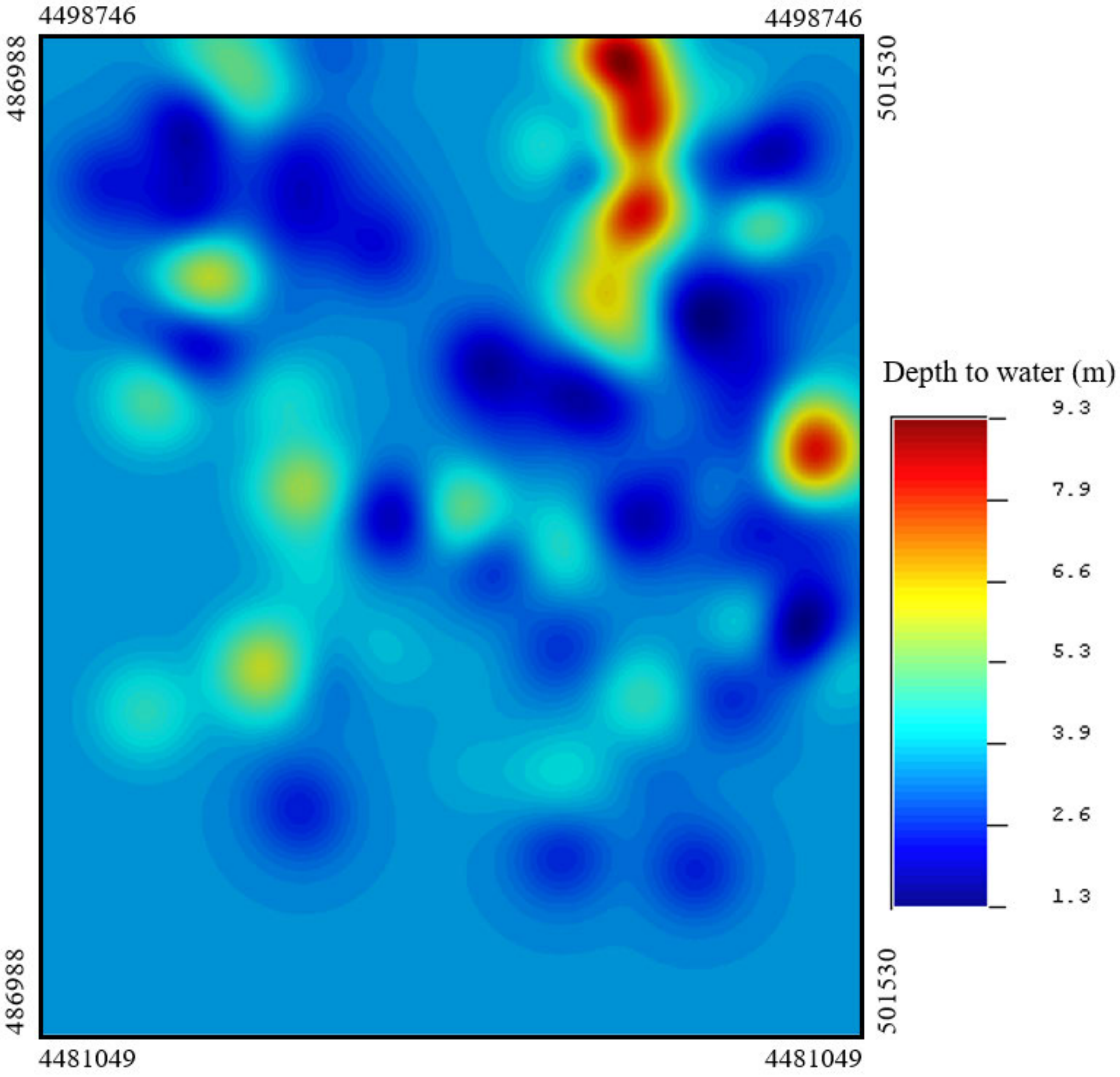


Figure 14 Interpolated old (1959-1979) depth to water data for study area using SGeMS (NAD 1983 UTM Zone 13N Meter)

2.3.2 Crossvalidation

Clark et al. (1986) claim that crossvalidation is used to test the fit of the variogram model to the data and to support the choice of the kriging technique used for performing the interpolation. It is the following procedure:

- A small sample is chosen (test data) and eliminated from the data set, where the remaining data is called the training data. In this study, the test data is five percent of the data set. Also, two trials were done for each data set (Fig. 15, 16, &17).
- The training data is then used to provide estimated values at the (now) unsampled locations (locations of test data) using geostatistical estimation method.
- The actual and theoretical error is then calculated.

Actual error = Actual value – Estimated value (Eq. 1)

Authors differ on which type of error should be calculated (Clark et al. 1986); however, in this thesis, the root mean square error (RMSE) was measured for validation (Nikroo et al. 2009).

$$RMSE = \sqrt{\frac{\sum(Zi_* - Zi)^2}{n}} \qquad \text{(Eq. 2)}$$

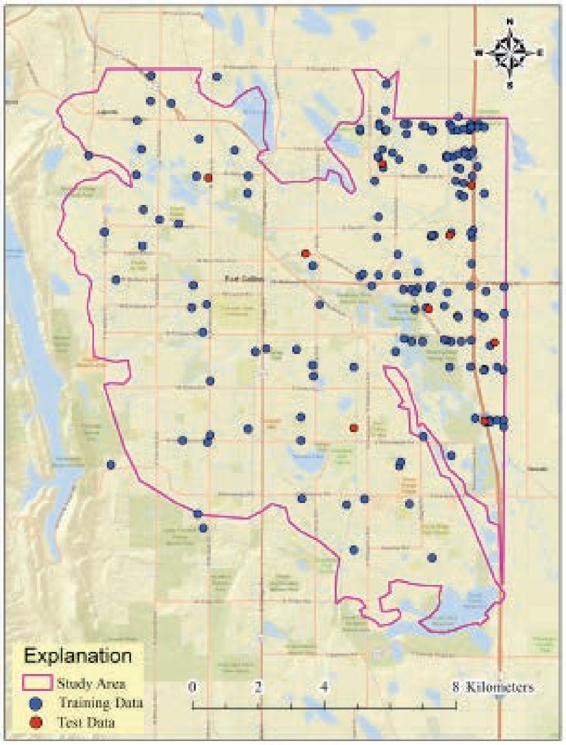
Where:

Zi is the actual value

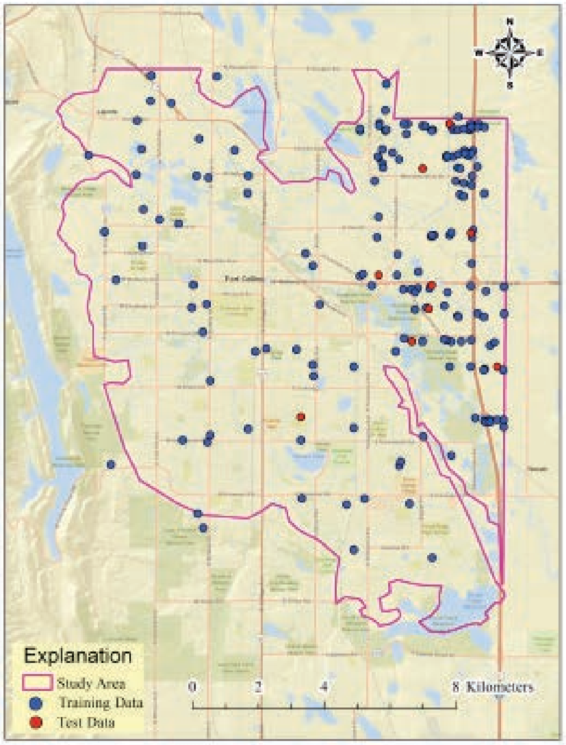
Zi* is the predicted value

n is the number of observations

The variogram model of each data set of each trial was used to perform both ordinary and simple kriging methods (Fig. 18)

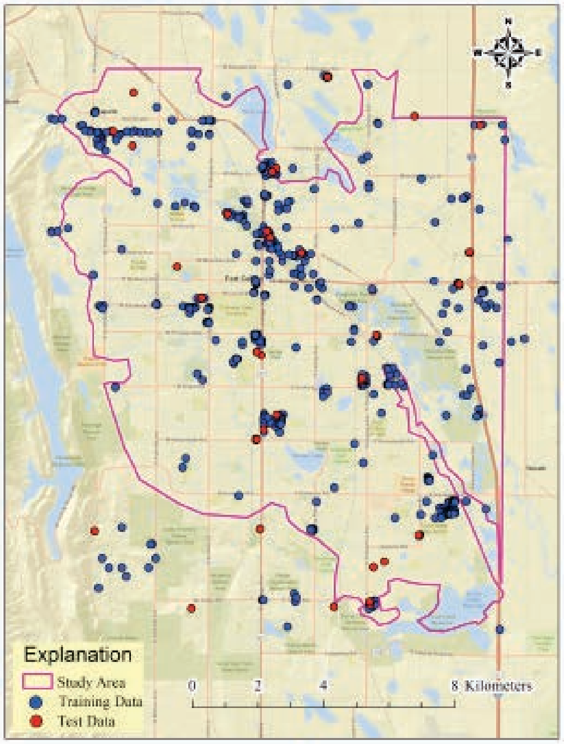


(a) Trial 1

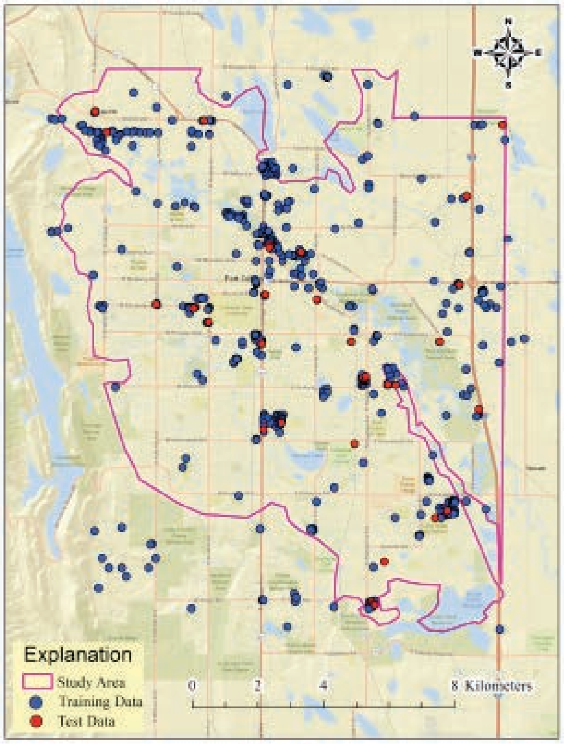


(b) Trial 2

Figure 15 Old (1959-1979) depth to water dataset crossvalidation training and test data for each trial

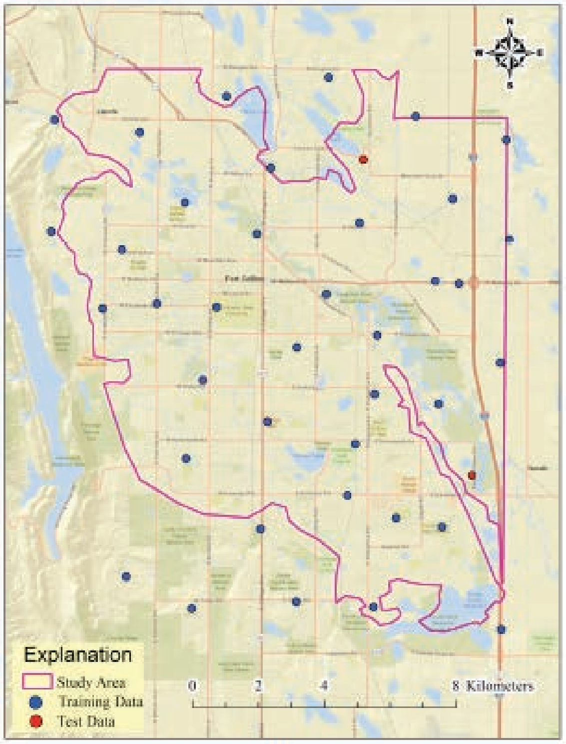


(a) Trial 1

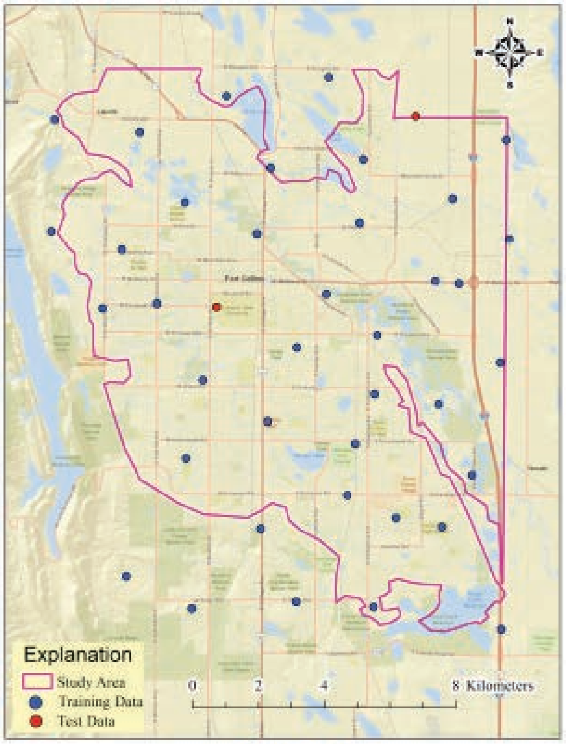


(b) Trial 2

Figure 16 New (2000-2017) depth to water dataset crossvalidation training and test data for each trial



(a) Trial 1



(b) Trial 2

Figure 17 Sy dataset crossvalidation training and test data for each trial

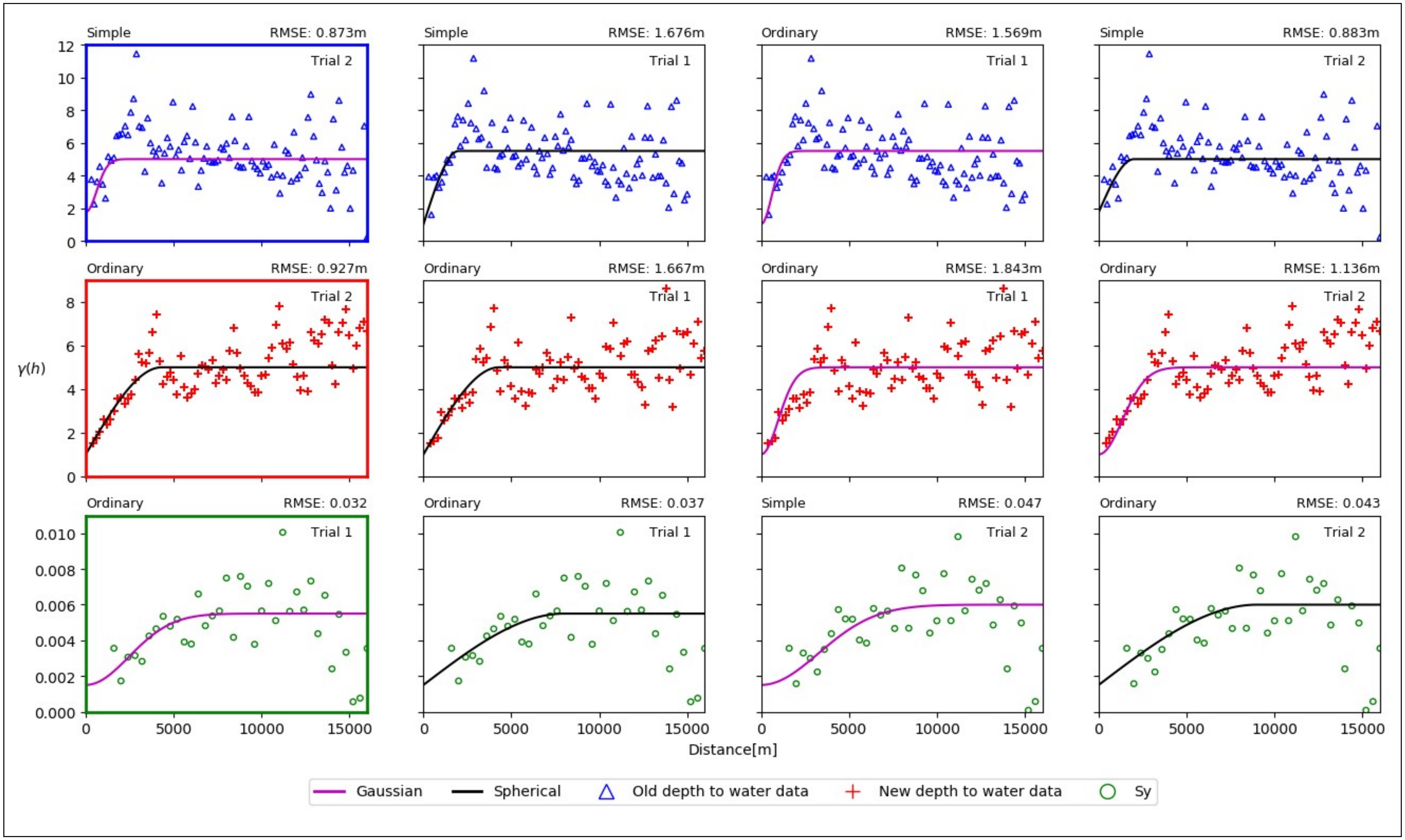


Figure 18 Crossvalidated variogram models

2.3.3 Current Groundwater Storage and Change in Storage in 30 Years

- Water table and saturated thickness maps:

The saturated thickness along with the specific yield is needed to estimate the current volume of groundwater available and can be used in the area. Therefore, the following procedure was adapted from the USGS Geohydrology of the shallow aquifers in the Fort Collins-Loveland area publication (2000) to develop water table maps first and then the saturated thickness maps for both old (1959-1979) and new (2000-2017) depth to water table data in ArcMap 10.3.1:

- The interpolated depth to water table for both old (1959-1979) and new (2000-2017) data in SGeMS (Fig. 13&14) were exported to ArcGIS as a raster. Using Resample tool in ArcToolbox, the interpolated depth to water raster was converted from a 10m cell size raster to 1m. The reason for that is to get a more accurate result of the water table map and the saturated thickness map because the digital elevation model is a 1m cell size raster.
- Using Raster Calculator in ArcToolbox, the interpolated depth to water table was subtracted from the digital elevation model to get the water table elevation map.
- The bedrock elevation map was subtracted from the developed water table maps for both old (1959-1979) and new (2000-2017) data to get the saturated thickness maps.

A contour map of water elevation was developed from the interpolated water elevation map of the new (2000-2017) data. The line feature class of contours were developed using the contour tool in ArcToolbox. The same steps were followed to generate a topographic contour map using the digital elevation model (DEM).

- Quantifying groundwater storage in the study area:

Old (1959-1979) and current (2000-2017) storage

The amount of extractable groundwater will be calculated using the following equation:

$$Volume = A\ x\ ST\ x\ Sy \qquad \text{(Eq. 3)}$$

Where:

A is the saturated thickness raster cell size (= 1m)
ST is the cell value of the saturated thickness raster
Sy is the specific yield

Definition of specific yield:

Nearly all soil and rock materials contain interstices or void spaces. Porosity is usually used to quantify the void spaces, and the American Society for Testing and Materials (1961) defines it as the ratio of the volume of voids of a given soil mass to the total volume of the soil mass. Therefore, in a saturated zone, groundwater fill all the voids in the soil or rock, and porosity can be used as a measure of groundwater quantity per unit volume (Todd, 1959). However, the water that is available to be used is the water that will drain by gravity and called gravity groundwater. Retained groundwater is the water that is retained by molecular and surface tension forces in the void spaces. Gravity and retained groundwater are represented by specific yield and specific retention, respectively (Johnson, 1967).

Therefore, the following steps were followed to quantify the groundwater storage (AcDonald, Bonsor, Dochartaigh, & Taylor, 2012):

- The saturated thickness maps for both old (1959-1979) and new (2000-2017) depth to water table data were multiplied by the average specific yield map by the area (1 m^2) using the raster calculator.
- The generated groundwater storage maps for both data were then used to measure the groundwater storage by adding all the cell values together.

Change in storage

The change in storage was calculated using the following formula in Raster Calculator:

Change in storage = old (2000-2017) storage – new (2000-2017) storage (Eq. 4)

The cell values of the change in storage raster were then added together using the Zonal Statistics tool in ArcToolbox to calculate the total change in storage.

2.3.4 Current Affected parcels With High Groundwater Levels and Parcels Affected by the Rise of Groundwater Table for Different Rainfall Scenarios

- Currently affected parcels with high groundwater levels:

The currently affected parcels by high groundwater level in the Fort Collins area were identified by following the next steps:

- The average basement and foundation depth (10 ft) was set to be the limit.
- A map of affected parcels was developed by clipping the parcels' shapefile with the shapefile of depth to water table equal to or less than the average basement and foundation depth (10ft).

- Quantifying the amount of recharge and the rise of groundwater table due to different rainfall events:

Rainfall scenarios:

Two different return periods were used to quantify the rise in the water table (Table 7).

Table 7 Rainfall events from the City of Fort Collins Rainfall Intensity-Duration-Frequency Curves

1-hr storm			
Return-period (year)	Intensity (in/hr)	depth (in)	depth (mm)
10	1.5	1.5	38.1
100	2.9	2.9	73.7

Recharge

NRCS curve-number model (Chin, 2000):

The rise in the water table and the groundwater recharge for both return periods was measured using the NRCS curve-number model, a common method in the United States to estimate the rainfall excess (runoff). This method divides rainfall (P) into the following (Fig. 19):

- Q: rainfall excess
- Ia: initial abstraction (interception, initial infiltration, and depression storage)
- F: retention (consists mainly of infiltrated water)

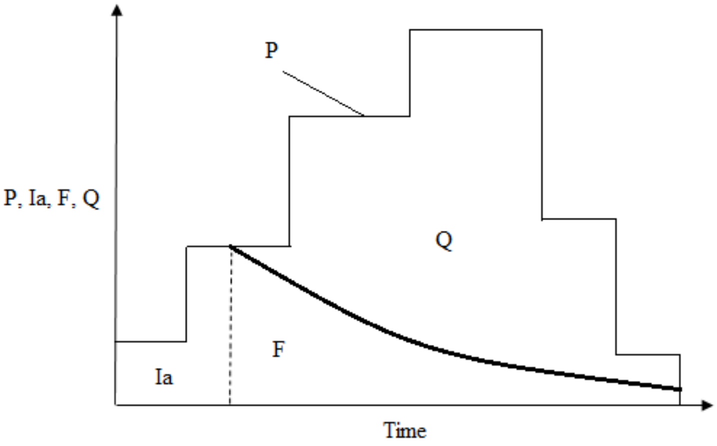


Figure 19 Curve-number components

Ia is directly related to the maximum retention, S (measures the catchment's retention capacity). However, the relation between Ia and S is as following:

$$Ia = \lambda x S \qquad \text{(Eq. 5)}$$

The factor λ is commonly assumed to be equal to 0.2 for large storms in rural areas and can vary from 0.01 to 0.18 (Schneider and McCuen, 2005). In this study, the value of λ is assumed to be equal to 0.1 cause the study area is urban. Therefore, the following equation can be used to calculate the runoff (Q):

$$Q = \frac{(P-0.1S)}{P+0.8S}, \qquad P > Ia\ (0.1\text{S}) \qquad \text{(Eq. 6)}$$

Where S (mm) is calculated using the curve-number (CN):

$$S = \frac{1}{0.0394}\left(\frac{1000}{CN} - 10\right) \qquad \text{(Eq. 7)}$$

CN was obtained using Table 8 where the landcover and the soil group were identified first. Then, the landuse GIS polygon shapefile (Fig. 20) was used along with the surface layer soil GIS polygon shapefile (Fig. 5) to determine the CN for each landuse (Table 9).

Table 8 Curve Numbers for Various Urban Land Uses (Chin, 2000)

Cover type and hydrologic condition	Curve numbers for hydrologic soil group			
	A	B	C	D
Lawns, open spaces, parks, golf courses:				
Good condition: grass cover on 75% or more of the area	39	61	74	80
Fair Condition: grass cover on 50%-75% of the area	49	69	79	84
Poor condition: grass cover on 50% or less of the area	68	79	86	86
Paved parking lots, roofs, driveways, etc.	98	98	98	98
Streets and roads:				
Paved with curbs and storm sewers	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89
Paved with open ditches	83	89	92	93
Commercial and business areas (85% impervious)	89	92	94	95
Industrial districts (72% impervious)	81	88	91	93
Row houses, town houses, and residential with lot size ≤ 0.05 ha (1/8 ac) (65% impervious)	77	85	90	92
Residential average lot size:				
0.10 ha (1/4 ac) (38% impervious)	61	75	83	87
0.14 ha (1/3 ac) (30% impervious)	57	72	81	86
0.20 ha (1/2 ac) (25% impervious)	54	70	80	85
0.40 ha (1 ac) (20% impervious)	51	68	79	84
0.80 ha (2 ac) (12% impervious)	46	65	77	82
Developing urban areas (no vegetation established) Newly graded area	77	86	91	94
Western desert urban areas:				
Natural desert landscaping (pervious area only)	63	77	85	88
Artificial desert landscaping	96	96	96	96
Cultivated agricultural land				
Fallow				
Straight row or bare soil	77	86	91	94
Conservation tillage (poor)	76	85	90	93
Conservation tillage (good)	74	83	88	90

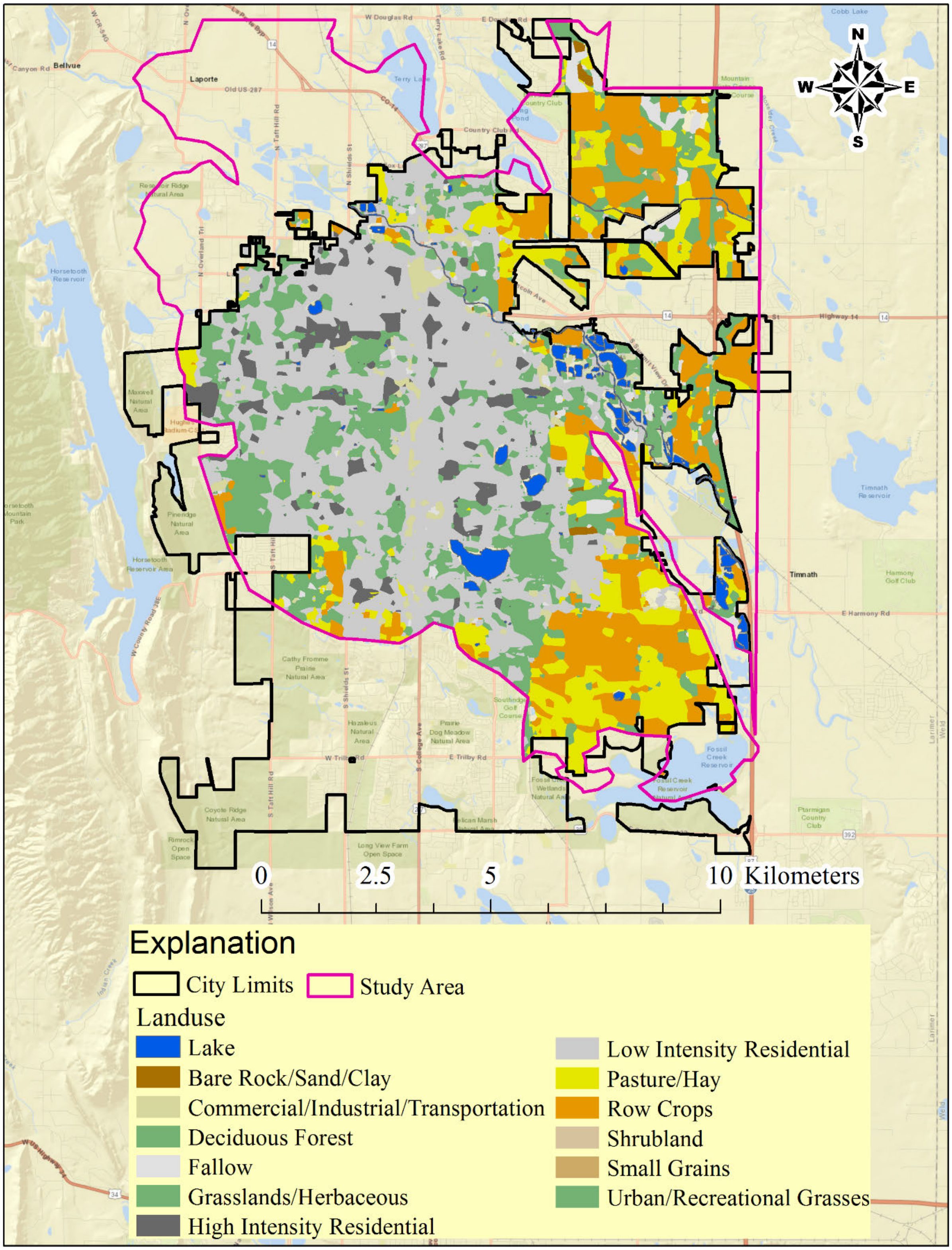


Figure 20 Landuse map

Table 9 CN for each landuse in the Fort Collins area

Description	CN		
	Soil A	Soil B	Soil C
Bare Rock/Sand/Clay	68	79	86
Commercial/Industrial/Transportation	85	90	92.5
Deciduous Forest	39	NA	NA
Fallow	77	86	91
Grasslands/Herbaceous	39	61	74
High Intensity Residential	57	72	81
Low Intensity Residential	54	70	80
Pasture/Hay	74	83	88
Row Crops	77	86	91
Shrubland	49	69	NA
Small Grains	74	83	88
Urban/Recreational Grasses	49	69	79

After calculating the runoff value (Q) for each landuse for two different return periods using Raster Calculator, the infiltration (F) for each landuse was measured using the following equation:

$$F = P - Q - Ia \qquad \text{(Eq. 8)}$$

It was assumed that the all infiltrated water would percolate and recharge the aquifer, and maps that show the amount of infiltrated water was then developed (Fig. 21&22).

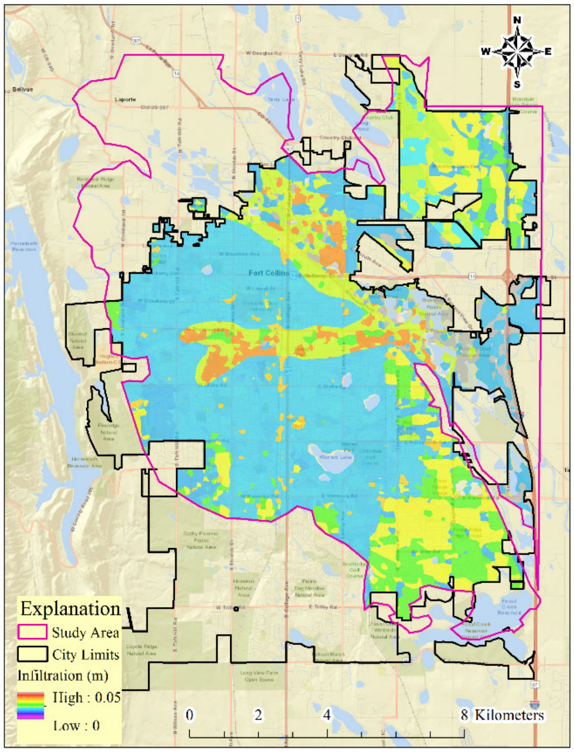


Figure 21 Amount of infiltrated water of 10-year return period precipitation

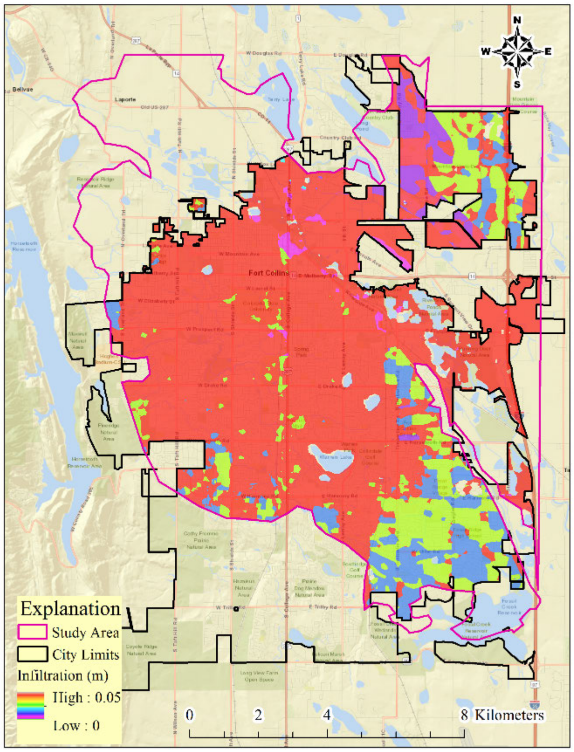


Figure 22 Amount of infiltrated water of 100-year return period precipitation

The cell values of the amount of infiltrated water raster were then added together using the Zonal Statistics tool in ArcToolbox to calculate the recharge for both rainfall scenarios.

Rise in the water table

The maps of infiltrated water were then used along with the specific yield map to determine the rise in the water table (Fig. 24&25) using the following equation:

$$\Delta\mathrm{h} = \frac{\mathrm{Infiltraion}}{\mathrm{Sy}} \qquad \text{(Eq. 9)}$$

Where:

Δh is the rise in the water table (Fig. 23).

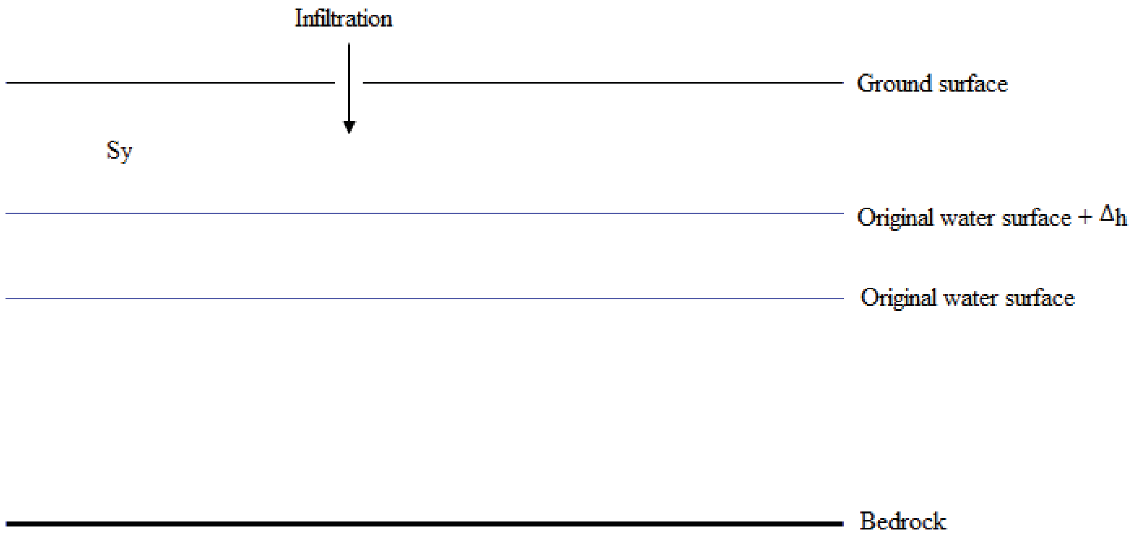


Figure 23 Rise in the water table

The average Sy values (Table 4) were used to determine the rise in the water table.

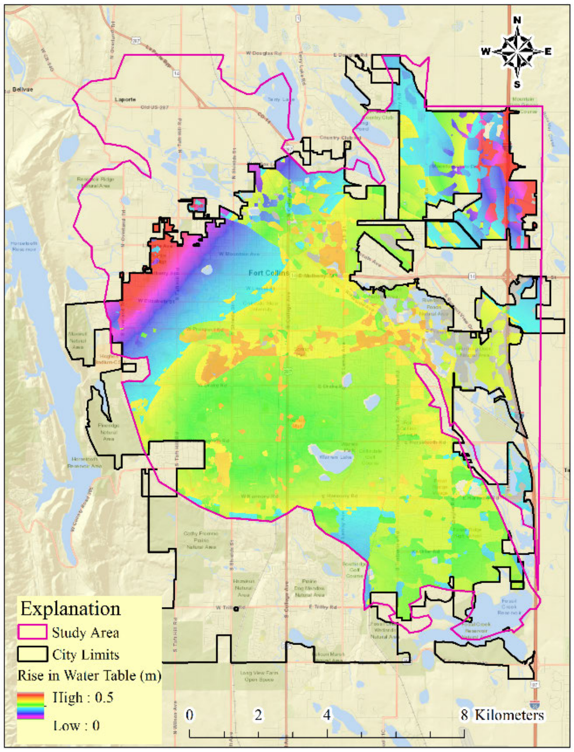


Figure 24 Rise in water table from a 10-year return period precipitation

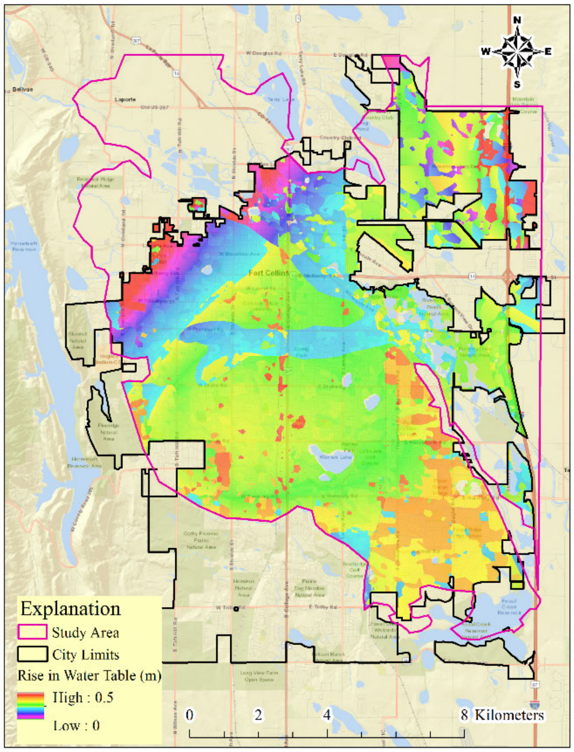


Figure 25 Rise in water table from a 100-year return period precipitation

The rise in water table maps were subtracted from the original depth to water table maps. The new (2000-2017) depth to water table maps where then used to identify the parcels affected with high groundwater following the same steps mentioned earlier in Section 2.3.4.

CHAPTER 3: RESULTS AND DISCUSSION

3.1 Interpolated depth to water and specific yield data

3.1.1 Depth to water table

The highest depletion in groundwater was in the northeast region of the study area due to groundwater withdrawals for irrigation (Fig. 26).The water level has declined around 9m in 30 years in that region of the study area. The depth to water table for the unconfined aquifer for both old (1959-1979) and new (2000-2017) data is presented in Figures 27 and 28. The average depth to the water table is slightly higher for the new (2000-2017) data (Table 10).

Table 10 Depth to water table statistics

Data	Depth to water table, m		
	Minimum	Maximum	Average
Old (1959-1979)	1.33	9.33	3.58
New (2000-2017)	0.96	18.02	3.9

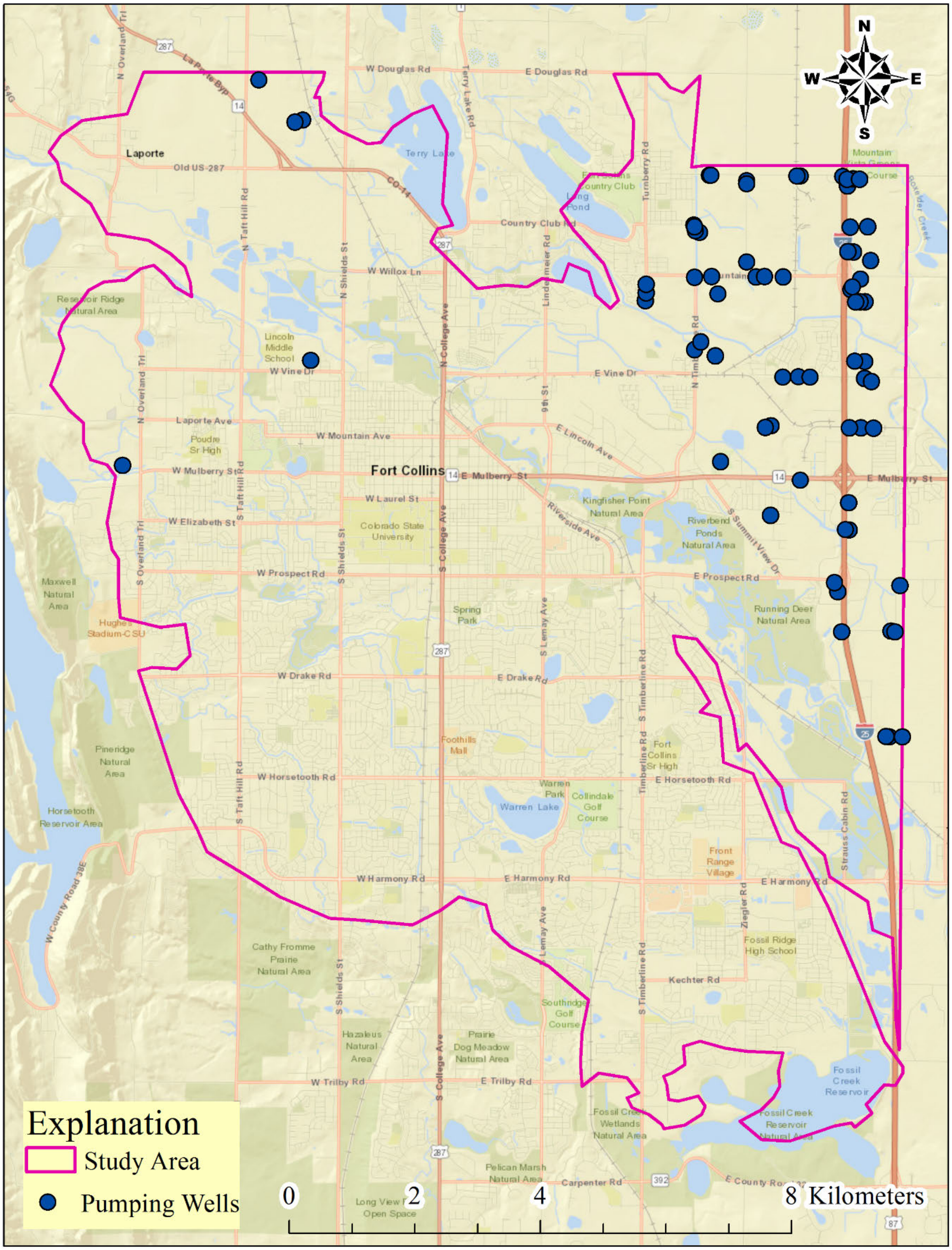


Figure 26 Locations of pumping wells, from Colorado Division of Water Resources

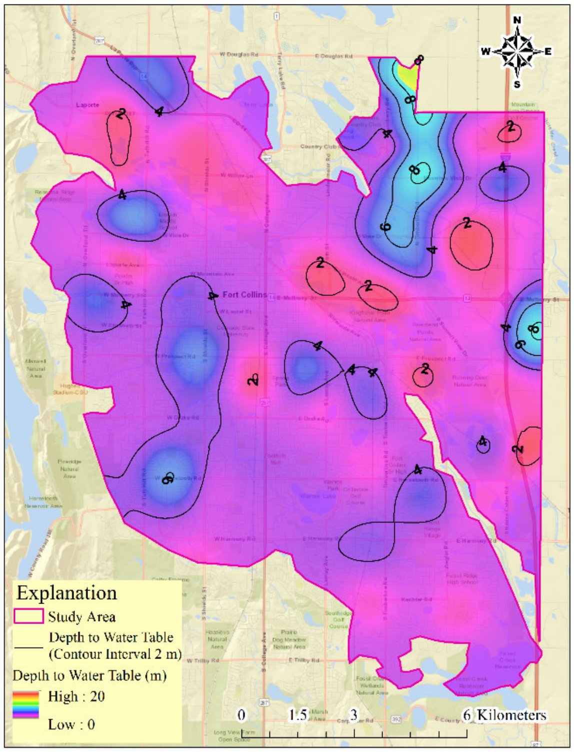


Figure 27 Old (1959-1979) depth to water table map

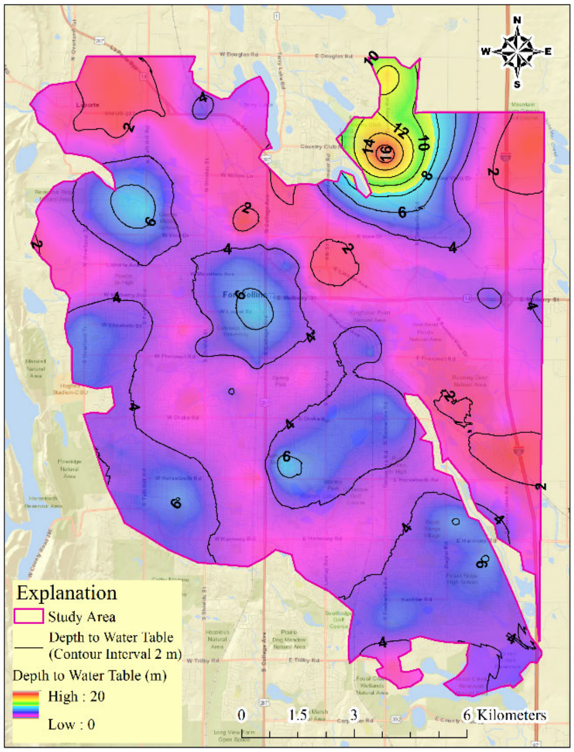


Figure 28 New (2000-2017) depth to water table map

3.1.2 Water table elevation and flow direction

A water table elevation map is important in quantitatively managing the water as a resource (Nikroo et al. 2009). In addition, the water table maps (Fig. 29&30) show the general direction of groundwater where it flows from the higher to the lower elevation. The water table elevation has changed slightly over the last few decades where some locations showed an increase in the water table elevation and others showed a decrease. However, the greatest depletion was in the northeast region of the study area due to pumping the groundwater for irrigation (Figure 31).

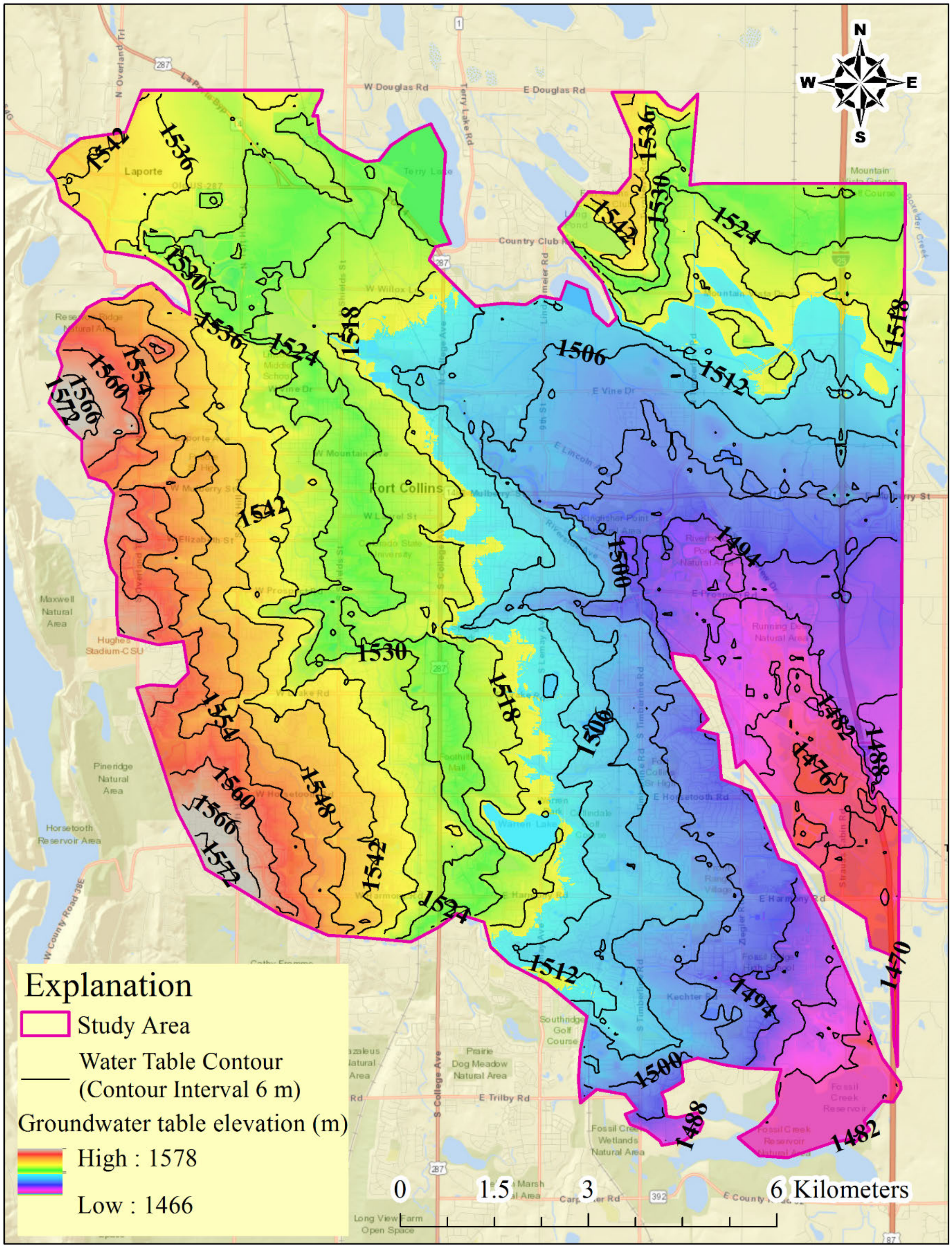


Figure 29 Old (1959-1979) water table elevation map

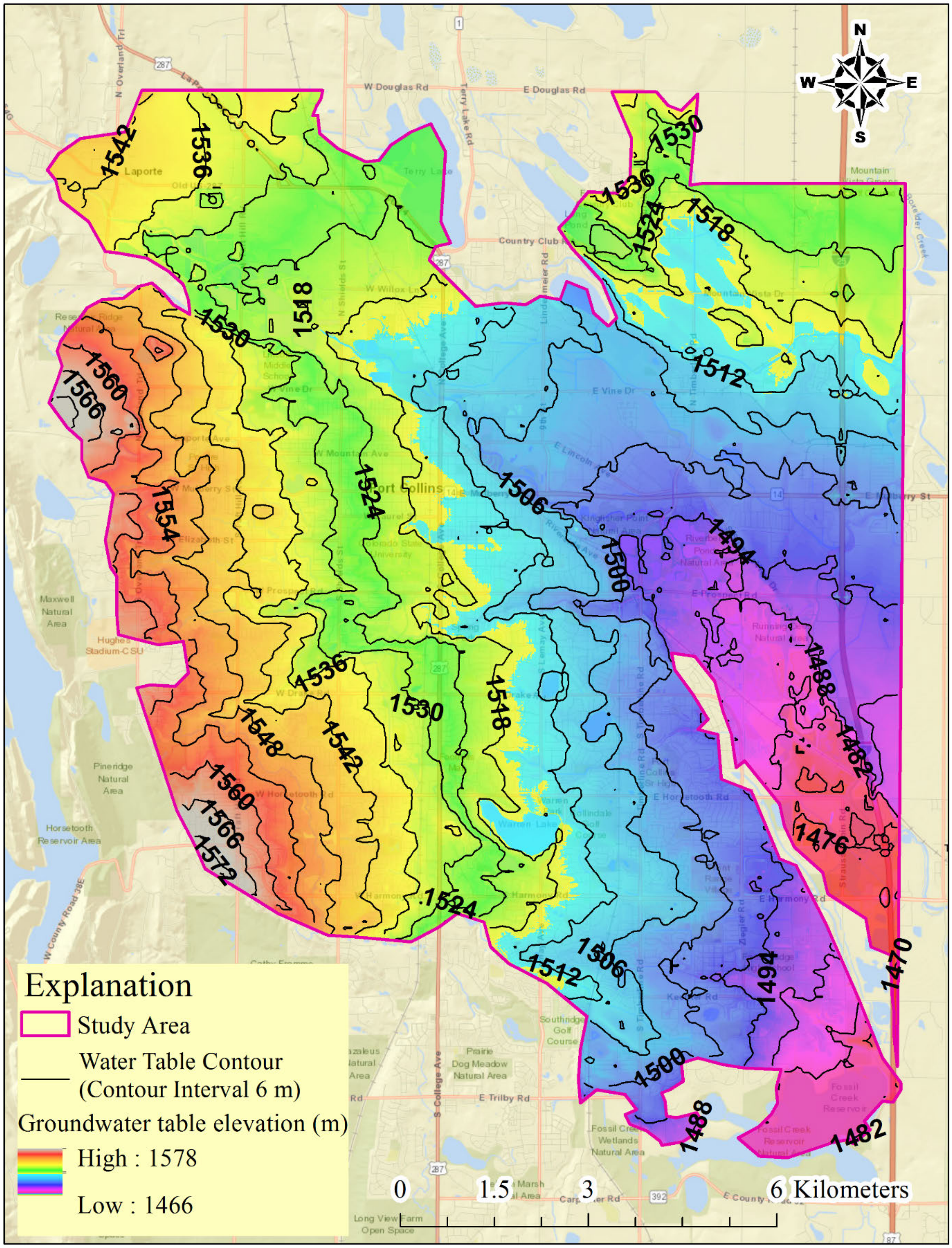


Figure 30 New (2000-2017) water table elevation map

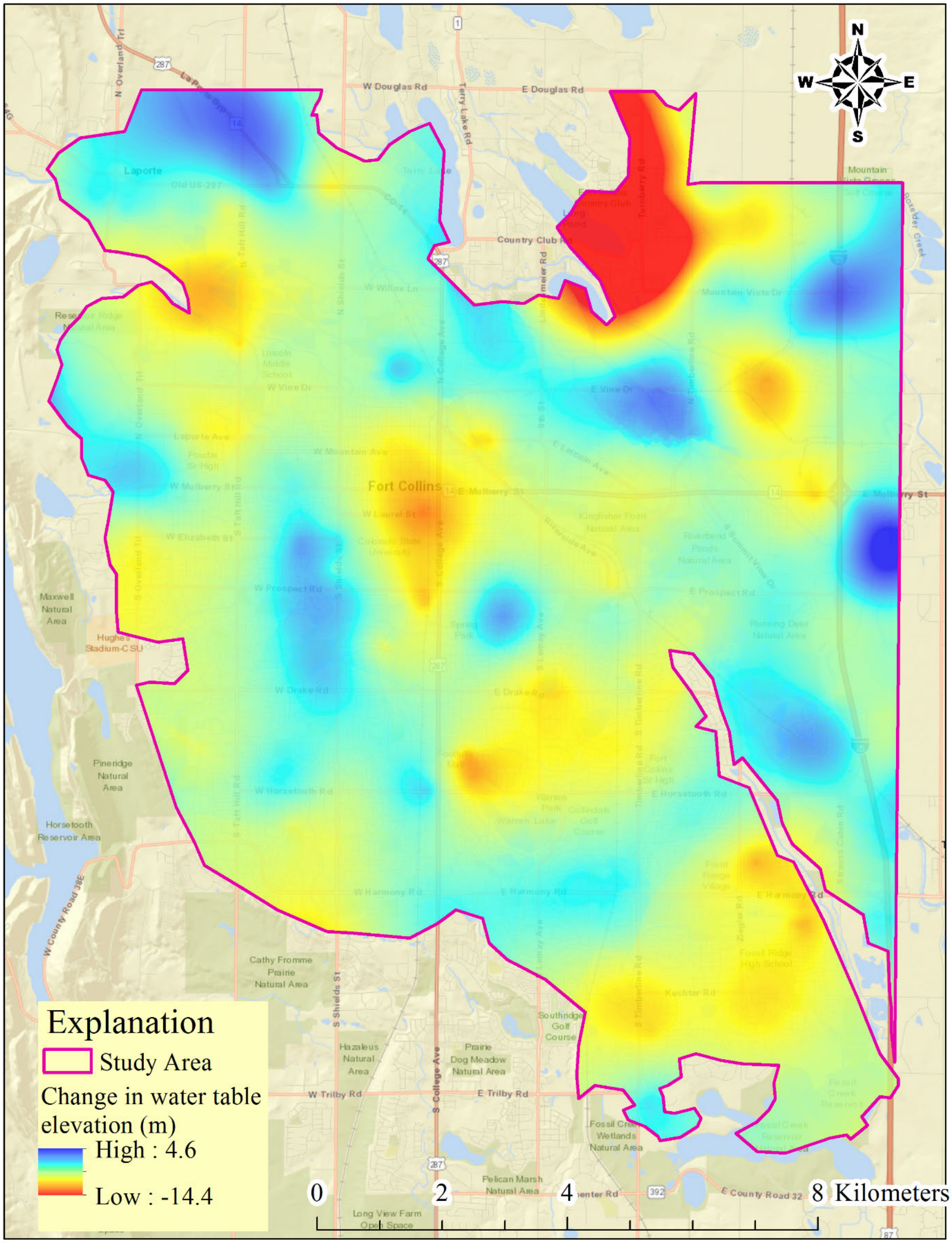


Figure 31 Change in water table elevation over the last three decades

The elevation of the uppermost saturated layer of an unconfined aquifer is represented by a contour map of the water table elevation. The direction of the horizontal groundwater flow is perpendicular to the contour lines (Fig. 32) (Conlon, Wozniak, Woodcock, Herrera, Fisher, Morgan, Lee, and Hinkle, 2005).

Figure 32 Contour map of new (2000-2017) water elevation

By comparing the ground surface contour map (Fig. 33) with the water table elevation contour map (Fig. 32) in the unconfined aquifer in the study area, the water table elevation is a subdued replica of the ground surface. The contours of the water table elevation show that the water table presents the features of the hills and valleys relatively similar to the relief forms of the surface: the water table being low where the ground surface is low, and higher where the ground surface is high. Therefore, groundwater is a source for the Cache la Poudre River. As a result, if the groundwater is contaminated, the river will be at a potential risk of contamination.

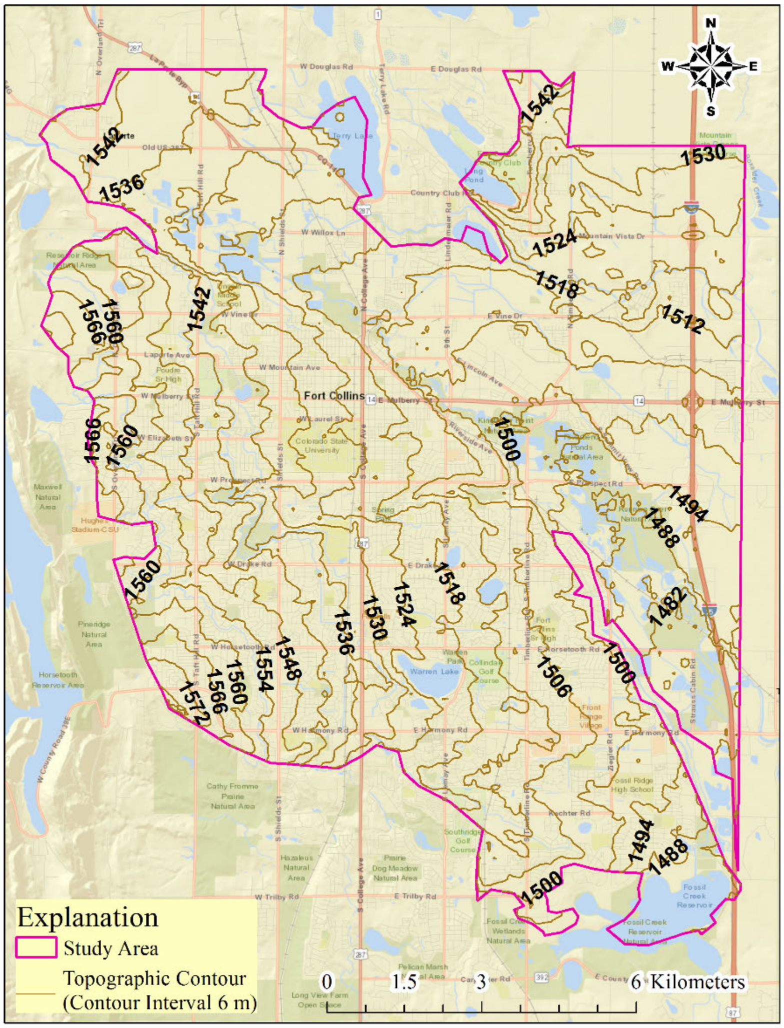


Figure 33 Ground surface contour map

3.1.3 Saturated thickness and specific yield

The saturated thickness at different locations in the study area is shown in (Fig. 34&35). However, the real amount of water is a combination of the saturated thickness and specific yield. Therefore, the saturated thickness value does not necessarily show the amount of groundwater storage.

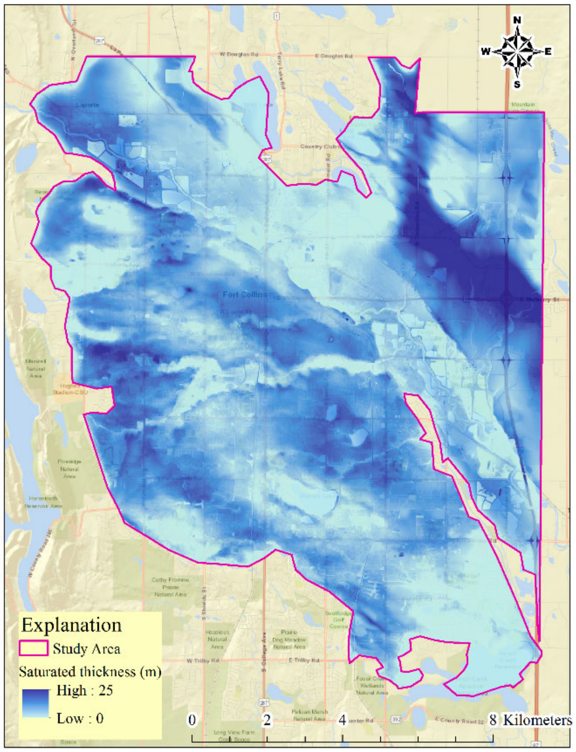


Figure 34 Old (1959-1979) saturated thickness map

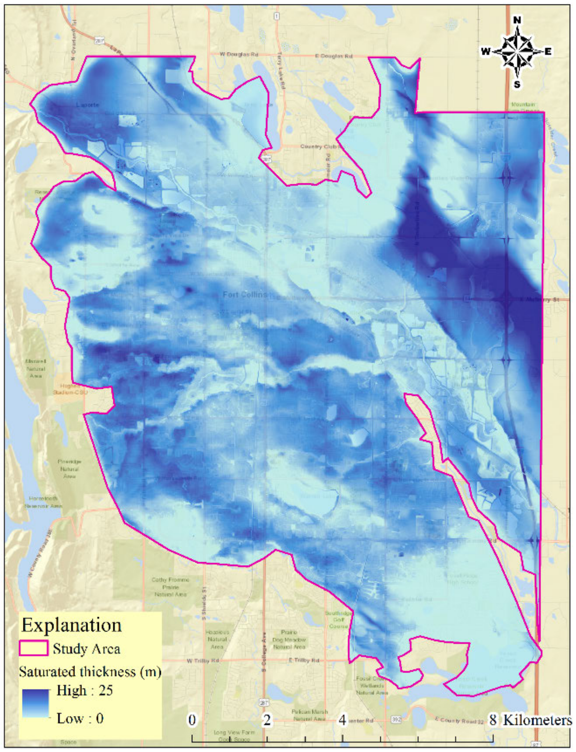


Figure 35 New (2000-2017) saturated thickness map

The estimated specific yield over the study area (Fig. 36) is used to assess the quantity of groundwater in the shallow aquifer. The specific yield has an average value of 0.21 over the study area. This value is in agreement with the overall average Sy values in the study area where SandyClay soil type is the dominant.

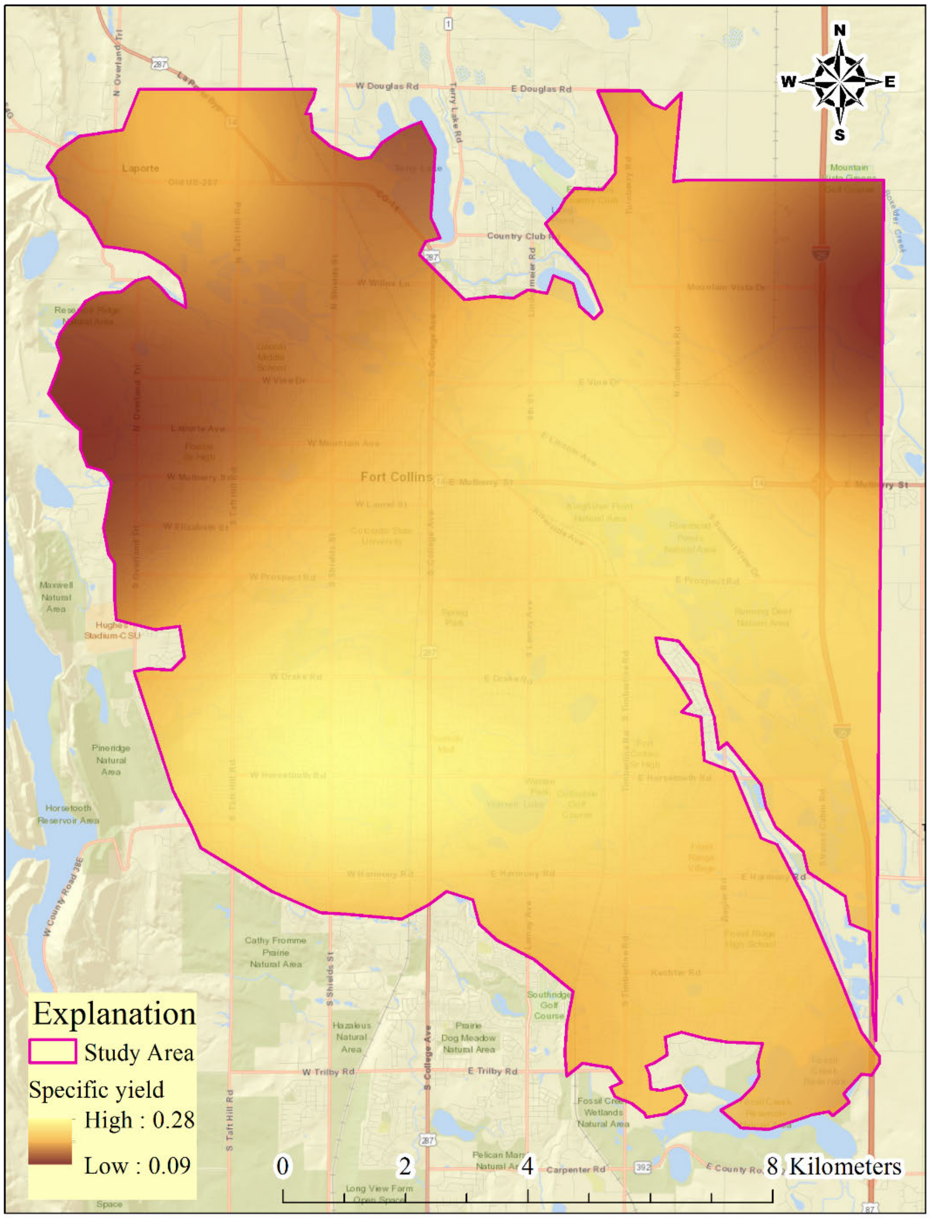


Figure 36 Shallow aquifer specific yield map

3.2 Groundwater storage

The groundwater storage of the study area has decreased 3.7% in the last few decades (Table 11). The irrigation activity in the northeast part of the study area has contributed the most to the loss of groundwater.

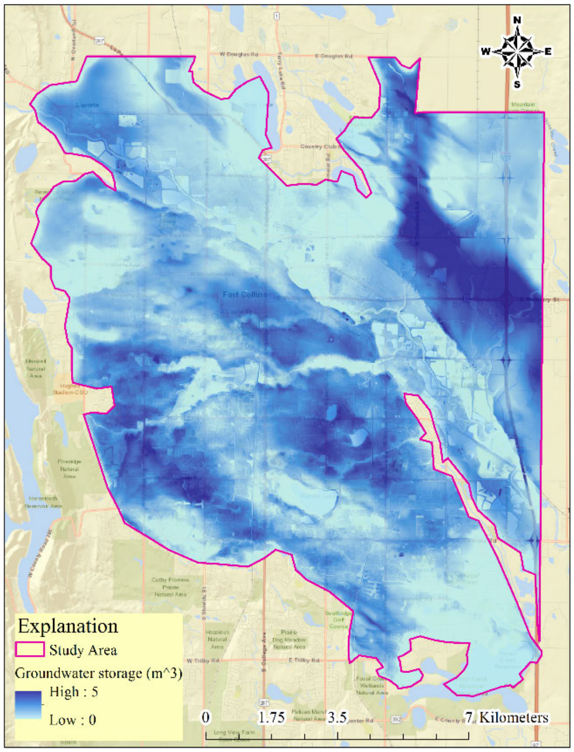


Figure 37 Old (1959-1979) groundwater storage

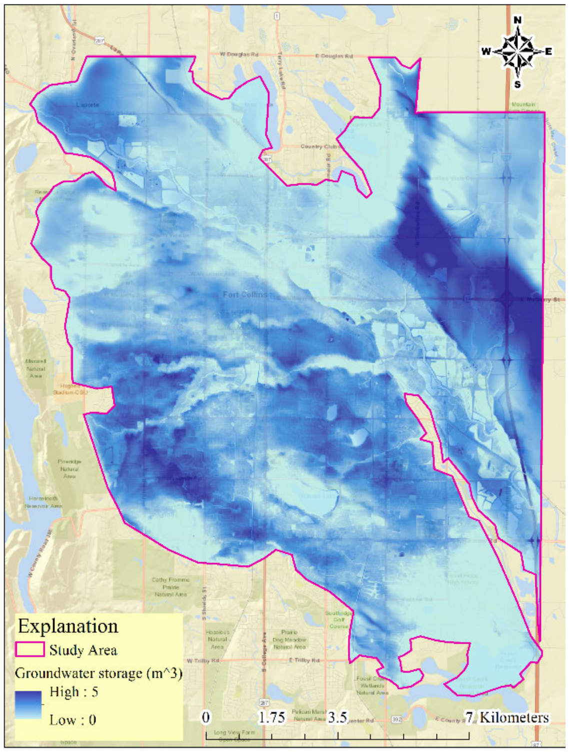


Figure 38 New (2000-2017) groundwater storage

Table 11 Old and new groundwater storage

Unit	Old Storage (1959-1979)	New Storage (2000-2017)	Change in storage
m3	126,843,900	122,087,700	4,756,200
gallon	33,508,613,000	32,252,158,000	1,256,455,000
percent decrease			3.7

According to Mihelich et al. (2016), the average daily water demand of the City of Fort Collins is around 21.2 million gallons. Therefore, if the city uses groundwater as the only source of water supply, the source will last around four years.

3.3 Parcels affected with high groundwater and the rise of the water table due to the recharge from precipitation

Floodplains or low-lying areas are probably the main two causes of high groundwater in the study area. The consequences of high groundwater on the affected parcels could be structural damages, corrosion, or damages to the basement contents. The currently affected parcels with high groundwater (Fig. 39) are the parcels that already experience high groundwater with the current level of the groundwater table. However, when the groundwater level increases due to heavy precipitation, the number of affected parcels will increase (Fig. 40&41)

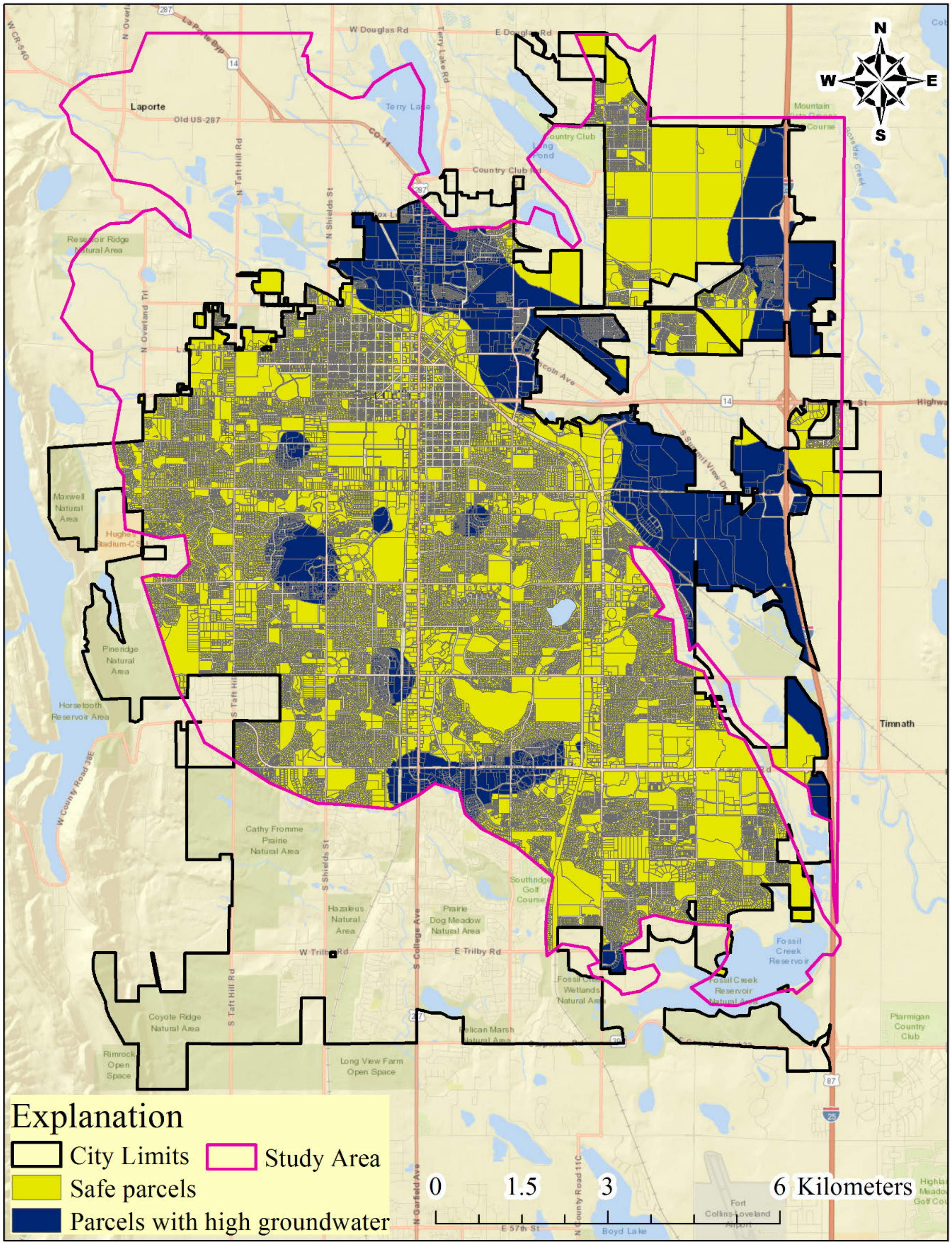


Figure 39 Currently affected parcels with high groundwater

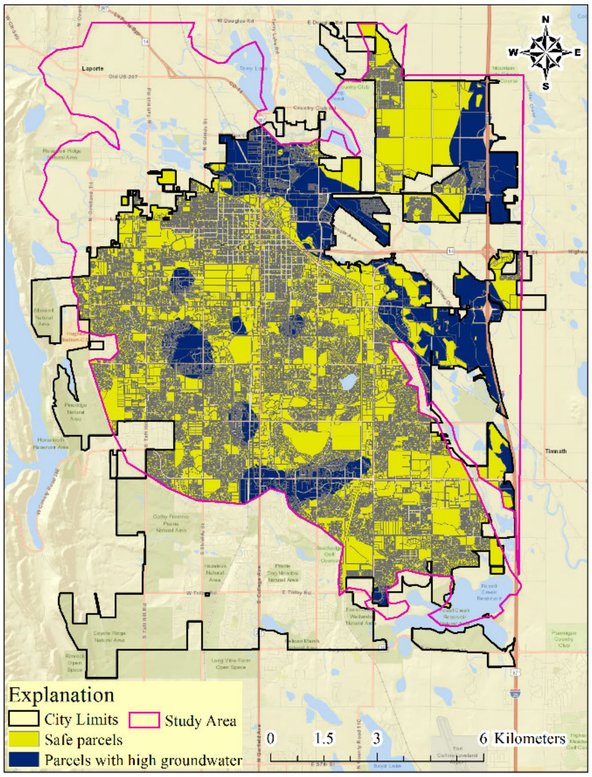


Figure 40 Parcels affected with the rise of water table due to a 10-year storm

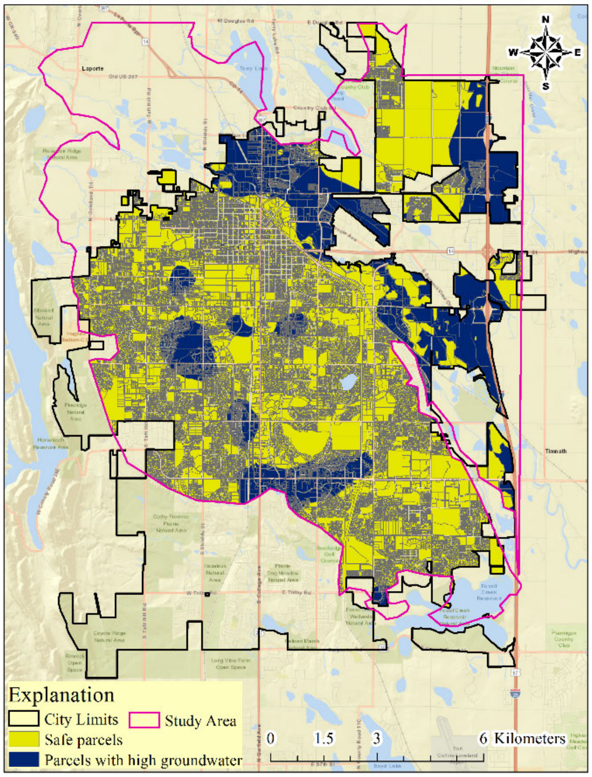


Figure 41 Parcels affected with the rise of water table due to a 100-year storm

Table 12 Parcels affected with high groundwater

Description	Current	10-year storm	100-year storm
Total # of parcels	58973	58973	58973
# of parcels affected by high groundwater	5678	7057	7950
Percentage	9%	11%	12%
Total area of parcels (Km^2)	224.2	224.2	224.2
Area of parcels affected by high groundwater (Km^2)	25.5	28.0	34.8

The amount of recharge to the shallow aquifer in the Fort Collins area due to different rainfall scenarios is presented in the following table:

Table 13 Recharge to the groundwater due to different rainfall scenarios

	Return-period (year)	
Description	10	100
Recharge (m^3)	1,940,500	3,288,900

CHAPTER 4: CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

This study aims to provide an overall assessment of the groundwater in the Fort Collins area. The assessment includes the development of quantitative groundwater maps, shallow aquifer soil map, and maps of affected parcels with high groundwater for multiple scenarios. Also, there was an estimation of the groundwater storage and change in storage in 30 years, and an estimation of the amount of recharge for different rainfall events. The collected data of the depth to groundwater table was for two different time periods (1959-1979 and 2000-2017), and was obtained from multiple sources. Soil type data for the shallow aquifer was collected from construction geotechnical reports and well permits' borehole logs. Geostatistics principles were applied in the analysis of the data. The key findings of the analysis along with recommendations for future research are presented in sections 4.1 and 4.2.

4.1 Key Findings

- The current average depth to water table in the study area is 3.9m. In the last three decades, the average depth increased marginally (0.32m). Nevertheless, a 9m dropdown in the water table elevation was noticed on the northeast side of the study area due to groundwater use for irrigation.
- The contour map of the water table elevation showed that the general direction of the groundwater flow in the study area is southeast. Moreover, the water table is a subdued replica of the ground surface.
- Around 122 million m^3 of water is currently stored in the unconfined shallow aquifer in the study area. The amount of stored water has decreased around 4.7 million m^3 in the last three

decades. The pumped groundwater for irrigation has contributed mostly to the reduction of storage.

- The amount of recharge to the shallow aquifer in the Fort Collins area due to heavy precipitation is around 1.9 million m^3 and 3.3 million m^3 for 10 and 100 year return period storms, respectively.
- At present, 9% of the parcels in Fort Collins area are at risk of high groundwater level. The rise in the water table elevation due to 10 and 100 year return period storms will increase the percentage of parcels at risk of high groundwater level to 11% and 12%, respectively.

4.2 Recommendations for Future Work

Based on outcomes from this thesis, the following recommendations are made for providing a further understanding of the groundwater situation in the Fort Collins area:

- Expand research work on quantifying the amount of recharge and build a hydrological model.
- Evaluate the model comparing simulated with observed water table elevations.
- Use the model to quantify groundwater storage under the combined impacts of projected climate conditions, land use changes, and groundwater development scenarios.

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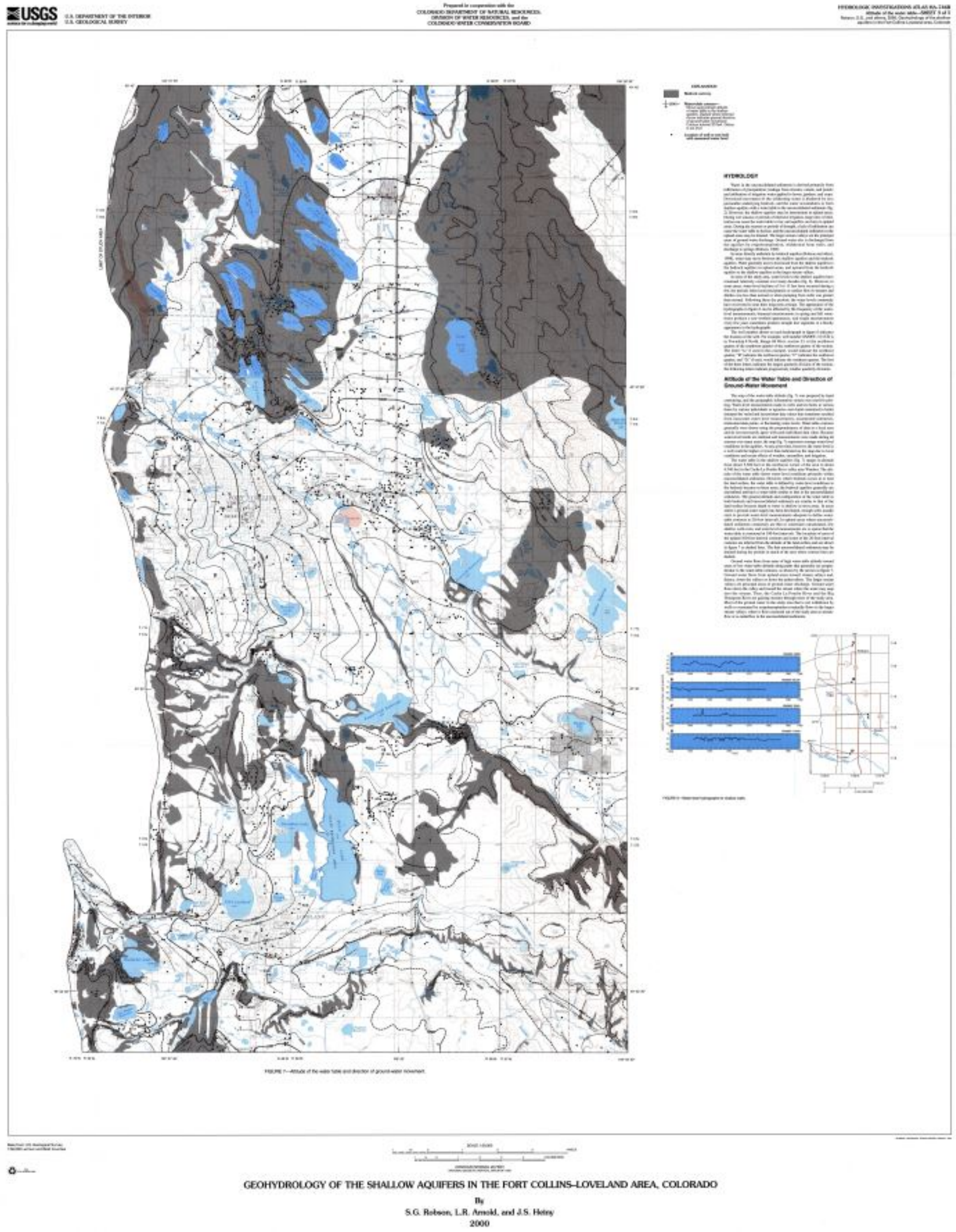
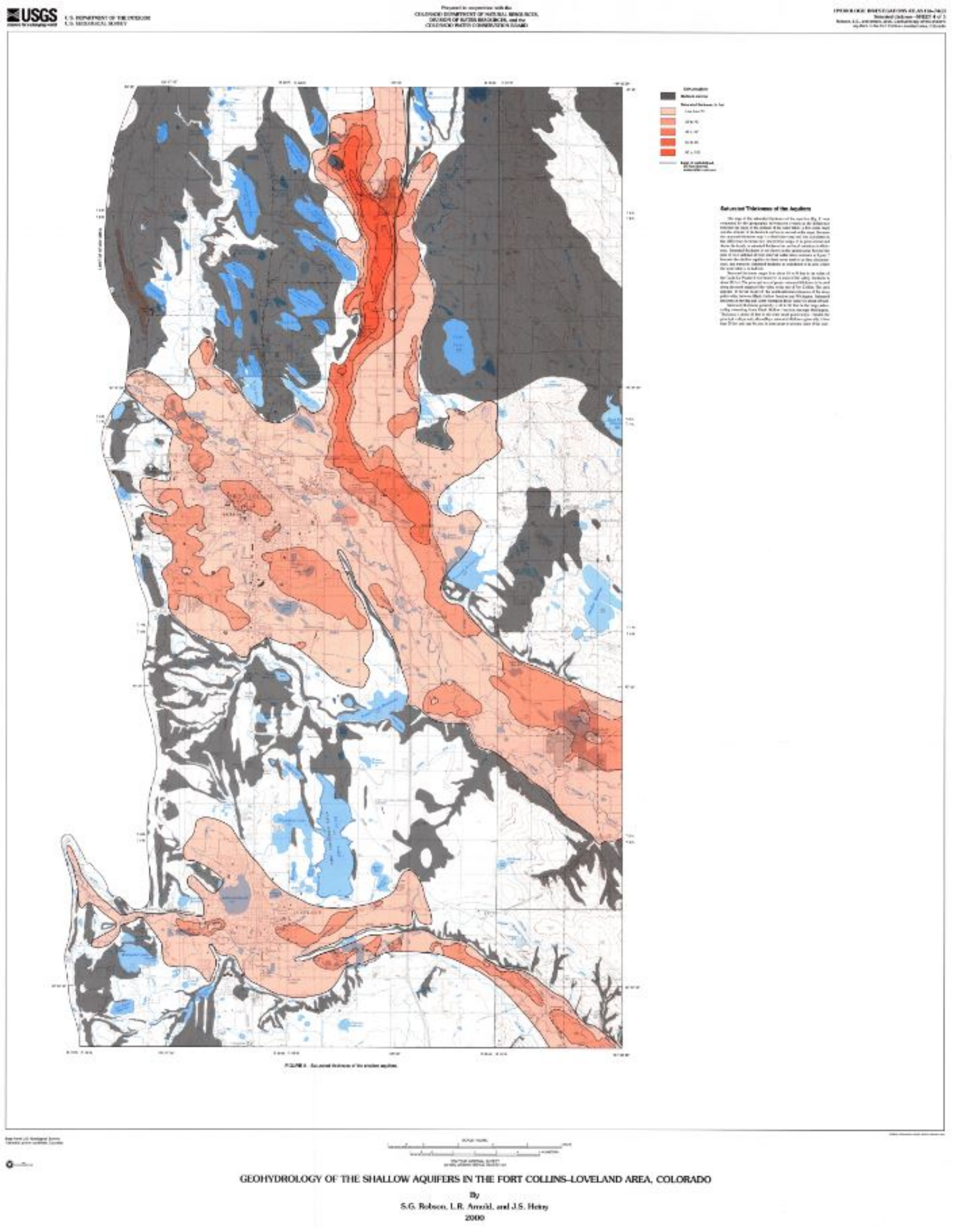
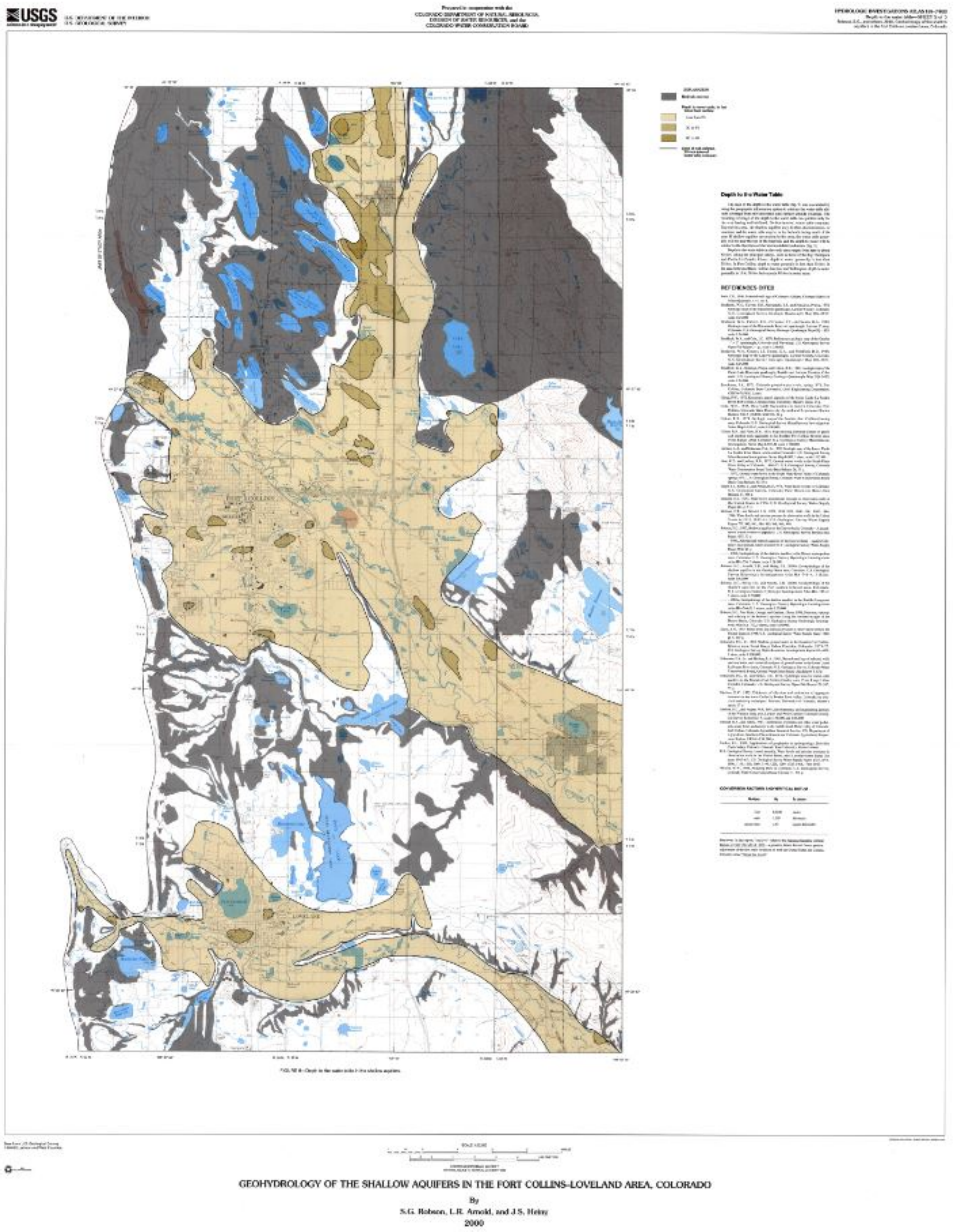
APPENDICES



A1 The water table altitude



A2 The Saturated Thickness of the aquifers



A3 Depth to the water table