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A Comparison of Four Methods to Estimate Groundwater Recharge for Northeastern South Dakota

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A COMPARISON OF FOUR METHODS TO ESTIMATE GROUNDWATER RECHARGE FOR NORTHEASTERN SOUTH DAKOTA

BY

BADR QABLAWI

A thesis submitted in partial fulfillment of the requirements for the

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2016

A COMPARISON OF FOUR METHODS TO ESTIMATE GROUNDWATER RECHARGE FOR NORTHEASTERN SOUTH DAKOTA

This thesis is approved as a credible and independent investigation by a candidate for the Master of Science in Civil Engineering degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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I would like to dedicate this thesis to the beautiful soul my wife, Rawda, for her love, patience, support, encouragement, and understanding. She allowed me to spend most of the time on this thesis. For the past six months, my wife kept on reminding me: “Badr, go to the office and write your thesis!”

This thesis is dedicated to my grandmother, Naziha, and to the memory of my mother, Maha, may she rest in peace, I hope that this achievement will complete the dream that they had for me all those many years ago.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

A COMPARISON OF FOUR METHODS TO ESTIMATE GROUNDWATER RECHARGE FOR NORTHEASTERN SOUTH DAKOTA

BADR QABLAWI

2016

The rate of groundwater recharge is one of the most important elements in the analysis and management of groundwater resources. In addition, it is also the most difficult quantity to determine. This thesis, which is the result of a study made in northeastern South Dakota, presents an overview of four methods for estimating groundwater recharge, including an evaluation of the accuracy and suitability of each. These methods are the soil water balance, Chaturvedi formula, seasonal recession method (Meyboom method), and the well level data. Furthermore, this study seeks to find a selection of methods best suited based on climate classification. The soil water balance method and the well level data method appeared to be more efficient for the study area where the climate is sub humid continental. On the other hand, the Chaturvedi formula and Meyboom method are more efficient in tropical regions. Climate data was used for the calculation of the soil water balance and Chaturvedi formula while streamflow data was used in the Meyboom method. For the well level data method, observation well data was used. Every method has advantages and disadvantages. However, in order to have an accurate estimation of groundwater recharge, a variety of methods may have to be used.

The soil water balance had the best fit when it was compared with the well level data method. The Chaturvedi formula and Meyboom method did not allow negative values; therefore, there were not a good fit compared with the well level data method.

Chapter 1: Introduction

1.1 Background

Some of the world's water is located under the Earth's surface such as beneath hills, mountains, plains, and deserts. This important natural resource is not always obtainable, and sometimes it's hard to locate, measure, or describe this water. Groundwater could be near the land surface or it could be in many hundreds of feet below the surface. This renewable resource could be at shallow, moderate, or great depths. Its age is between hours up to thousands of years. Groundwater moves naturally where it is stored in aquifers that have low or high permeability. Groundwater is one of the largest supplies of fresh water that is available for use by humans. Many uses of water depend on this water resource solely as it is of high quality and available in low price for agricultural, industrial and domestic users (U.S. Geological Survey. 2013).

Groundwater recharge process is that water enters the saturated zone and until it reaches the water table surface (Freeze et al. 1979). The valuable resources of groundwater have to have an appropriate management and protection in order to get accurate determination of groundwater recharge rates. Many methods have been used for decades to estimate recharge. However, it is hard to evaluate the accuracy of any method. As a result, it is useful to apply multiple methods to estimate groundwater recharge (Healy and Cook 2002). This study reviews methods for estimating groundwater recharge that are based on knowledge of climate data, streamflow data, and well level data.

1.2 Scope and Objectives

The objective of this study is to estimate the groundwater recharge by using four different methods for northeastern South Dakota with the available data such as precipitation, evaporation, streamflow and well levels. In addition, the historical records of this area are used to define climatic scenarios of how these could affect the groundwater recharge based on the annual total precipitation and evaporation for the period 1978 - 1998.

The basic sub-objectives of the study are:

I. To calculate the groundwater recharge by using the soil water balance method, Chaturvedi formula, seasonal recession method (Meyboom Method), and the well level data method.

II. Compare the similarities and the differences among the four groundwater recharges for the study area.

III. Find the most appropriate method to use in estimating groundwater recharge.

1.3 Overview of the Thesis

This thesis is arranged by chapters starting with the introduction in chapter one. The review of relevant literature is discussed in Chapter two which presents the background of the research describing the importance of groundwater recharge and the used data to estimate the groundwater recharge for a twenty-year period in a particular area as well as a description of the study area. Chapter three covers materials and methodologies and describes the source of data and discussion on methods followed in order to analyze data and to produce four groundwater recharges. Chapter four presents the results from the analysis. Chapter five presents the discussion of the results from analysis of the data. Chapter six presents the summary and conclusion. Chapter seven presents suggestion for future research.

Chapter 2: Literature Review

2.1 General Review of Hydrologic Cycle and Groundwater

Water is necessary to sustaining life on Earth, and helps tie together the Earth's lands, oceans, and atmosphere into an integrated system. This hydrologic cycle occurs due to energy exchanges among the atmosphere, ocean, and land that determine the Earth's climate and causes much natural climate variability (See Figure 1) (NASA, 2016).
This cycle of water consists of the continuous following processes: water evaporates from oceans, lakes, and rivers to become water vapor that is carried over the atmosphere. This water precipitates as rain or snow on the land and oceans where it evaporates, runs off into streams and rivers, or it infiltrates into the ground. As a result, the remaining water becomes groundwater, which eventually discharges to streams or lakes. Groundwater is that part of precipitation that infiltrates through the soil to the water table. The unsaturated zone above the water table contains air and water while the saturated zone below the water table is called groundwater(Chow et al. 1988; Waller 2001).

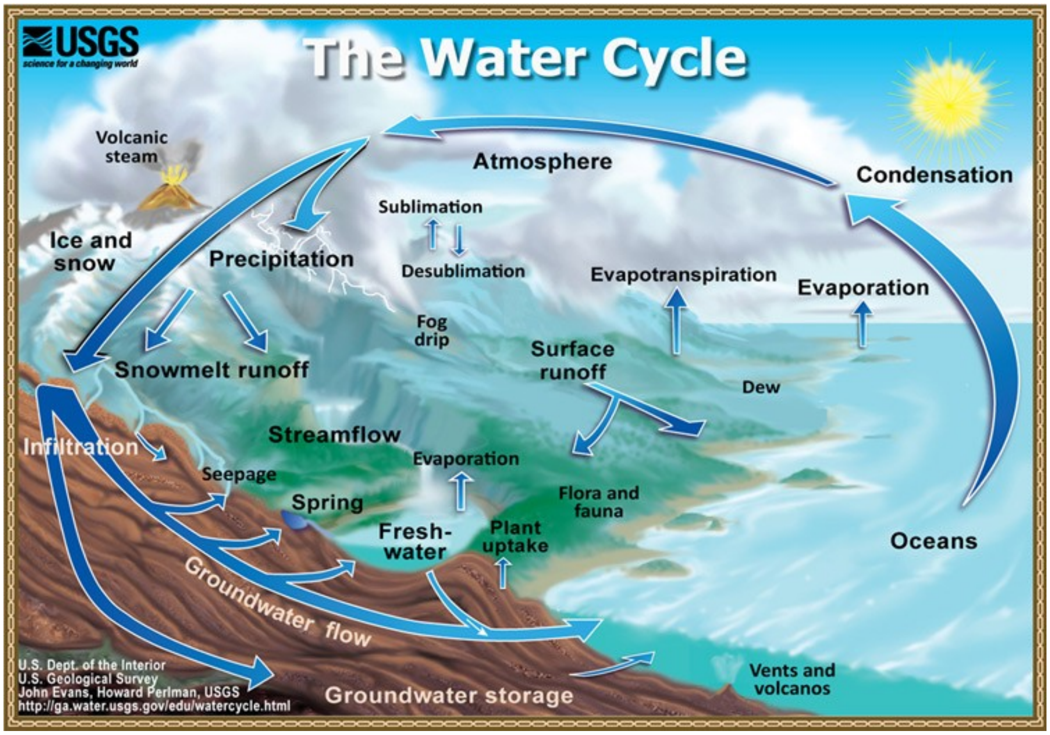

Figure 2.1 The Water Cycle adopted from (U.S. Geological Survey. 2015).

2.2 Water Year

According to USGS (2016), the water year is the 12-month period starting October 1 for any given year through September 30 of the following year. The water year is designated by the calendar year in which it ends and which includes 9 of the 12 months. Thus, the year ending September 30, 1999 is called the "1999" water year.

2.3 Groundwater Recharge

Groundwater recharge happens when a part of precipitation on the ground surface infiltrates through the soil and reaches the water table. Recharge can be known as water moving from the land surface to the unsaturated zone. When water reaches the water table, it can go out of the groundwater to surface water, which is called discharge. (Shukla and Jaber 2006). Measuring groundwater recharge is difficult to be accurately estimated; therefore, more than one method should be used to verify the estimates (Sumioka and Bauer 2003).

2.4 Recharge Estimation Techniques

Estimating the groundwater recharge is one of the most difficult measures regarding groundwater resources. There are more than one method that estimate groundwater recharge, yet a large amount of errors is normally subordinate. However, calculating groundwater recharge can be estimated on a wide set of methods in order to give the closest estimation of recharge.

There are numerous methods regarding estimating groundwater recharge. From the literature, there are several techniques to estimate ground water recharge. The water table fluctuation method is one of the most common ones. This method is based on measuring groundwater level over time and space. The water table fluctuation method (WTF) is basically performed by estimating the specific yield for an area of fluctuation of the groundwater level (Healy 2010). Another method of estimating groundwater recharge is the recession curve displacement method (Rorabaugh Method). The Rorabaugh method is used when a series of groundwater recharge events occur during one runoff season. This method can be implemented when the recession curve is moved upward by a recharge event. The groundwater recharge can be estimated by the size of the upward movement of the recession (Rorabaugh 1964; Rorabaugh and Simons 1966). As a result, in this study the following four methods have been used: soil water balance method, Chaturvedi formula, seasonal recession method (Meyboom Method), and the well level data method.

2.4.1 Soil Water Balance

The soil water balance has been widely used. This approach has an advantage since it estimates direct groundwater recharge using available climate data (Rushton and Ward 1979). The parameters of the soil water balance method are precipitation, runoff, evapotranspiration, and soil water storage.

2.4.2 Chaturvedi Formula.

The Chaturvedi formula was based on the water level fluctuation method and rainfall amounts. According to (Chaturvedi 1973), groundwater recharge was defined as a function of the annual precipitation. The Chaturvedi formula was used in India where the climate is tropical.

2.4.3 Seasonal Recession Method (Meyboom Method).

The Meyboom method is based on comparing the recession curve for streamflow data. Basically, this method estimates the groundwater recharge in a basin. The Meyboom method assumes that the catchment area does not have dams or other methods that regulate streamflow (Meyboom 1961).

2.4.4 Well Level Data.

The well level data method is the most accurate method since it measures the groundwater recharge based on the difference in water level in a well at the beginning of the water year and at the end of the same year with consideration of the soil porosity.

2.5 Description of the Study Area

South Dakota lies in the Mid-Western region of the United States, bordered by the states of North Dakota, Minnesota, Iowa, Nebraska, Wyoming, and Montana (See Figure 2.2). The geographic area of South Dakota is the sixteenth-largest state in the United States and it is situated on the Missouri Plateau (Hogan et al. 2001).

Figure 2.2 Map of the United States adopted from (USGS 2016)

The Waubay Lakes Chain is located in Day County in a closed subbasin of the Big Sioux River Basin, northeastern South Dakota. The study area, 409 mi^2, is located in the Coteau des Prairies, a highland plateau between the Minnesota River-Red River lowlands to the east and the James River lowland to the west. The Coteau des Prairies has an average width of 50 mi and maximum elevations more than 2,100 ft. above sea level. The north edge of the Coteau des Prairies is in North Dakota and the south edge ends in northwestern Iowa and southwestern Minnesota. The Coteau des Prairies is a rugged, poor drainage landscape (See Figure 2.3) (Gries 1996; Niehus et al. 1999).

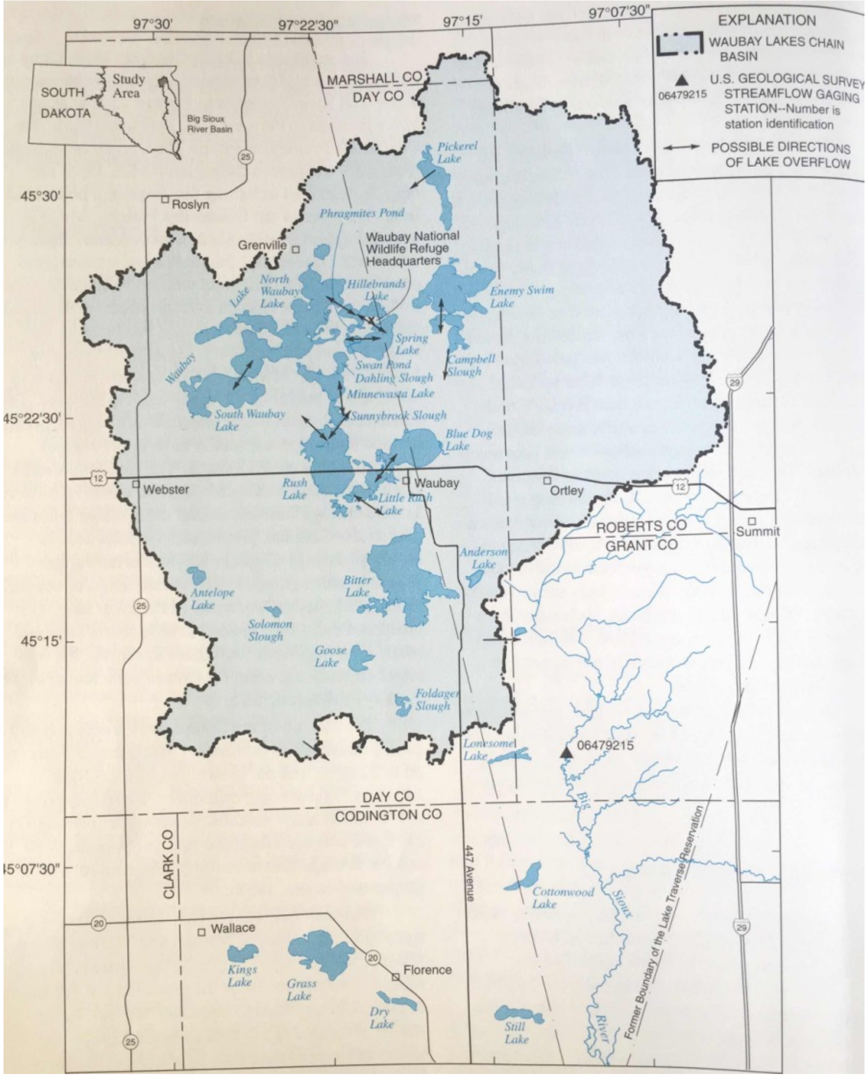

Figure 2.3 Location of study area adopted from (Niehus et al. 1999).

2.5.1 General Climate Characteristics

The climate of South Dakota is continental as the state's location is in the Mid-West of the North American Continent. The climate zone of South Dakota is based on average condition and consists of four climate types or zones: the Humid Continental Type "A", the Humid Continental Type "B", the Dry Continental, and the Unclassified Continental. Figure 2.3 shows map of South Dakota dividing it into four climate types or zones. Humid Continental "A" is long summer type and consists of four seasons with longer summer and a shorter, milder winter. Humid Continental "B" also has four seasons with warm to hot, medium in length summer while winter is long and cold. The Dry continental climate consists of dry atmosphere where clouds and fogs are rare. Both the temperature and humidity are low with cold winter. The Unclassified Climate is located in the upper elevation of the Black Hills (Hogan et al. 2001).

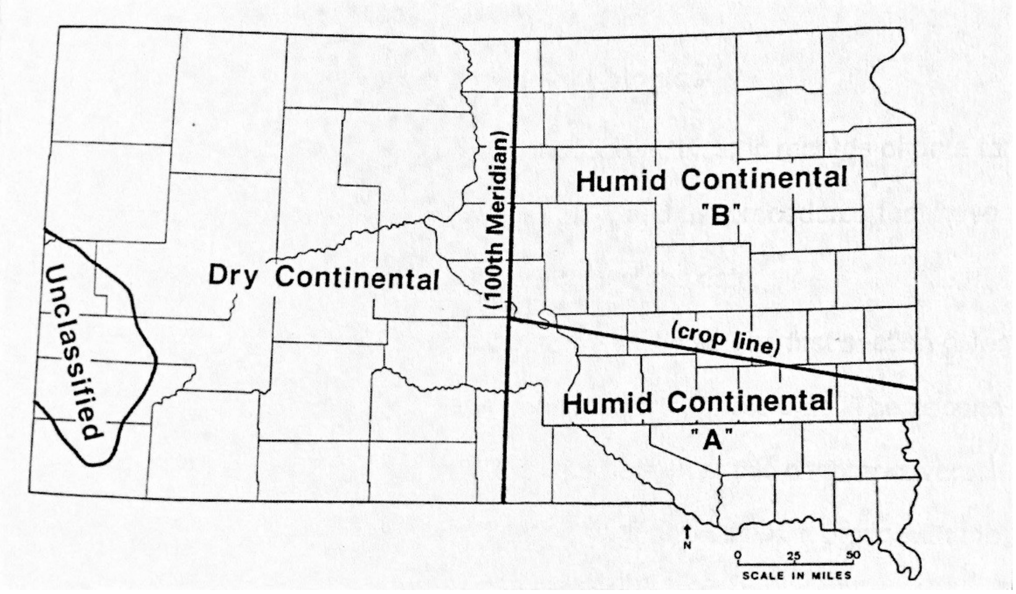

Figure 2.3 Climate zones of South Dakota adopted from (Hogan et al. 2001).

Chapter 3: Materials and Methods

This chapter describes four different methods that have been used to estimate the groundwater recharge. These four methods are; the soil water balance method, Chaturvedi formula, the seasonal recession (Meyboom) method, and a well level data method. Moreover, this chapter discusses the data sources for these methods as well as quality control in order to meet the objectives of this study.

3.1 Analysis Methods

3.1.1 Soil Water Balance Method

The soil water method can be described as in equation 1 (Kumar 1997; Thornthwaite and Mather 1955; Thornthwaite 1948):

$$R = P - ET + W - R_0 \tag{1}$$

Where:

R = Groundwater Recharge, in.

P = Precipitation, in.

ET = Actual Evapotranspiration, in.

W = Soil Water Storage, in.

R_0 = Runoff, in.

The actual evapotranspiration can be estimated using equation 2. (Fetter and Fetter 2001; Jensen et al. 1990):

$$E_{tr} = k_p E_{pan} \tag{2}$$

Where

E_{tr} = Evapotranspiration, in.

k_p = Pan coefficient

Table 3.1 k_p Values when using the pan method (Jensen et al. 1990).

Method	April	May	June	July	August	September	October
E_{pan}	0.75	0.86	0.92	0.94	0.92	0.92	0.91

E_{pan} = Measured pan evaporation, in.

Soil water storage (W) was determined by equation 3 (Nyvall 2002) :

Soil Water Storage = Rooting Depth x Available Water Storage Capacity (3)

Where:

Rooting Depth = Volume of water stored in the soil for the crop to draw upon between irrigations, ft. (See Table C1).

Available Water Storage Capacity = In Soil, in. /ft. (See Table C2).

The volume of runoff can be estimated using the NRCS curve number procedure equation 4. (NRCS 1974).

$$Q = \frac{(P-0.2S)^2}{(P+0.8S)} \tag{4}$$

Where:

Q = Runoff, in.

P = Rainfall depth, in.

S = A parameter given by:

$$S = \frac{1000}{CN} - 10$$

CN = Curve number

According to the soil survey provided from United States Department of Agriculture, the hydrologic soil group was C and the land description used was pasture or range (poor condition) based on Niehus et al. (1999) .The curve number can be found from Table 2.

Table 3.2 Curve number for antecedent soil moisture condition.(NRCS 1974).

Land use description	hydrologic soil groups			
	A	B	C	D
Commercial	80	85	90	95
Fallow, poor condition	77	86	91	94
Cultivated with conventional tillage	72	81	88	91
Cultivated with conservation tillage	62	71	78	81
Lawns, poor condition	58	74	82	86
Lawns, good condition	39	61	74	80
Pasture of range, poor condition	68	79	86	89
Pasture of range, good condition	39	61	74	80
Meadow	30	58	71	78
Pavement and roofs	100	100	100	100
Woods of forest thin stand, poor condition	45	66	77	83
Woods of forest, good cover	25	55	70	77
Farmsteads	59	74	82	86
Residential quarter-acre lot, poor condition	73	83	88	91
Residential quarter-acre lot, good condition	61	75	83	87
Residential half-acre lot, poor condition	67	80	86	89
Residential half-acre lot, good condition	53	70	80	85
Residential 2-acre lot, poor condition	63	77	84	87
Residential 2-acre lot, good condition	47	66	77	81
Roads	74	84	90	92

3.1.2 Chaturvedi Formula

According to (Kumar 1997), groundwater recharge can be predicted from the following formula (Chaturvedi 1973):

$$R = 1.35(P - 14)^{0.5} \quad (5)$$

Where:

R = Groundwater recharge due to precipitation during the year, in.

P = Annual precipitation, in.

3.1.3 Seasonal Recession Method (Meyboom Method)

This method consists of presenting the streamflow data in four hydrographs. Each hydrograph shows five years during the chosen period (1978-1998). Equation 6 indicates that (Q_0) varies logarithmically with time (t). As an example illustrating the Meyboom method is as follows. Figure 3 shows streamflow data for the year (1978-1982) on a semi log plot. The baseflow recessions are shown as dashed lines. Equation 6 is used to calculate the volume of the total potential groundwater discharge (Meyboom 1961). The amount of estimated groundwater recharge was calculated for every five years. Furthermore, this amount has been divided by five in order to give an estimated groundwater recharge per year.

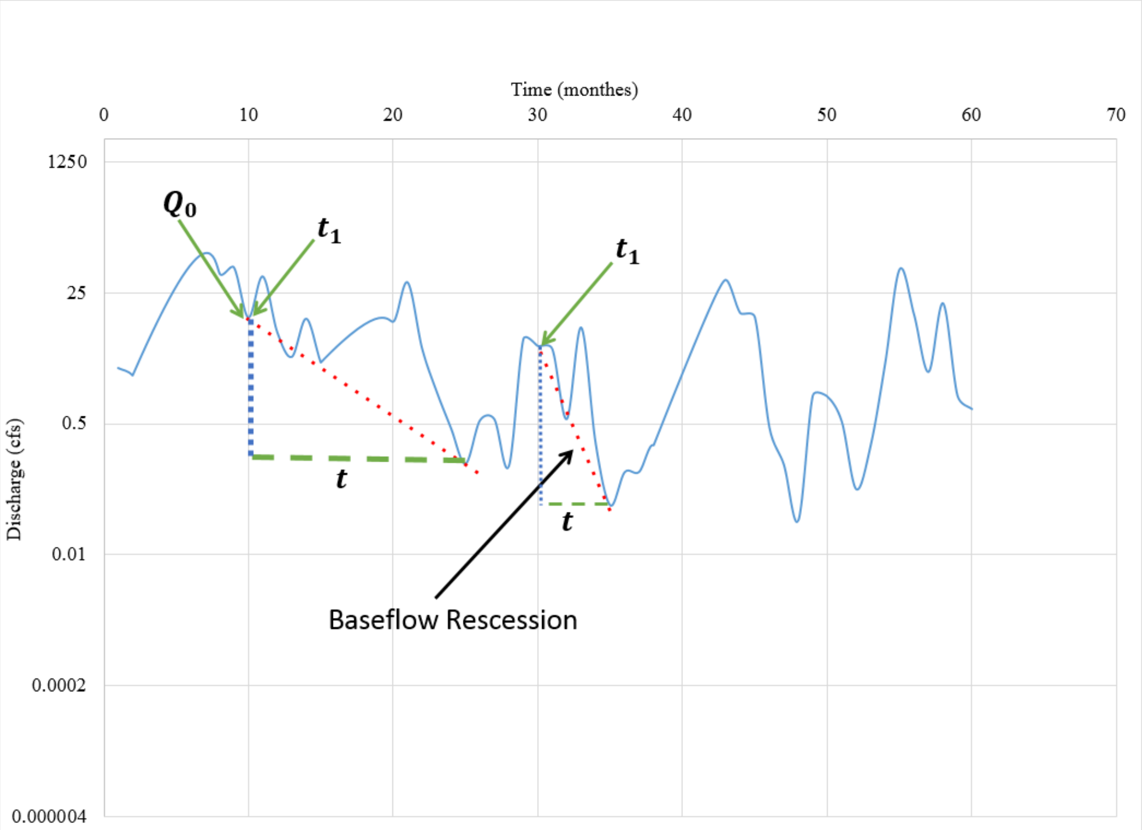

Figure 3.1 Streamflow data for 1978-1982.

The total volume of groundwater recharge could be found as equation 6 and 7 show (Fetter and Fetter 2001; Meyboom 1961) :

$$V_{tp} = \frac{Q_0 t_1}{2.3026} \tag{6}$$

Where:

V_{tp} = Volume of the total potential groundwater discharge, ft^3

Q_0 = The baseflow at the start of the recession, ft^3/sec (see Figure 1)

t_1 = The time that it takes the baseflow to go from Q_0 to $0.1Q_0$, sec (see Figure 1)

$$V_t = \frac{V_{tp}}{10^{\left(t/t_1\right)}} \tag{7}$$

Where:

V_t = The amount of potential baseflow, ft^3

t = Time after the start of the baseflow recession, sec (see Figure 3.1)

Then, the estimated groundwater recharge can be calculated from equation 8:

$$R = \frac{(V_{tp} - V_t)}{A}$$

(8)

Where:

R = Estimated groundwater recharge, in.

A = Contributing drainage area, in^2.

3.1.4 Well Level Data Method

The estimation of groundwater recharge has been done by

$$R = (WL_2 - WL_1)P \tag{9}$$

Where:

R = Estimated recharge, in.

WL_2 = Water level at the beginning of water year, in.

WL_1 = Water level at the end of the same year, in.

P = Adjusting for porosity 0.2 (Ward and Trimble 2003).

3.2 Data Sources

First, the Waubay Lakes Chain is a unique location that has a closed basin which is hydrologically not connected to the rest of the area and it is well studied (Niehus et al. 1999). The data used in this thesis was collected from different locations in South Dakota for the time period 1978-1998. Assumption is that the recharge area is well represented by the regions where the data is measured. This period was chosen as there was a lack of data from some sources for years earlier than 1978. Also, later than 1998 the availability of data did not match between datasets. There were some studies that have been performed in this location and within the same time frame, so this was another reason for choosing this time period. (See Figure 3.2 and Table 3.3).

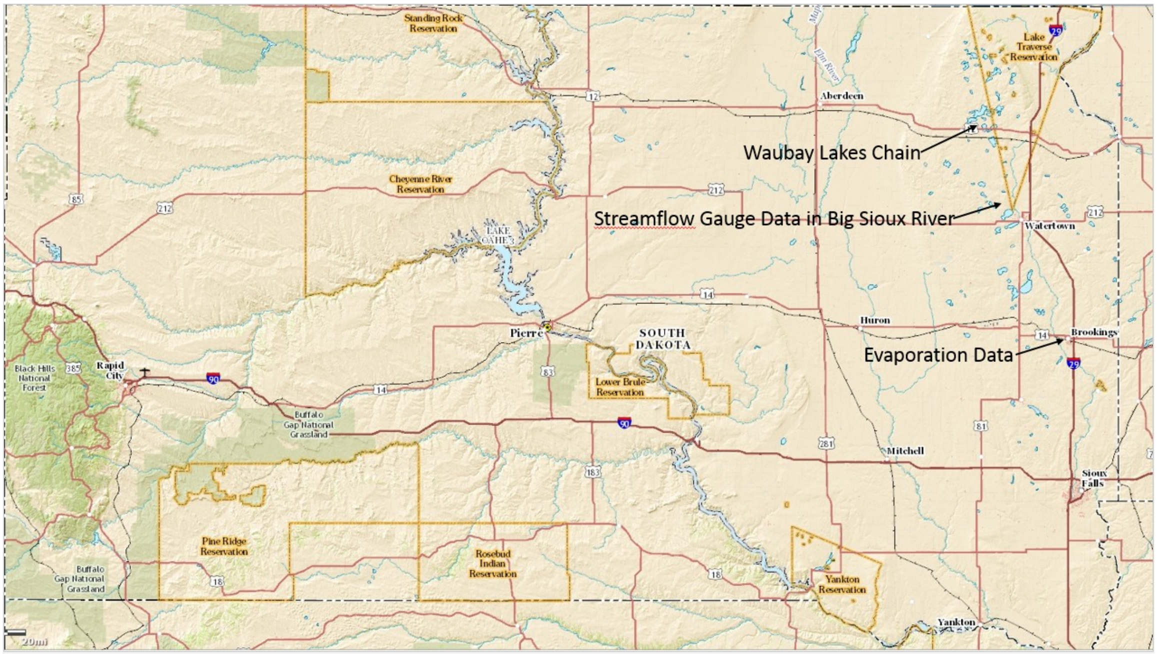

Figure 3.2 Data sources locations adopted from (USGS 2016).

Table 3.3 Data Sources.

Data type	Source
Precipitation and Evaporation	(Niehus et al. 1999).
Evapotranspiration	(Fetter and Fetter 2001; Jensen et al. 1990).
Runoff	United States Department of Agriculture and (NRCS 1974).
Soil water storage	(Nyvall 2002).
Streamflow Gauges	U.S. Geological Survey web-page (USGS 2013).
Well Level Data	South Dakota Department of Environment & Natural Resources (DENR 2015) and United States Department of Agriculture (USDA 2015).

3.2.1 Soil Water Method

In order to obtain an estimate for the groundwater recharge with this method, all the parameters in the soil water balance equation were obtained from multiple sources. First, the U.S. Geological Survey's report, Lake-Level Frequency Analysis for the Waubay Lakes Chain, Northeastern South Dakota (Niehus et al. 1999) provided the climate data (precipitation and evaporation) for a location near Waubay Lakes Chain in South Dakota. Second, with the available data for evaporation, the estimated evapotranspiration was calculated by using equation 2. The third parameter in the soil water balance is change in soil water storage. The determination of change in soil water storage was performed by defining the crop rooting depth and the available water storage capacity (Nyvall 2002). The last parameter in this method was runoff, and it was estimated by using the NRCS curve number procedure. The NRCS curve number is a function of the ability of soil to infiltrate water, land use, and the soil water conditions at the start of a rainfall event (See equation 4) (NRCS 1974).

3.2.2 Chaturvedi Formula

Precipitation data was the only data needed in order to estimate the groundwater recharge by using the Chaturvedi formula, and it was obtained from the U.S. Geological Survey's report, Lake-Level Frequency Analysis for the Waubay Lakes Chain, Northeastern South Dakota (Niehus et al. 1999).

3.2.3 Meyboom Method

For the Meyboom method, streamflow gauge data for the Big Sioux River, near the Waubay Lakes Chain, was downloaded from the U.S. Geological Survey web-page (USGS 2013) as an EXCEL spreadsheet for the years 1978-1998.

3.2.4 Well Level Data Method

For the well level data, the South Dakota Department of Environment & Natural Resources (DENR 2015) provided this study with the available data for the study area. Table 3.4 represents general characteristics of the well and its location while Figure 3.3 shows the well location.

Table 3.4 Well DA-78C general characteristics (DENR 2015)

Well Information	
County	Day
Location	122N55W12DCCC
Latitude	45.384722
Longitude	-97.376058
Ground Surface Elevation (ft.)	1814 T
Aquifer	Prairie Coteau
Well Name	DA-78C
Casing Type	PVC
Screen Type	Unknown
Total Casing and Screen (ft.)	78.3
Casing Top Elevation (ft.)	1817.1 T
Casing Diameter (in.)	2
Screen Length (ft.)	0
Casing Stick-up (ft.)	3.1

Figure 3.3 Well DA-78C location adopted from (DENR 2015)

3.3 Quality Control

The climate records, well level data, and streamflow data were reviewed for the period 1978-1998. There was a limited amount of data that was only available at certain times. Regarding the missing data, the evaporation data was not available for the Waubay Lakes Chain, so Brookings evaporation data was used instead (Niehus et al. 1999). Also, the streamflow gauge data was for the Big Sioux River near Watertown because there were no streamflow gauges near the Waubay Lakes Chain due to its topography.

The well level data was not consistently available at the start and end of each water year. As a result, we adjusted the beginning date or end date for the calculation by one month to approximate the water year level when data was missing.

Chapter 4: Presentation of Results

This section presents the estimated groundwater recharge for the four methods used for the water years 1978-1998. This chapter is divided into four sections. Every section covers the presentation of each method's results.

4.1 Soil Water Balance Method

The amount of the estimated groundwater recharge is presented in Table 4.1:

Table 4.1 Estimated groundwater recharge using the soil water balance method.

Water year	Precipitation, in.	Evapotranspiration, in.	Estimated Recharge, in.
1978	25.94	30.90	4.09
1979	18.22	27.26	0.03
1980	16.97	29.96	-3.91
1981	15.22	28.47	-4.17
1982	18.94	25.99	2.02
1983	20.32	28.25	1.13
1984	21.46	28.60	1.92
1985	19.99	28.06	1.00
1986	33.74	27.79	14.99
1987	13.02	29.09	-6.98
1988	17.74	35.55	-8.74
1989	20.65	31.02	-1.30
1990	21.28	31.05	-0.71
1991	29.07	29.63	8.49
1992	15.74	25.86	-1.04
1993	25.59	24.31	10.33
1994	21.69	26.50	4.26
1995	29.05	25.70	12.39
1996	19.53	23.43	5.16
1997	23.03	27.29	4.80
1998	24.32	26.36	7.01

The estimated groundwater recharge was found to be between -8.74 in. and 14.99 in. with an average of 2.42 in. and standard deviation of 6.08 in..

Figure 4.1 shows the relationship between groundwater recharge, deviation from average precipitation, and deviation from average evapotranspiration. It is seen from the figure that as precipitation increases, recharge increases, and as evapotranspiration increases, recharge decreases. In the year 1982, a decrease in precipitation, but also a decrease in evapotranspiration was seen; however, the estimated recharge increased for that combination. Whereas in 1986, there was an increase in precipitation but evapotranspiration was essentially normal and estimated recharge increased.

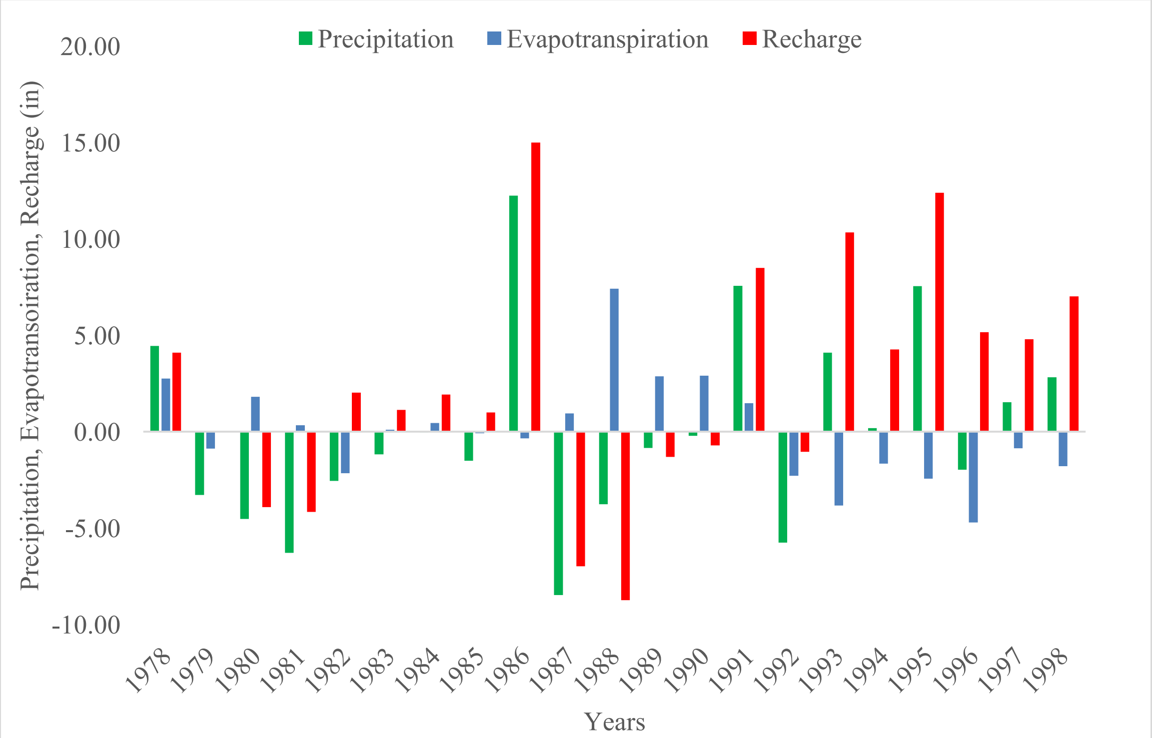

Figure 4.1 Comparison of the estimated groundwater recharge using soil water method with deviation from average precipitation and deviation from average evapotranspiration.

4.2 Chaturvedi Formula

The results for the Chaturvedi formula with precipitation data as an input are presented in Table 4.2.

Table 4.2 The groundwater recharge using Chaturvedi formula

Water year	Precipitation, in.	Estimated Recharge, in.
1978	25.94	4.66
1979	18.22	2.77
1980	16.97	2.33
1981	15.22	1.49
1982	18.94	3.00
1983	20.32	3.39
1984	21.46	3.69
1985	19.99	3.30
1986	33.74	6.00
1987	13.02	Not Defined*
1988	17.74	2.61
1989	20.65	3.48
1990	21.28	3.64
1991	29.07	5.24
1992	15.74	1.78
1993	25.59	4.60
1994	21.69	3.74
1995	29.05	5.24
1996	19.53	3.17
1997	23.03	4.06
1998	24.32	4.34

* The value of recharge is undefined when precipitation is less than 14 inches.

The estimated groundwater recharge was found to be between 1.49 in. and 6.00 in. with an average of 3.63 in. and standard deviation of 1.16 in.. Note: there are no values less than zero as the formula does not allow the computation of negative value.

Figure 4.2 represents the relationship between groundwater recharge and deviation from average precipitation. The amount of the estimated groundwater recharge decreases and increases along with the deviation from average precipitation as expected since precipitation is the only input to the recharge calculation.

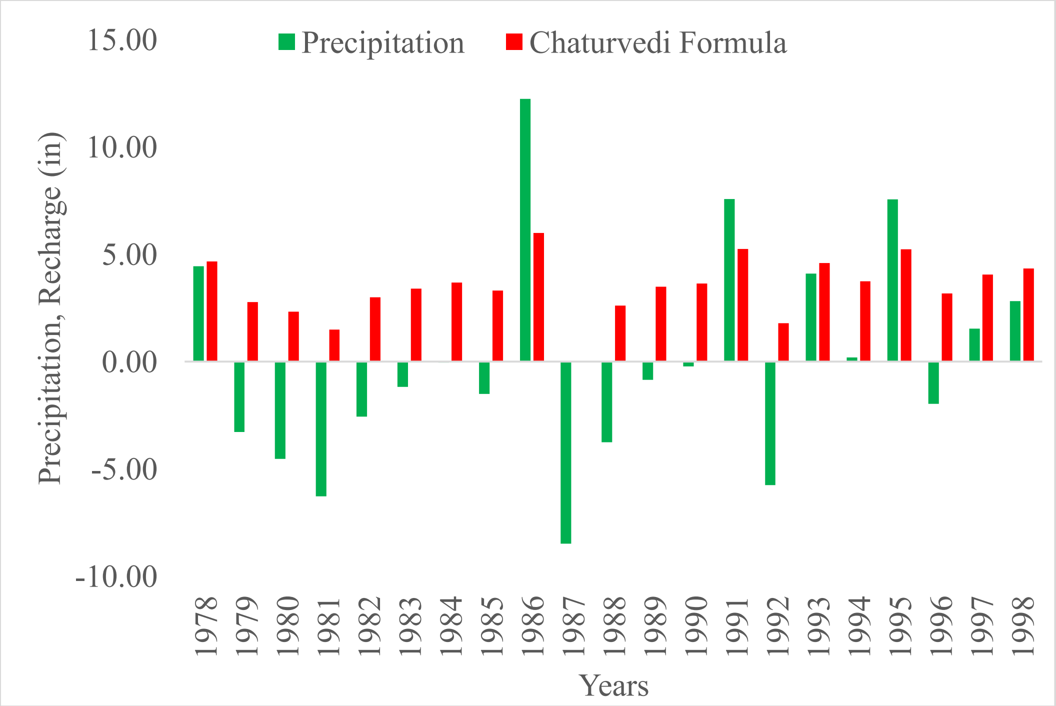

Figure 4.2 Comparison of the estimated groundwater recharge using the Chaturvedi formula with deviation from average precipitation.

4.3 Seasonal Recession Method (Meyboom Method)

As discussed in chapter 3, the Meyboom method estimates the groundwater recharge for every five years. The final results for the four different periods are presented in Table 4.3.

Table 4.3 Estimated groundwater recharge using Meyboom method.

Water Year	Average Annual Discharge, ft^3/s	Estimated Recharge, in.
1978-1982	15.89	15.11/5 = 3.02 in/yr.
1983-1987	42.09	0.59/5 = 0.11 in/yr.
1988-1992	35.55	11.49/5 = 2.29 in/yr.
1993-1997	115.50	90.49/5 = 18.09 in/yr.

The estimated groundwater recharge was found to be between 0.11 in. /yr. and 18.09 in. /yr. with an average of 5.88 in. /yr. and standard deviation of 7.32 in./yr..

Figure 4.3 represents the relationship between the estimated groundwater recharge and deviation from the five year average of the annual average stream discharge. It is noted that during 1983-1987 the average of the estimated recharge was 0.59 in. although the average of annual discharge rates was high. Results in the other years follow a similar trend with an increase in discharge related to an increase in recharge.

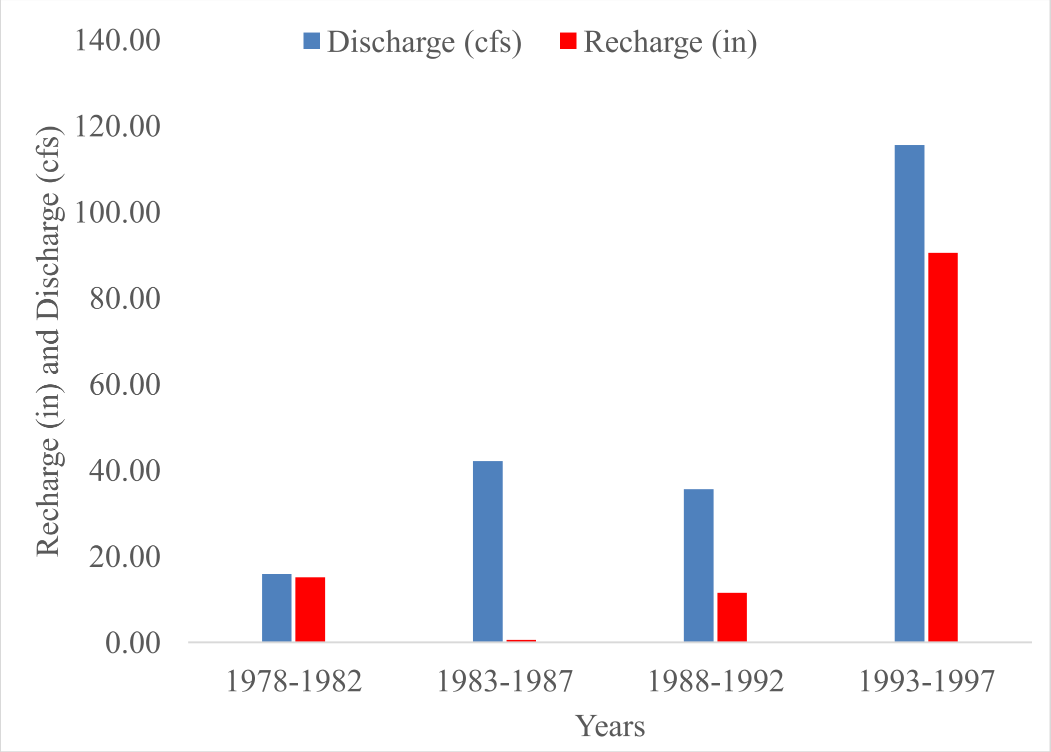

Figure 4.3 The estimated groundwater recharge using the Meyboom method with deviation from the five year average of the annual average stream discharge.

4.4 Well Level Data Method

The final results for the well level data method are presented in Table 4.4.

Table 4.4 The estimated groundwater recharge using the well level data method

Water year	Ave. Annual Water Level, ft.	Recharge, in.
1979	32.41	3.6
1980	32.41	-4.56
1981	35.18	-15.12
1982	36.66	-5.16
1983	34.97	-1.8
1984	35.71	-3.6
1985	38.3	-6.48
1986	32.61	17.28
1987	33.51	-9.84
1988	36.21	-10.32
1989	36.07	-7.44
1990	34.07	0
1991	31.37	6.96
1992	30.94	-2.16
1993	28.96	9.24
1994	26.69	3.6
1995	22.93	4.8
1996	21.16	2.76
1997	18.9	15.12
1998	17.11	4.32

The estimated groundwater recharge was found to be between -15.12 in. and 17.28 in. with an average of 0.06 in. and standard deviation of 8.38 in..

Figure 4.4 represents the estimated groundwater recharge for the well level data method. 1986 shows a large amount of recharge while from 1980 to 1985 and from 1987 to 1990 the amount of recharge was below zero. It is noted that the amount of recharge increased during the 90's except 1992 where it was below zero.

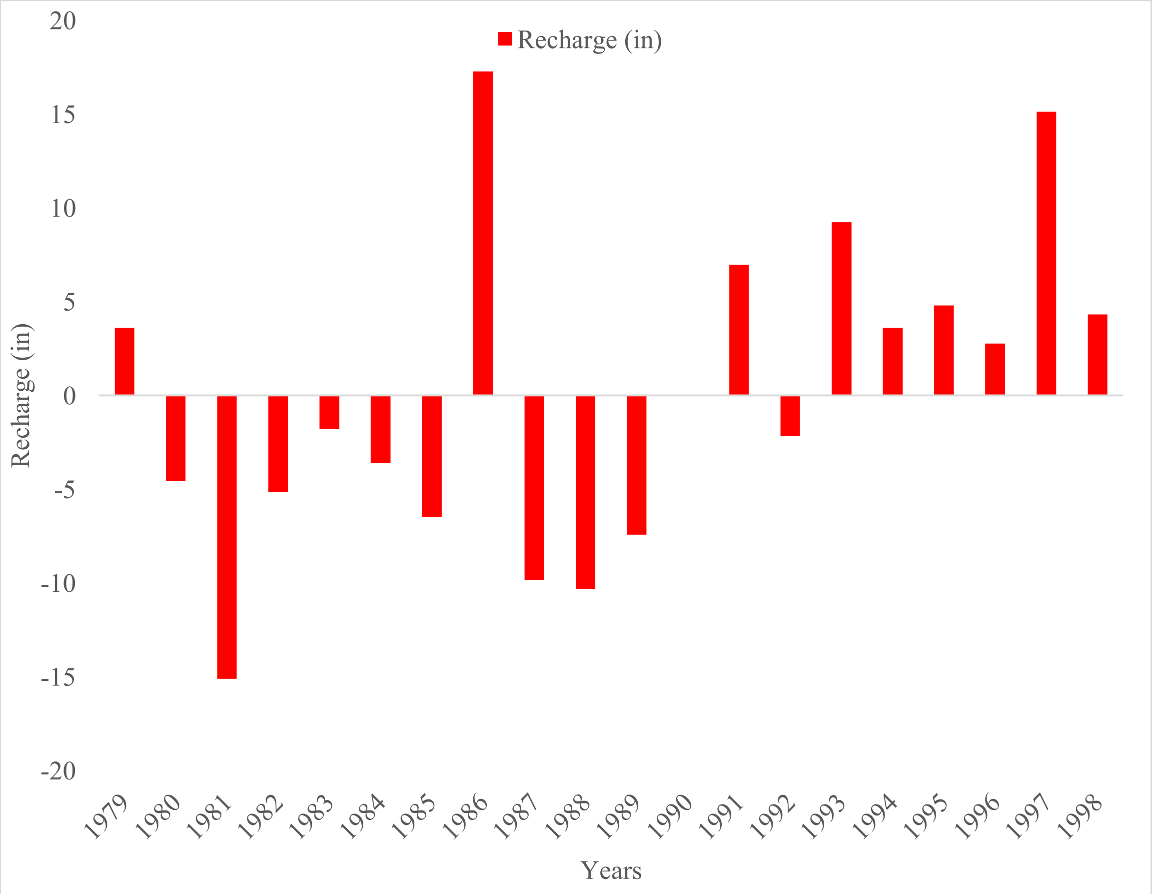

Figure 4.4 The estimated groundwater recharge using the well level data method

Chapter 5: Discussion of the Result

The discussion of the results from the four methods is presented in this section. We consider the well level data method as the most direct method for assessing what recharge is. This chapter is mainly divided into five sections. The first section covers precipitation and evaporation trends where the next three sections cover a comparison between each of the numerical methods with the well level data method regarding the similarity, differences, advantages, and disadvantages. The last section will cover a comparison of the four methods.

5.1. Precipitation and Evaporation Measurement

Measurement of precipitation and evaporation is one of the most important factors in this study. Therefore, in order to obtain an accurate measurement for precipitation and evaporation, the number of gauges is based on the size of the study area. In other words, if one gauge represents a large area, the potential error in the actual average precipitation and evaporation is going to increase (See Table 5.1 and Figure 5.1) (Brakensiek et al. 1979).

Table 5.1 Guide for network gauge numbers (Brakensiek et al. 1979)

Size of Watershed (Square Miles)	Number of Gauge Sites
5	10
10	15
100	50
300	100

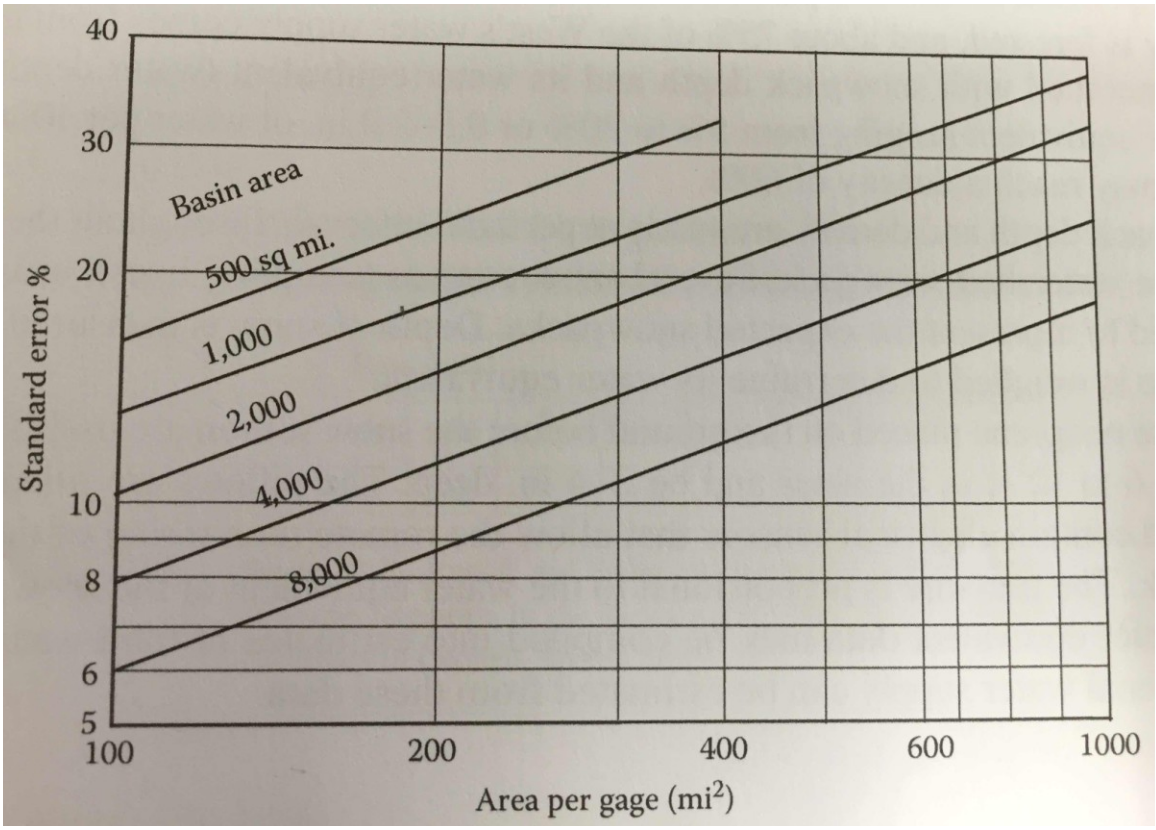

Figure 5.1 Relationship among basin area, rain gauge spacing, and percentage standard error of rain gauges

5.1.1 Precipitation Data

From precipitation data, the deviation from average precipitation was calculated in order to define higher than normal precipitation periods and lower than normal precipitation periods from 1978 to 1998. The higher periods were in 1978, 1986, 1991, 1993, 1995, 1997, and 1998. Average precipitation yeas were 1984, 1990, and 1994 while the lower periods were in the rest of the years. (See Table 5.2 and Figure 5.2)

Table 5.2 Precipitation Data (red color represents dry periods, blue color represents wet periods, and black color represents normal)

Year	Annual Precipitation, in.	Deviation from Average Precipitation, in.
1978	25.94	4.44
1979	18.22	-3.28
1980	16.97	-4.53
1981	15.22	-6.28
1982	18.94	-2.56
1983	20.32	-1.18
1984	21.46	-0.04
1985	19.99	-1.51
1986	33.74	12.24
1987	13.02	-8.48
1988	17.74	-3.76
1989	20.65	-0.85
1990	21.28	-0.22
1991	29.07	7.57
1992	15.74	-5.76
1993	25.59	4.09
1994	21.69	0.19
1995	29.05	7.55
1996	19.53	-1.97
1997	23.03	1.53
1998	24.32	2.82
Average, in.	21.50	
Standard Deviation, in.	5.08	

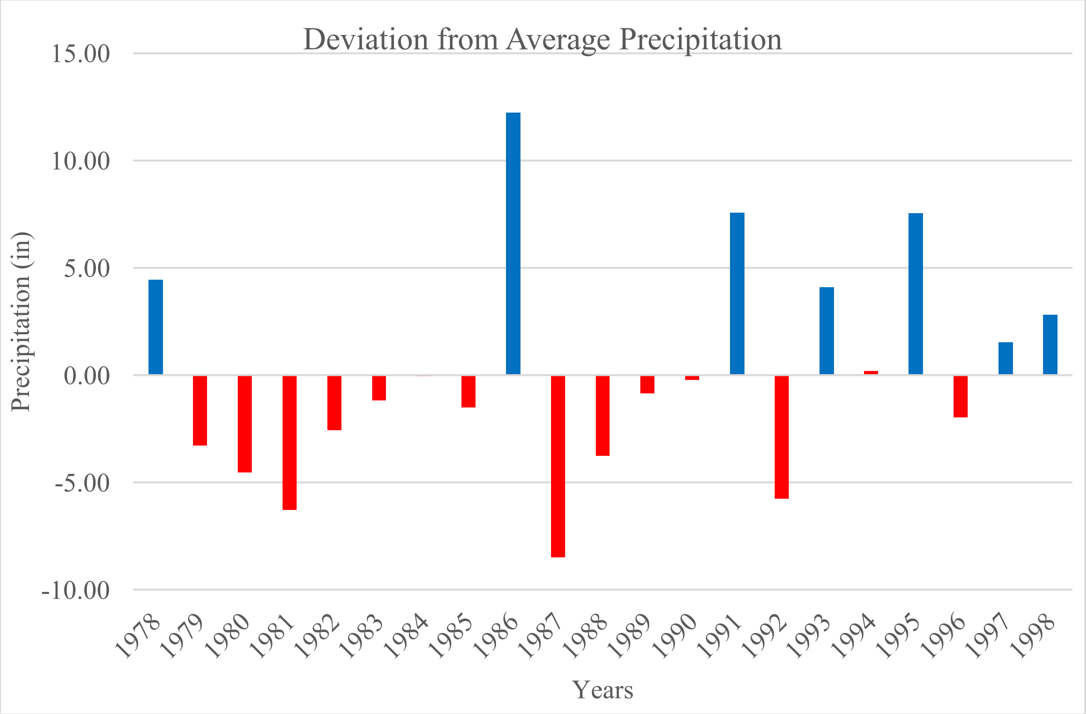

Figure 5.2 Deviation from average precipitation

5.1.2 Evaporation Data

From evaporation data, the deviation from average evaporation was calculated in order to define higher than normal evaporation periods and lower than normal evaporation periods from 1978 to 1998. The higher periods were in 1978, 1980, and from 1987 to 1991. The lower periods were very prominent during the 90's while the normal periods were in 1979, 1981, from 1993 to 1986, and 1997. (See Table 5.3 and Figure 5.3)

Table 5.3 Evaporation data (red color represents high periods, blue color represents low periods, and black color represents normal)

Year	Annual Evaporation, in.	Deviation from Average Evaporation, in.
1978	33.97	3.02
1979	29.96	-0.99
1980	32.96	2.01
1981	31.3	0.35
1982	28.57	-2.38
1983	31.08	0.13
1984	31.45	0.50
1985	30.85	-0.10
1986	30.56	-0.39
1987	32	1.05
1988	39.13	8.18
1989	34.08	3.13
1990	34.15	3.20
1991	32.57	1.62
1992	28.42	-2.53
1993	26.73	-4.22
1994	29.15	-1.80
1995	28.26	-2.69
1996	25.76	-5.19
1997	30.03	-0.92
1998	28.98	-1.97
Average, in.	30.95	
Standard Deviation, in.	2.98	

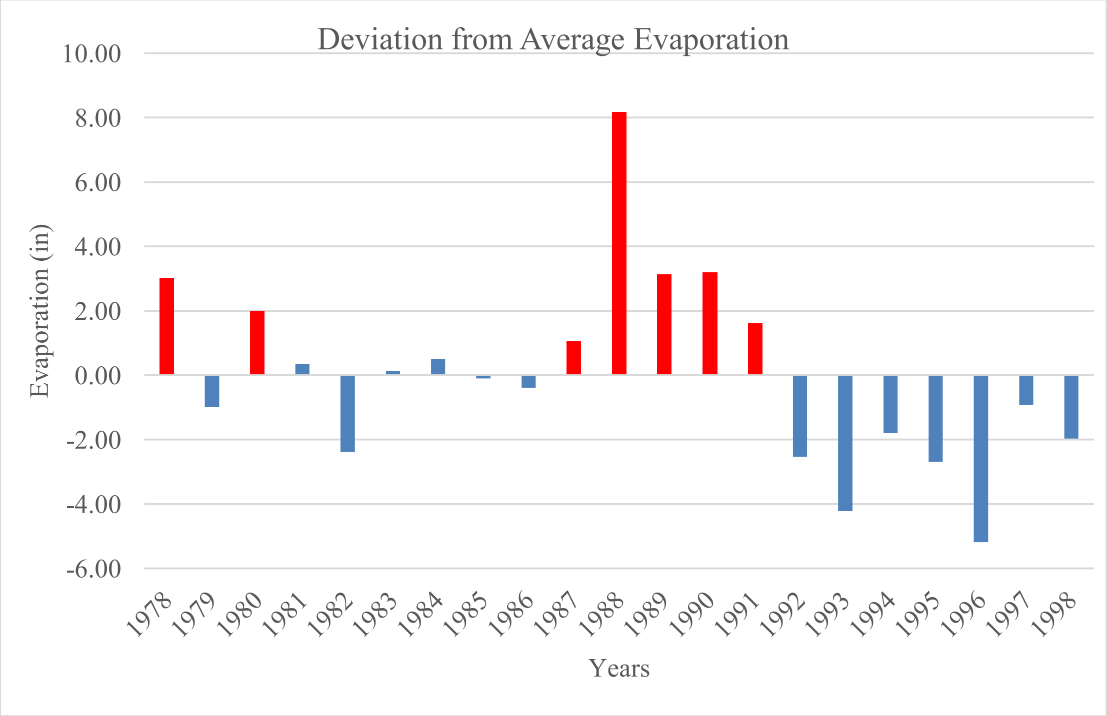

Figure 5.3 Deviation from average evaporation

5.1.3 Wet, Dry, and Normal Periods

After calculating the deviation from average precipitation and the deviation from average evaporation, the deviation from average precipitation was subtracted from the deviation from average evaporation in order to determine when the wet and dry periods were. The wet periods were found when the final results are above zero and, the dry periods were found when the final results are below zero (See Table 5.4, Figure 5.4). The wet periods were in 1978, 1986, 1991, 1993, 1994, 1995, 1996, 1997, and 1998. The dry periods were in the rest of the years while 1982 and 1984 were normal.

Table 5.4 Wet and Dry Periods

Year	Precipitation – Evaporation, in	Wet, Dry, Normal
1978	1.42	Wet
1979	-2.29	Dry
1980	-6.54	Dry
1981	-6.63	Dry
1982	-0.18	Normal
1983	-1.31	Dry
1984	-0.54	Normal
1985	-1.41	Dry
1986	12.63	Wet
1987	-9.53	Dry
1988	-11.94	Dry
1989	-3.98	Dry
1990	-3.42	Dry
1991	5.95	Wet
1992	-3.23	Dry
1993	8.31	Wet
1994	1.99	Wet
1995	10.24	Wet
1996	3.22	Wet
1997	2.45	Wet
1998	4.79	Wet

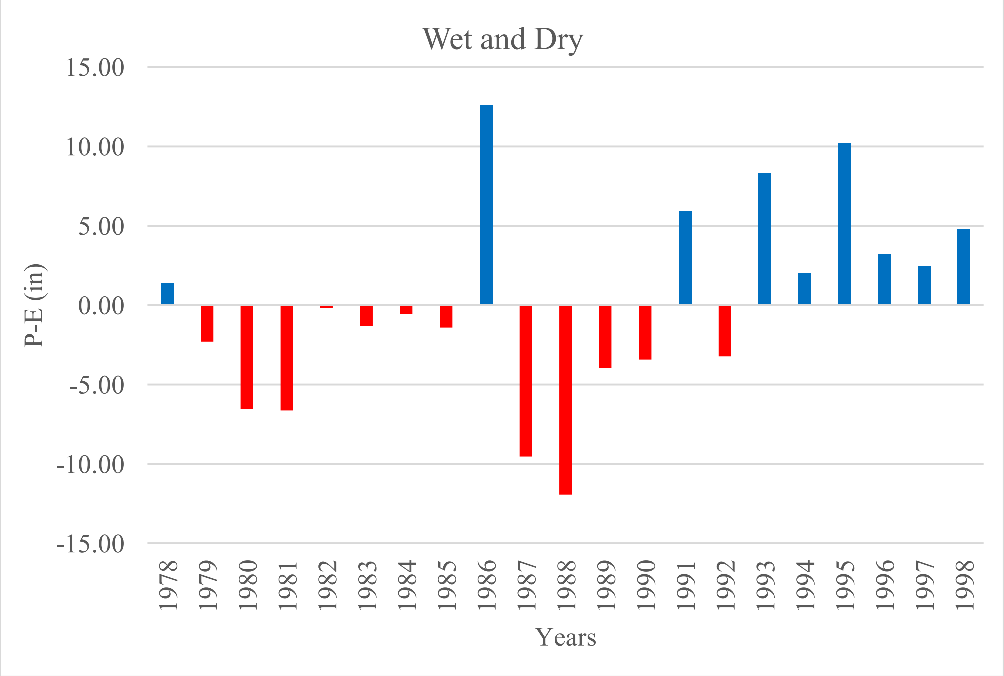

Figure 5.4 Wet and dry periods

5.2.Comparison Between Soil Water Balance Method and Well Level Data Method

As Table 5.4 shows there are some similarities in the calculated groundwater recharge values between the two methods. For example, in 1980 and in the early 1990 there were some similarities between the two methods' recharge. Also, it is noted that the maximum amount of recharge was found to be in 1986 for both methods. Table 5.5 and Figure 5.5 show a correlation between the two methods for wet and dry periods.

Table 5.5 Soil water balance recharge, well level data recharge, and wet and dry periods

Water year	Well Level Data Recharge, in.	Soil Water Balance Recharge, in.	Wet, Dry, Normal
1978	unknown	4.09	Wet
1979	3.6	0.03	Dry
1980	-4.56	-3.91	Dry
1981	-15.12	-4.17	Dry
1982	-5.16	2.02	Normal
1983	-1.8	1.13	Dry
1984	-3.6	1.92	Normal
1985	-6.48	1	Dry
1986	17.28	14.99	Wet
1987	-9.84	-6.98	Dry
1988	-10.32	-8.74	Dry
1989	-7.44	-1.3	Dry
1990	0	-0.71	Dry
1991	6.96	8.49	Wet
1992	-2.16	-1.04	Dry
1993	9.24	10.33	Wet
1994	3.6	4.26	Wet
1995	4.8	12.39	Wet
1996	2.76	5.16	Wet
1997	15.12	4.8	Wet
1998	4.32	7.01	Wet

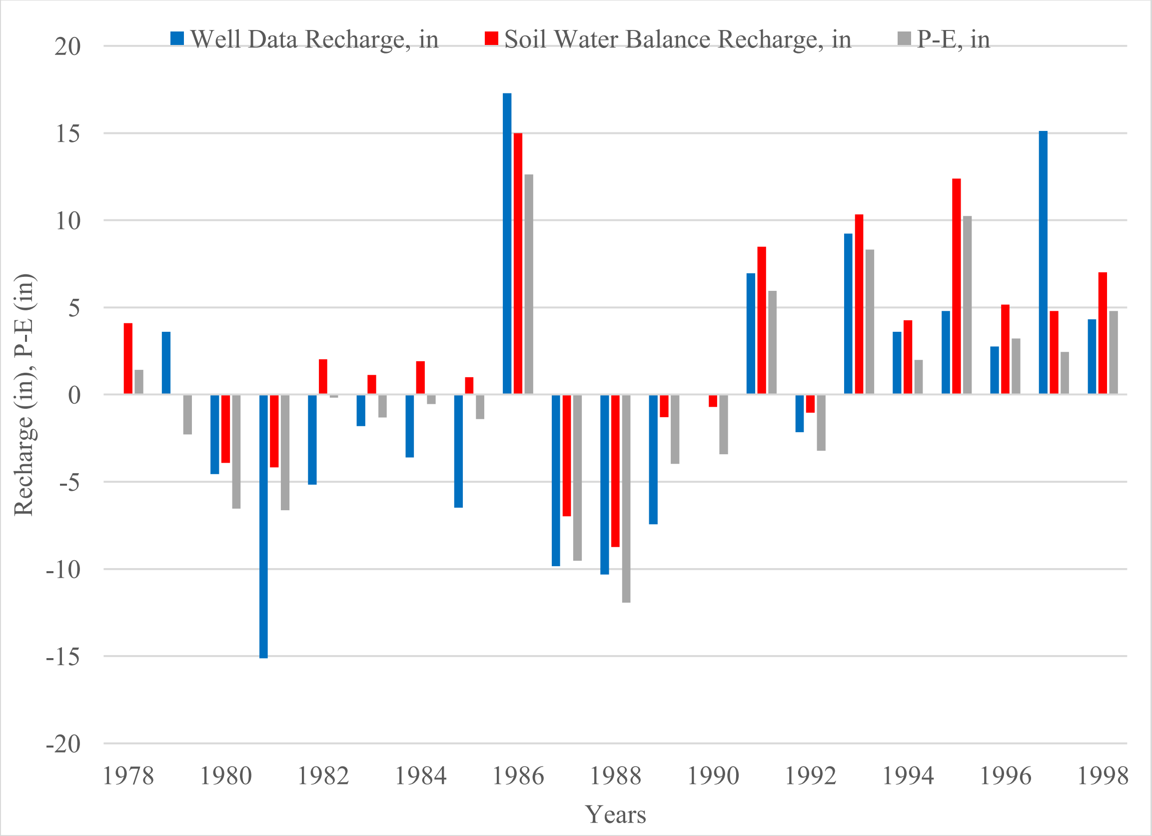

Figure 5.5 Comparison of recharge from soil water balance to the well level data method

Results of this method are valuable but there is uncertainty in the input data (precipitation and evapotranspiration) which would affect the calculated recharge. As noted earlier, when a small number of gauge represents a very large area the percentage of error as a result will be high. A disadvantage in the soil water balance method is that the evaporation data was for Brookings, SD and not Waubay Lakes Chain. Therefore, the evaporation data was not directly measured at the same location as the precipitation. The method may not be easily applied in some geographic areas due to a lack of evaporation data. Depending on the method used to calculate evaporation, the calculation of recharge would be affected.

5.3.Comparison Between Chaturvedi formula and Well Level Data Method

In Table 5.5 there were some similarities in the groundwater recharge values between the two methods. On the other hand, the minimum and maximum amount of recharge in both methods occurred in 1981 and 1986 respectively. According to wet and dry periods' data, 1986 was a wet year and 1981 was a dry year (Table 5.4). One of the biggest disadvantages in the Chaturvedi formula is that it does not consider either evaporation or evapotranspiration as a parameter in its equation. Therefore, if the amount of precipitation is less than 14 inches during the year, there is no result from the equation. In other words, this method would be more applicable in areas that have a small amount of evaporation that could be disregarded. Table 5.6 and Figure 5.6 show a correlation between the two methods for wet and dry periods.

Table 5.6 Groundwater recharge for Chaturvedi formula and the well level data method

Water year	Well Level Data Recharge, in.	Chaturvedi Formula Recharge, in.	Wet, Dry, Normal
1978	unknown	4.66	Wet
1979	3.6	2.77	Dry
1980	-4.56	2.33	Dry
1981	-15.12	1.49	Dry
1982	-5.16	3	Normal
1983	-1.8	3.39	Dry
1984	-3.6	3.69	Normal
1985	-6.48	3.3	Dry
1986	17.28	6	Wet
1987	-9.84	Not Defined	Dry
1988	-10.32	2.61	Dry
1989	-7.44	3.48	Dry
1990	0	3.64	Dry
1991	6.96	5.24	Wet
1992	-2.16	1.78	Dry
1993	9.24	4.6	Wet
1994	3.6	3.74	Wet
1995	4.8	5.24	Wet
1996	2.76	3.17	Wet
1997	15.12	4.06	Wet
1998	4.32	4.34	Wet

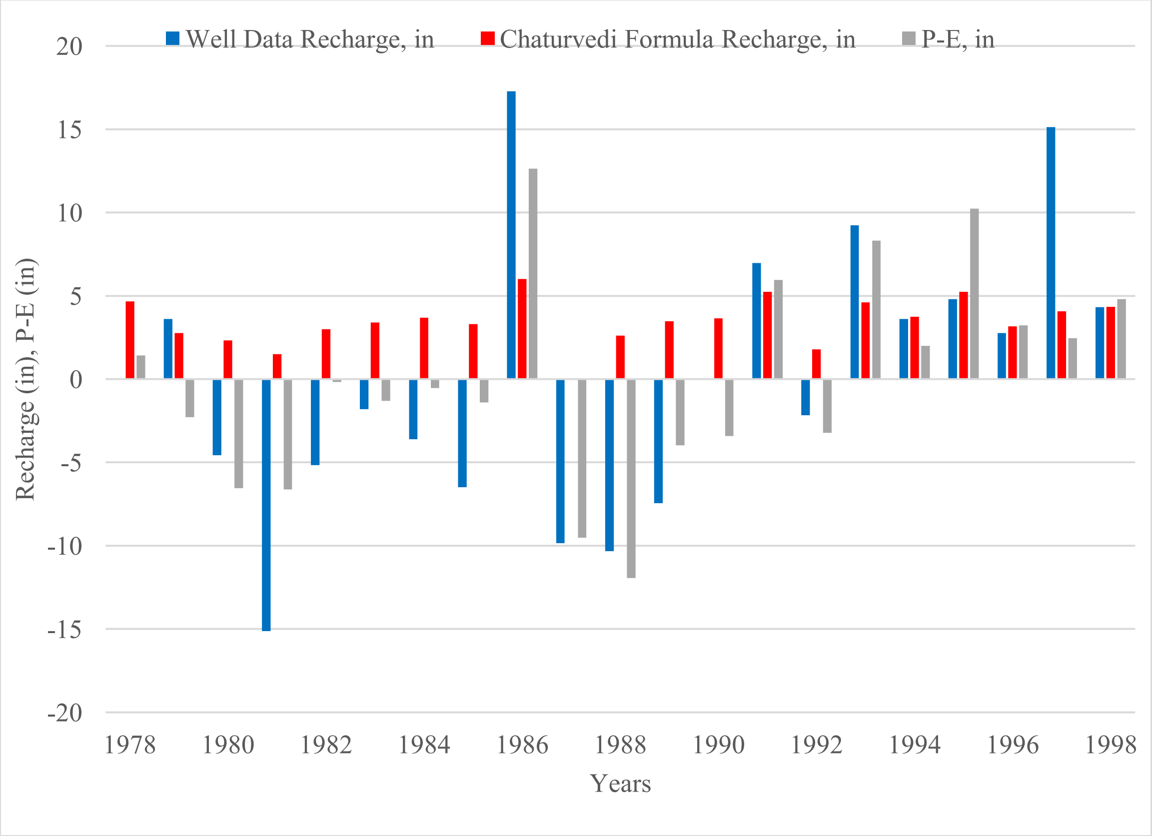

Figure 5.6 Comparison of recharge from Chaturvedi formula to the well level data method

5.4.Comparison Between Meyboom Method and Well Level Data Method

The Meyboom method is only applicable to streamflow records of catchments where regulation and diversion of flow are disregarded. Flow as total ground-water discharge can be based on previous recession while surface runoff is negligible (Chen and Lee 2003). The Meyboom method is the least accurate method since it gives the average of groundwater recharge for five years.

In this comparison, the estimate of the groundwater recharge for the well level data method is calculated for every five years, so it can be compared with Meyboom method results, and is shown in Table 5.7 and Figured 5.7.

Table 5.7 Groundwater recharge for Meyboom method and the well level data method

Water Year	Meyboom Recharge, in.	Estimate Well Level Data Recharge, in.	Wet, Dry, Normal, in.
1978-1982	15.11	-21.24	Dry
1983-1987	0.59	-4.44	Normal
1988-1992	11.49	-12.96	Dry
1993-1997	90.49	35.52	Wet

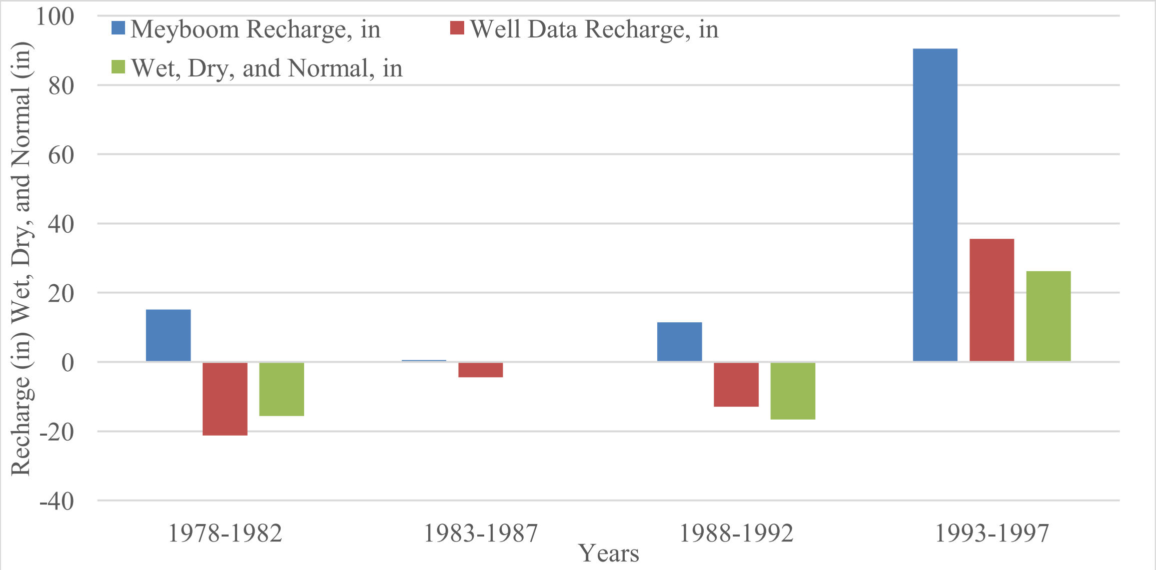

Figure 5.7 Comparison between groundwater recharge using Meyboom method to cumulative groundwater recharge using well level data method

5.5.Comparison of the final results for each method

The recharge calculated from the Chaturvedi formula tends to be much smaller than the other methods. On the other hand, the Meyboom method results tend to be much larger. In addition, these two methods cannot calculate negative values for groundwater recharge. (See Table 5.8 and Figure 5.8)

Table 5.8 The statistical values of the final results for the estimated recharge for each method

Method	Average, in.	Standard Deviation, in.	Maximum, in.	Minimum, in.
Soil Water Balance	2.42	6.08	14.99	-8.74
Chaturvedi Formula	3.63	1.16	6.00	1.49
Meyboom (annual)	5.88	7.32	18.09	0.11
Well Level Data	0.06	8.38	17.28	-15.12

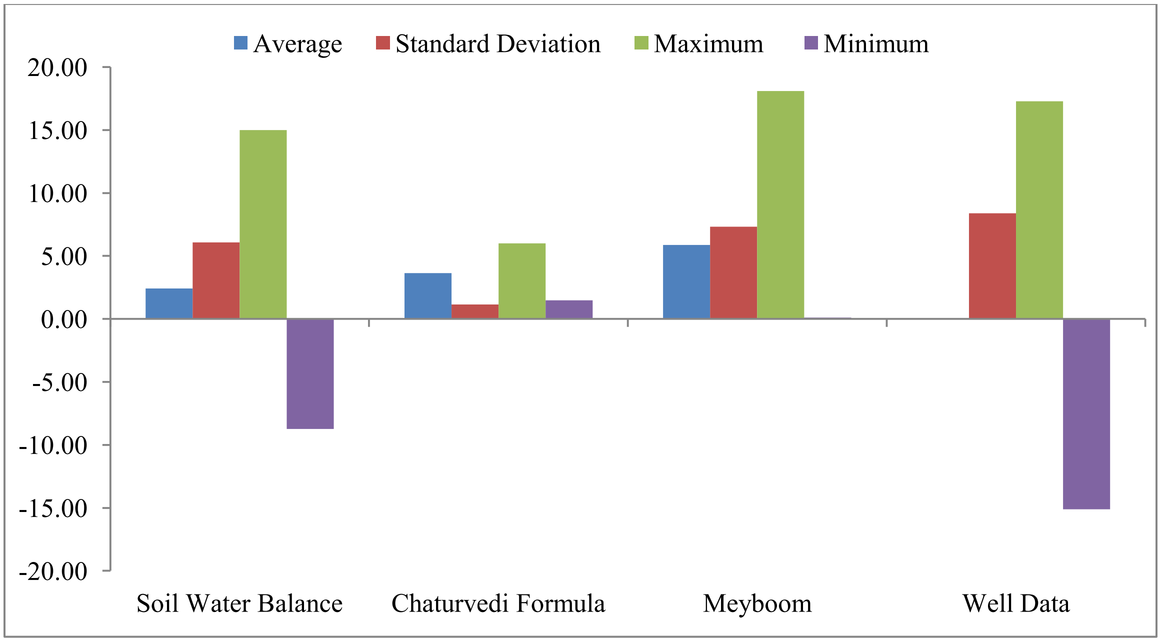

Figure 5.8 Comparing the statistical values of the final results for the estimated groundwater recharge for each method

The soil water balance and the well level data gave the best estimate for recharge while the Meyboom method was the least accurate method.

Chapter 6: Summary and Conclusion

For a sub humid continental climate region, the most useful method would be the well level data and the soil water balance comes as a second option. Although the soil water balance has a limited functional value, the groundwater recharge for a region can be estimated. However, the well level data should be applied on the same region in order to give more accurate estimation.

On the other hand, the Chaturvedi formula appears to be more accurate if used in regions where climate is tropical. As a result, the Chaturvedi formula results were less accurate than the soil water balance and the well level data method since the climate in study area was sub humid continental. Likewise, the accuracy of the Meyboom method results was weak for two reasons: the method estimates the average of groundwater recharge for five years and it cannot calculate a negative number.

In conclusion, even though the well level data has lack of data in some months, yet it is the most direct method for assessing of what recharge is. Based on the final results from the four methods, the soil water balance method and the well level data method appeared to be the best fit.

Chapter 7: Recommendation and Future work

This thesis presented an estimation of the groundwater recharge using four different methods in Waubay Lakes Chain in South Dakota. Some of the methods could be applied in the future for other locations in South Dakota in order to assist in the management of groundwater resources. Hence, following work could be suggested for the future work:

a) The four methods should be checked in other climate regions.

b) Check multiple methods of estimating evapotranspiration to better characterize recharge calculation.

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Appendices

Appendix A: Data Used

Table A1 Precipitation data, in inches (Niehus et al. 1999)

Water year	October	November	December	January	February	March	April	May	June	July	August	September
1978	2.40	2.35	0.67	0.25	0.16	0.39	2.13	3.15	5.97	3.45	4.30	0.72
1979	0.67	0.56	0.32	0.86	0.24	1.53	2.02	1.45	3.87	3.11	3.27	0.32
1980	1.95	0.06	0.14	0.86	0.57	0.50	0.31	1.35	4.40	2.24	4.25	0.34
1981	1.47	0.00	0.04	0.03	1.02	1.34	0.68	1.75	3.39	2.10	2.35	1.05
1982	2.37	0.78	0.33	0.63	0.23	1.14	0.55	2.63	1.04	3.71	1.98	3.55
1983	3.45	0.49	0.02	0.20	0.46	1.82	0.55	1.06	2.55	3.59	4.14	1.99
1984	0.91	1.39	0.35	0.45	0.56	1.10	2.76	1.32	6.82	1.45	3.13	1.22
1985	3.76	0.06	0.54	0.20	0.15	0.85	0.66	2.36	2.14	2.60	3.89	2.78
1986	1.78	1.66	0.39	0.34	0.75	0.51	5.54	3.42	4.13	7.32	3.43	4.47
1987	0.30	0.48	0.00	0.15	0.98	1.90	0.00	1.63	0.86	3.63	1.34	1.75
1988	0.31	0.60	0.18	0.34	0.23	0.28	0.39	4.03	1.04	1.19	5.96	3.19
1989	0.28	0.95	0.48	0.51	0.45	1.69	3.19	1.63	1.58	2.15	4.85	2.89
1990	0.40	0.66	0.00	0.00	0.28	1.78	1.69	1.74	4.09	3.27	5.81	1.56
1991	0.82	0.00	0.56	0.15	0.63	0.69	4.16	5.40	6.75	3.63	3.08	3.20
1992	0.59	0.57	0.08	0.35	0.40	0.87	0.89	0.60	6.21	2.38	1.15	1.65
1993	0.48	1.17	0.49	0.54	0.30	0.81	1.74	2.72	5.83	9.06	1.28	1.17
1994	0.49	2.05	0.76	1.43	0.85	0.30	2.28	2.46	1.11	6.28	2.52	1.16
1995	3.08	0.73	0.27	1.18	0.60	2.46	2.25	2.90	2.71	5.13	4.25	3.49
1996	2.51	0.20	0.36	0.83	0.36	0.66	0.19	4.32	2.60	3.14	0.94	3.42
1997	3.94	0.99	1.12	1.60	0.31	0.65	1.81	1.49	1.68	5.71	2.89	0.84
1998	2.35	0.59	0.49	1.25	1.11	1.10	4.16	5.42	3.00	1.97	2.66	0.22

Table A2 Evaporation data, in inches (Niehus et al. 1999)

Water year	October	November	December	January	February	March	April	May	June	July	August	September
1978	3.01	0.97	0.50	0.29	0.55	1.41	2.81	4.24	5.16	5.51	5.28	4.24
1979	2.86	0.92	0.47	0.25	0.48	1.23	2.45	3.70	4.50	4.80	4.61	3.69
1980	2.49	0.81	0.41	0.28	0.55	1.40	2.79	4.21	5.12	5.46	5.24	4.20
1981	2.84	0.92	0.47	0.26	0.51	1.30	2.58	3.89	4.74	5.05	4.85	3.89
1982	2.62	0.85	0.44	0.24	0.46	1.18	2.35	3.55	4.32	4.60	4.42	3.54
1983	2.39	0.77	0.40	0.27	0.51	1.32	2.62	3.96	4.82	5.14	4.93	3.95
1984	2.67	0.86	0.44	0.27	0.51	1.32	2.62	3.95	4.81	5.13	4.92	3.95
1985	2.66	0.86	0.44	0.26	0.50	1.29	2.56	3.87	4.71	5.02	4.82	3.86
1986	2.61	0.84	0.43	0.26	0.50	1.28	2.54	3.84	4.67	4.98	4.78	3.83
1987	2.59	0.84	0.43	0.27	0.53	1.35	2.68	4.05	4.93	5.25	5.04	4.04
1988	2.73	0.88	0.45	0.34	0.66	1.68	3.34	5.04	6.14	6.55	6.28	5.04
1989	3.40	1.10	0.56	0.28	0.54	1.39	2.77	4.17	5.08	5.42	5.20	4.17
1990	2.81	0.91	0.47	0.29	0.56	1.43	2.86	4.31	5.25	5.59	5.37	4.30
1991	2.91	0.94	0.48	0.27	0.53	1.35	2.69	4.06	4.95	5.27	5.06	4.06
1992	2.74	0.89	0.45	0.24	0.45	1.17	2.32	3.50	4.26	4.54	4.36	3.50
1993	2.36	0.76	0.39	0.22	0.43	1.11	2.21	3.34	4.07	4.34	4.16	3.34
1994	2.25	0.73	0.37	0.25	0.48	1.23	2.46	3.71	4.52	4.82	4.62	3.71
1995	2.50	0.81	0.41	0.24	0.46	1.17	2.34	3.53	4.30	4.58	4.40	3.52
1996	2.38	0.77	0.39	0.21	0.42	1.06	2.12	3.20	3.89	4.15	3.98	3.19
1997	2.15	0.70	0.36	0.26	0.50	1.28	2.56	3.86	4.70	5.01	4.80	3.85
1998	2.60	0.84	0.43	0.24	0.47	1.20	2.39	3.61	4.40	4.69	4.50	3.61

Table A3 Evapotranspiration data, in inches

Water Year	October	November	December	January	February	March	April	May	June	July	August	September
1978	2.74	0.97	0.50	0.29	0.55	1.41	2.11	3.65	4.75	5.18	4.86	3.90
1979	2.60	0.92	0.47	0.25	0.48	1.23	1.84	3.18	4.14	4.51	4.24	3.39
1980	2.27	0.81	0.41	0.28	0.55	1.40	2.09	3.62	4.71	5.13	4.82	3.86
1981	2.58	0.92	0.47	0.26	0.51	1.30	1.94	3.35	4.36	4.75	4.46	3.58
1982	2.38	0.85	0.44	0.24	0.46	1.18	1.76	3.05	3.97	4.32	4.07	3.26
1983	2.17	0.77	0.40	0.27	0.51	1.32	1.97	3.41	4.43	4.83	4.54	3.63
1984	2.43	0.86	0.44	0.27	0.51	1.32	1.97	3.40	4.43	4.82	4.53	3.63
1985	2.42	0.86	0.44	0.26	0.50	1.29	1.92	3.33	4.33	4.72	4.43	3.55
1986	2.38	0.84	0.43	0.26	0.50	1.28	1.91	3.30	4.30	4.68	4.40	3.52
1987	2.36	0.84	0.43	0.27	0.53	1.35	2.01	3.48	4.54	4.94	4.64	3.72
1988	2.48	0.88	0.45	0.34	0.66	1.68	2.51	4.33	5.65	6.16	5.78	4.64
1989	3.09	1.10	0.56	0.28	0.54	1.39	2.08	3.59	4.67	5.09	4.78	3.84
1990	2.56	0.91	0.47	0.29	0.56	1.43	2.15	3.71	4.83	5.25	4.94	3.96
1991	2.65	0.94	0.48	0.27	0.53	1.35	2.02	3.49	4.55	4.95	4.66	3.74
1992	2.49	0.89	0.45	0.24	0.45	1.17	1.74	3.01	3.92	4.27	4.01	3.22
1993	2.15	0.76	0.39	0.22	0.43	1.11	1.66	2.87	3.74	4.08	3.83	3.07
1994	2.05	0.73	0.37	0.25	0.48	1.23	1.85	3.19	4.16	4.53	4.25	3.41
1995	2.28	0.81	0.41	0.24	0.46	1.17	1.76	3.04	3.96	4.31	4.05	3.24
1996	2.17	0.77	0.39	0.21	0.42	1.06	1.59	2.75	3.58	3.90	3.66	2.93
1997	1.96	0.70	0.36	0.26	0.50	1.28	1.92	3.32	4.32	4.71	4.42	3.54
1998	2.37	0.84	0.43	0.24	0.47	1.20	1.79	3.10	4.05	4.41	4.14	3.32

Table A4 Discharge data, in cubic feet per second USGS (2016)

Water Year	October	November	December	January	February	March	April	May	June	July	August	September
1978	2.64	2.11	0.98	0.00	0.00	35.60	398.90	44.70	53.10	11.90	40.50	7.64
1979	3.68	11.50	3.11	1.11	0.00	56.00	28.60	10.50	34.00	4.76	1.32	0.44
1980	0.15	0.55	0.57	0.14	6.22	5.09	4.66	0.58	8.82	0.28	0.04	0.12
1981	0.12	0.26	0.07	0.00	0.86	17.10	36.50	13.50	12.00	0.45	0.15	0.03
1982	1.16	1.13	0.54	0.07	0.26	3.03	50.30	12.90	2.35	18.20	1.15	0.78
1983	1.46	6.16	1.33	0.69	36.70	156.80	123.00	41.10	154.90	14.50	5.83	1.49
1984	18.90	15.80	6.34	2.17	10.30	277.70	42.10	32.50	5.58	27.20	4.57	34.30
1985	18.10	8.03	3.09	2.21	0.72	320.90	403.00	170.30	120.60	27.40	32.10	49.60
1986	33.00	19.00	10.60	6.81	8.45	110.50	66.00	17.40	7.56	3.75	3.81	2.88
1987	2.06	2.81	2.74	0.20	0.97	28.80	10.30	8.56	1.32	0.10	0.18	0.06
1988	0.03	0.10	0.34	0.32	0.30	144.60	37.70	21.70	2.81	0.50	0.22	0.59
1989	0.42	1.05	0.54	0.00	0.00	2.67	2.95	9.52	11.20	3.08	1.85	1.35
1990	0.93	0.89	0.89	0.06	0.03	2.22	11.50	29.10	156.70	111.20	120.20	21.20
1991	7.61	9.45	5.52	3.53	10.60	46.60	35.80	16.60	63.30	91.90	8.67	16.80
1992	4.18	11.30	7.45	2.34	3.48	187.00	182.70	60.70	93.50	467.30	67.50	30.20
1993	20.50	17.30	18.40	10.20	10.40	310.50	130.90	94.10	139.20	166.50	39.20	27.50
1994	32.00	28.20	15.00	8.24	7.20	282.60	305.90	290.00	183.70	289.70	190.40	124.80
1995	221.30	155.40	55.70	26.50	22.90	281.00	214.90	264.70	111.50	41.30	26.20	12.20
1996	19.50	20.00	7.73	4.07	4.38	9.97	1415.00	275.50	60.70	30.90	19.20	13.30
1997	19.20	19.30	16.30	9.41	120.20	121.50	227.70	189.70	73.50	44.50	25.10	7.53
1998	101.00	72.90	40.80	11.50	33.40	92.20	95.90	69.00	44.60	16.50	3.97	4.83

Table A5 Water levels for a well, in feet

Water year	October	November	December	January	February	March	April	May	June	July	August	September
1978												33.70
1979	33.40	33.10						32.85	31.90	32.10	31.65	31.90
1980	31.40			31.00		30.80	30.90	33.10	33.00	34.40	33.75	33.30
1981	32.10		31.90			32.00	31.60	36.90	33.40	39.95	40.40	38.40
1982	35.70							33.95	34.25	37.25	40.95	37.85
1983	35.00				33.90		33.80	33.60	36.10	35.55	36.85	35.75
1984	35.10	34.80					34.00	33.80	34.05	37.55	39.77	36.60
1985	36.00							33.75	35.00	43.15	43.20	38.70
1986	37.40					34.00	33.60	32.40	32.05	30.97	30.30	30.20
1987	29.80						28.60	28.80	37.35	36.95	39.20	33.90
1988	32.60	31.30					30.20	35.00	35.77	43.60	41.20	36.90
1989	35.90						31.70	31.20	34.25	43.10	41.20	39.00
1990	35.20	33.80				31.70	31.60	31.60	31.35	37.45	38.75	35.20
1991	32.90					31.90		31.75	31.15	30.38	30.30	30.00
1992	29.80	29.70					29.90	33.30	32.10	30.80	31.20	30.70
1993	30.65	30.60					29.90	30.20	29.55	28.60	27.10	26.80
1994	27.20						25.80	25.40	27.00	29.05	26.65	25.70
1995	25.00						24.30	22.90	22.20	22.20	23.00	23.00
1996	23.00							21.50	20.90	21.05	21.20	21.85
1997	22.50								17.60	18.20	18.40	16.20
1998	17.80						16.20			15.13	20.40	16.00

Appendix B: Additional Figures

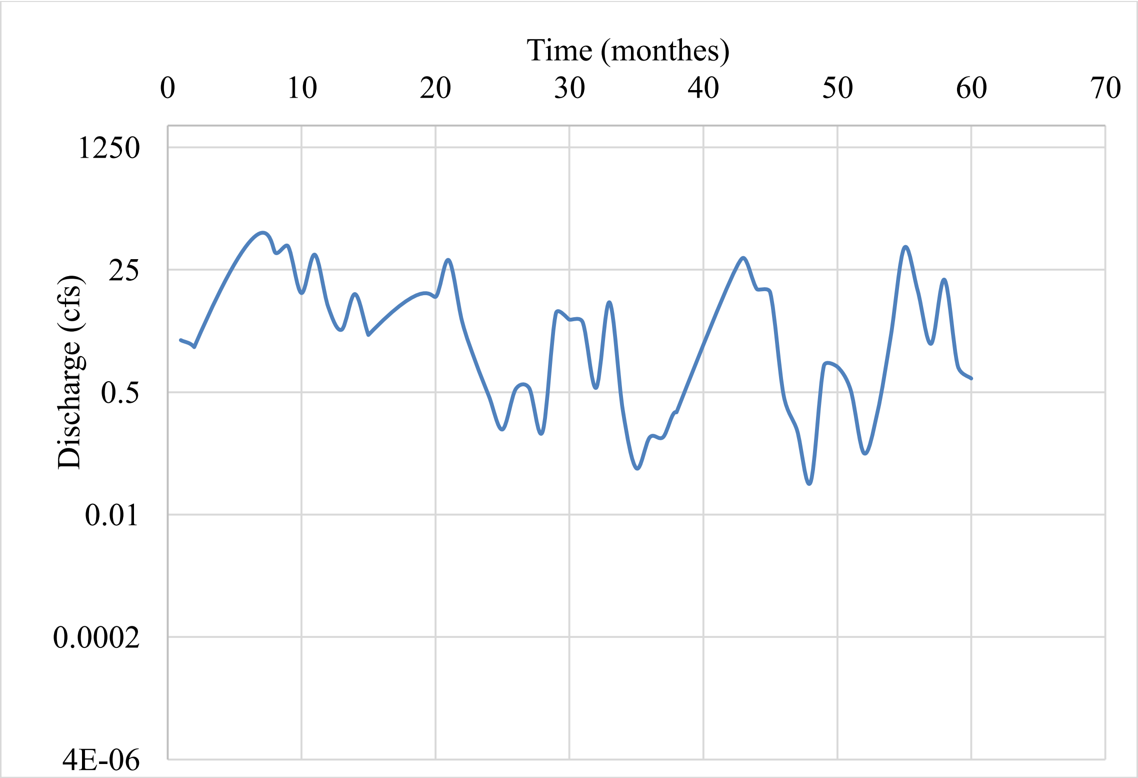

Figure B1 Streamflow data for 1978-1982.

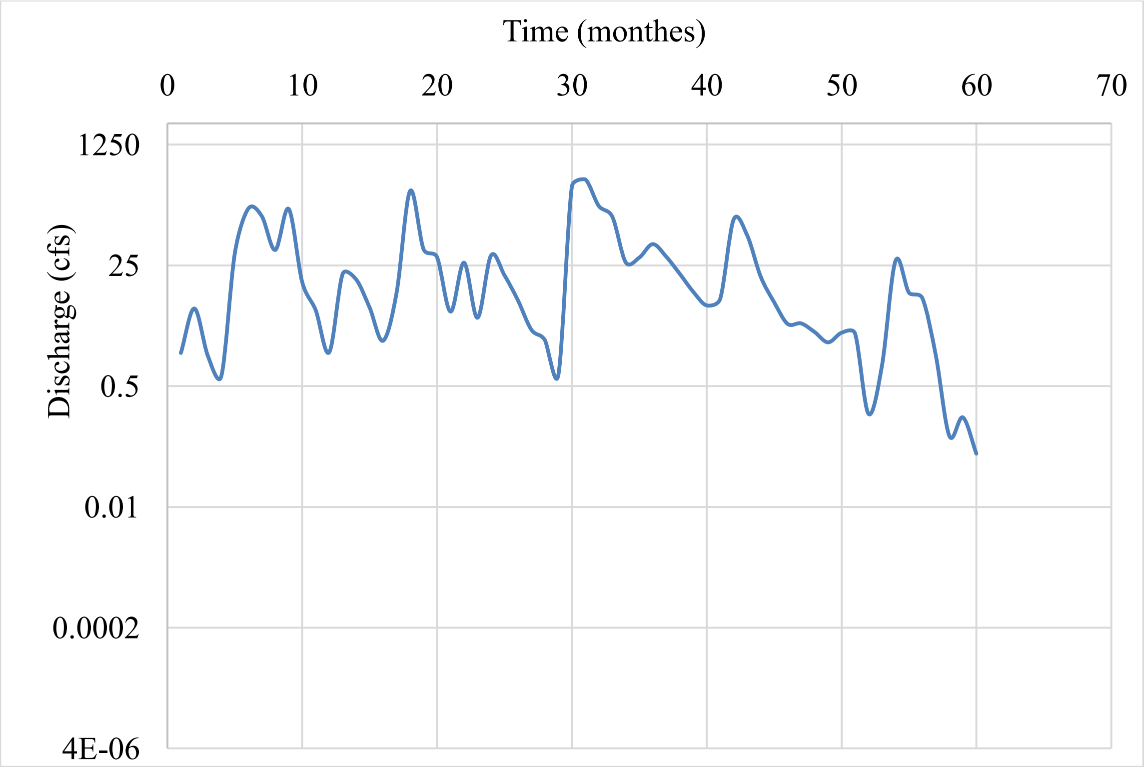

Figure B2 Streamflow data for 1983-1987.

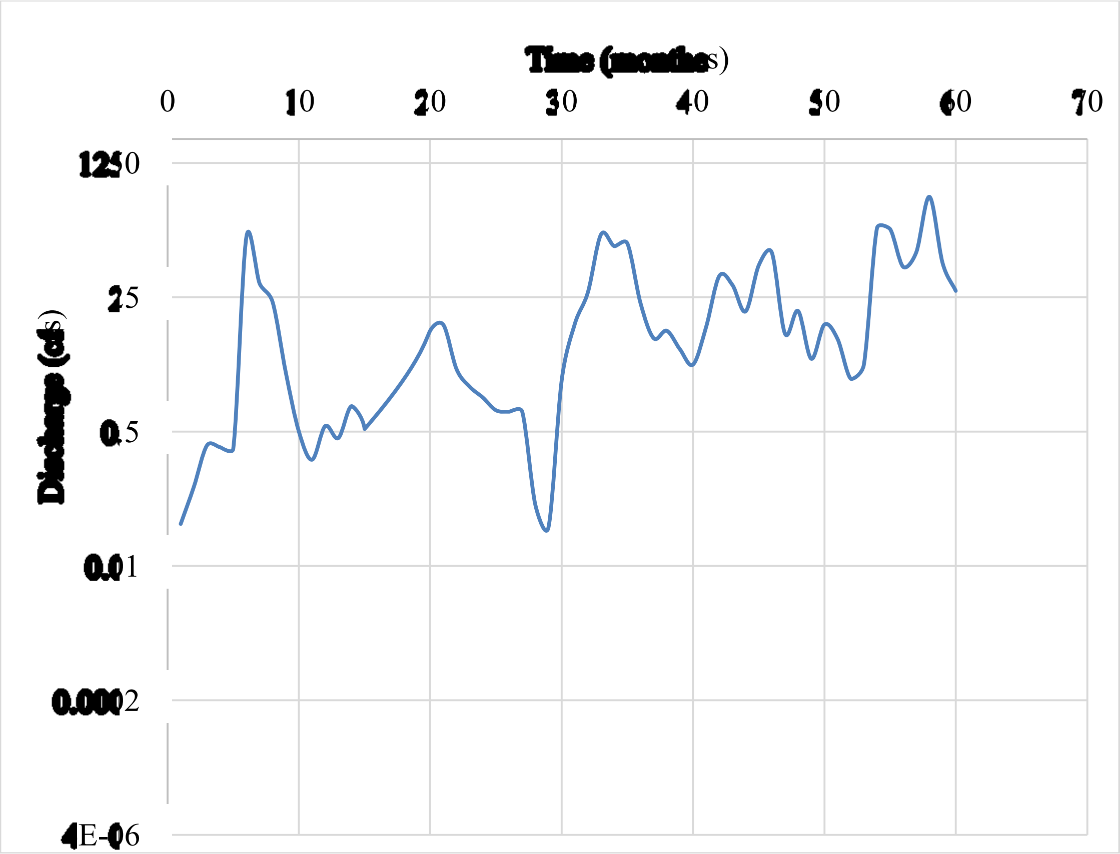

Figure B3 Streamflow data for 1988-1992.

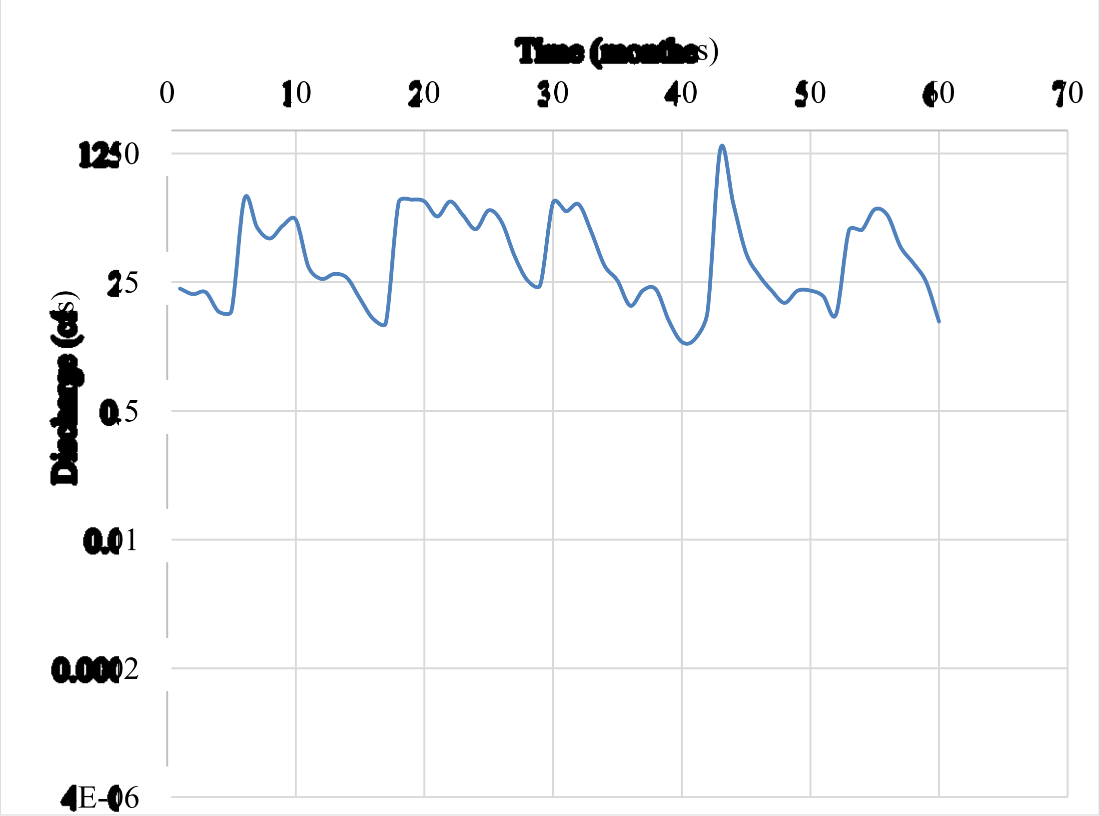

Figure B4 Streamflow data for 1993-1997.

Appendix C: Tables

Table C1 Effective Rooting Depth of Mature Crops for Irrigation System Design. (Nyvall 2002)

Shallow 0.45 m (1.5 feet)	Medium Shallow 0.60 m (2 feet)	Medium Deep 0.90 m (3 feet)	Deep 1.20 m (4 feet)
Cabbages Cauliflower Cucumbers Lettuce Onions Radishes Turnips	Beans Beets Blueberries Broccoli Carrots Celery Potatoes Peas Strawberries Tomatoes Tree Fruits (spacing 1m x 3m)	Brussels Sprouts Corn (sweet) Eggplant Kiwifruit Peppers Squash Saskatoon Tree Fruits (spacing 2m x 4m)	Asparagus Blackberries Grapes Loganberries Raspberries Sugar Beets Tree Fruits (spacing 4m x 6m)

Table C2 A guide to available water storage capacities of soils. (Nyvall 2002)

Textural Class	Available Water Storage Capacity (in. water / in. soil)	Available Water Storage Capacity (in. water / ft. soil)	Available Water Storage Capacity (mm water / m soil)
Clay	0.21	2.5	200
Clay Loam	0.21	2.5	200
Silt loam	0.21	2.5	208
Clay loam	0.20	2.4	200
Loam	0.18	2.1	175
Fine sandy loam	0.14	1.7	142
Sandy loam	0.12	1.5	125
Loamy sand	0.10	1.2	100
Sand	0.08	1.0	83