Estimating Renewable Water Flux Using Landscape Features

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Heidi Marie Peterson

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Dedication

To my husband and best friend, Joel; although I am sure there were other things you wanted to do besides proofreading papers, tutoring me in Visual Basic Programming or babysitting, you stood by my side and encouraged me to achieve my goal even through sacrifice. Without you I would not have had the confidence to move forward.

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Abstract

The complexity of vadose zone, groundwater and surface water interactions presents hydrological research challenges specifically in the area of quantifying groundwater recharge. To acknowledge unity of the surface and groundwater systems requires an interdisciplinary approach that organizes knowledge about an analysis domain based on hydrologic units rather than on aquifers, enabling an integrative, system viewpoint of the terrestrial hydrologic system. By establishing the relationship between landscape components and water balance characteristics, hydrologic response units are established. This dissertation hypothesizes that regionalization can identify hierarchical hydrogeological units (HHUs) composed of unique combinations of surface water, groundwater and vadose zone landscape characteristics with statistically different recharge rates ($p<0.05$), and that these units can be used to estimate the renewable water flux of the groundwater system. Three interdependent studies were pursued to address the hypothesis:

(i) a statewide regionalization of mean annual streamflow that defined independent hydrologic regimes within Minnesota;

(ii) a regionalization focusing on East Central Minnesota which established unique HHUs based on unique combinations of landscape characteristics with statistically significant differences in mean minimum recharge;

(iii) a water management application which used the regionalization methodology to quantify the renewable groundwater flux and assess a water resources sustainability indicator within the Twin Cities Metropolitan Area.

Results from the three studies indicate that landscape characteristics control the rate of

renewable water flux within the groundwater system. The results identified at one analysis scale could be used to extrapolate data at refined scales where long-term hydrologic monitoring data is lacking but informed water management decisions are crucial for the sustainable future of freshwater resources. Within the state of Minnesota, five hydrologic regimes were identified, each with varying inter- and intra-annual flow characteristics. Kendall-tau results suggest that mean annual streamflow within the regimes is either increasing or remaining stable. Focusing on a smaller, regional analysis territory within East-Central Minnesota, regionalization using the Watershed Characteristics Approach (WCA) identified HHUs composed of unique combinations of hydrogeologic characteristics, bedrock material, Quaternary thickness, topography and available water capacity. These HHUs and their corresponding minimum monthly recharge rates represent the renewable groundwater flux. HHUs previously identified within the Twin Cities Metropolitan Area (TCMA) were used together with water use estimates to calculate the sustainability indicator for each community within the TCMA. Although the WCA has few assumptions, limitations of the methodology include that the hierarchical refinement is based on the availability of streamflow data, and the accuracy of the estimated recharge rates associated with each HHU is pre-determined by the resolution of spatial landscape attribute data. Future research should further evaluate the defined HHUs to confirm that they are consistent for all five of the hydrologic regimes identified within Minnesota.

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Chapter 1

Introduction: Quantifying the Renewable Flux

Defining and measuring sustainability is a major challenge confronting science (Loucks et al., 2000; Alley and Leake, 2004; Heintz, 2004; Lant, 2004; Jabareen, 2007). The term originated in the field of ecology, referring to an ecosystem's potential for subsisting over time, with little alteration (Jabareen, 2007). The Brundtland Commission offered the popular definition of sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). To operationalize the definition to reflect water resources sustainability, it must encompass a multi-scale perspective – global, statewide and local- and include all future generations. Genuine sustainability requires that consumption by humans and ecological services will not cause a decline or depletion of freshwater resources (Kanivetsky and Shmagin, 2005).

When assessing sustainability, focus should be put on quantifying recharge (Devlin and Sophocleous, 2005) rather than on assessing how much water is stored within the system. This is because recharge provides an estimate of the system's renewable flux, which represents the sustainable freshwater resource. To maintain sustainability, a key principle is that for any given territory the natural renewable flux of water should not be exceeded by the sum of the uses for human needs and the requirements for sustaining the existing ecological services.

Recharge varies across the landscape because controlling factors, including precipitation, soil and geology, vegetation and land use, topography and land form and depth to groundwater, vary in nature and size, which makes finding ways to estimate and predict this variability a major problem in recharge assessments (Lerner et al., 1990;

Devlin and Sophocleous, 2005). A systematic approach must be used to quantify recharge based on these underlying, interdisciplinary controlling factors, which begins with good conceptualization of different recharge mechanisms and their importance in the study territory (Sophocleous, 2002). The recharge mechanism at a particular location can depend on a variety of factors, which may be different from the influencing factors elsewhere, which is why it must be analyzed both spatially and temporally.

A reductionist paradigm focusing on small-scale processes and relying on calibration has dominated hydrological science for the past 30 years (Beven, 2000; Kirchner, 2003; Sivapalan, 2005; McDonnell et al., 2007). Sustainable water management requires recognition of system interconnections operating at multi-scales, along with the dynamic nature of the process interactions. To move in this direction, the heterogeneity that exists within the hydrologic system must be identified and then the controlling landscape components comprising the entire terrestrial system need to be characterized. The lack of holistic process theory development has limited the formulation of alternative hypotheses to advance catchment hydrology; there is a need for a classification system based on a set of predictor variables and governed by the understanding of underlying process controls to help recognize data patterns (Sivapalan, 2005).

This dissertation hypothesizes that regionalization can be applied to identify hierarchical hydrogeological units (HHUs) composed of unique combinations of surface water, groundwater and vadose zone landscape characteristics with statistically different recharge rates ($p<0.05$), which could then be used to estimate the renewable water flux of the groundwater system. Three interdependent studies were pursued to address the hypothesis and illustrate how it could be used to address sustainable water management: (i) a statewide regionalization of mean annual streamflow which defined independent hydrologic regimes within Minnesota, (ii) a regionalization focusing on East Central Minnesota (ECM) which established unique HHUs based on unique combinations of landscape characteristics with statistically significant differences in mean minimum recharge and (iii) a water management application which used the regionalization methodology to quantify the renewable groundwater flux and assess a water resources sustainability indicator within the Twin Cities Metropolitan Area (TCMA).

Chapter 2

Hydrologic Regionalization to Assess Anthropogenic Changes

2.1 Introduction

Land use change, including agricultural management, urbanization and timber harvesting, has historically responded to economic development and government incentives. These changes continue to progress and will likely accelerate to satisfy demands of an increasing global population. Research has focused on the link between vegetative cover, hydrologic processes and water quality; however, the consequence of anthropogenic land use change on hydrology has received minimal attention (DeFries and Eshleman, 2004).

The effects of these anthropogenic land use changes can be examined using a hydrologic systems analysis. This holistic approach looks at data from a broad sense and refines results to represent a specific homogeneous response unit. It promotes multi-scale and interdisciplinary research and produces results which could be applied to multiple study areas. Although numerous examples exist on the complex behavior of hydrology, catchment hydrology continues to be operating under a reductionist paradigm (Sivapalan, 2005). While it is important to understand processes occurring at a fine scale, a holistic system approach is necessary to advance research and address today's most perplexing water resources problems; specifically those attributed to anthropogenic changes.

The holistic theory of hydrology requires that actual predictions be based or conditioned on observations at the catchment scale to identify the influence of the underlying spatial heterogeneities in landscape properties (Winter, 2001; Wolock et al., 2004; Sivapalan, 2005; McDonnell et al., 2007; Troch et al., 2008). While the complexity and differences between catchments can be overwhelming, it has been hypothesized that there are distinct underlying structures shared between catchments; identification and characterization of such structures can lead to the development of hydrologic relationships between structural characteristics and hydrologic response that have general applicability for hydrologic prediction (Wagener et al., 2007). Identifying and characterizing the shared structures through a system analysis provides insight for further investigation necessary at more local levels to address specific water management related issues.

Watersheds are "self-organizing" systems, whose characteristics result from adaptive ecological, geomorphic, and land-forming processes; therefore, they produce geometric patterns valuable to hydrologic analysis and predictions (Sivapalan, 2005). By identifying these patterns through an initial regionalization using mean annual streamflow time-series data for watersheds extending across a large area, hydrologic regimes, each composed of watersheds with common hydrologic controlling characteristic structures, have been identified (Bartlein, 1982; Lins, 1985; 1997; Sophocleous, 1992; Diekrüger et al., 1999; Maurer et al., 2004; Shmagin and Kanivetsky, 2006; Kahya et. al., 2008). To fully understand the hydrologic system, further analyses could then focus on the set of watersheds defined by each regime to identify the dominant controlling structure(s) and advance the understanding of the connections between structure(s) and hydrologic response. For example, recharge varies spatially because the controlling structure, including precipitation, soil and geology, vegetation and land use, topography, land form and depth to groundwater, vary in nature and size (Lerner et al., 1990).

Previous research in Minnesota has indicated that, on a statewide scale, streamflow characteristics are correlated to hydrogeological units (Shmagin and

Kanivetsky, 2002). These units are stationary landscape characteristics which do not change with time. Those characteristics which may change with time include drainage management, vegetation/land cover and precipitation. As stated by Johnston and Shmagin (2008), before one can evaluate the impact of future climate change or land use change on streamflow, it is necessary to first understand past spatio-temporal patterns of streamflow variability and their relationship to hydrogeological landscape characteristics.

To recognize the geographic variations in streamflow across Minnesota, this chapter describes how by applying factor analysis techniques to complete a statewide regionalization for Minnesota and adjacent areas, five regimes with unique hydrologic signatures were identified. A trend analysis of each regime was completed and the hydrologic signature variation identified within each regime was determined to correspond to ongoing climatic and anthropogenic changes.

2.2 Regionalization

2.2.1 Watershed Delineation

United States Geological Survey (USGS) gauging station locations and mean annual streamflow data for 129 sites throughout Minnesota and surrounding states were downloaded from the USGS Water Data for the Nation website (http://waterdata.usgs.gov/nwis). Gauging station data in the United States is generally considered to be accurate to ±5% (Rantz, 1982). Data was sorted and 69 sites were selected for further analysis based on consistent, consecutive available annual data. Three analysis periods were chosen based on the time intervals with the greatest number of watersheds with available data. These intervals are discussed further in the Results and Discussion, section 2.4. To identify possible anthropogenic influences on streamflow characteristics, the objective was to select two slightly overlapping intervals; one initiating prior to the major human-induced land use alterations including the switch from mixed crop (perennials, row crops) agriculture to primarily row crop agriculture and associated enhanced land drainage, and the second beginning later to capture any resulting effects on streamflow. The third interval combines the two shorter intervals into one extended analysis period.

The latitudinal and longitudinal coordinates for each gauging station were georeferenced in ArcGIS®, a Geographic Information System (GIS). Using Arc Hydro (Maidment, 2002), a GIS mapping plug-in software for water resources, along with NHDPlus data (http://nhd.usgs.gov/index.html), an integrated suite of application-ready geospatial data sets available through the USGS and U.S. Environmental Protection Agency (EPA), watershed boundaries were delineated for each gauging station using raster analysis (Figure 2.1).

2.2.2 Multivariate Statistical Analysis

Multivariate statistical analysis is commonly used to perform streamflow regionalization (Bartlein, 1982; Lins, 1985, 1997; Sophocleous, 1992; Maurer, et. al., 2004; Shmagin and Kanivetsky, 2006; Johnston and Shmagin, 2008; Kahya, et. al., 2008). It explains correlations in a large set of variables by reducing the number of underlying independent components or variables. In these studies regions containing watersheds manifesting similar behavior were delineated. The hydrologic regimes within each of these regions had distinct patterns of seasonality and persistence (Lins, 1985, 1997; Kahya et. al., 2008).

Bartlein (1982) used a principal components analysis and approximately 20 years of monthly flow records from 102 streams to create a streamflow regionalization map for the United States. Roughly 75% of the total variance of mean monthly flow was accounted for by 24 components. When the analysis was completed by rotating the components, 18 regions (hydrologic regimes) were identified. A strong relationship existed between these large scale hydrologic regimes and the climatic anomalies identified across the United States and southern Canada.

Since there was a large dataset available for our analysis, the hydrologic regionalization of Minnesota watersheds was performed using a factor analysis within the Statistica® software (StatSoft, 2011). Factor analysis is a multivariate analysis technique used for data reduction by minimizing the number of variables and detecting latent structure in the relationships between variables (classifying variables) (Thurstone, 1931; StatSoft, 2011). It is used to study the patterns of relationships amongst many dependent variables, with the goal of discovering something about the nature of the independent variables that affect them, even though those independent variables may not be directly measured. In a previous study, factor analysis was used to define five regions within the U.S. Great Lakes Basin with statistically distinct stream discharge patterns (Johnston and Shmagin, 2008).

When a factor analysis is performed, the correlation between two or more variables is summarized in a scatterplot. This correlation is called the factor load. A regression line with the maximum variance is then fit to represent a linear relationship between the variables. For the Minnesota regionalization, the variables summarized in the factor analysis were each watershed's mean annual streamflow. After this first factor has been identified, additional lines are drawn to maximize the remaining variability in a consecutive step-by-step extraction of factors. Variance maximizing rotation is the method used in the process of extracting each consecutive factor. The Kaiser criterion is the most widely used method to evaluate the maximum number of factors (i.e. linear combinations) to extract from the dataset (Kaiser, 1960). This criterion requires that factors are retained only if their associated eigenvalues are greater than one. The watersheds with the highest factor loadings within each separate factor will likely share a common characteristic or combination of characteristics. These factor loadings are the correlation coefficients between the variables (each watershed) and factors (hydrologic regimes).

During a factor analysis, factor scores, which are linear combinations of all of the original variables (each watershed) used in making the new factor, are also calculated. This is the score of each observation (mean annual streamflow data) on the newly identified factors, and is a linear combination of all of the original variables that were relevant in making the new factor (hydrologic regime). Analyzing and/or plotting factor scores can enable each factor's variation to be clearly expressed (Hair et al., 1992).

Using this factor analysis technique with the mean annual streamflow time-series data from the delineated Minnesota watersheds, factor loadings were recorded for each watershed and viewed digitally within the GIS to spatially define hydrologic regimes. The advantage of representing data within a GIS framework is the ability to display and analyze information within a geospatial context (Strassberg et al., 2007). Physically-based models using GIS are powerful tools for addressing the complexity of hydrological processes and basin wide characteristics (De Smedt and Batelaan, 2003). This facilitates the process of identifying how the hydrologic data are spatially distributed and related (Mutua and Klik, 2007).

To identify intra-annual streamflow periods within the hydrologic regimes defined by the Minnesota factor analysis, the watershed with the highest factor load within each initial factor (regime) was further analyzed using an additional factor analysis consisting of mean monthly streamflow data. In this case the variables were the twelve months for each year; resulting in factors representing periods of similar intra-annual flow response for each previously defined hydrologic regime.

2.2.3 Trend Analysis

To avoid assuming the probability distribution of the variables used throughout the analysis, a nonparametric Kendall Tau correlation test served as the statistical basis for all trend analyses. This test can be used to indicate the likelihood of an increasing or decreasing trend over time and is effective for identifying trends in streamflow because extreme values and skewness in the data have little effect on the outcome (Helsel and

Hirsch, 2002). For this study a trend was considered to be significant if the probability (p) value of the test was less than or equal to 0.05; which represents a 95-percent confidence level (Kendall and Gibbons, 1990).

In addition to the Kendall Tau test, the slope of the linear trend line was used as a measure of the magnitude of the streamflow trend. For this analysis the factor scores from each defined regime were used to compare the direction of the trend between factors (i.e. streamflow regimes).

There are four statistically detectable climatic trends which vary across the state of Minnesota including warmer winters, higher minimum temperatures, increased episodes of high summer dew points and greater annual precipitation –primarily as snowfall and thunderstorms (Seeley, 2006). To evaluate whether annual precipitation change was correlated to the streamflow trends between 1936 and 2008, a Kendall Tau trend test was used to evaluate annual precipitation falling within each watershed representing the strongest hydrologic signature of the corresponding regime, indicated by the largest factor load. In addition, an algorithm which signals the possibility of a regime shift in real time using a sequential t-test (Rodionov, 2004) was applied to the total annual precipitation to detect if a trend shift occurred. Precipitation data for the climate divisions overlapping each watershed was obtained through the Western Region Climatic Center (http://www.wrcc.dri.edu/divisional.html). To address watersheds overlapping several climate divisions, annual precipitation for a watershed was calculated using an area weighted mean.

2.3 Results and Discussion

Sixty-nine of the 129 original watersheds were used for the analysis because they had an area between 460 to 22,000 km^2 and consecutive available mean annual flow data for the periods of 1936 through 2008 (32 watersheds), 1936 through 1980 (45 watersheds), or 1950 through 2008 (56 watersheds) (Table 2.1). If a watershed was missing one or two years of data, it was still used; however, the missing year was estimated as an average of all mean annual values for the time period of analysis. Eleven of the 69 watersheds were missing at least one year of data, two of which were missing data for two years.

2.3.1 Analysis Period 1936 through 2008

This analysis period was the longest interval used in the study. Five factors were identified based on the number of eigenvalues of the correlation matrix greater than one (Table 2.2). These 5 factors account for 85% of the total variance of the mean annual flow data among the watersheds.

As previously discussed, a varimax normalized rotation is used because it makes identifying correlated variables (watersheds) more apparent within each factor; the higher the loading, the stronger the correlation (Table 2.3). By plotting each watershed's factor loadings onto a 3-dimensional scatterplot representing Factors 1 through 3, it appears that using a cut-off of 0.60 creates a clustering break of variables within each of the five factors (Figure 2.2). It is important to remember that the factors are uncorrelated since an orthogonal rotation was used. The factor loadings greater than 0.60 are shown in bold font in Table 2.3, and the watersheds associated with factors that have bold factor loadings are shown on Figure 2.3. By mapping out the spatial location of the watersheds with the highest factor loading, visual boundaries of five streamflow regimes are distinguished.

Factor scores are summarized in Table 2.4 with the corresponding time series plotted as Figure 2.4. To illustrate the relationship that the factor scores have with the mean annual streamflow and precipitation, Figure 2.5 includes the mean annual streamflow time series plot for each watershed with the highest factor loading for each corresponding factor and Figure 2.6 is the corresponding total annual precipitation. The linear trend line is included on each graph of the figures. The factor score provides a dimensionless plot of the mean annual streamflow.

The general shape of the linear trend lines, as well as the occurrences of peak and minimum flows, is consistent between the factor score and flow values. By using the factor scores, if monitoring at a specific gauge ceased, the corresponding streamflow could be estimated. To illustrate this estimation, mean annual flow was calculated for USGS stream gauge 5130500, Sturgeon River near Chisholm, Minnesota, using the factor scores from the northeast regime. This gauging station was not used to derive this set of factor scores; however, it falls geographically within the spatial boundary of the regime. A regression equation with an r–squared of 0.73 was developed using solely the first ten years of available mean annual streamflow data (1943 through 1952) together with the corresponding factor scores (equation 2.1). This equation was then used to calculate the mean annual flow for the period of 1943 through 2008 using the corresponding factor scores.

$$\text{Mean Annual Flow}_{\text{Year}} = (31.46) * (\text{Factor Score}_{\text{Year}}) + 113.79 \qquad \textbf{(2.1)}$$

Comparing the estimated and the actual mean annual flow for the 1943 through 2008 interval, the resulting r–squared was 0.64 with a $p<0.05$. Review of Figure 2.7 illustrates that the prediction capability weakens in the late 1980s; and as expected since they are based on the same set of factor scores, this prediction capability also deteriorates for the watershed with the highest factor loading for the regime (USGS gauge 5127500). Further analysis of the residuals from USGS gauge 5130500 using a 10-year moving average indicates that after 1992 the regression begins to significantly underestimate the flow ($p<0.05$). A comparison of aerial photos and land cover data for the watershed shows that coniferous forest harvesting within the watershed, specifically immediately adjacent to streams and rivers, increased after 1990 leaving behind only young stands and brush. Harvesting timber from an area will lead to a decrease in evapotranspiration, thereby leading to increases in streamflow. This decrease can be temporary if the same tree type is regenerated on the harvested site, or it can be permanent if a different species of tree or a non-woody plant is established on the site (Swank and Miner, 1968; Swank and Douglas, 1974; Verry, 1986). The deviation from the predicted regression equation may be attributable to the harvesting activity in that watershed.

2.3.2 Analysis Period 1936 through 1980

A factor analysis was completed using data up through 1980 to determine whether more recent anthropogenic influences (1981 through 2008) have altered mean annual flow within the watersheds enough to change factor loadings for the watersheds, thereby potentially redefining the composition of the five hydrologic regimes.

This factor analysis also led to the identification of five factors, accounting for 83% of the total variance of mean annual streamflow between watersheds (Table 2.5). The factor loadings for this analysis are summarized in Table 2.6, with those greater than 0.60 shown in bold font. Watersheds associated with factors that have bold factor loadings are shown on Figure 2.8. Similar to what was shown in Figure 2.3, by mapping out the spatial location of the watersheds with the highest factor loading, visual boundaries of five streamflow regimes are distinguished.

2.3.3 Analysis Period 1950 through 2008

The largest number of variables (watersheds) with available streamflow data was identified for the time period of 1950 through 2008. Using this expanded dataset resulting from using streamflow data available after 1950 for a third factor analysis and comparing these results to the 1936 through 1980 and 1936 through 2008 analyses, hydrologic regime variations occurring from climatic or anthropogenic changes may be identified.

This factor analysis also led to the identification of five factors accounting for 84% of the total variance of mean annual streamflow between watersheds (Table 2.7). The identified factor loadings are summarized in Table 2.8, with factor loadings greater than 0.60 shown in bold font. The watersheds associated with factors that have bold factor loadings are shown on Figure 2.9. Again, mapping out the spatial location of the watersheds with the highest factor loading, provides visible boundaries of five streamflow regimes.

2.3.4 Temporal Variation

In this analysis the streamflow trends were related to land use management changes and changes in annual precipitation. The five streamflow regimes of Minnesota defined by the factor analysis results will be referred to as northwest, northeast, west central, east central, and southern.

Using the watersheds representing the strongest hydrologic signature of each defined hydrologic regime for the period of 1936 through 2008, precipitation trends were compared to the corresponding streamflow trend using results of Kendall Tau tests. These watersheds are from Table 2.3: southern regime (Factor 1) - 6606600, Little Sioux River at Correctionville, Iowa; northeast regime (Factor 2) - 5127500, Basswood River near Winton, Minnesota; northwest regime (Factor 3) - 5066500, Goose River at Hillsboro, North Dakota; east central regime (Factor 4) - 5356000, Chippewa River at Bishops Bridge near Winter, Wisconsin; and west central regime (Factor 5) - 5291000, Whetstone River near Big Stone City, South Dakota.

For all five watersheds, using the entire 1936 to 2008 analysis interval, there was a correlation between annual precipitation and mean annual streamflow ($p<0.01$). However, an increasing precipitation trend at the $p<0.05$ significance level was only observed for the northwest ($p=0.00$) and west central ($p=0.04$) regimes. Using a regime shift tool (Rodionov, 2004), a shift increase was detected in 1991 in the 20-year moving average (p=0.00) for the total annual precipitation in both the northwest (48.0 cm to 57 cm) and west central regimes (51.3 cm to 61.5 cm). Streamflow at USGS gauge 5066500, located in the northwest regime, had two shift increases detected, in 1965 (p=0.01) from 0.99 $m^3 s^{-1}$ to 2.54 $m^3 s^{-1}$ and in 1993 (p=0.00) from 2.54 $m^3 s^{-1}$ to 5.82 $m^3 s^{-1}$.

Although precipitation increased significantly in the west central regime, Kendall Tau streamflow results within corresponding USGS gauge 5291000 did not show a trend increase at the p<0.05 level (p=0.11). However, a 20-year moving average shift increase in mean annual streamflow was detected in 1993 (p=0.00) from 1.35 $m^3 s^{-1}$ to 2.81 $m^3 s^{-1}$. Although a shift in the annual precipitation variance was not detected within this watershed, there was a shift in 1983 in the mean annual streamflow variance (p=0.01).

Streamflow at USGS gauge 6606600, located in the southern regime, increased (p=0.00) while the increasing precipitation trend was not significant at the p<0.05 level (p=0.07). There was a shift increase detected in 1982 in the 20-year moving average (p=0.02) for the total annual precipitation from 70.0 cm to 76.8 cm. A shift in the mean annual flow was also detected at that same time (p=0.00) from 20.6 $m^3 s^{-1}$ to 34.5 $m^3 s^{-1}$. Although a shift in the annual precipitation variance was not detected, there was a shift in 1993 in the mean annual streamflow variance (p=0.00). Change in streamflow variability has been attributed to land use in a previous Minnesota study (Novotny and Stefan, 2007).

The annual factor scores for each of the three analyzed time periods were compared using the slope of the linear trend line (Table 2.9) and results from a Kendall Tau test for each period (Table 2.10). The streamflow trend results observed within each of the five regimes as displayed in Table 2.9 are consistent with results found by Novotny and Stefan (2007), which focused on streamflow in Minnesota as an indicator of climate change.

While reviewing Table 2.9, it is important to remember that the use of factor scores provides a dimensionless or standardized view of the streamflow data. This allows an analysis of an entire regime instead of each watershed individually. The factor score is a linear combination of all of the original variables (mean annual streamflow for each individual watershed) that were relevant in making the new factor. Therefore, scores are scaled so that they have a mean of zero. A score greater than +1.00 corresponds to a year with an unusually high mean annual streamflow while a score less than -1.00 corresponds to a year with an unusually low mean annual streamflow. Since each watershed has a specific factor loading value, the actual change in flow will vary between watersheds falling within each regime.

The northeast regime showed a decreasing streamflow trend during the period of 1936 through 2008, though the Kendall Tau test indicated the trend was not significant at the $p<0.05$ level. The watersheds of northeast Minnesota are predominantly forested (Figure 2.10). The slope of the factor score changed only slightly, with an increase of 0.001 between 1936 through 1980 and 1950 through 2008. This is the smallest change observed within any of the five regimes.

The east central regime also showed a decreasing streamflow trend during 1936 through 2008; although like the northeast, the Kendall Tau test indicated the trend was not significant at the $p<0.05$ level. The slope of the streamflow trend in east central

Minnesota (northwestern Wisconsin) began to decrease more rapidly during the 1950 through 2008 period. With the growth and development of the dense forests and undercover, runoff from forestland tends to decrease. During the 1930s, tree planting was initiated in this regime by the Civilian Conservation Corps to restore the cleared land which had previously been pine barrens; eventually the land developed into dense forests (Radeloff et al., 2000). Today most of the historic pine barrens are pine plantations and open expanses are rare (Niemuth and Boyce, 1998).

The northwest, west central and southern regimes each showed an increasing streamflow trend; however, results of the Kendall Tau test indicated that this trend was only significant at the $p<0.05$ level for the northwest and southern regimes. Within the northwest, the positive trend in the factor scores dropped 0.014 during the period 1950 through 2008 in comparison to the positive trend for the period 1936 through 1980. In contrast, the positive trends increased for west central and southern Minnesota for the period 1950 through 2008 relative to the period 1936 through 1980. We postulate that after 1985, when conservation was introduced into the Farm Bill, highly erodible fields which were previously planted to row crop in the northwest regime enrolled into federal conservation or wetland reserve programs, which reduced the effect of agricultural runoff. Data available through the United States Department of Agriculture National Agricultural Statistics Service (USDA-NASS; http://www.nass.usda.gov/) for the eastern agricultural regions of North Dakota and the northwest agricultural region of Minnesota, collectively comprising the northwest hydrologic regime, indicated that between 1997 to 2007 (period of available data) total land area enrolled into reserve programs increased by more than 62% or approximately 3,500 km^2. Compared to the west central and southern regimes, the northwest regime has the most land area enrolled in conservation reserve programs.

Due to a shift away from livestock programs, land cover is changing in the northwest regime from pasture and hay to rotational crops such as corn and soybean (Peel, 1998). This land use change can lead to increased baseflow (Schilling and Libra, 2003; Zhang and Schilling, 2006; Schilling and Helmer, 2008a). Using data available through the USDA-NASS (http://www.nass.usda.gov/) for the northwest region of Minnesota, Kendall Tau test results indicated that between 1972 and 2009 the total area planted to corn (p=0.00) and soybean (p=0.00) increased significantly while the total area planted to wheat decreased (p=0.02). These trends are depicted in Figure 2.11.

When mean annual streamflow data for the watershed representing the strongest hydrologic signature of the northwest regime (USGS gauge 5066500) was compared against the annual total area planted corn, soybean or wheat between 1936 to 2008, Kendall Tau results indicated that streamflow has increased significantly as the area planted to soybean (p=0.01) increased. The correlations to corn (p=0.06) and wheat (p=0.98) were not at the $p<0.05$ significance level. In 1936 there was no land area recorded as utilized by soybean crops; however, in 2008 approximately 30% of the area was devoted to soybeans. Research has found that switching from corn and wheat rotations to soybean rotations tend to have the greatest influence on increased runoff rates (O’neal et al., 2005; Schilling et al., 2008). Although much attention has been given to climate change, it has been suggested that the impacts of land use change will exceed those of climate change, specifically in the conversion of *blue water* (e.g. aquifers, rivers, lakes and dams) to *green water* (e.g. atmospheric and soil moisture) (FAO, 1995; Falkenmark, 2006; Stonestrom et al., 2009). Not only does this include land use, but also land management (Potter, 1991; Bhaduri et al., 2000; DeFries and Eshleman, 2004).

In the west central and southern regimes, the rate at which the streamflow is increasing has also increased between the years 1950 through 2008 relative to the period 1936 through 1980. This area is predominantly agricultural and the use of tile drainage is common, which can increase baseflow (Schilling and Helmer, 2008a; 2008b). Looking at the changes in trends between time intervals and also the Kendall's Tau coefficient, the rate of increase between 1936 through 1980 and 1950 through 2008 is higher for the west central and southern regimes in comparison to the northwest. The primary difference is that the use of tile drainage is relatively rare in eastern North Dakota and northwest Minnesota; although very recently the use of tiling has begun to increase in the Red River Valley area (Sugg, 2007). In contrast, by the early 1990's tile-drained land area in some counties within the southern regime was estimated as high as 88% (Sugg, 2007). A study focusing on watersheds which fall within the west central and southern regime indicated that seasonal discharge to precipitation ratios have significantly increased during low flow seasons indicating a contribution other than precipitation (Lenhart et al., 2011).

2.3.5 Intra-Annual Variability

To identify the intra-annual streamflow variations within each of the five previously defined hydrologic regimes, a second factor analysis was completed using each regime's representative watershed and the mean monthly streamflow data for every year between 1936 to 2008 (n=73). Within each of the newly defined factors, the months with a factor loading greater than 0.60 tend to be correlated and have similar streamflow characteristics throughout the analysis period. Results highlighting which months comprised each intra-annual streamflow period for the five regimes are summarized in Table 2.11. The season explaining the greatest total variance was different for each regime.

Focusing on the mean monthly flow of the watershed representing the northeast regime (USGS gauge 5127500), indicated that there are four distinct flow periods within this forested regime (Table 2.11). Review of mean monthly streamflow data indicated that over the analysis period, the highest mean monthly flows occurred between May and July with May typically highest (105.2 $m^3 s^{-1}$). Low flow occurred between January and March, with the lowest mean monthly flow typically in March (16.0 $m^3 s^{-1}$).

Results focusing on the watershed representing the east central regime (USGS gauge 5356000) indicated that there are also four distinct intra-annual flow periods within this currently forested regime. Lowest mean monthly flows occur between March and April, but like the northeast regime, March typically has the lowest mean monthly streamflow (12.9 $m^3 s^{-1}$). Using mean monthly streamflow for the entire 1936 through 2008 period, December flow is the highest (28.5 $m^3 s^{-1}$) and appears to be unique compared to the other 11 months. Breaking the interval into two time intervals focusing on prior to and after 1980, December (31.0 $m^3 s^{-1}$) mean monthly flow was highest prior to 1980, whereas after 1980 mean monthly flow shifted and became highest in May (28.1

$m^3\ s^{-1}$). This concentration of streamflow further into spring could possibly reflect the response to the recovering coniferous forests within the watersheds constituting that regime; snow melt often occurs further into spring months as forest canopies become denser (Verry, 1986). These variations may also explain why the months explaining the greatest variance in seasonal streamflow differ from the forested, northeast regime.

Results focusing on the watersheds representing the northwest (USGS gauge 5066500), west central (USGS gauge 5291000) and southern (USGS gauge 6606600) regimes indicated three distinct intra-annual flow periods with lowest mean monthly flow in January (0.19 $m^3\ s^{-1}$, 0.21 $m^3\ s^{-1}$ and 6.8 $m^3\ s^{-1}$, respectively) and highest mean monthly flow in April (15.7 $m^3\ s^{-1}$, 6.8 $m^3\ s^{-1}$ and 60.1 $m^3\ s^{-1}$, respectively). The duration of each intra-annual flow period varied between the three regimes (Table 2.11).

For the northwest regime, although November through February tend to be lower mean monthly flow periods, streamflow in June has exhibited similar intra-annual patterns even though it is a month of higher streamflow. Mean monthly flow in west central Minnesota follows the same intra-annual flow pattern as the northwest regime, except that mean monthly flow in June is not grouped into an intra-annual flow period meaning that its flow has not been consistent each year during the analysis interval.

A difference in the southern regime from the northwest and west central regimes is represented by the months explaining the highest variance extracted as Factor 1. For the northwest and west central regimes the late summer and early fall months had the highest factor loadings; whereas the winter, low flow months, January through March, were first extracted for the southern regime. These are months which tend to receive minimal overland flow, subsurface drainage and water loss to evapotranspiration due to subfreezing temperatures (Zhang and Schilling, 2006; Schilling et al., 2008; Nangia et al., 2010). Flow during the months of September through December was extracted as the second factor, which defines the second distinct intra-annual streamflow period for the southern regime. The length of the highest intra-annual streamflow period for this regime, extracted as the third factor, includes April through August which varies from the northwest and west central regimes. Possible reasons for this difference in the intra-annual streamflow period should be further investigated.

2.3.6 Spatial Variation

If streamflow trends were solely dependent upon precipitation with all other watershed characteristics remaining constant, the clusters of watersheds comprising each factor would likely remain consistent between analysis intervals. The five defined regimes identified in this study correspond spatially to the statewide hydrogeologic units discussed by Shmagin and Kanivetsky (2002). Review of the three maps (Figures 2.3, 2.8 and 2.9) depicting the spatial location of the regimes enabled a comparison of temporal changes in streamflow with respect to apparent anthropogenic and climatic changes which have occurred during respective time periods.

The watersheds most likely influenced by changes in land management and/or land cover composition can be identified by comparing the 1936 through 1980 (Figure 2.8) and 1950 through 2008 (Figure 2.9) maps; the boundaries of the southern regime expand in the latter period. This regime had the greatest increase in the streamflow trend in the 1950 through 2008 analysis period. The hydrologic signature for five of the watersheds from the 1936 through 1980 west central regime shifts after 1950 making them instead fall within the southern regime during the 1950 through 2008 analysis period, which has a higher increasing flow rate trend. The location of the watersheds categorized into the northeast, east central and northwest regimes appear to remain relatively constant over the three analyzed time intervals. Apparently climatic or anthropogenic changes that have occurred within the geographical boundaries of those three regimes were either not sufficiently large to affect the hydrologic stability of the watersheds within the regimes, or the changes occurred evenly across the entire regime affecting all watersheds proportionally.

2.4 Conclusions

To evaluate the implications of future climate or land use change on hydrologic systems, it is first necessary to recognize spatial variations in stream runoff. A factor analysis of mean annual streamflow in Minnesota defined five hydrologic regimes for three analysis periods, 1936 through 2008, 1936 through 1980 and 1950 through 2008. These regimes are consistent with statewide hydrogeological units identified in earlier studies (Shmagin and Kanivetsky, 2002).

Depending on whether the regime was predominantly agricultural or forested land use, the hydrologic signature of the intra-annual streamflow varied between 3 or 4 flow periods, respectively. The number of months associated with each period varied among the regimes.

Although the spatial location of the regimes remained relatively consistent over the three analysis periods, the area of the southern hydrologic regime expanded during the most recent analysis period (1950 through 2008). Streamflow within five watersheds from the west central regime increased significantly making their hydrologic signature shift closer in character to that of the southern regime during the 1950 through 2008 period. If this shift was due solely to a precipitation increase, the hydrologic signature for the entire west central regime should have shifted similarly to what was observed in those five watersheds. This larger trend in streamflow may reflect the hydrologic impact of changes in land use management and/or land cover composition, similar to what has been shown by Schilling et al. (2008).

Overall, results of this study illustrate the importance of evaluating data using differing time intervals to identify possible influences in climate and/or land use changes on hydrologic regimes. It is known from plot, field and small watershed scale studies that changes in land use including vegetative cover management, land drainage, land irrigation, and development (residential/municipal/commercial/industrial) can all have measurable influences on hydrologic balances. Although changes in climate can affect hydrologic balances, specifically through changes in precipitation regime, our analysis of watershed flow regimes suggests the effect of land use/land cover change on watershed water balances should be the focus of additional regional scale analyses.

An additional future research need requires that the underlying landscape characteristics controlling each hydrologic regime be identified. This will enable more accurate prediction of the hydrologic response to future land use or climate change and provide insight to future hydrologic management implications.

Table 2.1 List of USGS gauging stations that were used for each analysis period

USGS Gauging Station	Delineated Drainage Area (km^2)	Analysis Period			USGS Gauging Station	Delineated Drainage Area (km^2)	Analysis Period		
		1936-1980	1936-2008	1950-2008			1936-1980	1936-2008	1950-2008
4010500	1576	•	•	•	5211000	8665	•	•	•
4024000	8834	•	•	•	5227500	15363			•
4027000	1546			•	5270500	2678	•		
4027500	705			•	5275000	1447	•		
5046000	4468	•	•	•	5280000	7128	•	•	•
5050000	3080			•	5286000	4017	•	•	•
5051500	10215			•	5291000	1046	•	•	•
5054000	17215	•	•	•	5292000	3001			•
5058000	10341			•	5294000	2239	•		
5059000	13932			•	5300000	2490	•		
5059500	14035	•	•	•	5304500	4862			•
5062000	2526	•	•	•	5311000	16152	•	•	•
5062500	2418	•			5313500	1720	•	•	•
5064000	4052			•	5315000	670			•
5066500	3199	•	•	•	5316500	1630	•	•	•
5069000	1087			•	5317000	3379	•	•	•
5074500	5233	•			5320000	6214			•
5075000	5901	•			5320500	2870			•
5076000	2553	•	•	•	5333500	3998	•		
5078500	3587	•	•	•	5340500	16183	•	•	•
5079000	13548	•	•	•	5356000	2029	•	•	•
5084000	1023			•	5356500	4240	•	•	•
5085000	1413			•	5374000	2969	•		

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Table 2.1 continued from previous page

USGS Gauging Station	Delineated Drainage Area (km^2)	Analysis Period			USGS Gauging Station	Delineated Drainage Area (km^2)	Analysis Period		
		1936-1980	1936-2008	1950-2008			1936-1980	1936-2008	1950-2008
5087500	661			•	5385000	3234	•		
5090000	1809	•	•	•	5421000	2724	•	•	•
5100000	5897	•	•	•	5457000	1034			•
5104500	1113			•	5458500	4331			•
5107500	2818	•			5459500	1323	•	•	•
5127000	3163	•	•	•	5476000	3229	•	•	•
5127500	3673	•	•	•	5479000	3326			•
5128000	7051	•	•	•	6481000	11297			•
5129000	1269	•			6483500	4108			•
5130500	467			•	6485500	21631	•	•	•
5131500	4346	•	•	•	6606600	6455	•	•	•
5132000	3841	•							

Table 2.2 Eigenvalue results for analysis period 1936 through 2008

	Eigenvalue	% Total Variance	Cumulative Eigenvalue	Cumulative % Variance
Factor 1	14.8	46.2	14.8	46.2
Factor 2	4.9	15.2	19.7	61.4
Factor 3	4.2	13.2	23.9	74.6
Factor 4	2.0	6.3	25.9	80.9
Factor 5	1.3	3.9	27.2	84.9

Table 2.3 Factor loadings for analysis period 1936 through 2008

USGS Gauging Station	Factor[a]				
	1	2	3	4	5
4010500	0.13	**0.90**	0.07	0.19	-0.07
4024000	0.18	**0.70**	0.28	0.45	0.19
5046000	0.21	0.04	**0.64**	0.19	0.51
5054000	0.33	0.02	**0.66**	0.04	0.58
5059500	0.34	0.07	**0.84**	-0.05	0.19
5062000	0.23	0.03	**0.69**	0.04	0.45
5066500	0.20	0.11	**0.87**	-0.08	0.09
5076000	0.07	0.22	**0.84**	0.16	0.08
5078500	0.04	0.38	**0.78**	0.16	0.27
5079000	0.05	0.30	**0.82**	0.24	0.19
5090000	0.09	0.16	**0.81**	-0.02	-0.17
5100000	0.15	-0.03	**0.79**	-0.01	0.03
5127000	0.06	**0.95**	0.08	0.16	0.03
5127500	0.10	**0.95**	0.13	0.14	0.04
5128000	0.09	**0.94**	0.14	0.14	0.04
5131500	0.04	**0.79**	0.38	0.12	0.16
5211000	0.05	0.41	**0.62**	0.32	0.35
5280000	0.55	0.03	0.23	0.51	0.47
5286000	0.19	0.23	0.17	**0.72**	0.41
5291000	0.43	0.15	0.26	0.08	**0.69**
5311000	0.48	0.08	0.39	0.23	**0.69**
5313500	**0.70**	0.07	0.13	0.21	0.58
5316500	**0.82**	0.03	0.18	0.16	0.44
5317000	**0.85**	0.08	0.18	0.18	0.36
5340500	0.21	0.36	0.12	**0.80**	0.32
5356000	0.18	0.24	0.02	**0.89**	-0.02
5356500	0.24	0.23	-0.01	**0.88**	-0.06
5421000	**0.83**	0.16	0.13	0.03	-0.14
5459500	**0.87**	0.09	0.21	0.18	-0.11
5476000	**0.90**	0.06	0.17	0.13	0.26
6485500	**0.83**	0.08	0.22	0.13	0.40
6606600	**0.91**	0.11	0.07	0.16	0.13

[a] *Loadings in bold are >0.60*

Table 2.4 Factor scores computed from 1936 through 2008 analysis

	Factor						Factor				
Year	1	2	3	4	5	Year	1	2	3	4	5
1936	-0.21	-0.23	-1.14	-0.51	-0.87	1972	-0.77	1.14	0.23	1.32	1.44
1937	-0.15	-0.10	-1.26	-1.21	-0.08	1973	0.31	-0.17	-0.88	1.43	-1.24
1938	-0.01	0.56	-1.14	0.15	-0.97	1974	-0.94	0.98	1.37	0.62	-1.25
1939	-0.50	-0.65	-1.22	1.20	-0.94	1975	-0.96	0.14	0.92	0.25	1.07
1940	-0.79	-0.49	-1.11	-1.03	-0.16	1976	-0.92	-0.49	-0.12	0.17	-0.64
1941	-0.38	-0.42	-0.45	0.66	-1.19	1977	-0.70	-1.19	-1.09	-1.12	-0.07
1942	0.21	-0.16	-0.15	1.20	-1.59	1978	-0.41	1.98	-0.16	-0.07	0.71
1943	-0.11	0.23	-0.12	0.50	0.28	1979	0.87	0.18	1.09	0.26	-0.75
1944	0.14	1.40	-1.07	0.42	0.67	1980	0.48	-1.25	-0.68	-0.67	-0.36
1945	-0.39	0.39	0.15	0.85	-0.39	1981	-0.43	0.49	-0.90	-0.07	-1.28
1946	-0.67	-0.43	-0.40	0.36	0.29	1982	-0.12	0.17	0.12	0.42	-0.49
1947	0.08	2.15	-0.58	-0.70	0.63	1983	2.53	0.60	-0.42	1.16	-1.70
1948	-0.44	0.51	0.35	-1.49	-0.17	1984	2.14	0.41	-1.14	0.63	0.85
1949	-0.31	-0.52	-0.04	-1.54	-0.31	1985	-0.24	-0.22	-0.05	1.48	2.03
1950	-1.23	2.44	2.76	-0.15	-1.69	1986	1.30	0.02	-0.23	2.18	2.66
1951	0.71	0.77	-0.36	0.89	-0.82	1987	0.27	-0.59	0.22	-1.18	0.37
1952	-0.16	0.39	-1.07	1.55	2.06	1988	-0.50	0.11	-0.99	-1.98	0.31
1953	-0.67	0.19	-1.01	0.72	1.44	1989	-0.93	1.04	-0.84	-1.64	0.94
1954	-0.96	0.88	-0.92	1.15	0.46	1990	-0.22	-0.06	-1.19	-1.17	0.05
1955	-0.92	-1.45	-0.21	0.92	-0.56	1991	0.66	-0.87	-1.26	1.01	-0.17
1956	-1.12	-0.16	0.08	0.00	-0.49	1992	0.77	-0.11	-0.67	0.98	-1.12
1957	-0.99	-0.02	-0.62	-0.49	1.68	1993	4.97	-0.24	-0.15	-0.65	-0.84
1958	-1.08	-1.63	-0.53	-0.31	0.82	1994	1.09	0.22	0.03	-0.58	1.42
1959	-0.52	-0.73	-0.65	-0.83	-0.65	1995	1.16	-1.76	1.65	0.39	0.00
1960	0.18	-0.70	-0.32	-0.01	-0.80	1996	-0.06	1.00	1.41	1.24	0.21
1961	-0.06	-0.80	-0.97	-0.75	-0.76	1997	0.84	-0.53	2.82	0.31	0.58
1962	0.40	0.15	0.60	-1.17	1.03	1998	0.14	-2.02	1.63	-0.46	0.34
1963	-0.41	-1.05	-0.30	-0.83	0.17	1999	0.45	0.76	2.42	-0.85	-0.56
1964	-0.84	0.16	-0.31	-1.45	0.06	2000	-0.66	-0.22	0.47	-1.13	0.66
1965	0.34	-0.02	0.61	0.20	-0.19	2001	0.93	0.95	1.34	-0.43	1.57
1966	-1.01	1.60	1.37	0.53	-0.18	2002	-0.73	-1.34	0.56	1.84	0.71
1967	-1.01	-0.87	0.84	1.23	-0.62	2003	-0.36	-2.09	-0.17	1.50	0.02
1968	-0.75	0.77	-0.51	0.14	-0.97	2004	0.27	-0.80	1.17	0.01	-2.12
1969	1.37	1.30	0.08	0.00	0.65	2005	-0.15	-0.80	2.26	-0.79	0.53
1970	-0.70	1.05	0.49	-1.25	-0.42	2006	0.79	-1.14	0.98	-0.48	0.88
1971	0.44	1.73	-0.57	-0.22	-1.12	2007	0.96	-1.91	0.72	-2.10	0.42
						2008	1.58	1.80	-0.99	-1.37	-0.58

Table 2.5 Eigenvalue results for analysis period 1936 through 1980

	Eigenvalue	% Total Variance	Cumulative Eigenvalue	Cumulative % Variance
Factor 1	22.3	49.6	22.3	49.6
Factor 2	6.4	14.2	28.7	63.8
Factor 3	3.6	7.9	32.3	71.7
Factor 4	2.8	6.1	35.0	77.8
Factor 5	2.3	5.2	37.3	83.0

Table 2.6 Factor loadings for analysis period 1936 through 1980

USGS Gauging Station	Factor[a]				
	1	2	3	4	5
4010500	0.28	0.13	0.29	0.17	**0.79**
4024000	0.34	0.28	0.53	0.04	**0.62**
5046000	**0.62**	0.37	0.51	0.04	0.00
5054000	**0.61**	**0.64**	0.26	0.13	0.09
5059500	**0.85**	0.20	0.03	0.11	0.26
5062000	**0.66**	0.40	0.24	-0.03	0.01
5062500	**0.80**	0.15	0.26	0.17	0.27
5066500	**0.78**	0.11	-0.08	0.05	0.34
5074500	**0.74**	0.19	0.21	0.19	0.02
5075000	**0.79**	0.17	0.21	0.19	0.05
5076000	**0.88**	0.09	-0.03	-0.05	0.20
5078500	**0.81**	0.29	0.13	0.05	0.29
5079000	**0.93**	0.19	0.12	0.11	0.17
5090000	**0.73**	-0.12	-0.11	0.00	0.36
5100000	**0.61**	-0.13	-0.03	0.24	0.32
5107500	**0.78**	-0.02	-0.03	0.03	0.37
5127000	0.33	0.23	0.30	0.07	**0.81**
5127500	0.40	0.20	0.29	0.09	**0.80**
5128000	0.43	0.19	0.27	0.10	**0.80**
5129000	0.40	0.23	0.18	0.16	**0.79**
5131500	0.56	0.25	0.05	0.08	**0.69**
5132000	**0.64**	0.32	0.09	0.14	0.51
5211000	**0.74**	0.31	0.41	0.13	0.14
5270500	0.29	**0.70**	0.50	0.08	0.07
5275000	0.29	**0.64**	0.55	0.19	0.21
5280000	0.31	**0.72**	0.43	0.13	0.08
5286000	0.31	0.49	**0.68**	0.13	0.21
5291000	0.15	**0.80**	0.20	0.06	0.18
5294000	0.48	**0.77**	0.27	0.11	0.04
5300000	0.11	**0.86**	0.19	0.07	0.27
5311000	0.26	**0.87**	0.33	0.05	0.09
5313500	0.03	**0.90**	0.08	0.15	0.12
5316500	0.08	**0.89**	-0.08	0.29	0.08
5317000	0.08	**0.77**	-0.11	0.48	0.19
5333500	0.03	0.24	**0.80**	0.16	0.26
5340500	0.23	0.37	**0.80**	0.11	0.31
5356000	-0.01	0.03	**0.80**	0.30	0.23
5356500	-0.03	0.01	**0.75**	0.45	0.23
5374000	0.15	0.12	0.39	**0.80**	0.08
5385000	0.12	0.03	0.39	**0.80**	0.01

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Table 2.6 continued from previous page

USGS Gauging Station	Factor[a]				
	1	2	3	4	5
5421000	0.15	0.33	0.08	**0.81**	0.17
5459500	0.21	0.31	0.14	**0.83**	0.05
5476000	0.09	**0.68**	-0.07	**0.61**	0.14
6485500	0.02	**0.77**	0.08	0.46	0.22
6606600	0.08	0.50	0.16	**0.75**	0.14

[a] *Loadings in bold are >0.60*

Table 2.7 Eigenvalue results for analysis period 1950 through 2008

	Eigenvalue	% Total Variance	Cumulative Eigenvalue	Cumulative % Variance
Factor 1	25.6	45.7	25.6	45.7
Factor 2	8.9	15.8	34.5	61.6
Factor 3	6.8	12.2	41.3	73.8
Factor 4	3.7	6.5	45.0	80.3
Factor 5	2.1	3.7	47.0	84.0

Table 2.8 Factor loadings for analysis period 1950 through 2008

USGS Gauging Station	Factor[a]				
	1	2	3	4	5
4010500	0.15	0.12	**0.87**	-0.09	0.25
4024000	0.17	0.30	**0.68**	0.20	0.49
4027000	0.17	-0.06	0.26	-0.07	**0.87**
4027500	0.07	-0.14	0.25	0.07	**0.83**
5046000	0.17	0.49	0.06	**0.64**	0.10
5050000	0.34	0.41	0.04	**0.76**	-0.05
5051500	0.28	0.47	0.07	**0.78**	0.02
5054000	0.25	0.52	0.04	**0.76**	-0.04
5058000	0.31	**0.84**	0.09	0.18	0.02
5059000	0.30	**0.83**	0.08	0.30	-0.02
5059500	0.31	**0.81**	0.06	0.34	-0.05
5062000	0.18	0.56	0.07	0.60	-0.09
5064000	0.14	**0.68**	0.08	0.48	0.01
5066500	0.16	**0.88**	0.10	0.24	-0.04
5069000	0.12	**0.81**	0.20	0.36	0.07
5076000	0.06	**0.79**	0.29	0.22	0.06
5078500	0.00	**0.72**	0.39	0.39	0.13
5079000	0.01	**0.76**	0.32	0.30	0.20
5084000	0.08	**0.86**	0.18	-0.09	0.10
5085000	0.03	**0.87**	0.17	-0.08	0.07
5087500	0.12	**0.78**	0.12	0.30	-0.11
5090000	0.06	**0.86**	0.12	-0.06	0.05
5100000	0.11	**0.77**	-0.06	0.18	0.00
5104500	-0.01	**0.67**	0.33	0.17	0.10
5127000	0.06	0.12	**0.91**	-0.04	0.25
5127500	0.11	0.16	**0.93**	-0.02	0.19
5128000	0.08	0.16	**0.92**	0.02	0.17
5130500	0.16	0.42	**0.79**	0.14	0.19
5131500	0.04	0.38	**0.82**	0.20	0.11
5211000	0.00	0.52	0.50	0.41	0.29
5227500	0.03	0.42	0.59	0.39	0.42
5280000	0.49	0.12	0.01	0.50	0.57
5286000	0.13	0.09	0.20	0.38	**0.73**
5291000	0.33	0.15	0.12	**0.79**	0.13
5292000	0.39	0.24	0.08	**0.79**	0.05
5304500	0.32	0.28	0.03	**0.74**	0.40
5311000	0.38	0.25	0.06	**0.79**	0.30
5313500	**0.61**	0.06	0.03	**0.62**	0.33
5315000	**0.76**	0.12	0.00	0.49	0.16
5316500	**0.76**	0.11	-0.03	0.49	0.25
5317000	**0.79**	0.13	0.02	0.45	0.24

Continued on next page

Table 2.8 continued from previous page

USGS Gauging Station	Factor[a]				
	1	2	3	4	5
5320000	**0.92**	0.14	0.05	0.21	0.14
5320500	**0.89**	0.19	0.08	0.15	0.13
5340500	0.17	0.09	0.35	0.32	**0.81**
5356000	0.17	0.11	0.21	0.04	**0.90**
5356500	0.25	0.06	0.24	0.02	**0.85**
5421000	**0.86**	0.06	0.16	-0.04	-0.05
5457000	**0.88**	0.14	0.09	0.10	0.04
5458500	**0.93**	0.11	0.14	0.01	0.00
5459500	**0.91**	0.16	0.08	0.01	0.08
5476000	**0.86**	0.13	0.01	0.38	0.17
5479000	**0.81**	0.10	0.12	0.24	0.05
6481000	0.56	0.19	0.04	**0.68**	0.25
6483500	**0.83**	0.14	0.03	0.41	0.15
6485500	**0.76**	0.15	0.04	0.52	0.20
6606600	**0.90**	0.02	0.07	0.21	0.18

[a] *Loadings in bold are >0.60*

Table 2. 9 Factor score trend line variation analysis for the five hydrologic regimes

Region	Time Period	Trendline Slope
Northwest	1936-1980	0.030
	1950-2008	0.016
	Trend variation[a]	-0.014
Northeast	1936-1980	-0.015
	1950-2008	-0.013
	Trend variation	0.001
West Central	1936-1980	0.009
	1950-2008	0.015
	Trend variation	0.006
East Central	1936-1980	-0.001
	1950-2008	-0.014
	Trend variation	-0.013
Southern	1936-1980	0.009
	1950-2008	0.023
	Trend variation	0.014

[a]Difference between 1936-1980 and 1950-2008.

Table 2.10 Trend analysis results for three time periods using factor scores to represent standardized mean annual streamflow for each corresponding regime

	1936-2008		1936-1980		1950-2008	
Regime	Kendall's tau[a]	Probability value	Kendall's tau	Probability value	Kendall's tau	Probability value
Northwest	**0.292**	**0.000**	**0.303**	**0.003**	**0.220**	**0.014**
Northeast	-0.132	0.097	-0.178	0.085	-0.157	0.079
West central	0.144	0.072	0.085	0.411	0.172	0.054
East central	-0.061	0.446	-0.034	0.739	-0.153	0.088
Southern	**0.236**	**0.003**	0.028	0.784	**0.326**	**0.000**

[a] *Bold signifies significance at p<0.05.*

Table 2.11 Factor loading results defining the intra-annual streamflow for the five hydrologic regimes

	Northwest Regime			Northeast Regime				West Central Regime		
USGS Gauge[a]	5066500			5127500				5291000		
Resulting Seasons	**1**	**2**	**3**	**1**	**2**	**3**	**4**	**1**	**2**	**3**
January	0.31	0.36	**0.64**	**0.88**	-0.14	0.13	0.12	0.18	**0.63**	0.42
February	-0.03	-0.05	**0.74**	**0.94**	-0.15	0.10	0.10	-0.09	**0.87**	0.02
March	0.37	0.27	0.25	**0.93**	-0.03	0.07	-0.08	0.13	0.30	0.56
April	0.02	**0.86**	0.00	0.59	0.06	-0.03	-0.23	0.03	0.00	**0.84**
May	0.05	**0.86**	0.09	0.40	-0.09	**0.69**	-0.18	0.51	0.15	**0.61**
June	0.11	0.16	**0.71**	0.03	0.03	**0.92**	0.04	0.43	0.08	0.30
July	**0.65**	0.15	0.43	-0.04	0.13	**0.82**	0.24	**0.73**	0.09	0.06
August	**0.83**	0.04	0.09	0.05	0.00	0.29	**0.86**	**0.81**	-0.08	0.01
September	**0.95**	0.03	0.03	-0.12	0.31	-0.15	**0.85**	**0.86**	0.10	0.30
October	**0.82**	-0.01	0.20	-0.17	**0.83**	-0.15	0.27	**0.72**	0.37	0.16
November	0.36	-0.09	**0.77**	-0.05	**0.97**	0.12	0.00	**0.67**	**0.60**	0.11
December	**0.65**	0.09	**0.69**	0.00	**0.92**	0.11	0.06	0.54	**0.65**	0.23

	East Central Regime				Southern Regime		
USGS Gauge	5356000				6606600		
Resulting Seasons	**1**	**2**	**3**	**4**	**1**	**2**	**3**
January	0.07	0.12	**0.83**	0.18	**0.83**	0.11	0.23
February	0.02	0.05	**0.90**	-0.19	**0.84**	-0.04	0.10
March	-0.18	0.01	0.32	**-0.79**	**0.69**	0.36	0.27
April	0.06	0.11	-0.30	**-0.77**	0.41	0.17	**0.64**
May	0.14	**0.64**	-0.16	-0.26	0.40	0.35	0.59
June	-0.19	**0.74**	0.14	0.00	0.30	-0.01	**0.83**
July	0.13	**0.83**	0.02	0.06	0.13	0.21	**0.86**
August	0.25	**0.62**	0.30	0.03	0.00	0.41	**0.80**
September	**0.77**	-0.04	0.01	-0.09	-0.19	**0.70**	0.40
October	**0.84**	0.25	-0.11	0.03	0.14	**0.89**	0.15
November	**0.67**	0.05	0.37	0.28	0.17	**0.93**	0.07
December	0.50	0.07	0.46	0.37	0.22	**0.87**	0.25

[a] *Factor analysis was based on the USGS stream gauge with the strongest hydrologic signature from the annual analysis. Loadings in bold are >0.60.*

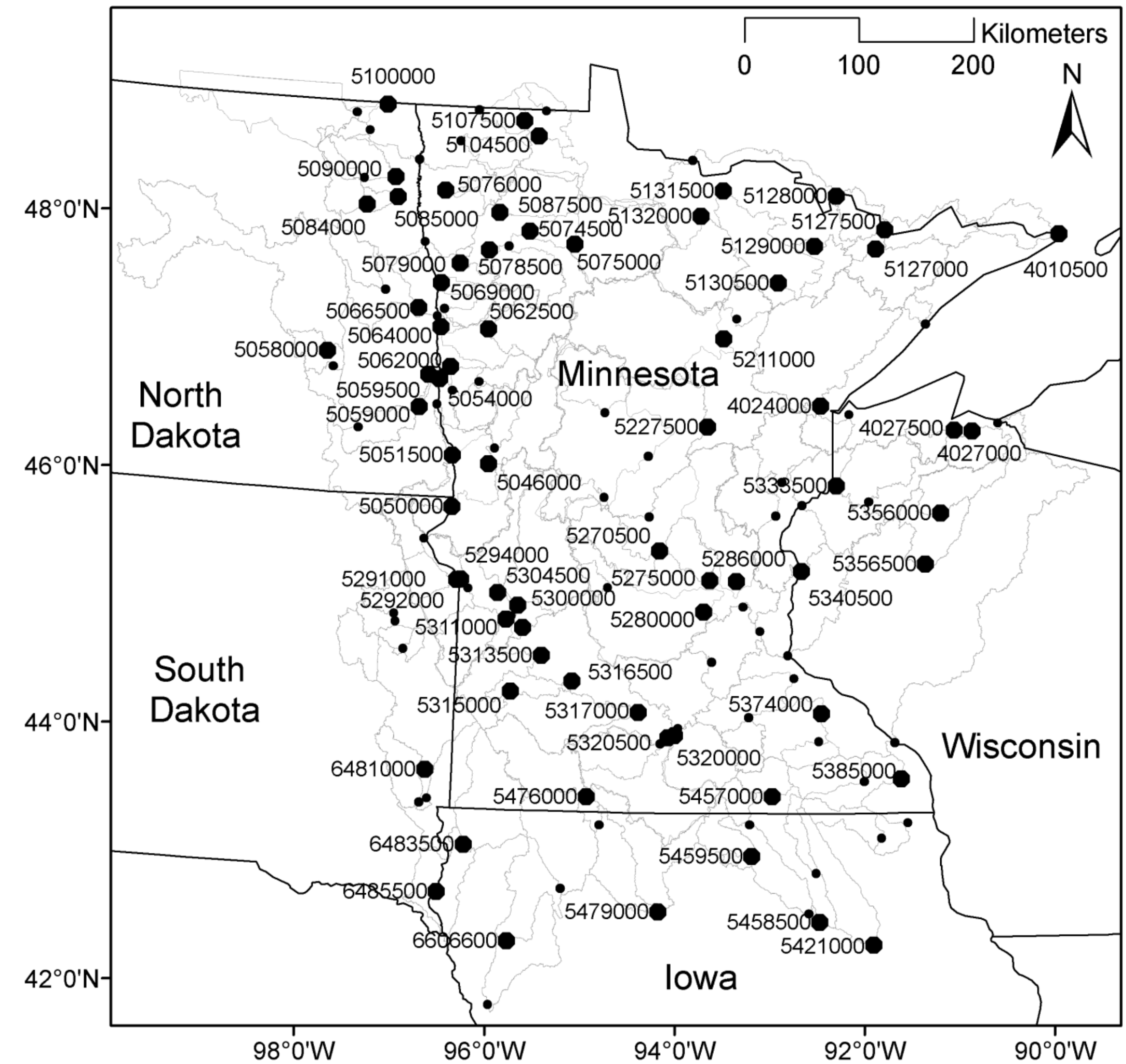

Figure 2.1 Location of 129 USGS gauging stations and corresponding delineated watershed boundaries located across and adjacent to the State of Minnesota which were reviewed for analysis; the larger labeled points represent the location of the 69 watersheds used for the factor analyses

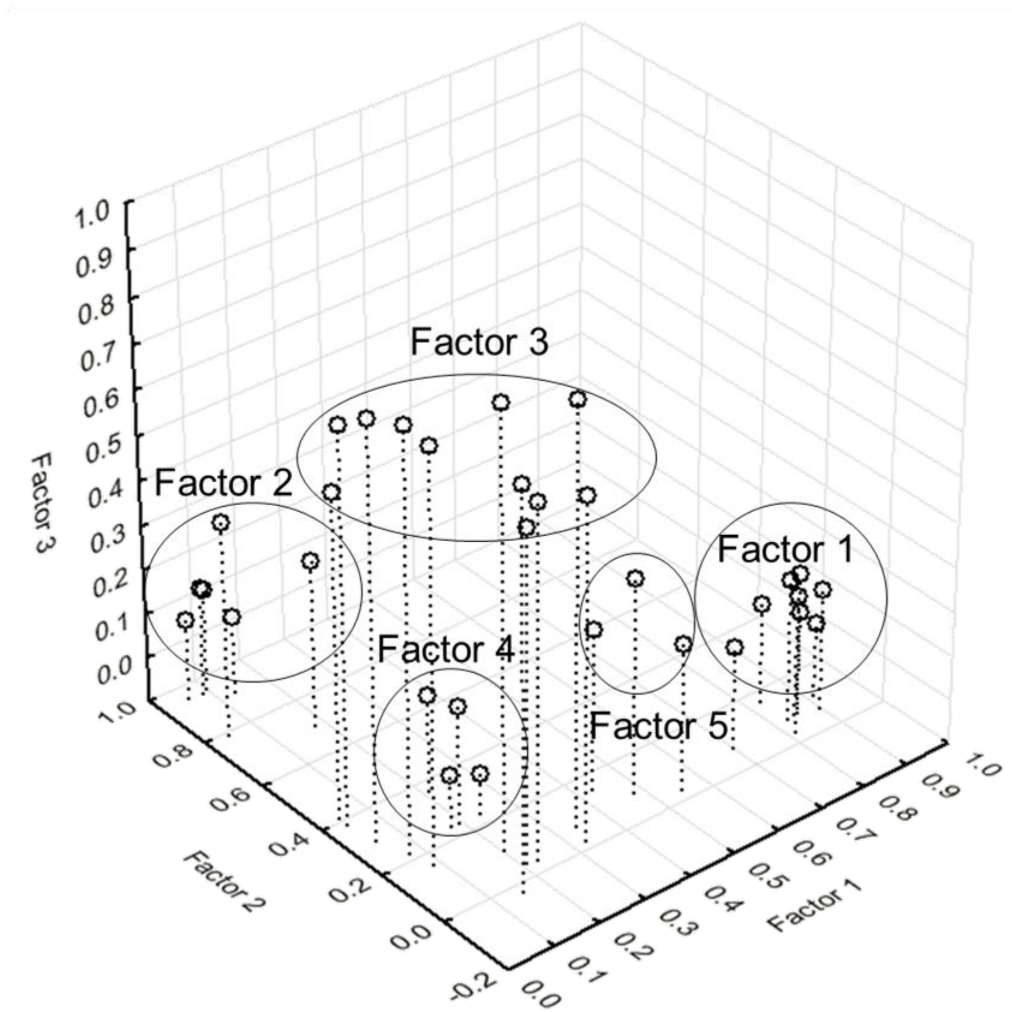

Figure 2.2 Clustering into five factors, or hydrologic regimes, using watershed factor loads for the period 1936 through 2008

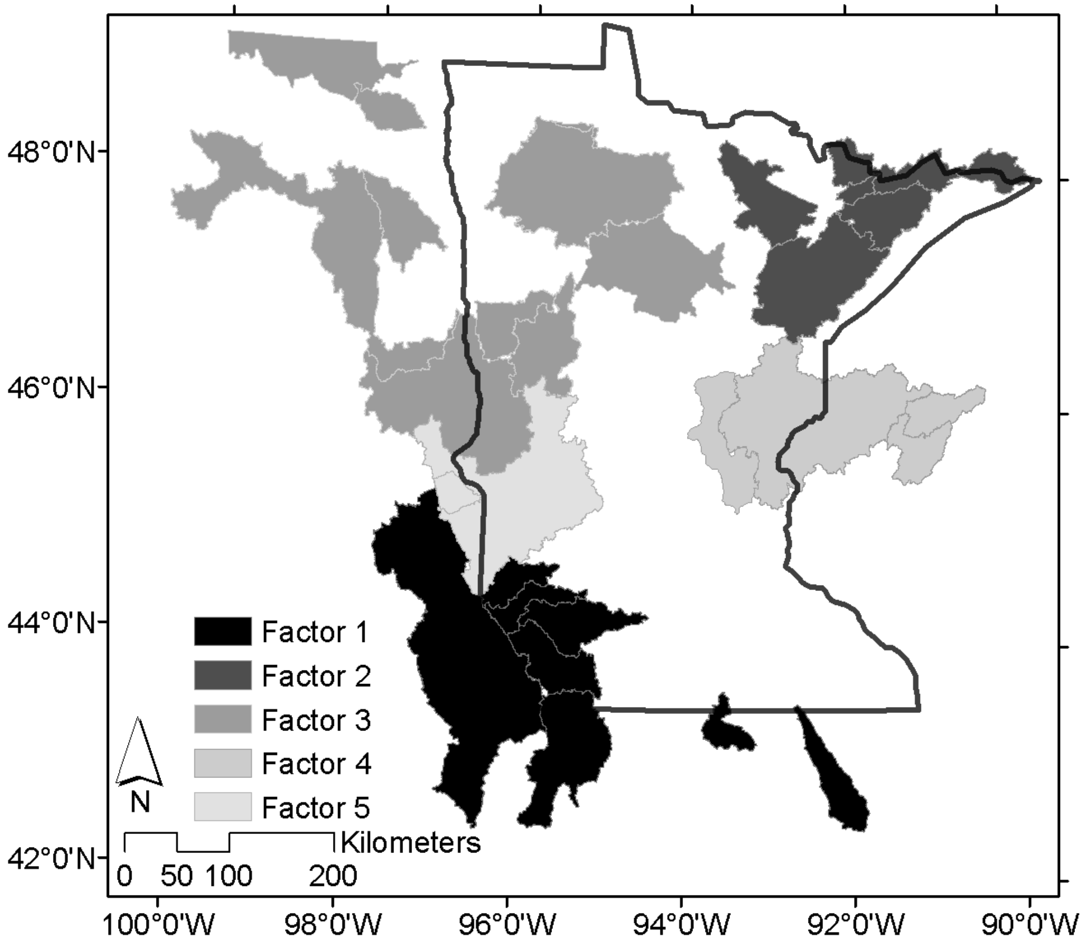

Figure 2.3 Watersheds with factor loadings >0.60 for each factor, or hydrologic regime, using the period 1936 through 2008

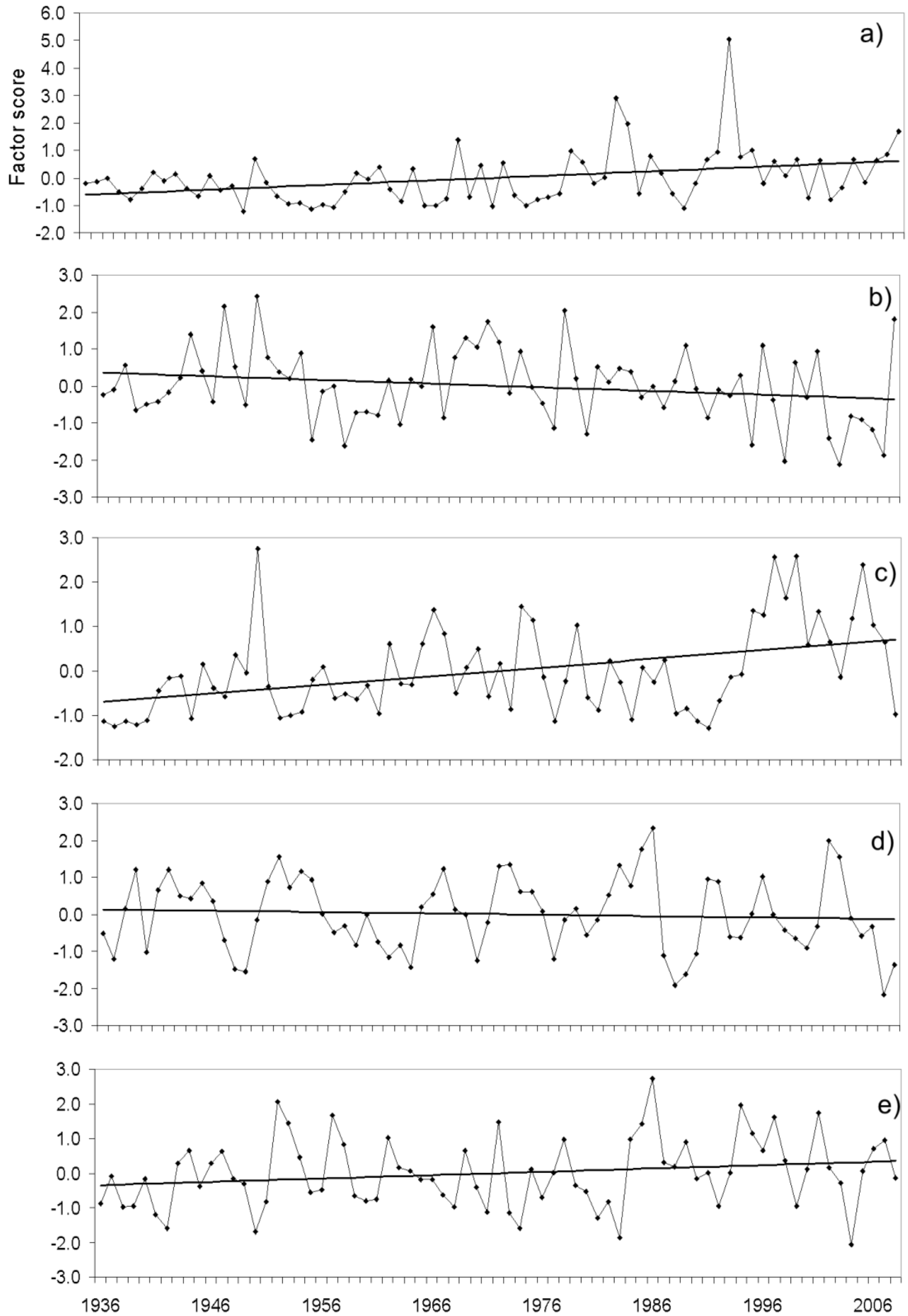

Figure 2.4 Time series comparison for factor score results observed for a) Factor 1, b) Factor 2, c) Factor 3, d) Factor 4 and e) Factor 5 using the period 1936 through 2008; the linear trend line is depicted on each plot

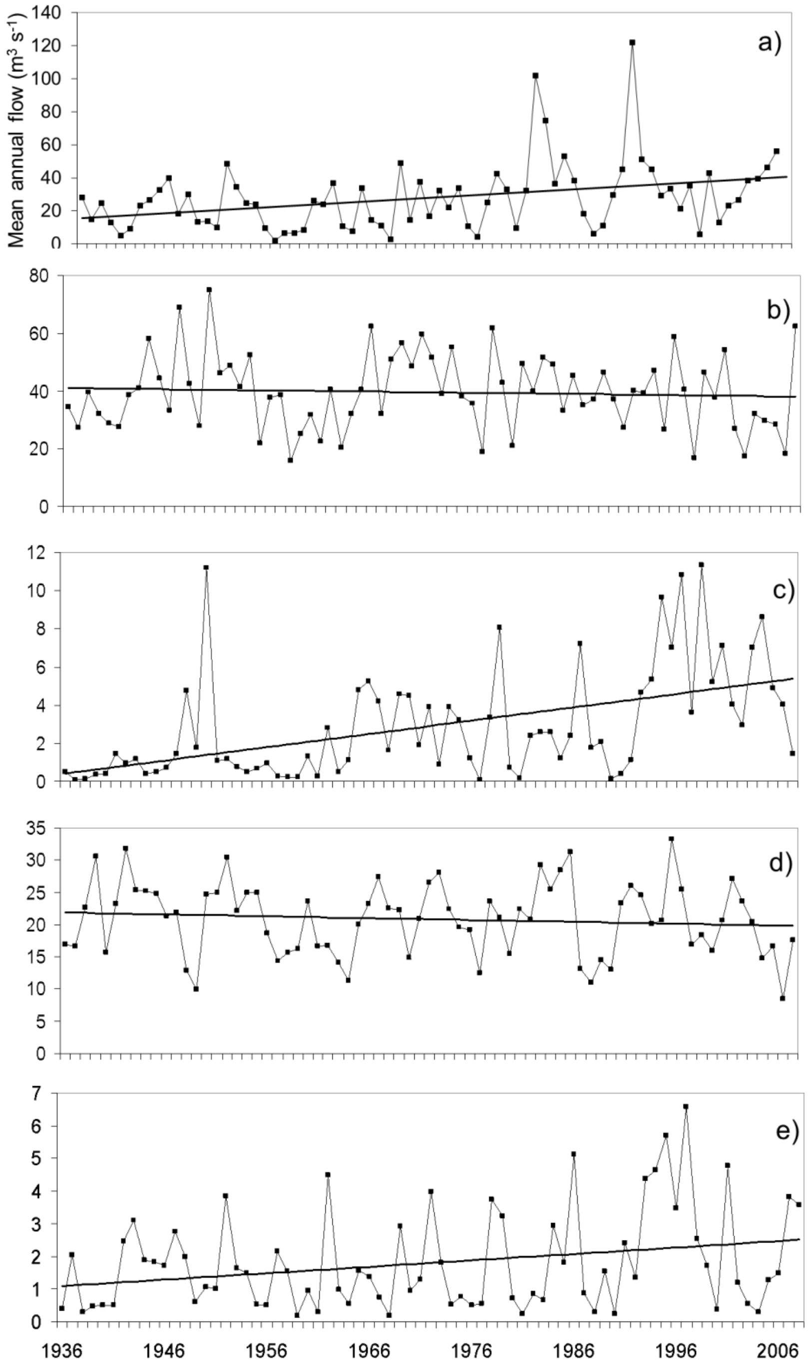

Figure 2.5 Time series comparison of mean annual flow for each watershed with the greatest strength (i.e. factor load) for Factor 1 a)#6606600, Factor 2 b)#5127500, Factor 3 c) #5066500, Factor 4 d)#5356000 and Factor 5 e)#5291000 using the period 1936 through 2008; the linear trend line is depicted on each plot

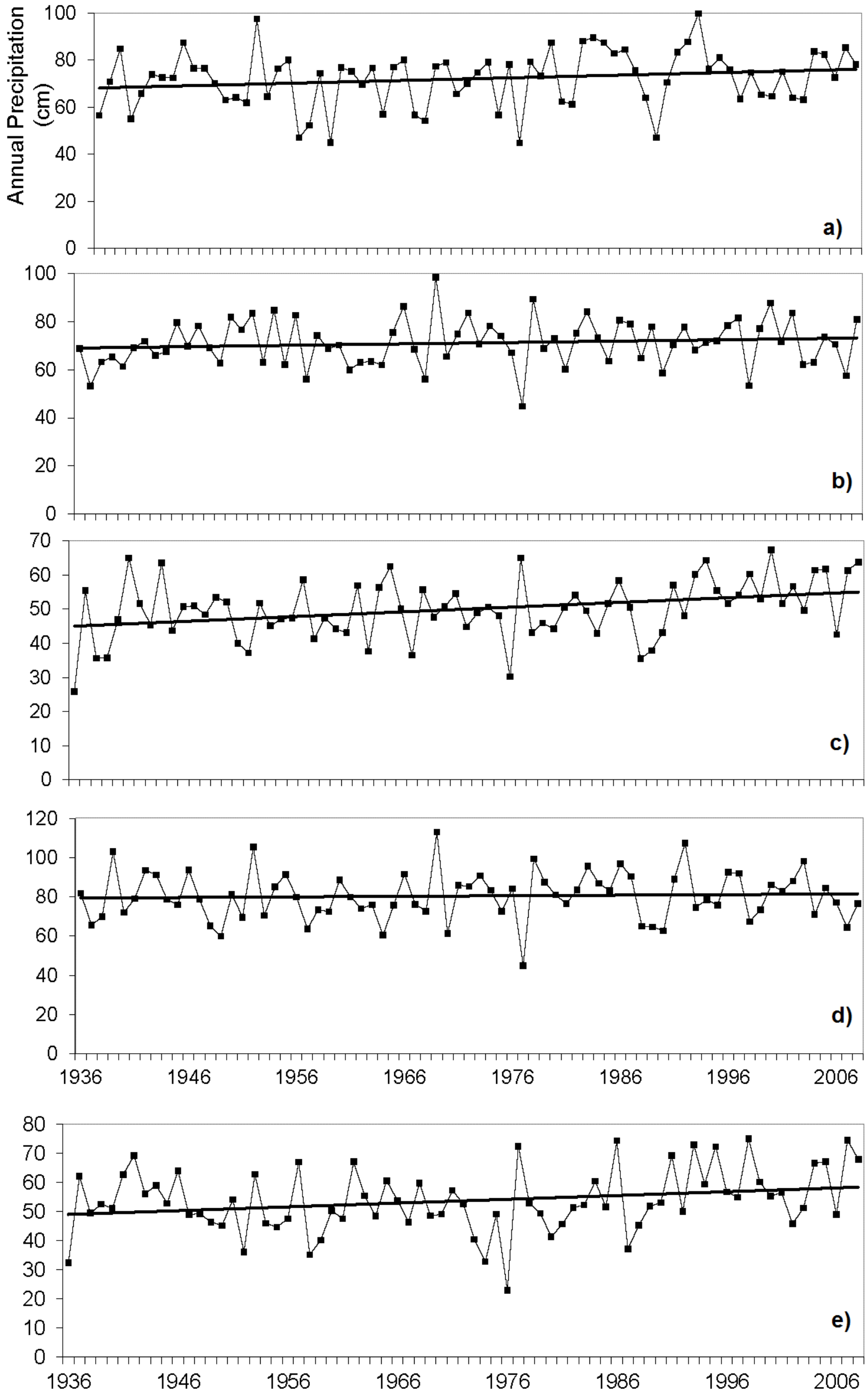

Figure 2.6 Time series comparison of total annual precipitation for each watershed with the greatest strength (i.e. factor load) for Factor 1 a)#6606600, Factor 2 b)#5127500, Factor 3 c) #5066500, Factor 4 d)#5356000 and Factor 5 e)#5291000 using the period 1936 through 2008; the linear trend line is depicted on each plot

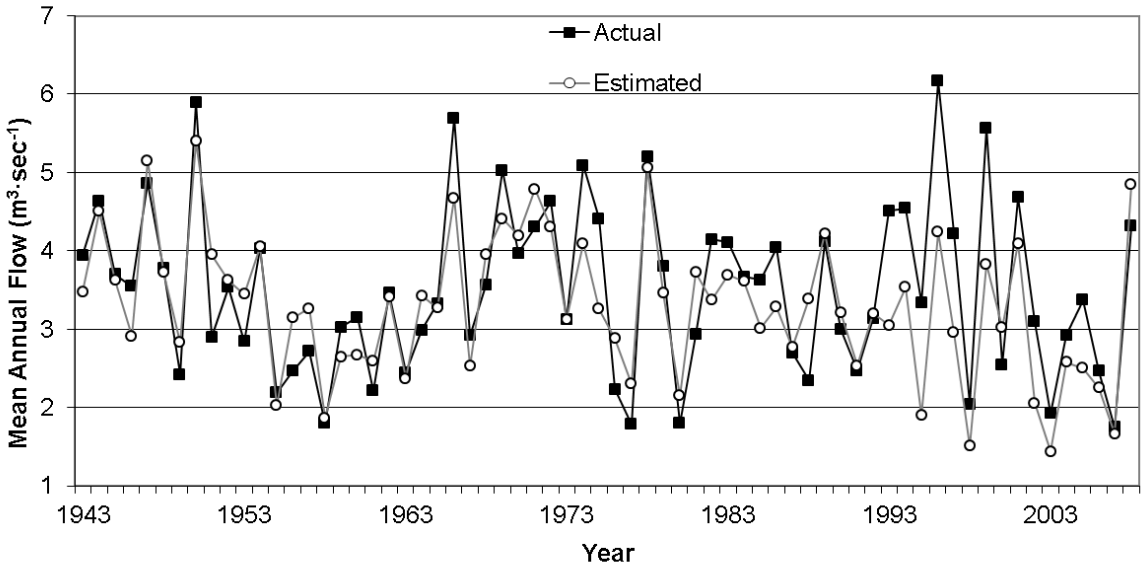

Figure 2.7 Comparison time-series plot illustrating actual mean annual streamflow for USGS gauge 5130500 and streamflow estimated using a regression equation based on the first 10 years of available data (1943-1952) and the factor loadings for the northeast hydrologic regime

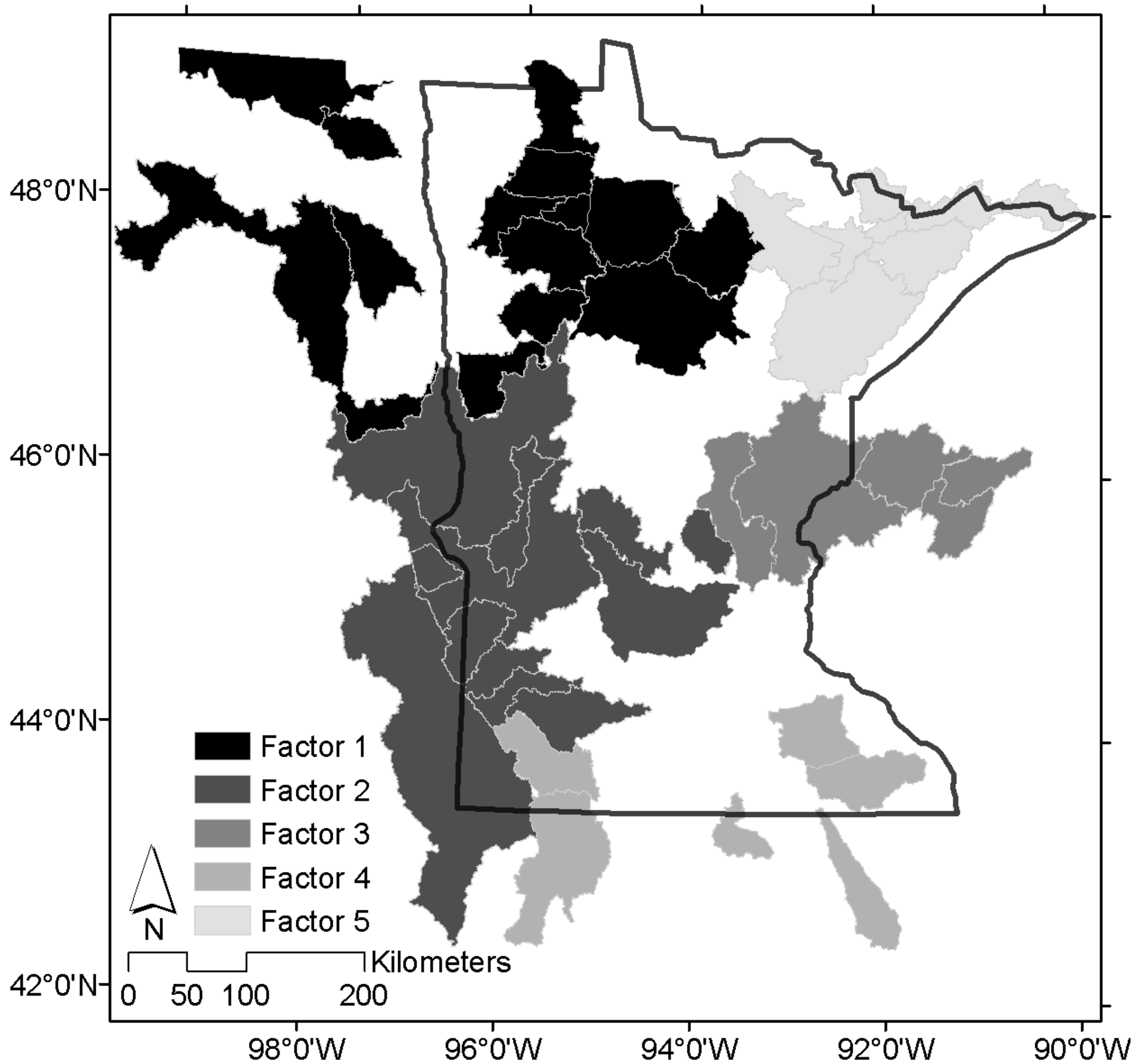

Figure 2.8 Watersheds with factor loadings >0.60 for each factor using period 1936 through 1980

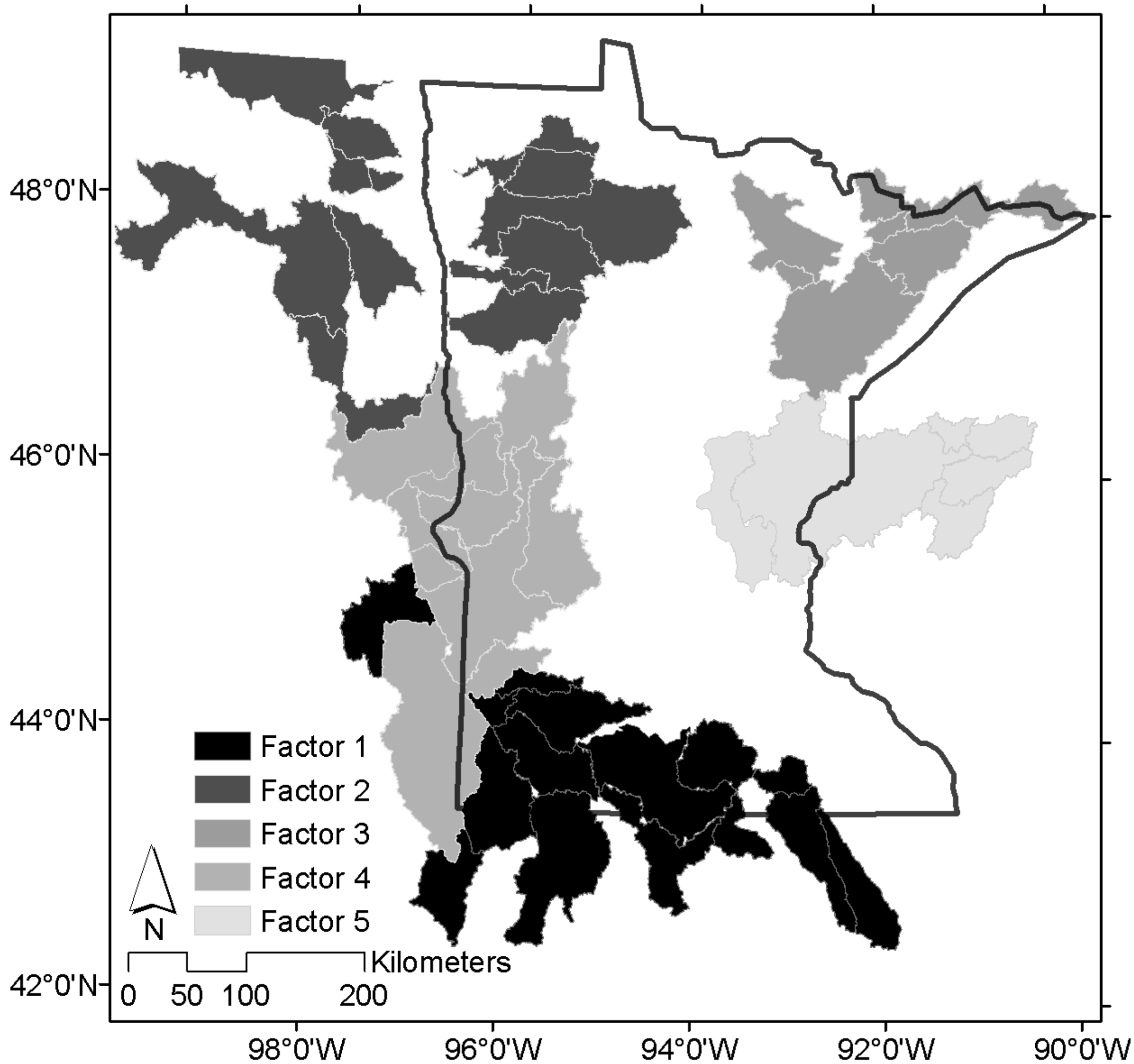

Figure 2.9 Watersheds with factor loadings >0.60 for each factor using period 1950 through 2008

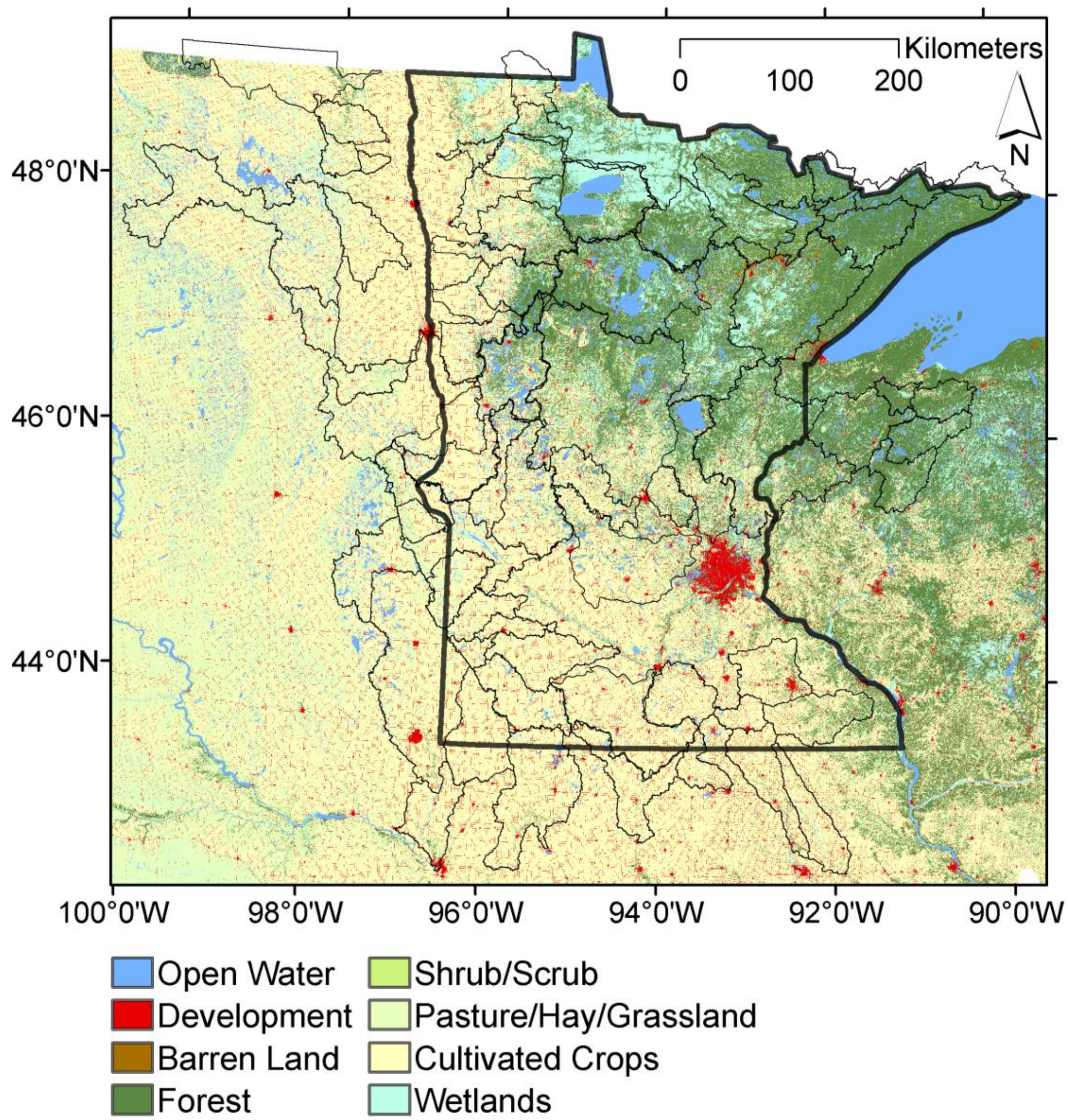

Figure 2.10 Delineated 69 analysis watersheds extending across Minnesota and bordering states overlaying the 2001 National Land Cover Dataset (Homer et al., 2004)

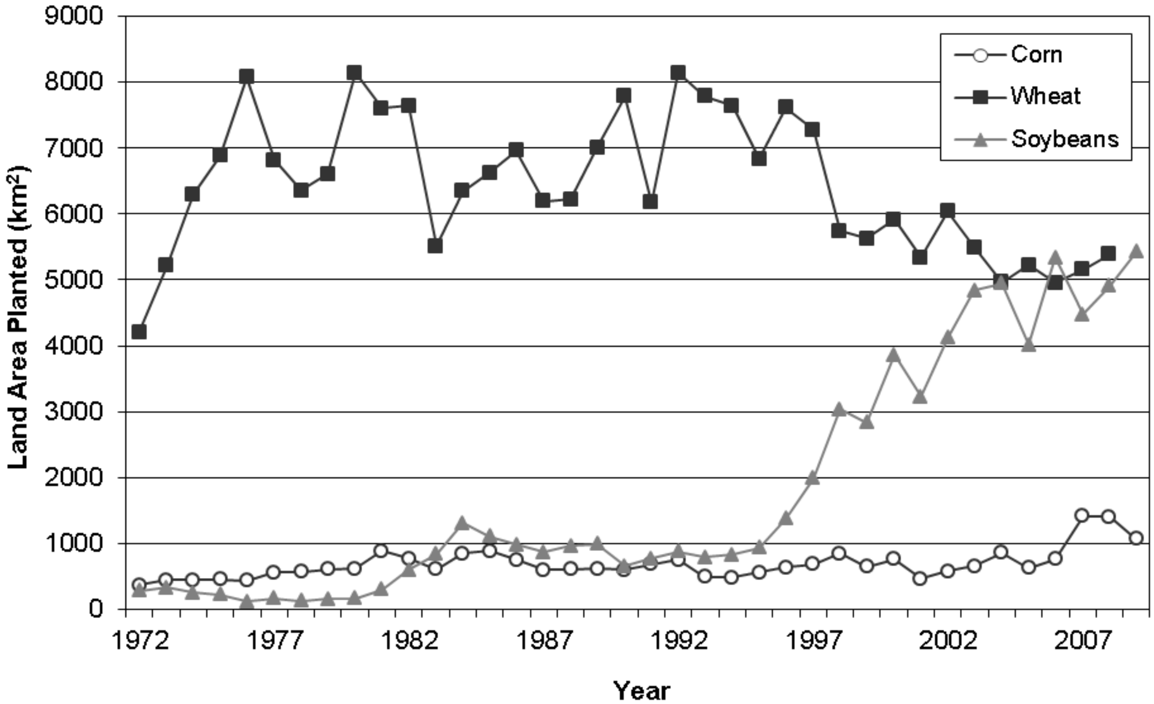

Figure 2.11 Agricultural land area planted corn and soybean in northwest Minnesota has significantly increased over the past few decades while land area planted wheat has declined

Chapter 3

Mapping Regional Recharge Using the Watershed Characteristics Approach

3.1 Introduction

3.1.1 Watershed Characteristics Approach

The ability to estimate regional groundwater recharge at various scales is crucial for basin planning, water resources sustainability management, protection and enhancement of ecosystem health and water budget research of natural and human impacted ecosystems (NRC, 2004). Although much attention has been given to quantifying recharge/discharge fluxes (Simmers, 1988; Lerner et al., 1990; De Vries and Simmers, 2002; Scanlon et. al., 2002; Scanlon and Cook, 2002; Cherkauer, 2004; Dripps and Bradbury, 2007, 2010; Chenini et al., 2010), there is a need to have the ability to spatially depict these fluxes across multiple scales for aiding future water planning and management decision making (NRC, 2004; NSTC, 2007). The study summarized in this chapter demonstrates how using a system-based approach integrating groundwater, surface water and vadose zone systems, the terrestrial hydrologic system can be used to spatially map recharge spanning local to global scales, even when long term data is not available.

The Watershed Characteristics Approach (WCA) is a recharge estimation model developed by using a system-based approach focused on the regionalization of landscape characteristics to define unique HHUs and establish their linkage to hydrologic characteristics. It is based on the regionalization approach described by Pinneker (1983), which first requires that parameters for dividing a given territory be defined and next the boundaries of these parameters be mapped. To do so, this model couples Krcho's (2001) system model of geospheres (Figure 3.1) with Freeze and Cherry's (1979) conceptual watershed model for water balance components (Figure 3.2); thereby enabling it to depict recharge estimates spatially and temporally making it a powerful mapping tool applicable at multiple scales.

Watersheds are self-organizing systems, whose characteristics are all a result of adaptive, ecological, geomorphic or landforming processes; therefore, they may establish patterns which upon examination can lead to a simplification of descriptions used in analysis and predictions (Sivapalan, 2005). This is why the methodology is referred to as the "Watershed Characteristics Approach," indicating that all variables of landscape components (geology, hydrogeology, the stream network system, topography, soils, vegetation, and climate) are associated with water balance characteristics, using the watershed as a quantification unit (Kudelin and Fideli, 1970). By establishing the relationship between the landscape components and water balance characteristics, hydrologic response units are established.

3.1.2 Status of Mapping Regional Recharge

Rising water demands for both humans and nature makes the need for improved regional recharge estimates critical (Barlow et al., 2002). Many current regional recharge estimation methodologies do not apply interdisciplinary approaches which facilitate creation of the connectivity within the hydrologic system. The complexity of the hydrological issues at hand requires an interdisciplinary approach to extrapolate data from gauged to ungauged watersheds (Wagener et al., 2004). Water is a single resource, regardless of whether it appears as ground or surface water; therefore, in order to address complex hydrologic issues, both ground and surface water must be characterized together (Alley and Leake, 2004; Falkenmark, 2008).

Many hydrologic models ignore spatial and temporal variations in recharge rates because of limited available critical parameter measurements or the method is not adequate to accurately evaluate the variations at the scales of interest (Hyndman et al., 2007). There are several specific types of models that are commonly used in these mapping methodologies to estimate regional recharge.

Physically-based distributed parameter models rely on calibration to account for the lack of knowledge due to spatial heterogeneities in landscape properties and the corresponding uncertainty of actual processes and interactions (McDonnell et al., 2007). In some analyses where observed hydrologic data is not available, a conceptual lumped parameter method is chosen and historic climatic, land use or landscape data is used in calibration. Examples include HSPF (Barnwell and Johanson, 1981), SWAT (Arnold et al., 1993; 2000) and TOPMODEL (Beven and Kirkby, 1979); each have parameters that can be adjusted to fit measurements but cannot be independently measured, therefore resulting in difficulty predicting flow in a new system without independent calibration or projecting changes in a system due to solely climate or land cover changes (Hyndman et al., 2007). Models, such as MODFLOW (McDonald and Harbaugh, 2003), require independently measured parameters based on laboratory analyses or field studies. These models typically only assess groundwater and do not incorporate the landscape or processes occurring in the unsaturated zones (Hyndman et al., 2007).

When a regression method is used, it is hoped that the response of the hydrologic system can be predicted by separating out the individual components of a system (Neff et al., 2005, Delin et al., 2007; Eng and Milly, 2007; Lorenz and Delin, 2007); however, the response of a hydrologic unit is not simply the linear combination (regression) of its component parts. Instead, the response is generally nonlinear and results from the complex interaction of the component parts. Regression analysis is not able to predict this nonlinear response because the connectivity within the entire hydrologic system is not taken into account. It is necessary to look at the response of the hydrologic unit as a whole. This traditional approach for regional recharge quantification has long been plagued with perceptions that fail to adequately acknowledge that intimate relationships exist between the landscape (surface and interior) and hydrologic response (Smakhtin, 2001; Kroll et al., 2004; Wolock et al., 2004; Stepinski et al., 2011).

Linking the landscape and hydrology spatially, the WCA, as described in this chapter, incorporates mapping to quantify regional recharge at multiple scales. To characterize each component of the terrestrial landscape, specifically the hydrogeology, there needs to be a grasp on the connectivity within the entire hydrologic system. This regional recharge mapping is based on the idea of regionalization of the entire terrestrial hydrologic system in a hierarchical organization (Pinneker, 1983), as well as on valid and reliable hydrologic characteristics to represent groundwater recharge (Kanivetsky and Shmagin, 2005). The recharge is generally the most difficult component of the groundwater system to quantify (Bredehoeft, 2007). Classical hydrologic regionalization is the determination of hydrologically similar units (Diekruger et al., 1999). These similar units have a specific set of unique landscape characteristics, which the WCA defines based on soils, topography, geology, climate, hydrology and vegetation. This regionalization works at a multi-scale level to account for the characteristic hydrologic response of an entire unit. The hydrologic response of this unit is based on measurements at an appropriate scale, which can be directly related to the hydrologic response of geometrically similar hydrologic units elsewhere. This concept is becoming increasingly recognized and has resulted in the advocacy for examining the entire hydrologic system through a watershed-based methodology (Pinneker, 1983; Lin et al., 2006, Reed et. al., 2006; McDonnell et al., 2007).

To demonstrate the validity of the WCA to map regional recharge at a scale lacking long-term stream gauge monitoring data, the approach is summarized here as applied to the ECM area (Figure 3.3).

3.2 Methodology

3.2.1 System Model for Watershed Water Balance

The WCA is based on the idea that the landscape is composed of different layers, each representing a fundamental landscape component. These landscape components are from the concept of geospheres (Krcho, 2001), where the various layers represent the atmosphere (i=1), hydrosphere (i=2), pedosphere (i=3), lithosphere (i=4) and biosphere (i=5) (Figure 3.1). At a given point on the Earth's surface, a combination of these layers yields unique features to which hydrologic response is sensitive.

For each of these geospheres, the matrix of structure and relationship can be written as (Krcho, 1995; Shmagin and Kanivetsky, 2006):

(3.1)

$$Sa_i = \{a_{ji}, R_i\};$$

where a_{ji} is a system of j-components (j = 1, 2,….n) of the i^{th} -sphere (i = 1, 2,….5). Each of these j-components may be characterized by a matrix of inputs $\{W_i\}$, outputs $\{Q_i\}$ or states $\{H_i\}$. R_i represents a matrix of the interactions occurring between each of the $\{W_i\}$, $\{Q_i\}$ *or* $\{H_i\}$ geosphere matrices.

The hydrosphere structure *(Sa_2)* could be written in matrix form as:

(3.2)

$$Sa_2 = \{g_1, g_2, g_3 .... g_9\};$$

where g_1 is water of seas and oceans, g_2 is the stream runoff system, g_3 is water of closed lakes, g_4 is atmospheric water, g_5 is water of glaciers, g_6 is water of permafrost rocks, g_7 is connate groundwater, g_8 is water trapped in rocks and minerals of the lithosphere, and g_9 is water of the biosphere. Therefore, the stream runoff system *(Sg_2)* as part of the hydrosphere and included in the WCA is represented as:

(3.3)

$$Sg_2 = \{g_{ji}, R_q\};$$

where g_{ji} is the system of j-watersheds (j=1,2,…….97) with i-attributes representing runoff and landscape characteristics (i=1, 2, 3,…n) and R_q is the interaction of watershed g_{ji} as a component of the stream runoff system with the other eight hydrosphere components at a planetary, global, regional and basin scale and also the interactions between the $\{W_i\}$, $\{Q_i\}$ *or* $\{H_i\}$ matrices.

Using this idea, any area of land can be subdivided into hierarchical units based on differences in combinations of landscape characteristics. The composite landscape characteristics within a particular hierarchical unit are related to the landscape data layers (geospheres) associated with that unit. For example, these variations of characteristic combinations can be visualized by imagining a borehole capturing the sequence of landscape characteristics as layers. Various water balance components of the hydrologic cycle for the hierarchical unit can then be related to the composite landscape characteristics (i.e. series of layers within the borehole). For hydrological applications dealing with groundwater systems, these land units can be defined as HHUs. They are derived from maps and data depicting geology, hydrogeology, the stream network, topography, soils, vegetation and climate. By identifying similar units having unique landscape characteristics, the flow and transport domains are assumed to be more uniform within a unit than between units, allowing simpler mathematical treatment of hydrologic processes (Santra et al., 2011).

The WCA uses a multi-level system structure for landscapes in which the boundaries of a given watershed represents a subsystem, which can be analyzed from global to continental to sub-continental to regional and finally, to more local scales to quantify hydrologic characteristics as well as to classify hydrologic units.

3.2.2 Quantification of Watershed Hydrologic Characteristics

Discharge Theory

The watershed as a part of the Earth's landscape (including both the surface and interior), can be studied as a unit with three-dimensional boundaries to characterize the freshwater system. In doing so, it is assumed that the groundwater divide coincides with the surface topographic divide used to delineate the watershed drainage area (Tóth, 1963; Tóth and Sheng; 1996). By recognizing that the watershed is a unit of the water system and combining it with the hydrosphere structure, the land surface can be represented by a set of watersheds. Under the "watershed unit" any land area that drains to a single body of water, such as stream, is considered. Watersheds are thus "nested"; larger watersheds encompass many smaller watersheds.

In this analysis watersheds of interest are those which have actual recorded stream runoff measurements. Based on those watersheds, empirical data and other attributes can be collected and analyzed. The corresponding discharge measurements, in combination with the landscape components comprising the watershed, are used to create the initial matrix, defined by equation 3.3, representing the myriad of landscape characteristics and hydrologic characteristics within the study area. This matrix is then used to find a statistical link between hydrologic characteristics (e.g. stream runoff) and landscape components; resulting in the creation of statistically significant HHUs.

To account for annual seasonal variability of discharge, the WCA uses a uniform value of mean minimum monthly discharge (Kanivetsky and Shmagin, 2005). The rate of mean minimum monthly stream runoff is used as a conservative proxy for the minimum groundwater recharge rate. This is taken from actual measurements, representing true recharge, and not from using methods such as hydrograph separation which may overestimate recharge due to bank storage (Halford and Mayer, 2000; Scanlon et al., 2002) or unaccounted surface storage resulting from recent rainfall events. Streamflow records indicate that Minnesota monthly streamflow is at its minimum during February, when, because of subfreezing temperatures, it typically consists of baseflow with little or no surface runoff (Ruhl et al., 2002). In the case where a semi-arid or arid climate is present and perennial streams are lacking, an alternative proxy would need to be considered.

The methodology uses the watershed area as a quantification unit; a module of minimum recharge as a unit of watershed area ($L \cdot s^{-1} \cdot km^{-2}$) is computed so that each watershed could be compared and related (Zekster, 2002). Because of this uniformity, minimum monthly flow values are comparable for any area and the results can be mapped as hydrological units in a hierarchical organization. Recharge values are assumed to be equal to watershed discharge values, which are considered to be constant and uniform for each defined HHU, but may vary between individual units. This distinction is important because organizing knowledge based on hydrologic units rather than on aquifers acknowledges unity of the surface and groundwater system, enabling an integrative, system viewpoint of the terrestrial hydrologic system.

The WCA assumes that the groundwater recharge is just the discharge measured in the river (Bredehoeft, 2007). The idea that details of hydrologic processes or heterogeneity within watersheds need not be examined rather instead characterized by the hydrologic behavior of the watershed, can be viewed compatible and further supported with the Representative Elementary Watershed (REW) approach as introduced and outlined by Reggiani et al. (1998; 1999) and applied in various watershed modeling efforts (Lee et al., 2006; Reggiani and Rientjes, 2005; Zhang et al., 2005; Zhang et al., 2006). In the REW approach, a river basin or large watershed is subdivided into subwatersheds at spatial scales corresponding to the available data and/or to the scale of desired watershed modeling information. The subdivision into REWs is conducted by using surface topography to identify the dividing line between adjacent REWs, and the subsurface of each REW is bounded by a vertical mantle extended to some specified bottom boundary. The resulting REWs are further subdivided into regions or zones corresponding to the hydrologic processes prevalent in the REW. Adjacent REWs within the subdivided basin or watershed have the possibility of exchanging mass between each other through the subsurface domain, but not as overland flow since the surface topography prevents exchanges over the surface.

The hydrologic behavior of the REW can be quantified and characterized by either conducting detailed numerical modeling experiments (Duffy, 1996; Harman and Sivapalan, 2009; Lee, 2007) to derive responses at the REW scale, or by acquiring field measurements at the REW scale. Equations governing the transport and exchange of mass, momentum, energy and the balance of entropy for an REW could be written for each subregion. For instance, for the saturated subregion the mass balance equation for the saturated region for REW j is

$$\frac{d}{dt}(\rho y \varepsilon \omega) = \sum_{l \neq j} e_{l,j} + e_{\text{ext}} + e_{\text{bot}} + e^{\text{su}} + e^{\text{so}} + e^{\text{sr}} \quad ; \tag{3.4}$$

where ρ is the average density of the water in the saturated zone, y is the average thickness of the saturated zone, ε is the mean porosity in the saturated zone, ω is the fraction of horizontal area of the REW occupied by the saturated zone, l is the number of REWs adjacent and connected to REW j, $e_{l,j}$ is the mass flux of water between REW j and REW l, e_{ext} is the flux of water between the saturated zone and the external boundary of the REW j, e_{bot} is the flux of water between REW j and regional groundwater beneath it, e^{su} is the flux of water between the unsaturated zone and the saturated zone in REW j, e^{so} is the flux of water between the saturated overland flow and the saturated zone of REW j, and e^{sr} is the flux of water between the river channel and the saturated zone of REW j. A similar mass balance equation can be written for the l REWs adjacent and connected to REW j.

For the WCA as described in this chapter using ECM, time varying changes are not incorporated so $\frac{d}{dt}(\rho y \varepsilon \omega)$ vanishes. Each watershed is treated as an REW, with external mantle only, and no exchange among adjacent REWs, so the term $\sum_{l \neq j} e_{l,j}$ vanishes, and it is assumed that the groundwater divide coincides with the surface topographic divide (Tóth, 1963; Tóth and Sheng; 1996), thus making $e_{\text{ext}} = 0$. The bottom boundary of each watershed is assumed to be impermeable, thus not allowing for exchange of water between REW j any underlying regional groundwater system, thus making $e_{\text{bot}} = 0$. The groundwater recharge is the e^{su} term and the flux measured in the stream/river is given by the $\left(e^{\text{so}} + e^{\text{sr}}\right)$ term. The result from equation 3.4 is that

$$e^{\text{su}} = -\left(e^{\text{so}} + e^{\text{sr}}\right) \quad \textbf{;} \tag{3.5}$$

meaning that the groundwater recharge is just the discharge measured in the river (Bredehoeft, 2007).

Data Extrapolation

Ninety-seven small scale gauging stations representing ECM were selected based on availability of low-flow characteristics data described by the USGS (Lindskov, 1977; Kanivetsky, 1979b). These watersheds varied in area from 43 to 1925 km^2. Available one-time, low-flow discharge observations collected between years 1940 through 1976 were recorded for each of these 97 watersheds.

For large scale analyses, the period of record available for hydrologic monitoring is typically much longer and complete than those records accessible for a smaller scale analysis. To address this limitation, benchmark watersheds are proposed to extrapolate data from partial or one-time observations recorded at small scale watersheds (Figure 3.4). These benchmark watersheds have relatively long-term streamflow records which can be used to represent the hydrologic characteristics of smaller watersheds within the same territory with short-term records. For this analysis three benchmark watersheds were chosen based on stream runoff pattern identification derived from a previous statewide analysis (Shmagin and Kanivetsky, 2002). These benchmark watersheds had

USGS daily observations for overlapping consecutive years of 1940 through 1983, therefore were selected to represent the ECM area. They included Elk River near Big Lake (USGS gauge #5275000), Yellow Medicine River near Granite Falls (USGS gauge #5313500) and the Root River near Houston (USGS gauge #5385000). Mean minimum monthly (February) discharge for the period of 1955 through 1978 was calculated for the three benchmark watersheds. This period was selected because watersheds had recovered from the drought conditions of the Dust Bowl period, but had not yet experienced significant hydrologic influence from recent anthropogenic landscape changes (Chapter 2). Additional time periods were estimated, including 1955 through 2008 and 1978 through 2008; however, 1955 through 1978 provided the lowest, most conservative recharge estimates.

Each watershed analyzed was assigned to a corresponding benchmark based on proximity to the benchmark watershed and results of the statewide streamflow regionalization discussed in Chapter 2 (Figure 3.5). Mean minimum monthly runoff values for the 97 analysis watersheds were estimated by determining the linear proportion between the discharge of the specific corresponding benchmark watershed and the regional watershed's observed discharge value. If the watershed could be represented by more than one benchmark watershed, runoff values were estimated using each benchmark and the lowest estimate was chosen.

The extrapolation was completed by first recording the low-flow observations collected between 1955 and 1978 for each of the 97 analysis watersheds listed in Lindskov (1977). These flow rates were converted to a yield (d_i) based on the delineated drainage area. The flow rate and yield for the assigned benchmark watershed (b_i) was recorded for the corresponding sample data. The mean February (minimum) streamflow (recharge) for the time interval of 1955 through 1978 was calculated for each of the three benchmark watersheds (m_i). The proportion of the benchmark watershed's low flow observation to the mean minimum recharge could then be calculated $\left(\frac{b_i}{m_i} = p_i\right)$. Each analysis watershed's yield could then be divided by this calculated benchmark proportion to get the estimated mean minimum groundwater recharge $\left(\frac{d_i}{p_i} = f_i\right)$ for that specific analysis watershed. These values defined by f_i are the recharge rates used throughout the regionalization analysis to be presented.

3.2.3 System Characterization Through GIS Integration

A GIS provides a consistent method for watershed and stream network delineation using digital elevation models of land-surface terrain (Maidment, 2002). The advantage of representing data within a GIS is the ability to display and analyze information with a geospatial context. Data from various sources are assimilated and can be viewed and analyzed based on spatial relationships (Strassberg et al., 2007). Physically based models using GIS are powerful tools for addressing the complexity of hydrological processes and basin wide characteristics (De Smedt and Batelaan, 2003). The use of GIS facilitates analyses of complex, large-scale, spatially distributed hydrological data (Mutua and Klik, 2007).

The latitudinal and longitudinal coordinates for the 97 gauging stations selected from Lindskov (1977) were georeferenced in ArcGIS®. Using Arc Hydro (Maidment, 2002), a GIS mapping plug-in software for water resources, along with NHDPlus data (http://nhd.usgs.gov/index.html), an integrated suite of application-ready geospatial data sets available through the USGS and the U.S. EPA, watershed boundaries were delineated for each gauging station using raster analysis (Figure 3.6). Based on these delineations, the drainage area was calculated for each watershed.

Landscape characteristic files in raster and shapefile format were added into the GIS to complete the watershed characterization based on these delineated watershed boundaries. Data layers superimposed for the analysis included three 1:500,000 scale statewide hydrogeological maps representing the bedrock material (Kanivetsky, 1978) (digital data available from the Land Management Information Center at http://www.lmic.state.mn.us/chouse/), Quaternary sediment (Kanivetsky, 1979a), and depth to bedrock (R. Lively, Minnesota Geological Survey, unpublished data, 2007). Statewide soil data at a scale of 1:250,000 from the United States General Soil Map (STATSGO2) Database, downloadable through the National Resources Conservation Service (NRCS) (http://soildatamart.nrcs.usda.gov/USDGSM.aspx), was formatted and analyzed within the GIS database. Lastly, a seamless, 30-meter resolution digital elevation model (DEM) compiled from the USGS National Map Seamless Server (http://seamless.usgs.gov/website/seamless/viewer.htm) was used for various topographic analyses.

Mapping the spatial relationship of the watershed boundaries with respect to the various landscape characteristics derived from these digital data layers enables all of the geospheres or layers within the hydrologic system to be defined and incorporated into the analysis matrix defined by equation 3.3. Using a GIS to overlay the delineated watershed boundary onto the landscape characteristic data layers, each watershed's landscape characteristics were identified (Figure 3.6).

3.2.4 Classification of Hierarchical Hydrogeological Units

Initial Matrix

To discover the link between the unique series of characteristic layers and minimum groundwater discharge recharge, each watershed's characterization was summarized in matrix format, with each row dedicated to a specific watershed. The first column of the matrix includes the minimum recharge value and subsequent columns represent series of landscape characteristics.

The qualitative landscape characteristics were summarized based on the fraction of each watershed that comprised the specific characteristic. This summary was completed by overlaying landscape characteristic data layers within the GIS (Figure 3.7). Fuzzy rule-based classification (Beven, 2000; Li et al., 2011; Santra et al., 2011), an efficient tool to classify domains having multiple parameters and parameter range while providing expert knowledge-based inferences about the system, was used to assign characteristic codes to each watershed based on the predominant characteristic found within the boundaries of the watershed. For instance, when evaluating Quaternary sediments, the fraction of each watershed falling into units Q1 (predominantly gravel with sand), Q2 (predominantly sand with gravel) or Q3 (till) was indicated in the matrix with each unit listed as a separate column. In a fourth column, the watershed was then coded to represent whichever unit comprised the largest fraction of the watershed. Therefore, if 53% of a watershed was Q2, the watershed would be coded to reflect that this was the predominant characteristic. This coding process was completed for each qualitative landscape characteristic.

In the case where a quantitative characteristic was summarized, such as available water capacity, the characteristic was coded based on a defined range of values with a noticeable shift in recharge. This shift was identified by plotting the recharge data in numerical order to observe whether any breaks in the rates exist.

Defined Hierarchical Hydrogeological Units

Once all characteristics were coded, statistical analyses were used to distinguish which unique series of characteristic layers or HHUs, significantly influences the corresponding mean minimum ground water recharge. The mean minimum groundwater recharge was calculated for each coded landscape characteristic identified in the initial matrix. In addition to the mean, the upper and lower quartiles were calculated to provide a range of recharge values within the characteristics to show the distribution attributed to the fuzzy classification scheme.

Kruskal-Wallis analysis of variance (ANOVA) was used to determine if the minimum groundwater recharge was statistically different between each coded characteristic at each hierarchical level. This non-parametric statistical analysis was used because unlike basic parametric analyses, characteristics are not assumed to be normally distributed. In addition, non-parametric statistical analyses can be used with small data sets to identify differences between independent groups. This benefits the methodology because as characteristics are layered and combined, the number of watersheds which exhibit those unique sets of characteristics becomes limiting. Following the hierarchical procedures defined by Pinneker (1983), the regionalization begins with the most general landscape features at the Province hierarchical level, and as more specific characteristics are applied in combination with that general feature, HHUs are refined at subsequent levels from Sub-province to Region to Subregion and lastly, to the most refined level possible with currently available data, District (Figure 3.8). Based on the results of the ANOVA at each hierarchical level, characteristics exhibiting a significant statistical difference ($p \leq 0.05$) in mean minimum recharge values were used to establish the regionalization of HHUs.

3.2.5 Recharge Map

Upon completion of the regionalization, the corresponding calculated mean minimum recharge rates for each landscape characteristic used to define each refined HHU were digitally linked in GIS to create a regional map of mean minimum recharge. These recharge rates represent the renewable groundwater flux through the system; therefore, depicting the values spatially across the study territory creates a map of renewable groundwater recharge rates where long-term monitoring data is otherwise unavailable (Alley, 2007). The key indicator of sustainable water use is the ratio of the renewable capacity (i.e. limit) of the hydrologic system to the water use by humans and the environment (Kanivetsky and Shmagin, 2005). Therefore, this map can also depict the sustainable groundwater flux.

3.3 Application

3.3.1 Description of Study Area

Regional recharge was estimated and mapped for ECM using the WCA. Although there is not consistent long-term data available, ECM has an extensive historic gauging station network. It encompasses approximately 45,000 km^2 and includes the St. Paul and Minneapolis (Twin Cities) Metropolitan Area, which has received increased attention due to concern over potential hydrologic impacts associated with increased development of the urban corridor which extends west toward the city of St. Cloud (Figure 3.3). This concern has made ECM the focus of several hydrological and ecological studies, with a few concentrating specifically on recharge (Ruhl et al., 2002; Lorenz and Delin, 2007; Delin et al., 2007).

Using the three benchmark watersheds, mean minimum groundwater recharge rates were calculated using the previously discussed extrapolation method. Tables 3.1 through 3.3 summarize the 97 analysis watersheds and delineated drainage area by the benchmark watershed used for the data extrapolation and calculated mean minimum groundwater recharge rate. Gray scale coding in Figure 3.5 cluster watersheds based on this benchmark assignment.

3.3.2 Hierarchical Hydrogeological Units

Table 3.4 outlines the final HHU regionalization resulting from combinations of landscape characteristics with corresponding statistically significant mean minimum recharge rates. The broadest hierarchical level is defined as the Province, followed by the Subprovince, Region, Subregion and lastly, the most refined level possible, District.

Province Level

Landscape characteristics used to define Province and Subprovince hierarchical levels were based on previous analyses using the WCA at the statewide regionalization (Shmagin and Kanivetsky; 2002). The Province level HHUs are the most general and defined using the hydrogeologic boundaries of the Paleozoic artesian basin (PAB) and Precambrian crystalline basement (PB), illustrated in Figure 3.9. The Paleozoic rocks form an artesian system consisting of beds of sandstone, shale and limestone while the Precambrian basement are composed of more ancient rocks acting as confining layers. Therefore, the minimum recharge results at the Province level depicted in Table 3.4 are supported by the underlying hydrogeology, estimating higher mean minimum recharge values for HHU PAB. A box plot illustrating the data spread between PB and PAB is included as Figure 3.10.

Subprovince Level

At the Subprovince level, each Province HHU was further subdivided based on the number of groundwater flow field layers. The PB HHU was subdivided to isolate units with two or three flow field layers. Most of the PB HHU contains two flow field layers (B); however, the western border contains a third layer consisting of Cretaceous shale deposits (K) which underlies the Quaternary sediments. These Cretaceous deposits cause the K HHU to have a significantly lower mean minimum recharge compared to the areas without the deposits.

The PAB HHU was refined into two units based on one or two groundwater flow field layers. Areas of PAB with shallow (<21 meters) or exposed bedrock (A) were separated from those with thicker layers (AQ) of Quaternary sediments. As expected HHU A resulted in a higher mean minimum recharge rate due to a shallower system resulting in quicker groundwater recharge.

The distribution of mean minimum recharge within the four Subprovince HHUs is depicted in Figure 3.11.

Region Level

Refining HHUs after the Subprovince level became less straightforward as each HHU began to have varying underlying controlling factors. Results did not identify any discriminating hydrogeologic characteristics for the K and B HHUs at the Region level; however A and AQ HHUs were further divided.

It is hypothesized that the underlying bedrock aquifer influenced the recharge rate for HHU A. The four aquifers located within ECM include the St. Peter (A1), Prairie du Chien Jordan (A2), Franconia-Ironton-Galesville (A3) and lastly the Keweenawan Volcanic Rocks (A4). The calculated mean minimum recharge rates for each aquifer varied but corresponded to the aquifer material. Those composed of sandstone had the highest recharge rates while the Keweenawan had the lowest rate (Figure 3.12). For the Subprovince A HHUs, this is the most refined scale statistically acceptable due to the limited number of watersheds comprising each Region HHU. Applying additional characteristics, such as available water capacity or slope, within each bedrock aquifer did not produce statistically significant recharge rates.

Since Subprovince AQ HHUs have a thick layer of Quaternary sediments, they were further refined based on the Quaternary material. The presence of till material reduced the recharge rates in comparison to the gravel and sand. Most of the AQ watersheds were comprised predominantly of till making it possible to further refine the AQ3 HHUs into Subregion and District levels. The AQ1 and AQ2 units could not be further refined. Mean minimum recharge rates are summarized in Figure 3.13 for the Region level.

Subregion Level

It is important to acknowledge that at this hierarchical level, the number of watersheds subdivided into each unit became the limiting factor in computing statistical significance. The methodology is limited by the number of watersheds with available discharge data. Although non-parametric statistical analysis can be used with smaller data sets, a minimum of five watersheds should be used for each level.

Results indicated Subprovince HHUs K and B could be further refined based on the available water capacity of the soil overlaying the geologic unit. A soil with a higher available water capacity can absorb more infiltrating water than a soil with a lower capacity. This is reflected in the Subregion K and B HHUs because the lower the available water capacity, the higher the mean minimum recharge rates (Figures 3.14 and 3.15). This suggests that more precipitation is being held by the soil rather than extracted by plants or converted direct surface runoff or deep drainage (Sophocleous and McAllister, 1987; Sophocleous, 2004). The combination of Cretaceous deposits and a high available water capacity produced the lowest recharge rates within ECM.

In addition, HHU AQ3 was refined by the thickness of the Quaternary sediment. All of the units developed from the AQ Subprovince already were previously defined by having a thickness >21 meters. However, because of the till Quaternary sediment that the AQ3 HHUs have at the Region level, this thickness could be further divided. When sediments are present >40 meters in thickness (AQ3t), the till acts as a confining unit further impeding groundwater recharge. Areas with sediments <40 meters in thickness (AQ3s) have a significantly higher minimum recharge rate (Figure 3.16). The AQ3 Subregions were the only HHUs that could be further refined to the District level due to the limitation in available watershed data.

District Level

HHU AQ3s represents landscape areas having moderate Quaternary thickness overlaying till. These units are located primarily along the eastern boundary of ECM. Some of this area is represented by deep valleys creating a higher mean average watershed slope. Karst geology is often found in these areas of higher slope within ECM, which may be contributing to the statistically significant higher mean minimum groundwater recharge compared to the areas with a slope <9% (Figure 3.17).

3.3.3 Regional Recharge Map

Upon completion of the regionalization, boundaries for the most refined HHUs were delineated in GIS (Figure 3.18) and used to create a map of sustainable groundwater recharge rates for the ECM area (Figure 3.19). District level HHUs were not applied to the map because the two units (AQ3sl and AQ3sh) were defined based on mean watershed slope which varies across the territory.

3.4 Discussion

3.4.1 Additional Mapping

This process of defining the HHUs into more specific hierarchical subdivisions reflects each unit's similar hydrologic properties with respect to recharge. Because of these similarities, this methodology can provide a characterization of the groundwater system. Similarity allows for scaling and translation of hydrologic response from one location to another. Through this characterization of the groundwater system the three-dimensional structure of the watershed is recognized and boundaries for the specific units of regionalization are quantified. This information is essential for multi-scale mapping of regional recharge for the hierarchical quantification of units, prediction of functional patterns and bridging the scales as a concept- and content-based approach.

The ECM regionalization defined five hierarchical levels, each level refined by varying landscape characteristics leading to significant differences between calculated mean minimum recharge rates. Further division into a Subdistrict hierarchical level is possible; however, the HHU recharge values would not be statistically significant due to an insufficient set of study watersheds falling within each unit. In this case where recharge rates could not be calculated, expert judgment based on unit material and spatial location would be necessary to estimate values.

Although the WCA focuses on the use of minimum recharge, the methodology can be applied to additional freshwater recharge mapping; however, because of the uncertainty of baseflow separation, it is necessary to first identify the hydrogeologic units using the minimum flow and once those units are identified and, more importantly, mapped, it is possible to use the map and those identified units to quantify mean annual recharge; which in essence reflects total sustainable water resources because it captures both ground and surface water together. This next step of quantifying mean annual recharge can occur after the unit identification and mapping with minimum recharge estimates is completed. Thus, the identification of hydrogeologic units with similar landscape and hydrologic properties is essential to provide accurate scaled recharge estimates. Similarity does not require the same size or shape of the unit, but only similarity in characteristics (e.g. relief, material composition). This similarity allows the scaling up or scaling down of hydrologic response based on the absolute size of the unit.

3.4.2 Limitations and Verification

The accuracy of this method depends on the correct selection of benchmark watershed runoff characteristics, as well as the use of accurate maps reflecting landscape components. In short, the effectiveness of the analysis is measured by benchmarking of the hydrologic data. To demonstrate this limitation, minimum recharge was estimated for USGS gauge 5270500-Sauk River near St. Cloud, Minnesota. This gauge has long term data available, was part of the statewide regionalization and falls within ECM. Low flow data was estimated using the same technique used for all of the ECM analysis watersheds as if consistent long-term data were not available, but rather selecting a few random "partial-record" samples. Following the extrapolation discussed in the methodology of determining the linear proportion between the discharges of each benchmark watershed to the observed discharge value of gauge #5270500, a mean minimum recharge value was estimated for the watershed. A date of observed low flow during a year of average precipitation (6 September 1974) was chosen to base the extrapolation, and the estimated minimum recharge rates were compared using the three benchmarks. The calculated rates were 0.51 $l \cdot s^{-1} \cdot km^{-2}$ using benchmark #5313500, 6.31 $L \cdot s^{-1} \cdot km^{-22}$ using benchmark #5385000 and 0.91 $l \cdot s^{-1} \cdot km^{-2}$ using benchmark #5275000. Using the actual data for gauge #5270500, the mean minimum recharge for the interval 1955 through 1978 was 1.06 $L \cdot s^{-1} \cdot km^{-2}$. Benchmark #5275000, located adjacent #5270500 provides a conservative estimate, but is also the most reasonable when comparing it to the actual mean value.

In addition, using the HHUs that resulted from this ECM analysis, mean minimum recharge was calculated for gauge #5270500. The proportion of total area that each HHU comprised within the corresponding watershed boundary (Figure 3.20) was multiplied to the corresponding mean minimum recharge listed for each HHU in Table 3.4. This was done using the quartile rates as well. The mean minimum recharge rate was 0.49 $L{\cdot}s^{-1}{\cdot}km^{-2}$ with lower and upper quartiles at 0.15 $L{\cdot}s^{-1}{\cdot}km^{-2}$ and 0.64 $L{\cdot}s^{-1}{\cdot}km^{-2}$, respectively. This back calculation using the developed HHUs and corresponding recharge rates demonstrates that the groundwater recharge rates are true "minimum" rates representing sustainable groundwater resources.

A major assumption for this approach is hydrologic stationarity. As discussed in the methodology, the 1955 through 1978 time interval was chosen for the quantification of watershed hydrologic characteristics because it produces the most conservative recharge rates since it is a period prior to documented climatic variations or anthropogenic alterations. The idea is to produce a benchmark for water resources and use the recharge rates as a means to expand through additional research to identify changes due to more recent non-stationary trends. Research within Midwestern states has identified streamflow variation due to landuse/landcover changes (Schilling et al., 2010; Lenhart et al., 2011).

Theoretically, there are no general limitations with the analytical methodology regarding the possible scale of compilation, except as demonstrated with ECM, the availability of data can put a limit on the achievable detail. The more detailed the map desired, the more detailed data and analysis watersheds required. Using only geological information for outlining the hydrologic units leads to a map detail no better than 1:500,000. However, because of the ever increasing availability of hydrological geospatial data (e.g., Consortium of Universities for the Advancement of Hydrologic Science, Incorporated (CUAHSI) and Total Maximum Daily Load (TMDL) monitoring programs) that can be related to landscape water flux fields, it appears that future results may be feasible at refined scales. A further reduction in scale was achieved by applying the results from ECM to the TCMA, which encompasses Minneapolis and St. Paul, at a scale of 1:200,000 (Ruhl et al., 2002). This application of the WCA demonstrates that it is a sound approach that could tackle the problem of bridging across spatial scales and processes.

3.4.3 Application to Sustainability

In recent years it has become increasingly apparent that in order to link water balance characteristics with the landscape, there is a need to look into hydrologic similarity of land areas with commonality in landscape components (Lin et al., 2006; Reed et al., 2006). This new conceptual vision is also dictated by shifting water resources management strategies from water supply management to water demand management (Scanlon et al., 2007). Because of this shift in the water management paradigm influenced by the increased stresses on limited water resources: “it is urgent that the “L” (land) be incorporated in strategic planning of water for livelihoods and sustainability, since evidence clearly shows that the freshwater legacy of the past is definitely inadequate to enable us to face the challenges ahead of us” (Falkenmark and Rockstrom, 2006). Areas exhibiting increased stresses are often outside of monitoring areas. The application of the WCA using ECM demonstrated in this chapter illustrates how sustainable groundwater recharge maps could be produced for areas where long-term stream gauge monitoring is not available. These maps illustrate the renewable flux in a given area; therefore, maintaining groundwater extraction within these estimated recharge rates will reduce the risk of depleting the storage. Comparing the values depicted on these maps to human and ecological freshwater needs will provide an indicator of water sustainability which can be used to advance water resources management.

The WCA is an important management tool for integrating land and water resources because of the growing challenge due to the increased demand and competition for water. Generating geospatial data for water balance characteristics by compiling expert information into a decision support system can meet this challenge. Information from this research has been applied by the Minnesota Environmental Quality Board (http://www.eqb.state.mn.us/documents/Managing_for_Water_Sustainability_12-08.pdf) to address water resources sustainability in Minnesota and the mapping tool has been used to define an indicator of water resources sustainability at the national level by the Sustainable Water Resources Roundtable (http://water.usgs.gov/ogw/gwrp/activities/gw_recharge.html).

3.5 Conclusions

Regional recharge mapping was demonstrated using the WCA at a small scale using a territory within the state of Minnesota with limited available monitoring data. The ECM regionalization results summarized in this paper are based on an analysis of the holistic groundwater system represented by HHUs defined by landscape characteristics, rather than solely focusing on aquifers.

For the scale represented by ECM, assuming stationarity, it was determined that unique combinations of hydrogeologic, topographic and vadose zone properties control the minimum groundwater recharge. Incorporating the interdisciplinary processes occurring between landscape characteristics enables a holistic system approach to groundwater recharge estimation.

Within ECM, minimum groundwater recharge rates, or sustainable groundwater flux, were highest in areas dominated by Paleozoic artesian aquifers composed of sandstone materials overlain with a thin layer of Quaternary sediments. The lowest minimum groundwater recharge rates occur where Cretaceous deposits dominant and are overlain with soils having a high available water capacity.

By first defining the hydrologic controlling characteristics within the watersheds of a study area and then mapping those results to spatially depict the recharge rates, quantitative water management decisions could occur in areas with otherwise limited data availability.

Further analyses comparing the results summarized in this paper to actual water use within the area would provide an indicator of groundwater sustainability, which could be used in water resources management to reduce the risk of over-extraction of the freshwater resource.

Table 3.1 Analysis watersheds corresponding to benchmark watershed 5275000-Elk River near Big Lake, MN

USGS Gauging Station	Mean Minimum Groundwater Recharge[a] ($L\ s^{-1}\ km^{-2}$)	Drainage Area[b] (km^2)
5270110	1.93	139
5270180	0.98	630
5270210	0.29	226
5270230	0.30	1114
5270350	0.85	1658
5270455	1.01	113
5272300	0.69	144
5272600	0.74	77
5273000	0.09	202
5273498	0.30	446
5273600	0.42	135
5273990	0.09	87
5274000	0.34	299
5274300	0.29	97
5274380	1.58	608
5274480	3.11	83
5284810	1.19	77
5284950	0.25	381
5284970	0.66	113
5326400	0.35	1046
5329900	0.15	332
5335110	0.33	180
5335130	0.25	118
5335151	0.50	473
5335170	1.25	238
5335755	0.54	200
5335890	0.66	73
5335900	1.07	292
5337500	0.49	1149
5337530	0.03	83
5337600	0.27	163
5337700	0.97	194
5339490	0.34	140
5339720	0.46	144
5339750	0.42	176
5339800	0.24	135
5339950	1.23	139
5340110	0.04	69
5340130	2.84	135
5340170	3.60	182

[a] Extrapolated using benchmark watershed for the time interval of 1955 through 1978.

[b] Watersheds were delineated using USGS stream gauge stations.

Table 3.2 Analysis watersheds corresponding to benchmark watershed 5313500- Yellow Medicine River near Granite Falls, MN

USGS Gauging Station	Mean Minimum Groundwater Recharge[a] ($L\ s^{-1}\ km^{-2}$)	Drainage area[b] (km^2)
5270130	0.68	68
5270150	0.36	333
5270250	0.04	76
5270280	0.07	179
5275970	0.50	392
5277050	0.14	127
5278100	0.63	1925
5278150	0.03	218
5278590	0.10	1192
5278830	0.03	588
5278835	0.12	247
5278950	0.04	1062

[a] Extrapolated using benchmark watershed for the time interval of 1955 through 1978.

[b] Watersheds were delineated using USGS stream gauge stations.

Table 3. 3 Analysis watersheds corresponding to benchmark watershed 5385000-Root River near Houston, MN

USGS Gauging Station	Mean Minimum Groundwater Recharge[a] (L s^{-1} km^{-2})	Drainage Area[b] (km^2)	USGS Gauging Station	Mean Minimum Groundwater Recharge (L s^{-1} km^{-2})	Drainage Area (km2)
5288700	1.95	82	5355350	2.08	187
5288900	0.23	105	5372800	2.46	401
5320020	0.12	198	5372930	2.64	203
5320040	0.05	128	5372990	0.75	99
5320060	0.57	62	5373100	0.17	74
5320070	0.26	460	5373130	0.72	151
5320330	0.01	790	5373150	1.20	527
5320480	0.10	885	5373200	0.30	197
5341540	1.44	77	5373290	1.07	547
5345000	1.23	328	5373400	1.66	76
5352010	0.23	863	5373850	1.70	452
5352810	0.06	108	5373950	2.08	140
5352850	0.66	529	5373995	1.10	119
5352900	0.24	104	5374420	0.92	85
5353600	0.06	283	5374480	0.98	164
5354600	0.14	109	5374520	1.67	70
5355020	0.04	106	5375000	0.28	43
5355040	0.44	218	5376200	2.76	138
5355080	0.96	204	5376500	3.18	203
5355140	1.32	220	5377510	3.05	830
5355215	1.82	188	5378240	2.57	123
5355260	1.64	59	5378400	2.42	129
5355280	4.31	119			

[a] Extrapolated using benchmark watershed for the time interval of 1955 through 1978.
[b] Watersheds were delineated from USGS stream gauge stations.

Table 3.4 Mean minimum groundwater recharge rates for hierarchical hydrogeological units defined for East-Central Minnesota

Province	Mean Minimum Recharge ($L \cdot s^{-1} \cdot km^{-2}$)	Subprovince	Mean Minimum Recharge ($L \cdot s^{-1} \cdot km^{-2}$)	Region[c]	Mean Minimum Recharge ($L \cdot s^{-1} \cdot km^{-2}$)	Subregion	Mean Minimum Recharge ($L \cdot s^{-1} \cdot km^{-2}$)	District	Mean Minimum Recharge ($L \cdot s^{-1} \cdot km^{-2}$)
PB - Precambrian Basement (33)[a]	0.55 (0.10-0.69)[b]	**K** (6) - Three ground water flow field layers: Quaternary sediments, Cretaceous deposits & Precambrian Basement	0.36 (0.09-0.63)			**Kl** (3) - Low Available Water Capacity <0.13	0.65 (0.30-1.01)		
						Kh (3) - High Available water capacity >0.13	0.07 (0.03-0.10)		
		B (27) - Two ground water flow field layers: Quaternary sediments & Precambrian Basement	0.59 (0.12-0.74)			**Bl** (13) - Low Available Water Capacity <0.15	0.89 (0.34-0.98)		
						Bh (14) - High Available water capacity >0.15	0.31 (0.04-0.49)		

Continued on next page

Table 3.4 continued from previous page

Province	Mean Minimum Recharge (L·s^{-1}·km^{-2})	Subprovince	Mean Minimum Recharge (L·s^{-1}·km^{-2})	Region[c]	Mean Minimum Recharge (L·s^{-1}·km^{-2})	Subregion	Mean Minimum Recharge (L·s^{-1}·km^{-2})	District	Mean Minimum Recharge (L·s^{-1}·km^{-2})
PAB - Paleozoic Artesian Basin (64)	1.09 (0.25-1.67)	**A** (26) - One ground water flow field layer: Quaternary sediments <21 m thick, Paleozoic artesian aquifers	1.57 (0.75-2.42)	**A1** (7) - St. Peter aquifer	2.11 (1.32-3.05)				
				A2 (5) - Prairie du Chien Jordan aquifer	1.44 (0.98-1.64)				
				A3 (5) - Franconia-Ironton-Galesville aquifer	2.15 (1.67-2.42)				
				A4 (6) - Keweenawan Volcanic Rocks aquifer	0.67 (0.33-1.07)				
		AQ (38) - Two ground water flow field layers: Quaternary sediments >21 m thick & Paleozoic artesian aquifers	1.17 (0.35-1.85)	**AQ1** (6) - Gravel and sand Quaternary sediment	1.35 (0.66-1.95)				
				AQ2 (1) - Sand and gravel Quaternary sediment	3.60*				
				AQ3 (31) - Till Quaternary sediment	0.54 (0.12-0.66)	**AQ3s** (14) - Quaternary sediment thickness <40 m	0.89 (0.24-1.44)	**AQ3sl** (7) – <9% slope	0.29 (0.06-0.44)
								AQ3sh (7) – >9% slope	1.50 (1.07-2.08)
						AQ3t (17) - Quaternary sediment thickness >40 m	0.25 (0.10-0.30)		

[a] (#) refers to the number of watersheds included in analysis.

[b] Range of the lower and upper quartile.

[c] Watersheds included in analysis at Region level may not equal those in Subregion level due to combination of predominant characteristic not identified within the boundaries of East Central Minnesota.

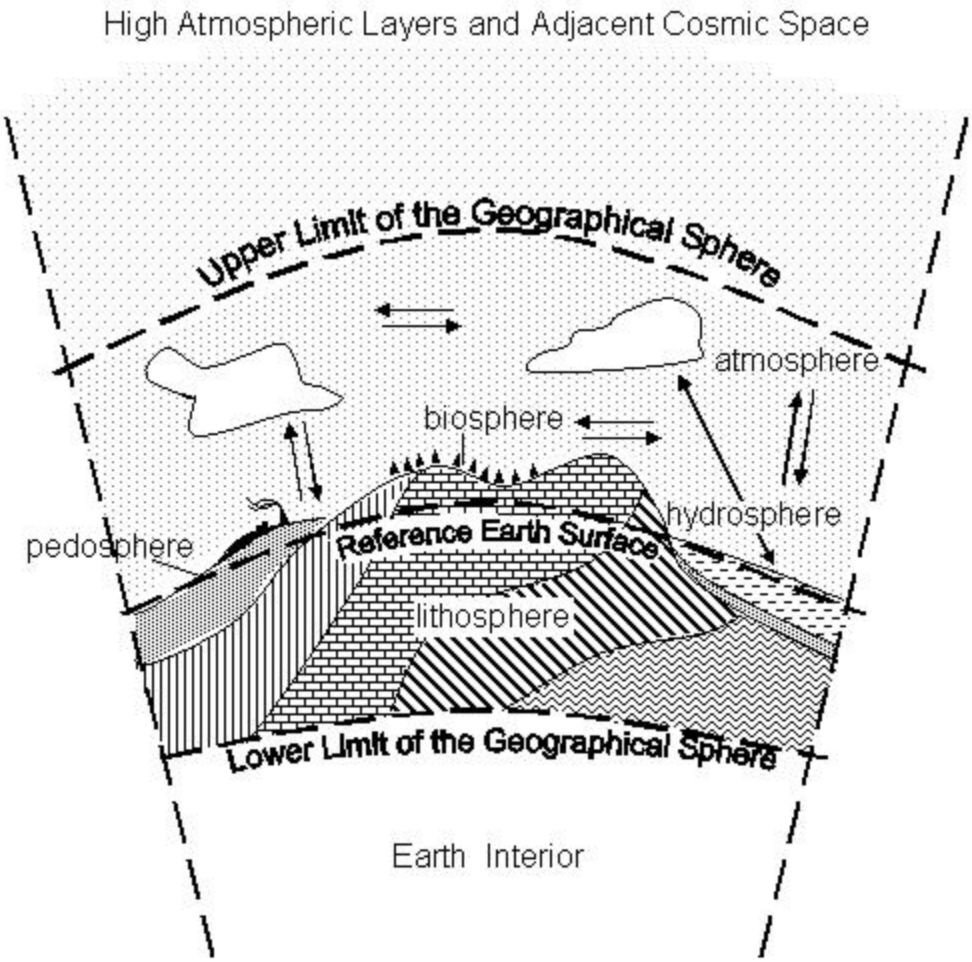

Figure 3.1 System model of geospheres adapted from Krcho (2001), depicting the composition of Earth's layers

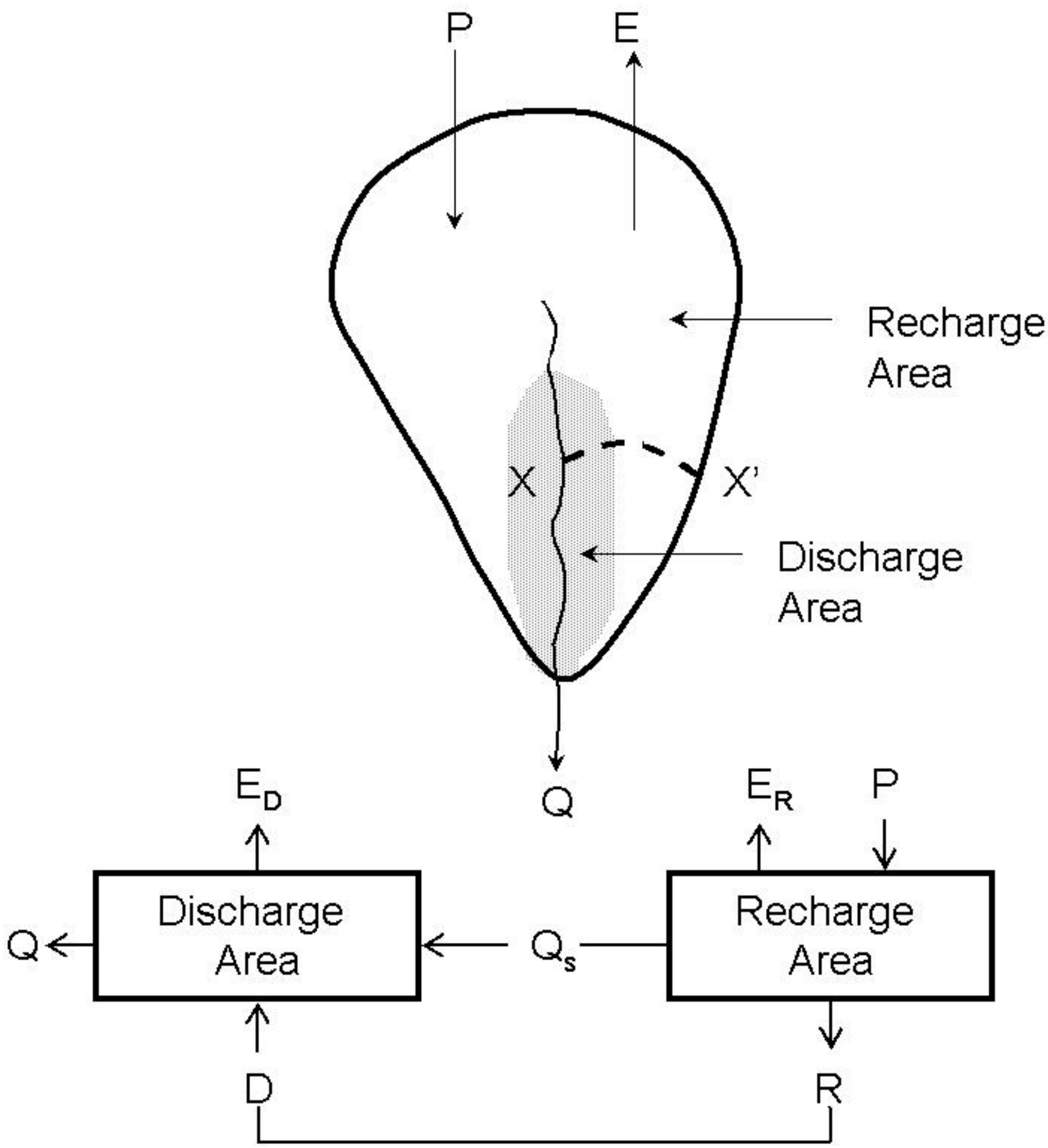

Figure 3.2 Conceptual watershed model adapted from Freeze and Cherry (1979). P is precipitation, Q the runoff, and E the evapotranspiration. Q becomes the sum of the groundwater component of average annual runoff or baseflow and the surface-water component of average annual runoff (Q_S). E_R is average annual evapotranspiration from the recharge area, R is the average annual groundwater recharge, D is the average annual groundwater discharge (equal to R) and E_D is the average annual evapotranspiration from the discharge area

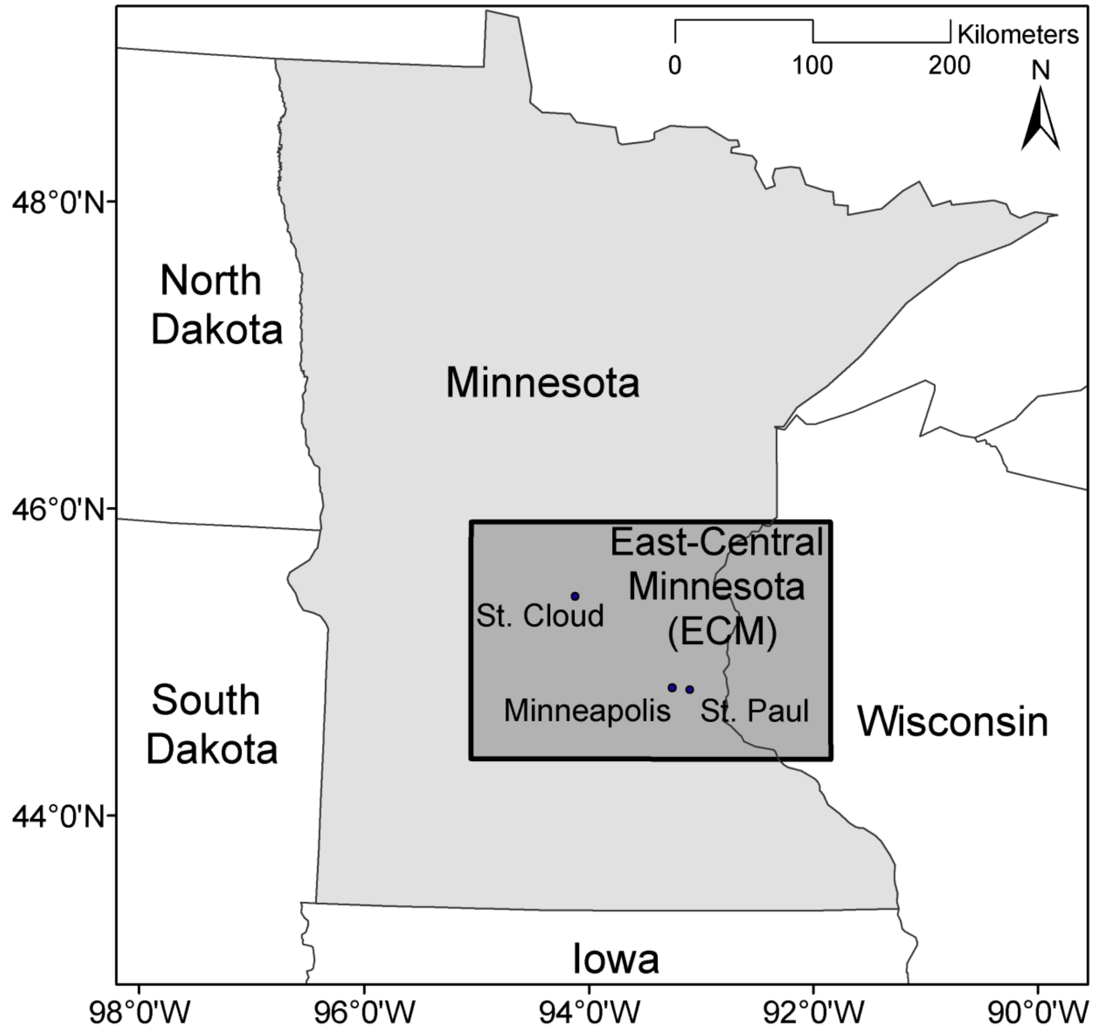

Figure 3.3 Geographic location of the application area referred to as the East-Central region of Minnesota (ECM)

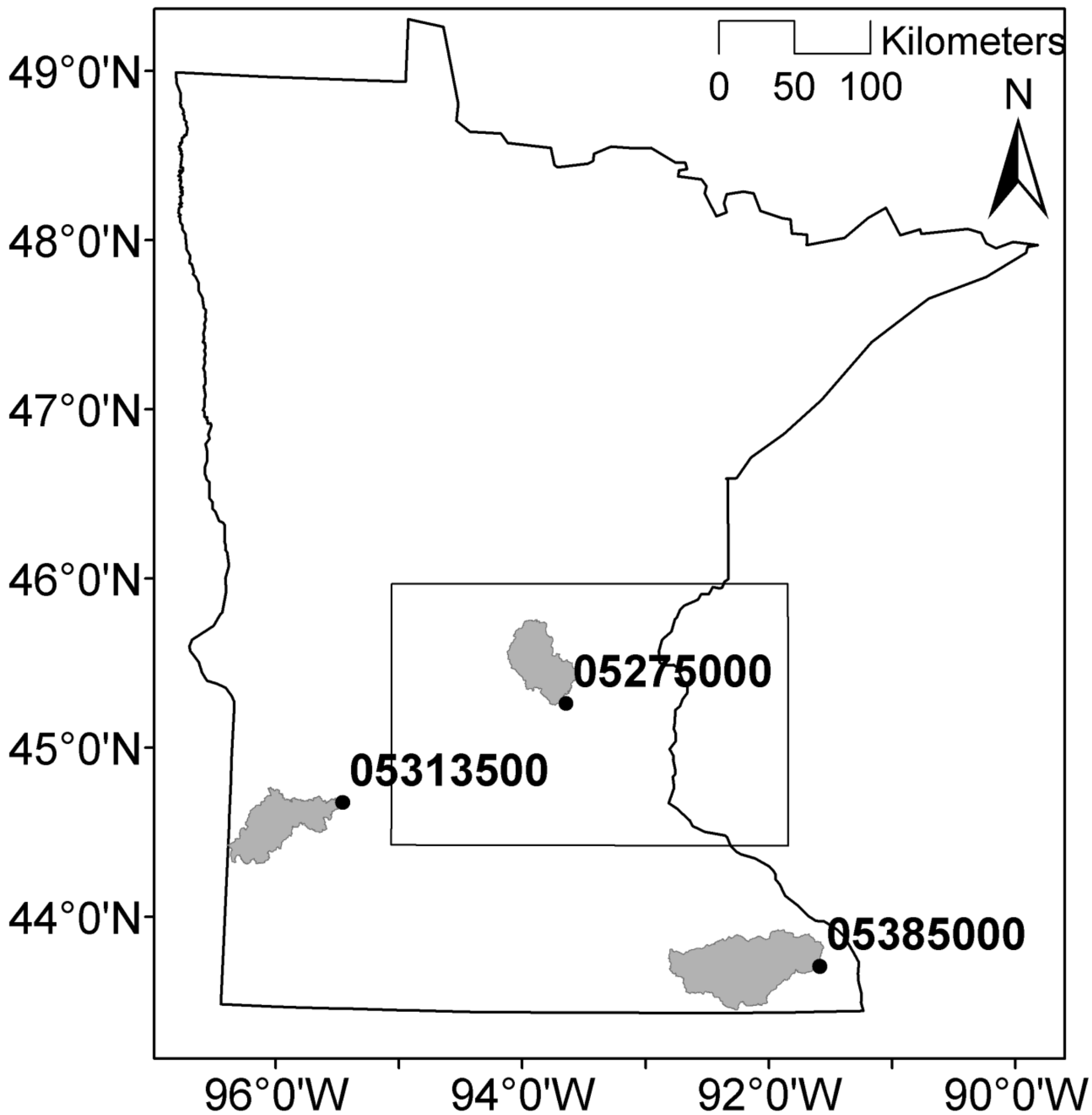

Figure 3.4 Three benchmark watersheds were selected to represent the East-Central region of Minnesota

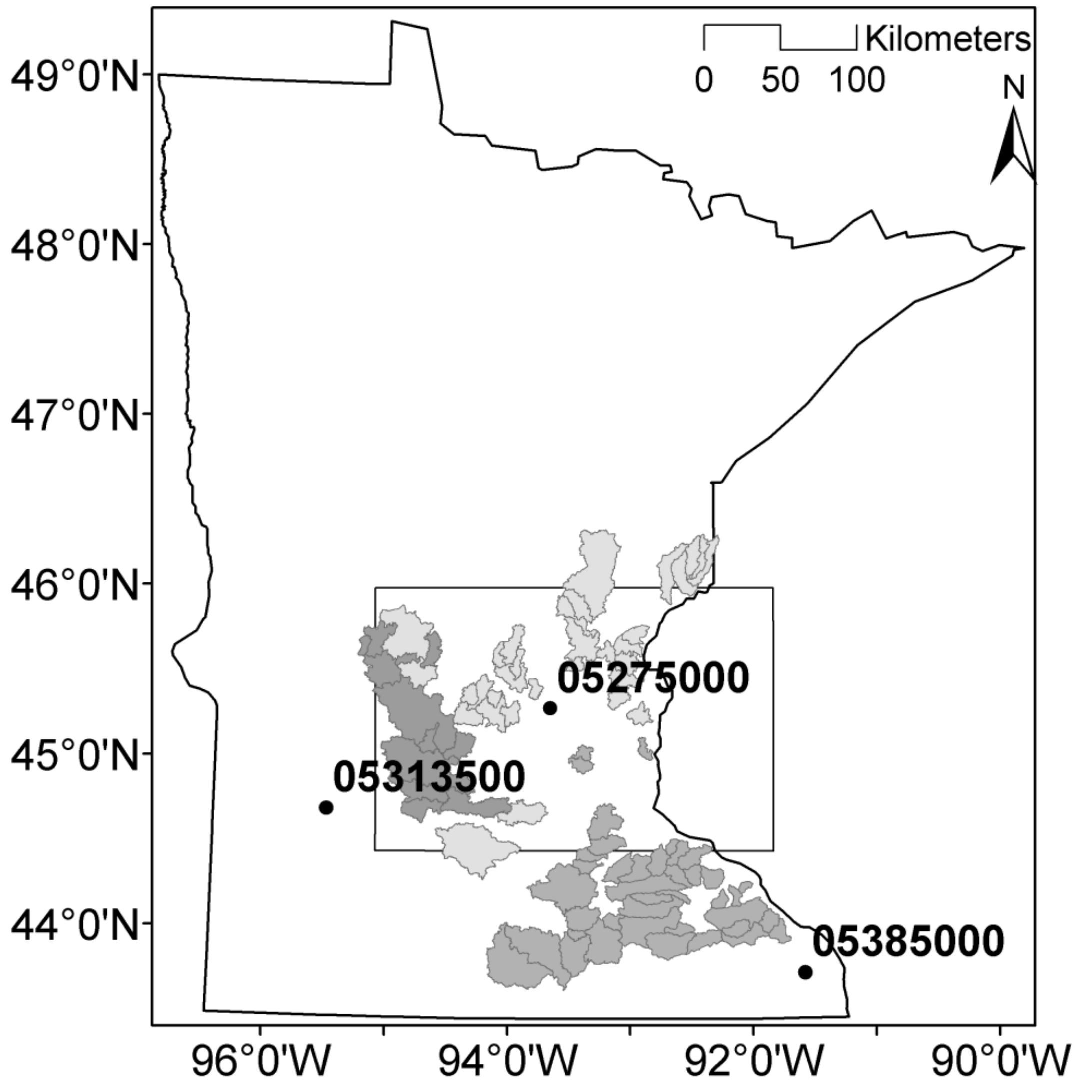

Figure 3.5 Ninety-seven watersheds were delineated from stream monitoring locations and used to apply the Watershed Characteristics Approach to the East-Central region of Minnesota

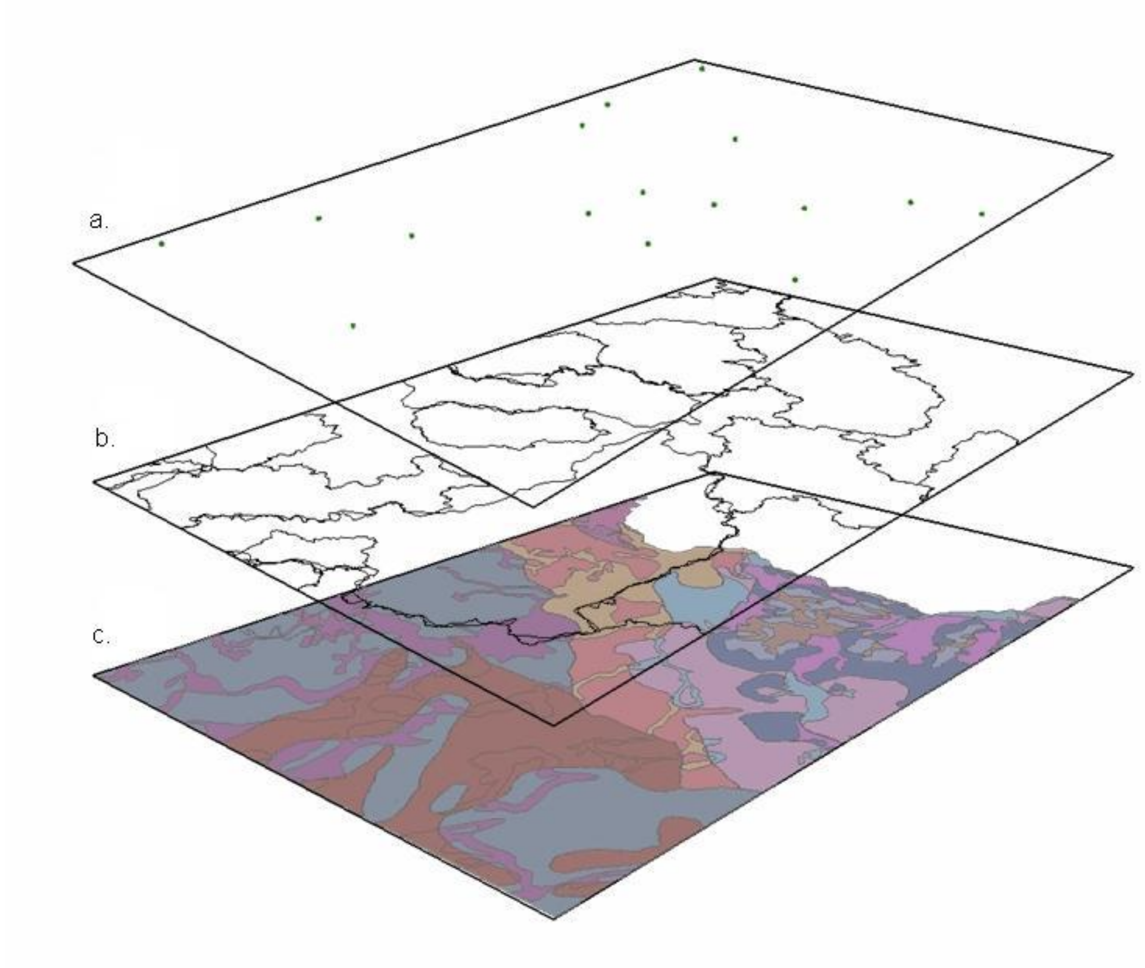

Figure 3.6 Overlay of a) gauging stations, b) watershed boundaries and c) landscape characteristics in a GIS used to extract values incorporated into the initial matrix for the watershed characterization

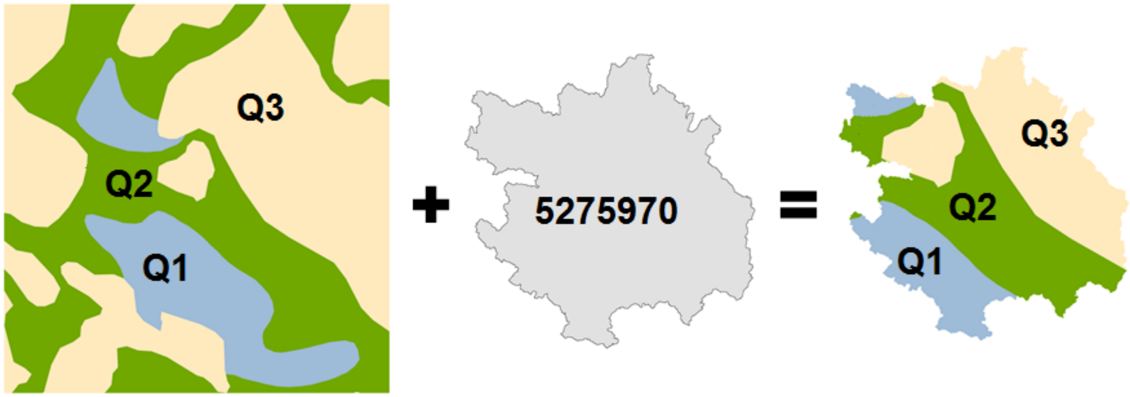

Figure 3.7 Depiction of the watershed landscape characterization process illustrating that if a GIS map of Quaternary sediments is available along with the boundary of a watershed (USGS low-flow partial record gauge #5275970), the fraction of each watershed falling into units Q1 (predominantly gravel with sand), Q2 (predominantly sand with gravel) or Q3 (till) could be quantified

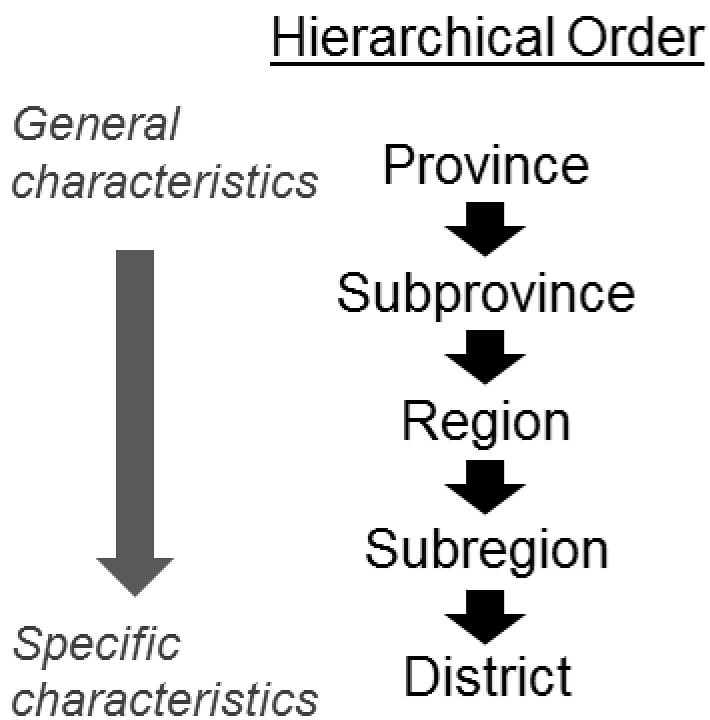

Figure 3.8 Hierarchical order diagram used in the hydrogeological regionalization

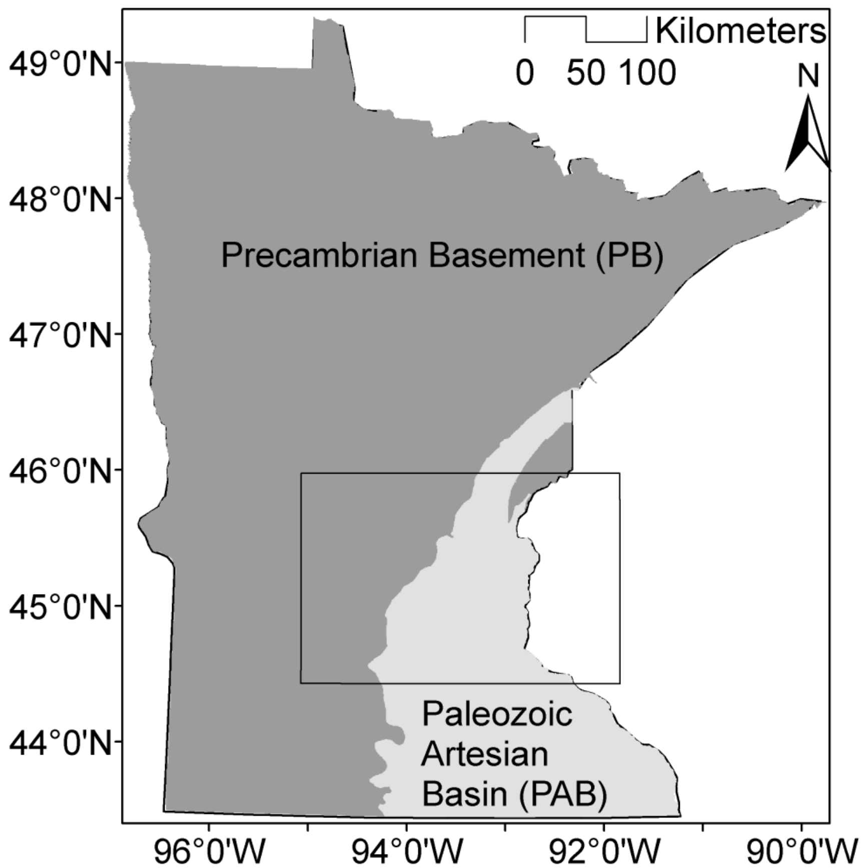

Figure 3. 9 Distribution of Precambrian Basement (PB) and Paleozoic Artesian Basin (PAB) within the state of Minnesota

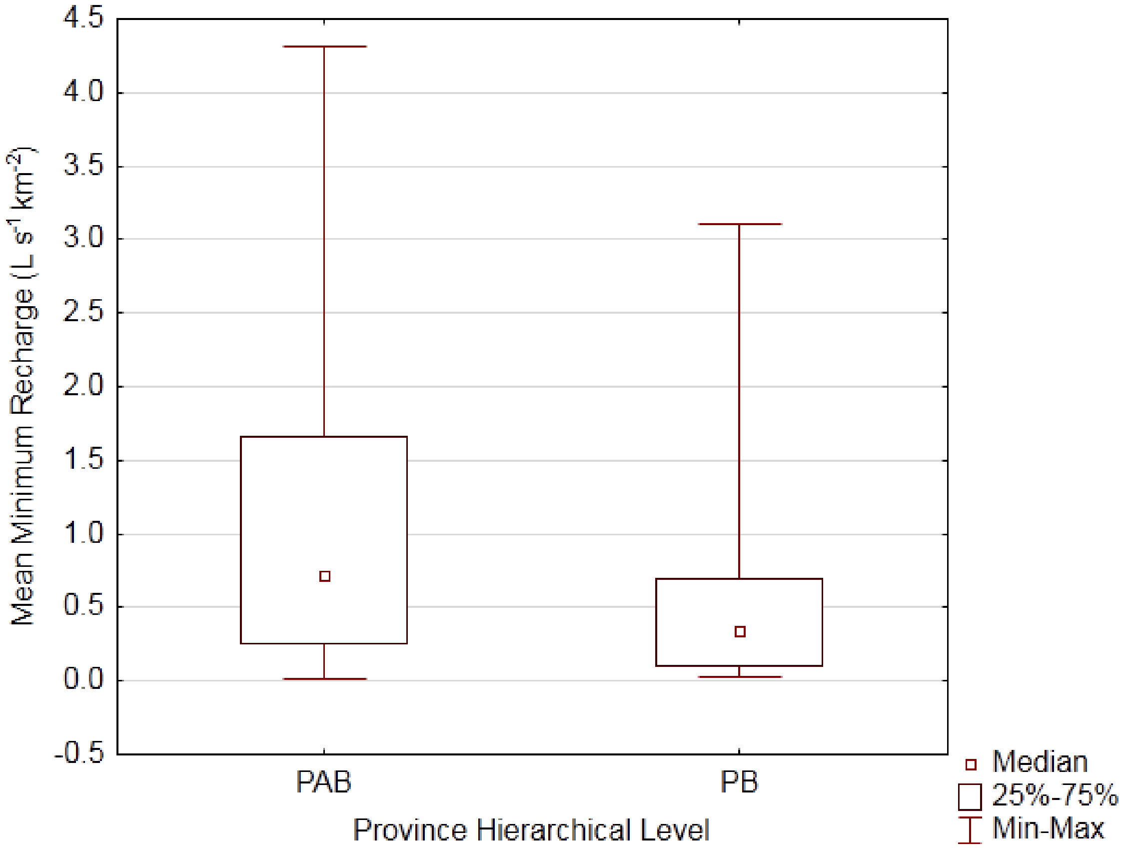

Figure 3.10 Box plot illustrating the quartile spread, median, minimum and maximum distribution of mean minimum recharge within the hydrogeological units that comprise the most general, Province hierarchical level

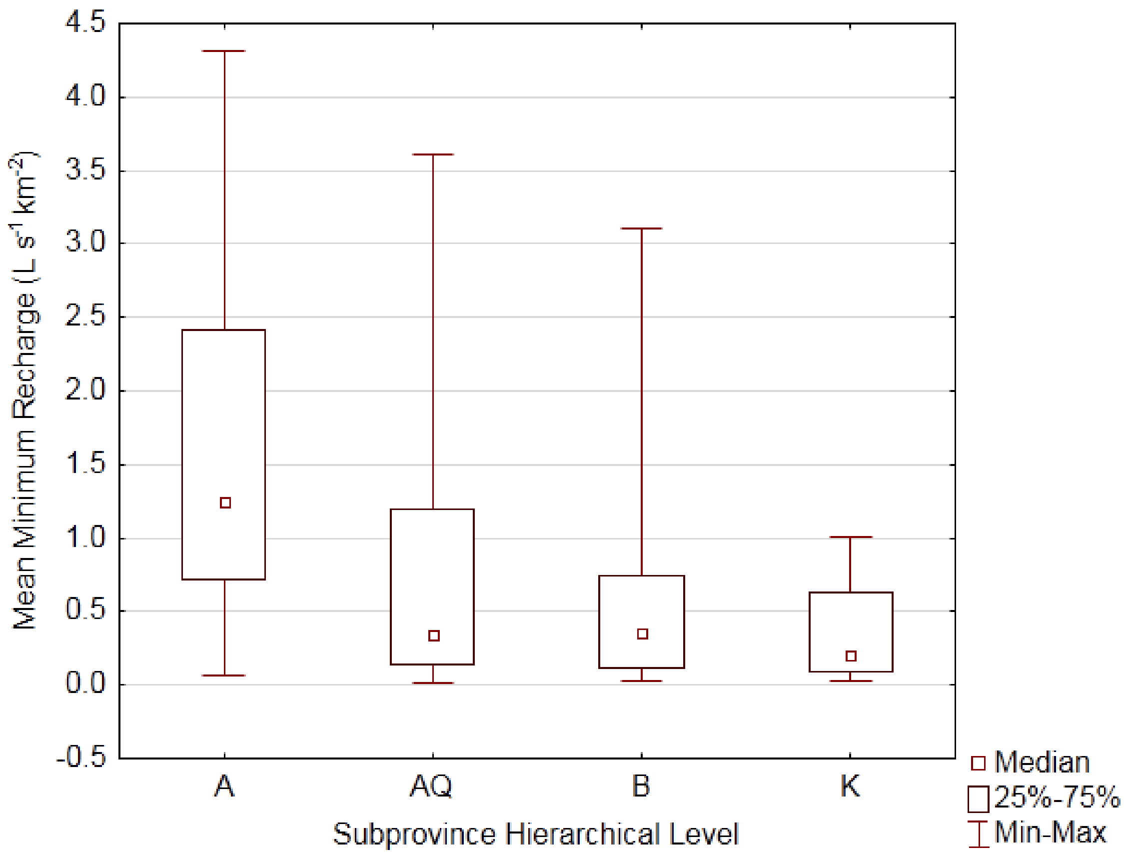

Figure 3.11 Box plot illustrating the quartile spread, median, minimum and maximum distribution of mean minimum recharge within the hydrogeological units that comprise the Subprovince hierarchical level

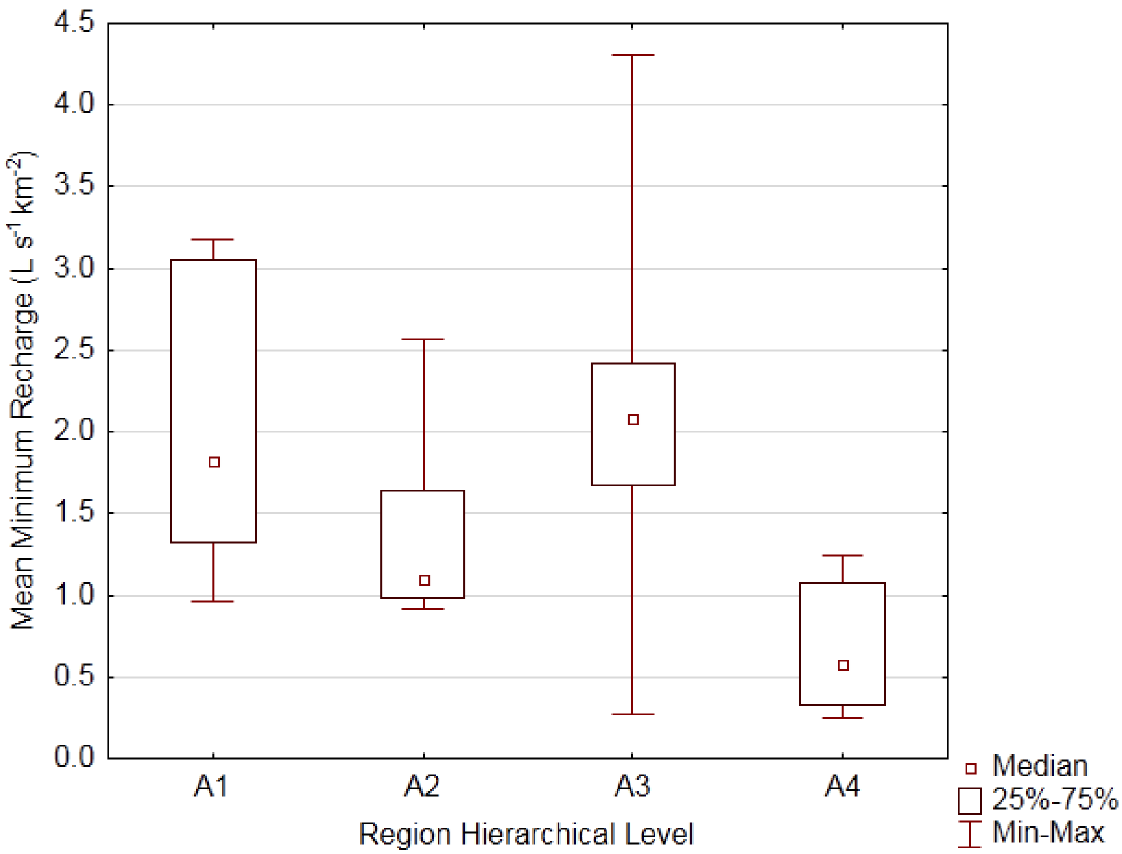

Figure 3.12 Box plot illustrating the quartile spread, median, minimum and maximum distribution of mean minimum recharge within the hydrogeological units that comprise the Region hierarchical level with one groundwater flow field layer within the Paleozoic Artesian Basin (PAB)

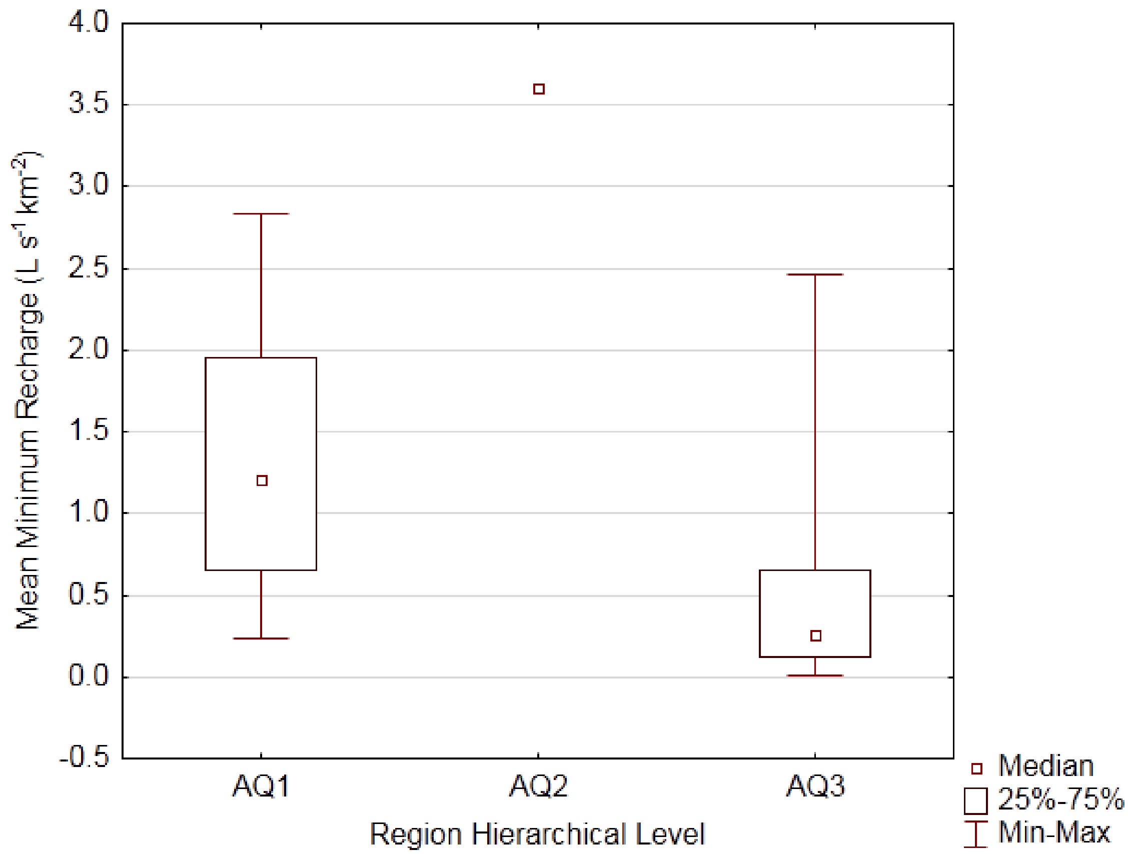

Figure 3.13 Box plot illustrating the quartile spread, median, minimum and maximum distribution of mean minimum recharge within the hydrogeological units that comprise the Region hierarchical level with two groundwater flow field layers within the Paleozoic Artesian Basin (PAB)

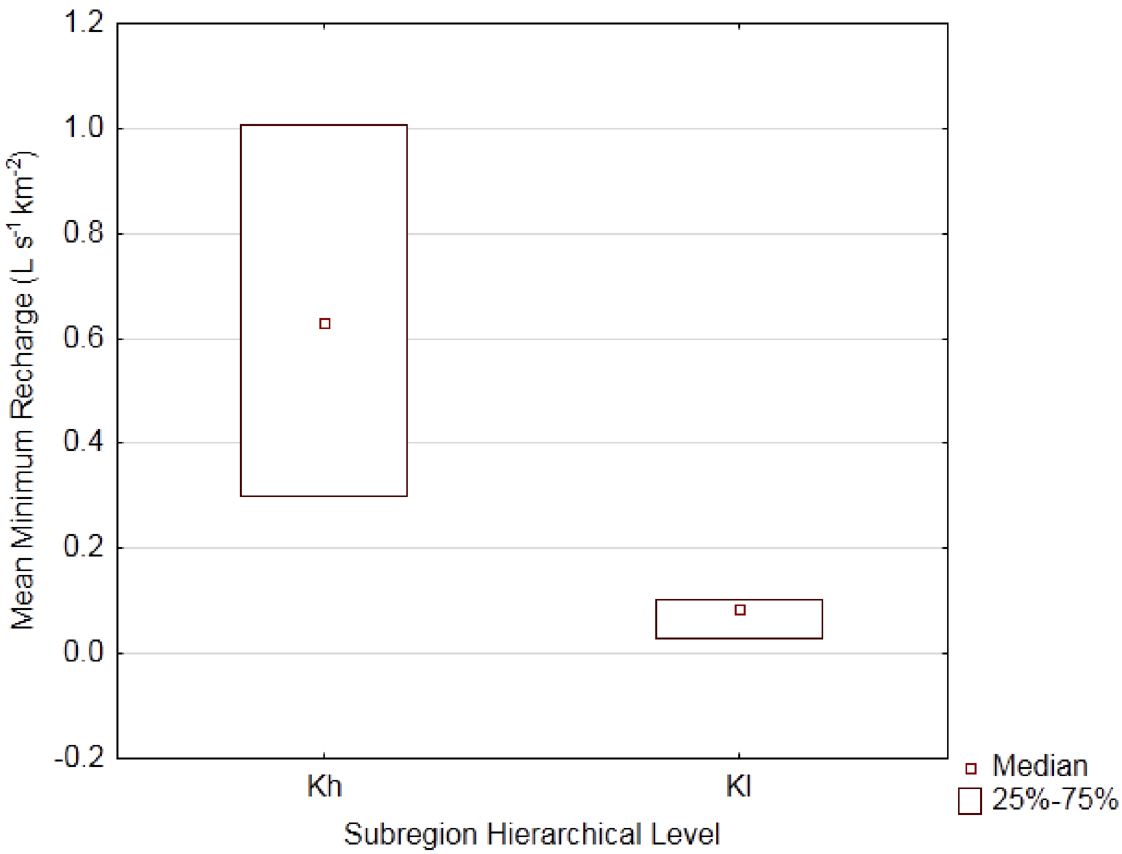

Figure 3.14 Box plot illustrating the quartile spread and median distribution of mean minimum recharge within the hydrogeological units that comprise the Subregion hierarchical level with three groundwater flow field layers within the Precambrian Basement (PB)

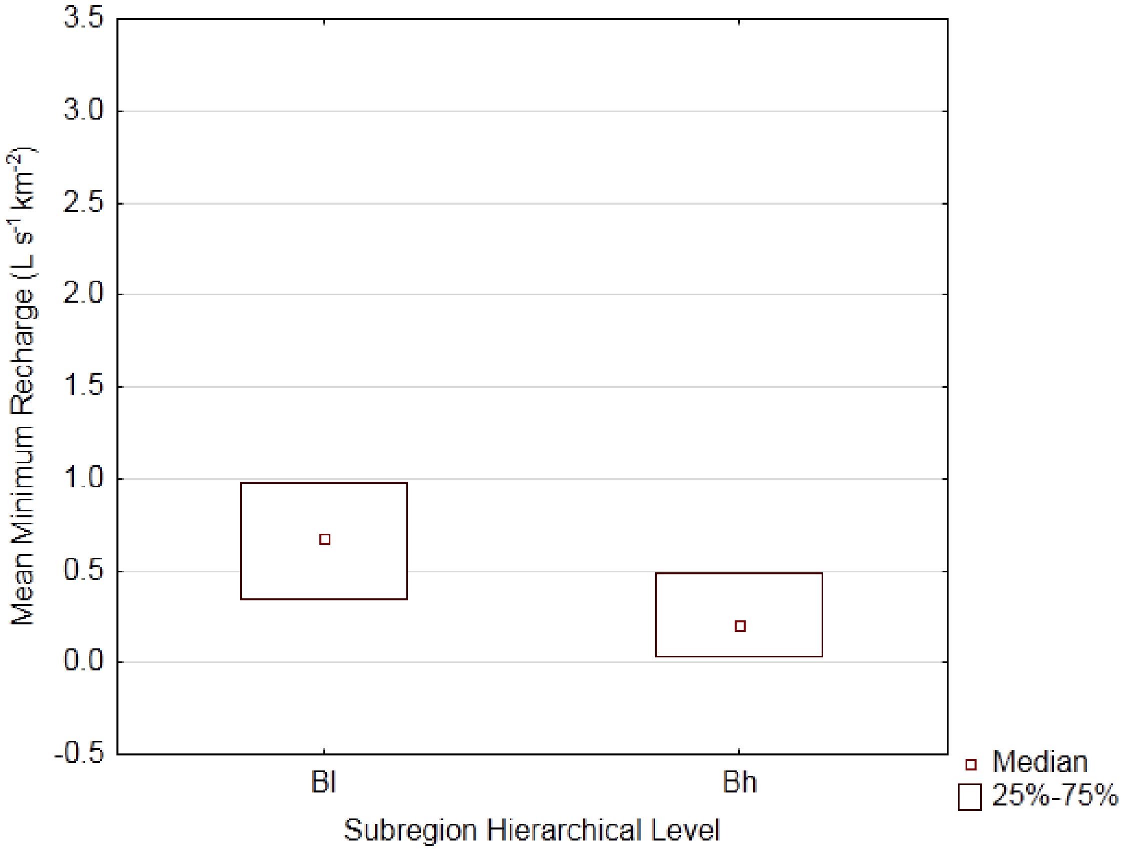

Figure 3.15 Box plot illustrating the quartile spread and median distribution of mean minimum recharge within the hydrogeological units that comprise the Subregion hierarchical level with two groundwater flow field layers within the Precambrian Basement (PB)

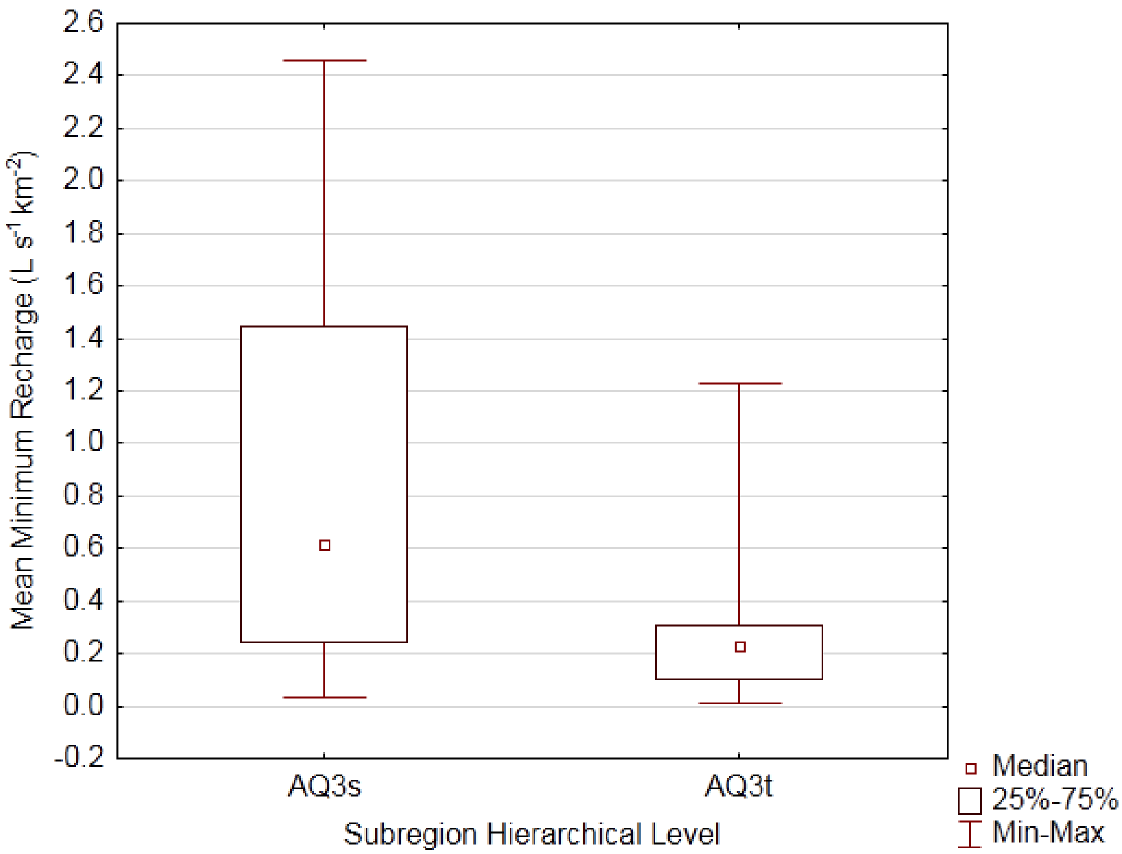

Figure 3.16 Box plot illustrating the quartile spread, median, minimum and maximum distribution of mean minimum recharge within the hydrogeological units that comprise Subregion hierarchical level with glacial till Quaternary sediments within the Paleozoic Artesian Basin (PAB)

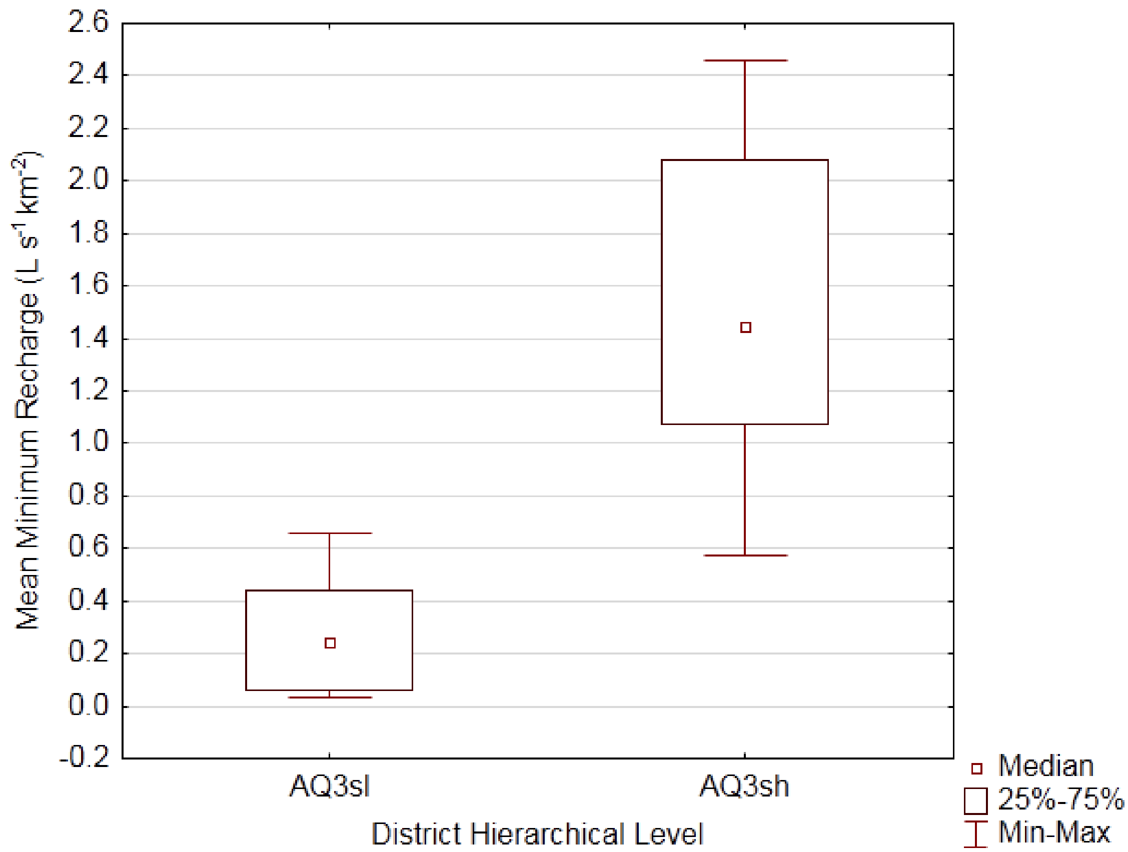

Figure 3.17 Box plot illustrating the quartile spread, median, minimum and maximum distribution of mean minimum recharge within the hydrogeological units that comprise the most refined, District hierarchical level

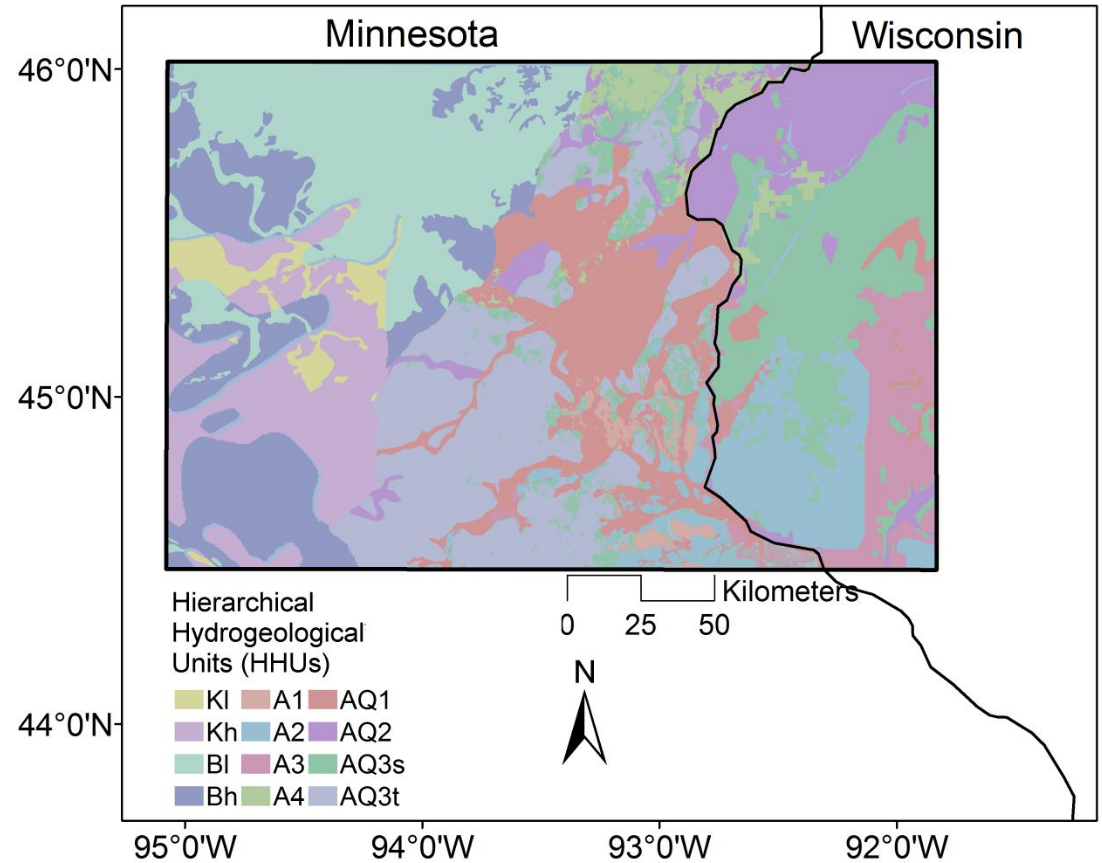

Figure 3.18 Map depicting spatial location of Hierarchical Hydrogeological Units (HHUs) refined to the Subregion level within the East-Central region of Minnesota

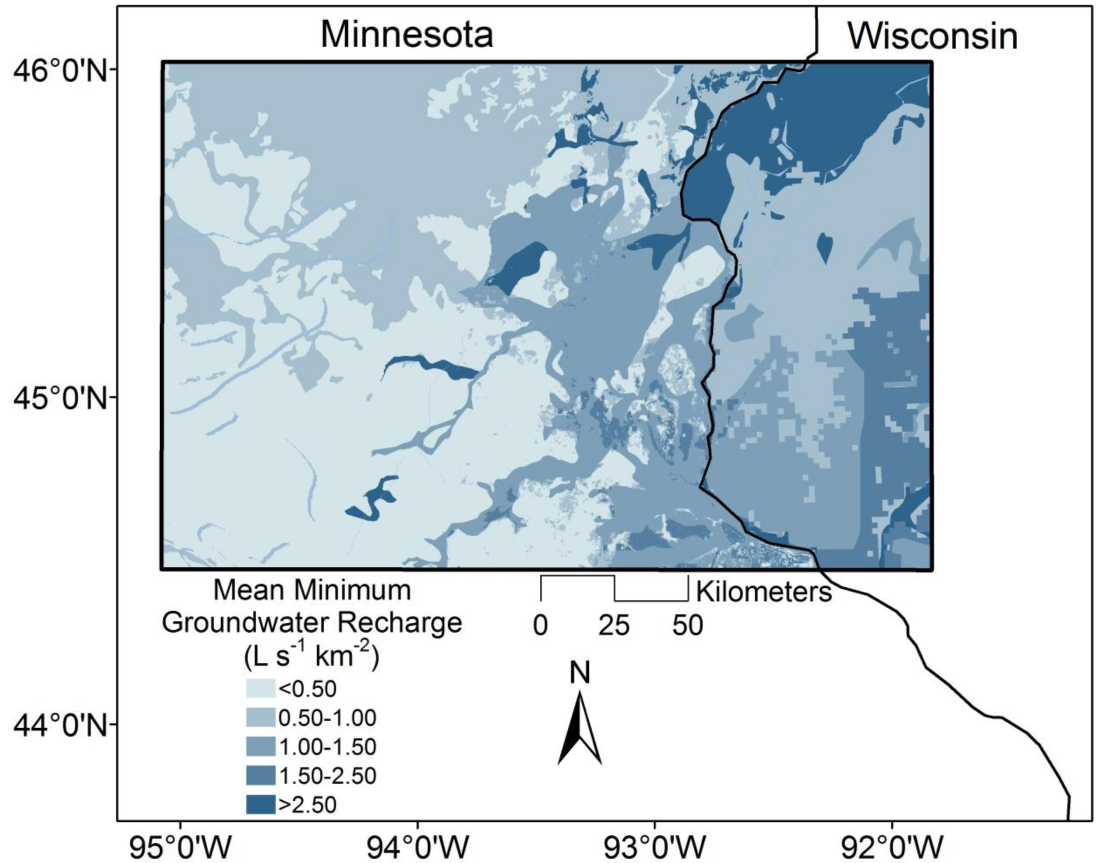

Figure 3.19 Map of mean minimum (sustainable) groundwater recharge rates for the East-Central region of Minnesota

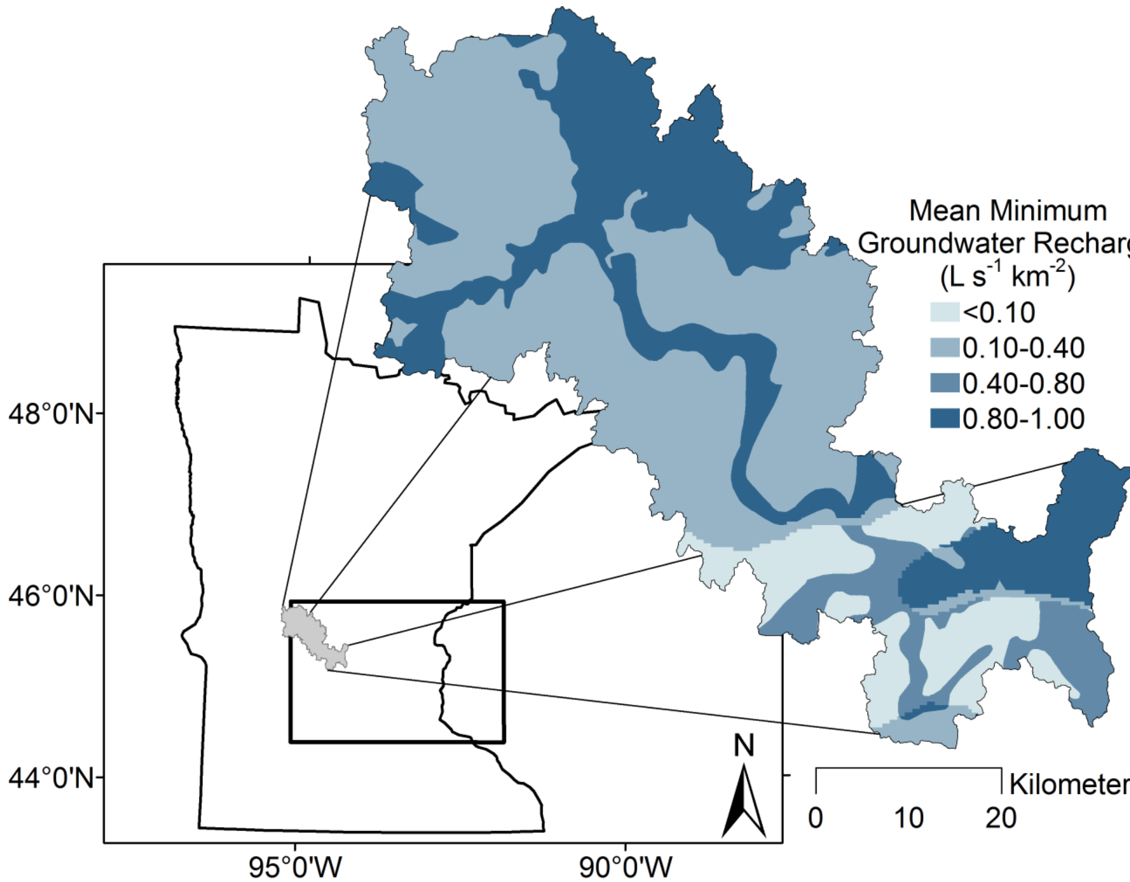

Figure 3.20 Mean minimum (sustainable) groundwater recharge rates depicted for USGS stream gauge #5270500-Sauk River near St. Cloud, Minnesota

Chapter 4

Water Resources Sustainability Indicator: Application of the Watershed Characteristics Approach

4.1 Introduction

Understanding the complexity of sustainability requires a holistic "system thinking" approach. The foundation involves three-pillars: the environment, economics and society (Holdren, 2008). Water is central to the environment and its sustainability is the key to the state of Minnesota's economy, healthy ecosystem functioning and the well-being of its present and future generations. Annually the people of Minnesota spend billions of dollars on water recreation. As water resources become depleted and degraded, so does the natural resource base that sustains the economy (Nelson, 1998). Accelerated economic development in Minnesota since World War II resulted in non-sustainable practices evident through damage to its myriad of ecosystem services, namely stream flow depletion and lake desiccation, degradation of water quality in streams and rivers, loss of wetlands and sensitive areas, loss of biodiversity, decrease in stream flow and groundwater levels, contamination of surface and groundwaters, land use/land cover (LULC) changes, and lastly, competition for in-stream flow needs for recreation, navigation, waste assimilation and aquatic habitat.

Water is a single resource, regardless of whether it appears as ground or surface water. Therefore, to address the complex issue of water resources sustainability, both ground and surface water must be quantified together (Alley and Leake, 2004; Falkenmark, 2008). Water flowing through the hydrologic system (Menció et al., 2010), rather than the volume stored within, represents the renewable amount available for sustainable use. Thus, sustainable water management must be based on connectivity as a property of all components of the terrestrial hydrologic system linked to water balance characteristics operating at multi-scales, along with the dynamic nature of interactions in the complex environment (McDonnell et al., 2007).

Even if water resources are regionally abundant, intensive water use in centralized metropolitan areas can create significant stresses resulting in large depression cones. In 1971, a cone of depression under the TCMA was measured 40 kilometers in diameter and 30 to 45 meters deep (Norvitch et al., 1973; Schoenberg, 1984). Groundwater management decisions in the United States are made at a local level, even though aquifer systems may cross political boundaries. Each regional groundwater system is unique in terms of its climate, hydrogeologic framework and boundary conditions causing each system to respond differently to stresses from human development and climate (Reilly et al., 2008). According to the Minnesota Department of Administration (McMurry, 2007), Minnesota's population is projected to increase by 24% between 2005 and 2035 with growth concentrated within the approximately 8000 square-kilometer, seven-county TCMA (Figure 4.1). In 2004, approximately 1.7 million cubic meters of water per day were used within the TCMA, two-thirds of which comes from groundwater sources. Approximately 70% of the water used within the TCMA is supplied through municipal water works serving residential, commercial and industrial customers (Metropolitan Council, 2007). The total water demand is projected to increase 16% by 2030. Currently in the TCMA there is insufficient information on the availability of groundwater for addressing water resources sustainability for human needs and ecological services. The key indicator of sustainable water use is the ratio of the renewable capacity (i.e. limit) of the hydrologic system to the water use by humans and the environment (Kanivetsky and Shmagin, 2005). For a sustainable system this ratio needs to be greater than unity.

Long-term continuous monitoring of stream flow and groundwater elevations is costly and not always available at the necessary management area or scale, such as the TCMA. There is a need for an alternative catchment-scale hydrologic model capable of predicting stream flow at ungauged sites (Mutua and Klik, 2007); especially for assessing temporal hydrologic variations due to climatic and LULC changes. This study demonstrates using the TCMA how the WCA applies hydrogeologic regionalization results based on available gauging data, to quantify a sustainability indicator (SI) for water resources at a scale where consistent, consecutive gauging data is not available. Using this methodology, areas of potential hydrologic limitation could be identified to advance future community development toward sustainable water resources management.

4.2 Methodology for Sustainability

4.2.1 Watershed Characteristics Approach

To assess the sustainable water resources in the TCMA, the flux (or flow) through the system was assessed using results of the WCA, a methodology described in previous papers (Shmagin and Kanivetsky, 2002; Kanivetsky and Shmagin, 2005; Shmagin and Kanivetsky, 2006) and Chapter 3. It follows the system ideology of Krcho (1995) that at a given point on Earth’s surface, a combination of different layers, each representing fundamental landscape components, yields unique features related to hydrologic and hydrogeologic response. Although the methodology requires complex statistical analyses of detailed landscape data and long-term streamflow records, the advantage is that the results are more independent of time and scale than other recharge estimation methods (Ruhl et al., 2002).

The WCA is a regionalization methodology using nonparametric and descriptive data analysis techniques to parameterize and quantify relationships between watershed landscape properties and water balance characteristics to develop statistically-based HHUs. This regionalization approach can be used at various scales to define HHUs for different territories. As the territory analyzed becomes smaller and more specific, HHUs generally become refined because of the increased availability of higher resolution data. For example, research at the statewide scale identified two hydrogeologic units within Minnesota. Studying a smaller territory focusing on ECM, HHUs were defined based on the unique overlay combinations of hydrogeological landscape characteristics including aquifers, bedrock and quaternary material that had statistically significant influences on recharge (Shmagin and Kanivetsky, 2002; Kanivetsky and Shmagin, 2005). This concept of refining recharge rates at various scales follows the theory of three groundwater flow systems (regional, intermediate and local systems) within a basin (Tóth, 1963; Tóth and Sheng, 1996). The defined HHUs each had a corresponding associated recharge value which was determined based on the watersheds composed predominantly of the specific landscape characteristics.

When an assessment of sustainability is the objective, efforts must be made to measure accurate recharge rates (Devlin and Sophocleous, 2005). To conservatively estimate the sustainable groundwater recharge, the WCA uses mean minimum monthly streamflow taken from actual measurements, representing true recharge. Alternative methods, such as hydrograph separation, can yield significant errors in recharge estimation by effects such as bank storage (Scanlon et al., 2002). For Minnesota, the minimum monthly flow is in February (Ruhl et al., 2002; Shmagin and Kanivetsky, 2002) and it is assumed that any stream flow during this month is due to groundwater and not surface recharge since soils are generally frozen due to subfreezing temperatures. This method is similar to stable-base-flow analysis in that it lessens the likelihood of overestimating recharge due to surface runoff generated by rainstorm events (Lee et al., 2006).

The WCA has been used to estimate mean minimum recharge in three stages (Figure 4.1): first, for the entire state of Minnesota (Shmagin and Kanivetsky, 2002), next for ECM (Chapter 3) and finally for the TCMA (Kanivetsky and Shmagin, 2001). Following the identification of the initial hydrogeologic units at the statewide analysis, more refined HHUs were identified for the ECM and the TCMA as additional landscape characteristics were identified by using higher resolution spatial data not available at the scale of the state.

For analyses covering a large territory, such as at the statewide scale, the period of streamflow records available is generally much longer and complete than those records accessible for a smaller analysis area, where continuous stream gauge data is limited or not available. To address this data limitation, benchmark watersheds from the statewide analysis can be used to extrapolate data from partial or one-time observations recorded at smaller watersheds. For example, three benchmark watersheds were used in Chapter 3 to extrapolate mean minimum recharge rates for the watersheds within the ECM territory, where only low-flow, partial streamflow data was available. By identifying the predominant landscape characteristics of these watersheds which significantly influenced the extrapolated mean minimum recharge rates, HHUs were identified at the refined scales.

When the analysis area covered less territory then the ECM, such as with the TCMA, gauged watersheds with even one recorded low-flow observation become so scarce that recharge rates for any further refinement of HHUs need to be identified directly from the ECM results. There is generally not enough data to extrapolate values using benchmark watersheds. Refined HHUs were identified at this more local scale because there was higher resolution landscape data available, but it was not possible to quantify a recharge value for each of these refined HHUs based on hydrologic monitoring data due to lack of sufficient monitoring data. Instead the recharge rates for the refined HHUs were derived based on extrapolation of the HHU values from the ECM scale and expert judgment based on documented local level hydrogeological data. Following the completion of the data extrapolation from the ECM analysis to the TCMA, HHUs with corresponding mean minimum recharge rates were spatially depicted in GIS, creating a map of mean minimum recharge (sustainable groundwater flux) in an area with an otherwise limited stream gauge network.

In addition to mean minimum recharge, mean annual flux was also calculated for the hydrogeologic units defined for the state since there was an abundance of available mean annual streamflow data for the analysis watersheds. As opposed to mean minimum recharge, the mean annual flux can be used to quantify total sustainable water resources because it includes both surface runoff and groundwater contributions, whereas the minimum is solely from groundwater. The hydrogeologic units defining the mean annual flux at the statewide scale were based on statistically significant mean annual streamflow rates within varying Bailey Ecoregions (Kanivetsky and Shmagin, 2005).

4.2.2 Sustainable Flux

The sustainable groundwater and total sustainable flux for the TCMA were calculated using the HHUs defined by Kanivetsky and Shmagin (2001). Digital polygons for each of the thirty HHUs extracted from the final TCMA recharge map (Kanivetsky and Shmagin, 2001) were obtained through the Minnesota Geological Survey and analyzed within a GIS. The total area encompassed by each HHU was calculated in GIS and used to compute the corresponding groundwater recharge volume for each corresponding unit (Figure 4.2).

Since the WCA uses the watershed area as a quantification unit, the recharge value corresponding to each HHU is a module of recharge as a unit of area (m^3 s^{-1} km^{-2}) (Zekster, 2002). Multiplying the total land area composed by each HHU to this module of recharge and applying a specific duration of time would give the sustainable flux as a volume of water. Although the upper and lower recharge quartiles were also provided by Kanivetsky and Shmagin (2001), for this study the mean module of recharge for each HHU was used as a representative value for the volume calculations. By adding each of these volumes together, the total annual volume of groundwater recharge within the boundaries of the TCMA was calculated. By completing these same basic calculations using the statewide hydrogeologic units based on Bailey Ecoregions for mean annual flux (Kanivetsky and Shmagin, 2005), the total sustainable flux (groundwater and surface water combined) was also computed.

4.2.3 Sustainability Indicator

Genuine sustainability requires that consumption by humans and ecological services will not cause a decline or liquidation of freshwater resources (Kanivetsky and Shmagin, 2005). To assess the SI, usage estimations and projections for the TCMA (Metropolitan Council, 2007) were compared to the calculated sustainable volumes, looking at groundwater alone, as well as the total flux including both ground and surface water. These usage values do not include volumes for power generation, as much of this water directly re-enters the hydrologic cycle via power plant effluent discharges.

By comparing the minimum groundwater recharge rates and total flux of the system to the historical water use in the area, the system's SI can be approximated (equation 4.1) for either the groundwater system alone or the combined ground and surface water system. Once spatially depicted onto a map, the SI quantification can be based on the multi-scale functioning HHUs. An indicator value less than 1 signifies unsustainable water use.

$$\mathbf{SI} = \frac{\textbf{Renewable water supply}}{\textbf{Water use by humans \& environment}} \tag{4.1}$$

The purpose of regional assessments is generally to determine natural water resources in large territories, such as river basins, and to calculate relative quantitative characteristics and total natural water resources (Zektser, 2002). This study evaluates the renewable limit of the hydrologic system within the TCMA using the natural flux of the freshwater system defined by the HHUs established with the WCA. Creation of these community accessible multi-scale water resources maps provides quantitative indicators for transitioning to sustainable water resources management and enables further study of the regional impacts from climate and LULC influences.

4.2.4 Trend Analysis

The SI for the TCMA cannot be assumed stationary and may change not only because of population growth, but also due to climatic and/or LULC changes. To illustrate this non-stationarity, temporal precipitation and streamflow variations for a watershed located near the TCMA was examined using a nonparametric Kendall Tau correlation test to indicate the likelihood of an increasing or decreasing trend over time (Helsel and Hirsch, 2002). Results would suggest whether the flux may have a corresponding change for the TCMA. A trend was considered to be significant if the probability (p-value) was less than or equal to 0.05; which represents a 95% confidence level (Kendall and Gibbons, 1990). In addition, an algorithm which signals the possibility of a regime shift in real time using a sequential t-test (Rodionov, 2004) was applied to the watershed's total annual precipitation, mean annual streamflow and mean minimum streamflow to detect when, if any, the shift occurred.

Since there is not long-term stream gauge data available for any watersheds located within the TCMA, USGS gauge 05275000-Elk River near Big Lake located upstream and northwest of the TCMA off of the Mississippi River, was reviewed for trend analysis. This was the only nearby watershed with available long-term discharge data; however, there was a 3-year gap between 1988 and 1990.

Using the location of the gauge as an outlet (pour) point, the corresponding drainage area was delineated using Arc Hydro (Maidment 2002), a GIS mapping plug-in software for water resources, along with NHDPlus data (http://nhd.usgs.gov/index.html), an integrated suite of application-ready geospatial data sets available through the USGS and the U.S. EPA, through raster analysis (Figure 4.3). Mean annual and monthly streamflow data for the gauge were compiled from the *USGS Water Data for the Nation* website (http://waterdata.usgs.gov/nwis). Total annual precipitation data for the watershed was obtained through the Minnesota Climatology Working Group (http://climate.umn.edu/wetland/).

4.3 Results and Discussion

4.3.1 SI Estimates

By comparing the estimated natural flux, with the 2004 municipal water use for the TCMA (Figure 4.4; Table 4.1), it is evident why a cone of depression is present beneath the region (Bradley, 1950; Norvitch et al., 1973; Schoenberg, 1984). The total groundwater use in the TCMA (Figure 4.5) is shown to be exceeding the sustainable recharge (Figure 4.6), as defined by the minimum annual groundwater recharge volume

(Figure 4.7). Groundwater sources provide approximately two-thirds of the water consumed in the TCMA, servicing nearly 1.6 million people through municipal water systems (Metropolitan Council, 2007).

The TCMA falls within the Eastern Broadleaf Forest Ecoregion (Bailey, 1995). The mean annual flux associated with this hydrogeological unit was 0.004 $m^3 \cdot s^{-1} \cdot km^{-2}$ (Kanivetsky and Shmagin, 2005). As previously discussed, this mean annual flux is used as an estimate of the total sustainable water resources because it includes both surface runoff and groundwater contributions. This mean annual flux was transformed into an annual volume for the area by multiplying it by the entire surface area of the TCMA defined using GIS (8146.8 km^2) and then converting this resulting volume into an annual total. Comparing this volume to the total annual water use for the TCMA suggests that the mean annual flux (ground and surface water) is not yet exceeded (SI >1); however, it is important to remember that these values do not take into account the ecosystem needs. The quantification of these environmental needs should be done by ecologists working together with hydrologists, and then factored into the renewable flux. Depletion of a small part of the total volume of groundwater storage (as little as a few percent) can have substantial effects on surface water availability (Alley, 2007), and presumably this can then affect aquatic ecosystem health.

By applying the projected water use through years 2030 and 2050, the diminishing amount available for ecosystem needs becomes apparent. The negative values in Table 4.1 indicate water available for ecosystem needs after applying human consumption; therefore representing sustainable water use or an indicator >1. When balancing the flux of the system with the total water use, it is also important to account for droughts and other natural and human made stresses. As water use increases, communities will see a larger stress on the system during periods of low precipitation. This illustrates the importance of conservative estimates, as sustainability of water resources should always err on the side of caution (Daily, 1997). The projected water use increase through 2050 is to occur primarily in areas extracting surface water from the Mississippi River (Metropolitan Council, 2007). Results using a different regional groundwater model, Metro Model 2, indicated that in some areas projected declines will have little impact on natural resources, while other areas may experience adverse impacts to aquifer productivity and/or surface water features that rely on groundwater discharge (Metropolitan Council, 2011).

Water-level fluctuations are not always an indicator of groundwater recharge or discharge. Fluctuations occurring over a period of decades can be attributed to naturally occurring climatic changes or anthropogenic activities including LULC changes, pumping and irrigation. Seasonal fluctuations are common due to the seasonality of evapotranspiration, precipitation and irrigation. Short-term fluctuations occur from rainfall, pumping and barometric-pressure fluctuations (Healy and Cook, 2002). When long-term groundwater extraction exceeds recharge, decreases in the hydrologic unit storage and hydraulic head occur, leading to groundwater overdraft (Zektser et al., 2005). The recharge values associated with the HHUs defined by Kanivetsky and Shmagin (2001), which were used in the TCMA volume calculations, were based on historic data (1935 through 1981), prior to the incorporation of more recent hydrologic anthropogenic influences. In addition, during more recent decades, Earth's climatic system began changing at a rate beyond natural variations; therefore, stationarity can no longer be assumed in water resources (Milly et al., 2008). Therefore, forecasting the SI for the next 50 to 100 years or more is becoming more important for addressing water resources sustainability. Long term monitoring programs need to be established for all water balance characteristics; not solely aquifers.

4.3.2 Trend Analyses

To illustrate that the SI is not stationary within the TCMA, a trend analysis was completed to examine precipitation and streamflow data upstream of the TCMA. Since long-term streamflow data is not available within the TCMA, data from USGS gauge #5275000, Elk River near Big Lake, Minnesota, was analyzed. Although this is not an urban watershed and the land use is primarily row-crop, it is the smallest watershed located adjacent to the TCMA with available long-term streamflow data. The drainage area of the watershed is approximately 1,448 km^2. Kendall Tau trend tests using data available between years 1935 through 2009 indicated that mean annual flux and mean minimum recharge both increased significantly, while total annual precipitation remained stable (Table 4.2). To identify when these increases occurred, a regime shift analysis using both a 10 and 20-year moving average was completed.

The increasing mean minimum recharge (baseflow or groundwater flux) is evident with both the 10 and 20-year analyses. The mean annual flux increases during the 10-year analysis but is stable using a 20-year moving average (Figure 4.8; Figure 4.9).

As expected, Kendall Tau analyses indicated that although precipitation is stable within the watershed, the mean annual flux is correlated to the precipitation (p=0.00). However, the baseflow is not correlated to the precipitation (p=0.84). The Kendall Tau coefficient indicates that baseflow is increasing faster than mean annual flux, indicating an additional influence other than precipitation (Table 4.2). Review of Figure 4.9 and statistical confirmation using an F-test indicates that after 1966 the variance becomes significantly greater for the mean minimum recharge (p=0.00); whereas the temporal variance change in mean annual flux is not significant at the $p<0.05$ level (p=0.06). If baseflow is increasing rapidly one would expect a similar response in mean annual flux, the contrary results presented here may be the response to a LULC change or an increased use of surface water.

Regardless of the reason for the trend changes observed adjacent to the TCMA, what these results illustrate is that there are multiple factors influencing the availability of freshwater. The documented change in variance demonstrates why it is crucial when assessing water sustainability that long term data is evaluated and conservative estimates are calculated.

Climate is not the only contributor to the variations observed in the system flux. LULC changes have been contributed to approximately 30% of the increase of water flux in the Upper Mississippi River Basin (Schilling et al., 2010). If groundwater flux and total system flux are both increasing upstream of the TCMA as our results suggest, one would think this is a positive direction for the SI; this increase in flux should signify a larger renewable water supply. However, if these increases are a result of LULC changes and not solely precipitation, it would be important to understand how this redistribution of groundwater is altering local and regional storage and the renewable groundwater flux. The trend analysis summarized in this study indicates that the renewable groundwater flux is increasing more rapidly than the total sustainable flux. The SI for groundwater recharge may in response be moving closer toward unity, suggesting more sustainable groundwater use; however, since the total sustainable flux is not increasing as rapidly, the use of surface water alone may be becoming less sustainable. This trend could negatively impact urban precipitation fed surface water bodies.

Climate and LULC changes in Minnesota will continue to alter regional hydrologic cycles, impacting the quantity and quality of regional freshwater resources (Novotny and Stefan, 2006; Lenhart et al., 2011). To account for these environmental changes, any method used to assess the impact to water resources must consider the spatial variation of water balance characteristics not only across the study area, but also at larger regional levels (Shmagin and Kanivetsky, 2006). Since recharge and groundwater levels are not affected equally over a regional catchment, especially with regards to urban areas with concentrated water use like the TCMA, sustainable management methods must have the capacity to work across scales, thereby assessing changes spatially and temporally within nested watersheds. Quantifying the spatial impact of environmental change on water resources is critical for transitioning toward sustainable water resources management and for promoting sustainable land use allocation and development (Jyrkama and Sykes, 2007).

4.4 Conclusions

The main conclusions of this study are summarized as follows:

(1) The WCA, a hydrologic regionalization approach which results in multi-scale HHUs, could be applied using existing landscape data to assess the sustainability of water resources in urban communities, even if local long-term monitoring is not available.

(2) Although result estimations suggest that the total water supply of the TCMA, including both ground and surface water together, is sustainable with current and future (projected to year 2050) water usage volumes, groundwater use alone is exceeding the sustainable rate. These estimations do not account for ecosystem needs and assume hydrologic stationarity.

(3) Streamflow trends adjacent to the TCMA indicate that mean minimum recharge (baseflow or groundwater flux) is increasing more rapidly than mean annual flux. This is an example of non-stationarity in which climatic and/or LULC changes are influencing the hydrologic balance of Minnesota's watersheds. Understanding how these changes will alter regional water supplies is imperative for transitioning toward sustainable resource management.

(4) Through continued monitoring of surface and groundwater systems, the issue of water resources sustainability in a changing environment can be predicted into the future using the WCA and applied to other metropolitan areas. SI results could be used as input for economic and social models to develop incentive tools and adapt into institution and water governance, in order to make a transition toward

environmental, economic and social sustainability.

Table 4. 1 Summary of TCMA water resources availability, use and sustainability

	Calculated Volume[a] (m^3 d^{-1})
Minimum annual recharge (sustainable groundwater)[b]	7.87E+05
Total groundwater use[c]	1.12E+06
Water use exceeding sustainable groundwater recharge	**3.37E+05**
Mean annual flux (sustainable ground and surface water)[d]	3.06E+06
Total (ground and surface) water use[c]	1.68E+06
Water use exceeding sustainable flux	-1.38E+06
Projected 2030 ground and surface water use[c]	1.95E+06
Projected 2030 water use exceeding sustainable flux	-1.11E+06
Projected 2050 ground and surface water use[c]	2.27E+06
Projected 2050 water use exceeding sustainable flux	-7.88E+05

[a] *Bold value indicates exceedance of sustainable recharge.*

[b] *Based on February monthly discharge mean measurements period 1935-1981.*

[c] *Total water use does not include water for power generation or ecosystem needs (Metropolitan Council, 2007).*

[d] *Extrapolated from MN statewide stream runoff related to ecological subdivision map.*

Table 4. 2 Temporal trend analysis results for USGS gauge #5275000

	Kendall's Tau	Z	p-value
Mean Annual Flow (m^3 s^{-1})	0.16	2.08	0.04
Mean February Flow (m^3 s^{-1})	0.31	3.95	0.00
Annual Precipitation (cm)	0.07	0.86	0.39

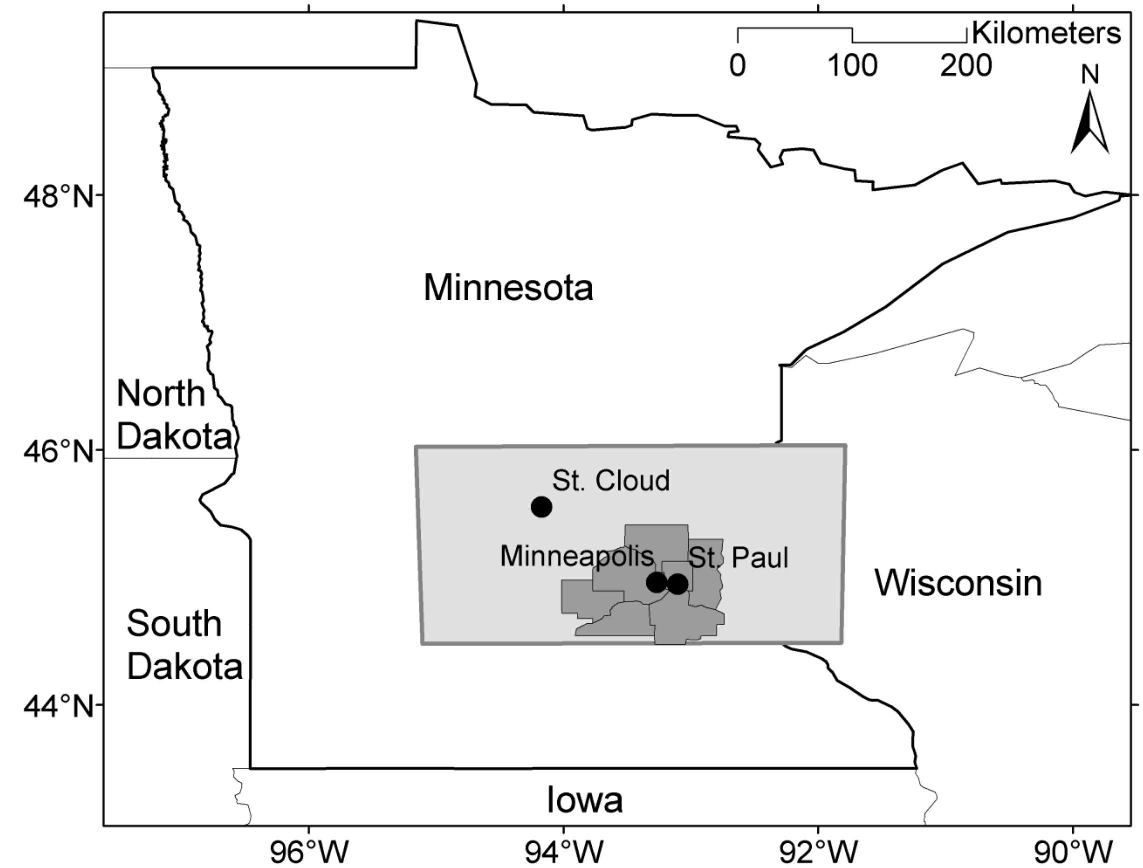

Figure 4.1 Three scales analyzed using the Watershed Characteristics Approach: state of Minnesota, East Central Minnesota (ECM) and the seven-county Twin Cities Metropolitan Area (TCMA)

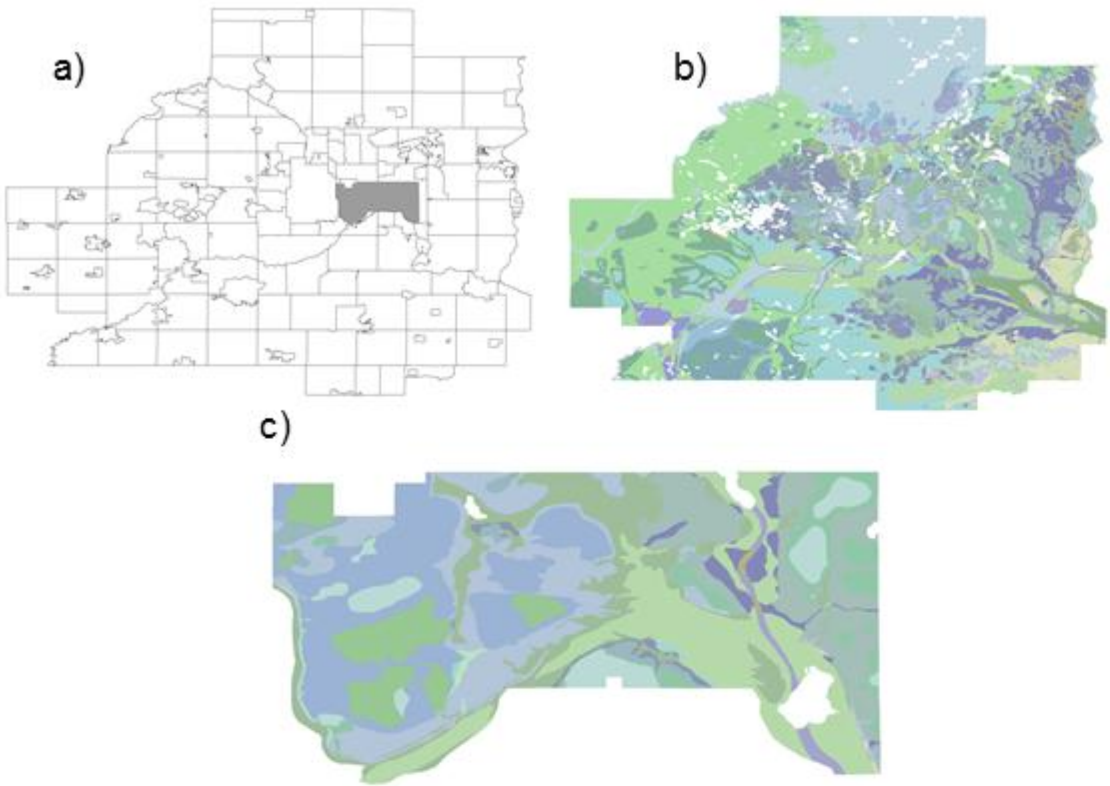

Figure 4.2 Using the boundary of a study area, such as the city of St. Paul (a), the HHUs could be added (b) and the digital data layer clipped (c) and used to calculate the total land area composed of each HHU

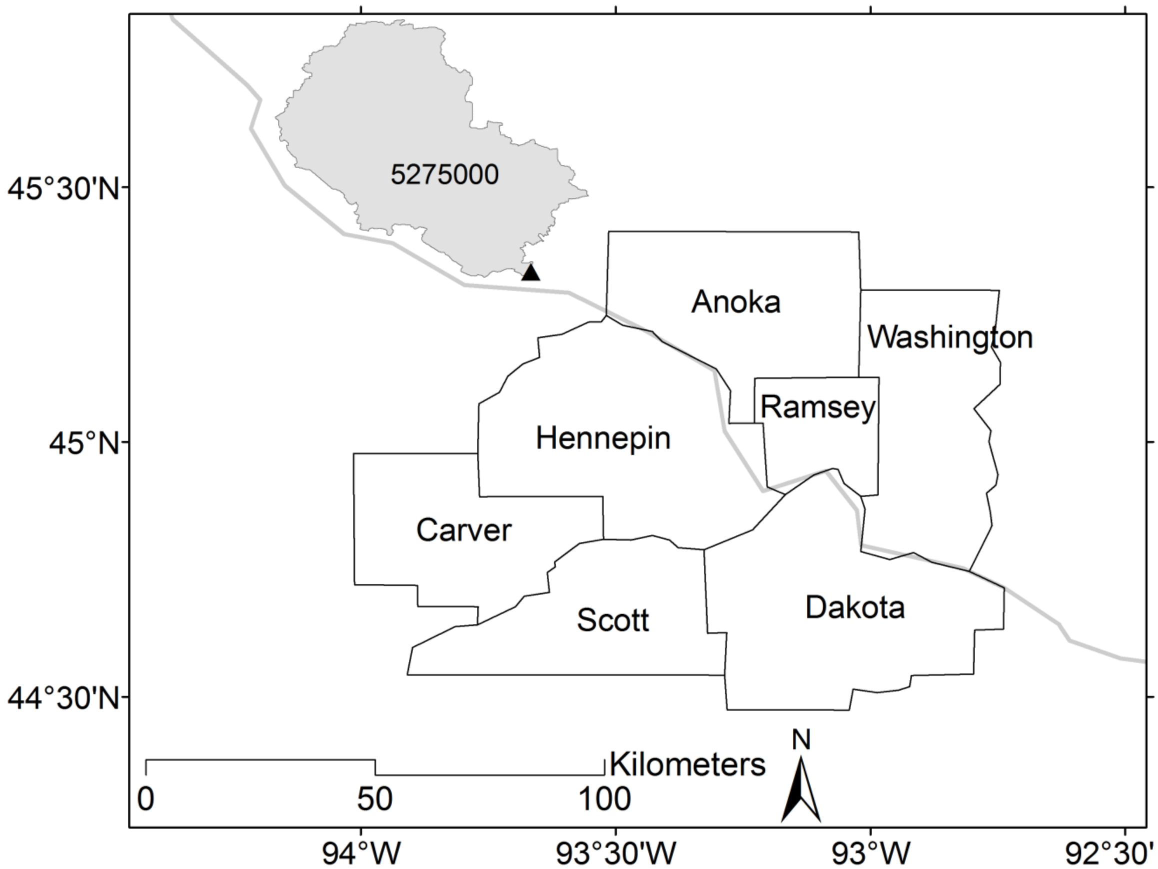

Figure 4.3 Data from USGS gauge #5275000, located along the Mississippi River adjacent the Twin Cities Metropolitan Area (depicted with county names), was reviewed to identify potential temporal precipitation and streamflow trends

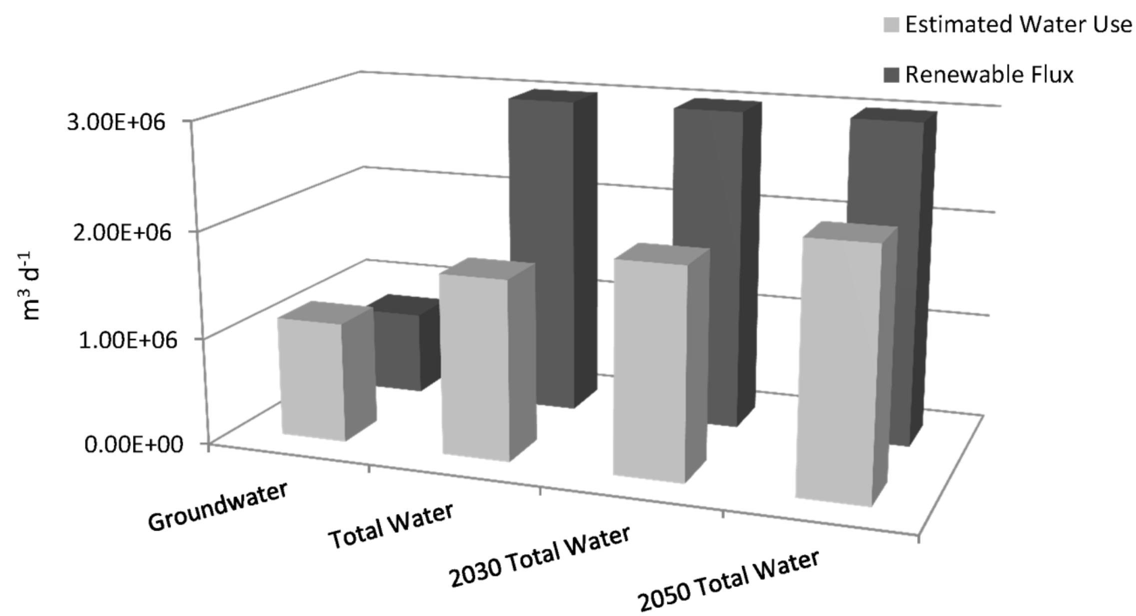

Figure 4.4 Renewable groundwater and total (surface and groundwater) flux compared to the estimated and projected (total only) water use for the TCMA using data available from the Metropolitan Council (2007)

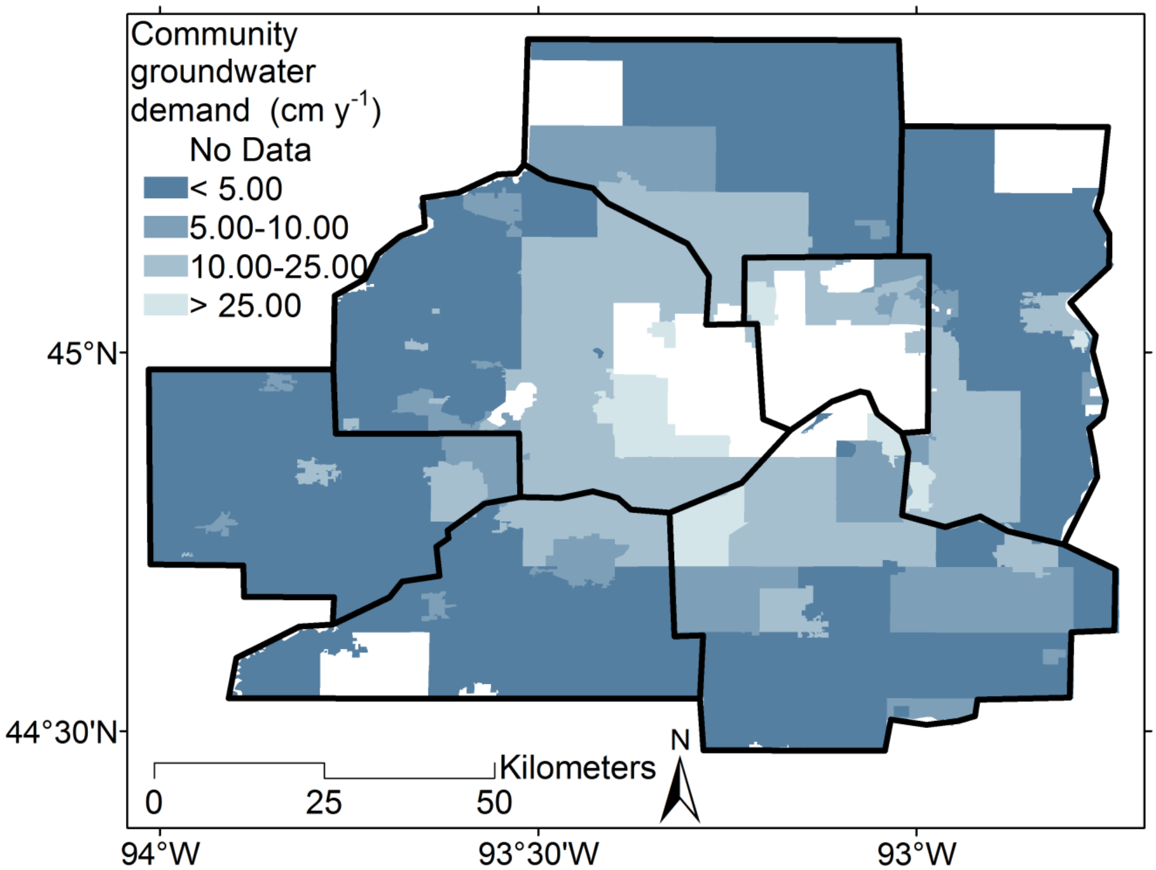

Figure 4.5 TCMA groundwater demand estimates spatially depicted by community using data from 2004 (Metropolitan Council 2007); estimates are for human uses and do not incorporate ecosystem needs; areas without shading rely solely on surface water or do not have available groundwater demand estimates

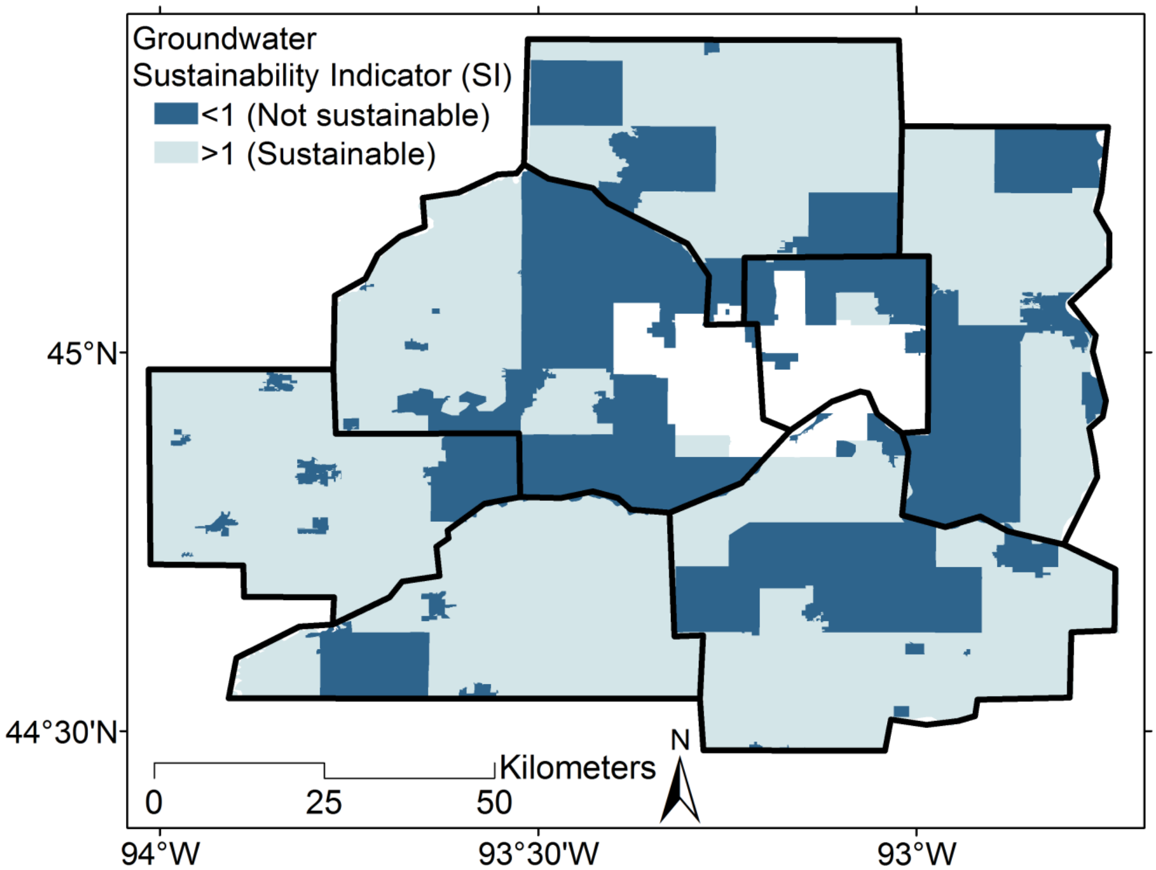

Figure 4.6 TCMA groundwater SI map depicted by community to indicate which areas are not operating sustainably based on the renewable groundwater flux; areas without shading rely solely on surface water or do not have available groundwater demand estimates

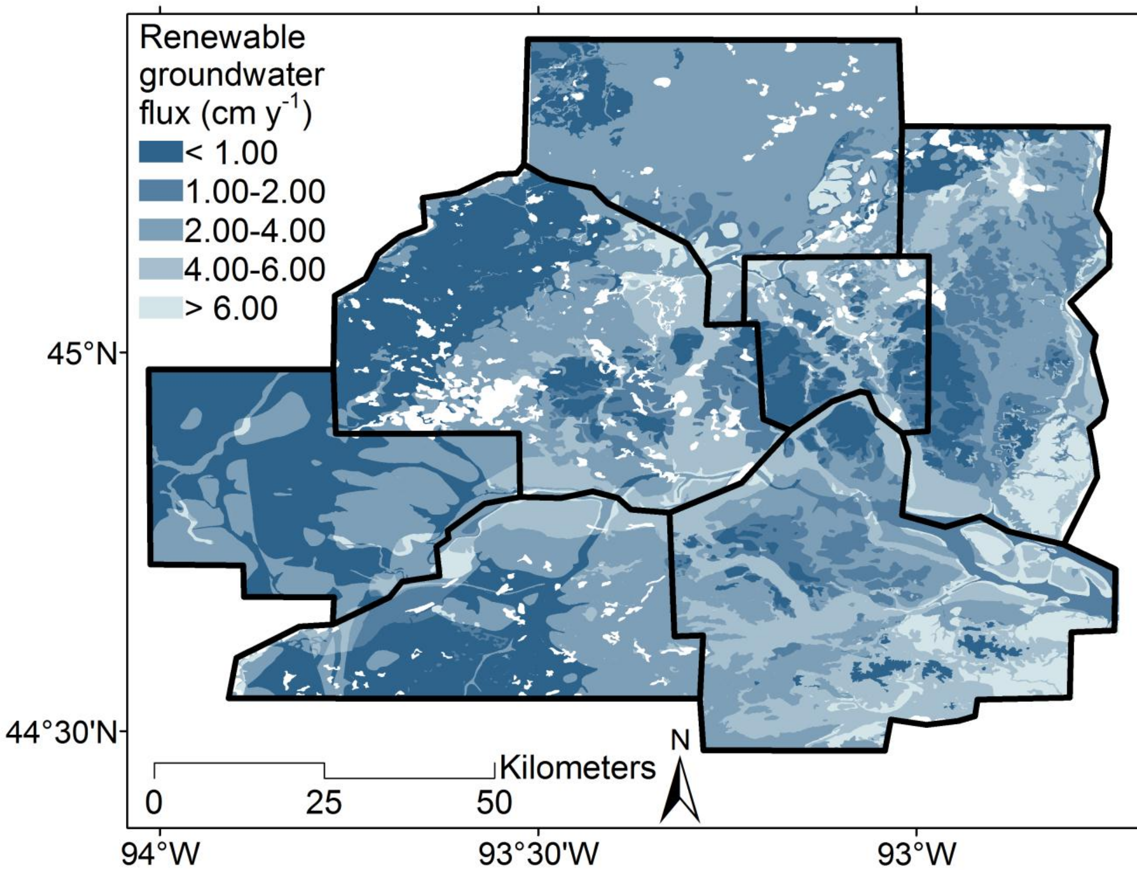

Figure 4.7 TCMA renewable groundwater flux estimates spatially depicted based on HHUs (Kanivetsky and Shmagin, 2001)

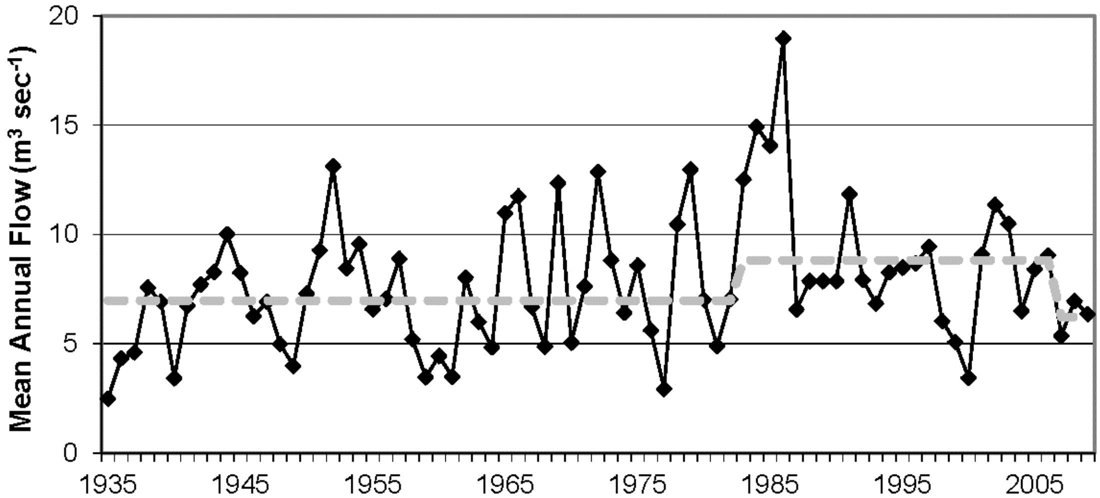

Figure 4.8 Regime shift using a 10-year moving average in USGS gauge 5275000 depicting the temporal flow and precipitation variation with the corresponding 10-year moving average plotted as a grey dashed line

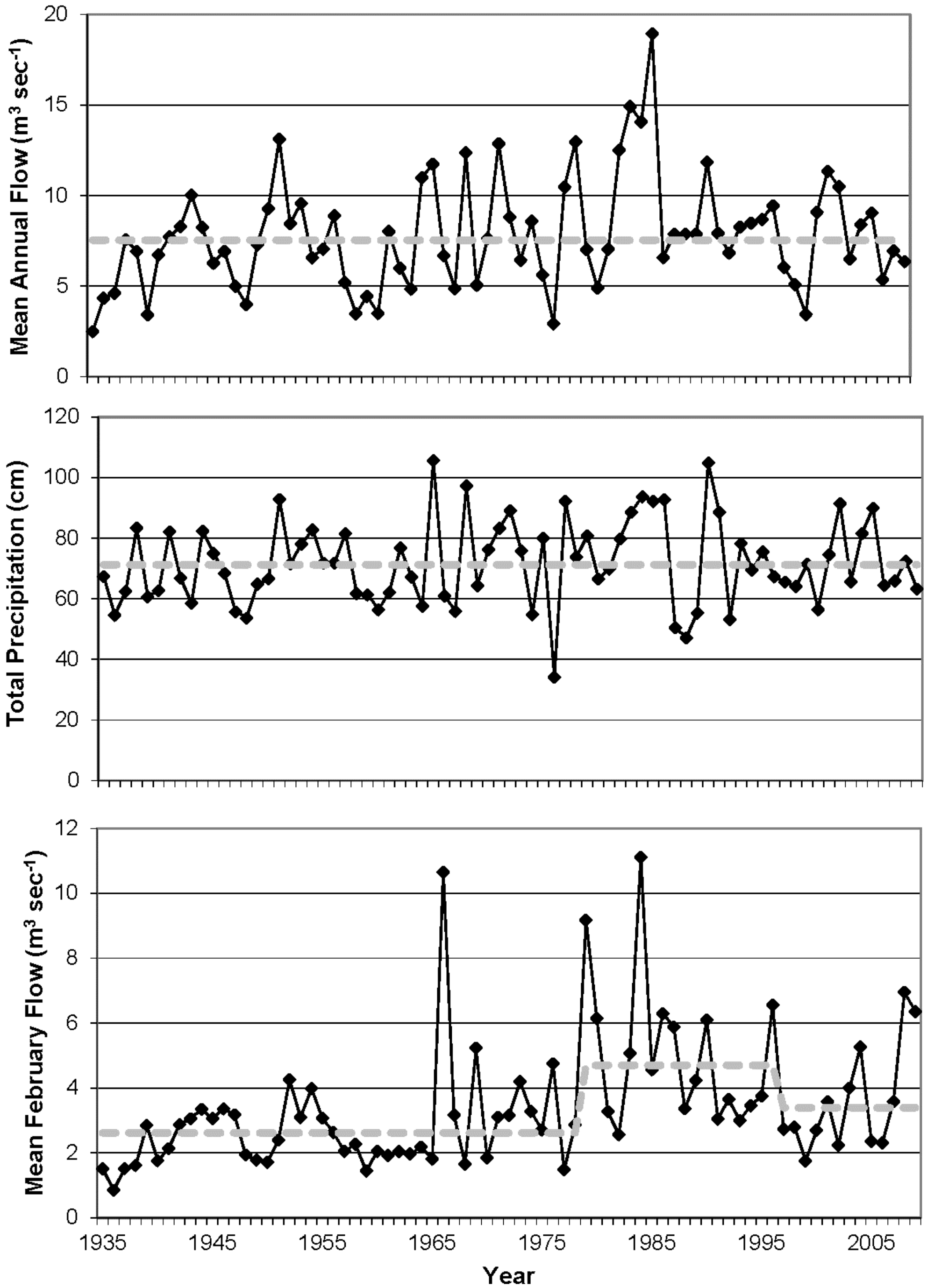

Figure 4.9 Graphs for USGS gauge #5275000, located upstream of the TCMA, depicting the temporal flow and precipitation variation with the corresponding 20-year moving average plotted as a grey dashed line

Chapter 5

Conclusions

Three studies were completed as part of this dissertation to address the hypothesis that regionalization could be applied to identify HHUs composed of unique combinations of surface water, groundwater and vadose zone landscape characteristics with statistically different recharge rates ($p<0.05$), which could then be used to estimate the renewable water flux of the groundwater system. The studies examined both the spatial and temporal variation of landscape and hydrologic characteristics.

Chapter 2 identified that even though hydrologic characteristics are no longer stationary across the state of Minnesota, five regimes exist, each with varying inter-annual flow patterns. Intra-annual streamflow varied between 3 or 4 flow periods based on predominant watershed land use; the number of months associated with each flow period varied among the regimes. The five defined regimes are consistent with statewide hydrogeological units identified by Shmagin and Kanivetsky (2002). The results focus on the total sustainable freshwater system since it was an evaluation of mean annual flow which incorporates both the contributions of surface runoff and groundwater flow, integrating the influence of climate patterns across the state. Trend results for each of the regimes suggest that in addition to climatic variations, land use management and/or land cover composition may be influencing the hydrologic signature of Minnesota's watersheds.

Chapter 3 supported the overall dissertation hypothesis by applying regionalization techniques to identify unique combinations of landscape characteristics based on combinations of hydrogeologic characteristics, bedrock material, Quaternary thickness, topography and available water capacity to create HHUs with statistically different ($p<0.05$) minimum recharge rates, which were used to estimate renewable groundwater flux. This interdisciplinary combination of characteristics incorporates the surface water, groundwater and vadose zone to represent the entire terrestrial system.

Chapter 4 demonstrates the application of the WCA as a sustainable water management tool. HHU results previously generated for the TCMA (Kanivetsky and Shmagin, 2001) were used together with water usage estimates to quantify a freshwater SI. If the demand by humans and the environment is greater than the renewable flux of the system, the SI is <1 signifying a non-sustainable system. In this situation, continued use at the same rate would result in a reduction of the stored volume, which could have substantial effects on land subsidence and reduced availability of surface water for use by humans or riparian and aquatic ecosystems (Alley, 2007).

The results of the trends identified in Chapter 2 within each of the five regimes should be considered when using the estimated recharge rates presented in Chapter 3 to obtain SI results, such as those demonstrated in Chapter 4. The trends in Chapter 2 are based on the total sustainable freshwater resource, therefore further analyses need to be conducted to identify if the increase or decrease in trend reflects surface or groundwater contributions. However, it is suspected that the increase in trends reflects an increase in surface runoff, which may eventually lead to a reduction of the sustainable groundwater resource if less water is entering the system as deep percolation. Future research comparing groundwater elevations within one of the regimes with an increasing mean annual streamflow trend, such as the northwest or southern regime, to the corresponding streamflow trends could be completed to confirm this. The hypothesis would be:

Groundwater elevations have decreased in Minnesota's southern hydrologic regime due to increasing surface runoff and reduced deep percolation.

One limitation of this dissertation is that the combinations of terrestrial landscape components that comprise the identified HHUs were based on results of an analysis territory with spatial location primarily within one of the five identified hydrologic regimes. East Central Minnesota was chosen as the focus area of Chapter 3 since there is a high demand on water resources in that territory; however, future research should reproduce the methodology using watersheds representative of other regimes defined in Chapter 2. Although it is hypothesized that results would produce HHUs based on the same landscape characteristics, the study would confirm that the renewable groundwater flux within each of the five regimes located across Minnesota are controlled by the same underlying landscape components. If this future research were to be pursued, the hypothesis could be:

Regionalization methods can identify HHUs composed of unique combinations of hydrogeologic characteristics, bedrock material, Quaternary thickness, topography and available water capacity with statistically different recharge rates ($p<0.05$) which could be used to estimate the renewable water flux of the groundwater system.

Overall, hydrologic regionalization results produced using the WCA can be applied as a useful tool for aiding and promoting sustainable water management within communities at the state or more local levels.

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