GRADUATE SCHOOL

STATISTICAL ANALYSIS OF STREAMFLOW HYDROGRAPHS AND THE RELATION OF HYDROGRAPH CHARACTERISTICS TO GEOLOGICAL AND ECOLOGICAL LANDSCAPE UNITS

A THESIS
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL
OF THE UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

JANUARY 1999

ABSTRACT

Dependence of river runoff on climatic, topographic, geologic and vegetation factors is an axiom in our days. It represents great interest to reveal major factors influencing runoff within not only individual basins but for large areas such as Minnesota. For this scale it is convenient to conduct studying using a concept of natural complexes as a research objects. Investigated complexes were based on ecological and quaternary geology landscape subdivisions. Hydrological characteristics were derived from flow data for watersheds, sorted by criteria of 100 to 1,300 mi^2 for area and periods of observation not less than 20 years, for 69 Minnesota watersheds. Unit runoff and monthly modules (discharge per unit area) were calculated and used as a set of random samples for statistical analysis. Statistical tools such as hypothesis testing allowed regionalization of hydrology on the base of changing quaternary and ecological conditions. Hydrological response based on ecological units was a reflection of climate patterns; hydrologic response based on quaternary geology was associated largely with topographic expression and sediment type.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

As this last piece of my work at UMD Geology Department is completed I would like to thank people who made it happen.

Most of all I would like to thank my adviser, Professor Howard Mooers. It is not only the support and advise he has given me in my work but it is also his unique personality, a character that changed a lot in my own perception of certain things and even transferred me to a person more confident and ambitious in life.

I would like to thank Boris Shmagin for allowing me to develop the analysis of the problem he designed.

I am grateful to all members of Geology Department, faculty, stuff and students, for support, belief and understanding during my studies and stay in Duluth. These qualities are twice as important for someone like me, person with other native language. Everybody was incredibly nice and helpful whenever I needed a word of support. This always made it easier for me to go on not only in my studies and research but also in my life here, far away from family and friends.

I would also like to thank my only Russian friend in Duluth, Aleksandra Krasutskaya who was always there for me, in good times and times of frustration and also her family for atmosphere of home I was always welcomed to.

My appreciation to my husband is beyond the words. The very first thing he made me realize was that I could actually learn another language, the skill that eventually served me to produce this manuscript.

1. Introduction and objectives of streamflow analysis.

Because the major part of Minnesota's water supply comes from streams, the study of streamflow is an important aspect of water resources research. A search of the literature reveals very little quantitative information on the influence of natural landscape characteristics on streamflow in the State of Minnesota. Ackroyd et al. (1967) attempted to relate streamflow to basin characteristics of 38 Minnesota watersheds. This research attempted to classify watersheds on the basis of surficial deposits, bedrock, percentage of lake area, forest cover and precipitation. The study had little success because of lack of geological information. However, it enabled several important conclusions concerning groundwater runoff. No maps were produced as a result of that study.

The goal of this investigation was to determine the major factors that impact runoff of Minnesota streams. Minnesota is geologically and climatically diverse and can be easily divided into regions or natural complexes reflecting natural landscape characteristics. The major factors that influence Minnesota runoff were determined and geographically subdivided maps reflecting such dependence were compiled for this study.

It is not particularly useful to use small (less than 100 mi^2) watersheds for the purpose of regionalization. An attempt to reveal a hydrologic difference induced by climate patterns between adjacent watersheds most likely would fail. In fact, adjacent units of this scale in an area like Minnesota would rarely show dramatic climatic differences and would be expected to be greatly homogeneous (Hanson and Hargrave, 1996). This can be explained simply by their closeness and by the fact that climatic characteristics do not experience sudden and significant changes between adjacent drainage basins with areas of 100 mi^2 or even 1000 mi^2. The change is rather gradual and successive. Two small watersheds would possess characteristics of the particular climate zone to which they belong. These climatic characteristics would be so similar for both of the units making it impossible to quantify any climate differences of this scale.

On the other hand, on the scale of the entire state climate becomes the overriding factor in importance. Several climatic zones can be defined for the state, e.g. temperature isograds for Minnesota trend latitudinally and show temperature increase from North to South; therefore, a few temperature zones can be delineated. Such conditions make it easy to see hydrologic response produced by climatic effects. This implies that large (greater than 1000mi^2) landscape units should be considered to observe noticeable change in climatic characteristics and the consequent change of natural characteristics affected by climate (Hanson and Hargrave, 1996).

The preceding paragraphs describe the concept of scale in hydrologic analysis. This concept is important in analysis of local, regional and statewide hydrological characteristics. At the statewide scale, further referred to as "small scale" (mapping scales of 1:500,000 or 1:1,000,000) representing units of a large area, climatic factors play an important role in variations in hydrological response among watersheds. At the scale of two small, juxtaposed watersheds, further described as units of a “big scale” (mapping scales of 1:100,000 or 1:24,000) related to geographically small areas, climatic gradients are unimportant and geological characteristics are the controlling variables.

Streamflow data can be analyzed quantitatively to show responses to changing natural conditions. For example, given two drainage basins with different physical characteristics that influence hydrology (e.g., geology, climate, vegetation. etc.), this natural factor (geology or climate or vegetation) can be eliminated as a cause of hydrologic variability if no difference between hydrological characteristics for these regions is found. In other words, similar hydrology of two geologically different regions suggests control other than geology. Therefore some other natural factor defines the hydrologic pattern of both regions. Apparently this "factor" has a "scale" that encompasses both of these regions.

In contrast, if any two or more climatically different regions show different hydrologic patterns as well, hydrology may be predominantly controlled by climate.

The steps to achieve the goals of the investigation are therefore:

1) To divide landscape into units based on natural (climatic and geological) units

2) To compile all streamflow data to develop streamflow records for each of these units

3) To compare all these units statistically and quantify hydrological similarities and differences among watersheds.

Two kinds of landscape units are used in this study: the Ecological Classification System (ECS) compiled by Minnesota Department of Natural Resources, to test whether this system of classification has hydrological significance; the second division is based on the Quaternary geology of Minnesota. Hydrological response was studied using streamflow data. Streamflow was evaluated with data collected by the United States Geological Survey.

2. Streamflow, runoff and controlling factors.

Streamflow consists of surface runoff and groundwater runoff or base flow (Ackroyd et. al 1967, Dingman, 1994; Fetter, 1988) Surface runoff is defined as precipitation that enters the stream channel as overland flow. Overland flow may also include runoff that percolates into and moves through the unsaturated zone (interflow) (Ackroyd et. al, 1967; Fetter, 1988). Groundwater runoff is precipitation that initially infiltrates to the saturated zone and then flows laterally to the stream channel (Ackroyd et. al, 1967; Fetter, 1988; Freeze and Cherry, 1979).

The runoff cycle (Dingman, 1994; Freeze and Cherry, 1979; Manning, 1987; Morisawa, 1968) is best illustrated by following a raindrop as it comes to the earth and travels toward the nearest stream. Unless this raindrop lands on the surface of the stream itself, it may travel a circuitous route before it joins the flowing water of the stream. Many factors affect runoff within a drainage basin. The first is supply of water, making climate an important item (Anonymous, 1959; Carlston, 1966). However, the uniqueness of the runoff-rainfall relationship for each basin is a result of the fact that streamflow is influenced by factors other than rainfall alone. It is more importantly determined by the amount of rainfall excess. Rainfall excess is determined by complex relationships among climate factors and basin characteristics (Leopold, 1994; Manning, 1987; Morisawa, 1968). Climatic elements include the amount, duration, intensity, and time distribution of rain in a particular basin; evapotranspiration is controlled by insolation, temperature, relative humidity, vegetation and wind. Vegetation influences runoff by providing interception of water by foliage, by promoting infiltration in slowing and dividing surface flow, and by contributing to detention storage in holding water on the surface (Fetter, 1988; Horton, 1933; Manning, 1987; Williams, 1940). Its effect varies with type and density of growth.

Even with an adequate water supply, runoff and streamflow might be influenced in a number of ways by the natural characteristics of the drainage basin. Terrain conditions affecting runoff can be considered in two broad categories: (1) conditions inherent in the natural landscape, and (2) conditions in which nature has been altered by human use of the land (Manning, 1987). Some of the natural features might be basin size, elevation and orientation, stream network density, topography (shape and slope of the land), amount and type of soil, and geology (Allison, 1932; Dingman, 1994; Leverett, 1932; Manning, 1987; Morisawa, 1968). The land-use practices having the most general effects on natural drainage are those related to agricultural or urban developments (Manning, 1987).

The main effects of elevation are related to temperature. At higher elevations, cooler temperatures result in less water loss by evapotranspiration. Above timberline there is not much vegetation to transpire water, and most of the annual precipitation comes as snowfall. Most of the runoff from high basins comes between the spring thaw in April or May and the next freeze in October. Low runoff in winter comes chiefly from groundwater seeping into streams below the frost line (Manning, 1987). The main variations on the runoff regime in the high attitudes are the result of basin orientation. In north facing basins snow often lasts into summer, while in south-facing basins snow melts early in the spring.

At lower elevations of Minnesota, warmer temperatures lead to significantly different hydrology. An abundant vegetation and rain as dominating form of precipitation predetermine greater water loss by evapotranspiration. At lower altitudes runoff variations associated with basin orientation are small. Snow melts almost equally fast in north and south facing basins. Most of the runoff still occurs during summer and fall months as the spring thaw and rain storms define hydrology this time of the year.

Basin orientation in relation to the prevailing storm tracks may also have an effect on runoff. The direction of storm movement in relation to the direction of stream flow in the drainage net will determine when and where the highest stream flows occur and also the total duration of runoff as storm waters move through the basin (Manning, 1987).

The general shape of the landscape, the steepness of the slopes, and the total relief all affect the way precipitation reaches the streams in the drainage basin. The steeper the slopes, the quicker the tributaries feed storm runoff into the main stream draining the basin (Manning, 1987; Morisawa, 1968).

Most of the physical characteristics of a drainage basin are influenced by geology (Freeze and Cherry, 1979; Manning, 1987; Morisawa, 1968; Schwartz and Thiel, 1963). Geologic processes elevated the land so that the erosional process could take place. The nature of the rocks and their response to erosion determine how drainage patterns develop. Geologic structures such as folds, faults, etc. commonly give a predominant shape to the landscape.

Geologic factors also determine the storage time during which water is held between precipitation and runoff as stream flow. A permeable soil or rock allows the water to percolate to the ground water table, where it is slowly discharged into streams as base flow. Thus the groundwater component of streamflow is increased while the overland flow component is reduced. Basins on bedrock or soil that is relatively impermeable have a high volume of direct runoff and very little groundwater flow.

Human use of land and control and use of water resources have the potential to affect the large-scale characteristics of the water cycle (Freeze and Cherry, 1979; Manning, 1987; Wisler and Brater, 1959). In modern cities, where people cover the soil surface with buildings and pavement, artificial drains are necessary to carry away storm water. Modern farming methods have sometimes accelerated the erosion of bare soil and have resulted in minor to major changes in natural drainage nets.

1. Review of streamflow and drainage basin analysis.

There are multiple examples in the literature describing dependence of streamflow on the previously discussed factors. It appears, however, that factors that almost exclusively define streamflow are climate, geology, and topography (Dingman, 1994; Manning, 1987; Morisawa, 1968).

Meko and Stockton (1984, p.889-897) analyzed selected streamflow records in various parts of western North America and concluded that significant hydrologic changes related to climate have taken place in the area in the past century. In general, major low-frequency variations in streamflow have tracked variations in precipitation and temperature; minima in the low-frequency component of streamflow have generally been associated with periods of both low precipitation and high temperature. Kalinin and Szesztay (1970, p. 102-115) in their analysis of the global water system emphasized that basic features of the surface water systems and those of the streamflow regime are specified by climatic conditions. Carlston (1966, p.62-69) examined the relation of drainage density to base flow in the 15 basins in the climatically different parts of United States and obtained evidence that the base flow was affected by precipitation or recharge (climatic variable). Other evidence was found in Pionke's (1970, p. 62-64) studies of salinity of the Washita River in Oklahoma. It was shown that average salinity of the Washita River increased substantially between 1954 and 1967. Among all variables studied, climatic changes appeared to exert the greatest influence on stream salinity levels.

Streamflow investigations provide as well a wide range of evidence of its dependence on regional geology. Bingham (1986, p.1-88) developed procedures for estimating winter low-flows at ungaged stream sites in Tennessee. Using regression analysis he determined that geology and drainage basin size are the most significant variables affecting low-flows in Tennessee streams. Hughes (1978), studying annual runoff from hydrologic units in Florida, showed that spatial variations in runoff result from regional differences in rainfall, differences in the evaporation potential, and differences in the topographic and geologic characteristics of the land surface.

Dillon and Kirchner (1975, p.135-148) investigated the export of total phosphorus from 34 watersheds in southern Ontario over a 20-month period. They discovered that export differences among watersheds of different geology were highly significant. Low-flow characteristics of streams in the Puget Sound region of Washington were described, and some of the factors that influence low-flow were explained by Hidaka (1973, p. 2-55). It was noted that data collected at 150 gaging stations show a wide variation between streams because of the complex interrelation between climate, topography and geology. Evaluation of streamflow data for Hawaii was done by Yamanaga (1972, p.2-28). Variability in streamflow was accounted for by differences in geology and rainfall variability.

Wandle and Randall (1993, p.2-45) developed equations by multiple-regression analysis of data from 49 drainage basins in Massachusetts, New Hampshire, Rhode Island, Vermont and southwestern Maine. These equations indicate that low-flow of streams in this region is largely a function of the amount of water available to the basin and the extent of surficial sand and gravel relative to the extent of till and fine grained stratified drift. Low-flow per square mile from areas of surficial sand and gravel was consistently much greater than that from areas of till and bedrock.

The role of topography in streamflow studies has been described and discussed in numerous publications. Riggs and Harvey (1990, p.81-96) showed that the variations of runoff in North America are controlled by major climatic and physiographic factors. Variations in the flow across the continent are due largely to the variability of the climatic factors of precipitation and temperature. Physiographic factors, such as geology and topography, also have considerable influence on the amount and distribution of surface water in North America. Black (1972, p.309-329) studied the effect of selected watershed characteristics on hydrograph parameters under a rainfall simulator. The results obtained from this study claim no large effect of watershed shape on peak discharge magnitude. Watershed size, slope and drainage pattern had greater effect on peak magnitude under the same conditions. Chorley (1971, p.30-52), who studied drainage basin geomorphology and particularly discussed geometry of landforms, made the same conclusion. Tyagi et al. (1970, p.7-12) reviewed and evaluated the physiographic characteristics of watersheds affecting peak flows and runoff yield. They compared hydrologic performance of two watersheds in the Nilgiris, India. These two watersheds showed significant difference in runoff yield (83%) while amount of received rainfall varied just slightly (22%). Because of relatively insignificant differences in climatic variables, the marked variation in hydrologic performance was attributed only to physiographic factors such as total watershed relief, stream slope and drainage density.

Commer and Zimmerman (1969, p.98-108) looked at minimum flows of two watersheds during a 6-year period in northern Vermont. The minimum flow per unit area for a 3.2 mi^2 basin was $2.7*10^{-4}$ in/hr whereas minimum flow for an 8.4 mi^2 basin was $0.3*10^{-4}$ in/hr. They concluded that as climate, geology, and land use in the two basins were similar, the differences in low flow were probably caused by differences in topography and soils. Later in his study of the effects of certain climatic and basin characteristics on minimum runoff at the 32 small drainage basins during 1958-69 in various parts of Finland, Mustonen (1971, p.3-64) showed that the most important basin factor was slope.

It has to be emphasized that topography is not a static factor but rather constantly undergoes changes. Schumm and Parker (1973, p.2-17) demonstrated that hydrologic data collected for a small drainage system changed in response to the morphology of the evolving drainage system.

Although not the first to study streamflow, Horton (1945, p.275-370) was first to describe erosional development of stream channels and river networks with simple equations and attempt to relate his equations to hydrophysical processes. It was the first attempt to create a unified quantitative model of a fluvially eroded surface. Leopold (1953) first developed quantitative relationships between width, depth and velocity of stream channels. Leopold's study represents one of the first quantitative approaches to understanding of river networks. Later Shreve (1966, p.138-155) showed that Horton's laws of drainage composition can be derived from a link-based random model. Tests of randomness of network topology led to new methods of network classification and the development of a probability distribution for different classes. Using Shreve's (1966) work as a foundation, subsequent developments of link-based theory further developed an understanding of environmental and spatial constraints on stream network topology and hydrodynamic processes.

Statistical approaches are now recognized as an important tool in evaluation and interpretation of a wide range of geological processes and data and its contribution in research is immense.

Streamflow studies in Minnesota.

As mentioned earlier, very little has been done to describe factors controlling streamflow in Minnesota. Even less was done to characterize such control quantitatively and to represent it geographically. Most of the studies on Minnesota's runoff have local objectives with areas of interest being one to several watersheds.

Ackroyd et al. (1967) were first to recognize the importance of such an analysis for predicting the yields from drainage basins and for planning water development and management procedures. Determination of relationships between groundwater runoff and such basin characteristics as geologic environment, precipitation and temperature, and percentage of lake and wetland cover was done using standard streamflow hydrograph separation methods. These methods were used to estimate an annual groundwater contribution to streamflow in 38 drainage basins of Minnesota. The relations between groundwater runoff during years of near, below, and above normal precipitation, the ratios $(Q_{25}/Q_{75})^{1/2}$ (Q_{25} - streamflow equalled or exceeded 25% of the time, Q_{75} - streamflow equalled or exceeded 75% of the time) and the basin characteristics were studied qualitatively. Basins were separated into categories depending upon their gross characteristics. In general, groundwater runoff was determined to increase by the presence of lakes and wetlands, glacial outwash deposits, glacial till deposits, loess deposits and permeable bedrock. It was also shown to increase with increases in annual precipitation.

Stark et al. (1994) evaluated the quantity and quality of both the surface water and groundwater in the Straight River watershed and described the interaction between the river and the aquifer with emphasis on the effects of irrigation on the ground- and surface water.

Brown (1988) studied storm-runoff quantity and quality in three watersheds near St. Paul in Ramsey County to determine qualitatively the effects of precipitation and selected land uses. The greater quantity of runoff was related to watersheds with the largest amount of impervious area and the smallest amount of wetland area. The differences of runoff quantity in an urban watershed were related to average amount of precipitation during the study period whereas for watersheds that contain wetlands the differences were related to total precipitation during the same period.

Baker and Mace (1977) showed that spring runoff from two forested watersheds in northern Minnesota is a function of annual snowfall, soil water recharge and water supply rates. The average soil water recharge rate for the clay soil was 28% less than for the sandy soil.

Timmons et al. (1977) measured nutrients transported in surface runoff and interflow from an undisturbed aspen-birch forest. Three years of data showed that surface runoff from snowmelt accounted for 97% of the average annual surface runoff. It has been also noted that the slope aspect influenced the amount, rate, and time of snowmelt runoff.

Several other studies are also watershed-scale analyses of hydrology and do not show trends at the state-wide scale. Most of the studies and their results are qualitative with no geographical coverage produced.

2. Physiography, geology and climate of Minnesota.

Minnesota has diverse landscape and vegetation assemblages. The geology, glacial history, and the climatic settings are responsible for this diversity (Wright, 1972). The bedrock is covered almost everywhere by glacial drift. Nevertheless, bedrock terrain has great topographic importance in the northeastern and southeastern parts of the state. It represented by highlands and hills in the northeast. In the southeast the Mississippi River and its tributaries cut through flat-lying Paleozoic rocks producing sharp valleys. Predominant glacial features in the state are massive moraines with numerous lakes and also broad outwash plains, drumlin fields, flat glacial lake plains and rolling till plains covered by loess (Wright, 1972).

For the most part, the variable and changing landscape is a result of a complex sequence of Laurentide Ice Sheet advances and retreats during the Late Wisconsinan (Wright, 1972; Mooers et al., 1991; Mooers and Lehr, 1997). The Laurentide Ice Sheet had accumulation centers in Quebec, Hudson Bay and areas to the west in the district of Keewatin. Ice advanced into the state from three general directions (Figure 1). The Rainy and Superior lobes advanced from the northeast from accumulation centers in the Hudson and James Bay lowlands, respectively. The Itasca lobe advanced from the north-northeast with a source in the central Hudson Bay (Mooers and Lehr, 1997). The Red River lobe (including the Des Moines lobe, Koochiching lobe and St. Louis sub-lobe) came from north-northwest and is attributed to the Keewatin ice center (Meyer, 1997). The movement of these lobes was predisposed by topographical and bedrock settings. The bedrock geology and resultant topography are responsible for direction of glacier movement, with ice lobes moving along lowlands (Wright, 1969). The Superior lobe advanced from the Lake Superior basin (Wright, 1969). The Rainy lobe advanced parallel to the Superior lobe, but over topographically higher terrain (Mooers, 1997). The Wadena lobe invaded the area west of the Rainy lobe. This area is geologically similar but topographically lower than that occupied by the Rainy lobe. The Red River lobe advanced into northwestern and southwestern parts of the state (Mooers, 1997).

Invasion of the ice lobes shaped the landscape of the state, and the landscape has not experienced any dramatic changes for the last 10,000 years since the end of Wisconsinan glaciation. The total thickness of the drift exceeds 200 feet in a large part of the state and is 400 to 500 feet in the South-central and at certain localities in the western part. In general the drift is thicker in the southwestern and thinnest in the southeastern and northeastern parts of the state (Leverett, 1932; Olsen and Mossler, 1982). Moraines are prominent features of the surface deposits in central and South-central Minnesota. Outwash sands and gravels lie in front of end moraines. The major outwash plains are therefore found in the central part of the state. Transition of outwash plains into valley train deposits along major stream valleys can be found there as well (Ackroyd et. al, 1967). The Quaternary geology map (Hobbs and Goebel, 1982) of the state is represented in Figure 2.

The topography of Minnesota is moderately flat, with the highest and lowest altitudes being in the northeastern part. The lowest point (602 feet above mean sea level) is the surface of Lake Superior. The highest (2,031 feet) point lies just a few miles inland. Most of the state has altitudes between 1,000 and 1,500 feet with local morainal features rising 50 to 300 feet above surrounding land (Ackroyd et. al, 1967; Wright, 1972).

Minnesota is sub-humid and has moderately large total water supply because of the cool temperatures. The climate is continental, characterized by wide and rapid variations in temperature. The average annual precipitation is about 19 inches at the west-central edge, 20 inches - at the NW part and 25 inches at the SW corner. Precipitation increases eastward and southeastward to 32 inches (Ackroyd et. al, 1967). Therefore, temperature isotherms are roughly latitudinal (Figure 3), and precipitation isopleths are longitudinal (Figure 4) with resultant vegetation boundaries (Figure 5) having a diagonal trend (Wright, 1972). Conifer forest is predominant in the NE and passes into deciduous forest in the center. The western and southwestern parts of the state are dominated by prairie (Heinselman, 1974; Marschner, 1930; Wright, 1972).

Figure 1

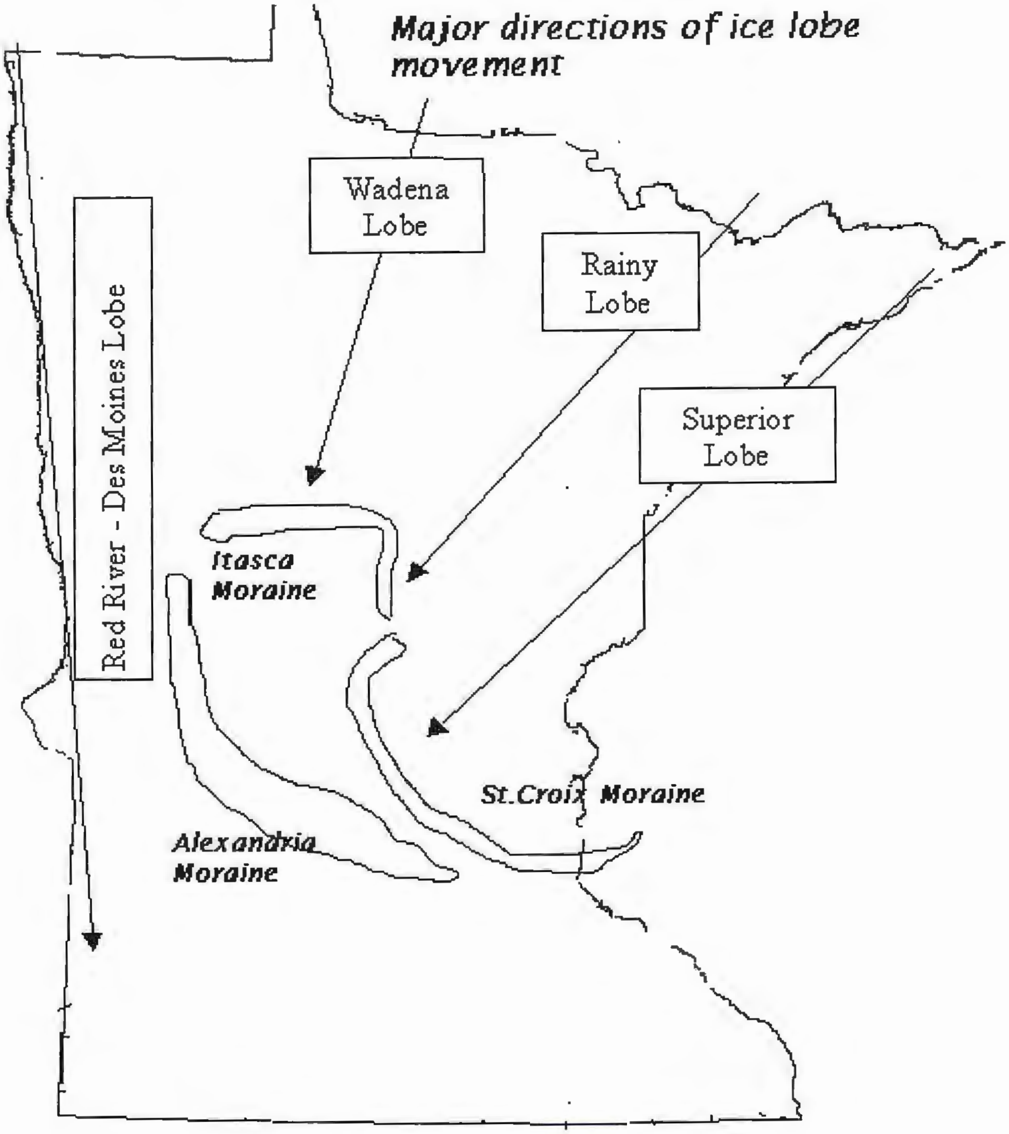
Major directions of ice lobe movement
Wadena Lobe
Rainy Lobe
Superior Lobe
Red River - Des Moines Lobe
Itasca Moraine
Alexandria Moraine
St.Croix Moraine

Figure 2

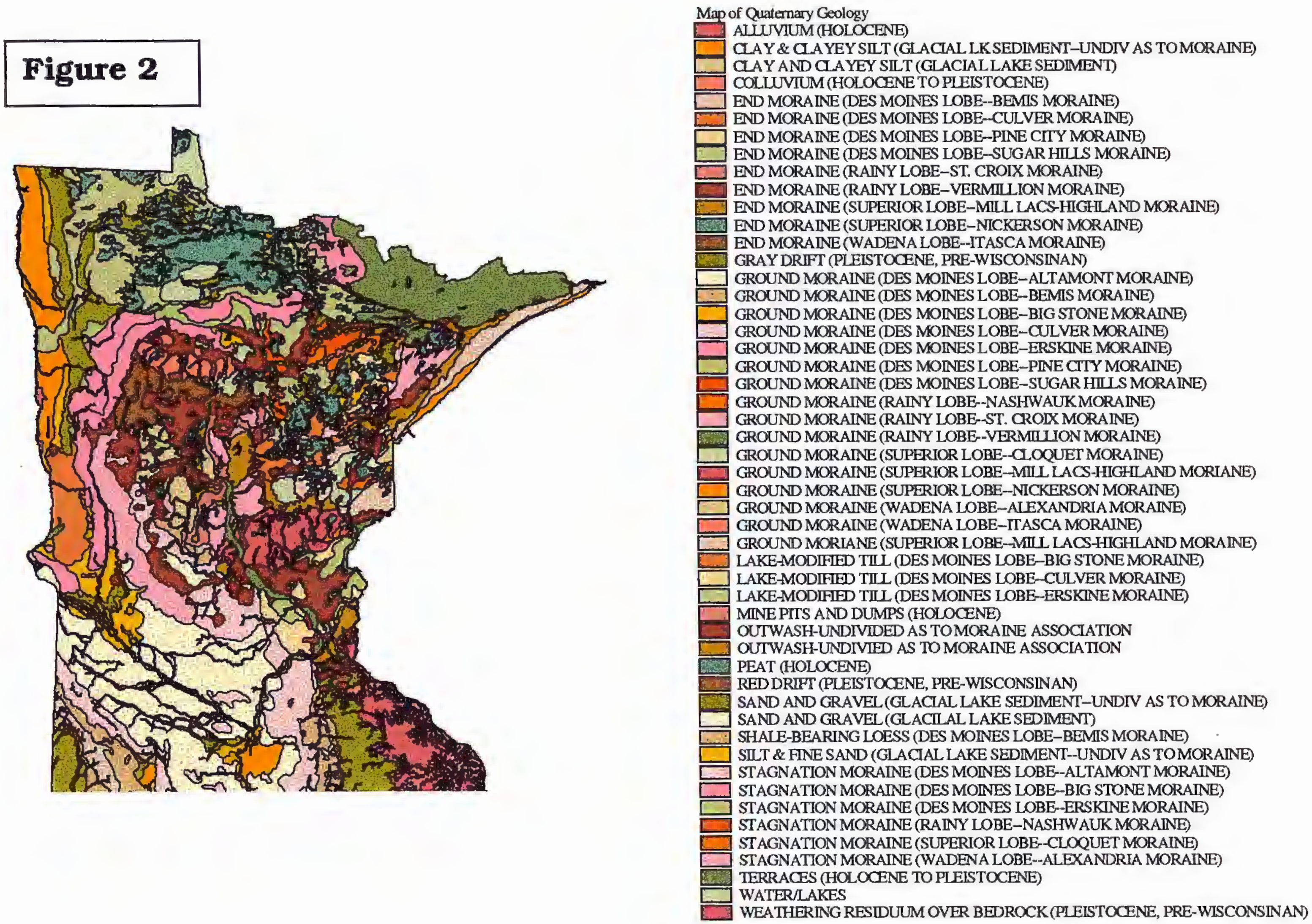
Map of Quaternary Geology
ALLUVIUM (HOLOCENE)
CLAY & CLAYEY SILT (GLACIAL LK SEDIMENT--UNDIV AS TO MORAINE)
CLAY AND CLAYEY SILT (GLACIAL LAKE SEDIMENT)
COLLUVIUM (HOLOCENE TO PLEISTOCENE)
END MORAINE (DES MOINES LOBE--BEMIS MORAINE)
END MORAINE (DES MOINES LOBE--CULVER MORAINE)
END MORAINE (DES MOINES LOBE--PINE CITY MORAINE)
END MORAINE (DES MOINES LOBE--SUGAR HILLS MORAINE)
END MORAINE (RAINY LOBE--ST. CROIX MORAINE)
END MORAINE (RAINY LOBE--VERMILLION MORAINE)
END MORAINE (SUPERIOR LOBE--MILL LACS-HIGHLAND MORAINE)
END MORAINE (SUPERIOR LOBE--NICKERSON MORAINE)
END MORAINE (WADENA LOBE--ITASCA MORAINE)
GRAY DRIFT (PLEISTOCENE, PRE-WISCONSINAN)
GROUND MORAINE (DES MOINES LOBE--ALTAMONT MORAINE)
GROUND MORAINE (DES MOINES LOBE--BEMIS MORAINE)
GROUND MORAINE (DES MOINES LOBE--BIG STONE MORAINE)
GROUND MORAINE (DES MOINES LOBE--CULVER MORAINE)
GROUND MORAINE (DES MOINES LOBE--ERSKINE MORAINE)
GROUND MORAINE (DES MOINES LOBE--PINE CITY MORAINE)
GROUND MORAINE (DES MOINES LOBE--SUGAR HILLS MORAINE)
GROUND MORAINE (RAINY LOBE--NASHWAUK MORAINE)
GROUND MORAINE (RAINY LOBE--ST. CROIX MORAINE)
GROUND MORAINE (RAINY LOBE--VERMILLION MORAINE)
GROUND MORAINE (SUPERIOR LOBE--CLOQUET MORAINE)
GROUND MORAINE (SUPERIOR LOBE--MILL LACS-HIGHLAND MORIANE)
GROUND MORAINE (SUPERIOR LOBE--NICKERSON MORAINE)
GROUND MORAINE (WADENA LOBE--ALEXANDRIA MORAINE)
GROUND MORAINE (WADENA LOBE--ITASCA MORAINE)
GROUND MORIANE (SUPERIOR LOBE--MILL LACS-HIGHLAND MORAINE)
LAKE-MODIFIED TILL (DES MOINES LOBE--BIG STONE MORAINE)
LAKE-MODIFIED TILL (DES MOINES LOBE--CULVER MORAINE)
LAKE-MODIFIED TILL (DES MOINES LOBE--ERSKINE MORAINE)
MINE PITS AND DUMPS (HOLOCENE)
OUTWASH-UNDIVIDED AS TO MORAINE ASSOCIATION
OUTWASH-UNDIVIED AS TO MORAINE ASSOCIATION
PEAT (HOLOCENE)
RED DRIFT (PLEISTOCENE, PRE-WISCONSINAN)
SAND AND GRAVEL (GLACIAL LAKE SEDIMENT--UNDIV AS TO MORAINE)
SAND AND GRAVEL (GLACILAL LAKE SEDIMENT)
SHALE-BEARING LOESS (DES MOINES LOBE--BEMIS MORAINE)
SILT & FINE SAND (GLACIAL LAKE SEDIMENT--UNDIV AS TO MORAINE)
STAGNATION MORAINE (DES MOINES LOBE--ALTAMONT MORAINE)
STAGNATION MORAINE (DES MOINES LOBE--BIG STONE MORAINE)
STAGNATION MORAINE (DES MOINES LOBE--ERSKINE MORAINE)
STAGNATION MORAINE (RAINY LOBE--NASHWAUK MORAINE)
STAGNATION MORAINE (SUPERIOR LOBE--CLOQUET MORAINE)
STAGNATION MORAINE (WADENA LOBE--ALEXANDRIA MORAINE)
TERRACES (HOLOCENE TO PLEISTOCENE)
WATER/LAKES
WEATHERING RESIDUUM OVER BEDROCK (PLEISTOCENE, PRE-WISCONSINAN)

Figure 3

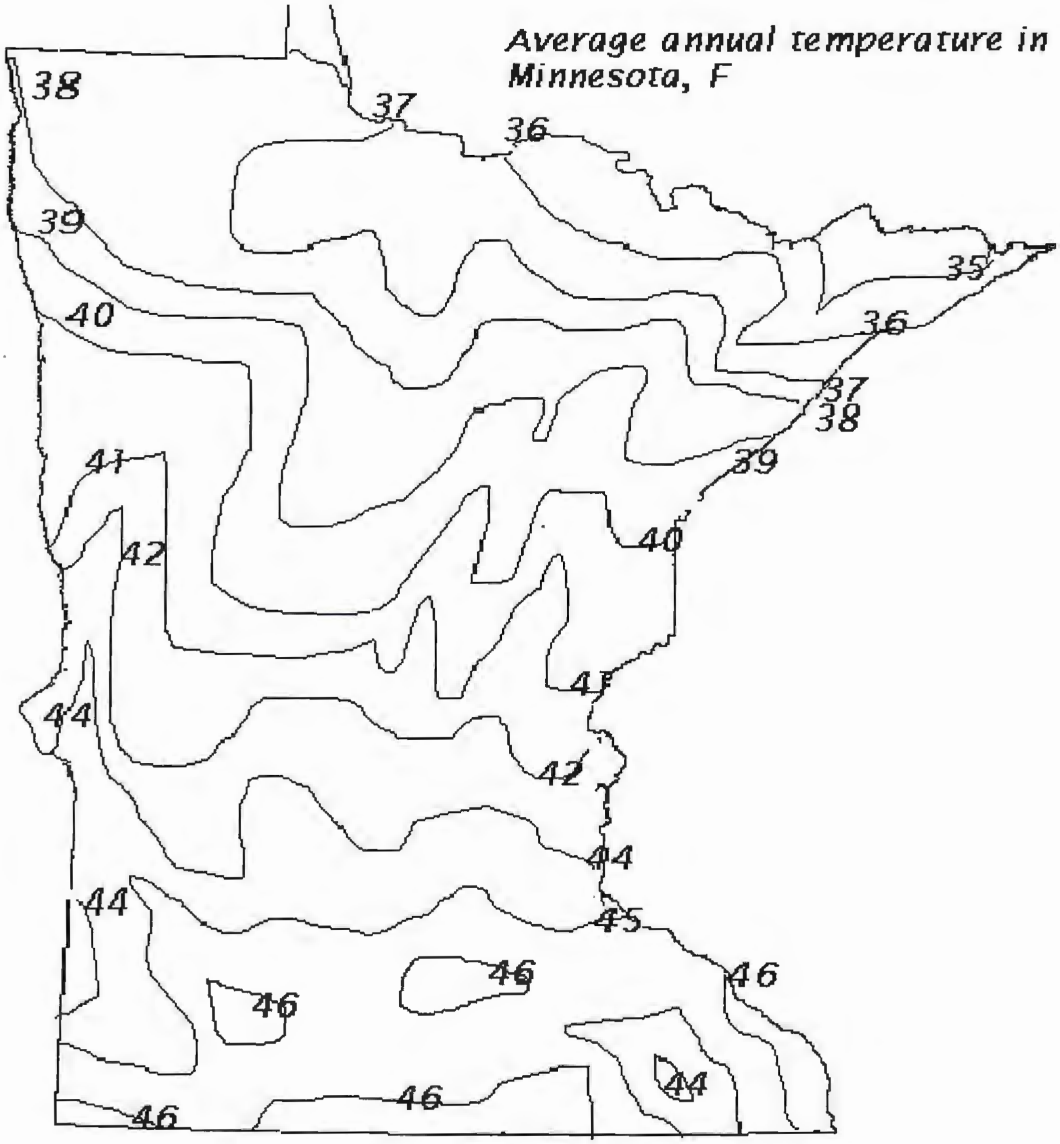
Average annual temperature in Minnesota, F
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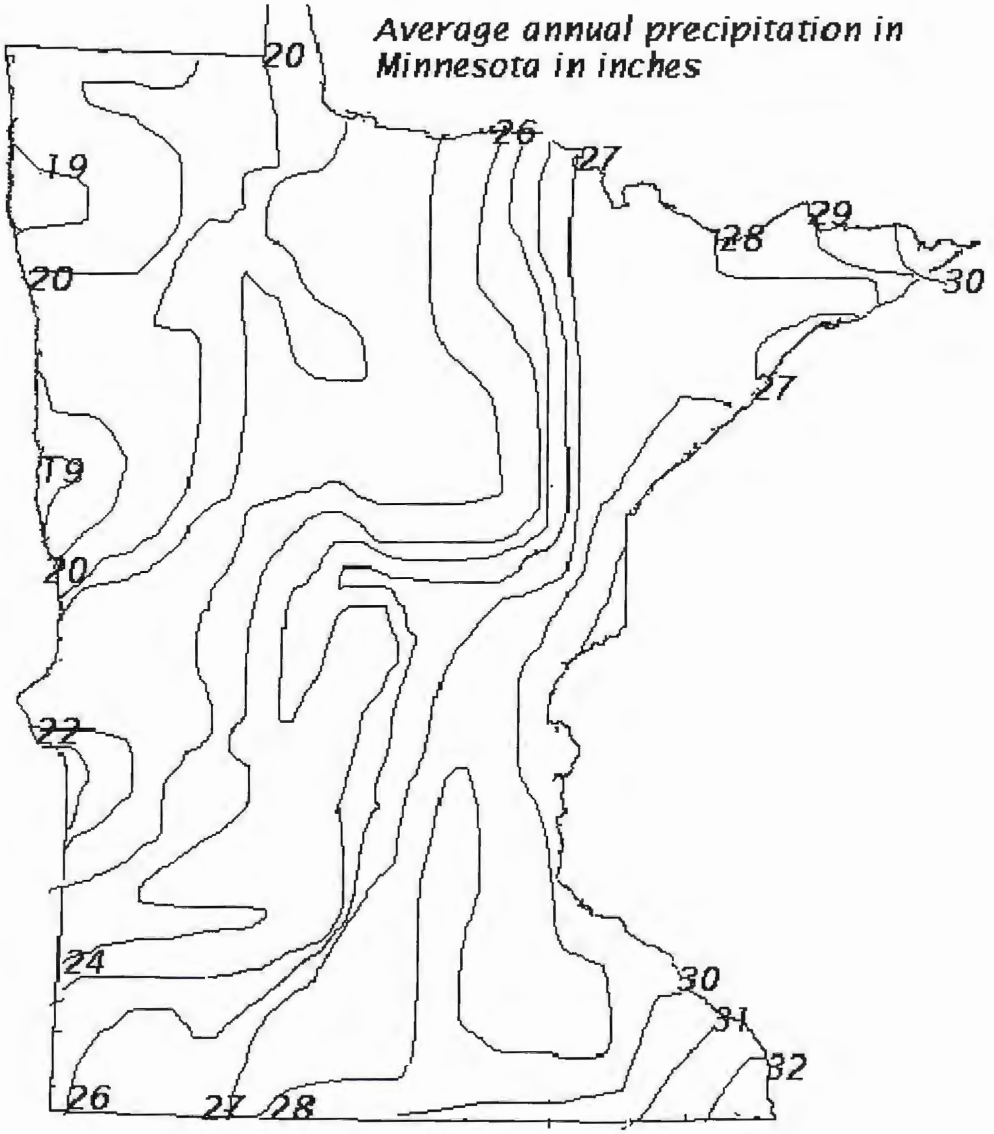
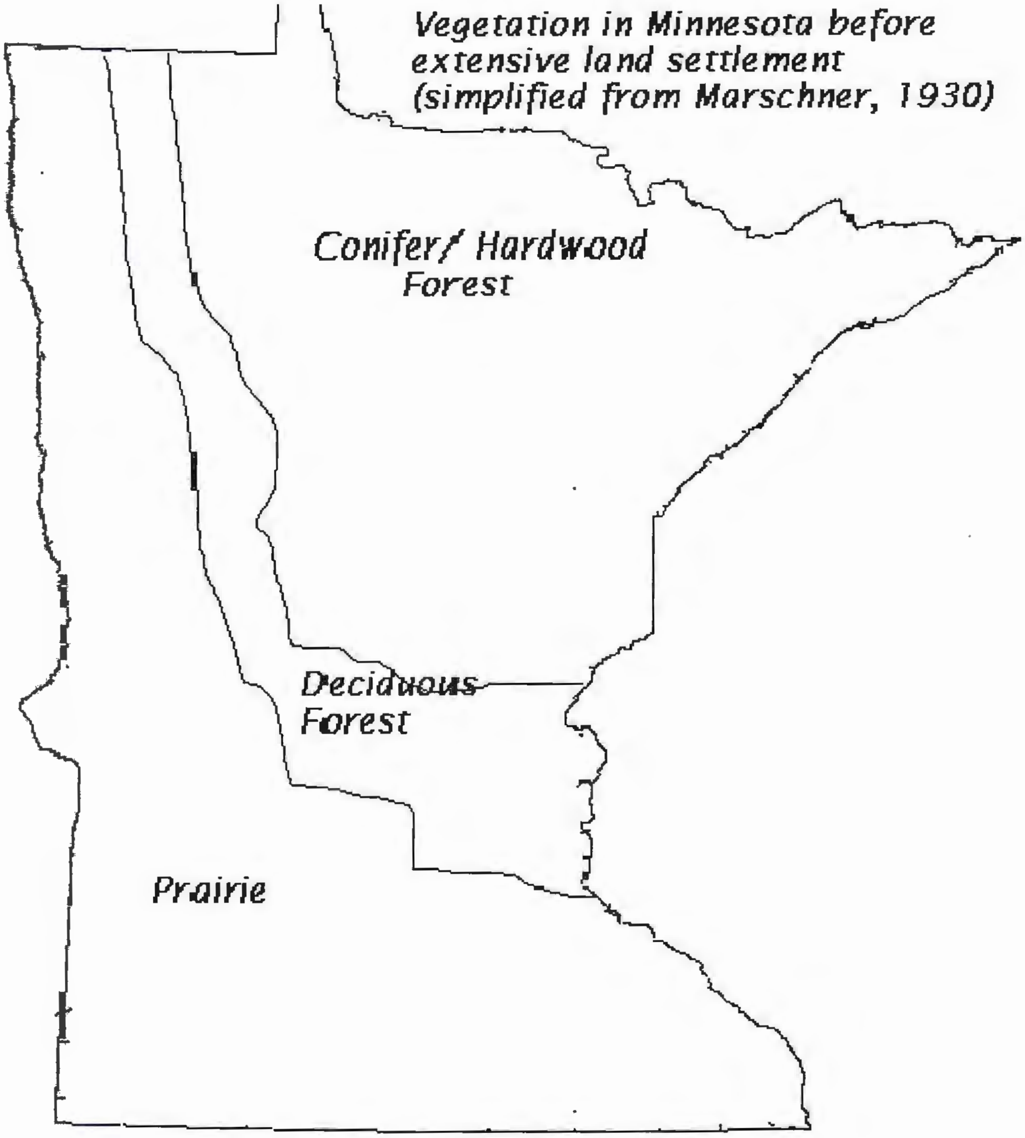
Figure 4



Average annual precipitation in Minnesota in inches

Figure 5


Vegetation in Minnesota before extensive land settlement (simplified from Marschner, 1930)
Conifer/ Hardwood Forest
Deciduous Forest
Prairie

5. Data and data analysis techniques.

5.1 Landscape classification schemes.

Three landscape classification systems are used in this analysis. The first two are components of the Minnesota Ecological Classification System (ECS). The ECS is a method to identify, characterize, and delineate units of land with similar climatic, geological, physical, and biological features that are significant for natural resource management. There are three levels in the Minnesota ECS. The Province Map represents the largest landscape units, and each subsequent level contains progressively smaller subdivisions. Ecological units for each level are defined by the dominant environmental factors that affect ecosystem processes and functions at that particular scale. The system has a nested hierarchical organization. The levels of our interest are two upper levels, the Province and Section units. The reason why the third and all subsequent levels of ECS were excluded from analysis is that their scale did not satisfy the "scale of control" requirement. Very little or no variability is expected between small geographic units, because analyzing controlling factors require adequate "scale" or size of landscape units to help spot natural changes. This size issue has already been discussed in the introduction. The third ECS level is based primarily on glacial processes and landforms predominant in Minnesota and therefore was replaced with the generalized map of Quaternary Geology, which was at an appropriate scale.

The Province-level stratification (Figure 6) was established by the Minnesota DNR using GIS analyses of the following information: continental climate patterns, regional physiography, and pre-European-settlement vegetation (Hanson and Hargrave, 1996). The resulting three Provinces are the Prairie Parkland Province in the west, the Eastern Broadleaf forest Province in a central and southeastern zone, and the boreal Laurentian Mixed Forest Province in the northeast.

Each Province was subdivided into two to five Sections (Figure 7) based on qualitative assessment of the following information: surficial geology, bedrock geology, pre-European-settlement vegetation, climate and natural watershed boundaries.

As an example of the process by which Provinces were subdivided, the Laurentian Mixed Forest Province in the northeastern part of the State was divided into five Sections. Two of these were associated with predominantly calcareous parent material (Northern Minnesota and Ontario Peatlands, Northern Minnesota Drift & Lake Plain Sections). Other Section boundaries within this Province were then recognized mainly on the basis of climate and glacial processes. The Northern Superior Uplands Section is dominated by Precambrian igneous and metamorphic bedrock, while the Southern and Western Superior Upland Sections are covered with ice contact and glaciofluvial material. Climatically, sections were subdivided on the basis of differences in growing season.

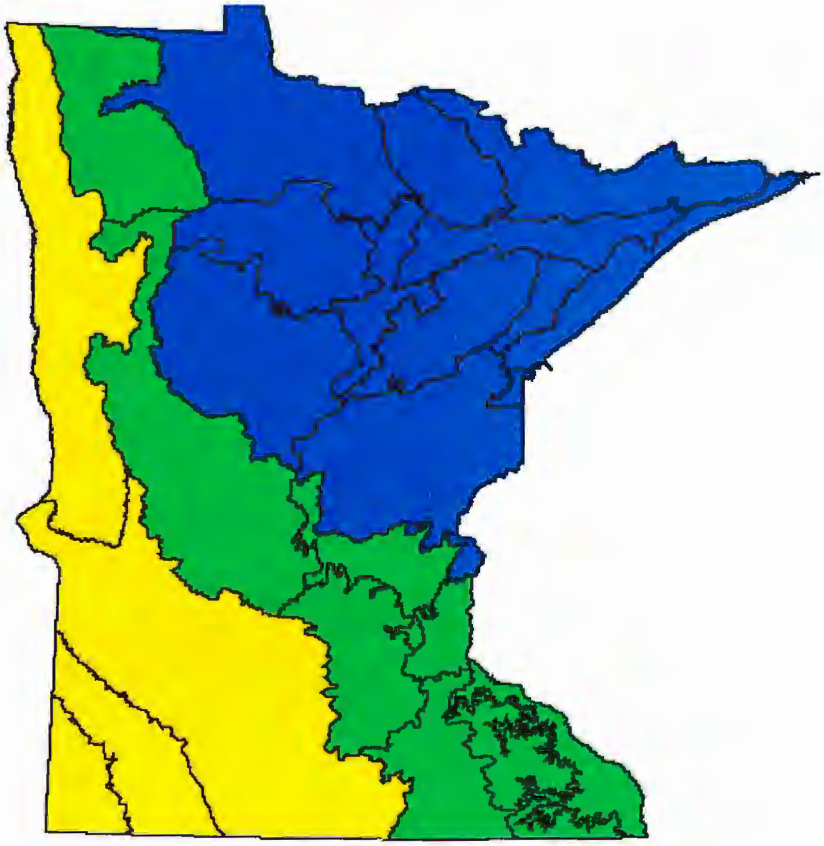
The map of Quaternary Geology (Figure 2), which reflects the complex nature of glaciated environments, was generalized (Figure 8) using

GIS in the following manner: smaller units representing similar deposits and landforms of different glacial advances were integrated into large units as shown in Table 1. The deposits associated with the Wadena, Rainy and Superior lobes were defined as sandy, whereas those ones of the Des-Moines lobe were defined as clayey. Subsequently, all ground moraines of the sandy glacial lobes were combined into a unit called sandy till plains. All the end moraines of the same lobes were incorporated into a sandy moraines unit. All the glacial lake sediments were brought into Sandy or Clayey lake sediments according to their relation to one or another lobe. Clayey till plains and clayey moraines were defined by the same means for Des-Moines lobe. All organic soils produced a separate peat unit. An outwash was also delimited as a separate unit disregarding the lobes that produced it. The resulting map consists of 9 geologically different units. It represents clayey and sandy lake sediments in NW of the State. Clayey till covers most of SW part. Sandy till is in NE and in some central parts. Peat is in the north central part. Clayey moraines wrap from the west deposits of central part, and finally, the interior consists of sandy moraines and outwash pretty much mixed together. The ninth unit is situated on the SE and represents predominantly deposits of pre-Wisconsinan age and for this reason was eliminated from the analysis.

Table 1

Sandy Till Plains	***Sandy Moraines***	***Clayey Till Plains***	***Clayey Moraines***	***Sandy Lake Sediment***	***Clayey Lake Sediment***	***Peat***	***Outwash***	***Pre-Wisconsinan Deposits***
Nickerson Ground Moraine	Nickerson End Moraine	Erskine Ground Moraine	Erskine Stagnation Moraine	Glacial lake sediment (Des-Moines Lobe) -Sand and Gravel	Glacial lake sediment (Des-Moines Lobe) -Silt	Peat (Holocene)	Des-Moines Lobe - Outwash	Red Drift
Cloquet Ground Moraine	Cloquet End Moraine	Big Stone Ground Moraine	Big Stone Stagnation Moraine	Glacial lake sediment (Superior Lobe) - Sand and Gravel	Glacial lake sediment (Des-Moines Lobe) -Clay		Superior Lobe - Outwash	Gray Drift
Mille Lacs-Highland Ground Moraine	Mille Lacs-Highland End Moraine	Culver Ground Moraine	Culver End Moraine		Glacial lake sediment (Superior Lobe) - Clay and Clayey Silt		Rainy Lobe - Outwash	Weathered Residuum over Bedrock
St. Croix Ground Moraine	St. Croix End Moraine	Sugar Hills Ground Moraine	Sugar Hills End Moraine				Wadena Lobe- Outwash	
Vermilion Ground Moraine	Vermilion End Moraine	Altamont Ground Moraine	Altamont Stagnation Moraine					
Nashwauk Ground Moraine	Nashwauk End Moraine	Pine City Ground Moraine	Pine City End Moraine					
Itasca Ground Moraine	Itasca End Moraine	Bemis Ground Moraine	Bemis End Moraine					
Alexandria Ground Moraine	Alexandria End Moraine	Shale-bearing loess-covered drift outside						

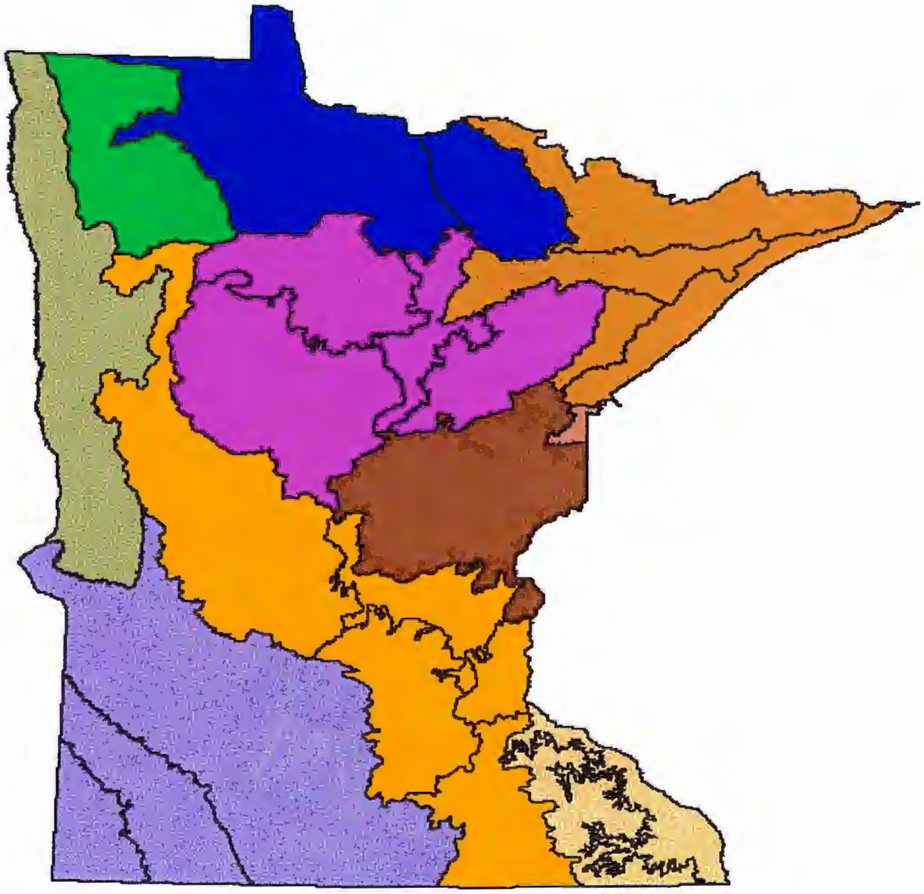
Figure 6



ECS Province Map of Minnesota

🟩 Eastern Broadleaf Forest Province
🟦 Laurentian Mixed Forest Province
🟨 Prairie Parkland Province

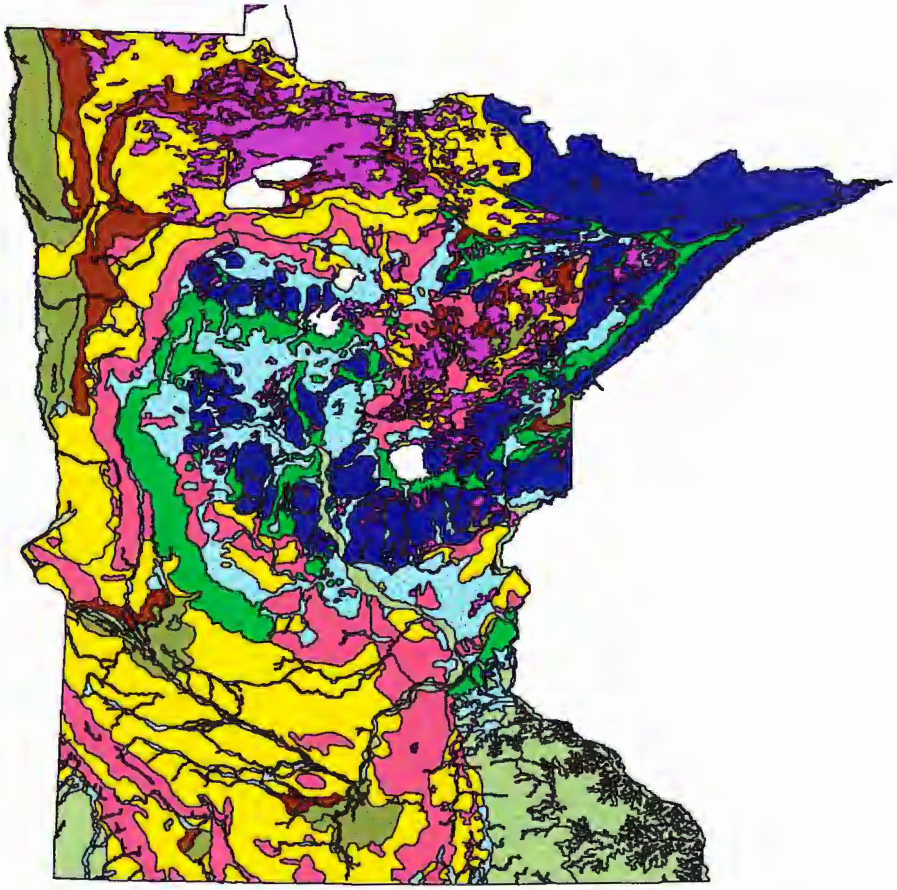
Figure 7



ECS Section Map of Minnesota

- 🟩 Lake Agassiz, Aspen Parklands
- 🟧 Minnesota & NE Iowa Morainal
- 🟦 N. Minnesota & Ontario Peatlands
- 🟪 N. Minnesota Drift & Lake Plains
- 🟪 North Central Glaciated Plains
- 🟧 Northern Superior Uplands
- 🟨 Paleozoic Plateau
- 🟩 Red River Valley
- 🟥 Southern Superior Uplands
- 🟫 Western Superior Uplands

Figure 8



Generalized Map of Quaternary Geology

- ▨ Clayey Lake Sediment
- 🟥 Clayey Morains
- 🟨 Clayey Till Plains
- 🟦 Outwash
- 🟪 PEAT (organic soils)
- 🟫 Sandy Lake Sediment
- 🟩 Sandy Morains
- 🟦 Sandy Till Plains
- ☐ Water
- 🟩 pre-Wisconsinan

5.2 Numerical data

Based upon the goals laid out in the introduction to this manuscript, two types of data are used in our studies: streamflow data and ecological and Quaternary geology maps.

Daily average flow data are available from the United States Geological Survey on CD ROM. The data supplied on this software product are "as received" by Earthinfo from the government agency, business, etc. It includes over 600,000 station-years on stream flow and other related data from USGS WATSTORE database dating back to 1850. The data were sorted, counted, indexed and summary statistics derived for all existing and abandoned stations. The bulk of the data is historical stream flow daily records, but there are also observations on more than 50 parameters including water and soil temperature, wind, dissolved oxygen and reservoir storage. We used only stream flow data, which varied greatly in space and time and was organized as follows. The first step was applying descriptive statistics to sort data by area and duration of record criteria. Observations available from the database were carried out through the last hundred years with the last year of observation being 1992. There are about 317 watersheds in Minnesota. Each watershed is represented by a gaging station coded with an eight-figure ID number with 1 to 102 recorded years of daily runoff observation and with drainage areas from less than 1 sq.mi to 59,000 sq.mi. The total number of stations includes 95 stations that were eliminated from analysis because of absence of areal data. Most of them have periods of observation not exceeding 1 year and therefore are of little use for analysis of long term trends. Hence, 222 watersheds were left in the working database.

Figure 9 and Table 2 show that majority of watersheds (132 basins making up 60% of all) have observation periods greater than 20 years. Another extensive group of watersheds (60 basins, 20%) have observation periods not exceeding 10 years.

Figure 9

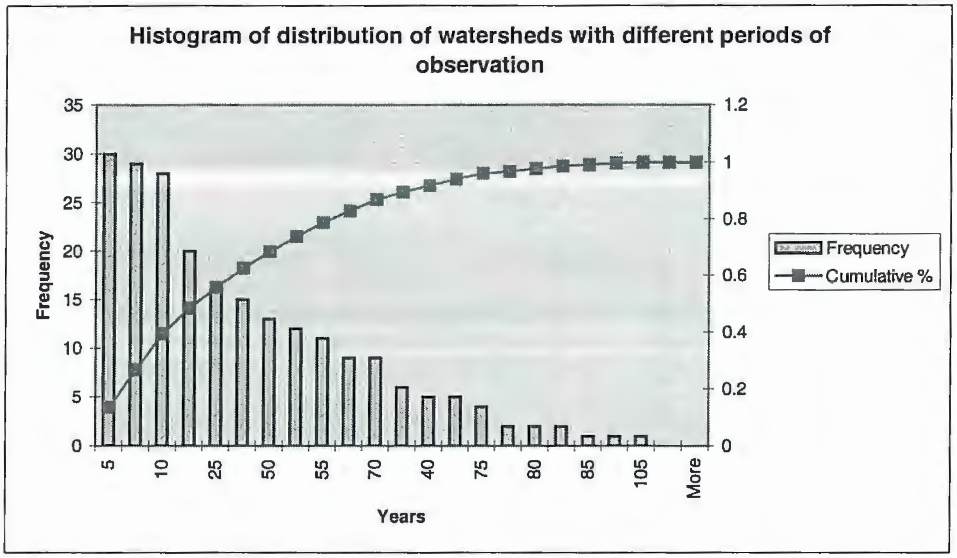


Table 2

Years	*Frequency*	*Cumulative %*
1	2	.90%
5	30	14.48%
10	28	27.15%
15	29	40.27%
20	20	49.32%
25	16	56.56%
30	12	61.99%
35	9	66.06%
40	5	68.33%
45	5	70.59%
50	13	76.47%
55	11	81.45%
60	6	84.16%
65	15	90.95%
70	9	95.02%
75	4	96.83%
80	2	97.74%
85	1	98.19%
90	2	99.10%
95	1	99.55%
100	0	99.55%
105	1	100.00%
More	0	100.00%

Figure 10 and Table 3 illustrate the frequency distribution of the size of watersheds represented by the gaging stations. There are 82 watersheds (31%) with an areas larger than 1,000 mi^2, 182 (75%) watersheds larger than 100 mi^2 and 3 watersheds smaller than 1 mi^2.

Figure 10

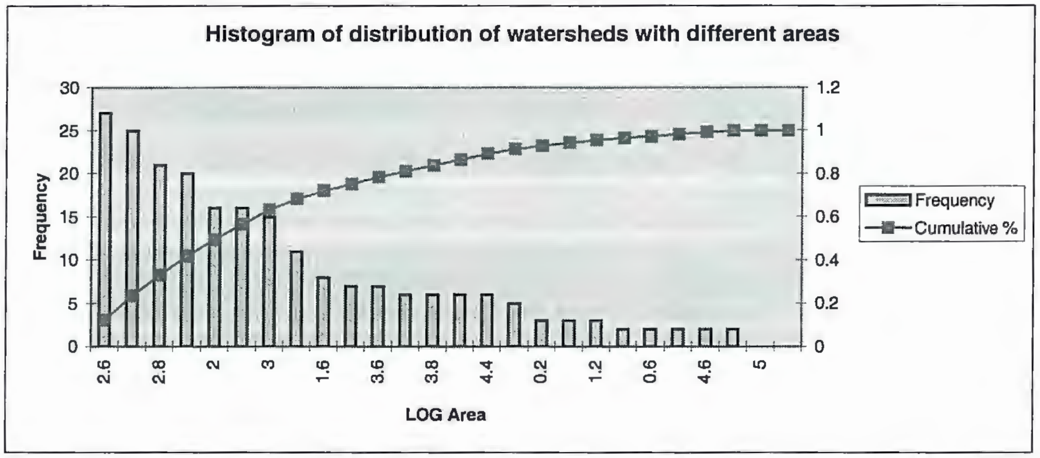


Table 3

Area (sq.mi)	*Area (LOG10)*	*Frequency*	*Cumulative %*
1.6	0.2	3	1.36%
2.5	0.4	2	2.26%
4.0	0.6	2	3.17%
6.3	0.8	3	4.52%
10.0	1	7	7.69%
15.8	1.2	3	9.05%
25.1	1.4	5	11.31%
39.8	1.6	8	14.93%
63.1	1.8	6	17.65%
100.0	2	16	24.89%
158.5	2.2	20	33.94%
251.2	2.4	16	41.18%
398.1	2.6	27	53.39%
631.0	2.8	21	62.90%
1000.0	3	15	69.68%
1584.9	3.2	25	81.00%
2511.9	3.4	11	85.97%
3981.1	3.6	7	89.14%
6309.6	3.8	6	91.86%
10000.0	4	2	92.76%
15848.9	4.2	6	95.48%
25118.9	4.4	6	98.19%
39810.7	4.6	2	99.10%
63095.7	4.8	2	100.00%
100000.0	5	0	100.00%
	More	0	100.00%

There are 106 basins that have observation periods greater than 20 years and drainage areas greater than 100 mi^2.

Regionalization requires using data sets that represent big spatial units under long observation. Several possibilities exist to meet this criterion. We could choose a group consisting of 106 watersheds (observation periods more than 20 years, areas greater than 100 mi^2) or a group consisting of 51 watersheds (observation periods more than 20 years, areas greater than 1,000 mi^2). In order to derive representative hydrologic characteristics and normalize data, the decision was made to use data for 100 to 1,300 mi^2 area range corresponding to observation periods more than 20 years. The main reason for this was that data falling within 100-1,300 mi^2 range were more consistent, i.e. included a larger number of time series and require fewer adjustments compared to the alternative set. Streamflow data for chosen watersheds were organized by annual and monthly mean streamflow values from the original set on CD-ROM.

The working data set used in subsequent analysis is shown in Tables 4, 5 and 6 and Figures 11,12 and 13. It represents 67 drainage basins whose characteristics were used in hydrological calculations and served as a database for purposes of regionalization. Table 1 contains three columns. The first is gaging station ID number, the second gives years of observations carried out on this station, and the third is the watershed area corresponding to each gaging station. Figure 11 statistically describes the proposed data set. The first histogram shows the distribution of watersheds with different areas and reveals that the majority of watersheds have areas in the range of 200 to 300 sq. mi. Figure 12 shows the distribution of watersheds with different periods of observation. Most of the stations were observed for 30 to 70 years. Figure 13 spatially locates all the stations.

Table4. Starting data.						
ID	**Years**	**Areas**		**ID**	**Years**	**Areas**
04010500	73	600		05244000	60	1010
04012500	35	112		05245100	20	432
04014500	65	140		05247000	30	287
04016000	41	161		05270500	63	925
04016500	46	290		05275000	68	615
04018750	27	713		05278000	39	179
05030000	35	270		05278500	20	221
05040500	45	482		05279000	46	1170
05049000	36	834		05292000	54	1160
05061000	49	322		05293000	52	398
05061500	48	522		05294000	61	905
05062000	63	1040		05300000	67	983
05062500	69	888		05311400	26	111
05067500	49	151		05313500	60	653
05069000	51	426		05315000	52	259
05076000	78	959		05316500	70	629
05078000	54	512		05317000	67	1280
05078230	34	266		05318000	20	132
05087500	44	265		05319500	22	812
05094000	54	444		05320500	49	1110
05104000	23	312		05336700	24	863
05104500	47	573		05338500	39	958
05107500	63	1220		05340050	22	231
05124480	28	253		05353800	26	442
05127000	80	1229		05373000	31	304
05129000	62	483		05374000	65	1130
05130500	52	187		05376000	25	101
05134200	30	543		05384000	60	615
05139500	35	162		05384500	38	129
05140500	21	102		05385000	67	1270
05206500	29	1163		05385500	34	275
05216860	26	114		05457000	54	425
05219000	29	421		05476000	68	1220
05231000	48	562				

Table 5

Area	Frequency	Cumulative %
100	0	.00%
200	13	19.70%
300	10	34.85%
400	4	40.91%
500	8	53.03%
600	5	60.61%
700	4	66.67%
800	1	68.18%
900	4	74.24%
1000	5	81.82%
More	12	100.00%

Figure 11

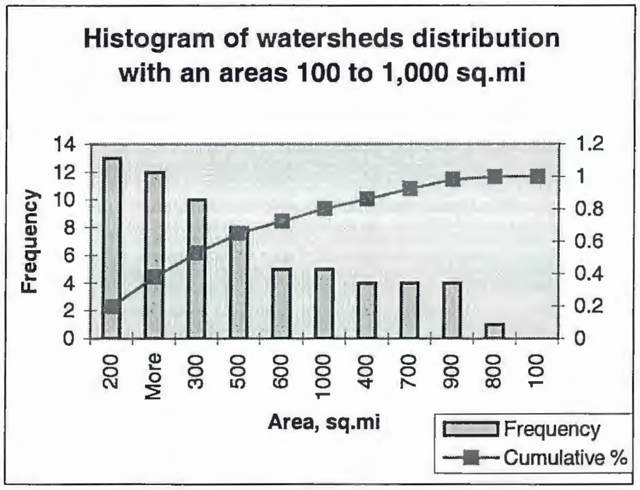


Table 6

Years	Frequency	Cumulative %
10	0	.00%
20	3	4.55%
30	15	27.27%
40	10	42.42%
50	11	59.09%
60	11	75.76%
70	14	96.97%
80	2	100.00%
90	0	100.00%
100	0	100.00%
More	0	100.00%

Figure 12

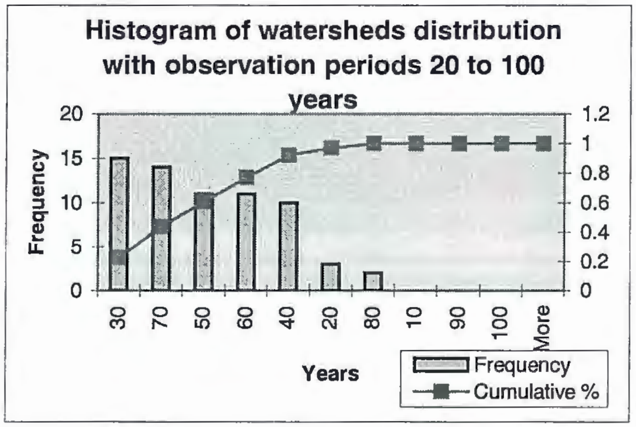
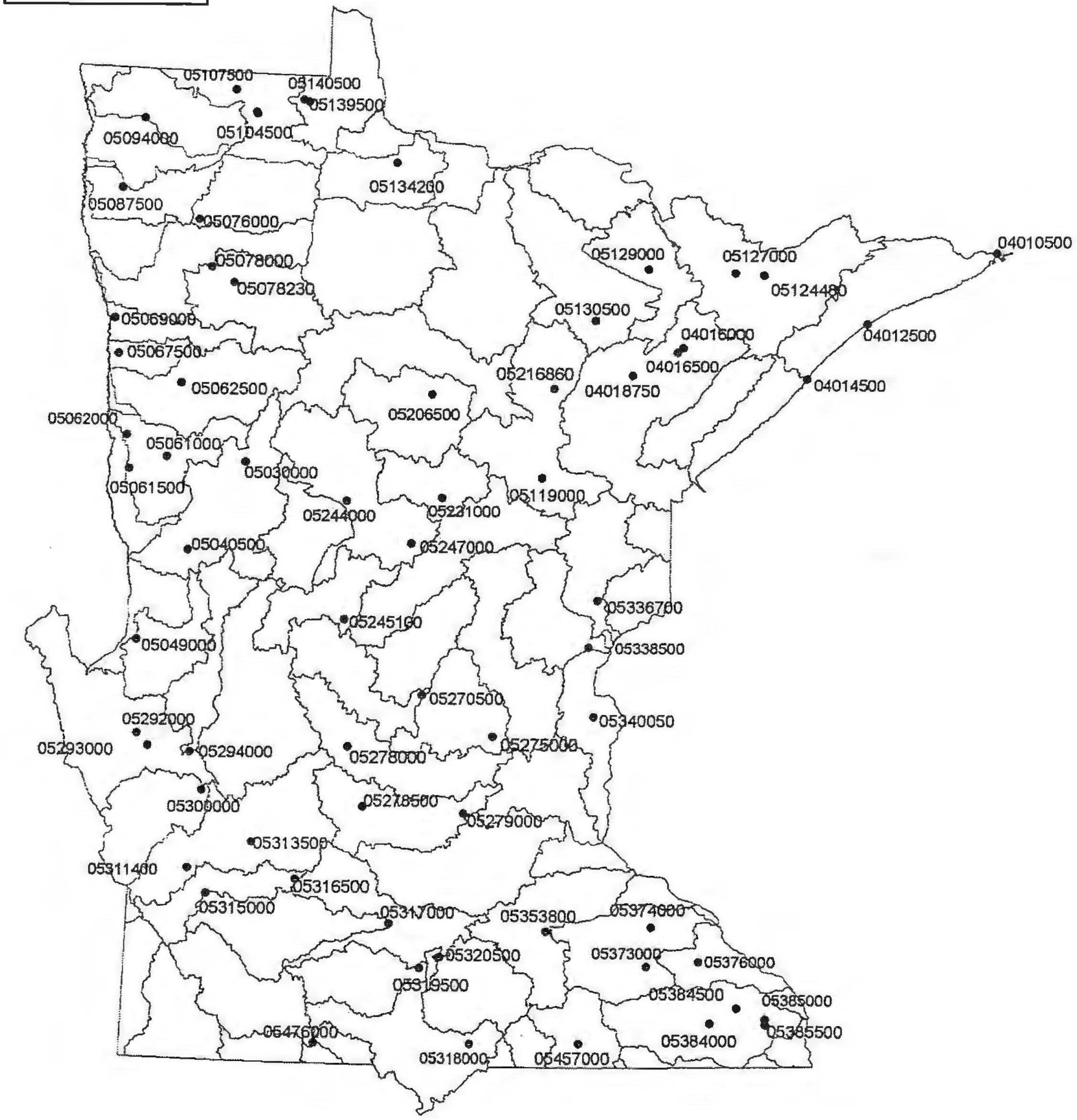


Figure 13


05107500
05140500
05139500
05094000
05104500
05134200
05087500
05076000
05129000
05127000
04010500
05078000
05124480
05078230
05130500
05069000
04016000
04012500
05067500
04016500
05216860
05062500
04018750
04014500
05062000
05206500
05061000
05030000
05061500
05119000
05231000
05244000
05247000
05040500
05336700
05245100
05049000
05338500
05270500
05292000
05340050
05293000
05294000
05275000
05278000
05278500
05300000
05279000
05313500
05311400
05316500
05315000
05317000
05353800
05374000
05320500
05373000
05376000
05319500
05384500
05385000
05476000
05385500
05384000
05318000
05457000

The aforementioned data set was amended after initial analysis because there were a few regions where existing data were insufficient to carry out statistical calculations. This was the case in the analysis of ecological classification system where two more stations were added to bring the total number of watersheds to 69. It was done to characterize the Northern Minnesota and Ontario Peatlands region lacking sufficient numerical data fitting our original criteria.

In the analysis of surficial deposits, the starting data consisting of 67 watersheds were reduced to 32. In this case the reduction was to eliminate as many watersheds as possible where streamflow did not explicitly characterize a certain type of deposit, since numerous rivers occupied several types of deposits.

Next step was data evaluation. The major characteristic used to describe streamflow was unit runoff. Comparison of drainage basins of different size is meaningless unless data are normalized. Consequently most of the correlations for the determination of hydrologic characteristics of a region use drainage area as a common denominator. Thus, for example, the volumes of runoff from different sized basins but similar in other respects can be compared directly if the volumes are divided by the respective areas. The *unit runoff volume* or *module* so obtained is the most convenient way of comparing yields of various basins.

Runoff Module *(cfs/mi^2)* = ***Streamflow Parameter*** *(cfs)* / ***Drainage Area*** *(mi^2)*

Recovered annual and monthly mean streamflow values were scattered within the 1913-93 period. A systematic approach demands analyzing data of the same time series, so a common observation period was chosen to calculate the final module for each time series. The common period was defined as 1947-79, because this time period was common for the largest number of drainage stations. The final or characteristic value of unit runoff for each series was determined as a ratio of the average value calculated using 32 annual mean values from 1947-79 period to watershed area.

However, there still were 31 watersheds in the size range 100-1300 mi^2. with missing data during this time interval. Such missing data had to be inferred. A mathematical technique of reducing incomplete time series using the one with longest observation period was used to estimate missing data. This technique is based on the fact that any characteristic of a less studied region can be successfully predicted from its relationship to the region that is best characterized, i.e. has the longest and most complete observation record. These two regions should be spatially correlated. In other words, they should belong to the same geographical unit. Such a unit is defined on the basis of maximum geographical extent to which each watershed can be used as representative to characterize other watersheds.

Let the less studied region with missing data be the "incomplete row" and region whose characteristics are well known is therefore the "complete row" or "base row". The "complete row" is the one with longest observation path for a given geographical region. Determination of the "complete rows" and their spatial boundaries to set correlation to "incomplete" rows was done by Shmagin et al. (1997). The next section contains a detailed description of the method.

Description of data reducing technique (Ovchinnikov, 1955)

Total discharge of the incomplete row (i) is determined by $\sum X_{ni}$ for some n years. Discharge of a base row (b) for the same period is $\sum X_{nb}$. In order to find representative average X'_o for incomplete row, it is necessary to calculate coefficient of dependency, which is determined by ratio:

$$K_{ni}=\sum X_{ni}/\sum X_{nb}$$

The average of the incomplete row is found as:

$$X'_o=K_{ni}*X_o$$

where X_o is the base row average.

This method assumes that K_{ni} is constant for any two rows compared and the relationship between two time series can be plotted as a straight line with one of the coordinates being (0;0). Figure 14 visualizes this technique with all the variables represented graphically.

The coefficient K_{ni} is determined from the ratio:

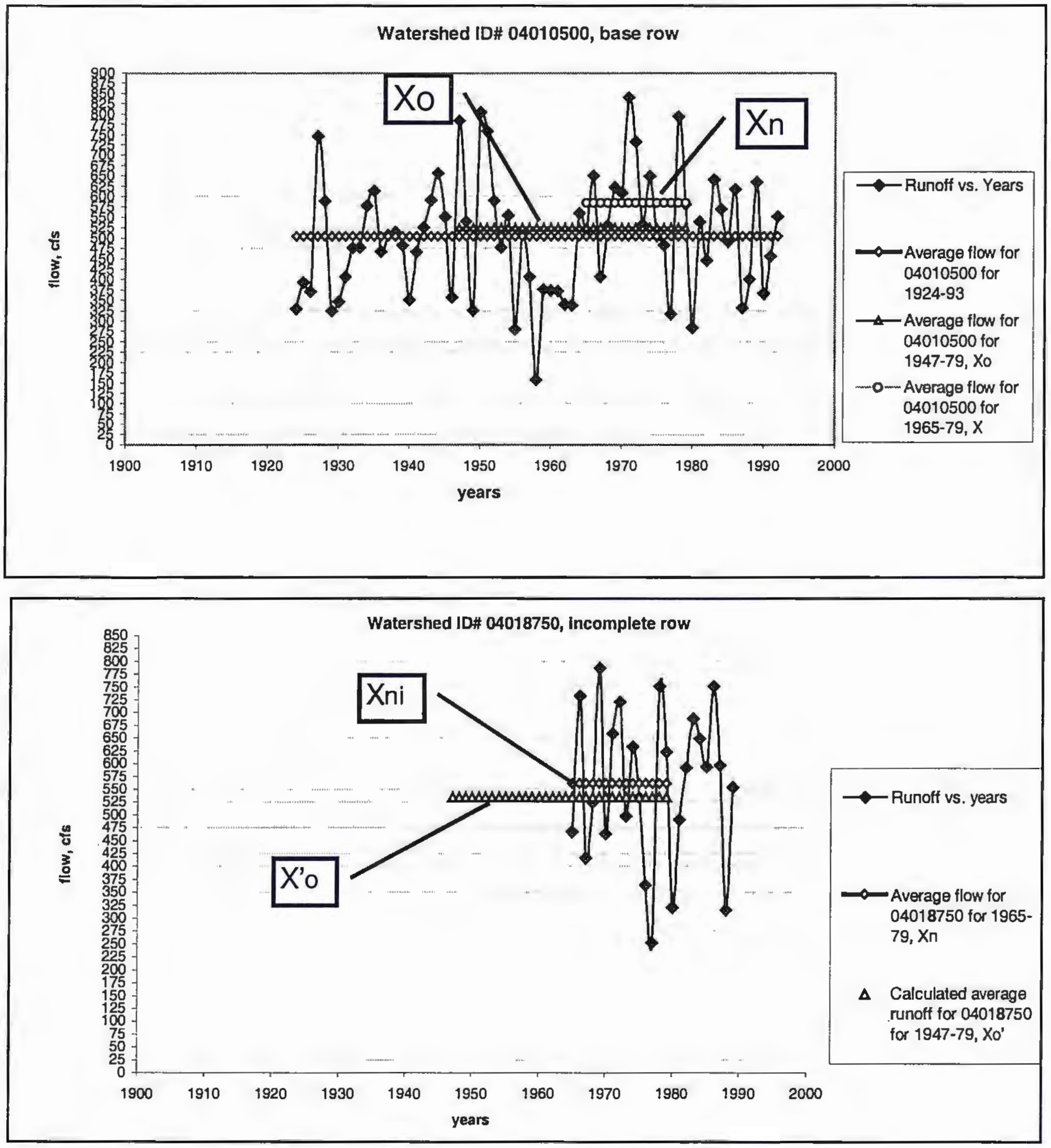
K_{ni} = *average flow for 04018750 for 1965-79 / average flow for 04010500 for 1965-79*

And the average of incomplete row is found as:

$X'_o = K_{ni} *$ *average flow for 04010500 for 1947-79*

Each one of the incomplete rows was correlated to the corresponding "base row". This allowed calculating averages and unit runoff for all time series.

Figure 14



Watershed ID# 04010500, base row
flow, cfs
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400
425
450
475
500
525
550
575
600
625
650
675
700
725
750
775
800
825
850
875
900
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
years
Xo
Xn
Runoff vs. Years
Average flow for 04010500 for 1924-93
Average flow for 04010500 for 1947-79, Xo
Average flow for 04010500 for 1965-79, X
Watershed ID# 04018750, incomplete row
flow, cfs
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
400
425
450
475
500
525
550
575
600
625
650
675
700
725
750
775
800
825
850
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
years
Xni
X'o
Runoff vs. years
Average flow for 04018750 for 1965-79, Xn
Calculated average runoff for 04018750 for 1947-79, Xo'

6. Analytical methods

6.1 Description of statistical tools

Analysis of variance is designed to answer a question whether population means of n samples differ significantly (Devore and Peck, 1986; Ott, 1988). For example, three random samples coming from three different populations are compared. They are declared different if variability among the sample means is significantly larger in comparison to the within-sample variation. When the comparison involves t population means, an independent random sample is drawn from each of the t populations. A measure of the within-sample variability is computed as

$$S^2_w = SSW/(n-t)$$

where S^2_w is the within-sample variability;

SSW - sum of squares of each group (within group);

n - number of observations in each sample.

Similarly, a measure of the between-sample variability is obtained as

$$S^2_b = SSB/(t-1)$$

where S^2_b is the between-sample variability;

SSB - sum of squares between samples

The decision to accept or reject the null hypothesis (H_0) of equality of the t population means depends on the computed value of F (the ratio of sum of squares between samples to sum of squares within each group):

$$F = S^2_b / S^2_w$$

SSB - sum of squares between samples;

SSW - sum of squares of each group (within group)

Under H_0, both S^2_b and S^2_w estimate σ^2_e the variance common to all t populations. Under the alternative hypothesis (H_a), S^2_b estimates ($\sigma^2_e + \theta$), where θ is a positive quantity, whereas S^2_w still estimates σ^2_e. Thus large values of F indicates a rejection of H_0. Critical values of F are obtained from published tables (Devore and Peck, 1986).

While rejection of the null hypothesis gives us information concerning the population means, the question of which means differ from each other is not answered (Ott, 1988). Multiple-comparison procedures have been developed to answer questions such as these. Fisher (1949) developed a procedure for making pairwise comparisons among a set of t

population means. The procedure is called Fisher's least significant difference (LSD) or Fisher's protected LSD if F test for treatments has been shown significant, i.e. ratio $F = S^2_b / S^2_w$ has been shown significant to declare that at least one of the means differs from the rest. The α-level of Fisher's LSD is valid for a given comparison only if LSD is used for independent comparisons. The error rate for the protected LSD is controlled on an experimentwise basis at a level approximately equal to the α-level for the F test. The routine of the analysis is as follows:

1. Perform analysis of variance to test H_0: $\mu_1=\mu_2= \ldots=\mu_n$ against the alternative hypothesis that at least one of the means differs from the rest.
2. If there is insufficient evidence to reject H_0 using $F = S^2_b / S^2_w$, we proceed no further.
3. If H_0 is rejected, then define the least significant difference (LSD) to be the observed difference between two sample means necessary to declare the corresponding population means different.
4. For a specified value of α, the least significant difference for comparing μ_i to μ_j is

$$LSD = t_{\frac{\alpha}{2}} \sqrt{S_w^2 \left(\frac{1}{n_i} + \frac{1}{n_j}\right)}$$

where n_i and n_j are the respective sample sizes from population i and j and t is the critical t value. For $n_I = n_j = n$

$$LSD = t_{\frac{\alpha}{2}}\sqrt{S_w^2 \frac{2}{n}}$$

5. All pairs of sample means are then compared. If

   $$\left|\overline{y_i} - \overline{y_j}\right| \geq LSD$$

   we declare the corresponding population means μ_i and μ_j different.
6. For each pairwise comparison of population means, the probability of Type I

   Error is fixed at a specified value of α.

6.2 Grouping of data and application of statistical technique

Each flow value in the runoff database is attributed to a gaging station. Each gaging station is accompanied with geographical information that allows spatial locating of all the stations. Gaging stations and corresponding flow values from the database created for this analysis were placed on the maps using GIS and given geographical data. Gaging stations lying within each Province form a random sample for each unit. Random samples so obtained characterize corresponding regions.

As mentioned earlier, the ecological Province map of Minnesota consists of three regions: Laurentian Mixed Forest, Eastern Broadleaf Forest and Prairie Parkland reflecting major climate patterns of North

America found in Minnesota. Three random samples of 23 stations for each Province (Table 7) were obtained for this landscape division by means described above.

Table 7. Flow random samples obtained for provinces.

Prairie Parkland (100*)		Eastern Broadleaf Forest (200)		Laurentian Mixed Forest (300)	
ID	**Unit Runoff,** *cfs/sq.mi*	**ID**	**Unit Runoff,** *cfs/sq.mi*	**ID**	**Unit Runoff,** *cfs/sq.mi*
5278500	0.214	5076000	0.234	5129000	0.697
5292000	0.093	5078000	0.359	5134200	0.586
5293000	0.152	5078230	0.263	5139500	0.274
5294000	0.13	5094000	0.26	5140500	0.239
5300000	0.149	5104000	0.252	4016000	0.681
5311400	0.182	5104500	0.265	4016500	0.792
5313500	0.177	5107500	0.256	4018750	0.75
5316500	0.184	5353800	0.583	5206500	0.389
5317000	0.224	5457000	0.45	5216860	0.548
5318000	0.306	5245100	0.355	5219000	0.667
5319500	0.265	5278000	0.354	5231000	0.441
5320500	0.363	5340050	0.331	5244000	0.48
5476000	0.221	5030000	0.223	5247000	0.419
5315000	0.178	5270500	0.335	4010500	0.874
5040500	0.171	5275000	0.434	4012500	1.121
5049000	0.084	5279000	0.25	4014500	1.21
5061000	0.229	5373000	0.494	5124480	0.806
5061500	0.11	5374000	0.487	5127000	0.936
5062000	0.149	5376000	0.381	5130500	0.663
5062500	0.228	5384000	0.526	5336700	0.837
5067500	0.455	5384500	0.422	5338500	0.634
5069000	0.169	5385000	0.524	5337400	0.658
5087500	0.16	5385500	0.484	4021530	0.755

* - code given to each province for the convenience of designation in statistical analysis.

The ecological map of Minnesota representing sections (Table 8) is subdivided into 10 regions:

1) Prairie Parklands Province: Red River Valley and North Central Glaciated Plains Sections;
2) Eastern Broadleaf Forest Province: Lake Agassiz and Minnesota, NE Iowa Morainal and Paleozoic Plateau Sections;
3) Laurentian Mixed Forest Province: N.Minnesota&Ontario Peatlands, N.Minnesota Drift&Lake Plains, Western Superior Uplands, Southern Superior Uplands and Northern Superior Sections.

Nine random samples (Table 9) were obtained by the same method as for province map (Southern Superior Uplands was merged with Western Superior Uplands because of small territory and no flow data for this region available from USGS source).

Table 8. Section List.

1	Lake Agassiz, Aspen Parklands
2	Minnesota & NE Iowa Morainal
3	N. Minnesota and Ontario Peatlands
4	N. Minnesota Drift and Lake Plains
5	North Central Glaciated Plains
6	Northern Superior Uplands
7	Paleozoic Plateau
8	Red River Valley
9	Southern Superior Uplands
10	Western Superior Uplands

Table 9. Flow random samples obtained for ECS Sections.

Prairie Parkland

ID	*cfs/sq.mi*
105*-N.Central Glaciated Plains	
5278500	0.214
5292000	0.093
5293000	0.152
5294000	0.13
5300000	0.149
5311400	0.182
5313500	0.177
5316500	0.184
5317000	0.224
5318000	0.306
5319500	0.265
5320500	0.363
5476000	0.221
5315000	0.178
108-Red River Valley	
5040500	0.171
5049000	0.084
5061000	0.229
5061500	0.11
5062000	0.149
5062500	0.228
5067500	0.455
5069000	0.169
5087500	0.16

Eastern Broadleaf Forest

ID	*cfs/sq.mi*
201-Lake Agassiz, Aspen Parklands	
5076000	0.234
5078000	0.359
5078230	0.263
5094000	0.26
5104000	0.252
5104500	0.265
5107500	0.256
202-Minnesota & NE Iowa Morainal	
5353800	0.583
5457000	0.45
5245100	0.355
5278000	0.354
5340050	0.331
5030000	0.223
5270500	0.335
5275000	0.434
5279000	0.25
207-Paleozoic Plateau	
5373000	0.494
5374000	0.487
5376000	0.381
5384000	0.526
5384500	0.422
5385000	0.524
5385500	0.484

Laurentian Mixed Forest Pro

ID	*cfs/sq.mi*
303-N.MN and Ontario Peatlands	
5129000	0.697
5134200	0.586
5139500	0.274
5140500	0.239
304-N.MN Drift and Lake Plains	
4016000	0.681
4016500	0.792
4018750	0.75
5206500	0.389
5216860	0.548
5219000	0.667
5231000	0.441
5244000	0.48
5247000	0.419
306-Northern Superior Uplands	
4010500	0.874
4012500	1.121
4014500	1.21
5124480	0.806
5127000	0.936
5130500	0.663
310-Western Superior Uplands	
5336700	0.837
5338500	0.634
5337400	0.658
4021530	0.755

* - number of hundreds corresponds to the Province to which the section belongs and the third number corresponds to Section from the list above, as for example 105 means: 100 – Pairie Parkland Province, 5 – North Central Glaciated Plains.

February or low-flow modules were used in order to characterize the Quaternary geology map. Using periods of no surface runoff helped to eliminate any impacts on hydrology other than geology. All contributions to streamflow during this period come from discharge of ground water storage in the geologic units alone (base flow). Rates of such contributions depend almost exclusively on hydrogeologic characteristics of the geologic units.

Analysis of surficial geological units was carried out in similar fashion. Nine landscape units obtained for Quaternary division yielded nine random samples each denoted with "R" sign (Table 10). Pre-Wisconsinan deposits, (unit R9) because they are older than the rest of the deposits and have such ununique topography, were excluded from further analysis.

Analysis of watershed boundaries and map units showed that in many cases one watershed combined characteristics of several Quaternary regions. Such a condition made an approach of assigning flow values complicated. Therefore, most flow values coming from rivers occupying several types of surficial deposits were eliminated from analysis. As a result the original data set was reduced to 32 watersheds.

Table 10 lists the Quaternary regions with codes denoting each region. Table 11 contains random samples obtained for Quaternary geology map by applying GIS.

Table 10

R1	Clayey Lake Sediment
R2	Clayey Moraines
R3	Clayey Till Plains
R4	Outwash
R5	Peat
R6	Sandy Lake Sediment
R7	Sandy Moraines
R8	Sandy Till Plains
R9	Pre-Wisconsinan deposits

Table 11

ID	years	annual modules	february modules	R1- CLakeSed	R2- Clayey Morains	R3- Clayey Till Plains	R4- Outwash	R5- Peat	R6- SLakeSed	R7- Sandy Morains	R8- Sandy Till Plains
05030000	35	**0.223**	0.091							0.091	
05040500	45	0.171	0.081							0.081	
05049000	36	**0.084**	0.001			**0.001**					
05061000	49	0.229	0.055		0.055						
05061500	48	0.110	0.002	0.002					0.002		
50680000	16		0.001						0.001		
05076000	78	0.234	0.004			0.004		0.004			
05087500	44	**0.160**	0.003	0.003		**0.003**			**0.003**		
50950000	9		0.003	0.003							
50955000	11	**0.215**	0.003	0.003							
50975000	10	**0.330**	0.003	0.003							
05104000	23	**0.252**	0.001					0.001			
05104500	47	0.265	0.009						0.009		
05107500	63	0.256	0.009			0.009					
05129000	62	0.697	0.279								0.279
05130500	52	0.663	0.110							0.11	
05134200	30	**0.586**	0.023					0.023			
05139500	35	0.274	0.015					0.015			
05140500	21	**0.239**	0.015					0.015			
05216860	26	**0.548**	0.223								0.223
05244000	60	0.480	0.300				0.300				
05245100	20	**0.355**	0.176								**0.176**
05247000	30	**0.419**	0.286				0.286				**0.286**
05278000	39	**0.354**	0.183				**0.183**				
05278500	20	**0.214**	0.006			**0.006**					
05294000	61	0.130	0.022		0.022						
05300000	67	0.149	0.011			0.011					
05311400	26	**0.182**	0.057		**0.057**						
05315000	52	0.178	0.029		0.029						
5337400	18	**0.658**									
05340050	22	**0.331**	0.238				**0.238**				
05373000	31	**0.494**	0.220								
05376000	25	**0.381**	0.353								
05384000	60	0.526	0.281								
05384500	38	0.422	0.375								
05385000	67	0.524	0.333								
05385500	34	**0.484**	0.095								
05476000	68	0.221	0.035		0.035						
average				0.003	0.040	0.006	0.252	0.012	0.004	0.094	0.241

In order to perform statistical analysis described above, it is necessary to check normality of the data. Normal probability plots were constructed to check this assumption. A normal distribution is indicated when all points (module values on Y-axes) fall on a straight line. The slope of the line is approximately equal to standard deviation of corresponding group. Such plots were constructed using SAS software used also to carry out all further statistical calculations. Figures 15 and 16 represent ECS and Quaternary data sets plotted to check an assumption of normality.

Figure 15. Normal probability plot for ECS data set.

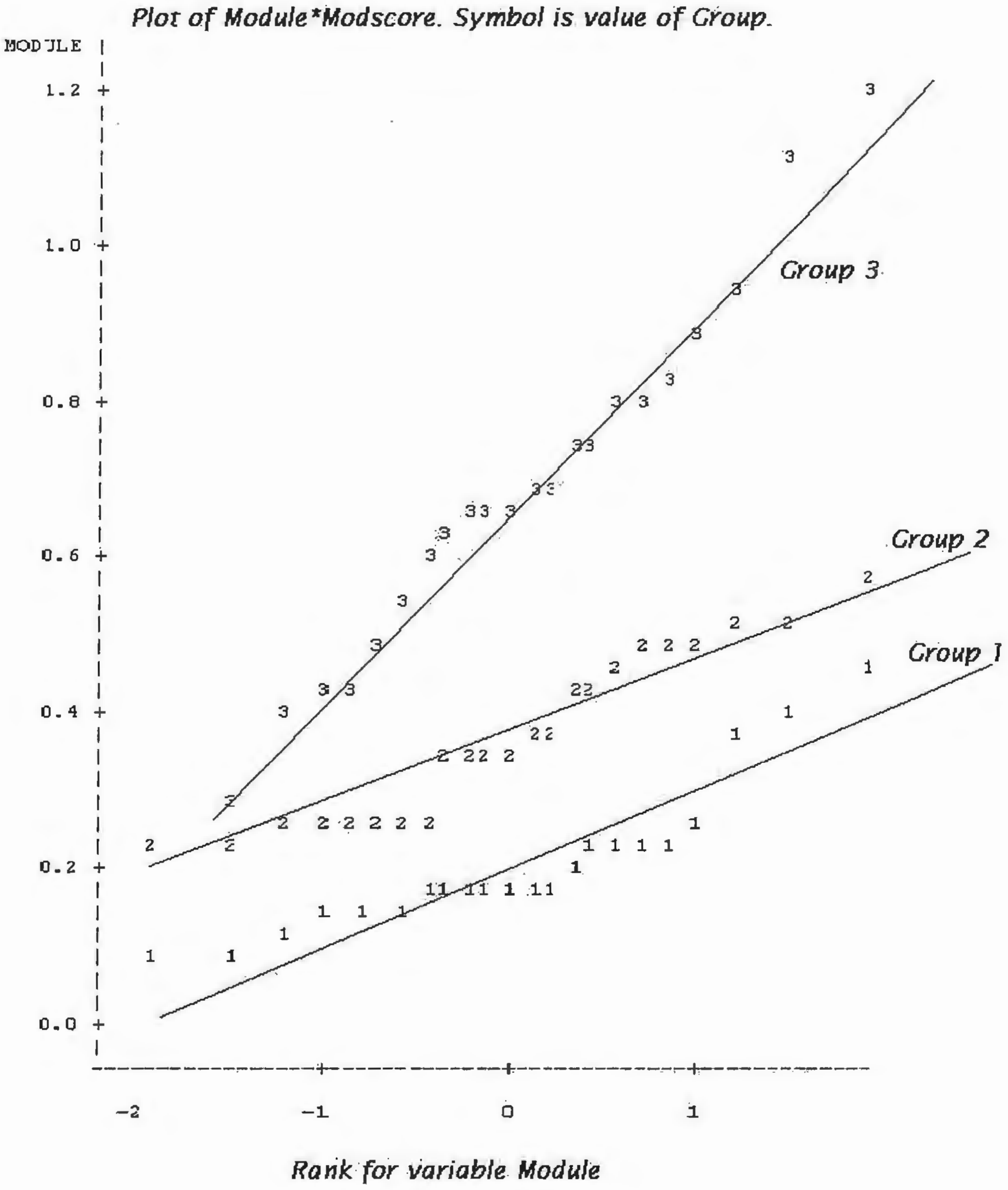
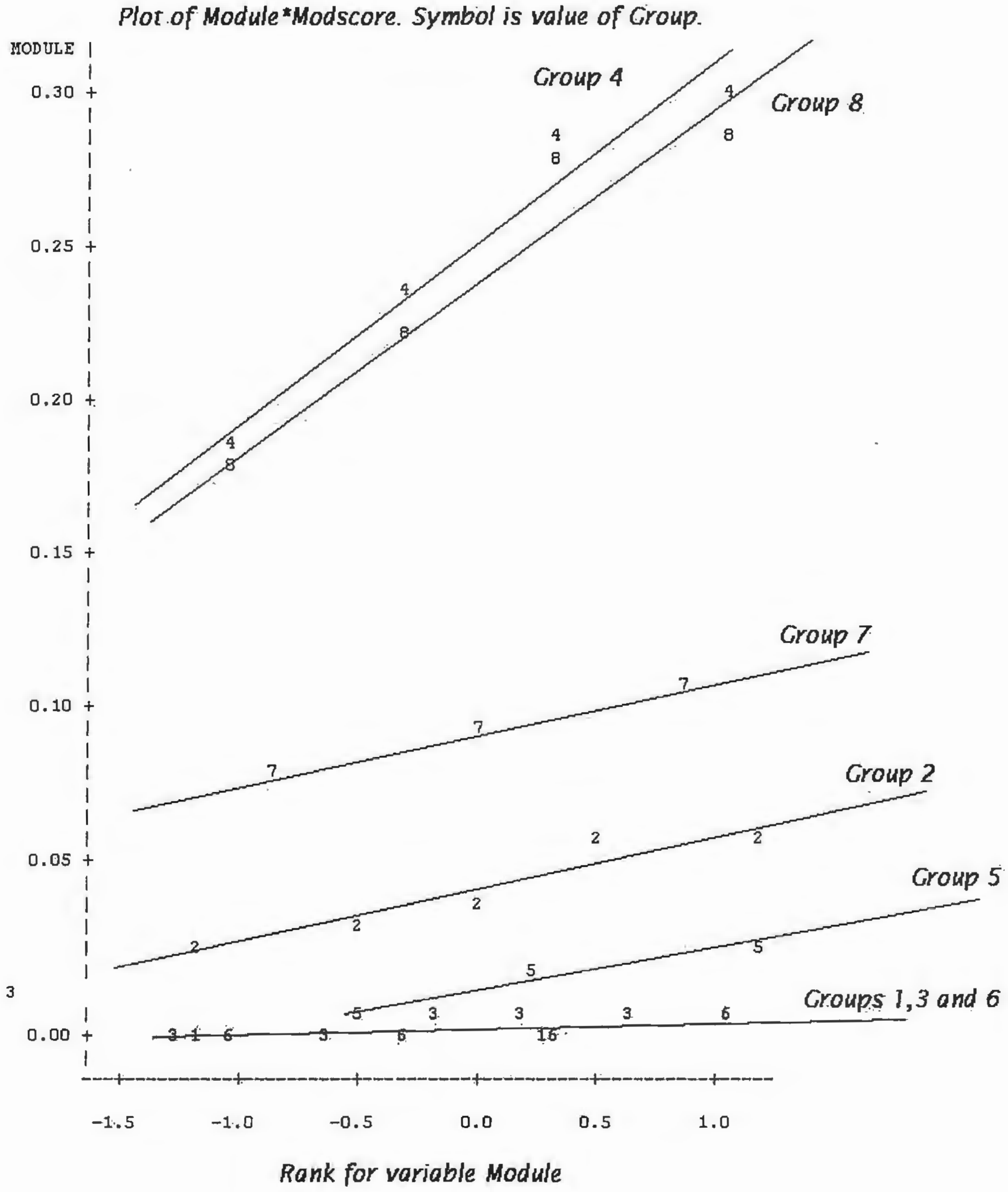


Figure 16. Normal probability plot for data set corresponding to Quaternary geology map.



As mentioned earlier, all statistical manipulations were carried out using SAS ("Statistical AnalysiS") software. In this particular case of the analysis SAS was used to produce an ANOVA table (Appendix). One-way ANOVA or a single-factor analysis of variance involves a comparison of t population or treatment means μ_1, μ_2, ... μ_t.. The ANOVA computations are summarized in a tabular format called an ANOVA table. The general form of such a table is depicted in Table 12.

As in each case F-test showed to be significant further analysis was performed to obtain an information on pairwise comparisons. Fisher's LSD analysis provided such an information while random samples obtained for each of analyzing maps are being used as input for SAS. An output in form of an ANOVA table and LSD test are attached in the appendix.

Table 12. General format for a single-factor ANOVA table.

Source of Variation	Degree of Freedom	Sum of Squares	Mean Square	F-value
Treatments	t-1	SSTr	MSTr=SSTr/(t-1)	F=MSTr/MSE
Error	n-t	SSE	MSE=SSE/(n-t)	
Total	n-1	SSTo		

t - number of population means;

n - number of observation in each sample;

SSTr = *SSB* - sum of squares between samples:

$$SSTr = SSB = \sum_i n_i(\overline{y_i} - \overline{y})^2$$

$\overline{y}_I$ - mean of *i*-th sample;

$\overline{y}$ - grand mean.

SSE = SSW - sum of squares within-group:

$$SSE = SSW = \sum_{i,j}(y_{ij} - \overline{y_i})^2$$

y_{ij} - observation within *i*-th sample;

$\overline{y}_i$ - mean of *i*-th sample;

SSTo =(SSTr + SSE) - total sum of squares;

MSTr = S_b^2 = SSTr/(t-1) - mean square between samples;

MSE = S_w^2 = SSE/(n-1) - mean square within sample.

7. Results

The statistical output was analyzed and relationships based on hydrology among regions on each investigating level were developed. This made it possible to construct maps showing ecological and geological control on hydrology. As the differences between means calculated for each region were confirmed, the corresponding natural factors controlling hydrologic variability were determined.

New relationships among regions are represented by logical schemes (Figures 17 and 18) and geographical by maps (Figures 19, 20 and 21).

A statistical analysis of the ECS Province map showed significant differences between means of three random samples indicating that each region has unique hydrologic characteristics. Figures 17 and 19 highlight the results of the comparison of means at the 95% confidence interval. The Prarie Province has a mean runoff module of 0.20 cfs/mi^2 with a standard deviation of 0.08; the Eastern Broadleaf Forest Province has a mean runoff module of 0.37 cfs/mi^2 with standard deviation of 0.11; the Laurentian Mixed Forest Province has a mean runoff module of 0.67 cfs/mi^2 with standard deviation of 0.25.

The next level of analysis highlights the relations among runoff modules at the ECS Section level (Figures 17 and 20). Two distinct regions are defined with a third that appears to be intermediate. The first group consists of the Red River Valley, the North Central Glaciated Plains, and the Lake Agassiz Aspen Parklands (Figure 20), and is referred to here as the westernmost region. The second region is represented by the Northern, Southern and Western Superior Uplands (Figure 20), and is here referred to as the easternmost region.

The third region produced in the ECS section analysis is statistically similar to both of the aforementioned regions and lies intermediate to them. This intermediate region was therefore separated as an independent area that combined characteristics of both adjoining regions.

Analysis of means of the runoff modules for the Quaternary geology map units described in the methods section produced five distinct regions (Figures 18 and 21). Mean runoff modules (cfs/mi^2) and standard deviations are shown in logical scheme represented on Figure 18. The regions are as follows:

1) Clayey Lake Sediment, Clayey Till Plains, Sandy Lake Sediment and Peat formed one group in the western part of the State. (Figures 18 and 21);

The following regions formed statistically significant separate areas:

2) Clayey Moraines (Figures 18 and 21);
3) Sandy Moraines (Figures 18 and 21);
4) Sandy Till Plains (Figures 18 and 21);
5) Outwash (Figures 18 and 21).

8. Discussion

An upper level of ECS has been divided in the analysis into three hydrological units, confirming that ECS Province divisions indeed have hydrological significance. This fact is not, however, unexpected as it reflects climatic control on hydrology of the State at a scale such as this.

As scale increases, other factors begin to influence hydrology. For example, a somewhat more complex relation can be seen in the ECS Section level. Statistical analysis of the 10 individual Sections produced two distinct regions with an intermediate transition zone that has characteristics of both adjacent areas. Three western regions (Red River Valley, North Central Glaciated Plains and Lake Agassiz Aspen Parklands) combine portions of the Prairie Parkland and the Eastern Broadleaf Forest Provinces (Figure 20). Three Sections with higher modules in eastern Minnesota (Northern, Southern and Western Superior Uplands) form a region of similar hydrology that corresponds to the easternmost part of Laurentian Mixed Forest Province. The intermediate zone consists of two Sections of Eastern Broadleaf Forest Province (Minnesota and NE Iowa Morainal and Paleozoic Plateau) and the Northern Minnesota and Ontario Peatlands and the N. Minnesota Drift and Lake Plains of the westernmost part of Laurentian Mixed Forest Province. The intermediate zone combines characteristics of both adjacent areas.

The existence of the transition zone that combines portions of the Prairie Parkland and Eastern Broadleaf Forest and portions of the

Laurentian Mixed Forest Provinces can be explained by the increasing influence of geological factors as the scale of the analysis increases. The Red River Valley and North Central Glaciated Plains are similar geologically. Both are flat to gently undulating terrains with highly impermeable soils (fine grained lacustrine sediment and silty to clayey till). At the scale of the ECS Provinces, the regions lie in different hydrological settings. At the scale of ECS Sections, however, geological similarities control a significant portion of the hydrologic variability. In similar fashion, the grouping of the Northern, Southern, and Western Superior Uplands, and therefore their similar hydrologic characteristics, is related to their similar geology. Bedrock exposures produce high runoff modules that characterize these regions. DNR (Hanson and Hargrave, 1996) description of the ECS Section and Sub-Section divisions characterizes Northern Superior Uplands as a region of broad bedrock exposure. In the case of Southern and Western Uplands bedrock outcrops are generally restricted to river valleys. The transition zone reflects the influence of climate, thus the general similarity to the ECS Provinces, but also the influence of geology and the grouping of Sections with similar characteristics from different Provinces.

Another feature was discovered in the analysis of the Section division. North Minnesota Drift & Lake Plains and Paleozoic Plateau Sections have common characteristics with the previously described transition zone but completely independent of easternmost and westernmost regions. Hence, they make up internal transition or transition inside transition. The fairly high module of the Paleozoic Plateau Section is comparable with that of North Minnesota Drift & Lake Plains Section. The high runoff module for Paleozoic Plateau can be explained by the high-relief karst geology of the region. The high values of the runoff module of the North Minnesota Drift & Lake Plains Section promoted by highly permeable outwash, sandy till plains and sandy moraines predominant in the central part of the State.

A pattern now begins to emerge. At a small scale (State wide), climate is the overriding control on hydrologic characteristics of local drainages. As the scale of interest increases to represent ECS Sections, geological controls increase in importance. As we shall see, this trend continues to more geological control as the scale of the analysis increases further.

Considering five regions obtained for the Quaternary geology map (Figure 21) and the basis on which they were grouped, the following should be noted:

Unit #1. This unit including Clayey Lake Sediment, Sandy Lake Sediment, Peat and Clayey Till Plains represents three of the western regions (Clayey Lake Sediment, Sandy Lake Sediment and Peat) that are fairly flat. It is a result of processes operating in such geological settings producing low topography. The last three regions are characterized by low streamflow modules, although the module for peat is somewhat higher than for other regions of this unit. For topographically flat peatlands, the increase in runoff can only be explained by the artificial drainage system that was established in the early years of the century to promote drainage of swampy areas for cultivation. While this innovation was not successful, the drainage network that was left behind greatly influences hydrology in this region.

Unit #2. The Clayey Moraines unit has higher module than for Clayey Till Plains, Clayey Lake Sediment and Sandy Lake Sediment but lower than for any other region. Clayey Moraines formed a separate unit. Hummocky morainal topography is most likely responsible for a module value higher than that of Lake Sediment, Clayey Till Plains and Peat.

Unit #3. Sandy Moraines stand alone with a module value lower than those of sandy Units 4 and 5 but much greater than for any clayey one. This fact can be explained by presence of the multiple lakes, characteristic feature of the morainal environment. Lakes store water from precipitation and act as a buffer lowering runoff rates. This fact places sandy moraines unit hydrologically between sandy till plains unit and clayey moraines unit.

Unit #4. Sandy Till Plains of the northeastern and partially central part shows high modules. It can be corresponded to the sandy content that promotes good and fast infiltration that favors fast water contribution to the stream runoff. High modules can also be explained by closeness to bedrock. An impermeable surface of bedrock allows water to join streamflow in very short periods of time.

Unit #5. Outwash Plains have almost exactly the same module despite the considerable thickness of deposits and level topography. The sandy texture and thus high permeability are probably essential in this case.

The higher module for Peat in its group (***Unit #1***) resulted in a relationship with Clayey Moraines region. No significant difference has been found between means of these two regions. Hence Peat showed common characteristics with Clayey Till Plains, Sandy and Clayey Lake Sediment and at the same time - with Clayey Moraines. The fact that the Clayey Moraines unit is shown to be significantly different from all the other regions correlated to Peat helped to resolve this dilemma. It was decided that Clayey Moraines would form an independent unit (***Unit #2***). The fourth unit of the first group (Clayey Till Plains) is also poorly drained. Clayey component of the deposits is probably responsible for poor drainage in this case. Such characteristics promoted combination of these four regions. As a result one unit characterized by low modules was produced.

All of the above facts strongly suggest that major controls on hydrology of State of Minnesota are as following. Continental climate pattern, when landforms of Province scale are considered; topography and type of surficial deposits for units of bigger scale, such as combining several watersheds.

As the scale of analyzing landform increases, factors controlling units of the smaller scale are less important. The scale of landform should be approximately equal to that of controlling factor to recognize its influence on hydrology.

The study carried out appears to be an important step toward developing sustainable water resources management in Minnesota. It precisely defines factors predominantly controlling hydrology on the discussed scales and gives a clue to what kind of hydrologic pattern can be found in one or another landform assemblage. Hydrology is undoubtedly an important ecosystem component having its impacts on other recourses and the environment. It hence should be considered as the differentiating criteria in the Ecological Classification System organization to provide adequate resource management. Hydrological information has not been considered in the stratification of three upper ECS levels. Nevertheless it could have provided a valuable piece of information for the purposes of ecological regionalization.

Figure 17. Scheme of regionalization of Minnesota territory based on distribution of river runoff within ecological regions.

N – size of random sample
$\bar{X}$ – mean
S – standard deviation
"≈" – hypothesis $a_1=a_2$ is accepted and corresponding ecoregions are referred to the one hydrological region.
"≠" – hypothesis $a_1=a_2$ is rejected and corresponding ecoregions are referred to two different hydrological regions
"*" – regions' codes, see explanation for Table 3

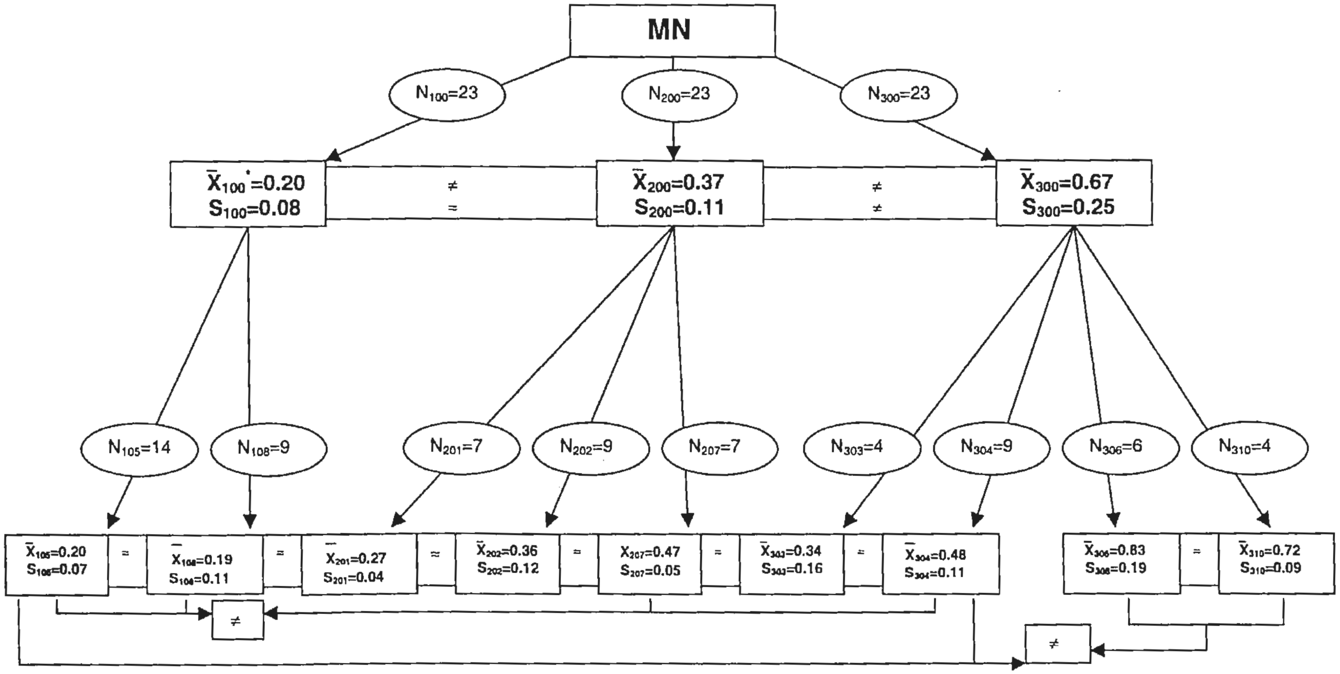


Figure 18. Scheme of regionalization of Minnesota territory based on distribution of river runoff within Quaternary regions.

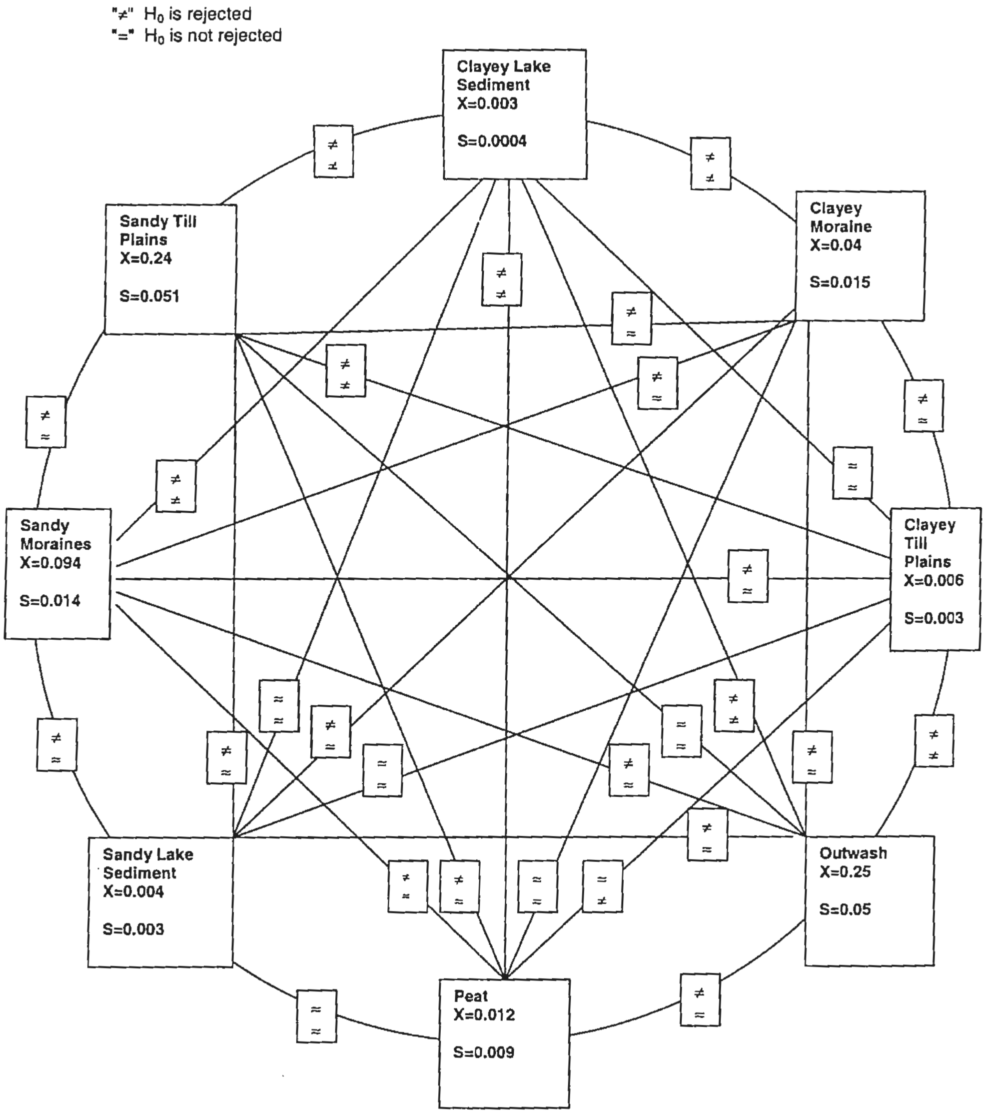
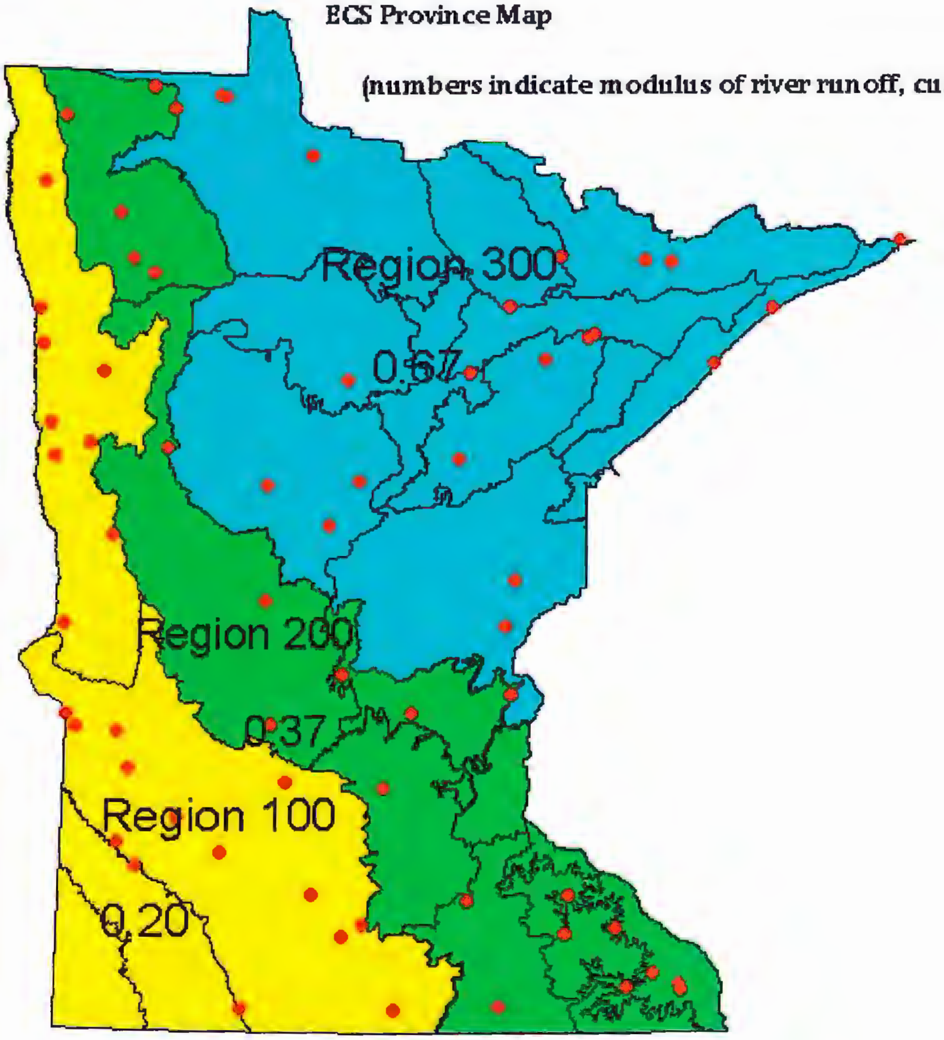


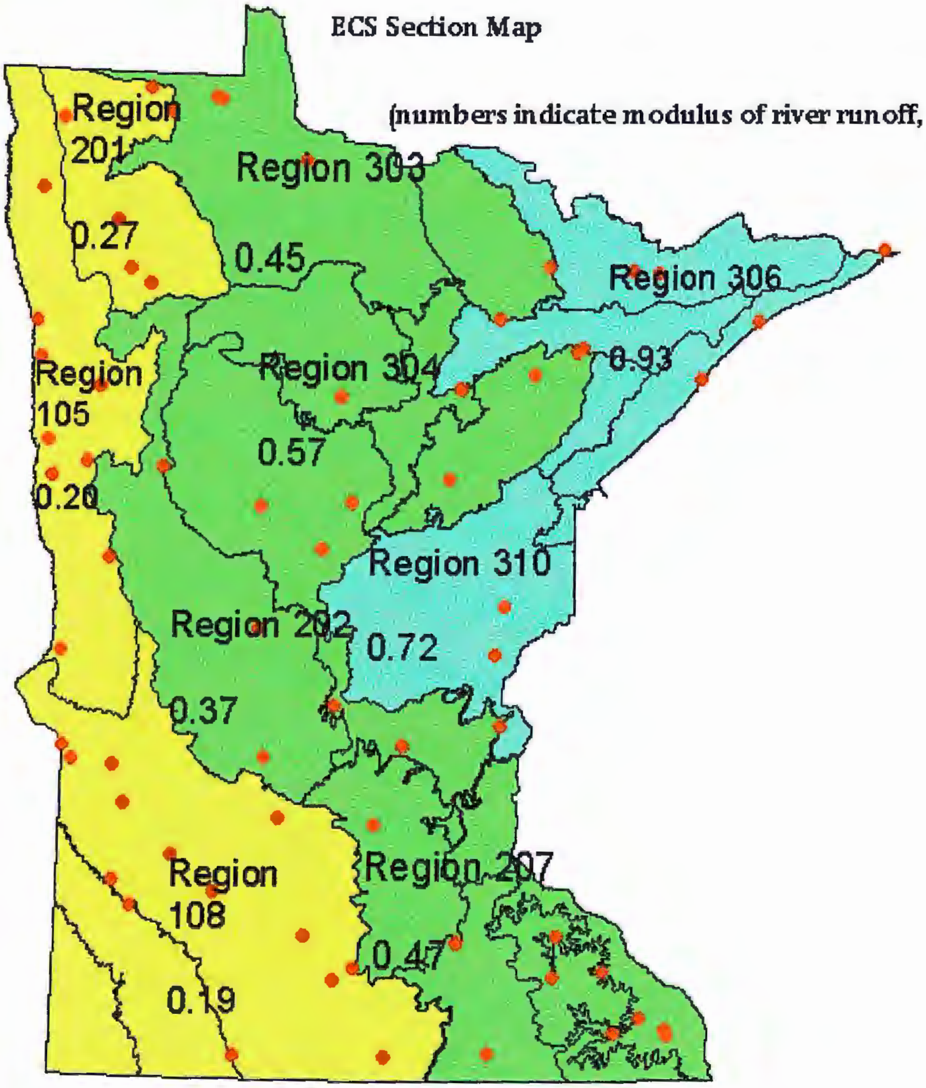
Figure 19



ECS Province Map

(numbers indicate modulus of river runoff, cu.ft/mi/s)

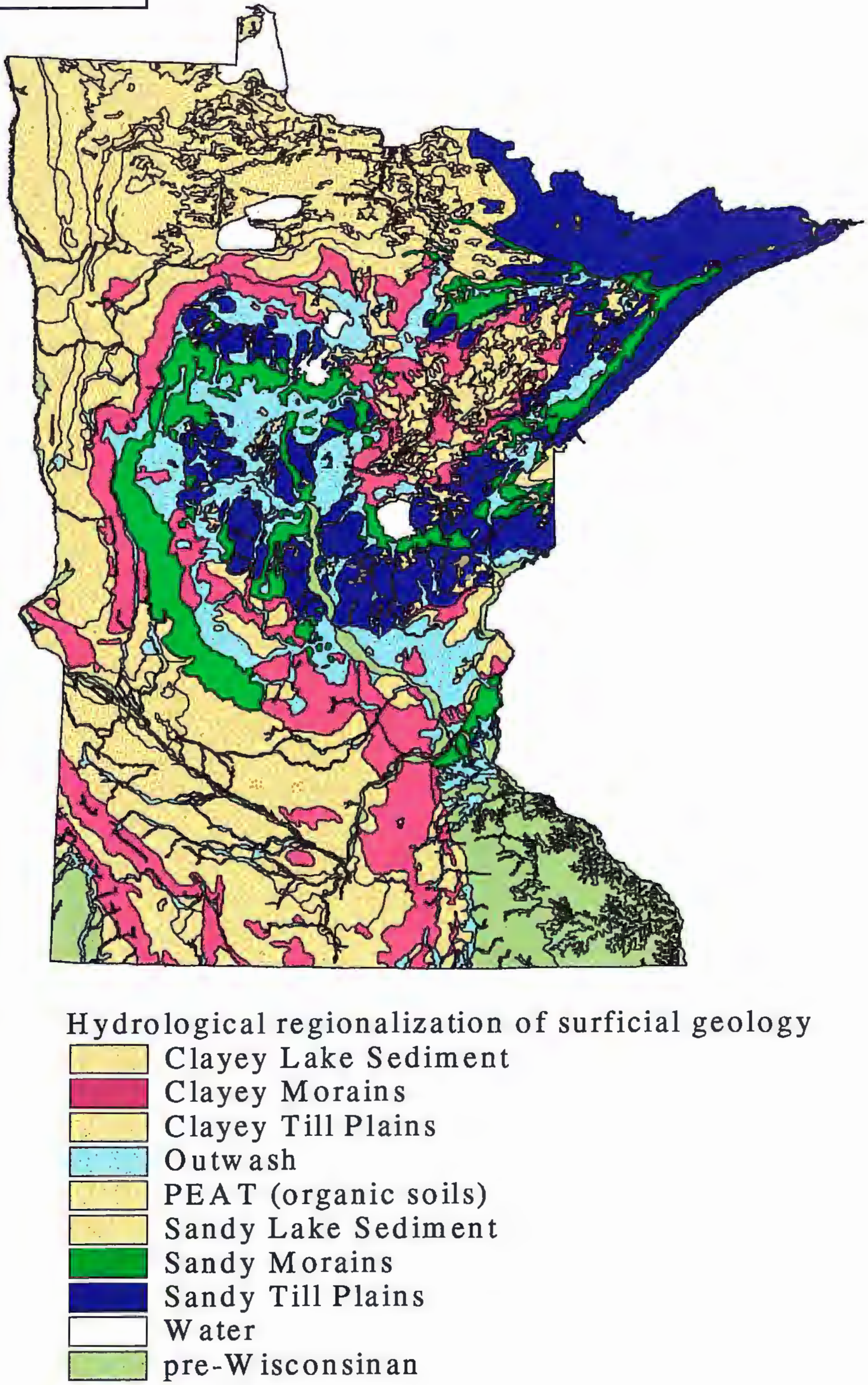
Figure 20



ECS Section Map

(numbers indicate modulus of river runoff, cu.ft/mi/s)

Figure 21


Hydrological regionalization of surficial geology
Clayey Lake Sediment
Clayey Morains
Clayey Till Plains
Outwash
PEAT (organic soils)
Sandy Lake Sediment
Sandy Morains
Sandy Till Plains
Water
pre-Wisconsinan

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Appendix

ANOVA tables and Fisher's LSD produced in the analysis of ECS and Quaternary Geology

ANOVA table and Fisher’s LSD analysis of ECS Provinces

OBS	REGION	MODULE
1	1	0.214
2	1	0.093
3	1	0.152
4	1	0.130
5	1	0.149
6	1	0.182
7	1	0.177
8	1	0.184
9	1	0.224
10	1	0.396
11	1	0.265
12	1	0.363
13	1	0.221
14	1	0.178
15	1	0.171
16	1	0.084
17	1	0.229
18	1	0.110
19	1	0.149
20	1	0.228
21	1	0.455
22	1	0.169
23	1	0.160
24	2	0.234
25	2	0.359
26	2	0.263
27	2	0.260
28	2	0.252
29	2	0.265
30	2	0.256
31	2	0.583
32	2	0.450
33	2	0.355
34	2	0.354
35	2	0.331
36	2	0.223
37	2	0.335
38	2	0.434
39	2	0.250
40	2	0.494
41	2	0.487
42	2	0.381
43	2	0.526
44	2	0.422
45	2	0.524
46	2	0.484
47	3	0.697
48	3	0.586
49	3	0.274
50	3	0.239
51	3	0.681
52	3	0.792
53	3	0.750
54	3	0.389
55	3	0.548
56	3	0.667
57	3	0.441
58	3	0.480
59	3	0.419
60	3	0.874
61	3	1.121
62	3	1.210
63	3	0.806
64	3	0.936
65	3	0.663
66	3	0.837
67	3	0.634
68	3	0.658
69	3	0.755

```
                              Analysis Variable : MODULE

------------------------------------ REGION=1 ----------------------------------

           N          Mean         Std Dev         Minimum         Maximum
          ----------------------------------------------------------
          23      0.2036087      0.0922397       0.0840000       0.4550000
          ----------------------------------------------------------

------------------------------------ REGION=2 ----------------------------------

           N          Mean         Std Dev         Minimum         Maximum
          ----------------------------------------------------------
          23      0.3705217      0.1104009       0.2230000       0.5830000
          ----------------------------------------------------------

------------------------------------ REGION=3 ----------------------------------

           N          Mean         Std Dev         Minimum         Maximum
          ----------------------------------------------------------
          23      0.6720435      0.2411656       0.2390000       1.2100000
          ----------------------------------------------------------


                            General Linear Models Procedure
                                Class Level Information

                          Class     Levels     Values

                          REGION         3     1 2 3

                   Number of observations in data set = 69


                                    The SAS System
                            General Linear Models Procedure

Dependent Variable: MODULE
                                         Sum of             Mean
Source                    DF            Squares           Square   F Value     Pr > F

Model                      2         2.59291626       1.29645813     49.32     0.0001

Error                     66         1.73486217       0.02628579

Corrected Total           68         4.32777843

                  R-Square                C.V.         Root MSE           MODULE Mean

                  0.599133            39.03041        0.1621289             0.4153913

Source                    DF          Type I SS      Mean Square   F Value     Pr > F

REGION                     2         2.59291626       1.29645813     49.32     0.0001

Source                    DF        Type III SS      Mean Square   F Value     Pr > F

REGION                     2         2.59291626       1.29645813     49.32     0.0001
```

```
                    General Linear Models Procedure

                 T tests (LSD) for variable: MODULE

     NOTE: This test controls the type I comparisonwise error rate not the
           experimentwise error rate.

                 Alpha= 0.05  df= 66  MSE= 0.026286
                     Critical Value of T= 2.00
                Least Significant Difference= 0.0955

     Means with the same letter are not significantly different.

             T Grouping              Mean      N  REGION

                      A           0.67204     23  3

                      B           0.37052     23  2

                      C           0.20361     23  1
```

```
                    General Linear Models Procedure
                          Least Squares Means

      REGION        MODULE   Pr > |T| H0: LSMEAN(i)=LSMEAN(j)
                    LSMEAN   i/j      1        2        3

      1         0.20360870   1    .       0.0009   0.0001
      2         0.37052174   2  0.0009    .        0.0001
      3         0.67204348   3  0.0001  0.0001    .

NOTE: To ensure overall protection level, only probabilities associated with
      pre-planned comparisons should be used.
```

ANOVA table and Fisher's LSD analysis of ECS Sections

```
 OBS    REGION    MODULE

  1       1       0.250
  2       1       0.214
  3       1       0.093
  4       1       0.152
  5       1       0.130
  6       1       0.149
  7       1       0.182
  8       1       0.177
  9       1       0.184
 10       1       0.224
 11       1       0.306
 12       1       0.265
 13       1       0.363
 14       1       0.221
 15       1       0.178
 16       2       0.084
 17       2       0.229
 18       2       0.110
 19       2       0.149
 20       2       0.228
 21       2       0.455
 22       2       0.169
 23       2       0.160
 24       3       0.234
 25       3       0.359
 26       3       0.263
 27       3       0.260
 28       3       0.252
 29       3       0.256
 30       4       0.171
 31       4       0.583
 32       4       0.450
 33       4       0.355
 34       4       0.354
 35       4       0.331
 36       4       0.223
 37       4       0.335
 38       4       0.434
 39       5       0.494
 40       5       0.487
 41       5       0.381
 42       5       0.526
 43       5       0.422
 44       5       0.524
 45       5       0.484
 46       6       0.265
 47       6       0.586
 48       6       0.274
 49       6       0.239
 50       7       0.389
 51       7       0.667
 52       7       0.441
 53       7       0.480
 54       7       0.419
 55       8       0.548
 56       8       0.697
 57       8       0.750
 58       8       0.792
 59       8       0.681
 60       8       0.874
 61       8       1.121
 62       8       1.210
 63       8       0.806
 64       8       0.936
 65       8       0.663
 66       9       0.837
 67       9       0.634
 68       9       0.658
 69       9       0.755
```

```
                              Analysis Variable : MODULE

------------------------------------ REGION=1 ----------------------------------

           N          Mean         Std Dev         Minimum         Maximum
          ----------------------------------------------------------------
          15     0.2058667       0.0697310       0.0930000       0.3630000
          ----------------------------------------------------------------
------------------------------------ REGION=2 ----------------------------------

           N          Mean         Std Dev         Minimum         Maximum
          ----------------------------------------------------------------
           8     0.1980000       0.1154717       0.0840000       0.4550000
          ----------------------------------------------------------------
------------------------------------ REGION=3 ----------------------------------

           N          Mean         Std Dev         Minimum         Maximum
          ----------------------------------------------------------------
           6     0.2706667       0.0444597       0.2340000       0.3590000
          ----------------------------------------------------------------
------------------------------------ REGION=4 ----------------------------------

           N          Mean         Std Dev         Minimum         Maximum
          ----------------------------------------------------------------
           9     0.3595556       0.1221271       0.1710000       0.5830000
          ----------------------------------------------------------------
------------------------------------ REGION=5 ----------------------------------

           N          Mean         Std Dev         Minimum         Maximum
          ----------------------------------------------------------------
           7     0.4740000       0.0535817       0.3810000       0.5260000
          ----------------------------------------------------------------
------------------------------------ REGION=6 ----------------------------------

           N          Mean         Std Dev         Minimum         Maximum
          ----------------------------------------------------------------
           4     0.3410000       0.1640061       0.2390000       0.5860000
          ----------------------------------------------------------------
------------------------------------ REGION=7 ----------------------------------

           N          Mean         Std Dev         Minimum         Maximum
          ----------------------------------------------------------------
           5     0.4792000       0.1101009       0.3890000       0.6670000
          ----------------------------------------------------------------
------------------------------------ REGION=8 ----------------------------------

           N          Mean         Std Dev         Minimum         Maximum
          ----------------------------------------------------------------
          11     0.8252727       0.1994317       0.5480000       1.2100000
          ----------------------------------------------------------------
------------------------------------ REGION=9 ----------------------------------

           N          Mean         Std Dev         Minimum         Maximum
          ----------------------------------------------------------------
           4     0.7210000       0.0933631       0.6340000       0.8370000
          ----------------------------------------------------------------
```

```
                        General Linear Models Procedure
                            Class Level Information

                      Class    Levels    Values

                      REGION        9    1 2 3 4 5 6 7 8 9

                    Number of observations in data set = 69


                        General Linear Models Procedure

Dependent Variable: MODULE
                                     Sum of            Mean
Source                  DF          Squares         Square   F Value     Pr > F

Model                    8       3.47834921      0.43479365     30.30     0.0001

Error                   60       0.86090227      0.01434837

Corrected Total         68       4.33925148

                  R-Square             C.V.        Root MSE          MODULE Mean

                  0.801601         28.92742       0.1197847            0.4140870

Source                  DF        Type I SS     Mean Square   F Value     Pr > F

REGION                   8       3.47834921      0.43479365     30.30     0.0001

Source                  DF      Type III SS     Mean Square   F Value     Pr > F

REGION                   8       3.47834921      0.43479365     30.30     0.0001
```

```
                     General Linear Models Procedure

                    T tests (LSD) for variable: MODULE

   NOTE: This test controls the type I comparisonwise error rate not the
         experimentwise error rate.

       Alpha= 0.05  Confidence= 0.95  df= 60  MSE= 0.014348
                   Critical Value of T= 2.00030

Comparisons significant at the 0.05 level are indicated by '***'.

                          Lower      Difference     Upper
         REGION         Confidence    Between     Confidence
       Comparison         Limit        Means        Limit

      8    - 9          -0.03563     0.10427      0.24417
      8    - 7           0.21684     0.34607      0.47531   ***
      8    - 5           0.23543     0.35127      0.46712   ***
      8    - 4           0.35802     0.46572      0.57341   ***
      8    - 6           0.34437     0.48427      0.62417   ***
      8    - 3           0.43300     0.55461      0.67621   ***
      8    - 1           0.52429     0.61941      0.71452   ***
      8    - 2           0.51594     0.62727      0.73861   ***

      9    - 8          -0.24417    -0.10427      0.03563
      9    - 7           0.08107     0.24180      0.40253   ***
      9    - 5           0.09682     0.24700      0.39718   ***
      9    - 4           0.21746     0.36144      0.50543   ***
      9    - 6           0.21057     0.38000      0.54943   ***
      9    - 3           0.29567     0.45033      0.60500   ***
      9    - 1           0.38030     0.51513      0.64997   ***
      9    - 2           0.37627     0.52300      0.66973   ***

      7    - 8          -0.47531    -0.34607     -0.21684   ***
      7    - 9          -0.40253    -0.24180     -0.08107   ***
      7    - 5          -0.13510     0.00520      0.14550
      7    - 4          -0.01400     0.11964      0.25329
      7    - 6          -0.02253     0.13820      0.29893
      7    - 3           0.06345     0.20853      0.35362   ***
      7    - 1           0.14960     0.27333      0.39706   ***
      7    - 2           0.14460     0.28120      0.41780   ***

      5    - 8          -0.46712    -0.35127     -0.23543   ***
      5    - 9          -0.39718    -0.24700     -0.09682   ***
      5    - 7          -0.14550    -0.00520      0.13510
      5    - 4          -0.00631     0.11444      0.23519
      5    - 6          -0.01718     0.13300      0.28318
      5    - 3           0.07003     0.20333      0.33664   ***
      5    - 1           0.15846     0.26813      0.37781   ***
      5    - 2           0.15199     0.27600      0.40001   ***

      4    - 8          -0.57341    -0.46572     -0.35802   ***
      4    - 9          -0.50543    -0.36144     -0.21746   ***
      4    - 7          -0.25329    -0.11964      0.01400
      4    - 5          -0.23519    -0.11444      0.00631

      4    - 6          -0.12543     0.01856      0.16254
      4    - 3          -0.03739     0.08889      0.21517
      4    - 1           0.05266     0.15369      0.25472   ***
      4    - 2           0.04513     0.16156      0.27798   ***

      6    - 8          -0.62417    -0.48427     -0.34437   ***
      6    - 9          -0.54943    -0.38000     -0.21057   ***
      6    - 7          -0.29893    -0.13820      0.02253
      6    - 5          -0.28318    -0.13300      0.01718
      6    - 4          -0.16254    -0.01856      0.12543
      6    - 3          -0.08433     0.07033      0.22500
      6    - 1           0.00030     0.13513      0.26997   ***
      6    - 2          -0.00373     0.14300      0.28973
```

```
3     - 8        -0.67621    -0.55461    -0.43300   ***
3     - 9        -0.60500    -0.45033    -0.29567   ***
3     - 7        -0.35362    -0.20853    -0.06345   ***
3     - 5        -0.33664    -0.20333    -0.07003   ***
3     - 4        -0.21517    -0.08889     0.03739
3     - 6        -0.22500    -0.07033     0.08433
3     - 1        -0.05094     0.06480     0.18054
3     - 2        -0.05673     0.07267     0.20207

1     - 8        -0.71452    -0.61941    -0.52429   ***
1     - 9        -0.64997    -0.51513    -0.38030   ***
1     - 7        -0.39706    -0.27333    -0.14960   ***
1     - 5        -0.37781    -0.26813    -0.15846   ***
1     - 4        -0.25472    -0.15369    -0.05266   ***
1     - 6        -0.26997    -0.13513    -0.00030   ***
1     - 3        -0.18054    -0.06480     0.05094
1     - 2        -0.09703     0.00787     0.11277

2     - 8        -0.73861    -0.62727    -0.51594   ***
2     - 9        -0.66973    -0.52300    -0.37627   ***
2     - 7        -0.41780    -0.28120    -0.14460   ***
2     - 5        -0.40001    -0.27600    -0.15199   ***
2     - 4        -0.27798    -0.16156    -0.04513   ***
2     - 6        -0.28973    -0.14300     0.00373
2     - 3        -0.20207    -0.07267     0.05673
2     - 1        -0.11277    -0.00787     0.09703
```

```
                     General Linear Models Procedure
                          Least Squares Means

                     REGION          MODULE    LSMEAN
                                     LSMEAN    Number

                     1           0.20586667     1
                     2           0.19800000     2
                     3           0.27066667     3
                     4           0.35955556     4
                     5           0.47400000     5
                     6           0.34100000     6
                     7           0.47920000     7
                     8           0.82527273     8
                     9           0.72100000     9

                   Pr > |T| H0: LSMEAN(i)=LSMEAN(j)

     i/j      1        2        3        4        5        6        7        8        9
     1    .       0.8813   0.2672   0.0035   0.0001   0.0495   0.0001   0.0001   0.0001
     2   0.8813    .       0.2658   0.0073   0.0001   0.0559   0.0001   0.0001   0.0001
     3   0.2672   0.2658    .       0.1643   0.0034   0.3667   0.0056   0.0001   0.0001
     4   0.0035   0.0073   0.1643    .       0.0628   0.7975   0.0784   0.0001   0.0001
     5   0.0001   0.0001   0.0034   0.0628    .       0.0816   0.9411   0.0001   0.0017
     6   0.0495   0.0559   0.3667   0.7975   0.0816    .       0.0906   0.0001   0.0001
     7   0.0001   0.0001   0.0056   0.0784   0.9411   0.0906    .       0.0001   0.0038
     8   0.0001   0.0001   0.0001   0.0001   0.0001   0.0001   0.0001    .       0.1412
     9   0.0001   0.0001   0.0001   0.0001   0.0017   0.0001   0.0038   0.1412    .

NOTE: To ensure overall protection level, only probabilities associated with
      pre-planned comparisons should be used.
```

ANOVA table and Fisher's LSD analysis of Quaternary Geology

```
OBS    GROUP    MODULE

  1      1       0.003
  2      1       0.003
  3      1       0.003
  4      1       0.003
  5      1       0.002
  6      2       0.022
  7      2       0.029
  8      2       0.055
  9      2       0.057
 10      2       0.035
 11      3       0.001
 12      3       0.004
 13      3       0.003
 14      3       0.009
 15      3       0.006
 16      3       0.011
 17      4       0.300
 18      4       0.286
 19      4       0.183
 20      4       0.238
 21      5       0.001
 22      5       0.004
 23      5       0.023
 24      5       0.015
 25      5       0.015
 26      6       0.001
 27      6       0.002
 28      6       0.003
 29      6       0.009
 30      7       0.091
 31      7       0.081
 32      7       0.110
 33      8       0.279
 34      8       0.223
 35      8       0.176
 36      8       0.286
```

```
                    Analysis Variable : MODULE

------------------------------------ GROUP=1 -----------------------------------

           N          Mean        Std Dev        Minimum        Maximum
           -----------------------------------------------------------
           5     0.0028000    0.000447214      0.0020000      0.0030000
           -----------------------------------------------------------

------------------------------------ GROUP=2 -----------------------------------

           N          Mean        Std Dev        Minimum        Maximum
           -----------------------------------------------------------
           5     0.0396000      0.0156780      0.0220000      0.0570000
           -----------------------------------------------------------

------------------------------------ GROUP=3 -----------------------------------

           N          Mean        Std Dev        Minimum        Maximum
           -----------------------------------------------------------
           6     0.0056667      0.0037771      0.0010000      0.0110000
           -----------------------------------------------------------

------------------------------------ GROUP=4 -----------------------------------

           N          Mean        Std Dev        Minimum        Maximum
           -----------------------------------------------------------
           4     0.2517500      0.0529678      0.1830000      0.3000000
           -----------------------------------------------------------

------------------------------------ GROUP=5 -----------------------------------

           N          Mean        Std Dev        Minimum        Maximum
           -----------------------------------------------------------
           5     0.0116000      0.0089889      0.0010000      0.0230000
           -----------------------------------------------------------

------------------------------------ GROUP=6 -----------------------------------

           N          Mean        Std Dev        Minimum        Maximum
           -----------------------------------------------------------
           4     0.0037500      0.0035940      0.0010000      0.0090000
           -----------------------------------------------------------

------------------------------------ GROUP=7 -----------------------------------

           N          Mean        Std Dev        Minimum        Maximum
           -----------------------------------------------------------
           3     0.0940000      0.0147309      0.0810000      0.1100000
           -----------------------------------------------------------

------------------------------------ GROUP=8 -----------------------------------

           N          Mean        Std Dev        Minimum        Maximum
           -----------------------------------------------------------
           4     0.2410000      0.0516978      0.1760000      0.2860000
           -----------------------------------------------------------
```

```
                    General Linear Models Procedure
                        Class Level Information

                   Class     Levels     Values

                   GROUP          8     1 2 3 4 5 6 7 8

                Number of observations in data set = 36


                           General Linear Models Procedure

Dependent Variable: MODULE
                                  Sum of            Mean
Source                  DF       Squares          Square   F Value      Pr > F

Model                    7    0.33739086      0.04819869     73.80      0.0001

Error                   28    0.01828603      0.00065307

Corrected Total         35    0.35567689

                  R-Square          C.V.        Root MSE           MODULE Mean

                  0.948588      35.76945       0.0255553             0.0714444


Source                  DF     Type I SS     Mean Square   F Value      Pr > F

GROUP                    7    0.33739086      0.04819869     73.80      0.0001

Source                  DF   Type III SS     Mean Square   F Value      Pr > F

GROUP                    7    0.33739086      0.04819869     73.80      0.0001
```

```
                General Linear Models Procedure

              T tests (LSD) for variable: MODULE

   NOTE: This test controls the type I comparisonwise error rate not the
         experimentwise error rate.

       Alpha= 0.05  Confidence= 0.95  df= 28  MSE= 0.000653
                  Critical Value of T= 2.04841

Comparisons significant at the 0.05 level are indicated by '***'.

                          Lower     Difference     Upper
      GROUP            Confidence    Between     Confidence
    Comparison            Limit        Means        Limit

   4    - 8           -0.02627      0.01075      0.04777
   4    - 7            0.11777      0.15775      0.19773   ***
   4    - 2            0.17703      0.21215      0.24727   ***
   4    - 5            0.20503      0.24015      0.27527   ***
   4    - 3            0.21229      0.24608      0.27987   ***
   4    - 6            0.21098      0.24800      0.28502   ***
   4    - 1            0.21383      0.24895      0.28407   ***

   8    - 4           -0.04777     -0.01075      0.02627
   8    - 7            0.10702      0.14700      0.18698   ***
   8    - 2            0.16628      0.20140      0.23652   ***
   8    - 5            0.19428      0.22940      0.26452   ***
   8    - 3            0.20154      0.23533      0.26912   ***
   8    - 6            0.20023      0.23725      0.27427   ***
   8    - 1            0.20308      0.23820      0.27332   ***

   7    - 4           -0.19773     -0.15775     -0.11777   ***
   7    - 8           -0.18698     -0.14700     -0.10702   ***
   7    - 2            0.01617      0.05440      0.09263   ***
   7    - 5            0.04417      0.08240      0.12063   ***
   7    - 3            0.05132      0.08833      0.12535   ***
   7    - 6            0.05027      0.09025      0.13023   ***
   7    - 1            0.05297      0.09120      0.12943   ***

   2    - 4           -0.24727     -0.21215     -0.17703   ***
   2    - 8           -0.23652     -0.20140     -0.16628   ***
   2    - 7           -0.09263     -0.05440     -0.01617   ***
   2    - 5           -0.00511      0.02800      0.06111
   2    - 3            0.00224      0.03393      0.06563   ***
   2    - 6            0.00073      0.03585      0.07097   ***
   2    - 1            0.00369      0.03680      0.06991   ***

   5    - 4           -0.27527     -0.24015     -0.20503   ***
   5    - 8           -0.26452     -0.22940     -0.19428   ***
   5    - 7           -0.12063     -0.08240     -0.04417   ***
   5    - 2           -0.06111     -0.02800      0.00511
   5    - 3           -0.02576      0.00593      0.03763
   5    - 6           -0.02727      0.00785      0.04297
   5    - 1           -0.02431      0.00880      0.04191

   3    - 4           -0.27987     -0.24608     -0.21229   ***
   3    - 8           -0.26912     -0.23533     -0.20154   ***
   3    - 7           -0.12535     -0.08833     -0.05132   ***
   3    - 2           -0.06563     -0.03393     -0.00224   ***
   3    - 5           -0.03763     -0.00593      0.02576
   3    - 6           -0.03187      0.00192      0.03571
   3    - 1           -0.02883      0.00287      0.03456

   6    - 4           -0.28502     -0.24800     -0.21098   ***
   6    - 8           -0.27427     -0.23725     -0.20023   ***
   6    - 7           -0.13023     -0.09025     -0.05027   ***
   6    - 2           -0.07097     -0.03585     -0.00073   ***
   6    - 5           -0.04297     -0.00785      0.02727
   6    - 3           -0.03571     -0.00192      0.03187
   6    - 1           -0.03417      0.00095      0.03607
```

```
1     - 4        -0.28407    -0.24895    -0.21383    ***
1     - 8        -0.27332    -0.23820    -0.20308    ***
1     - 7        -0.12943    -0.09120    -0.05297    ***
1     - 2        -0.06991    -0.03680    -0.00369    ***
1     - 5        -0.04191    -0.00880     0.02431
1     - 3        -0.03456    -0.00287     0.02883
1     - 6        -0.03607    -0.00095     0.03417
```

```
                    General Linear Models Procedure
                          Least Squares Means

                      GROUP         MODULE   LSMEAN
                                    LSMEAN   Number

                      1         0.00280000     1
                      2         0.03960000     2
                      3         0.00566667     3
                      4         0.25175000     4
                      5         0.01160000     5
                      6         0.00375000     6
                      7         0.09400000     7
                      8         0.24100000     8

                    Pr > |T| H0: LSMEAN(i)=LSMEAN(j)

       i/j      1       2       3       4       5       6       7       8
       1    .      0.0306  0.8544  0.0001  0.5904  0.9562  0.0001  0.0001
       2   0.0306   .      0.0368  0.0001  0.0942  0.0457  0.0069  0.0001
       3   0.8544  0.0368   .      0.0001  0.7043  0.9083  0.0001  0.0001
       4   0.0001  0.0001  0.0001   .      0.0001  0.0001  0.0001  0.5567
       5   0.5904  0.0942  0.7043  0.0001   .      0.6505  0.0001  0.0001
       6   0.9562  0.0457  0.9083  0.0001  0.6505   .      0.0001  0.0001
       7   0.0001  0.0069  0.0001  0.0001  0.0001  0.0001   .      0.0001
       8   0.0001  0.0001  0.0001  0.5567  0.0001  0.0001  0.0001   .

NOTE: To ensure overall protection level, only probabilities associated with
      pre-planned comparisons should be used.
```