

STREAMFLOW RESPONSE TO CHANGES IN LAND COVER

AND CLIMATE IN LOWER MICHIGAN

"Streamflow response to changes in land cover and climate in Lower Michigan"

A Thesis Presented to the Faculty
of
the University of Wisconsin - Madison

In Partial Fulfillment
of the Requirements for the Degree
of Master of Science

By

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December 2009

Abstract

Studies of the influence of basin land use on the hydrologic response of streams to climate change are limited, and have generally focused on individual land use types in isolation.

Prediction of future hydrologic change requires a comprehensive understanding of the relative influence of multiple land cover classes on streamflow response to changes in climate.

A statistical analysis of 20 Lower Michigan watersheds spanning various environmental gradients was used to determine the influence of land cover and climate on streamflow change during the period 1935-2008. A second analysis, a temporal, pairwise comparison of neighboring basins with similar climatic and environmental characteristics and different land use histories, was used to further refine the impacts of land cover change on stream hydrology and to identify explanatory trends.

Urbanization and agriculture were found to have significant effects on streamflow response to climate changes. Urbanized and agricultural basins were both observed to exhibit increases in baseflow and overall average streamflow, and declines in peak flows. Urbanization was found to generally contribute more significantly to these trends than agriculture. Peak flows were found to be negatively affected by urbanization, a likely consequence of increased stormwater management and retention capacity later in the study period. These findings suggest that conservation measures and increased outflows associated with human activity, coupled with significant increases in precipitation, have contributed to both higher delivery of water and reduced flood volumes to Lower Michigan streams.

1 Study Objectives and Introduction

1.1 Study Objectives

The objectives of this study are to:

- Determine the long-term impact of climate change on streamflow regimes in medium to large size (100 to 2500 km²) watersheds in Lower Michigan.
- Quantify differential response to changes in climate in watersheds with different land cover characteristics.
- Identify mechanisms driving land cover sensitivity of hydrologic response to climate change.

1.2 Study Area

The study region for this thesis is the Lower Peninsula of Michigan. The analysis begins with an examination of discharge trends in 20 watersheds across the region. A map of the study region and the study watersheds is provided in Map 1, and a list of the study watersheds is provided in Table 1-1. The second phase of research examines in greater detail the Battle Creek River and Upper Grand River basins, which are a subset of the 20 study watersheds in the first analysis. These two watersheds have the best available long-term records of environmental controls affecting streamflow hydrology in the study area. These watersheds are indicated in green in Figure 1.

1.3 Background

Major floods in the Midwest are believed to be increasing in frequency as a consequence of climate change (Knox 1993). Part of the difficulty in assessing impacts on fluvial systems from climate change is differentiating changes caused by climate change from those related to land cover conversion. Land cover changes associated with urban sprawl and changes in agricultural land uses greatly alter the landscape and, in turn, watershed hydrology (Leopold 1971). Due to the accelerating pace of both urban sprawl and climate change, there is an increasing need to understand how a watershed reacts to change, and how these changes might continue into the future.

Over the last century, streamflow patterns have changed in streams across Lower Michigan. Changes in climate and human land use have been observed and are likely driving much of this change in streamflow, although the relative contributions of each of these drivers and the role of other environmental factors in tempering or magnifying hydrologic change are unclear for a number of reasons. First, the density and nature of land use and land cover conversion varies substantially across the region, ranging from heavy urbanization in the Detroit metropolitan region, to widespread agriculture elsewhere in the southern half of Lower Michigan, to vast, second growth forests in the less developed northern half of the peninsula. Variations in environmental characteristics such as geology and local climate further complicate the process of establishing a definitive relationship between human activity and watershed hydrologic response. Most existing literature on the topic of human and climatic impacts on hydrologic change focuses on either a single watershed or pair wise comparison. While these studies adequately

identify the drivers of streamflow change for the watersheds in question, they lack the power to infer the effect of the physical and environmental characteristics of the watershed on affecting hydrologic change. This study, in order to adequately isolate the impact of distinct environmental and human factors on streamflow, examines a larger set of watersheds that represent a number of geologic, biologic, and climatic gradients.

The goal of this research is to quantitatively assess changes in streamflow across the last several decades in a set of watersheds in Lower Michigan, and to analyze these changes to determine the relative contributions of climate and human land use as drivers. Because developing an accurate land use history for a watershed is a time and data intensive process, doing so for each watershed used in the study proved prohibitive. Therefore, this study is comprised of two separate analyses: (1) a region-wide analysis of watershed hydrologic response across environmental gradients using simplified land cover change categories, and (2) a pair wise comparison between two nearby watersheds, the Battle Creek River and Upper Grand River, intended to establish a strong causal relationship between land use change and hydrologic change.

2 Literature Review

2.1 Effects of Land Cover Conversion on Streamflow

The fundamental goal of this thesis is to understand the factors that are driving long-term changes in streamflow from watersheds undergoing environmental change. This effect inherently includes examination of a number of variables that must be considered separately

including measures of changes in both land cover and climate. The following review summarizes previous studies of causal relationships between watershed environmental changes and changes in streamflow and surface hydrology.

2.1.1 Effects of Urbanization on Streamflow

Two papers by Luna Leopold, (Leopold, 1968) and (Leopold, 1971), provide two of the earliest detailed assessments of how urbanization influences streamflow by conversion of natural surfaces to impermeable surfaces and by installation of sewer systems and other modification of natural drainage networks. While the magnitude of hydrologic response by a watershed to land cover change is largely dependent on the individual characteristics and sensitivity of that watershed (Bledsoe, et al., 2001), certain land cover features and patterns are known to elicit certain responses across watersheds with different environmental and geographical characteristics.

Particularly noteworthy among the hydrologic changes that Leopold (1971) attributes to increased urbanization is an increase in the magnitude of peak floods. Leopold demonstrated a strong relationship between flood magnitudes and frequencies versus impervious surface area and percentage area served by sewer lines. His data represent a number of earlier studies from individual, geographically disparate watersheds characterized by low-density suburban housing. These watersheds all exhibit a large increase in peak flows in response to urbanization, in some cases as high as 6 times higher in watersheds with large areas of impervious surface. Leopold also cites Sopper and Lull (1969), who use a conversion of northeast Pennsylvania forest to

urban land cover change, to establish a relationship between percent impervious surface and peak flood volumes.

Leopold (1971) shows that the effect of urbanization to produce higher peak flows, in turn, impacted channel morphology, sediment transport, and water quality. Although Leopold's study represents a seminal understanding of the impacts of urban land cover on watershed hydrology, little effort was directed toward addressing the variability of other watershed environmental factors that contribute to changes in peak flows. The studies and data cited by Leopold involve temporal case studies of individual watersheds that differ appreciably in size, geology, soils, climate, and shape. These factors are known to have a substantial influence on stream runoff. Subsequent studies address these deficiencies and introduce different variables into the process of understanding long-term hydrologic change, and many attempt to identify the surface interactions that produce the observed effects in runoff hydrology.

Hollis (1975) builds upon the foundational concepts defined by Leopold (1971) by examining the patterns of change exhibited in urbanizing watersheds. Hollis evaluated the relationship that increases in peak flow magnitudes for floods of different return frequencies are not static. Hollis found that the positive association between flood magnitudes and surface modifications diminishes as flood recurrence intervals increase. For the more extreme floods, the soils of an agricultural or natural watershed may be saturated and overland flow takes place similarly to that expected to occur in a watershed with anthropogenic imperviousness. Hollis concluded that there was no measurable difference in flood magnitudes between agricultural watersheds and watersheds with light development (less than 5% impervious surface). He also

showed that for floods with a recurrence interval equivalent to the 100 year flood event, even a completely (100%) developed watershed would only double the flood magnitude of a natural watershed. This doubling is substantially less than the factors of 6-10 observed in Leopold's data. Hollis (1975) provides a valuable next step from Leopold (1971) in that more specific trends can be extracted, in turn providing more useful information for planners and stakeholders in a watershed.

2.1.2 Effects of Deforestation and Afforestation on Streamflow

Owe (1985) examines hydrologic change in a developing watershed with respect to a more complex assessment of development. The study assesses change based on 5 land cover classes: forest, urban residential, cultivated cropland, and open grass. Furthermore, while Leopold (1971) only examined peak floods, Owe analyzes the timing and net volumes of streamflows over the year to reveal how changes in land cover affect the overall shape of the annual hydrograph. Additionally, Owe's research documents how temporal changes in streamflow respond to changing vegetation cover and agricultural development. He also provides an estimate of the relative contributions of evapotranspiration and overland flow as components of land cover on the hydrologic change.

The studies that follow Leopold's pioneering investigations provide a more complete picture of both the driving mechanisms behind hydrologic change and of the nature of that change. By delineating seasonal changes in streamflow, Owe (1985) not only provides a useful indication of the temporal distribution of streamflow impacts, but facilitates a more comprehensive examination of the many components of hydrologic change and their influence on the long-term

hydrologic budget. Nevertheless, the specific nature of the land cover change being observed limits the usefulness of the data to comparable watersheds, if they even exist. The Pennsylvania watershed studied by Owe (1985) was originally completely forested, experienced deforestation during agricultural development, followed by a decrease in agriculture and an increase in low-density residential and even reforestation. While this pattern is not necessarily unique, it is certainly far from universal. The observations and relationships described by Leopold (1971) may be limited in complexity, but they provide a useful baseline from which impacts of land use across a wide variety of watersheds may be understood. It is important to note that, despite the sensitivities of flow frequencies indicated in Owe (1985), the general trend of increasing surface runoff is consistent with Leopold's findings.

Evaluation of hydrologic impacts of land cover has also been conducted by Whitehead and Robinson (1993). This study pairs watersheds with different characteristics from around the world, in a variety of different physical landscapes and climate regimes. The findings of the study testify to the complexity and sometimes watershed-specific characteristics that determine how streamflow responds to environmental changes. Comparison of the watershed pairs showed that both annual peak flows and base flow volumes increased with both deforestation and afforestation, as well as several other treatments applied to the watersheds. While it is possible to interpret these results as indicative of change relative to a disturbance of an equilibrium condition, soil compaction and greater overland flow, the authors suggest that the findings are the result of the specific sensitivities and characteristics of the watersheds being studied. The authors attribute a lack of large scale trends in hydrologic impacts to the multiplicity of variables

that affect regional responses to a seemingly greater degree than afforestation or deforestation alone, including “site disturbance, including possible soil compaction and road construction as a result of logging and any artificial drainage before tree planting.” These results, however, were similar to the conclusion of Owe (1985) that clear cutting itself has a generally minor impact on streamflows.

2.1.3 Effects of Agriculture

There have been numerous studies examining the impact of agricultural activity on stream hydrology. Several studies have found that agricultural land use increases overland flow and depletes groundwater discharge due to increased soil compaction, decreased annual vegetative cover, withdrawals of groundwater for irrigation, and rapid surface saturation due to exposed bare soil (Dunne, et al., 1978; Blake, et al., 1976; Knox, 2001). Knox (2003) finds that large floods are becoming increasingly common on the Upper Mississippi River in response to relatively modest climate change, but floods on small to moderate sized tributaries of the Upper Mississippi River have been, on average, declining since about 1950 (Knox 1987, 1999, 2006).

Potter (1991) also found that annual peak floods and winter/spring flood volumes in an agricultural, medium-sized (572 km²) Wisconsin watershed have declined in recent decades. The author also attributes this trend to better soil conservation practices, which have reduced overland flow and subsequently blunted peak floods. (Schilling, et al., 2003) examined 11 gaged watersheds of various sizes in Iowa, and found significant percentage increases in annual baseflow and minimum flows. In most of the rivers examined, this upward trend in low flows drove a rise in mean annual discharge. The study agrees with the above authors that improved

conservation practices are largely responsible for the observed rise in low flows. The study also hypothesizes that greater artificial drainage including underground drain tiles and ditching, increasing row crop production, and channel incision contribute to the observed trend.

As a critical component of the hydrologic budget strongly related to vegetation, evapotranspiration is likely to be affected by changes in agricultural practices. Zhang and Schilling (2006), examining the Mississippi River, conclude that streamflow and baseflow are rising due in part to changes in agricultural practices. The Mississippi River watershed, which is vastly larger than the study watersheds in this thesis, is used to minimize the influence of human withdrawals and diversions on calculating hydrologic budgets. The study concludes that increased groundwater recharge in agricultural areas is due to not only conservation practices, but to reduced evapotranspiration as a result of conversion of perennial vegetation to seasonal row crops, soybeans in particular.

2.2 Effects of Climate Change on Streamflows

A fundamental assumption of this thesis is that changes in climate are drivers of the hydrologic changes observed in the study region. This section provides a selection of relevant literature exploring the impacts of changes in precipitation and temperature on various streamflow attributes in Midwest U.S. watersheds, both independent from and in the context of changing land cover.

Much of the literature examining the impacts of climate on streamflow is focused on the development of computational models, and the results of these studies are ultimately speculative. The reason for this is that rapid climate change only exists in the latter part of the measured

hydrologic record, and this period of abrupt change is also accompanied by land cover conversion and widespread anthropogenic activity that makes distinction of changes as consequence of climate change alone difficult. Gleick (1987) provides an early example of such a study. Citing a lack of understanding of the impacts of climate change on water resources, the paper predicts long-term changes to hydrologic budgets based on climate projections derived from global climate models (GCMs). The study predicts significant decreases in summer runoff and soil moisture and increases in winter runoff primarily as a function of changing snowfall and snowmelt conditions. Earlier snowmelts and less precipitation falling as snow is projected to increase water supply and surface flow in winter and early spring at the expense of late spring, summer, and fall.

Knox (2000) uses geomorphologic analysis to construct a paleoflood record for streams in the Upper Mississippi River and Colorado River systems. Those data are then compared with existing historical climate records to infer responses of streamflows to changes in temperature and precipitation. The study finds that flood magnitudes and frequencies in the mid-latitudes have historically been higher during periods with high numbers of westerly waves, a phenomenon often associated with abrupt climatic changes. Consequently, rapid climate change in the second half of the 20th century is likely a factor in an observed increase in large floods during that time.

In recent years, the importance of climate change as a driver of hydrologic change has become well established. Karl and Riebsame (1989) find that the influence of temperature on streamflow is minimal, but that the influence of precipitation is significant, and often amplified

by a factor of two or more depending on basin characteristics such as land cover. Lins and Slack (1999) examine flows at different percentile magnitudes, and notes that flows of all but the highest magnitudes have increased across most of the United States in response to increases in precipitation. The study finds that trends in peak annual flooding are weak, and negative in many cases. Beyond changes in precipitation, Foster, et al. (1999) also find increases in streamflows related to urbanization, which they attribute to reduced evapotranspiration due to less vegetative cover and consistent, increased inputs from runoff and human water use such as treated sewage. Idso and Brazel (1984) provide an interesting explanation for rising streamflows: increased carbon dioxide in the atmosphere tends to induce partial stomatal closure in plants, reducing transpiration and thereby increasing soil moisture and runoff.

A number of recent publications examine the response of river systems to changes in climate taking land cover and other basin characteristics into consideration. In a series of papers from a study commissioned by the EPA in 1995, DeWalle, et al. (2000) provide a comprehensive analysis of annual streamflow changes over the second half of the 20th Century in 60 watersheds across the contiguous U.S. whereby they examine flow relations to changes in climate and population density (used as a proxy for urbanization). The study also examined seasonal trends in streamflow changes, and changes to both high and low flows. Among the most important findings of the study as summarized in DeWalle, et al. (2000) were:

- Precipitation increases cause greater high flows in streams, while temperature increases caused bigger reductions in low flows.

- Increases in annual streamflow are greater in urbanizing than rural basins regardless of climate change. Urbanization reduces the sensitivity of streamflow to temperature change
- Temperature increases caused greater flow changes on rural than urban basins, and greater flow changes in summer than in winter.

The authors attribute these differential changes to increases in impervious surface area, soil compaction, and removal of vegetation, which have the net effect of increasing hydrologic sensitivity to changes in both precipitation and temperature. In effect, the changes to streamflow in response to land cover change are magnified by urbanization. This study is also significant in that it provides a robust statistical method for isolating the most significant drivers of hydrologic change. This method, which employs a multiple regression model factoring both land use and climate change variables, is replicated in this thesis in a slightly modified fashion.

Dow and DeWalle (2000), as part of the same study, investigate the trends in evaporation and Bowen Ratio (ratio of sensible to latent heat fluxes) as a function of urbanization in eastern U.S. watersheds. The study finds a strong positive correlation between urbanization and Bowen ratio, and a strong negative correlation between urbanization and evaporation. The study projects additional evaporation of 22 cm/year for a completely urbanized watershed. While none of the watersheds in this study approach 100% urban area, even small changes in evaporation would have significant implications for hydrologic budgets in a region where annual precipitation is generally between 70 and 80 cm/year.

In a study similar to DeWalle, et al. (2000), Changnon and Demissie (1996) investigate watershed response to climate change from 1940-1990 in Illinois watersheds using two pair wise comparisons between urban and rural watersheds. The findings are consistent with DeWalle, et al. (2000). They observed most watersheds experienced an increase in mean annual streamflow during middle 20th Century, but this increase was more pronounced in urbanizing watersheds, and the magnitude of the increase was proportional to the scale of urbanization. It appears that most of the recent literature agrees upon a trend of higher mean annual streamflow in urbanizing basins.

2.3 Methods for Determining Influence of Basin Characteristics and Climate on Streamflow Change

Throughout the literature, there appear to be a few dominant trends in determining causality in streamflow changes. When assessing change in a single characteristic over time, many investigators base their results on study of a single watershed. An example is the study by Potter (1991), who conducted a study of long-term flow variations in a single tributary stream in Wisconsin. Paired watershed studies have also been a popular approach for evaluating streamflow sensitivity over time steps involving changes in precipitation, a single land cover characteristic, basin size, or geology. An example includes Whitehead and Robinson (1993), an examination of an array of basin attributes through pair wise comparisons. This approach is used in the second part of this thesis for testing the effects of urban and agricultural land cover under conditions of changes in precipitation. Finally, multiple regression models have frequently been

employed where multiple drivers are considered over a wide geographical area. DeWalle, et al. (2000) is an example of the multiple regression model application to determine the effects of urbanization on changes in streamflow in dozens of watersheds across the United States. Holtschlag and Croskey (1983) confirm the use of multiple regression methodology as a reliable method for generalization of hydrologic characteristics in Lower Michigan watersheds.

3 Study Area

3.1 Land Use History

Because historical land cover data have not been derived for Lower Michigan, it is not possible to provide a quantitative assessment of land cover change during the study period. Figure 3 displays the historical population of Lower Michigan, which would be expected to be related to urban and agricultural land uses. Population growth in the 20th Century, however, may not reflect farmland abandonment in northern Lower Michigan, and slowing population growth late in the 20th Century was likely accompanied by accelerated agricultural-to-urban land cover conversion due to urban sprawl. Figure 2 displays land cover proportions for 2001, as mapped by the IFMAP Land Cover project conducted by the Michigan Department of Natural Resources.

Prior to Euro-American settlement, Lower Michigan was predominantly forested; aside from a small area of prairie in the extreme southwestern part of the region, forest cover generally was interrupted only by extensive wetlands, concentrated primarily in lake-bottom plains (more discussion of Michigan's physiographic regions in Chapter 3.2). The forested regions were

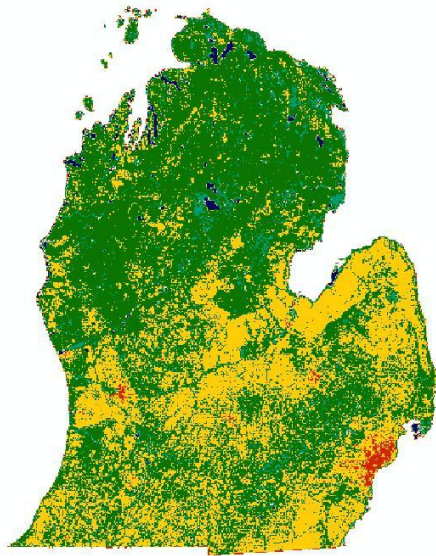


Figure 1: IFMAP Land Cover classes for 2001. Red: Urban; Yellow: Agricultural; Green: Forest; Blue-Green: Wetland; Dark Blue: Open Water (IFMAP)

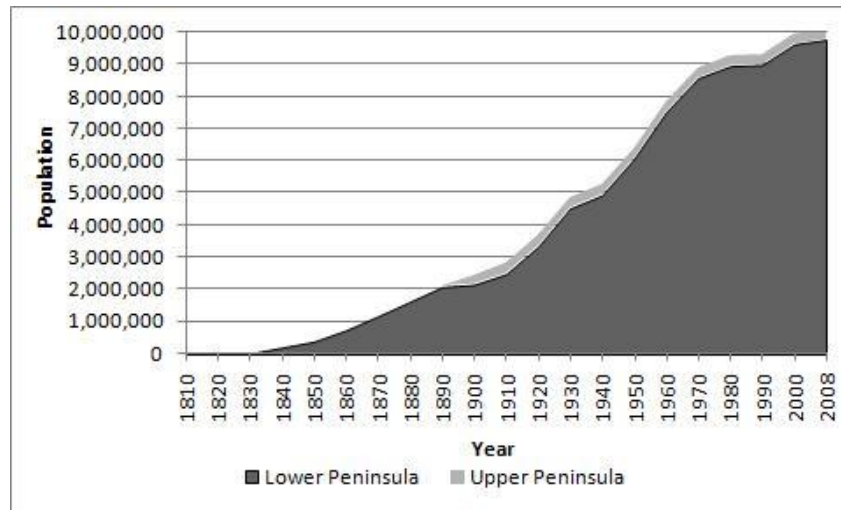


Figure 3: Michigan population since 1810. Note that population prior to 1880 includes both Lower and Upper Michigan. (U.S. Census Data)

comprised of both coniferous and mixed deciduous forest, with white pine dominant in the northern half of the peninsula.

These dense forests gave rise to a thriving timber industry in Lower Michigan beginning in the mid-19th Century, continuing through the second half of the 19th Century. Vast forests of white pine were cleared to provide lumber for growing cities to the south. When these forests were depleted, the remaining deciduous hardwoods were harvested to fuel the growing furniture industry in Grand Rapids. The passage of the Homestead Act in 1862 further accelerated the clearing of Lower Michigan's forests by encouraging agricultural activity, and the area devoted to agricultural use doubled by 1870. By 1880, Michigan's lumber output was more than the next three states combined, and by the time stocks were mostly exhausted in 1897, the state had produced more than 160 billion board feet of timber.

Much of this agricultural land was abandoned in the early 20th Century, particularly in the northern half of the peninsula, where the well-drained, sandy spodosols and short growing season proved difficult for farming. As a result, the northern part of the region was reforested in the following decades, facilitated by large-scale replanting projects beginning in the 1930s and by designation of state and national forests. In the southern half of the state, however, agriculture flourished, and most of the land remains in agriculture today.

The development of the automobile and subsequent growth of the Michigan auto industry in the early to mid 20th Century accelerated conversion of agricultural land to urban use. Land cover conversion was most drastic in the areas immediately surrounding existing urban centers, and generally confined to those areas within a few miles of the major urban corridors in the state.

(US Highways 12, 16, and 10 which are now Interstate Highways 94, 96, and 75, respectively).

Beginning in the 1960s and continuing through much of the remainder of the 20th Century, many Michigan regions experienced rapid suburbanization and urban sprawl. Population growth in previously rural regions was largely due to flight from older urban core areas such as the City of Detroit, which alone lost nearly 900,000 residents between 1950 and 2000). Urban land cover continued to expand despite stagnant population growth as a result of suburban expansion. A graph of Lower Michigan's population is provided in Figure 3.

3.2 Physiography

3.3 Climate

Southern Lower Michigan, which includes both the Upper Grand River and Battle Creek River basins, falls within the humid continental climate region, with 4 distinct seasons including hot summers and cold winters (Köppen climate classification: Dfa-summer wetter than winter). Precipitation is well distributed throughout the year, with rainfall heaviest during the summer months and snowfall

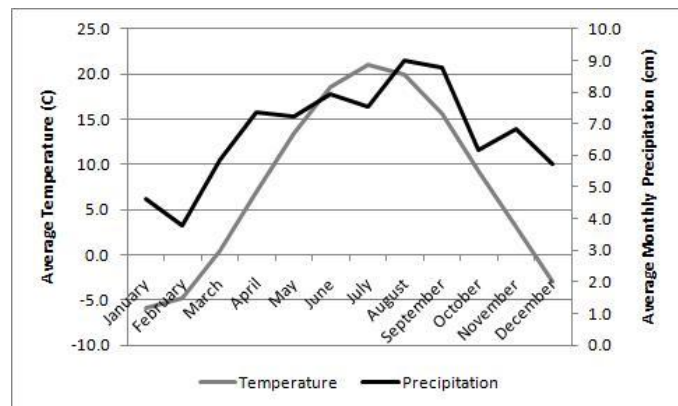


Figure 4: Monthly average precipitation (cm) and temperature (C). Data extracted from an average of all active NOAA climate stations in Lower Michigan for the period (1935-2008). List of stations is available in Appendix A.

persistent from late autumn through early spring (average annual snowfall of about 39.8 inches per year). Figure 4 plots average temperature and precipitation for the period (1970-2000) for the entire study region.

Over the course of the 20th Century, a slight warming trend and substantial increase in annual precipitation has been observed across the state. Figure 7 (a) displays change in mean annual temperature between Period 1 (1935-1979) and Period 2 (1980-2008) of this study. Figure 4 displays change in precipitation between the same periods. Note that changes in temperature have been slight, and mostly confined to the northeastern part of the region. Changes in precipitation have been much more distinct, and were only observed to significantly decrease in the far northeastern corner of the region.

At the seasonal scale, more significant trends emerge. Figure 5 displays change in average temperature between Period 1 and Period 2 for every season. Note that warming is most significant in winter, and least significant in fall, where very little change was observed. Change in temperature during the spring and summer appear to be less consistent and often vary locally. It is unclear whether this is due to increased variability in the summer or due to greater measurement error during warmer months. The greater relative warming trend observed in winter is hydrologically significant, as temperature changes during the winter months can have profound effects percent of precipitation falling as rain versus snow, and in turn influence the extent of snowmelt and frozen ground.

Seasonal precipitation changes exhibit radically different spatial patterns. During winter, precipitation in most of the state declined slightly, with large declines occurring near the Lake

Michigan shoreline. This is likely due to a change in lake-effect weather systems as a function of changing lake temperatures or ice cover, but this cannot be confirmed without further limnological analysis of the lake. During springtime, changes became more pronounced with significant declines in precipitation observed in belts across the far northern and southern parts of the region, while the middle of the region experienced significant increases in precipitation. As the year progresses, precipitation increases are observed across a greater proportion of the region, and increases are nearly universal in fall. It is hypothesized that this pattern of greater precipitation increases in summer and fall has significant impact on changing streamflow regimes during those months, as supported by studies such as (Knox, 1993) and (Potter, 1991).

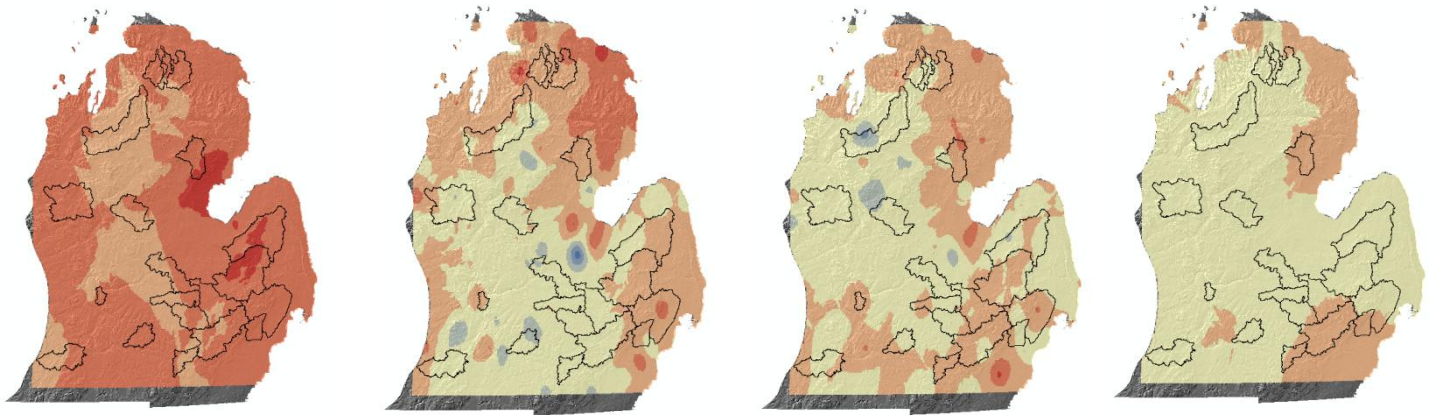


Figure 5 (a,b,c,d): Change in average temperature (C) for (a) winter, (b) spring, (c) summer, and (d) fall between Period 1 (1935-1979) and Period 2 (1980-2008). The legend for these maps is located below.

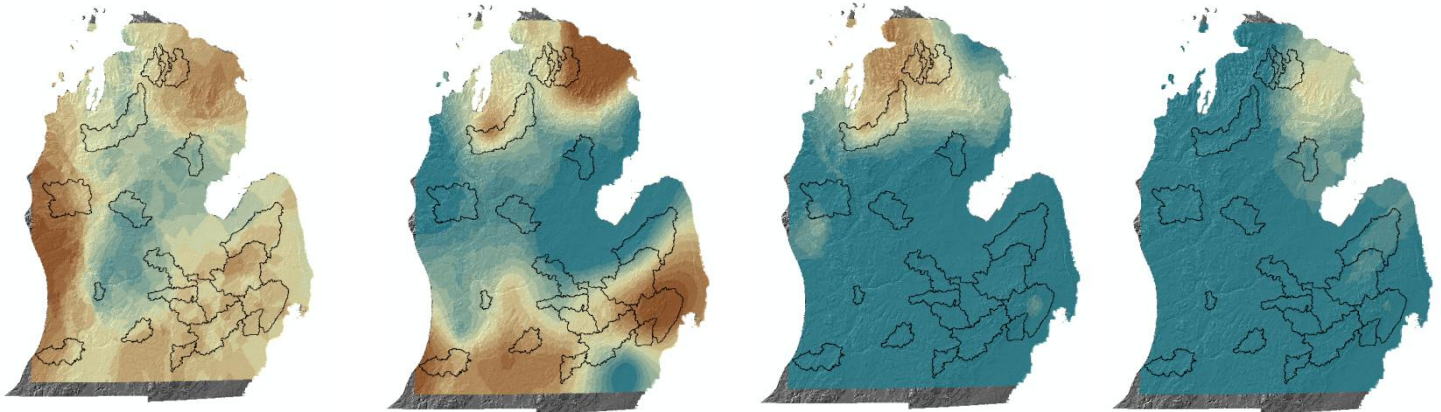


Figure 6 (a,b,c,d): Change in average precipitation in (cm) for (a) winter, (b) spring, (c) summer, and (d) fall between Period 1 (1935-1979) and Period 2 (1980-2008). The legend for these maps is located below.

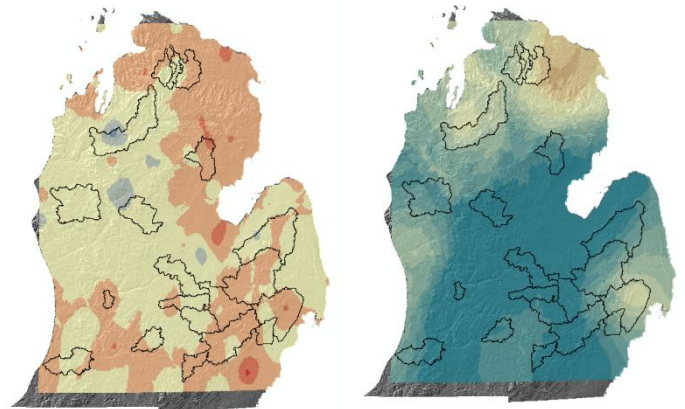
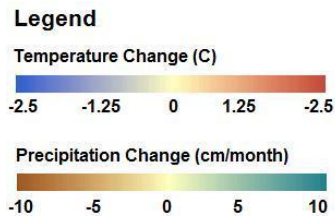


Figure 7 (a,b): Annual average temperature and precipitation change between Period 1 (1935-1979) and Period 2 (1980-2008)

These maps were generated using the kriging method to interpolate averages from all active NOAA climate stations in Lower Michigan as described in 4.1.3 and 4.1.4

4 Methodology

4.1 Streamflow

4.1.1 Basin Selection

The following criteria were used to identify all gauged Lower Michigan watersheds suitable for inclusion in the study: (1) basins must be larger than 25 km² and smaller than 2500 km², (2) gages must have a continuous record (no breaks larger than 2 years or no more than 10% missing data) beginning before 1955 and ending after 1995, (3) basins may not overlap, and (4) basins must lie completely within the State of Michigan (to ensure consistent data). The 20 watersheds included for study represent all Lower Michigan basins that satisfy these criteria.

The Battle Creek River and Upper Grand River basins were selected for further analysis due to their proximity, different land use patterns, centrality in the region, absence of any large-scale dams or diversions, and comparable size, climate, geology, and relief.

4.1.2 Hydrologic Data Acquisition

Stream flow data were acquired from the USGS's Surface Water Data statistics service (<http://waterdata.usgs.gov/>). For each basin, a daily mean streamflow record was acquired for the entire period of record falling in the designated study period. Custom scripts were written in Microsoft Visual Basic to facilitate the extraction of the desired streamflow attributes at annual and seasonal timescales.

For each analysis, three streamflow attributes were calculated from a daily streamflow record: mean daily discharge (Q_{tot}), maximum instantaneous discharge (Q_{max}), and minimum

instantaneous discharge (Q_{\min}). These were calculated at the seasonal and annual timescales, so that annual Q_{tot} , Q_{max} , and Q_{min} represent the mean, maximum, and minimum daily streamflows for the entire year, and seasonal Q_{tot} , Q_{max} , and Q_{min} represent the mean, maximum, and minimum daily streamflows for a given season. For seasonal data, “Winter” corresponds to the months January, February, and March, “Spring” to April, May, and June, “Summer” to July, August, and September, and “Fall” as October, November, and December.

4.1.3 Precipitation

Precipitation data were derived from daily precipitation totals from the National Climate Data Center (NCDC), a service of the NOAA (<http://ncdc.cdo.noaa.gov>). Data were collected for every climate station in the study region where data were available for at least 20 years in both of the two study periods (1935-1979, 1980-2008). For each station, average annual precipitation totals were calculated for each study period. The location of each station, the average annual precipitation between study periods for each period at that station, and the change in average annual precipitation at that station were imported into a GIS and interpolated across the region using the kriging method. A shapefile containing the outlines of all study watersheds was overlaid onto these interpolated layers, and a spatial average for precipitation averages for each period and precipitation change between periods was calculated for each watershed. The same procedure was used to determine change between study periods in average annual snowfall amounts by watershed. A list of all NOAA climate stations utilized in this analysis is provided in Appendix A. Because there tend to be edge effects when kriging is utilized as a spatial interpolation technique, there may be some error in the edges of the region. This is not expected

to radically alter the data, since there is a high density of climate stations, and the study watersheds are located far from the periphery of the region.

Kriging was chosen as an interpolation method because weighting using inverse distance weighting and other measures, while revealing the same patterns, were found to be less smooth and more prone to severe regional distortions.

4.1.4 Temperature

The procedure described in 3.2.1 was used to derive spatial temperature averages and two-period average temperature change for the study watersheds using average annual temperature data from NOAA (NCDC; <http://ncdc.cdo.noaa.gov>). A list of all NOAA climate stations utilized in this analysis is provided in Appendix A. Temperature change is not found to be spatially correlated with precipitation change in the region.

4.2 Watershed characteristics

4.2.1 Land Cover

Land use data were derived from aerial imagery for the years 1935, 1955, 1972, 1983, 1998, and 2005. The data were acquired from two different sources: black and white county-scale mosaics of aerial photographs were used for layers prior to 1998. These images were obtained from The Imagery Archive at Remote Sensing and GIS Research and Outreach Services at Michigan State University in East Lansing, Michigan. The Battle Creek River sets were constructed from aerial photo mosaics for Calhoun and Eaton Counties, while the Upper Grand River sets were constructed from aerial photo mosaics for Jackson and Hillsdale Counties.

While consistent dates were available across counties for each watershed, imagery for 1982 was not available in Eaton County, eliminating the possibility of using 1982 data for the Battle Creek River watershed. For 1998 and 2005, mosaics of USGS Orthophoto Quadrangles obtained from the Michigan Geographic Data Library (MGDL) were used.

Because assigning the entire land area of both watersheds into land cover classes at several time intervals would have been prohibitively time consuming, a random sampling approach was used. In this method, a field of randomly placed points was generated, and the land cover at that point was recorded at each time period. To ensure that the generated sampling field adequately captured areas where all types of land cover conversion might be found, the sampling was stratified. Strata were built based on a 1978 Land Cover map acquired from the MGDL, reclassified into the four land cover classes used in the analysis: Developed, Agricultural, Forest, and Wetland/Water. This layer was used due to its coarse resolution and broad zonal definitions of land cover regions. The sample size for each stratum was derived to achieve a 95% confidence level according to the following equation from (Congalton and Green, 1999):

$$n = B \prod_i (1 - \prod_i) / b_i^2$$

Where B is equal to the Chi square value for the confidence level 0.95, \prod_i represents the proportion of total watershed area occupied by the stratum, and b is the confidence interval.

ArcGIS was used to create a field of random points for each stratum, which were then merged into a single field of 379 points for each watershed.

For each time set, the imagery was georeferenced using township section boundaries and roads data from the MGD. The sampling points for each watershed were then overlain on the georeferenced imagery. Because mosaics for some of the older aerial images were compiled by hand, spatial accuracy was not always high. Therefore, point locations were verified using the 2005 orthophotos, and in some instances were corrected in earlier datasets according to location relative to roads or other recognizable features in the 2005 images. This problem did not occur with the 1998 dataset, which had very little positional error relative to the 2005 dataset.

At each point, the land cover was assigned to one of four land cover classes based on the following criteria:

1. Urban/Developed

Land use is defined as on or within developed land. This encompassed low to high density residential and commercial structures and associated cleared land (e.g., lawns, athletic fields, parks, or parking lots), large agricultural structures or clusters of farm buildings, roads and highway right-of-ways, and other areas determined to have a high runoff factor or be associated with non-agricultural irrigation or discharge.

2. Agricultural

Land use is mapped as fields devoted to agricultural uses, including all varieties of active or inactive farmland, pasture, or orchards.

3. Forested

Forested land cover is recognized as vegetated areas with distinguishable tree cover. This included rectangular woodlots and strips of trees associated with agricultural fields, riparian forests, natural areas and preserves, and forested parkland. Every effort was made to distinguish forest land from emergent wetlands, though this was often difficult to distinguish, particularly on the older images.

4. Wetlands and Open Water

Wetland and open water areas were places with visible water at the surface, or with vegetative cover indicative of permanently or semi-permanently saturated soils. Because areas of emergent forest could often be difficult to distinguish from non-wetland forests, layers featuring water table depth and wetland areas from the MGDL were used to validate the sight assessments.

4.2.2 Groundwater recharge and withdrawals

Groundwater recharge rates, intended to represent the hydraulic conductivity of the soils in a watershed, were derived from a raster dataset acquired from the MGDL (State of Michigan, 2005). A spatial average was taken for each basin and used in all analyses involving groundwater recharge.

Groundwater withdrawals were calculated based upon the State of Michigan's wells database, which contains every registered well in the state along with its pumping capacity. A coarse grid was created for the study region in ArcGIS, with the value of each cell equivalent to the sum of the pumping capacities of all wells within that grid cell. This average was converted

from gallons per second to centimeters per year, in order to make the data consistent with precipitation.

4.3 Regression Analyses

The multiple-regression method was adapted from similar studies by DeWalle, et al. (2000) and Holschlag and Croskey (1984) in which a multiple variable linear regression equation is derived to model the relationship between each streamflow attribute and a set of independent driver variables. For each regression equation, the coefficients for each driver variable are provided, along with the r^2 and a p-value derived from the F statistic. Furthermore, each driver variable is tested for significance by determining a t-statistic equal to (m_n/SE_n) where m_n is the variable slope coefficient and SE_n is the standard error for the variable. This t-statistic then compared to Critical-T values derived from a table. All statistical analyses were performed using Microsoft Excel 2007.

5 Region-wide Analysis

5.1 Introduction

In this chapter, trends in streamflow, land cover, precipitation, and temperature are examined at various timescales in order to establish causality. In the first section, a multiple regression analysis is performed on climate and land cover data from 20 watersheds across Lower Michigan at annual and seasonal timescales. This identifies the land cover and climate characteristics that are the most strongly associated with annual and seasonal streamflow trends in the region, and gives clues as to the physical drivers behind hydrologic change. In the second

section, a pair wise comparison between two nearby watersheds with similar geology, climate, and physiographic features but different human settlement patterns is performed. This analysis, which incorporates shorter timescales and a temporal land cover change analysis, is intended to validate or clarify the drivers identified in the first section.

	Annual		Winter		Spring		Summer		Fall	
	ΔP (cm)	ΔT (C)	ΔP (cm)	ΔT (C)	ΔP (cm)	ΔT (C)	ΔP (cm)	ΔT (C)	ΔP (cm)	ΔT (C)
Battle Creek	4.2	-0.1	-1.8	0.7	-3.8	0.1	13.6	-0.4	8.0	-0.1
Black	-6.6	-0.4	-3.8	0.6	-6.3	0.3	-2.0	0.3	1.6	-0.1
Cass	4.8	-0.2	-1.6	0.8	3.2	0.1	15.7	0.0	4.5	-0.2
Chippewa	5.3	-0.5	2.0	0.4	4.0	0.0	8.5	-0.1	9.0	-0.3
Clinton	0.7	0.2	-2.1	0.8	-7.3	0.3	5.6	0.2	5.7	-0.1
Flint	3.4	0.1	-2.6	0.8	-1.6	0.2	12.4	0.1	5.1	-0.2
Grand	5.0	0.1	-2.9	0.4	-2.9	0.0	14.5	-0.3	7.4	0.0
Huron	4.5	0.1	-2.2	0.5	-1.5	0.2	12.1	-0.1	7.5	0.2
Looking Glass	4.9	-0.1	-1.0	0.4	0.6	-0.2	10.6	-0.2	7.3	-0.2
Manistee	0.5	-0.6	0.0	0.3	-0.7	0.1	-0.7	0.0	6.1	-0.2
Maple	2.5	1.4	0.2	0.4	3.5	-0.2	10.8	-0.3	9.5	-0.3
Paw Paw	1.9	1.1	-3.4	0.4	-4.7	0.0	17.1	-0.1	11.1	-0.1
P. Marquette	3.4	-0.4	-4.0	0.6	5.0	0.1	5.4	-0.1	8.3	-0.1
Pigeon	-1.1	-0.1	-2.6	0.5	-2.2	0.2	-3.3	0.2	4.2	-0.2
Red Cedar	4.8	-0.1	-2.0	0.4	-1.0	-0.1	11.4	-0.3	7.1	-0.1
Rifle	4.0	0.4	1.2	0.8	5.3	0.3	5.7	0.4	3.2	0.1
Rouge	2.3	-0.1	-2.1	0.7	-4.3	0.4	7.3	0.1	7.3	0.1
Shiawassee	4.7	0.0	-2.0	0.6	-1.9	0.1	11.0	-0.1	7.0	0.0
Sturgeon	0.4	-0.1	-1.2	0.6	-0.9	0.3	-3.3	0.3	5.5	-0.1
Thornapple	6.5	0.4	2.2	0.5	0.8	0.0	14.9	0.1	8.7	-0.1

Table 5-1: Change in average monthly precipitation and temperature for 20 study watersheds between Period 1 (1935-1979) and Period 2 (1980-2008). Data were calculated according to the method described in 4.1.3 and 4.1.4.

Table 5-1 below contains change in annual and seasonal temperature and precipitation averages between Period 1 and Period 2 for each of the study watersheds. These data are used to construct the multiple regression analysis in 5.2.2.

The two-period analysis, separating hypothesized different climatic regimes, is performed using the periods 1935-1979 (Period 1), and 1980-2008 (Period 2). The two-period approach allows for the comparison of means and other quantitative measures to determine how the frequencies of different streamflow events have changed. The year 1980 was selected as a separation boundary because it approximates a time when both climate change and land cover conversion accelerated statewide.

Trends are measured at both the seasonal and full-year timescales. Differences in seasonal streamflow change can have significant implications for identifying the drivers of overall hydrologic change and assessing the effect of environmental changes. For instance, changes in winter flows tend to be more dominated by climate change than land use change because the effects of human impacts on hydrologic activity, through removal of vegetative cover and through increases in impervious surface area are less significant in winter when most plants are not in leaf and the ground is generally frozen.

A number of attributes hypothesized to contribute to changes in streamflows were excluded from the study when they were found either to be very closely related to another tested attribute, or if they were found to have poor explanatory power for any of the streamflow changes.

Attributes which had poor explanatory power included snowfall, basin area, basin compactness, and average slope. Attributes which were closely related to another included hydraulic conductivity, which yielded effectively the same causal relationships as forested land area, groundwater withdrawals which, except for two Metro Detroit watersheds, displayed a strong positive correlation with the composite of urbanization and agriculture, and instantaneous peak flows yielded nearly identical results to annual daily maximum.

5.2 Analysis of Trends between Watersheds

In this section, changes in streamflow in an array of 20 watersheds across Lower Michigan are analyzed at the two-period (1935-1979 and 1980-2008) timescale. For each basin, changes in mean annual and seasonal streamflow attributes (Q_{\max} , Q_{\min} , and Q_{tot}) are provided, along with changes in annual average precipitation and temperature, and static land cover (ca. 2001). The first part of this section describes the distribution and magnitude of streamflow and climate change in the study watersheds. The second part of the section examines a multiple-regression model which is intended to demonstrate which streamflow attributes are most sensitive to climate change and how land cover affects that sensitivity.

5.2.1 All Watershed Averages

Figure 8 and Table 5.2 display the change in average annual and seasonal streamflow attributes averaged for all of the study watersheds.

	Winter	Spring	Summer	Fall	Annual
Qmax	1.64	-3.40	36.90	34.12	0.51
Qmin	24.75	11.94	22.16	31.24	24.12
Qtot	8.46	3.29	29.12	36.62	14.77

Table 5-2: Percent change in streamflow attributes averaged over all study watersheds (raw data in Table 5.1)

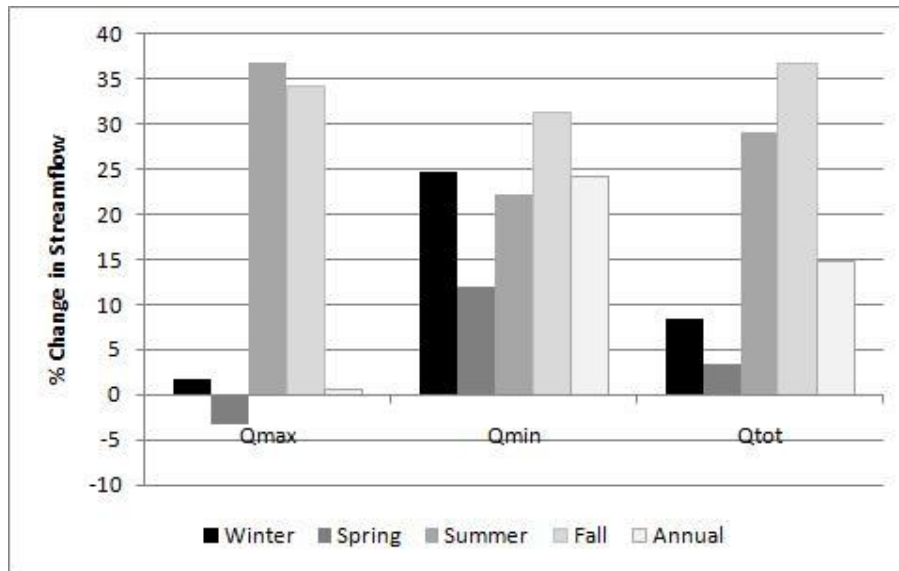


Figure 8: Percent change in streamflow attributes averaged over all study watersheds.

5.2.1.1 Q_{\max}

A statistically significant ($p < 0.05$) increase is observed in Q_{\max} for the summer and fall, when average seasonal peak flows rose by 48.43% and 41.54%, respectively. This is consistent with the literature: Leopold's (1968) early finding that rises in high flows are consistent with land use changes that increase surface runoff. Greater relative increases in summer and fall peaks observed by DeWalle, et al. (2000) elsewhere were attributed particularly to increased precipitation and reduced evaporation. Since precipitation and evaporation are relatively less during colder months, when the contribution of groundwater is proportionately greater, these drivers have only modest impacts on streamflow. Precipitation in the study region is observed to have increased significantly for summer and fall, whereas increases were modest in spring and insignificant in winter. This could exacerbate the conditions in the explanation provided by DeWalle, et al. (2000). Fall and summer Q_{\max} are also observed to vary significantly between watersheds, suggesting that this attribute may be more sensitive to local environmental changes.

The summer and fall increase in Q_{\max} is interesting, however, because the composite, all seasons combined Q_{\max} magnitudes are not observed to increase across the study watersheds. In fact, there is a small but statistically insignificant decline. This is likely due to a trend of reduced importance of snowmelt as a contributor to annual peak floods. Higher temperatures in winter, which have been observed in most of the study region, reduce seasonal snowpack and magnitudes of related floods. Since peak annual floods traditionally have occurred in late winter and early spring rather than in summer and fall, an increase in summer and fall Q_{\max} is observed that does not affect changes in annual peaks (Gleick, 1987).

5.2.1.2 Q_{\min}

Q_{\min} is observed to rise by a statistically significant margin during the winter and fall, and by a statistically insignificant margin during the other seasons and annually. The magnitude of these changes is much smaller than the significant changes in Q_{\max} : 20.37% for winter and 16.10% in the fall. Low flows tend to be driven largely by groundwater discharge, particularly in Michigan, where discharges from glacial deposits with high hydraulic conductivity tends to be high (State of Michigan, 2005). Groundwater in the winter can be influenced by changes in snow and ice cover, and by a greater proportion of precipitation falling as rain (Gleick, 1987). Higher recent baseflows in fall are the likely result of a combination of higher precipitation and less snow and ice cover in late autumn, particularly December. Like Q_{\max} , there is considerable variability between watersheds that appears to be closely linked to land use. This variability will be explored in subsequent sections.

5.2.1.3 Q_{tot}

Q_{tot} is observed to increase significantly from Period 1 to Period 2 during the summer and fall, an increase of 19.35% and 34.57%, respectively. It is the only streamflow attribute where the increase is greatest during the fall. Furthermore, it is the only streamflow attribute observed to significantly increase between the two periods at the annual timescale (11.08%).

Change in Q_{tot} is significant because in a large watershed, it effectively represents the principal outflow of water aside from evaporation. Therefore, changes in Q_{tot} must be explained largely by either depletion of groundwater, an increase in precipitation, an increase in evaporation, or transfers into or out of the basin. The latter is expected to be small relative to the

hydrologic budget for the large watersheds in this study. The increases do correspond mostly to changes in precipitation – the greatest increases in precipitation throughout the study region occurred in summer and fall. A large rise in temperature observed during winter would be expected to cause an increase in evaporation, which could also explain the relative reduction in Q_{tot} during that time. Less clear is the reason for the large change in fall streamflows. Changes in summer and fall Q_{max} were comparable, while fall Q_{min} was found to increase more than summer Q_{min} , suggesting that increases in baseflows in the fall may be driving the rise in fall Q_{tot} . One possible explanation for this rise is climate: average summer temperatures warmed significantly while average fall temperatures did not, suggesting that the rise in fall flows could be attributed to an increase in precipitation that, unlike summer, is not offset by a change in evaporation.

5.2.2 Multiple Regression Model

In this section, multivariate linear regression models are used to explore the relative importance of climate, land cover, geology, and human activity on changes in streamflow. The section is divided into four subsections, with each exploring a set of regression models with a different set of independent (driver) variables: (1) percent of basin are devoted to a particular land cover class and (2) climate. Tables 5-3 and 5-4 contain the regression equations for each sub-section. For each regression function, explained variance (r^2) and level of statistical significance are provided. Those coefficients which are significant at the 95% confidence level are indicated in bold, and those which exceed the 99% confidence level are indicated in bold-

italics. Significance is determined by a t-statistic and corresponding critical t from a table.

Tables B1 and B2 in the appendix contain the t-statistics for each variable.

5.2.2.1 Land Cover Only

Table 5-3 contains the regression equations developed to model the relationship between percent change in streamflow variables and proportional watershed area of land cover classes.

The data in Table 5-3 support the idea of a strong relationship between land cover and streamflow. Of the 12 streamflow attributes tested, 9 had a statistically significant relationship with land cover and explained variance greater than 0.5. It is worth noting that changes in annual Q_{\max} , winter Q_{\max} , and spring Q_{tot} , three streamflow attributes that were highly variable between watersheds, were not found to have a statistically significant relationship with land cover. This reflects the connection between these variables and winter climate.

Also worth noting is that, because land cover class proportions necessarily add up to 1, there are issues of collinearity. For example, trends found to be associated with forests and wetlands may not actually be caused by forest and wetland land cover, but rather, by an absence of urban and agricultural land cover. Nonetheless, because strong associations are found with individual streamflow attributes with urban and agricultural land cover, because these findings are consistent, explicable, and generally in line with many of the findings available in the literature, it is believed that the relationships identified in this section are robust and not a consequence of a statistical error.

Of the regression models, the strongest association between land cover and streamflow changes was found with annual Q_{tot} (mean annual streamflow), for which land cover was found to

account for 92% ($r^2 = 0.92$) of all change between periods. Figure 9 displays the strong association between observed change in mean annual streamflow and change predicted by the land cover regression equation. Of the land cover classes, only urban and agricultural land uses were found to have a statistically significant relationship with change in annual Q_{tot} , with agricultural land use having the strongest relationship. The relationship between land cover and seasonal Q_{tot} is less distinct and the influence of land cover on winter and spring Q_{tot} is statistically insignificant. Furthermore, the association is weaker during summer and fall than for the year as a whole. This disparity likely stems from the greater influence of climate changes on seasonal trends, as variation in climate is more distinct for individual seasons than for the year as a whole.

Land Cover	r^2	Coefficients			
		Wet.	For.	Ag.	Urb.
Annual Qmax	-	-	0.19	-	-
Annual Qmin	0.80	-	-	-	1.23
Annual Qtot	0.92	-	-	0.29	0.46
Winter Qmax	-	-1.42	0.25	-	-
Spring Qmax	0.53	-	-	-	-0.59
Summer Qmax	0.63	-	-	0.70	1.50
Fall Qmax	0.79	-	-	0.44	-
Winter Qmin	0.75	-	-	-	-
Spring Qmin	-	-	-	-	0.54
Summer Qmin	-	-	-	-	1.15
Fall Qmin	0.76	-	-	-	1.10
Winter Qtot	0.78	-	0.08	-	-
Spring Qtot	-	-	-	-	-
Summer Qtot	-	-	-	0.38	1.59
Fall Qtot	0.78	-	-	0.48	1.06

Table 5-3: Linear regression models for the relationship between percent change in streamflow and land cover classes (% of watershed land area). Included coefficients are significant at ($p < 0.1$), those in bold are significant at ($p < 0.05$), and those in bold-italics are significant at ($p < 0.01$).

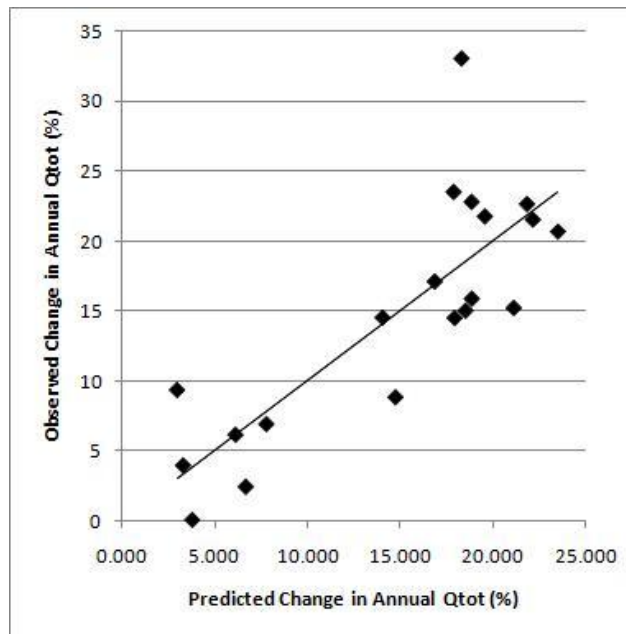


Figure 9: Predicted change in mean annual streamflow derived from linear regression model of relationship between land cover and Annual Qtot, demonstrating the significance of land cover in hydrologic change in the study watersheds. ($y = 0.29A + 0.46U$, $r^2=0.92$ where U is urban land cover proportion and A is agricultural land cover proportion)

Additionally, while agricultural land use was found to be most influential with respect to mean annual streamflow, urban land use was found to be more influential with regards to seasonal Q_{tot} , where it was found to have statistically significant positive influence during the summer. On the other hand, agricultural land use was not significantly associated with seasonal Q_{tot} during any season. The finding of changes of greater magnitude during the summer and fall is consistent with the finding of DeWalle, et al. (2000) that changes in streamflow in urbanized watersheds are the greatest in the summer, when the magnitudes of most components of the hydrologic budget are larger and more sensitive to small environmental changes. In particular, variations in precipitation and evapotranspiration would be expected to strongly influence streamflow trends in the summer, as the bulk of annual precipitation in Lower Michigan falls during the summer, and evapotranspiration is related strongly to vegetative cover which is in turn related to human land use. Human water use is also expected to be the greatest in the summer, which may be compensating for a drop in groundwater inputs into the stream as also found by Leopold (1968).

As stated earlier, annual Q_{tot} effectively represents the entire outflow from the basin not accounted for by inter-basin transfers, evaporation, and depletion of groundwater. Indeed, precipitation increased from the first to the second period in every season across the study watersheds, especially in the summer and fall. This is consistent with the findings of Karl and Riebsame (1989), who found that an increase in precipitation often resulted in an increase in streamflow by a factor of two or more, and of DeWalle, et al. (2000), who found that increases in

mean annual streamflow were closely associated with the proportion of urban land cover in a basin. A few studies attribute these changes to changes in evapotranspiration and changes in agricultural conservation practices, cropping methods, drainage, and channel modification related to agriculture (Potter, 1991; Zhang, et al., 2006; Schilling, et al., 2003). Based on the regression models presented in this section, it appears that both agricultural and urban land uses are influencing rising streamflows in the study watersheds, with urban land use exerting a stronger influence during the summer and early fall.

Other significant associations between land cover and streamflow changes were positive associations between urbanization and Q_{\min} during summer and fall. This finding is consistent with the findings of Lins and Slack (1999), who found that increased flows as a result of urbanization were the most significant at low magnitude, high frequency flows below the 75th percentile. Many of the studies in the literature regarding increased low flows and total flows associated with urbanization make little attempt to explain the phenomenon. A reasonable explanation is that offered by Foster, et al. (1999) who suggest that increasing high-frequency streamflows in urbanized areas are the combined result of reductions in evapotranspiration and increased delivery of precipitation into stream channels. More efficient delivery results from more impervious surfaces, and sustained, direct inputs of water into stream channels as a function of human activities such as lawn watering and treated sewage outflows. This is supported by the finding by DeWalle, et al. (2000) who showed population density had more predictive power than urban land use itself. More people equates with more discharge from human activities.

A statistically significant negative relationship also occurs in the regression of spring Q_{\max} against urbanization. This trend is not reflected in the literature, and appears to be somewhat anomalous. The strong correlation observed here appears to be the result of a pair of outliers in the dataset, and therefore probably is not realistic.

Beyond urbanization and agriculture, two other significant relationships were observed between land cover and streamflow. Forested land cover was found to be positively associated with annual and winter Q_{\max} (peak flows). There is evidence elsewhere that deforestation and afforestation both may increase peak flows (Owe, 1985), and most of the forests in Lower Michigan are actively managed with periodic timber harvests. Nonetheless, these trends were observed to be minor (Whitehead, et al., 1993; Owe, 1985) and largely insignificant.

Furthermore, there is no reason to suspect that logging activity has become more intensive in Period 2 than in Period 1. In fact, forest cover has increased from Period 1 to Period 2. As such, the most likely explanation for this trend is that forested watersheds in Lower Michigan tend to be the least modified by human activity. Therefore, hydrologic change in forested watersheds is most likely to reflect changes in climate. Since the observed increase in peak flows is in the winter when effects of human modifications exhibit relatively little hydrologic influence), it is likely that this trend is climatically driven and not related to changes in forest cover. Warming in the winter has been considerable across the study region. In turn, more winter rain leads to larger winter streamflows. Furthermore, forested watersheds in Lower Michigan tend to be those that were otherwise unsuitable for cultivation due to highly sandy soils, and these soils exhibit high hydraulic conductivity and favor groundwater recharge. As

such, summer floods are generally minimal, and annual peak flows often occur in winter. Consequently, annual Q_{\max} would rise as a function of changing winter climate.

5.2.2.2 Climate Only

Table 5-4 displays the multiple regression equations derived for streamflow attributes with changes in watershed averaged precipitation and temperature between Period 1 and Period 2. For this analysis, seasonal streamflow data were tested against climate changes for that season only. For example, the multiple regression analysis for summer Q_{\max} used changes in summer precipitation and summer temperature as independent variables, and annual streamflow data were only tested against annual climate data. While it is likely that climatic changes in some seasons are likely to affect streamflow in others, tests show that few of these relationships are revealed through a multiple-regression analysis. Additionally, the inclusion of so many generally unrelated variables weakens the significance values of other variables which are closely associated. One interesting relationship observed during preliminary testing was a statistically significant negative relationship between summer and fall temperatures and winter Q_{tot} . Conceivably, this suggests that warmer temperatures during summer result in increased evaporation and subsequently decreased groundwater recharge to be released into streams during winter.

Temperature was found to be significantly positively associated with only two streamflow attributes: winter Q_{\min} and Q_{tot} . This reaffirms the hypothesis presented in the

Climate	Coefficients		
	r ²	Δ Temp	Δ Pcp
Annual Qmax	-	-	-
Annual Qmin	0.37	-	3.31
Annual Qtot	0.46	-	2.01
Winter Qmax	-	-	-
Spring Qmax	0.30	-	-
Summer Qmax	0.61	-	4.12
Fall Qmax	0.81	-	4.42
Winter Qmin	0.71	41.90	-
Spring Qmin	-	-	-
Summer Qmin	0.67	-	2.37
Fall Qmin	0.59	-	3.97
Winter Qtot	0.79	11.18	-
Spring Qtot	-	-	-
Summer Qtot	0.70	-	3.26
Fall Qtot	0.68	-	4.49

Table 5-4: Linear regression models for the relationship between percent change in streamflow and changes in temperature (C) and precipitation (cm). Included coefficients are significant at (p < 0.1), those in bold are significant at (p < 0.05), and those in bold-italics are significant at (p < 0.01).

previous section, where it was found that forest land cover was positively associated with winter streamflow, a relationship that was presumed to be climatically driven given the low human impact on forested basins. It has been previously hypothesized (Changnon, et al., 1996; Gleick, 1987; Demissie, et al., 1993 ; DeWalle, et al., 2000) that warmer temperatures in winter influence snow cover and proportion of rain falling as snow. The data presented in this analysis appear to confirm this hypothesis in Lower Michigan. The absence of significant relationships between temperature and any other streamflow attributes appears to support the finding of Karl and Riebsame (1989) that temperature has significantly less impact on changing streamflow than precipitation. While DeWalle, et al. (2000) also find that temperature has less impact on streamflow than precipitation, they find that the influence of temperature on streamflow is greatest in the summer, which appears to contradict the finding of this thesis that the influence of changing temperature on changes in streamflow is most significant in the winter. This discrepancy may be attributable to the greater relative influence of precipitation and land cover on volatile summer flows.

Unsurprisingly, changes in precipitation are observed to be strongly associated with changes in streamflow. This relationship is strongest during the summer and also significant during the fall, and is explained in large part by the greater precipitation increases during these times, particularly given the finding by Karl and Riebsame (1989) that the rate of streamflow increase is more than double the rate of precipitation increase in some basins. This also supports the hypothesis that reduced evapotranspiration is significantly affecting streamflow change

during the study period, as such changes would be minimal during winter and spring when most plants in Lower Michigan are dormant.

Curiously, no significant relationships were found between streamflow and either precipitation or temperature during the winter and spring. There are a number of considerations that might explain this: first, precipitation change was lowest in winter, and is therefore less likely to cause a major change in streamflow exceeding the 95% confidence level. Second, the proportion of winter precipitation falling as snow is generally more important for streamflow change than the quantity of precipitation. For example, if a winter features unusually high precipitation, if that precipitation fell as rain, streamflows are significantly higher, while if most precipitation fell as snow, streamflows will not respond until spring. The timing of snowmelt and proportion of precipitation falling as snow weakens explanatory power of winter precipitation for winter streamflow. Snowfall was omitted from this portion of the study due to its poor explanatory power for streamflow. Snowfall was found to have no statistically significant relationship with total winter precipitation.

A significant positive relationship was found between precipitation and mean annual and minimum streamflow (Q_{tot} and Q_{min}). Additionally, t-statistics for changes in summer and fall Q_{tot} and Q_{min} were nearly identical. The similar response of these variables suggests that changes in baseflows and high-frequency, low-magnitude flows are largely driving changes in total discharge. This conclusion is consistent with Lins and Slack (1999) who also found that gains in annual streamflow paralleled gains in low and middle magnitude streamflows.

5.3 Conclusions

Present analyses lead to the following explanations for observed changes in streamflow attributes:

Q_{\max}

- Q_{\max} increased during summer and fall.
 - Precipitation increased substantially during these seasons.
 - Increased runoff, human diversions directly into stream channels occurred as a function of urbanization and agricultural land use.
- Annual Q_{\max} did not significantly change, and may have slightly decreased
 - Warmer winter temperatures altered snowmelt patterns, reducing the number of large floods related to snowmelt.

Q_{\min}

- Q_{\min} increased during summer and fall.
 - These increases were closely tied to urbanization, as a function of increased human discharge to streams compensating for groundwater depletion during dry periods as described by Foster, et al. (1999)
 - Increased precipitation during summer and fall is also likely contributing to higher Q_{\min} during these seasons, though climate is less influential than contributions from land use.

Q_{tot}

- Annual Q_{tot} increased for every watershed
 - Primarily a response to increased precipitation.
 - Strongly related to agricultural land use, likely due to changing agricultural practices such as drainage network modification and changes in cropping patterns for soil conservation.
 - Also related to urbanization, likely due to reduced evapotranspiration.
- Seasonal Q_{tot} increased for every watershed in every season except spring
 - Spring Q_{tot} strongly related to snowpack and winter climate in ways not captured or quantified by this analysis due to plurality of causation.
 - Change in seasonal Q_{tot} generally varied directly with changes in average precipitation.

Other conclusions drawn from this analysis include:

- Winter and spring flows are more related to climate than land cover.
 - Influence of land cover is reduced in winter and spring because evapotranspiration is insignificant, surface runoff is less significant, but subtle changes in winter climate can have major effects on snowmelt regime.
- Changing precipitation directly affects changes in streamflow vastly more than changes in temperature in all seasons except winter.
 - Plausible changes in evaporation related to observed changes in temperature are smaller than observed variability in precipitation.

- Temperature can dramatically influence winter streamflows due to aforementioned effects on snow versus rain proportions.
- Increases in precipitation tend to raise low flows more than high flows
 - High flows tend to reflect isolated storms or snowmelt more than low flows, which are more closely tied to precipitation.

6 Pairwise Analysis

6.1 Introduction

Lacking in the analyses presented in section 5.2, and in the literature in general, is an analysis of the differential streamflow response of urbanized versus agricultural basins to changes in climate. The multiple-regression analysis effectively revealed only one substantial relationship attributable to agriculture, which was mean annual streamflow (Q_{\max}), while urban land use tended to mask the effects of agriculture on other attributes. Furthermore, more change may have been attributed to urbanization than agriculture in the analysis in section 5.2 for the simple reason that in most, if not all of the study watersheds, agricultural land use area has been constant or declining while urban land use has increased. This differential is not accounted for in the multiple-regression model, and may explain why agricultural land use is not widely attributed to streamflow changes.

Previous long-term studies of streamflow in agricultural basins (Potter, 1991; Schilling, et al., 2003) generally identify the same streamflow trends, including increases in baseflow and

average flow and decreases in peak flows, as studies of urbanized basins (DeWalle, et al., 2000; Foster, et al., 1999). These studies, however, offer significantly different explanations. Studies of agricultural basins attribute long term trends such as rising baseflows and declining peak flows to factors such as improved conservation practices, more artificial drainage, and channel modifications, while studies of urban basins attribute the same changes to increased discharge directly to channels caused by reduced evapotranspiration and by human activities such as treated sewage outflows and lawn watering. It is likely that both sets of explanations are, at least in part, correct. For example, reduced evapotranspiration and increased drainage are phenomena associated with both urban and agricultural land uses. Differentiation of the specific effects of each, however, is necessary for projecting future basin response to climate change, particularly in basins with mixed agricultural and urban land uses. What was absent from both the multiple-regression study, as well as most other studies in the literature, is a temporal record of land use and land cover conversion.

6.2 Watershed Characteristics

6.2.1 Battle Creek River

The Battle Creek River and Upper Grand River watersheds are located in southern central Michigan, a region with a settlement and land use history largely representative of statewide trends. Both watersheds were cleared of original forest cover before the start of the 20th Century, cleared for commercial timber harvest and to clear land for agricultural use. The Battle Creek River watershed is situated midway between two urban centers—Lansing and Battle Creek, and has since the start of the study period been dominated by agricultural land uses.

	Land Cover Class			
	Urban	Agr.	For.	Wet.
Upper Grand River				
1938	11	51	22	17
1955	15	46	22	16
1971	21	40	22	16
1982	24	38	22	16
1998	27	34	22	16
2005	31	31	22	16
Battle Creek River				
1938	2	63	25	10
1955	5	63	24	9
1974	8	55	28	9
1998	13	50	28	9
2005	15	48	29	9

Table 6-1: Land cover proportions for the Upper Grand River and Battle Creek River basins for available years.

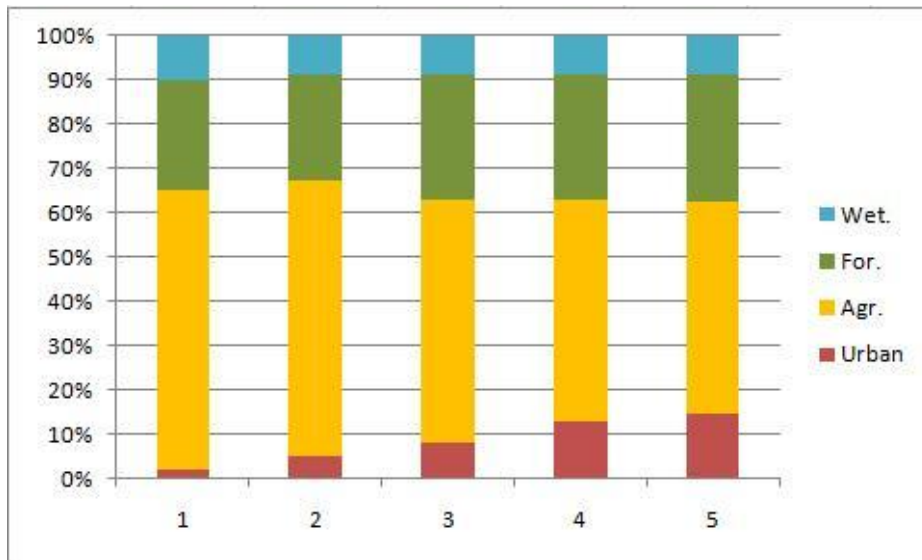


Figure 10(a): Land cover proportions in the Battle Creek River basin. Time 1 is 1938, Time 2 is 1955, Time 3 is 1974, Time 4 is 1998, Time 5 is 2005

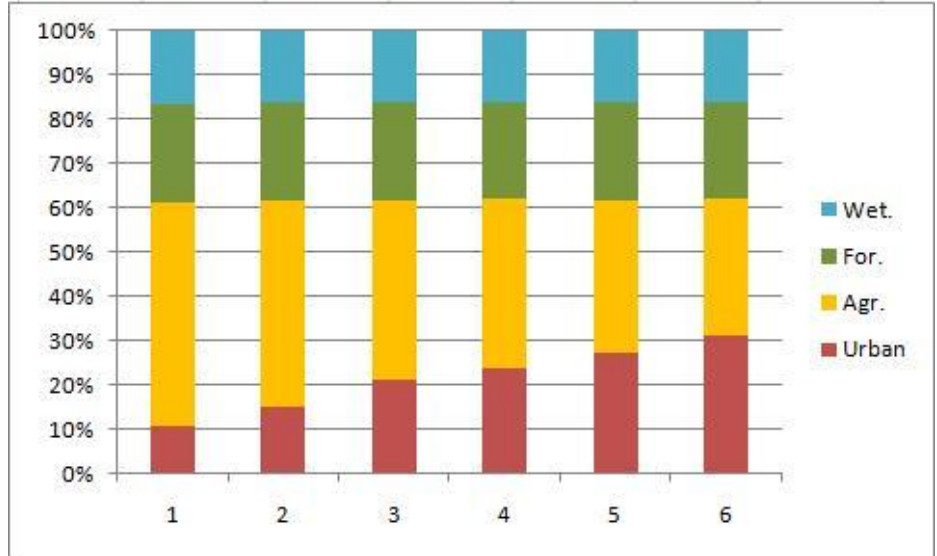


Figure 10(b): Land cover proportions in the Upper Grand River basin. Time 1 is 1938, Time 2 is 1955, Time 3 is 1971, Time 4 is 1982, Time 5 is 1998, Time 6 is 2005

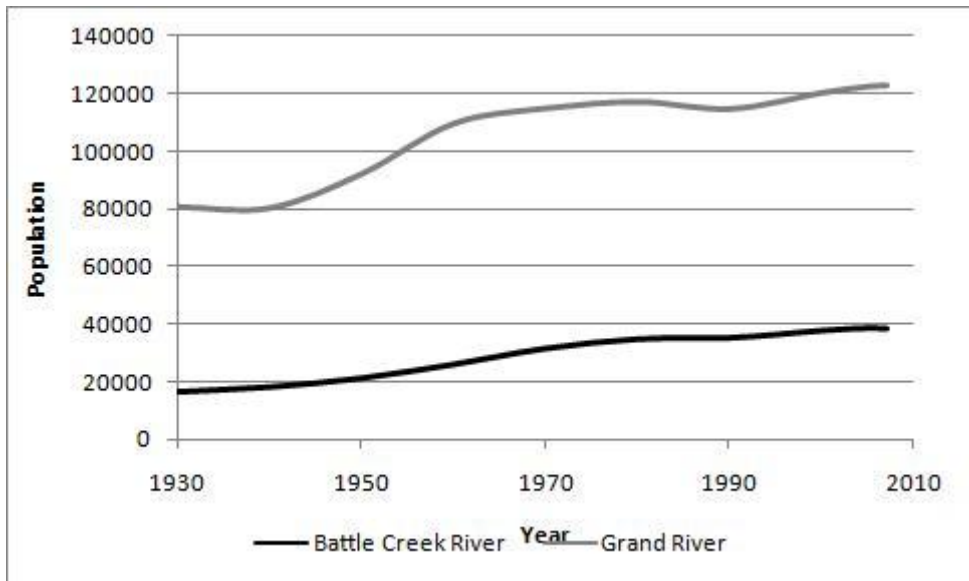


Figure 11: Historical populations for Battle Creek River and Upper Grand River basins (U.S. Census)

Lansing was generally too distant to generate land use change in the watershed until late in the 20th Century, and most development occurred near the outlet. Developed areas, constituted primarily by small agricultural towns and buildings in the 1930s, grew substantially throughout the second half of the 20th Century, most growth resulting from exurban development at the urban fringes of Battle Creek and the development of the town of Charlotte, situated within the watershed, as a bedroom community for workers from nearby Lansing. Growth slowed in the 1990s and early 2000s, and the Battle Creek Watershed remains overwhelmingly agricultural.

Due to increased farmland preservation and a reduction in the overall economic and population growth in the state of Michigan, the population of the Battle Creek River watershed has leveled off and remained largely stable since 1980. Forest cover is significant in the watershed and is more extensive than forest cover in the Upper Grand River watershed. This forest cover, however, is largely non-contiguous, comprised mostly of small woodlots associated with agricultural operations, as well as thin riparian buffers alongside the main branch of the river and larger tributaries. Limited reforestation occurred in the watershed, particularly in the years following World War II. This can be attributed to a number of factors, including abandonment of farmland, increased soil erosion prevention techniques, and planting in county parkland.

6.2.1.1 Upper Grand River

Unlike the Battle Creek River basin, the Upper Grand River basin contains extensive urban development in addition to agriculture. The City of Jackson, of which the majority lies in the Upper Grand River watershed, developed early and was at one time among Michigan's largest

cities. As of the beginning of the study period in 1930, The Upper Grand River watershed was significantly more urbanized than the Battle Creek River watershed, although it is important to note that the urban areas in 1930 were primarily concentrated to the area around the city of Jackson. Agriculture was still the dominant land use at the time. Rapid growth in urban areas is observed throughout the study period, even during times when population growth was minimal. This is attributable largely to urban sprawl, a widespread phenomenon throughout the region. While the city of Jackson grew rapidly early on, by mid-century the population of the city proper began to contract. This phenomenon is most obvious during the 1970s and 1980s, when population growth is zero or negative in the study watersheds, yet the expansion of urban land cover is at a maximum. Further settlement and development occurred in the hilly uplands of the watershed where the preponderance of small lakes drew substantial residential development by people fleeing central Jackson, as well as those commuting to nearby urban centers in Lansing, Ann Arbor, and suburban Detroit. By 2000, urban land use eclipsed agriculture and became the most widespread land use type in the basin.

6.2.2 Environmental Characteristics

6.2.3 Hydrology

The Upper Grand River and Battle Creek River drainage basins are physically similar in many respects including landscape position, size, terrain, and drainage density. Both rivers are tributaries to larger, adjacent river systems, the Grand River and Kalamazoo River, respectively. The Grand and Kalamazoo Rivers both drain into Lake Michigan, and together, drain much of the southern half of Lower Michigan. The two basins comprise 16.6% of the total land area in

the Lake Michigan drainage basin. The study watersheds and their position in the larger watersheds are shown on Figure 12.

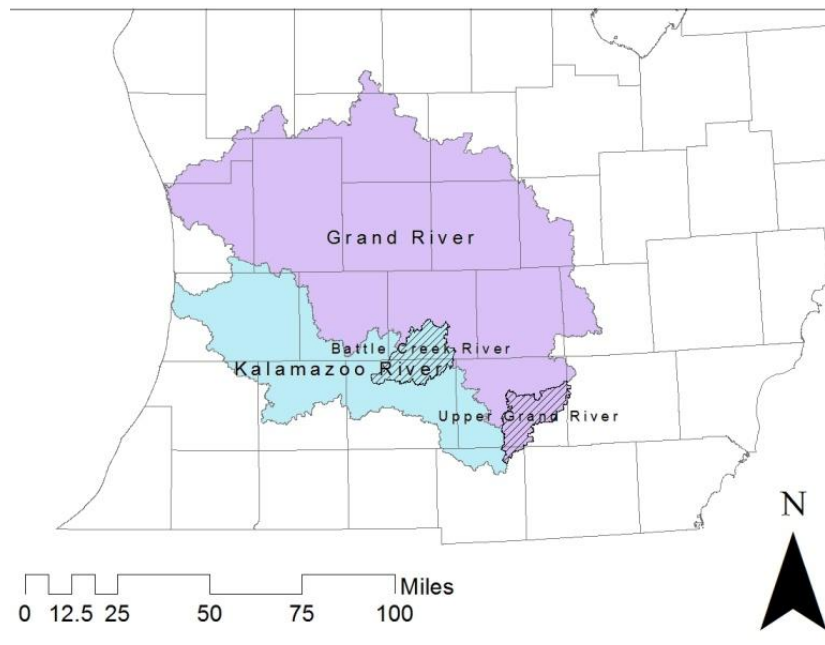


Figure 12: Location of Battle Creek River and Upper Grand River basins within their parent watersheds.

Watershed/Stream	Upper Grand River	Battle Creek River
Drainage Area (km ²)	489.77	709.66
Main Channel Length (km)	33.44	33.00
Min/Max Elevation (m)	273/381	248/304
Mean Slope (%)	0.53	0.45
Mean Base Flow (cms)	121.06	177.37
Discharge as Base Flow (%)	0.74	0.64
Wetland Area (Pre-settlement)	27.30	18.50

Table 6-2: Selected hydrologic characteristics for Battle Creek River and Upper Grand River.

Table 6-2 provides a comparison of selected physical and hydrological attributes. In most cases, deviation between the watersheds is generally minor. The most significant differences are the percent yield from base flow and pre-settlement wetland areas (defined as both open water features and areas with poorly-drained, saturated soils). These hydrologically wet areas are markedly higher in the Upper Grand River where distinct uplands are interspersed with low, poorly drained (excluding human-induced drainage) valleys. The Battle Creek River watershed features more flat, uniform uplands with less variation in slope. This might account partly for the difference in base flow percentage, as poorly-drained areas such as wetlands and connected lakes are found more commonly in the Upper Grand River watershed. Another notable difference between the two systems is the split in the main stem of the Upper Grand River just upstream of the gauge. The Upper Grand River watershed effectively consists of two sub-basins, whereas the Battle Creek watershed drains to a single main stem. Figures 13 through 16 illustrate some of the physical variables considered in this comparison.

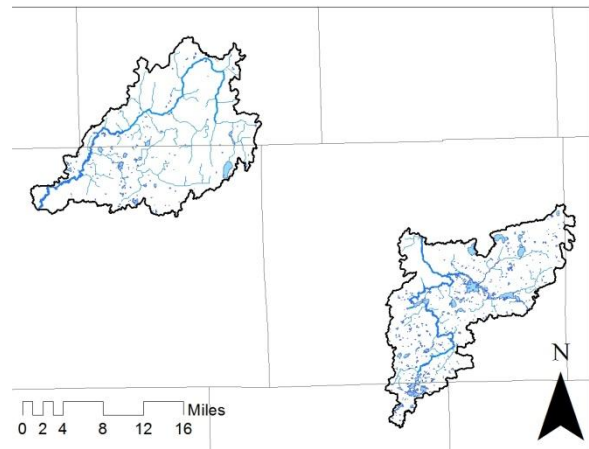


Figure 13: Surface water features in the Battle Creek River and Upper Grand River basins.

6.2.4 Geology

6.2.4.1 Bedrock Geology

The Battle Creek and Upper Grand watersheds are both underlain with late Mississippian through Pennsylvanian age sandstone and limestone. The two basins generally overlie the same bedrock formations, as illustrated on Map 14. Small areas of thin glacial drift and exposed bedrock do occur in the extreme south of the Upper Grand Watershed, but these areas represent only a minute fraction of the overall watershed area. Due to the thickness of glacial drift covering the vast majority of both areas, the bedrock composition is believed to have little impact on the hydrologic regime of either watershed.

6.2.4.2 Quaternary Geology

Both the Upper Grand River and Battle Creek River drainage basins are situated in the interlobate region bounded by the Lake Michigan, Saginaw, and Huron-Erie glacial lobes of the Laurentide Ice Sheet which last intruded the region during the Late Wisconsin, roughly 15,000 C¹⁴ yr B.P. (Sommers, 1984) The watersheds are bounded to the north by the Kalamazoo Moraine, the terminal moraine formed by the Saginaw lobe. As a result, these two watersheds feature greater relief and more morainic, unsorted glacial till than other area watersheds, most of which are characterized by sandy glacial outwash or silty lacustrine sediments. A digital elevation model showing the locations of the bounding glacial lobes, interlobate region, and Kalamazoo moraine is depicted in Figure 14.

The Battle Creek River watershed features a notable landform of Quaternary age. The downstream reach of the stream lies in a valley as much as a mile wide and as much as 200 feet deep. The valley is continuous with the Kalamazoo River Valley downstream from the Battle Creek River outlet, but substantially deeper and wider than the Kalamazoo River Valley upstream (Figure 15). The Battle Creek River is substantially under-fit to this large valley, which is believed to have been the result of catastrophic outburst flood associated with the Saginaw lobe (Kozlowski, 2002). As a result, large areas of wetlands, wide floodplains, and distinct

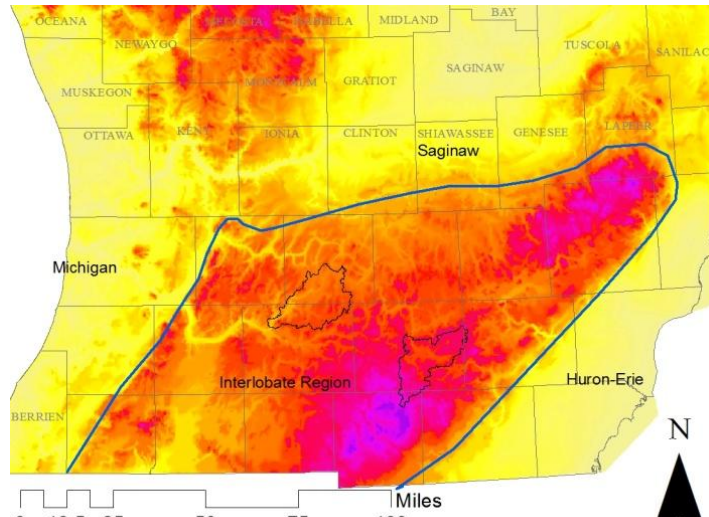


Figure 14: Digital elevation model of Lower Michigan showing the location of the Michigan, Saginaw, and Huron-Erie glacial lobes, the interlobate region, the Kalamazoo Moraine, and outlines of the Battle Creek River and Upper Grand River basins.

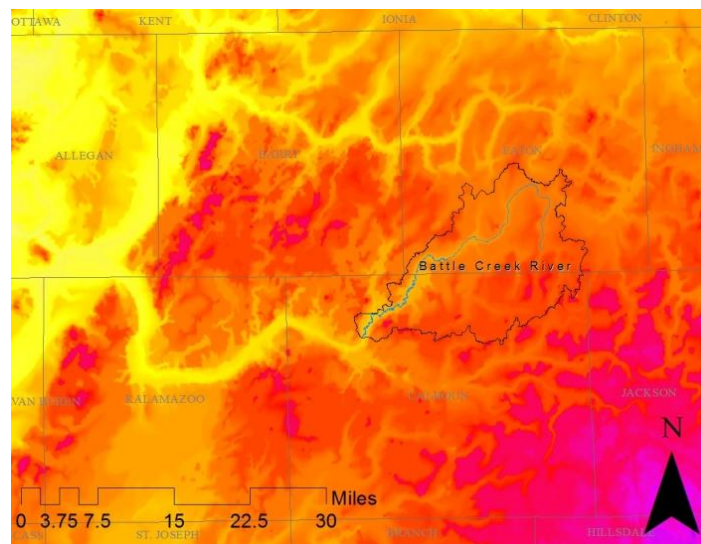


Figure 15: Digital elevation model displaying the excessively large valley carrying the Battle Creek River.

terraces are present on the lower Battle Creek River. These landform anomalies undoubtedly influence movement and storage of high flows on the river.

6.2.5 Soils

Generally, soils in both watersheds are characteristic of glacial till, with sand to loamy sand dominating most of the surface area. These areas tend to be well drained, gently rolling, and densely cultivated. Areas of hydric soils and poorly drained lowlands are present in both watersheds, though generally in smaller areas. The soils data used in this analysis were acquired from the national State Soil Geographic Database (Natural Resources Conservation Service, 1994), a statewide soil survey. The spatial resolution of these datasets is generally coarse – as a result, most wetland areas are not captured. Nonetheless, it can be reasonably assumed that the sand and sandy loam depicted in the watersheds and across most of the interlobate region of Lower Michigan is consistent with the actual upland soils in the region. A map of soil types from the nationwide STATSGO survey, along with an accompanying table of soil characteristics, is shown on Figure 16 and Table 6-3.

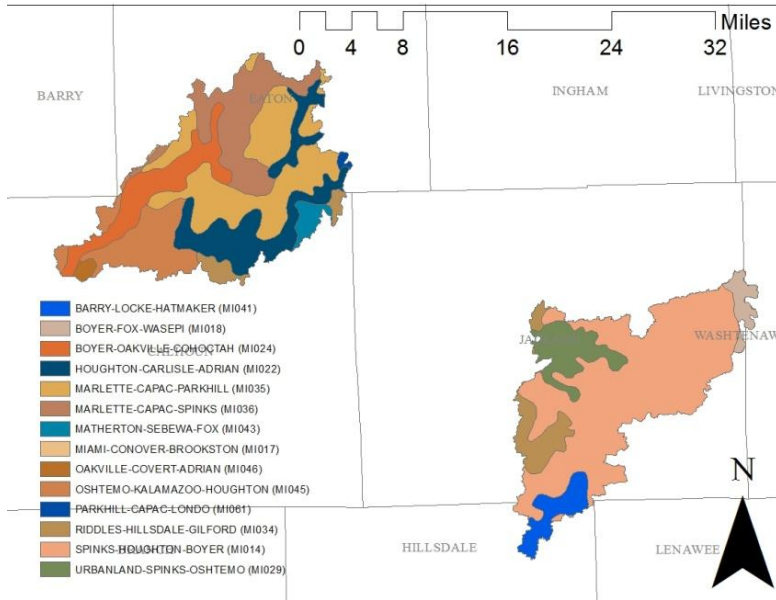


Figure 16: Map displaying the STATSGO soil classifications for the Battle Creek River and Upper Grand River basins. Key to soil names and properties found in Table 6-3.

Soil Type	Slope (%)	Surface Texture	Drainage
Urbanland-Spinks-Oshtemo	0 to 15	Urban to loamy sand	Excessive to poorly drained
Parkhill-Capac-Londo	0 to 1	Loam	Poorly drained, hydric
Barry-Locke-Hatmaker	1 to 4	Fine Sandy Loam	Somewhat poorly drained
Matherton-Sebewa-Fox	0 to 3	Sandy Loam	Somewhat poorly drained
Houghton-Carlisle-Adrian	0 to 1	Muck	Very poorly drained, hydric
Spinks-Houghton-Boyer	0 to 6	Loamy Sand	Well drained
Miami-Conover-Brookston	0 to 2	Loam	Well drained
Boyer-Fox-Wasepi	2 to 6	Silt Loam	Well drained
Boyer-Oakville-Cohoctah	0 to 2	Loamy Sand	Well drained
Riddles-Hillsdale-Gilford	0 to 2	Sandy Loam	Well drained
Marlette-Capac-Parkhill	2 to 6	Loam	Well drained
Marlette-Capac-Spinks	2 to 6	Loam	Well drained
Oshtemo-Kalamazoo-Houghton	0 to 2	Loam	Well drained
Oakville-Covert-Adrian	2 to 12	Fine Sandy Loam	Well drained

Table 6-1: STATSGO soil classifications occurring within the Battle Creek River and Upper Grand River watersheds

6.2.6 Climate

Figure 8 displays absolute change in precipitation and temperature for each month between Period 1 and Period 2 in the sub-region. Temperatures are calculated by an average of NOAA climate stations and Jackson and Battle Creek. These stations are not found to vary significantly in the long term, and their average is assumed to represent the average climatic conditions for both watersheds during the study period.

Temperature rose for every month, with the greatest warming occurring between June and October, when average temperatures rose between 1 and 1.5 degrees Celsius.

Precipitation also increased during the late summer and autumn, with the greatest increase in precipitation (1.4 cm/month) occurring during September. Aside from a large (3.3 cm) drop in June

temperatures, temperature change was generally lowest in late winter and highest in late summer. This climatic regime differs from the statewide averages in that precipitation increases peak during early

fall and are smaller during summer, whereas across the state, summer precipitation was observed to increase more than any other season.

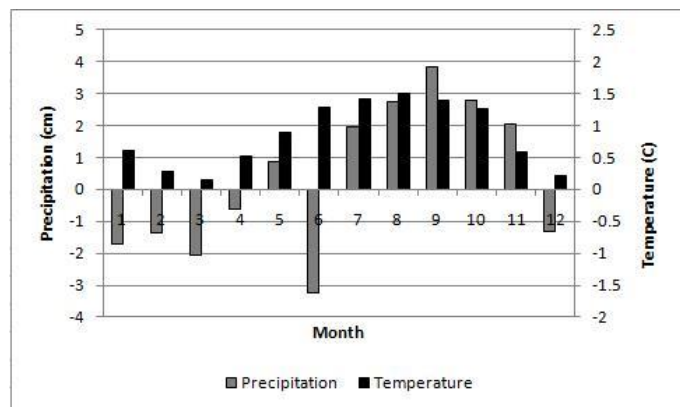


Figure 17: Change in precipitation (cm) and temperature (C) between Period 1 (1935-1979) and Period 2 (1980-2008) for the region containing the Battle Creek River and Upper Grand River, from an average of NOAA climate stations at Battle Creek and Jackson

6.3 Methodology

For this analysis, estimated land cover proportions for two adjacent watersheds, the Battle Creek River and Upper Grand River, were derived using the method described in Chapter 4. As described earlier, these basins are adjacent and share almost identical climate change parameters, but have experienced divergent land uses as shown in Chapter 3. Figures 5 and 6 display the divergent land cover proportions in the two basins over time.

The present analysis is broken up into two parts: (1) a two-period analysis to confirm that the long term streamflow trends observed in the preceding section apply to the Battle Creek River and Upper Grand River, and (2) a more detailed 5 period temporal analysis using estimate land cover change parameters to detect divergence between basin response to fluctuations in climate. The two-period analysis employs the same periods as the preceding analysis (Period 1: 1935-1979, Period 2: 1980-2008). The 5-period analysis employs the following time steps: Period 1: 1935-1954; Period 2: 1955-1972; Period 3: 1973-1982; Period 4: 1983-1998; Period 5: 1999-2005. These periods reflect the availability of aerial imagery, and while the intervals are not exactly equal, they represent time steps of sufficient length to capture measurable land use changes and fluctuations in climate. For the Battle Creek River, 1982 imagery was not available, so land cover data for that year are extrapolated based upon a midpoint between the 1972 and 1998 data.

6.4 Discussion

6.4.1 Two-Period Analysis

Tables 6-3 and 6-4 display the absolute and percent change between Period 1 (1935-1979) and Period 2 (1980-2008) for each streamflow attribute, as well as a p value for a two-tailed difference of means test. Table 6-5 displays change in recurrence interval between Period 1 and Period 2, and Figure 9 shows the change in magnitudes of floods at different recurrence intervals for the Battle Creek River and Upper Grand River.

<u>Battle Creek River</u>		1935-1979	1980-2000	Abs. Dif.	% Dif.	p
Winter	<i>Qmax</i>	33.06	33.53	0.47	1.43	0.91
	<i>Qmin</i>	2.89	3.58	0.68	23.62	0.01
	<i>Qtot</i>	8.35	9.17	0.83	9.91	0.32
Spring	<i>Qmax</i>	29.68	27.23	-2.45	-8.26	0.57
	<i>Qmin</i>	2.58	2.64	0.06	2.32	0.79
	<i>Qtot</i>	8.00	7.90	-0.10	-1.26	0.88
Summer	<i>Qmax</i>	6.85	8.91	2.06	30.14	0.22
	<i>Qmin</i>	1.43	1.64	0.21	14.42	0.07
	<i>Qtot</i>	2.57	3.08	0.51	19.64	0.10
Fall	<i>Qmax</i>	12.03	17.40	5.38	44.70	0.05
	<i>Qmin</i>	1.93	2.26	0.33	17.25	0.06
	<i>Qtot</i>	4.12	5.81	1.69	40.97	0.00
Annual	<i>Qmax</i>	40.07	39.94	-0.13	-0.33	0.97
	<i>Qmin</i>	1.43	1.63	0.20	14.12	0.07
	<i>Qtot</i>	5.74	6.47	0.73	12.73	0.07

Table 6-3: Period streamflow averages for Battle Creek River including absolute (cms) and proportional change between study periods. P-value based on two-tailed difference of means t-test. Data are from USGS gages #04105000 (Battle Creek River at Battle Creek) and #04109000 (Grand River at Jackson)

<u>Upper Grand River</u>		1935-1979	1980-2000	Abs. Dif.	% Dif.	p
Winter	<i>Qmax</i>	11.40	10.27	-1.14	-9.96	0.79
	<i>Qmin</i>	1.58	2.38	0.80	50.98	0.00
	<i>Qtot</i>	4.59	5.23	0.64	13.87	0.00
Spring	<i>Qmax</i>	11.49	10.17	-1.32	-11.50	0.09
	<i>Qmin</i>	1.50	1.88	0.38	25.21	0.13
	<i>Qtot</i>	4.79	4.99	0.19	4.01	6.84E-05
Summer	<i>Qmax</i>	4.98	5.74	0.75	15.15	1.28E-05
	<i>Qmin</i>	0.82	1.26	0.44	54.22	0.78
	<i>Qtot</i>	1.83	2.47	0.65	35.43	0.86
Fall	<i>Qmax</i>	5.91	7.29	1.38	23.34	1.12E-05
	<i>Qmin</i>	1.01	1.67	0.67	66.52	0.00
	<i>Qtot</i>	2.47	3.68	1.21	48.91	0.06
Annual	<i>Qmax</i>	13.28	11.90	-1.37	-10.35	0.22
	<i>Qmin</i>	0.80	1.24	0.44	55.39	4.88E-06
	<i>Qtot</i>	3.41	4.08	0.67	19.70	0.00

Table 6-4: Period streamflow averages for Upper Grand River including absolute (cms) and proportional change between study periods. P-value based on two-tailed difference of means t-test. Data are from USGS gages #04105000 (Battle Creek River at Battle Creek) and #04109000 (Grand River at Jackson)

Battle Creek River				Upper Grand River			
RI (years)	Period 1	Period 2	% Change	RI (years)	Period 1	Period 2	% Change
500	145.01	115.81	-20.13	500	38.31	28.60	-25.35
200	124.82	103.52	-17.06	200	35.22	26.94	-23.51
100	110.40	94.32	-14.57	100	32.87	25.65	-21.96
50	96.67	85.17	-11.89	50	30.46	24.32	-20.15
25	83.50	76.00	-8.99	25	28.02	22.93	-18.15
10	66.74	63.62	-4.67	10	24.63	20.96	-14.92
5	54.25	53.80	-0.84	5	21.84	19.26	-11.80
2	36.78	38.93	5.85	2	17.39	16.44	-5.47
1.5	30.27	32.93	8.79	1.5	15.48	15.17	-2.05
1	17.74	20.41	15.05	1	11.21	12.14	8.31

Table 6-5: Magnitude (cms) of floods for selected recurrence intervals, calculated for Period 1 (1935-1979) and Period 2 (1980-2008), and proportional change between periods. Data are from USGS gages #04105000 (Battle Creek River at Battle Creek) and #04109000 (Grand River at Jackson)

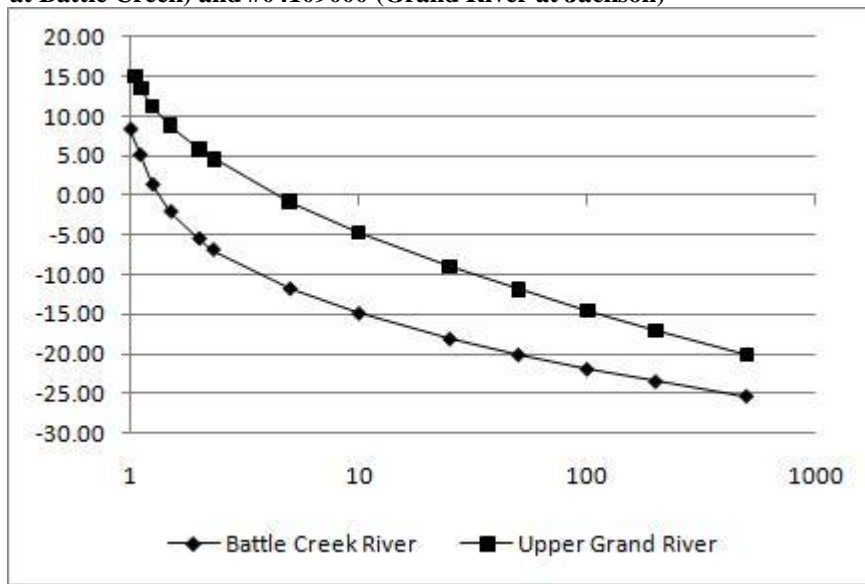


Figure 18: Proportional change in magnitude for floods by recurrence interval.

6.4.1.1 Q_{\max}

The high increase observed in fall precipitation (Figure 8) appears to be reflected in the streamflow data, as all seasonal streamflow attributes were found to rise in the fall. Consistent with the findings of the region-wide data, annual Q_{\max} was not found to change significantly in either watershed, while Q_{\min} and Q_{tot} both rose. Q_{\max} was only found to rise significantly in the fall, in response to the very large increases in precipitation during that season.

While annual average Q_{\max} declined slightly in both the Battle Creek River and Upper Grand River between study periods, a more detailed breakdown of annual peak flows is provided in Table 6-5 and Figure 18, which display change in floods of various recurrence intervals between Period 1 and Period 2. Figure 18 reveals that the negative trend in Q_{\max} is driven by declines in very large floods with recurrence intervals of greater than one year. In the Battle Creek River, only floods with a recurrence interval of greater than 5 years declined, while floods with higher recurrence frequency increased, with 1-year floods increasing in magnitude by about 15%. For the Upper Grand River, only floods with a recurrence interval of less than two years were found to increase, and floods of nearly every magnitude either grew by a smaller proportion, or declined by a greater proportion than floods of the same recurrence interval in the Battle Creek River. This finding is interesting because it seems to contradict the finding by Knox (1993) that increases in precipitation correlate with increases in the frequency of large floods during the Late Holocene prior to Euro-American land use influence. These data show that large floods have become less frequent between Period 1 and Period 2 despite a 4.2 cm increase in mean annual precipitation. The decline is greater in the Upper Grand River basin,

which is due to its more rapid urbanization and greater proportion of urban land cover.

Ordinarily, an increase in large floods might be expected in the urban environment based on the findings of Leopold (1971) and because of impervious land cover.

The explanation for this apparent anomaly may lie with snowmelt. A change in the magnitude of floods with a long recurrence interval is unlikely to be related to land cover, as large storms generating the needed rainfall to produce very large floods would induce rapid soil saturation and tremendous overland flow regardless of the land cover (Hollis, 1975). As such, any change in the magnitude of large floods can be expected

to be a function of climate. Figure 19 displays the annual distribution of peak annual floods for both study periods and basins, and indicates that peak floods most commonly occur in the spring, when rain-

on-snow events or rain on soils that are saturated from melted snow commonly trigger large floods. A change in snowpack persistence or buildup is likely to affect this behavior, and a reduction in snowpack would likely reduce the magnitude of spring floods. While the data do not indicate a significant change in the quantity of snowfall for either watershed, this does not preclude snowpack as an explanation. Increased winter temperatures were observed for both

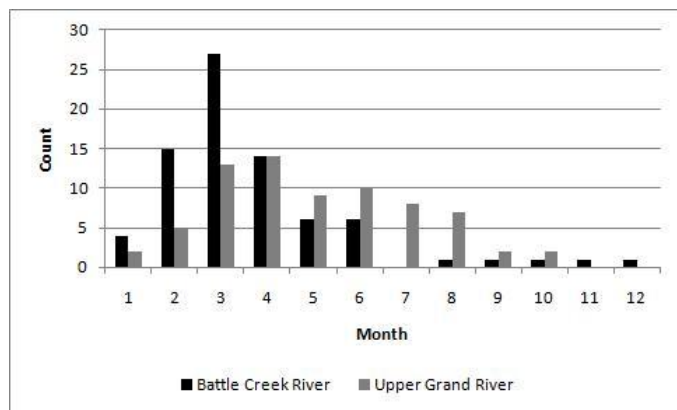


Figure 19: Number of annual peak floods occurring during each month of the year for the study period (1935-2008) in the Battle Creek River and the Upper Grand River. Data from USGS gages #04104000 (Battle Creek River at Battle Creek) and #04109000 (Grand River at Jackson)

basins, and this increase could reduce overall accumulation of snowpack during the winter and reduce the depth of soil freezing, both of which would reduce the magnitude of snowmelt floods. Another explanation for the trend in the data is an absence of relatively large (RI > 20 years) floods during Period 2, which may be the result of chance.

6.4.1.2 Q_{\min}

Q_{\min} rose more than average and high flows, with an upward trend observed in every season for the Upper Grand River and for every season except spring in the Battle Creek River, likely a function of changing snowmelt as described in the previous section. The rises for the Upper Grand River are greater than those for the Battle Creek River by a factor of 2 to 4. The 20-basin analysis conducted in the previous section affirmed the findings of Foster, et al. (1999), DeWalle, et al. (2000), and other studies that report higher streamflow rises in response to increases in precipitation in more urbanized basins. This appears to hold true for the Upper Grand River and Battle Creek Rivers, as streamflows in the more urbanized Upper Grand River basin are observed to rise substantially more than those in the Battle Creek River basin despite climatic similarity.

6.4.1.3 Q_{tot}

Q_{tot} rose significantly in the fall and annually for both the Battle Creek River and Upper Grand River, and in the summer in the Upper Grand River. Q_{tot} did not significantly change in either basin during winter or spring despite a drop in average precipitation of 2.38 cm in winter and a drop of 3.35 cm in spring.

6.4.2 5-Period Analysis

Tables 6-6 through 6-8 provide the data used in this analysis. Table 6-6 provides changes in monthly precipitation averages for each period of the analysis. Tables 6-7 and 6-8 provide daily averages for annual and seasonal streamflow attributes, while Tables 6-9 through 6-12 provide % and absolute changes for each attribute between periods.

Precipitation	Period 1	Period 2	Period 3	Period 4	Period 5
Winter	9.95	9.36	8.22	7.90	5.97
Spring	15.08	12.01	14.61	11.47	13.19
Summer	11.28	11.41	14.08	13.98	12.40
Fall	9.93	10.14	10.04	11.83	10.5
Annual	11.56	10.73	11.74	11.29	10.52

Table 6-6: Monthly precipitation averages for the study region containing the Battle Creek River and Upper Grand River basins.

Battle Creek River			Period 1	Period 2	Period 3	Period 4	Period 5
Period Means							
Winter	Qmax		38.44	25.70	40.22	32.50	31.79
	Qmin		3.03	2.49	3.42	3.71	3.49
	Qtot		9.11	6.72	10.04	9.47	8.80
Spring	Qmax		34.42	23.08	30.63	25.29	33.50
	Qmin		2.99	2.12	2.78	2.64	2.56
	Qtot		8.74	6.69	9.07	7.78	8.06
Summer	Qmax		7.63	5.47	8.88	10.28	6.00
	Qmin		1.53	1.27	1.70	1.68	1.42
	Qtot		2.78	2.20	3.30	3.22	2.48
Fall	Qmax		13.14	10.54	13.71	21.77	10.03
	Qmin		2.07	1.62	2.44	2.43	1.75
	Qtot		4.33	3.80	4.68	6.70	4.32
Annual	Qmax		46.39	30.66	47.22	37.90	42.48
	Qmin		1.53	1.26	1.69	1.68	1.41
	Qtot		6.22	4.84	6.75	6.78	5.89

Table 6-7: Streamflow averages for the Battle Creek River in cubic meters per second. Period 1: 1935-1954; Period 2: 1955-1972; Period 3: 1973-1982; Period 4: 1983-1998; Period 5: 1999-2005.

Upper Grand River		Period 1	Period 2	Period 3	Period 4	Period 5
Period Means						
Winter	Qmax	12.42	9.62	13.16	10.05	9.88
	Qmin	1.79	1.29	1.74	2.54	2.35
	Qtot	4.91	3.77	5.53	5.35	5.20
Spring	Qmax	13.31	9.79	11.42	9.92	10.15
	Qmin	1.64	1.32	1.78	1.85	1.85
	Qtot	5.42	4.02	5.45	4.91	4.76
Summer	Qmax	4.29	5.06	6.41	5.97	5.05
	Qmin	0.87	0.74	0.97	1.32	1.18
	Qtot	1.67	1.79	2.53	2.52	2.10
Fall	Qmax	6.04	5.54	6.86	7.85	6.05
	Qmin	1.03	0.90	1.30	1.80	1.44
	Qtot	2.38	2.40	3.15	4.05	2.93
Annual	Qmax	14.81	11.50	13.64	11.91	11.59
	Qmin	0.83	0.72	0.97	1.30	1.14
	Qtot	3.58	2.99	4.16	4.20	3.74

Table 6-8: Streamflow averages for the Upper Grand River in cubic meters per second. Period 1: 1935-1954; Period 2: 1955-1972; Period 3: 1973-1982; Period 4: 1983-1998; Period 5: 1999-2005

% Change		1 to 2	2 to 3	3 to 4	4 to 5
Annual	Qmax	-22.33	18.58	-12.68	-2.73
Fall	Qmax	-8.26	23.88	14.37	-22.87
Spring	Qmax	-26.41	16.64	-13.11	2.30
Summer	Qmax	17.90	26.51	-6.83	-15.43
Winter	Qmax	-22.55	36.79	-23.59	-1.69
Annual	Qmin	-12.53	33.06	33.91	-11.82
Fall	Qmin	-12.51	43.56	38.39	-20.06
Spring	Qmin	-19.60	34.62	3.86	0.25
Summer	Qmin	-14.58	30.52	36.05	-10.53
Winter	Qmin	-27.96	34.50	46.01	-7.43
Annual	Qtot	-16.58	39.05	1.07	-11.03
Fall	Qtot	0.83	31.53	28.37	-27.67
Spring	Qtot	-25.75	35.41	-9.83	-2.95
Summer	Qtot	7.18	41.30	-0.31	-16.96
Winter	Qtot	-23.21	46.68	-3.30	-2.72

Table 6-9: Proportional change in streamflow attributes for the Battle Creek River between periods (Period 1: 1935-1954; Period 2: 1955-1972; Period 3: 1973-1982; Period 4: 1983-1998; Period 5: 1999-2005).

% Change		1 to 2	2 to 3	3 to 4	4 to 5
Annual	<i>Qmax</i>	-33.90	53.98	-19.72	12.07
Fall	<i>Qmax</i>	-19.78	30.06	58.69	-53.89
Spring	<i>Qmax</i>	-32.94	32.68	-17.43	32.46
Summer	<i>Qmax</i>	-28.22	62.16	15.77	-41.63
Winter	<i>Qmax</i>	-33.14	56.52	-19.20	-2.15
Annual	<i>Qmin</i>	-17.27	34.16	-0.77	-16.22
Fall	<i>Qmin</i>	-21.28	50.28	-0.57	-28.05
Spring	<i>Qmin</i>	-29.00	30.93	-4.75	-3.10
Summer	<i>Qmin</i>	-16.96	34.33	-1.27	-15.59
Winter	<i>Qmin</i>	-17.98	37.70	8.45	-6.15
Annual	<i>Qtot</i>	-22.17	39.46	0.46	-13.07
Fall	<i>Qtot</i>	-12.28	23.11	43.31	-35.58
Spring	<i>Qtot</i>	-23.43	35.61	-14.16	3.57
Summer	<i>Qtot</i>	-20.73	49.87	-2.41	-23.09
Winter	<i>Qtot</i>	-26.17	49.27	-5.59	-7.07

Table 6-10: Proportional change in streamflow attributes for the Battle Creek River between periods (Period 1: 1935-1954; Period 2: 1955-1972; Period 3: 1973-1982; Period 4: 1983-1998; Period 5: 1999-2005).

Absolute Change		1 to 2	2 to 3	3 to 4	4 to 5
Annual	<i>Qmax</i>	-15.72	16.55	-9.31	4.57
Fall	<i>Qmax</i>	-2.60	3.17	8.05	-11.73
Spring	<i>Qmax</i>	-11.34	7.54	-5.33	8.21
Summer	<i>Qmax</i>	-2.15	3.40	1.40	-4.28
Winter	<i>Qmax</i>	-12.74	14.52	-7.72	-0.70
Annual	<i>Qmin</i>	-0.26	0.43	-0.01	-0.27
Fall	<i>Qmin</i>	-0.44	0.81	-0.01	-0.68
Spring	<i>Qmin</i>	-0.86	0.65	-0.13	-0.08
Summer	<i>Qmin</i>	-0.25	0.43	-0.02	-0.26
Winter	<i>Qmin</i>	-0.54	0.93	0.28	-0.22
Annual	<i>Qtot</i>	-1.37	1.91	0.03	-0.88
Fall	<i>Qtot</i>	-0.53	0.87	2.02	-2.38
Spring	<i>Qtot</i>	-2.04	2.38	-1.28	0.27
Summer	<i>Qtot</i>	-0.57	1.09	-0.07	-0.74
Winter	<i>Qtot</i>	-2.38	3.31	-0.56	-0.67

Table 6-11: Absolute change (cms) in streamflow attributes for the Upper Grand River between periods (Period 1: 1935-1954; Period 2: 1955-1972; Period 3: 1973-1982; Period 4: 1983-1998; Period 5: 1999-2005).

Absolute Change		1 to 2	2 to 3	3 to 4	4 to 5
Annual	<i>Qmax</i>	-3.31	2.13	-1.73	-0.32
Fall	<i>Qmax</i>	-0.49	1.32	0.98	-1.79
Spring	<i>Qmax</i>	-3.51	1.63	-1.49	0.22
Summer	<i>Qmax</i>	0.76	1.34	-0.43	-0.92
Winter	<i>Qmax</i>	-2.80	3.54	-3.10	-0.17
Annual	<i>Qmin</i>	-0.10	0.24	0.32	-0.15
Fall	<i>Qmin</i>	-0.13	0.39	0.50	-0.36
Spring	<i>Qmin</i>	-0.32	0.45	0.06	0.00
Summer	<i>Qmin</i>	-0.12	0.22	0.35	-0.13
Winter	<i>Qmin</i>	-0.50	0.44	0.80	-0.18
Annual	<i>Qtot</i>	-0.59	1.16	0.04	-0.46
Fall	<i>Qtot</i>	0.01	0.75	0.89	-1.12
Spring	<i>Qtot</i>	-1.39	1.42	-0.53	-0.14
Summer	<i>Qtot</i>	0.12	0.74	-0.00	-0.42
Winter	<i>Qtot</i>	-1.14	1.76	-0.18	-0.14

Table 6-12: Absolute change (cms) in streamflow attributes for the Upper Grand River between periods

(Period 1: 1935-1954; Period 2: 1955-1972; Period 3: 1973-1982; Period 4: 1983-1998; Period 5: 1999-2005).

6.4.2.1 Q_{\max}

Figures 10-14 displays percent change in Q_{\max} at annual and seasonal timescales between study periods. Tabular data and absolute values are available in Table A3 in the appendix.

6.4.2.1.1 Annual and winter

The data for periodic change in annual Q_{\max} are very closely related to the data for change in winter and spring Q_{\max} . This is consistent with the hypothesis that changes to high flows during those seasons are dominating observed changes in annual Q_{\max} due to the importance of snowmelt-related events such as rain on snow or rain on soil saturated with melted snow. Change in precipitation totals between periods determines the direction of change in Q_{\max} for the annual timescale and for every season except winter. The relationship between precipitation change and change in Q_{\max} is the strongest in spring, which suggests that rain on snow or saturated soils causes most Q_{\max} events in that season.

In particular, strong similarities are observed between winter and annual Q_{\max} . At both timescales, Q_{\max} is observed to change at a proportion that is greater than the proportional change in precipitation by a factor of 2 to 10. Additionally, both were observed to gradually change less between periods later in the study period. For example, annual Q_{\max} fell 33.90% in the Battle Creek River between Period 1 and Period 2 in response to a 7.16% decline in annual precipitation, while it rose 12.08% between Period 4 and Period 5 in despite a 6.89% decline in precipitation between those periods. Responses in the Upper Grand River for the same periods were declines of 22.34% and 2.73%, respectively. A similar trend is observed in winter peaks.

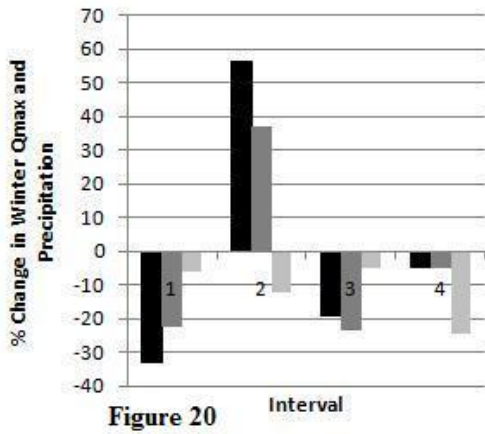


Figure 20

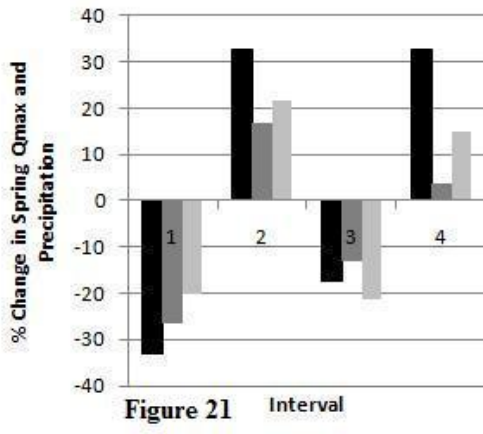


Figure 21

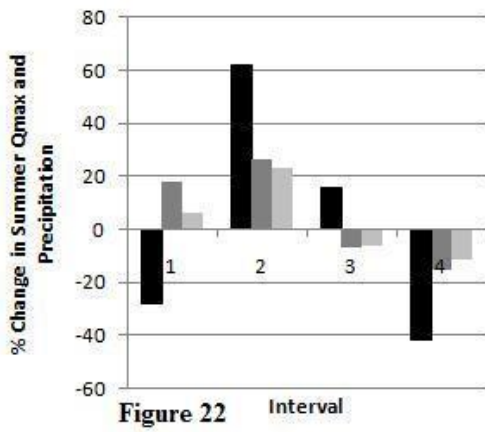


Figure 22

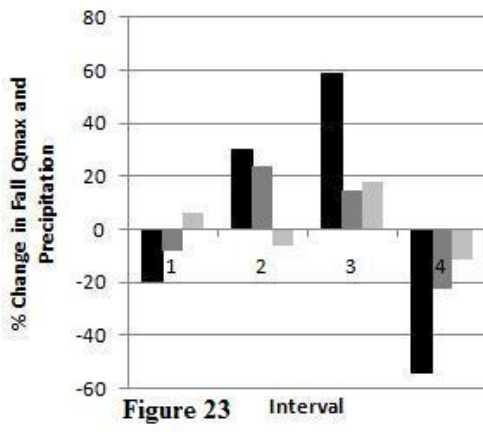
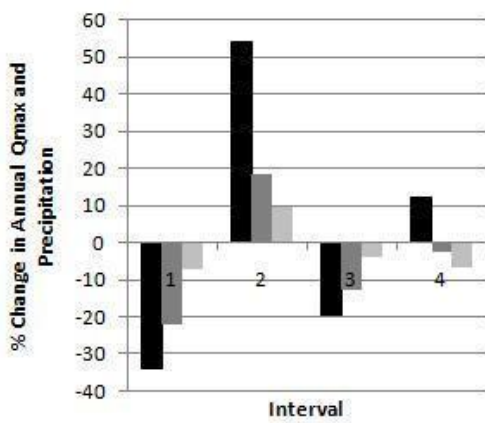


Figure 23



Interval

- Battle Creek River
- Upper Grand River
- Precipitation

Figures (20-24): % change in seasonal and annual Qmax for period intervals 1 (1935-1954 to 1955-1972), 2 (1955-1972 to 1973-1982), 3 (1973-1982 to 1983-1998), and 4 (1983-1998 to 1999-2005). Data acquired from USGS gages #04105000 (Battle Creek River at Battle Creek) and #4109000 (Grand River at Jackson)

Here, between Period 1 and Period 2, winter Q_{\max} dropped 33.15% for the Battle Creek River and 22.34% for the Upper Grand River in response to a decline in seasonal precipitation of 5.91%. Between Period 4 and Period 5, negligible Q_{\max} declines were observed for both the Battle Creek River (-2.15%) and Upper Grand River (-1.69%) despite a precipitation decline of 24.38%. A notable anomaly in this trend is a substantial increase (56.52% for the Battle Creek River and 36.80% for the Upper Grand River) in winter Q_{\max} between Period 2 and Period 3, despite a decline of 12.16% in winter precipitation during this interval. This anomaly exists in the Q_{\min} and Q_{tot} record as well, and suggests that the volume of winter precipitation is not the dominant factor in predicting changes in winter streamflow. Annual precipitation increased 9.36% during this interval, meaning that wetter year-round conditions may increase soil wetness and groundwater recharge, raising streamflows during winter. It is also likely that such anomalous winter changes in streamflow are a result of specific climatic conditions that influence snowmelt dynamics.

Proportional changes in annual and winter Q_{\max} between study periods were, without exception, greater in the Battle Creek River than the Upper Grand River. Because this trend exists even in the composite early part of the study period, when urban and agricultural land cover are comparable in both basins, it is unlikely that human land cover activities explain, or are significantly affecting, the differential response of the rivers to changes in precipitation. One possible explanation for the observed pattern is the greater proportion of wetlands and open water in the Upper Grand River watershed, which is mostly static through the study period.

Wetlands temper the delivery of overland flow to stream channels and blunt magnitudes of small and moderate floods while increasing baseflow, especially in winter (Demissie, et al., 1993).

These findings for the 5-period analysis confirm the analyses in Chapter 5, which also found no statistically significant relationship between winter Q_{\max} and either climate or land use. The Chapter 5 analysis did reveal a significant positive relationship between forest land cover and annual Q_{\max} , which was hypothesized to be a result of the physiological and/or climatic conditions in Lower Michigan's forested watersheds rather than the forest land cover itself. Because forest cover is not substantially different between the basins (22.00% in the Upper Grand River and 28.60% in the Battle Creek River in 2008), between period differences in winter Q_{\max} in this analysis lack the power to confirm or reject the climatic hypothesis. A possible physiological explanation for the modest changes in Q_{\max} in the Upper Grand River is the higher proportion of open water in the form of lakes and ponds there, which may serve as natural retention basins and absorb some of the change in precipitation. This hypothesis is supported by the finding of a strong negative relationship between winter Q_{\max} and wetlands and open water in the multiple-regression analysis in Chapter 5. Wetlands, lakes, and ponds can intercept overland flow and reduce the magnitude of floods.

6.4.2.1.2 Seasonal

Proportional changes in spring Q_{\max} are generally similar to proportional changes in precipitation. This is in contrast to winter, when streamflow changes were generally out of proportion to changes in precipitation by a factor of 2 to 10. Additionally, change in spring Q_{\max} relative to change in precipitation changes over time, and between watersheds. Between Period

1 and Period 2, spring Q_{\max} in both the Battle Creek River and Upper Grand River decline by 32.95% and 26.42%, respectively, in response to a change in spring precipitation of 20.37%. Between subsequent periods, however, change in spring Q_{\max} in the Upper Grand River becomes smaller relative to changes in precipitation, while change in spring Q_{\max} in the Battle Creek River becomes larger: between Period 4 and 5, spring Q_{\max} in the Battle Creek River rose 32.47% in response to a 15.04% rise in precipitation, compared to just 2.30% in the Upper Grand River.

The finding that proportional change in spring Q_{\max} becomes progressively smaller in the more urbanized Upper Grand River than in the Battle Creek River confirms the finding in Chapter 5 that urban land use has a significant negative relationship toward muting the magnitude of change in spring Q_{\max} . This finding was dismissed as an anomaly in the previous analysis because the negative correlation appeared to be a result of a pair of outliers in the data. Furthermore, there seems to be no reference in the literature that indicates magnitudes of spring flood decline in urbanized basins relative to rural basins.

Summer and fall Q_{\max} , like annual Q_{\max} , tend to change by a large proportion relative to changes in precipitation. Changes in streamflows in the Battle Creek River tend to be significantly larger than changes in streamflows in the Upper Grand River; this relationship, however, does not appear to appreciably change over time. Therefore, changes in land cover are unlikely to be significantly affecting changes in summer and fall Q_{\max} . The high proportional changes relative to precipitation suggests that climate is the dominant control on peak flows during the summer and fall months. This finding agrees with the findings of the Chapter 5 analysis, which found no significant relationships between changes in summer and fall Q_{\max} and

any land cover class, but found a significant relationship between changes in summer and fall Q_{\max} and changes in precipitation.

6.4.2.2 Q_{\min}

Figures 15-19 display inter-period changes in low flows. Tabular data and absolute changes are available in the appendix. When examining Q_{\min} , it is important to note that because of the smaller streamflows being measured, measurement error is larger relative to the data. Therefore, only larger changes are considered significant in this section.

6.4.2.2.1 Annual

Change in annual Q_{\min} closely mirrors change in annual precipitation. Large proportionate increases in streamflow response to annual precipitation occur in both the Upper Grand River and the Battle Creek River between Period 2 and Period 4, and equally declining during the initial and final study periods in response to declines in precipitation. The stark difference in basin response to changes in precipitation between Period 3 and Period 4 is likely attributable to land use.

Between Period 2 and Period 3, a large rise of 34.16% for the Battle Creek River and 33.06% for the Upper Grand River was observed in annual Q_{\min} in response to a 9.36% rise in precipitation. Between Period 3 and Period 4, a large rise of 33.06% occurred for the Upper Grand River, while streamflow in the Battle Creek River declined by a statistically insignificant 0.78% in response to a 3.77% decline in precipitation. Because long-term climatic factors are

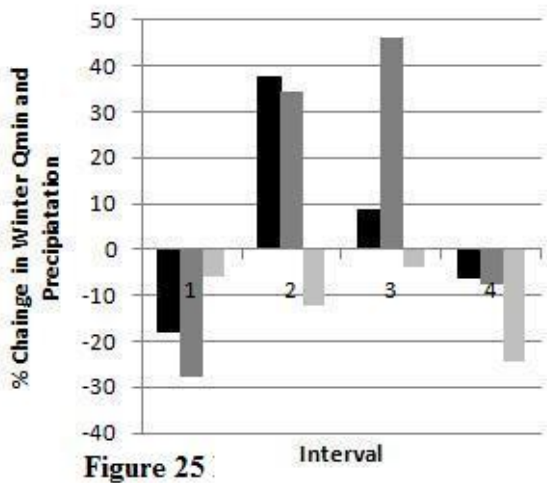


Figure 25

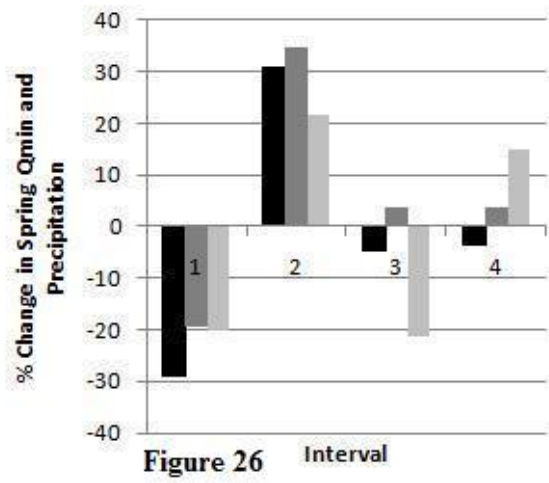


Figure 26

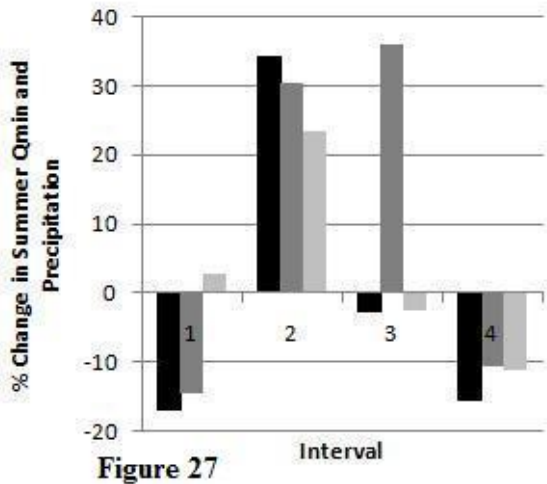


Figure 27

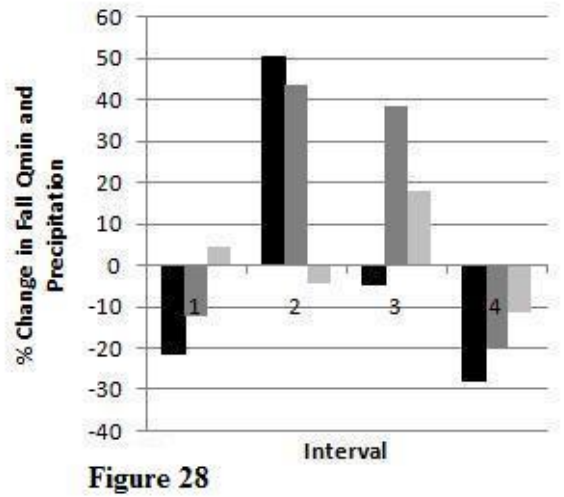


Figure 28

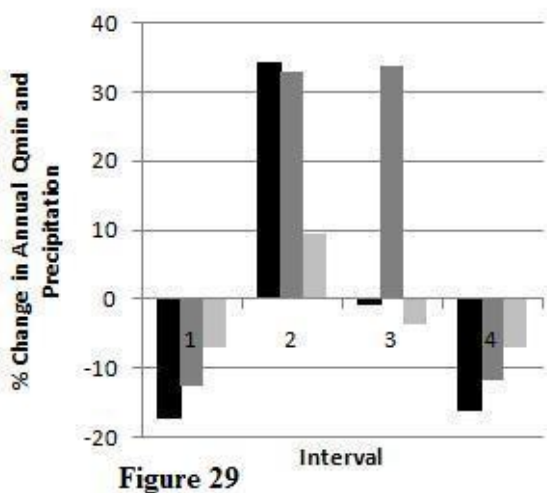


Figure 29

■ Battle Creek River
 ■ Upper Grand River
 ■ Precipitation

Figures (25-29): % change in seasonal and annual Qmin for periodic intervals 1 (1935-1954 to 1955-1972), 2 (1955-1972 to 1973-1982), 3 (1973-1982 to 1983-1998), and for (1983-1998 to 1999-2005). Data acquired from USGS gages #04105000 (Battle Creek River at Battle Creek) and #04109000 (Grand River at Jackson)

similar for both basins, this differential response is likely a result of anthropogenic activity in the basins.

In Periods 3 and 4 (1973-1998), the proportion of urban land use in the Upper Grand River became more than double the proportion of urban land use in the Battle Creek River. Most of the urban area in the Upper Grand River, however, was associated with the City of Jackson. Developed land in the Battle Creek River basin consists primarily of small rural hamlets, farmhouses, and other isolated clusters of development. Therefore, urban density and associated effects on hydrology such as stormwater drainage, wastewater outflows, and residential irrigation is likely much higher in the Upper Grand River basin. Furthermore, much of the suburban development surrounding Jackson during this period likely is not yet connected to sewer systems, and septic systems probably are widespread at the time. Septic systems deliver wastewater directly into the groundwater, which in turn constitutes the bulk of the flow into the Upper Grand River during baseflow conditions. It is very likely that this high urban density contributed to the rising baseflows in the Upper Grand River basin during this interval, an explanation consistent with the findings of Foster, et al. (1999)

Interestingly, response of both the Battle Creek River and Upper Grand River to a change in precipitation is almost identical in the first interval (Period 1 to Period 2) and fourth interval (Period 4 to Period 5) in this study: for the first interval, annual Q_{\min} fell 17.27% in the Battle Creek River and 12.53% in the Upper Grand River in response to reduced precipitation of 7.16%. During the fourth interval, annual Q_{\min} fell 16.22% in the Battle Creek River and 11.82% in the Upper Grand River in response to a reduction in precipitation of 6.90%. It is unclear

exactly why streamflow response returned to initial conditions after drastic differences were exhibited between intermediate periods. Connection of residential neighborhoods to sewers would reduce groundwater recharge and divert flow directly to the stream channel, most likely downstream of the gage. These results are consistent with the results of the analysis in Chapter 5, which found statistically significant relationships between annual Q_{\min} and both precipitation and urban land cover.

6.4.2.2.2 Seasonal

Seasonal trends in Q_{\min} do not depart significantly from the trends identified in annual Q_{\min} . Because groundwater is a major component of low flows, there is considerable seasonal lag between precipitation and streamflow. Consequently, differences between seasonal responses of minimum streamflow are not as large as with other streamflow characteristics. As an example, between Period 2 and Period 3, fall Q_{\min} was observed to increase markedly in both the Battle Creek River (62.17%) and Upper Grand River (26.52%) despite a decline in fall precipitation of 0.98%. These flow increases appear to be in response to a 23.33% increase in summer precipitation.

One interesting seasonal anomaly is that the distinct rise in annual Q_{\min} in the Upper Grand River observed between Period 3 and Period 4 is mirrored for every season except for spring. This appears to be the product of a large (21.48%) decline in spring precipitation, indicating that the seasonal lag described earlier may be reduced during spring.

6.4.2.3 Q_{tot}

Figures 20-24 display change in Q_{tot} between study periods. Tabular and absolute data are available in Table A4 in the appendix.

6.4.2.3.1 Annual

Annual Q_{tot} , or mean annual streamflow, was found in the Chapter 5 analysis to be the only streamflow attribute significantly associated with both agricultural and urban land uses, and is therefore a useful attribute for identifying which changes can be attributed to agriculture and which are attributable to urbanization. Combined urban and agricultural land uses are well distributed through the study period in both the Battle Creek River and Upper Grand River basins. These basins are differentiated primarily by the rate of agricultural-to-urban land cover. As such, changes observed in the more-rapidly urbanizing Upper Grand River basin and not in the Battle Creek River would be expected to be attributable to urbanization.

For both watersheds, changes were most significant between early periods. Change in magnitudes of annual streamflow during the first interval exceeded change in precipitation by a factor of 3 in the Battle Creek River and a factor of 2 in the Upper Grand River, consistent with the finding of Karl and Riebsame (1989) that mean annual streamflow rose by a factor of several times the change in precipitation in basins with significant proportions of agricultural and urban land cover. During the second interval, magnitudes of annual Q_{tot} rose by a factor of more than 4 times the change in precipitation. For subsequent periods, however, changes in streamflow were far smaller: during the third interval, annual Q_{tot} rose 0.47% in the Battle Creek River and 1.07% in the Upper Grand River despite a 3.78% decline in precipitation. During the fourth interval,

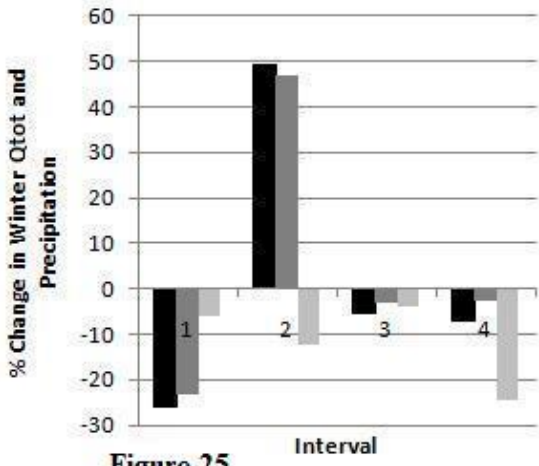


Figure 25

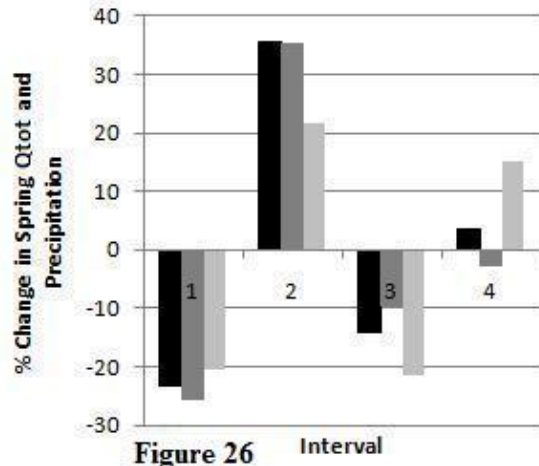


Figure 26

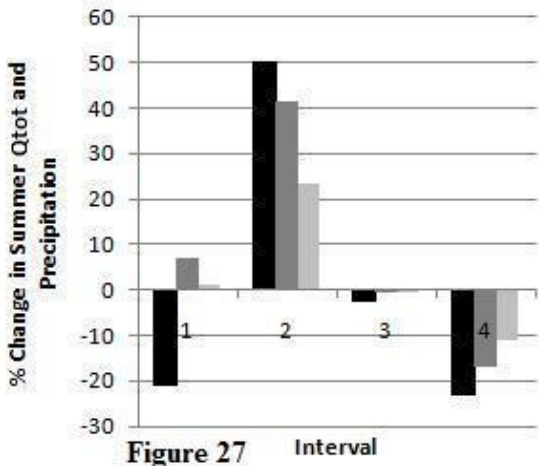


Figure 27

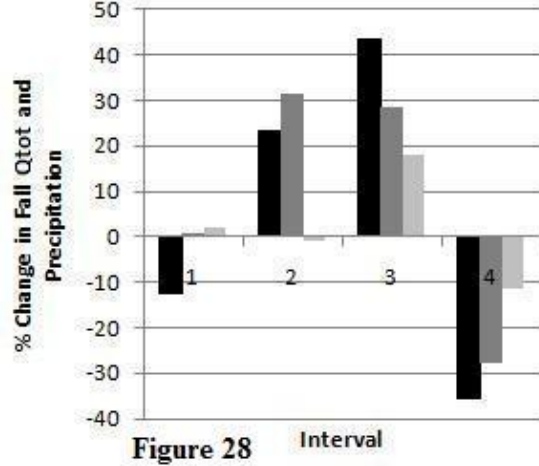


Figure 28

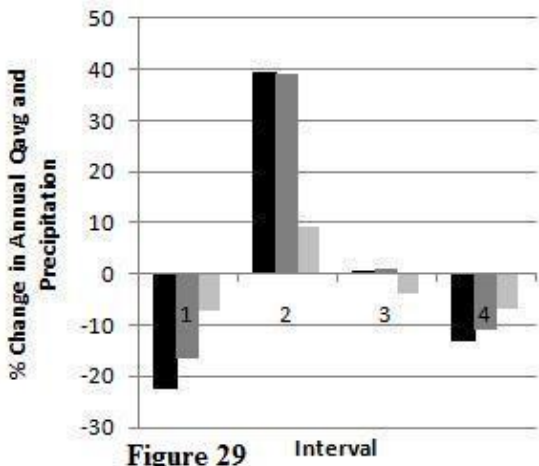


Figure 29

■ Battle Creek River
 ■ Upper Grand River
 ■ Precipitation

Figures (25-29): % change in seasonal and annual Qtot for periodic intervals 1 (1935-1954 to 1955-1972), 2 (1955-1972 to 1973-1982), 3 (1973-1982 to 1983-1998), and for (1983-1998 to 1999-2005). Data acquired from USGS gages #04105000 (Battle Creek River at Battle Creek) and #04109000 (Grand River at Jackson)

annual Q_{tot} declined 13.08% in the Battle Creek River and 11.03% in the Upper Grand River in response to a 6.90% decline in precipitation. This suggests that streamflow response to changes in precipitation were more subdued during the latter half of the period.

The most significant difference between annual Q_{tot} response to a change in precipitation occurred in the first interval (Period 1 to Period 2) and the final interval (Period 4 to Period 5). During these intervals, precipitation declined 7.16% and 6.90%, respectively, inducing changes of 21.10% and 13.08% in the Battle Creek River, and 16.58% and 11.03% in the Upper Grand River. Of note is that changes in Q_{tot} were larger in the Battle Creek River than the Upper Grand River, but that the difference was smaller for the second interval. Additionally, changes were smaller for both rivers despite a roughly equal decline in precipitation for the final interval.

Because there is little difference in changes related to Q_{tot} , it is difficult to attribute changes in this attribute to any specific land cover or climate variable. The literature suggests that changes in both agricultural and urban land uses are significant drivers of streamflow changes, so these changes may be complimentary or contradictory in such a way that trends are masked at the annual scale. Nonetheless, it appears that changes in annual Q_{tot} with regard to change in precipitation were substantially higher between early periods than later periods, suggesting that rising streamflows stabilized during the 1970s and 1980s. There are two principal explanations for stabilization during this period. First, this period corresponds to a leveling off of population growth in both basins. DeWalle, et al. (2000) use population density in lieu of land cover change data as an indicator for urbanization, and find that population density is strongly associated with streamflow change. Since streamflow rise in urbanized basins

is hypothesized to be a function of increased human discharges, it is likely that stagnant population growth or decline would reduce or eliminate differential response between time periods.

6.4.2.3.2 Seasonal

The most significant difference between seasonal streamflows in the Upper Grand River and Battle Creek River is observed between Period 1 and Period 2, when summer and fall streamflows are observed to decline in the Battle Creek River while rising or remaining constant in the Upper Grand River. Between Period 1 and Period 2, seasonal Q_{tot} declined between 20 and 25% for both the Battle Creek River and Upper Grand River during the winter and spring. Seasonal Q_{tot} for summer and fall, however, declined in the Battle Creek River by 20.74% in the summer and 23.44% in the fall and increased in the Upper Grand River by 7.18% in the summer and 0.84% in the fall. Period 2 (1955-1974) represents the period of the most rapid urbanization in the Upper Grand River watershed, which is likely the driver for the large increase in streamflow despite declines in precipitation. Two primary factors likely account for the differential response of the basins. First, human outflows from the increasingly urban Upper Grand River watershed likely compensated for diminished baseflows there as a result of significantly reduced spring precipitation. This hypothesis is supported by the fact that during interval 1, summer low flows (Q_{min}) declined by 14.59% in the Upper Grand River while average flows (Q_{tot}) increased by 7.18%, whereas declines were observed for both summer Q_{min} (-16.92%) and Q_{tot} (-20.74%) during the same interval. Second, agricultural-to-urban land cover conversion reduces vegetative cover and, in turn, evapotranspiration. This reduced

evapotranspiration may have led to a greater proportion of basin outflow as surface runoff during the period, a hypothesis supported by the fact that this phenomenon is strongest in summer, when evapotranspiration is the most significant.

6.4.3 Conclusions

Overall, the 5-period analysis reveals few significant trends in annual or seasonal Q_{\max} that appear to be linked with land cover. Of the relationships tested, the only streamflow attribute for which basin response diverged over time was spring Q_{\max} . Spring Q_{\max} was found in the 20-basin analysis described in Chapter 5 to be negatively associated with urban land cover. Since the Upper Grand River basin urbanized much more rapidly than the Battle Creek River basin during the study period, and was significantly more urbanized during the entire study period, there appears to be a casual relationship between urban land use and declining spring floods. Such a change may be attributable to urban flood control measures such as the construction of retention basins, or the construction of storm drains that deliver water downstream from the gage.

Changes in Q_{\max} in both basins tend to reflect changes in precipitation. Proportional changes in Q_{\max} tend to exceed proportional changes in precipitation by a factor of 2 to 10, which is consistent with a similar finding presented in Lins and Slack (1999). The changes are greater in the Battle Creek River than the Upper Grand River, but this difference is generally static over time, suggesting that basin physiography is the dominant factor that determines peak flow response to changes in precipitation. Retention ponds, which are mandated for developments in most of the Upper Grand River basin, are likely to be a factor in limiting Q_{\max} there. Since

natural physiographic variables are not tested in this thesis, it is impossible to determine whether the increased prevalence of open water and ponds in the Upper Grand River basin or the unique Quaternary geology of the Battle Creek River basin described in 6.2.3 are factors in the magnified response to precipitation changes there.

Aside from the relationship between spring Q_{\max} and urban land cover, no other land cover classes are found to have a significant relationship with changes in Q_{\max} . Therefore, I conclude that anthropogenic land cover change has little overall impact on peak flows in Lower Michigan watersheds, although the construction of retention ponds appears to reduce the size of large floods.

7 Conclusion

Based upon the analyses presented in preceding chapters, I conclude the following with respect to the stated research questions.

7.1 Effects of climate change on streamflow in Lower Michigan

Precipitation increased substantially across most of Lower Michigan over the course of the 20th Century. This increase generally resulted in a proportional increase in low and average streamflows of 2 or more times larger than the precipitation increase, consistent with the findings of Lins and Slack (1999). Changes in precipitation were far more significant for influencing change in streamflow than change in temperature, consistent with Karl and Riebsame (1989) and with DeWalle, et al. (2000) who also found temperature to be less significant than precipitation as a driver of hydrologic change in humid basins.

Beyond the delivery of additional water into the basin, changes in climate induced streamflow occurred through altering the snowmelt regime of the study watersheds. A strong positive relationship was identified between changes in winter temperature and winter Q_{min} and Q_{tot} , which indicates that warming winter temperatures cause higher streamflows, but not larger floods. Since no relationships were found with snowfall totals, it is likely that higher temperatures cause more frequent snowmelt and/or runoff during the winter, contributing to higher streamflow during that season.

7.2 Effects of land use on basin response to climate change

This study affirms the nearly universal conclusion in the literature that human land cover change activity has a significant effect on streamflow change. Consistent with studies such as Leopold (1968), Hollis (1975), Dunne and Leopold (1978), and Whitehead and Robinson (1993), urbanization is found to have the most profound impact on changing streamflows of any land cover class. Agricultural land use is also found to have a significant impact on changing streamflows. Changes in minimum and average streamflows are most significant in the summer and fall, confirming a similar finding by DeWalle, et al. (2000). Streamflow changes in winter and spring are not found to be significantly impacted by anthropogenic land use (urban or agricultural land cover), although it is believed that human modification of wetlands and construction of structures such as retention ponds also substantially alter streamflow regimes during these seasons.

Increasing proportions of urban and agricultural land uses are found to be weakly associated with decline in high flows. This finding runs contrary to the predictions of much of

the earlier literature such as Leopold (1971) and Sopper and Lull (1969) who assert that urbanization leads to higher peak flows as a consequence of increased area of impervious land cover, soil compaction, and channelization of streams. Potter (1991) also found reduced peak flows in an agricultural watershed, and attributed this finding to improved agricultural practices. Improved agricultural practices likely contribute to declining floods in Lower Michigan and may be significant in predominantly agricultural watersheds. Nonetheless, this explanation does not address the decline in high flows observed in urbanized watersheds. The explanation for this observed trend is less clear. Since open water has been found to be negatively associated with high flows, and construction of detention basins in developing Lower Michigan watersheds accelerated during the latter half of the 20th Century (Aichele, 2005).

Changes in low flows were found to be strongly positively related to urbanization and agriculture. Again, this finding runs contrary to some of the early literature as represented by Leopold (1971) and Sopper and Lull (1969), but is consistent with many more recent case studies such as reported by Potter (1991), Schilling and Libra (2003), Changnon and Demissie (1996), and DeWalle, et al. (2000), which all find increases in base flows and average flows with increasing magnitudes of agriculture and urbanization. Potter (1991) and Schilling and Libra (2003) attribute higher baseflows primarily to improved conservation practices which regenerate depleted groundwater. Foster, et al., 1999 and Idso and Brazel (1984) attribute rising streamflows to reductions in evapotranspiration as a result of changing agricultural practices, conversion of agricultural and forested land to urbanization, and outflows from human activities such as sewage and lawn irrigation. All of the above are plausible explanations for the observed

trends in low flows in the study area. The pair-wise analysis of the present study revealed a stark difference in changes in Q_{min} between an agricultural basin and an urban basin occurring between the 1970s and 1990s. This corresponds with a period in which sewers, storm drains, and stormwater retention ponds were greatly expanded (Aichele, 2005), suggesting an important role for these factors to account for the rise in streamflow observed in urbanized basins.

Finally, the trends observed in Q_{min} and Q_{tot} appear to be reversing or stabilizing in the last two decades, which suggests that the trends observed in the study period may have been a readjustment to rapid changes which took place in Lower Michigan prior to the start of the study period. The early decades of the study period, from the 1930s through the 1950s, essentially represent the nadir of conservationism in Lower Michigan. The conservation movement subsequently addressed the impacts of cutover forests, poor erosion control, and rapid population growth with little regard for sustainable development. Watershed hydrology had been immensely altered from pre-settlement conditions. Ultimately, the trends revealed in this study have been a response to not only increased settlement pressure and changing climate, but an advanced consciousness of water resources management.

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Appendix A

NOAA Climate Stations

Map	ID	Map	ID	Map	ID	Map	ID
0	202250	30	207820	60	202140	90	202395
1	200552	31	207820	61	203306	91	204078
2	205698	32	203663	62	206507	92	202423
3	200552	33	203661	63	206438	93	203529
4	203947	34	202631	64	201896	94	203527
5	203306	35	204797	65	206442	95	205662
6	203858	36	206587	66	206510	96	204150
7	204078	37	208167	67	202846	97	205698
8	204078	38	200758	68	202851	98	204244
9	201522	39	205892	69	204793	99	203504
10	205567	40	202445	70	203278	100	204257
11	203769	41	200710	71	200632	101	207684
12	203769	42	201675	72	203170	102	204258
13	207419	43	201122	73	202784	103	203333
14	200417	44	200094	74	208251	104	204944
15	203616	45	200552	75	202788	105	204939
16	203932	46	200552	76	208252	106	204320
17	208800	47	202250	77	208249	107	200446
18	202784	48	200925	78	204399	108	200159
19	203391	49	202381	79	200146	109	204655
20	200343	50	201468	80	203823	110	202268
21	200343	51	201492	81	207419	111	202270
22	200343	52	203616	82	200417	112	204659
23	203628	53	204641	83	203585	113	204662
24	203188	54	207280	84	200420	114	205097
25	200128	55	202331	85	202804	115	206005
26	200128	56	203391	86	206663	116	206007
27	200169	57	205981	87	206662	117	206012
28	200164	58	202437	88	201343	118	205603
29	207820	59	201476	89	209006	119	203969

Map	ID	Map	ID	Map	ID	Map	ID
120	200032	150	205450	180	208417	210	201238
121	208080	151	205563	181	203099	211	208950
122	203969	152	205451	182	203858	212	206020
123	208202	153	205822	183	203290	213	208184
124	200842	154	207320	184	206184	214	208950
125	203712	155	203429	185	207094	215	205488
126	205452	156	208468	186	203936	216	208443
127	203947	157	200343	187	202376	217	201299
128	208972	158	200343	188	203930	218	201361
129	205650	159	205712	189	207253	219	208367
130	208650	160	205567	190	207227	220	200864
131	207103	161	205801	191	207222	221	207690
132	205805	162	208890	192	207217	222	209014
133	205807	163	206658	193	201522	223	207308
134	206982	164	206303	194	207220	224	207312
135	207521	165	206303	195	207255	225	205050
136	202427	166	206303	196	202955	226	209218
137	205065	167	208779	197	205168	227	200230
138	208772	168	202691	198	207350	228	201502
139	208774	169	208941	199	201052	229	207312
140	204954	170	200716	200	204808	230	202103
141	200779	171	203769	201	206300	231	202015
142	205434	172	203632	202	206300	232	203477
143	208869	173	208800	203	201172	233	209110
144	203913	174	204967	204	206297	234	201225
145	206080	175	208800	205	201818	235	201062
146	203932	176	202671	206	202328	236	202016
147	204502	177	205531	207	206680	237	201176
148	205558	178	205533	208	209188	238	201176
149	202308	179	203096	209	207180		

Table A1: List of NOAA climate stations employed for climatological data in this thesis. Locator map is provided in Figure A1

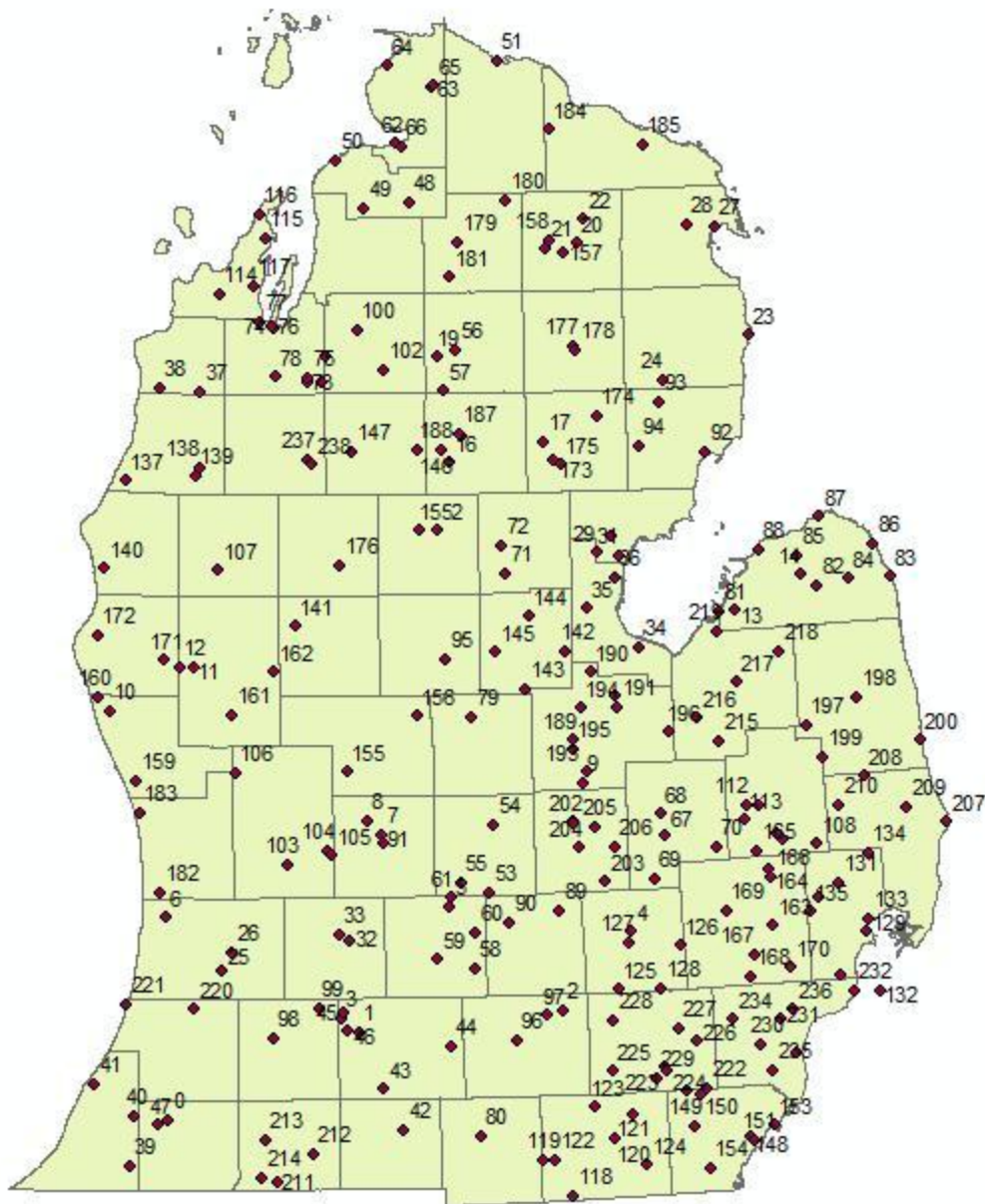


Figure A1: Locator map for NOAA climate stations listed in Table A1

Appendix B

T-statistics for multivariate regression equations

Alpha 5%	Critical T	2.119905		
	Wetland	Forest	Ag	Urban
Annual Qmax	-1.22929	2.35318	0.18068	-0.55749
Annual Qmin	0.424027	0.173773	1.344415	3.681977
Annual Qtot	0.00793	-1.00628	4.826863	3.82473
Winter Qmax	-1.859	2.738185	0.656646	-0.137
Spring Qmax	-1.18231	1.457396	0.798767	-3.36512
Summer Qmax	-0.28756	-0.07568	1.792735	1.889059
Fall Qmax	0.486033	0.726806	1.989037	1.261079
Winter Qmin	0.896976	-0.19621	1.524445	1.644794
Spring Qmin	-0.02838	-0.01907	1.199583	1.821413
Summer Qmin	0.490946	0.41471	0.994908	3.560396
Fall Qmin	1.025849	-0.40903	1.231572	2.270586
Winter Qtot	1.305316	2.116517	0.832985	-0.50684
Spring Qtot	-0.00984	-0.19373	0.990093	0.361912
Summer Qtot	-0.01518	-0.16646	1.841224	3.710179
Fall Qtot	0.62869	-0.1592	1.871087	2.029216

Table B1: T-scores for land use coefficients in multiple regression analysis. Critical t for 95% confidence is provided

Alpha 5%	Critical T	2.228139
Annual Qmax	0.965541	0.260572
Annual Qmin	-1.99642	3.178975
Annual Qtot	-1.82684	3.677307
Winter Qmax	-0.64478	-1.73898
Spring Qmax	-1.45234	1.551389
Summer		
Qmax	0.952084	5.141857
Fall Qmax	-1.12205	5.938157
Winter Qmin	4.705403	-0.27676
Spring Qmin	1.597213	0.172044
Summer		
Qmin	1.691592	6.001959
Fall Qmin	-0.34821	3.651346
Winter Qtot	4.540403	-1.9509
Spring Qtot	0.079756	1.263366
Summer Qtot	1.840757	6.413965
Fall Qtot	-0.87179	4.155966

Table B2: T-scores for climate coefficients in multiple regression analysis. Critical t for 95% confidence is provided