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Effects of Changing Land Cover and Human Development on the Fish Community and Hydrology of the Huron River Watershed

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EFFECTS OF CHANGING LAND COVER AND HUMAN DEVELOPMENT ON THE FISH COMMUNITY AND HYDROLOGY OF THE HURON RIVER WATERSHED

By

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ABSTRACT

EFFECTS OF CHANGING LAND COVER AND HUMAN DEVELOPMENT ON THE FISH COMMUNITY AND HYDROLOGY OF THE HURON RIVER WATERSHED

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Effective management of stream fish populations involves land use modifications occurring within a watershed that may influence the quality of the stream environment and fish habitat. Documenting changes in land cover over time and comparing them to quantitative changes in fish community composition is important to allow us to assess and predict the consequences of proposed or observed changes in land use for fish communities. This research evaluates changes in the fish community between 1938 and 1996 within a large Michigan watershed undergoing extensive urbanization. Of 65 fish species observed in 1938, 24 species have disappeared, the distribution of 35 species has been reduced, and only 6 species showed no change or increases in their distribution in 1996. Mean fish species richness declined significantly ($P<0.0001$) from 13.7 species per site in 1938 to 3.7 species per site in 1996. Changes in the distribution of mottled sculpin *(Cottus bairdi)*, a fish species known to be sensitive to anthropogenic sources of fish habitat degradation shows that populations distribution in 1996 was dramatically reduced from what it was in 1938. The reduced distribution of mottled sculpin within the watershed may be a response to increased urbanization and dam construction within the drainage basin since 1938. A linear model of mottled sculpin growth significantly related the annual incremental increase in fish length to fish length at the beginning of the growing season ($P<0.0001$), but showed no statistically significant difference in fish

length across the species current distribution in the watershed. Logistic regression on a suite of fish habitat parameters measured at each site failed to predict the presence or absence of mottled sculpin at a particular site.

Variability in streamflow often presents fish species with ecological "bottlenecks" representing critical stresses and opportunities for their survival. Evaluation of the historical hydrological regime of the Huron River since 1938 revealed a large amount of year-to-year variability in streamflow, with the general magnitude and frequency of high flow events in the daily records being reduced since that time. No trend was apparent in streamflow since 1938, and discharge appears to be stable in the Huron River relative to many other river systems in the State of Michigan. Water yields in the Huron River have fluctuated since 1938, being less variable and somewhat higher in recent years than they were historically. A decline in water yield between 1950 and 1970 coincides with a period of increased dam construction in the upper basin of the Huron River. Models evaluating the contribution of precipitation and land cover characteristics to the observed patterns in streamflow suggest that changes in land cover since 1938 have not had a major influence on the observed patterns of variability in streamflow. Simulations of projected increases in urban land covers do however predict an increase in discharge over the next twenty years. Extensive damming and urbanization of this watershed since 1938 has altered those processes important for forming fish habitat, but the extent to which these two impacts contribute to observed changes in the fish community can not be separated.

"We seem ultimately always thrown back on individual ethics as the basis of conservation policy. It is hard to make a man, by pressure of law or money, do a thing which does not spring naturally from his own personal sense of right and wrong"

-Aldo Leopold 1937

ACKNOWLEDGMENTS

Much like any educational journey like this, there are a number of people that make it possible in the first place, and more importantly enjoyable along the way. I have been blessed with many such individuals as I trudged this happy road. They have all taught me more about life than I could have dreamed when I first embarked upon this adventure. Any omission of these friends and teachers here is purely unintentional and the result of being overwhelmed with so many of you.

To begin at the beginning, thanks are due to my parents Ralph and Ruth Newman for teaching me to never give up. I owe special gratitude to my siblings Kathy, Karen, Christie, Carol, Patty and Peter who shared in my childhood lessons, the wisdom of which unfolds in all our lives everyday.

My thanks would be incomplete without recognizing the rest of my family that supported me throughout this journey. Bill, Diane, Mary, Kasey, Courtney, Linda and Amy, I thank you with all my heart.

There have been many teachers along the way, but special thanks are due here to my graduate committee. The advice and guidance of Dr. Richard Groop and Dr. Richard Merritt has been invaluable as I developed the research in this dissertation. Dr. William Taylor changed the course of my life nearly twelve years ago, and continues to mentor me through difficult times today. Your friendship will always be important to me. And to my major professor, Dr. Daniel Hayes, I simply could not have pulled this together without your patient guidance and support. Thank you for all you have done.

No journey is without bumps and mine has not been unique. As I struggled to decide which rock I should step on next to cross these turbulent rivers, I often turned to a handful of friends for direction and I am compelled to mention them here as well. I owe a deep sense of gratitude for the friendship and guidance of Dick Divelbiss, Jim McClintock and Paul Rosenbaum. Without your help my life would be much less than it is today. Special thanks are also due Bill and Bob for a second chance and to Jo-Jo for showing me the way.

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INTRODUCTION

The research presented in this dissertation examines the relationship between changes in land use and land cover and the fish community in a large Michigan watershed from the late 1930s to the present. The goal of my research was to determine whether or not there have been changes in human land use and land cover over time that have negatively impacted the fish community. In order to evaluate this relationship, several basic questions needed to be answered. First, I wanted to determine the nature and extent of any land use or cover changes that had occurred within the watershed since the late 1930's. I selected this date as my starting point because of the availability of aerial photography from which I could interpret land use and cover characteristics. Next, I needed to quantify whether or not there had been concurrent changes in the fish community within the watershed. I did this using a historical fish community survey that was also done in the late 1930's. Next, I refined my investigation of changes in the fish community to look at changes in the distribution of a single fish species, the mottled sculpin (*Cottus bairdi*), known to be sensitive to anthropogenic sources of fish habitat degradation (Whittier and Hughes 1998). Finally, I explored the explanatory power of land cover characteristics to predict temporal variability in streamflow. Streamflow is arguably one of the most important physical characteristic of stream ecosystems for fish because it determines so many other aspects of fish habitat (e.g., habitat volume, current velocity, channel geomorphology, substrate type and stability, and the availability of resting, feeding, and reproductive habitats).

I present findings for these questions in three separate chapters, each of which could stand alone as a separate study, but which are interrelated under the goal of my research as explained above. As such, there will be some redundancy in the general introduction and structure of each of the chapters because I build on several aspects that are important to all chapters (e.g., land cover characteristics). In an attempt to eliminate some of that redundancy, I have presented a generalized site description below.

Study Area

All studies were conducted in the Huron River watershed in southeastern Michigan (Figure 1). I chose the Huron River watershed because I felt it is typical of midwestern streams undergoing extensive urbanization, and again, because reliable data sets depicting land cover characteristics and the fish community were either available or could be developed for the time period of interest.

The Huron River watershed is located in southeastern Michigan, and includes portions of seven counties within the state. The watershed drains approximately 2300 square kilometers and eventually empties into the northwest corner of Lake Erie (Hay-Chmielewski et al. 1995). The headwaters of the mainstem originate in the northeast lobe of the watershed, and continue 218 kilometers to the outlet into Lake Erie. The mainstem has twenty-four tributaries that contribute an additional 587 linear kilometers of streams within basin. The elevation of the Huron River ranges from 310 meters at the headwaters to 174 meters above sea level at Lake Erie. Although there are some areas of relatively high gradient, the overall gradient of the Huron River is quite low, at 0.62 m/km. The Huron River watershed is situated on the southern and eastern edge of the Detroit metropolitan area; it has been projected that between 1990 and 2010 the human population of southeastern Michigan will increase by six percent and that urban and

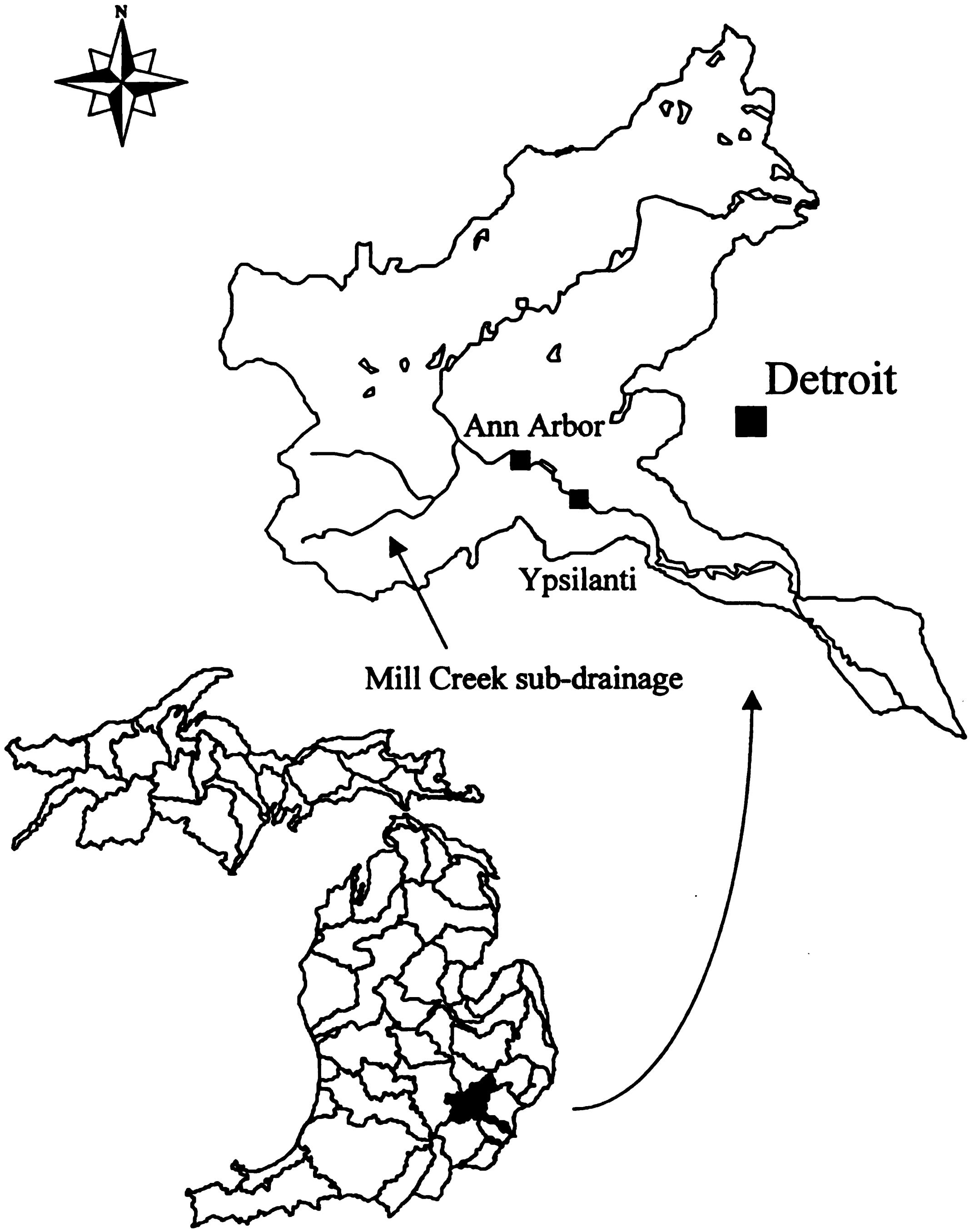

Figure 1. Location of the Huron River watershed study area in southeastern Michigan, including major cities and sub-drainage basins.

suburban land use will expand by forty percent (Southeast Michigan Council of Governments 1991). Much of this expansion is expected to take place within the Huron River watershed.

CHAPTER 1

THE EFFECT OF URBANIZATION ON FISH COMMUNITY STRUCTURE IN A LARGE MICHIGAN WATERSHED

Introduction

Changes in land use are thought to affect aquatic ecosystem health, species richness, diversity, and productivity (Larimore and Bayley 1996, Williams et al. 1997). Changes in human land use generally alter the composition of aquatic communities by modifying those physical processes that affect stream habitat and water quality. Impacts on stream habitat and water quality are particularly apparent in watersheds undergoing extensive urbanization.

A problem that commonly occurs in watersheds experiencing shifts in human land use to an urbanized landscape is accelerated runoff caused by an increase in the surface area of impermeable structures (Wood et al. 1997). In urbanized landscapes, wetlands are often filled and small tributaries are often channelized or converted to storm drains. Other components of the urban environment such as roads, parking lots, rooftops and gutters also contribute to accelerated runoff. These developments, combined with the loss of vegetative cover that allows precipitation to slowly percolate through the soils and recharge groundwater systems, result in increased frequency and magnitude of flood events, and reduced summer-time base flows (Sparks 1992). Such changes in flow regime can have direct impacts on fish survival. For example, reduced base flows can have a seasonal effect on survival by decreasing the amount of stream habitat available through changes in water temperature, velocity, depth and wetted stream width (Williams et al. 1997). Changes in flow regime also have longer-term effects on stream habitats by altering the geomorphology of the stream itself (Williams et al. 1997).

In addition to changes in flow regime, rivers and streams draining urbanized landscapes often suffer from poor water quality. Frequently, these systems receive substantial annual loads of urban pollutants (e.g., PCBs, trace metals, pesticides), sediment, and debris (Shepp and Cummins 1997). Combined sewer overflow events can also lead to reductions in dissolved oxygen levels below that required by many fish species. Such degradation of water quality can have serious ramifications for the structure of aquatic communities.

Another dimension of human land use is the construction of dams. Increased construction of dams associated with an urbanizing landscape also pose serious problems for fish and fish habitat. While the location and construction dates of dams within a watershed are easily determined from available maps and data sources, their effects on the fish community are much more difficult to determine. Habitat fragmentation, modification of streamflow patterns, and changes in temperature, dissolved oxygen, and sediment transport all have the potential to degrade a stream's ability to support a particular fish community.

Although there is good evidence demonstrating changes in stream ecosystem structure and function in urbanized watersheds, there is little empirical evidence quantifying changes in the fish community due to urbanization. The goal of this study is to determine the quantitative changes in the fish community of a watershed undergoing extensive urbanization. To accomplish this goal I used historical data on fish community composition and land cover from the Huron River watershed.

My a priori hypotheses were: 1) fish species richness at individual sites will decrease as urbanization in the watershed increases, and 2) the ubiquity (defined as the number of sites occupied by a species throughout the watershed) of species intolerant to human development (Whittier and Hughes 1998) will decrease as urban land cover increases. To evaluate these hypotheses, I had the following main objectives: 1) to quantify the land cover in the Huron River watershed in 1938 and 1996, 2) to determine the extent of changes in cover that took place over this time period, 3) to quantify fish species richness and ubiquity for 1938 and 1996 at 90 sites in the Huron River watershed, and 4) to evaluate the extent of changes in fish species richness and ubiquity over this same time period.

Methods

Land cover and dam construction

The first objective of this study was to quantify the land cover in the Huron River watershed in 1938 and 1996. Watershed boundaries were determined from 7.5-minute topographic maps available through the U.S. Geological Survey. The 1938 land cover patterns (referred to throughout the text as historical land cover) were determined by interpreting black and white aerial photographs obtained from the Center for Remote Sensing at Michigan State University. The 1996 land cover patterns (referred to as modern land cover) were available as coverages previously digitized and ground verified by the Huron River Watershed Council (HRWC). All land cover patterns were digitized and analyzed using ARC/INFO software (Environmental Systems Research Institute).

In this chapter I will use the term land cover as a description of the vegetation and artificial construction covering the land surface (Osborne and Wiley 1988). For both modern and historical coverages, the land cover classification system consisted of seven general categories: urban, agriculture, nonforested (herbaceous and shrub cover), forested, water, wetlands, and barren (beach, sand dune, and exposed rock). Land cover patterns and the watershed boundary were treated as polygons (enclosed areas), stream networks as line coverages, and fish sampling sites as point coverages. All digitized coverages were converted to a standardized geographic reference scale (Michigan State Plane 1927) so that spatial overlays of any coverage type (i.e., polygon, line, or point) could be accomplished during analyses.

The total areas of each land cover category for each era (historical and modern) were determined using ARC/INFO software. The data from the two time periods were compared to assess the net change for each land cover category in the Huron River watershed between 1938 and 1996. Maps depicting the land cover categories experiencing the largest absolute gains and losses were developed for visual comparisons between the two time periods. Maps depicting the location and date of dam construction relative to 1938 were also developed to evaluate the temporal and spatial arrangement of dam construction concurrent with changes in land cover.

Fish community

The next objective of this study was to analyze changes in fish species richness and ubiquity. To accomplish this, I based my sampling on a previous survey that characterized the fish species assemblage in the watershed in 1938 (Brown and Funk

1945). In the 1938 survey, samples were collected using a 3-meter by 1.2-meter seine net with a 0.42-centimeter square mesh. Although Brown and Funk (1945) identified 121 sites sampled in the previous survey, I found clear fish species and location information for only 90 of those sites on the original data sheets. In their survey, Brown and Funk recorded information on fish species caught and the size range of individuals caught. As such, I was limited to analyses on species richness and ubiquity. In the 1996 survey, I resampled the 90 sites identified above, employing the same sampling methods and sampling the same stream area as reported on the original data sheets. This allowed me to directly compare results from the two surveys under the assumption that each survey was subject to the same limitations imposed by the gear used. A paired t-test was performed to determine the significance of differences in species richness between the two surveys.

Maps of the 90 sites sampled in the Huron River watershed were generated to depict the species richness observed at each site in each survey. In order to evaluate the spatial arrangement of the severest losses in relation to those areas in which I observed increased urbanization or dam construction, I developed maps showing the percent change in species richness at each site.

Results and Discussion

Land cover and dam construction

In 1938, agriculture was the predominant land cover, encompassing 131,469 hectares or 55.8% of the Huron River watershed. Forested lands comprised the next largest percentage of the watershed, covering 38,617 hectares or 16.4%. Forests were followed by nonforested cover (27,047 hectares, 11.5%), and wetlands (17,102 hectares, 7.3%). Urban cover comprised only 12,955 hectares of the Huron River drainage in 1938 or 5.5% of the watershed. Approximately 8,576 hectares or 3.6% of the watershed were covered with water. Only 1 hectare or less than 1% of the watershed was barren lands. From 1938 to 1996, the acreage in five of the land cover categories increased while two decreased (Table 1). The greatest absolute change between 1938 and 1996 was in the agricultural land cover category, which decreased by more than 69,000 hectares or by about 53 percent of the 1938 value (Figure 1). As agricultural lands decreased within the watershed, urban land cover increased by 51,159 hectares. That increase represents nearly a 4-fold increase in urban land cover between 1938 and 1996 (Table 1). I observed the greatest concentration of urban development in the upper or northern portion of the watershed that sits nearest the expanding Detroit metropolitan area, and in the extreme southern arm of the watershed that encompasses the growing Ann Arbor and Ypsilanti urban areas (Figure 2). Nonforested cover gained more than 15,000 hectares, while about 12,000 hectares of forests were lost during the period. A notable increase was that of the combined area of water and wetland coverages observed in 1996. These two coverages increased a combined total of 14,421 hectares since 1938. One reason for this increase is due to increased reservoir surface area and the associated wetlands that resulted from increased dam construction throughout the drainage since 1938. The observed change in wetland area may also be due in part to the difficulty in identifying wetlands from the black and white aerial photographs available for 1938. Changes in barren land covers were small relative to the changes described above.

Table 1. Total area (hectares) encompassed by each of the major land cover categories in the Huron River watershed during the historical and modern era, along with the net absolute change observed for each category.

Land cover	1938 (ha)	1996 (ha)	net change (ha)
Urban	12,955	64,113	51,159
Agriculture	131,469	62,094	-69,375
Nonforested[a]	27,047	42,642	15,595
Forested	38,617	26,814	-11,803
Water	8,576	10,784	2,208
Wetland	17,102	29,315	12,213
Barren[b]	1	3	2
Total	235,766	235,766	0

a. Nonforested cover includes all herbaceous and shrub covered lands.

b. Barren cover includes all beach, sand dune, and exposed rock covered lands.

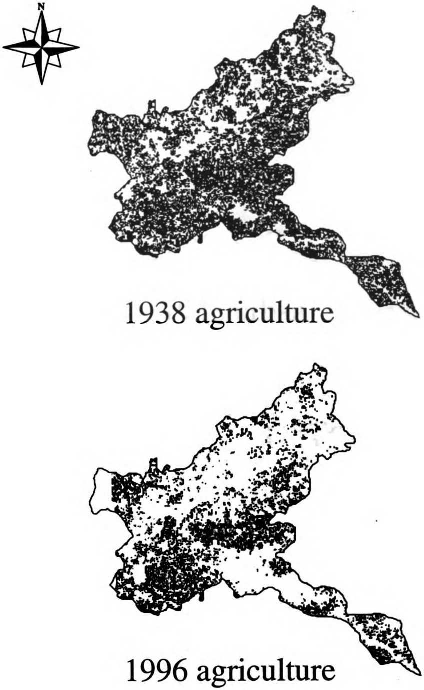

Figure 1. Change in agricultural land cover within the Huron River watershed between 1938 and 1996. Areas shaded in black represent the acreage encompassed by agriculture land cover; all other land cover categories are in white.

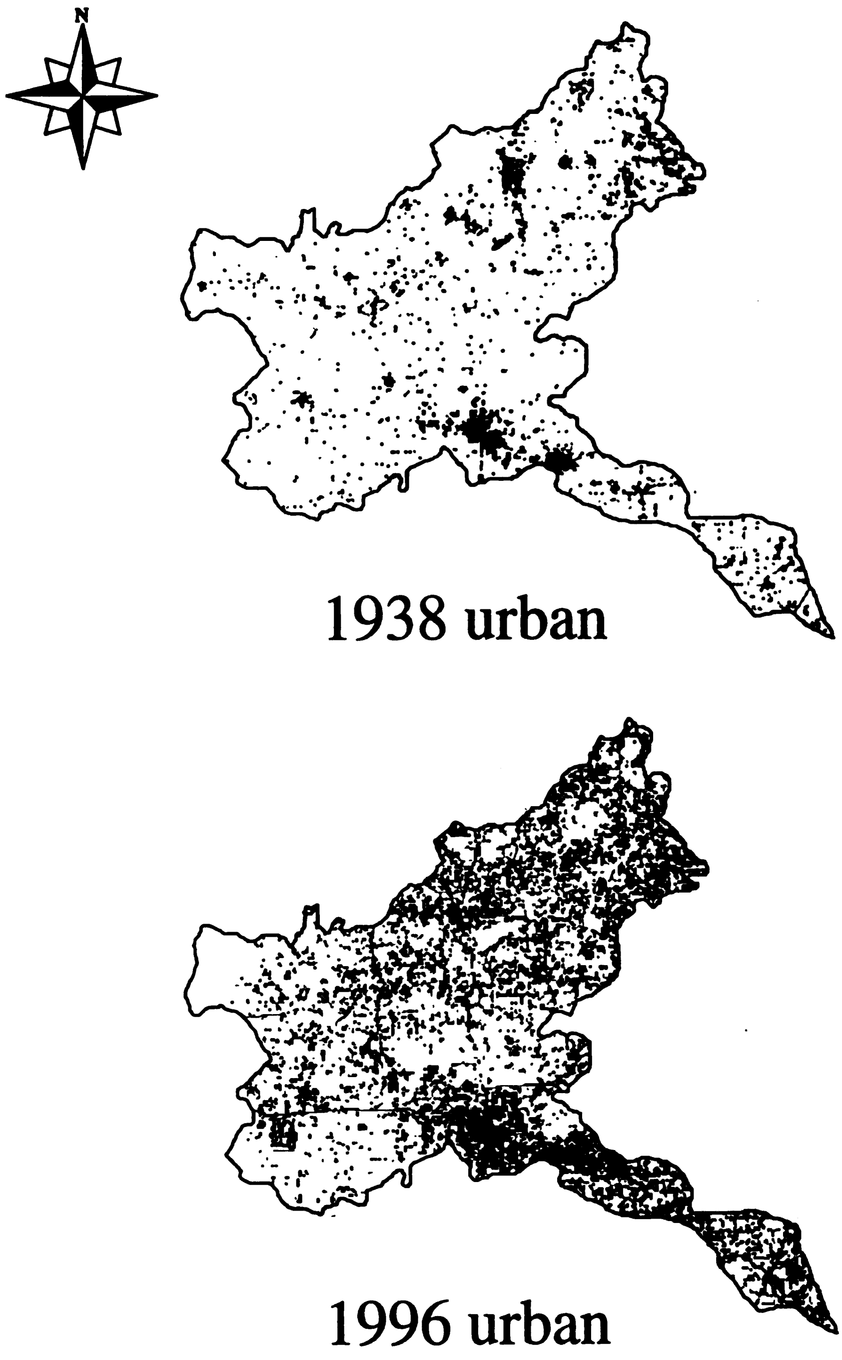

Figure 2. Change in urban land cover within the Huron River watershed between 1938 and 1996. Areas shaded in black represent the acreage encompassed by urban land cover; all other land cover categories are in white.

Of the 99 major dams located within the Huron River drainage basin, 24 were constructed in or before 1938, and 39 dams were constructed since that time (Figure 3). The construction date of 36 dams was not able to be determined. During the historical era, most dam construction was done on the mainstem of the Huron River. Since that time, both the frequency and extent of spatial coverage of dam construction has increased. Unfortunately for my analysis, most of the dam construction in the Huron River drainage basin overlaps with those areas experiencing the greatest amount of urbanization or other land cover changes. The least impacted areas of the watershed had relatively few dams constructed over the period of record. As such, it is difficult if not impossible to separate any observed effects of dam construction from that of urbanization on the fish community.

Fish community

I expected the increased urbanization and dam construction in the Huron River watershed to have significant influences on the fish community. For the watershed as a whole, Funk and Brown (1945) observed 65 fish species. In 1996, I observed 47 fish species, a net loss of 18 species (Table 2).

Species richness among the sites sampled in each survey was highly variable, but changes from 1938 to 1996 show an alarming trend. In 1938, fish species richness at individual sites ranged from 3 to 45 species, with a mean species richness ± one standard error of 13.7 species ± 0.80 across all sites. In 1996, fish species richness ranged from 0 to 12 species, with a mean of 3.7 species ± 0.32 across all sites. Results of a paired t-test indicate that the decline in species richness that occurred with the changing land use

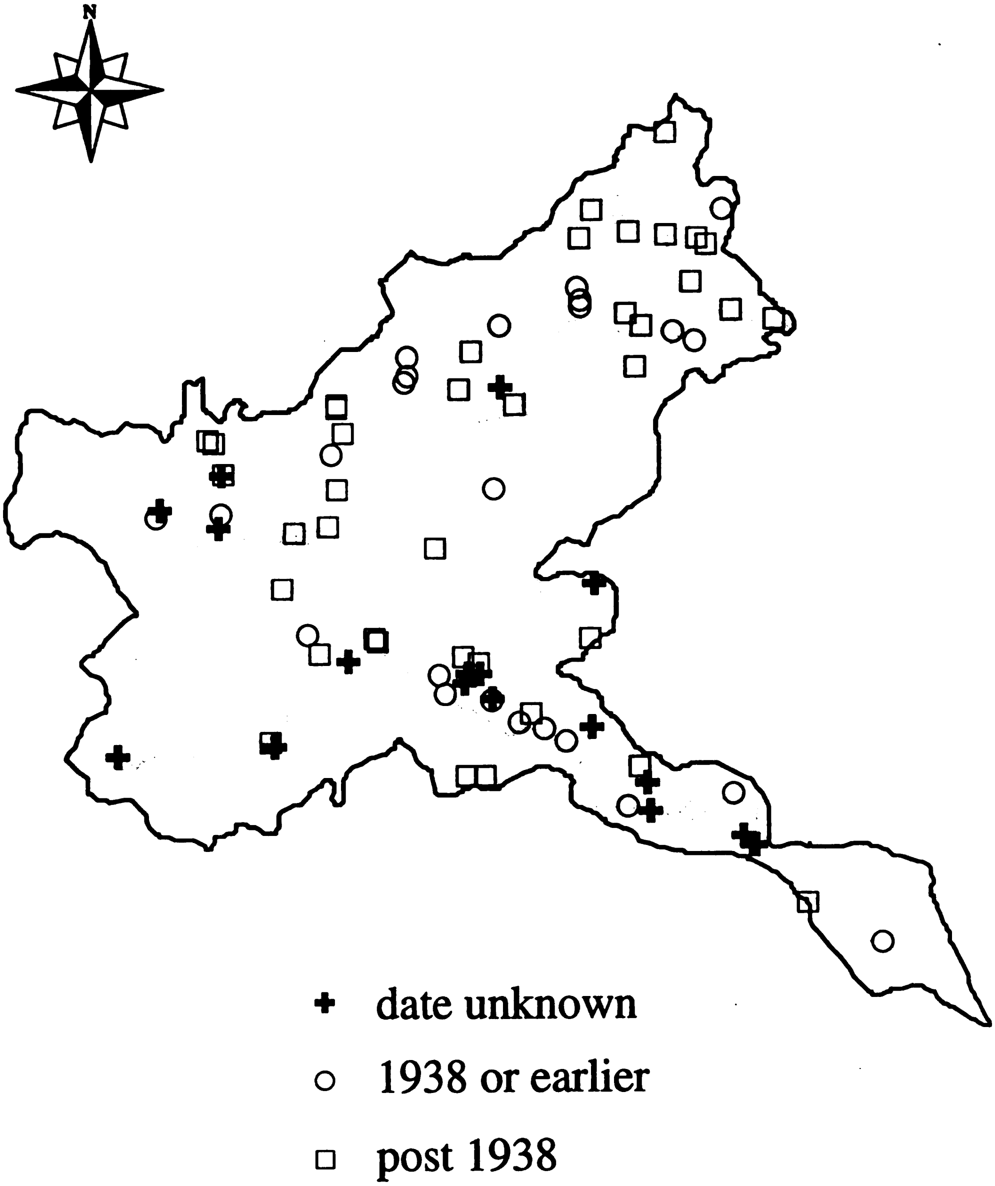

Figure 3. The location and date of dams constructed throughout the Huron River drainage basin.

Table 2. Changes in the ubiquity of fish species observed in the Huron River watershed between the 1938 and 1996 fish faunal surveys.

	1938		1996
fish species newly observed since 1938 survey	---		6
fish species with expanded ubiquity since 1938 survey		3	
Fish species showing no change in ubiquity since 1938 survey		3	
Fish species with reduced ubiquity since 1938 survey		35	
Fish species lost since 1938 survey	24		---
Total fish species richness	65		47

practices from 1938 to 1996 was highly significant ($t = 10.6$, degrees of freedom = 89.0, $P < 0.0001$).

Maps of fish species richness at individual sites show that although the loss in species richness was widespread, some areas experienced greater losses than others did. In 1938, the highest species richness values were observed in the northeastern lobe of the watershed, and in the extreme southern arm of the drainage (Figure 4). In contrast, relatively moderate or low species richness values were observed in the central and southwestern lobe of the watershed. Just the opposite pattern was observed in 1996; relatively low species richness values were recorded in the northeastern lobe and extreme southern arm of the watershed, while higher species richness values were recorded in the central and southwestern lobe of the drainage (Figure 5). Overwhelmingly, I observed high losses in species richness (75 to 100 percent) in those areas where urban cover and dam construction increased the most (Figure 6). Conversely, small gains or relatively little changes in species richness were observed near the center and in the southwestern lobe of the watershed where land cover has changed little from the agricultural landscape it was in 1938, and little in the way of dam construction had occurred.

Several changes in the ubiquity of individual fish species were observed across the Huron River watershed between the two surveys (Table 2). While six new fish species were observed in the 1996 survey, six other fish species either expanded their range or remained unchanged since 1938, the majority of the changes observed were either complete losses or reductions in the ubiquity of fish species since 1938 (Table 2).

The six new species found in the 1996 survey include the river chub, striped shiner, spotfin shiner, rainbow trout, fathead minnow, and the pearl dace (Table 3). Of

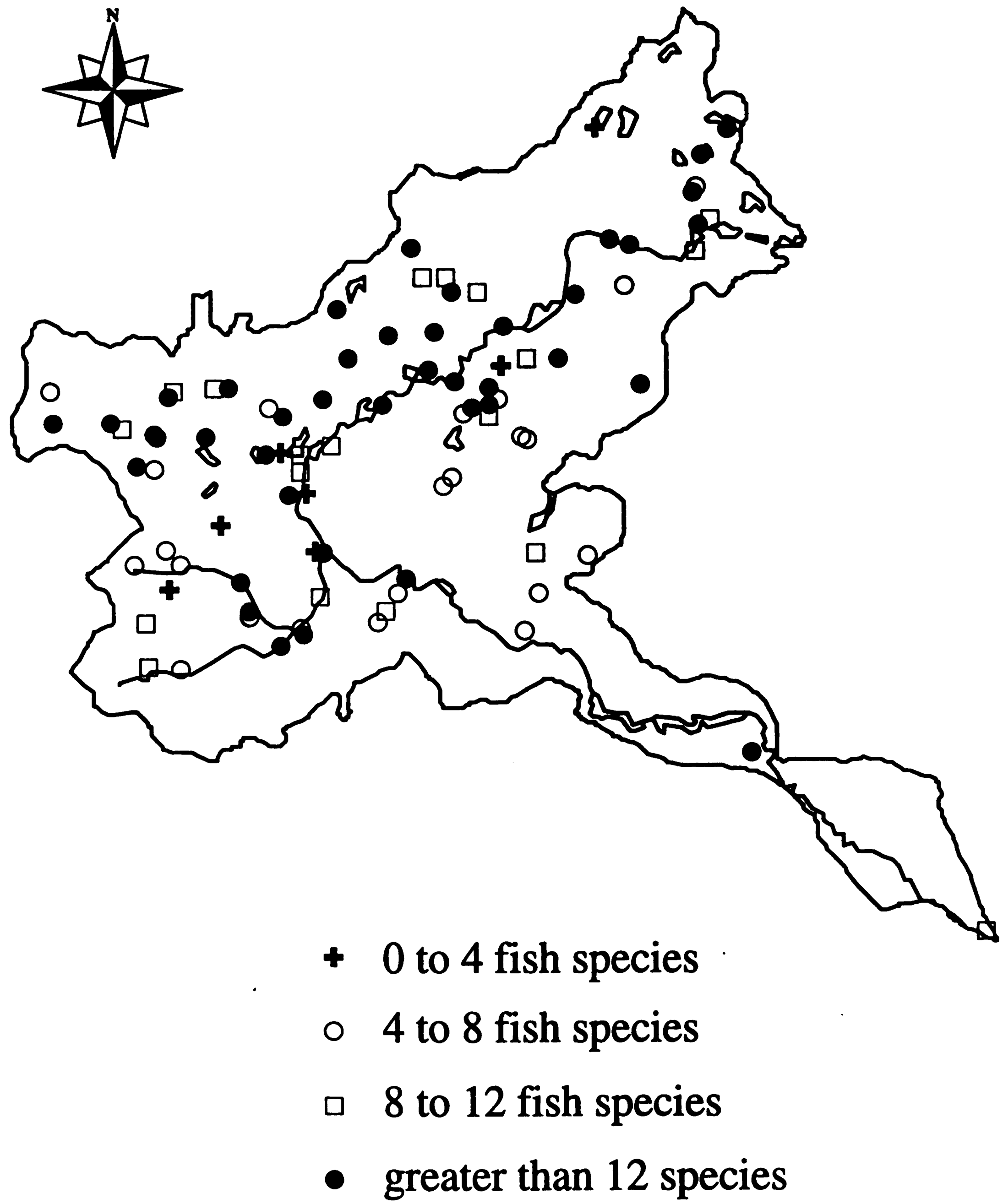

Figure 4. Fish species richness among sites sampled in 1938.

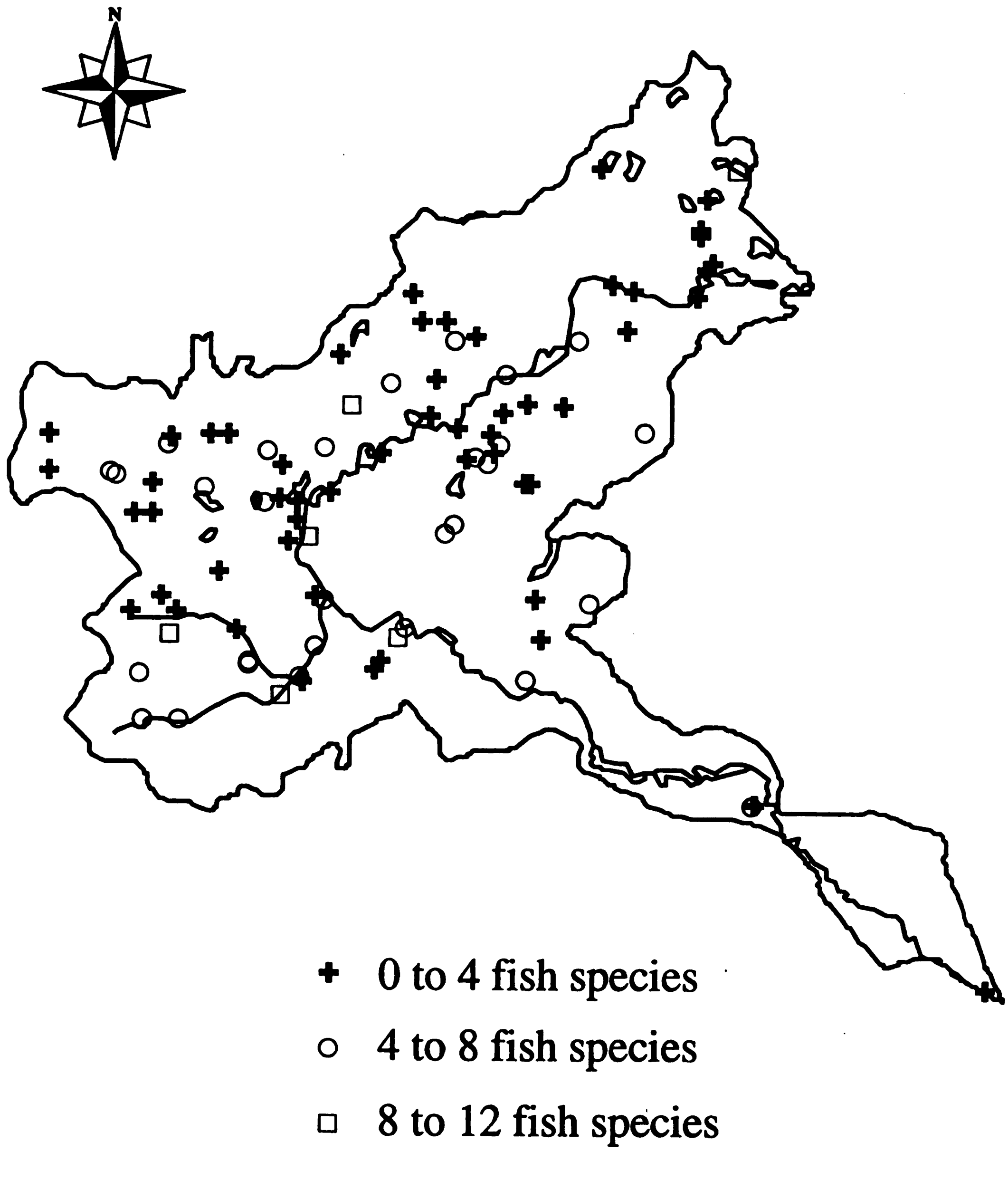

Figure 5. Fish species richness among sites sampled in 1996.

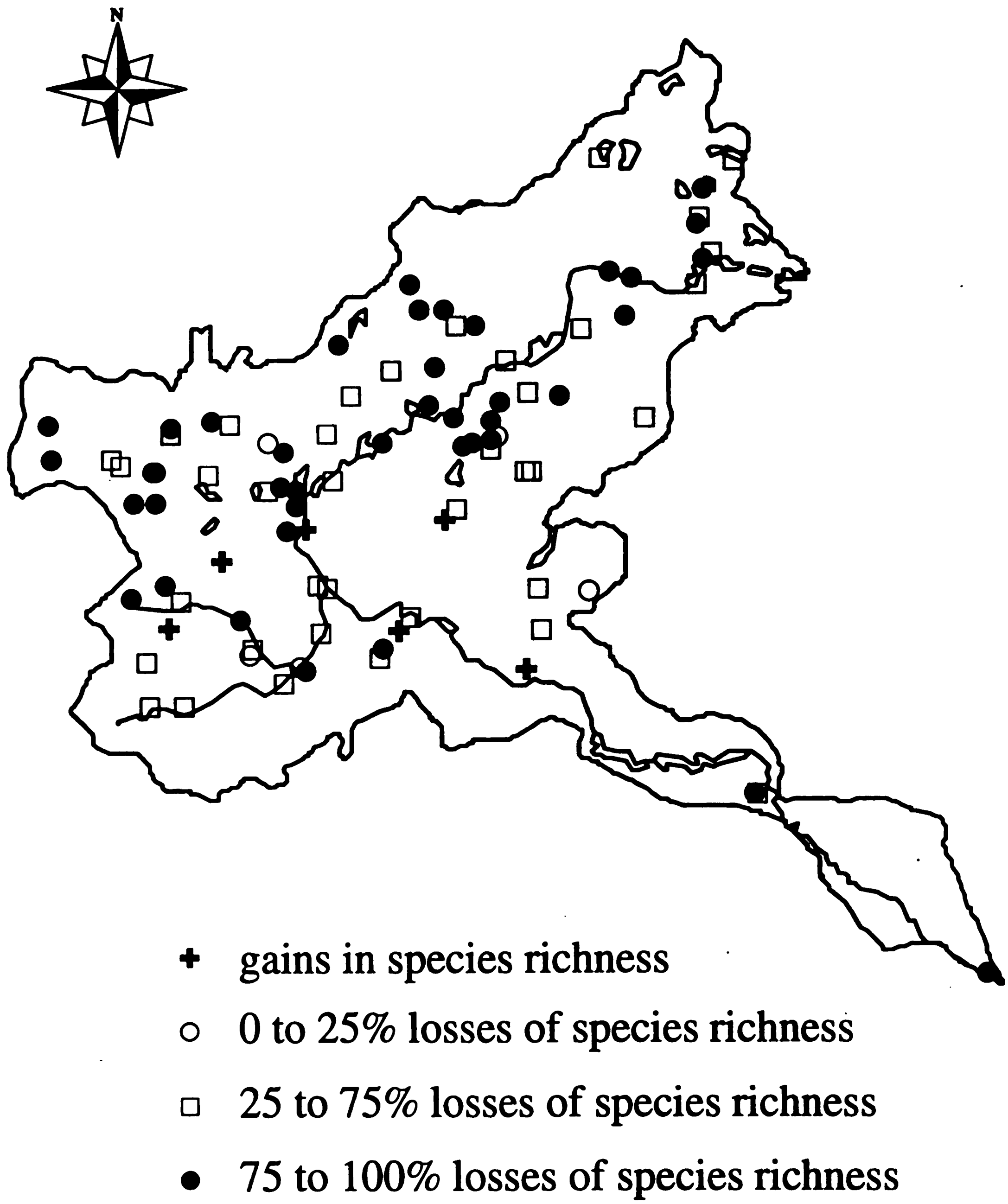

Figure 6. Percent change in fish species richness among sites sampled between 1938 and 1996.

Table 3. Fishes recorded from the Huron River in 1938 and 1996 faunal surveys, and the number of sites that individual species were observed at.

Common name	Scientific name	Year sampled 1938	1996
Rock bass	*Ambloplites rupestris*	48	6
Bowfin	*Amia calva*	4	1
Central stoneroller	*Campostoma anomalum*	16	7
Goldfish	*Carassius auratus*	2	0
White sucker	*Catostomus commersoni*	20	15
Mottled sculpin	*Cottus bairdi*	35	17
Lake chub	*Couesius plumbeus*	6	0
Brook stickleback	*Culaea inconstans*	1	10
Common carp	*Cyprinus carpio*	3	2
Gizzard shad	*Dorosoma cepedianum*	1	0
Creek chubsucker	*Erimyzon obiongus*	15	0
Lake chubsucker	*Erimyzon sucetta*	18	0
Grass pickerel	*Esox americanus*	57	3
Northern pike	*Esox lucius*	9	2
Greenside darter	*Etheostoma blennioides*	9	4
Rainbow darter	*Etheostoma caeruleum*	46	8
Iowa darter	*Etheostoma exile*	10	2
Barred fantail darter	*Etheostoma flabellare*	21	0
Least darter	*Etheostoma microperoa*	18	0
Johnny darter	*Etheostoma nigrum*	25	17
Banded killifish	*Fundulus diaphanus*	1	0
Blackstripe topminnow	*Fundulus notatus*	20	0
Northern hogsucker	*Hypentelium nigricans*	17	11
Northern brook lampry	*Ichthyomyzon fossor*	1	0
Black bullhead	*Ictalurus melas*	2	1
Yellow bullhead	*Ictalurus natalis*	46	3
Brown bullhead	*Ictalurus nebulosus*	3	4
Brook silverside	*Labidesthes sicculus*	9	4
Longnose gar	*Lepisosteus osseus*	1	0
Green sunfish	*Lepomis cyanellus*	32	12
Pumpkinseed	*Lepomis gibbosus*	47	18
Warmouth	*Lepomis gulosus*	4	2
Bluegill	*Lepomis macrochirus*	49	27
Longear sunfish	*Lepomis megalotis*	39	0
Smallmouth bass	*Micropterus dolomieui*	11	4
Largemouth bass	*Micropterus salmoides*	46	22
Black redhorse	*Moxostoma duquesnei*	1	0
Golden redhorse	*Moxostoma erythrurum*	4	0
Greater redhorse	*Moxostoma valenciennesi*	1	0
Horneyhead chub	*Nocomis biguttatus*	27	5

Table 3. (cont'd).

River chub	*Nocomis micropogon*	0	1
Golden shiner	*Notemigonus crysoleucas*	4	6
Emerald shiner	*Notropis atherinoides*	2	0
Striped shiner	*Notropis chrysochephalus*	0	18
Common shiner	*Notropis cornutus*	52	8
Pugnose minnow	*Notropis emillae*	1	0
Blackchin shiner	*Notropis heterodon*	7	0
Blacknose shiner	*Notropis heteroiepis*	6	0
Spottail shiner	*Notropis hudsonius*	2	2
Silver shiner	*Notropis photogenis*	1	0
Rosyface shiner	*Notropis rubellus*	4	3
Spotfin shiner	*Notropis spilopterus*	0	12
Sand shiner	*Notropis stramineus*	1	1
Mimic shiner	*Notropis volucellus*	2	0
Stonecat	*Noturus flavus*	1	0
Tadpole madtom	*Noturus gyrinus*	11	0
Brindled madtom	*Noturus miurus*	12	0
Rainbow trout	*Oncorhynchus mykiss*	0	1
Yellow perch	*Perca flavescens*	24	6
Logperch	*Percina caprodes*	14	9
Blackside darter	*Percina maculata*	25	1
Northern redbelly dace	*Phoxinus eos*	2	2
Bluntnose minnow	*Pimephales notatus*	27	20
Fathead minnow	*Pimephales promelas*	0	4
White crappie	*Pomoxis annularis*	1	1
Black crappie	*Pomoxis nigromaculatus*	3	6
Blacknose dace	*Rhinichthys atratulus*	16	5
Brook trout	*Salvelinus fontinalis*	1	0
Creek chub	*Semotilus atromaculatus*	59	22
Pearl dace	*Semotilus margarita*	0	1
Central mudminnow	*Umbra limi*	58	10

these, the river chub, rainbow trout, and pearl dace were found only at a single site each during the 1996 survey. Most of these additions to the fish community of the Huron River since 1938 likely represent unintentional introductions (e.g., bait-bucket), with the possible exception of the rainbow trout, which may have been stocked intentionally.

Three fish species expanded their ubiquity within the watershed in 1996: brown bullhead, brook stickleback, and golden shiner (Table 3). Each of these species has been categorized as being tolerant to human activity (Scott and Crossman 1973, Whittier and Hughes 1998). Three other fish species showed no change in ubiquity: sand shiner, black crappie, and northern redbelly dace (Table 3). Of these, the sand shiner and black crappie are considered tolerant to the observed changes in human land use, but the northern redbelly dace is considered intolerant (Whittier and Hughes 1998). However, neither the sand shiner nor the northern redbelly dace were widespread within the watershed, being found in only one and two sites respectively.

Of the 35 fish species showing reductions in ubiquity, the rock bass, grass pickerel, rainbow darter, blackside darter, common shiner, and mottled sculpin are examples of species that experienced dramatic reductions in the number of sites where they were detected (Table 3). Each of these species is severely to moderately affected by human disturbance in the watershed (Scott and Crossman 1973, Whittier and Hughes 1998). If the trends in urbanization and dam construction continue unchecked, these fish species may be subject to complete elimination from the watershed. Notable fish species that have disappeared since the 1938 survey include the barred fantail and least darters, the blackchin and blacknose shiners, the tadpole and brindled madtoms, and the longear sunfish (Table 3). Of this group, the darters, shiners, and madtoms are generally considered to be sensitive to human disturbance within the watershed.

My results suggest that urbanization and dam construction in the Huron River watershed has had a significant influence on the composition and distribution of the fish community. Clearly, multiple fish species have been lost or suffered reduced distribution throughout the watershed. Many of these fish species are known to be sensitive to anthropogenic degradation of their habitat (e.g., mottled sculpin). Land use has changed to include much more urbanized covers and far less agriculture ones. Dam construction has been on the increase since the late 1930's, including a substantial increase in dam construction on upstream tributaries. If we assume that fish are the ultimate integrators of human activities within the watershed (Taylor et al. 1998), these results suggest that the watershed is not ecologically healthy as defined by Williams et al. (1997). Clearly, the watershed has lost ecological structure and function as human demands on the landscape have changed, and the prognosis is not good in the face of the projected increase in demands over the next several decades. We need to consider the long-term consequences of societal decisions on the health, diversity, and productivity of the land to ensure the ability of human society to prosper into the future (Wood et al. 1997). Fortunately, local watershed councils are working with state and federal agencies to protect and restore the Huron River watershed. It is hoped that restoration efforts can reverse the trends observed in this study. Ultimately, the effectiveness of any restoration effort will depend upon our ability to integrate an ecosystem perspective with a better understanding of the needs of society as they relate to land use.

Summary

Both land cover and the fish community within the Huron River watershed have changed dramatically since 1938. Between 1938 and 1996 the predominant change in land cover was a shift from agricultural uses to urban and suburban covers. Agricultural covers were reduced to half of what they were in 1938 while urban cover increased to almost four times historical levels. Of the 65 fish species observed in 1938, 24 species have disappeared, the distribution of 35 species has been reduced, and only 6 species showed no change or increases in their distribution in 1996. Mean fish species richness declined significantly ($P<0.0001$) from 13.7 species per site in 1938 to 3.7 species per site in 1996.

It is difficult to determine the role human development of the Huron River watershed has played in observed changes in the fish community. As described earlier, I can not effectively separate the impacts of land cover changes from dam construction or other effects of human development in this watershed on the fish community. It is also important to understand that the fish community was unlikely to have been in a pristine state in 1938 given the extensive agricultural development of the landscape prior to that time. Other research suggests that past land use practices may have a time-lagged effect on the present-day diversity of stream invertebrate and fish assemblages (Harding et al. 1998). In this study the observed fish community composition of the Huron River watershed in 1996 may be due in part to the agricultural development of the landscape prior to 1938 in addition to the urban development since that time. There is no way to be sure of the causes of the observed decline given these data, however it is clear that the fish community of the Huron River watershed has experienced dramatic losses.

CHAPTER 2

CHANGES IN THE MOTTLED SCULPIN *(Cottus bairdi)* POPULATION IN A LARGE MICHIGAN WATERSHED UNDERGOING URBANIZATION

Introduction

As previously discussed, changes in land use are thought to alter the composition and distribution of aquatic communities, including fish, by modifying those physical processes that affect stream habitat, water quality, and general aquatic ecosystem health (Osborne and Wiley 1988, Larimore and Bayley 1996, Williams et al. 1997). Impacts on stream habitat and water quality are particularly apparent in watersheds undergoing extensive urbanization. Accelerated runoff, loss of permeable soils, reduction in wetlands, and channelization of small tributaries all contribute to changes in fish habitat. Modifications to natural patterns in streamflow resulting from urbanization and dam construction can also have direct impacts on fish survival (Chapter 1).

Relatively few long-term, broad geographical studies have been done that explore the cumulative effects of land use change on a closed population of fish. As such, it is difficult to link changes in fish habitat to observable changes in population dynamics (Hayes et al. 1996). I chose to examine these types of cumulative effects by studying the mottled sculpin population of the Huron River. I selected mottled sculpin because this species is relatively sedentary compared to other fish species (Koster 1936), reducing problems with seasonal changes in distribution. Further, mottled sculpin do not commonly inhabit large mainstem habitats, so they are unlikely to be moving into or out of the smaller tributary systems feeding the mainstem of the Huron River. Of course, there is some movement of fish throughout the mainstem and among tributaries, but generally, the population in the Huron River will meet my assumption that it is a closed population of fish. Mottled sculpin are also not subject to angling pressure nor are they stocked, so changes in their range within the watershed are unlikely to be confounded with angling pressure or stocking practices. They are known to be sensitive to the types of habitat degradation caused by human development of the landscape (Whittier and Hughes 1998), and they were widely distributed throughout the Huron River watershed historically.

My overall goal was to determine how fish respond to changes in land use and cover over time. More specifically, in this study I wanted to determine the quantitative changes in the distribution of a sensitive fish species, the mottled sculpin, in a watershed undergoing extensive urbanization. To accomplish this goal I used historical data on mottled sculpin distribution and land cover from the Huron River watershed. Secondly, I wanted to examine the growth of mottled sculpin within their current range in the Huron River watershed to identify sites where environmental conditions affect growth rate. To accomplish this goal, I collected mottled sculpin across their current range in the watershed, and developed descriptive models that allowed comparison of growth among sites sampled. Finally, I used a logistic regression model for binary response data (i.e., presence or absence of mottled sculpin at a particular site) to determine if habitat parameters measured at each site had any predictive ability for this fish species.

My a priori hypotheses were: 1) the ubiquity (defined as the percent of sites occupied throughout the watershed) of mottled sculpin will decline as urban land cover increases, 2) measurable differences in fish growth would exist among sites inhabited by mottled sculpin and subject to different amounts of human alteration, and 3) measurable habitat parameters would have some predictive ability with regards to mottled sculpin presence or absence. To evaluate these hypotheses, I had the following main objectives: 1) to quantify mottled sculpin ubiquity for 1938 and 1996 in the Huron River watershed, and evaluate the extent of changes in mottled sculpin ubiquity over this time period, 2) to quantify the land cover in the Huron River watershed in 1938 and 1996, and determine the extent of changes in land cover that took place over this time period, 3) to relate changes in mottled sculpin ubiquity to changes in land cover over the period of record, 4) to determine if mottled sculpin growth varied among sites currently occupied by this species, and 5) to determine if measurable habitat parameters could be used to predict mottled sculpin presence or absence at a site within this watershed.

Methods

Mottled Sculpin Distribution

The first objective of this study was to determine mottled sculpin distribution throughout the Huron River drainage in 1938 and 1996. To accomplish this, I evaluated data collected during a historical survey that characterized the fish species assemblage in the watershed in 1938 (Brown and Funk 1945), and a modern survey that repeated Brown and Funk's work in 1996 (Newman et al. 1999).

In the 1938 survey, samples were collected using a 3-meter by 1.2-meter seine net with a 0.42-centimeter square mesh. As previously noted, Brown and Funk (1945) identified 121 sites sampled in the 1938 survey, only 90 of the original 121 sites had location descriptions that were sufficient to allow their relocation. These 90 sites were resampled using similar sampling methodologies as that of the 1938 survey (Newman et al. 1999). These 90 sites provided extensive coverage of the entire drainage basin (Figure 1), and allowed me to directly compare results from the two surveys under the assumption that each survey was subject to the same limitations imposed by the gear used.

In their survey, Brown and Funk recorded information on fish species caught and the size range of individuals caught. As such, I was limited to analyses on mottled sculpin presence and absence when making my comparisons. Sampling in the historical survey occurred between the months of May and August, and was conducted over the years 1938 to 1941. Changes in the distribution of mottled sculpin were determined by examining locations where fish were found in the 1938 survey only, in both the 1938 and 1996 surveys, and in the 1996 survey.

Land Cover

The next objective of this study was to quantify the land cover in the Huron River watershed in 1938 and 1996. As in Chapter 1, watershed boundaries were determined from 7.5-minute topographic maps available through the U.S. Geological Survey. The 1938 land coverage (referred to as the historical coverage throughout the remainder of this chapter) was determined by interpreting black and white aerial photographs obtained from the Center for Remote Sensing at Michigan State University. The 1996 land coverage (referred to as the modern coverage throughout the text) was available to me as a digitized and ground verified coverage by the Huron River Watershed Council

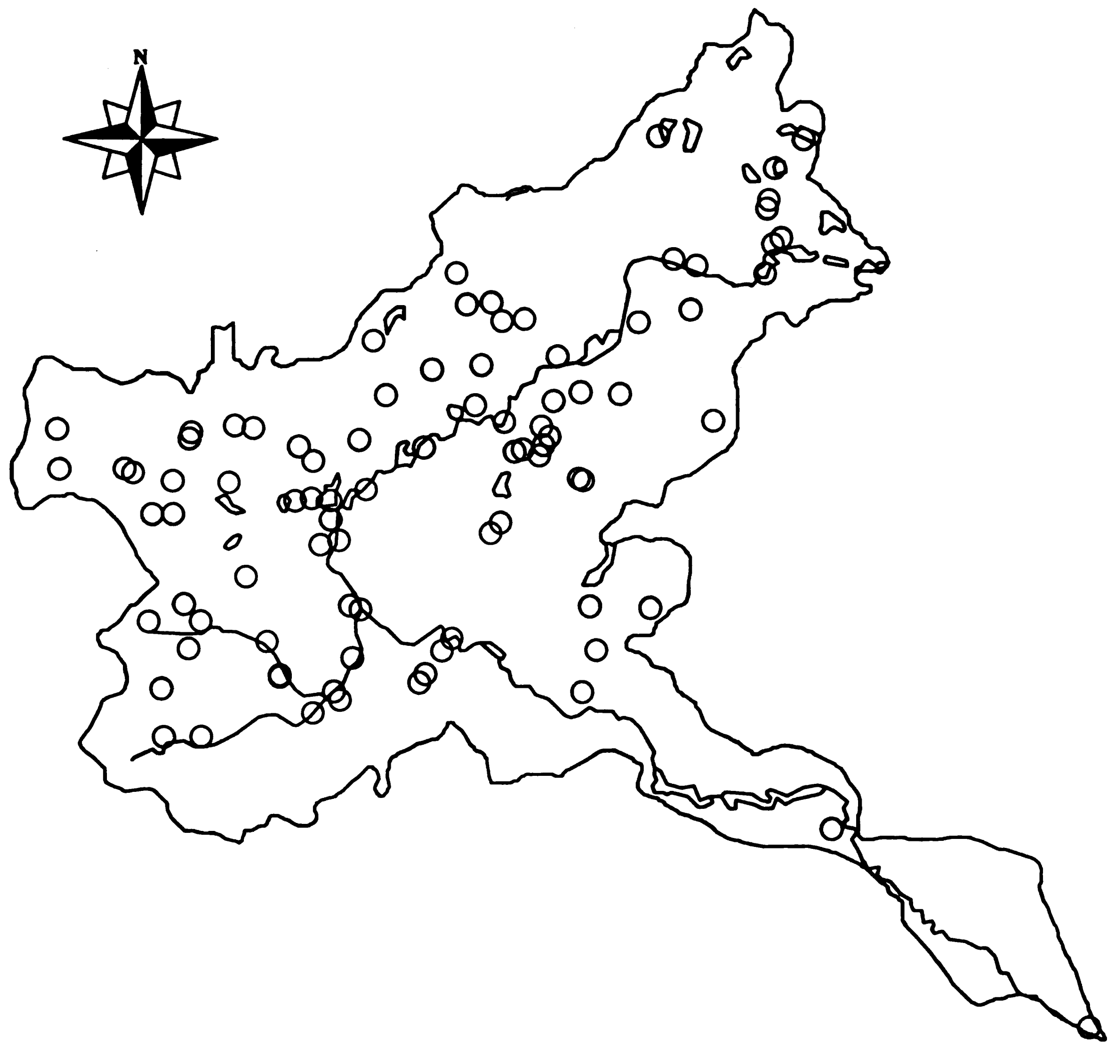

Figure 1. Extent of the 90 sites resampled in 1996 fish faunal survey of the Huron River watershed.

(HRWC). All land cover patterns were digitized and analyzed using ARC/INFO software (Environmental Systems Research Institute, 1998).

I will again use the term land cover as a description of the vegetation and artificial construction covering the land surface (Osborne and Wiley 1988). For both modern and historical coverages, the land cover classification system consisted of six general categories: urban, agriculture, nonforested (herbaceous and shrub cover), forested, water, and wetlands. Previously, I had included a category for barren lands but dropped that category because its contribution was insignificant to the total area of the watershed. Land cover patterns and the watershed boundary were treated as polygons (enclosed areas), stream networks as line coverages, and fish sampling sites as point coverages. All digitized coverages were converted to the Michigan State Plane NAD27 geographic projection. This standardization of the geographic projection was necessary to allow spatial overlays of any coverage type (i.e., polygon, line, or point) to be accomplished during analyses. The total area of each land cover category for each era (historical and modern) was determined using ARC/INFO software. The data from the two time periods were compared to assess the net change for each land cover category in the Huron River watershed between 1938 and 1996.

Mottled Sculpin Growth

My next objective in this study was to determine the pattern of growth of mottled sculpin throughout their current distribution in the Huron River watershed. To accomplish this, I resampled all of the sites where mottled sculpin were observed during the summer 1996 survey of the drainage basin (Newman et al. 1999). Mottled sculpin for age analysis were collected between October 2, 1996 and October 11, 1996, in order to allow fish to complete their growth for the season.

Mottled sculpin were captured using a Smith-Root, Inc., Model 12-A battery powered backpack electrofishing unit using programmable output waveforms (POW) which reduced the chance of causing damage to sensitive fish species (Barrett and Grossman 1988). Captured mottled sculpin were placed in a five-gallon bucket, and euthanized using tricaine methanesulfonate (MS-222) (Jearld 1983). Individual fish were measured to the nearest 1-mm total length and 0.1-g using a measuring board and a digital field scale. The fish were then placed in 95% ethanol for preservation and sealed individually in plastic bags with identifying tags made of waterproof paper.

In the lab, sagittal otoliths were used to age mottled sculpin. The sagittae were chosen because they are larger and easier to handle than lapilli, and have annuli that are relatively easy to observe (Katayama and Kawasaki 1994). The sagittae were removed by dissection. Otoliths were visible to the naked eye and usually easy to handle; however a dissecting microscope was used for the removal of otoliths from smaller fish. Both the right and left saggital otoliths were placed in individual labeled vials containing glycerin to promote clearing (Petrosky and Waters 1975, Hanson et al. 1992, Katayama and Kawasaki 1994).

After a period of five to ten days an otolith from each pair was removed from the glycerin and viewed under a dissecting microscope at 4.0X magnification. The right otolith was chosen preferentially for consistency, however there was no observable difference between right and left, as the left otolith was used on a few occasions when the right was lost or damaged. Measurements were taken from each otolith in the same way.

The total length of each otolith was taken, as well as measurements from the focus, the center of the opaque core, to each annulus and from the focus to the edge of the otolith.

The setup used to observe the otolith annuli was a simple slide on the microscope stage with a drop of glycerin added to the otolith being examined. A separate light source provided a combination of transmitted and reflected light. Depending on the size and clarity of the otolith, various combinations of transmitted and reflected light were most effective.

To examine differences in mottled sculpin growth among sites sampled, I used a general linear model of mottled sculpin growth (Weisberg and Frie 1987). The dependent variable in the model was the incremental growth observed for each fish in the sample during the 1996 growing season, and the independent variable was the estimated length of each fish at the beginning of the 1996 growing season. An analysis of covariance (ANCOVA) was used to test for differences among the sites sampled and any interaction between sites and the initial size of mottled sculpin in 1996.

Predictive ability of measured habitat parameters

A logistic regression model was developed using the SAS software as the platform (SAS Institute Inc. 1989). The logistic procedure in SAS fits a linear regression model for binary response data (i.e., presence verses absence) by the method of maximum likelihood. A model using temperature (°C), width (cm), depth (cm), and percent coarse substrates (> 8 mm in diameter) as explanatory variables was used. All variables were measured in the field while sampling the fish community in a separate but related study (Chapter 1), and information from all 90 sites sampled was used in this analysis. Substrate composition was based on a modified Wentworth classification for substrate particle sizes (Cummins 1962).

Results and Discussion

Changes in Mottled Sculpin Distribution between 1938 and 1996

Mottled sculpin were observed at 35 of the 90 sites sampled in the 1938 survey, and were widely distributed throughout the drainage basin (Figure 2). In 1996, the distribution of mottled sculpin within the Huron River watershed was greatly reduced from what was observed in 1938 (Figure 2), with mottled sculpin occurring in only 17 of the 90 sites we sampled. In fact, where mottled sculpin had once been distributed throughout the entire basin at the time of the historical survey, the distribution of the species in 1996 was primarily limited to the Mill Creek sub-drainage (Figure 2). Mottled sculpin were captured at four sites in 1996 where they were not reported from the earlier survey (Figure 2). These four sites may represent sampling variability during the historical survey, or could actually be shifts in the range of the species within the watershed since 1938.

Changes in Land Cover Between 1938 and 1996

Land cover changes and dam construction between 1938 and 1996 are described in Chapter 1. As before, agriculture was the predominant land cover in 1938, followed by forested lands, nonforested cover, and wetlands. Urban cover comprised only 5.5% of the watershed, while 3.6% of the watershed was covered with water. From 1938 to 1996, the acreage in four of the land cover categories increased while it decreased in two

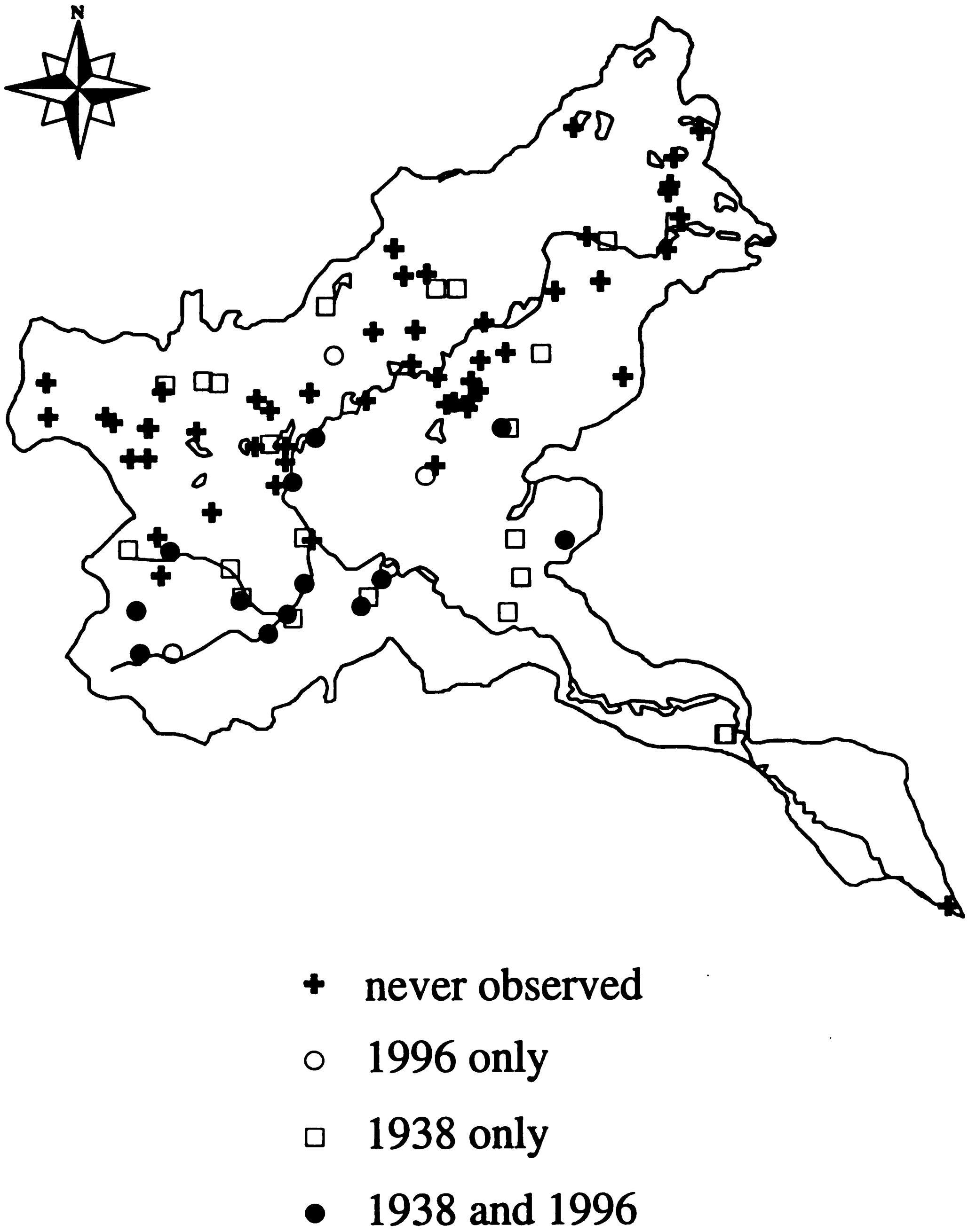

Figure 2. Changes in mottled sculpin distribution between the 1938 and 1996 fish faunal surveys of the Huron River watershed.

categories (Chapter 1, Table 1). The greatest absolute change between 1938 and 1996 was in the agricultural land cover category, which decreased by more than 69,000 hectares or by about 53 percent of the 1938 value (Figure 3). As agricultural lands decreased within the watershed, urban land cover increased by 51,159 hectares. As noted in Chapter 1, that increase represents nearly a 4-fold increase in urban land cover between 1938 and 1996. I observed the greatest concentration of increased urbanization radiating from the expanding Detroit metropolitan area (Figure 4).

Mill Creek is a large sub-drainage in the Huron River watershed that has undergone far less urbanization and dam construction since 1938 relative to the rest of the basin, and remains predominantly the agricultural landscape it was at the time of the historical survey (Table 1, Figure 3). It may be that the mottled sculpin in Mill Creek represent the source of a remnant population of fish from what was present earlier in the Huron River and its tributaries. I hypothesize that this remnant population likely exists due to the relatively small increase in human disturbance within the Mill Creek sub-drainage since 1938.

Mottled Sculpin Growth

In October of 1996, mottled sculpin were captured at fourteen sites of the seventeen sites where they were caught during the summer survey (Figure 5). A total of 223 individual fish were collected and preserved for otolith removal and analysis, however two individuals were destroyed during transport. Mean length and weight for all mottled sculpin collected were 70 mm and 6.0 g respectively, but varied considerably among sites sampled. Preservation in ethanol did not appear to damage otolith structure

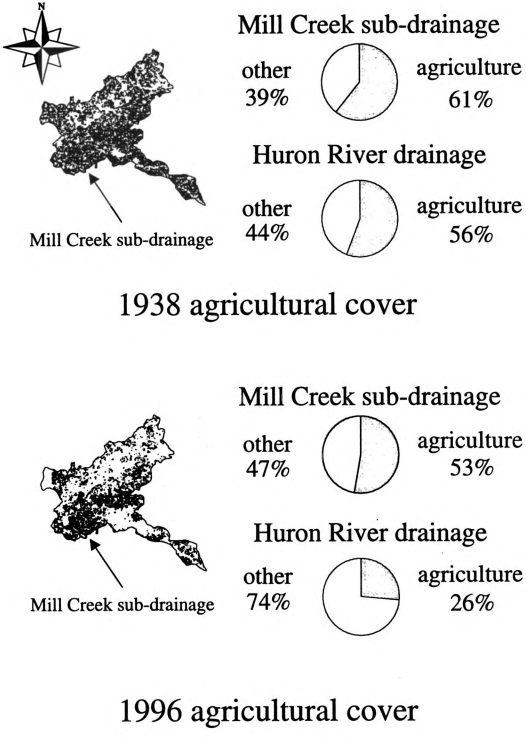

Figure 3. Basin-wide changes in the agricultural land cover observed within the Huron River watershed between 1938 and 1996. Agricultural lands shaded in black, all other land covers are white.

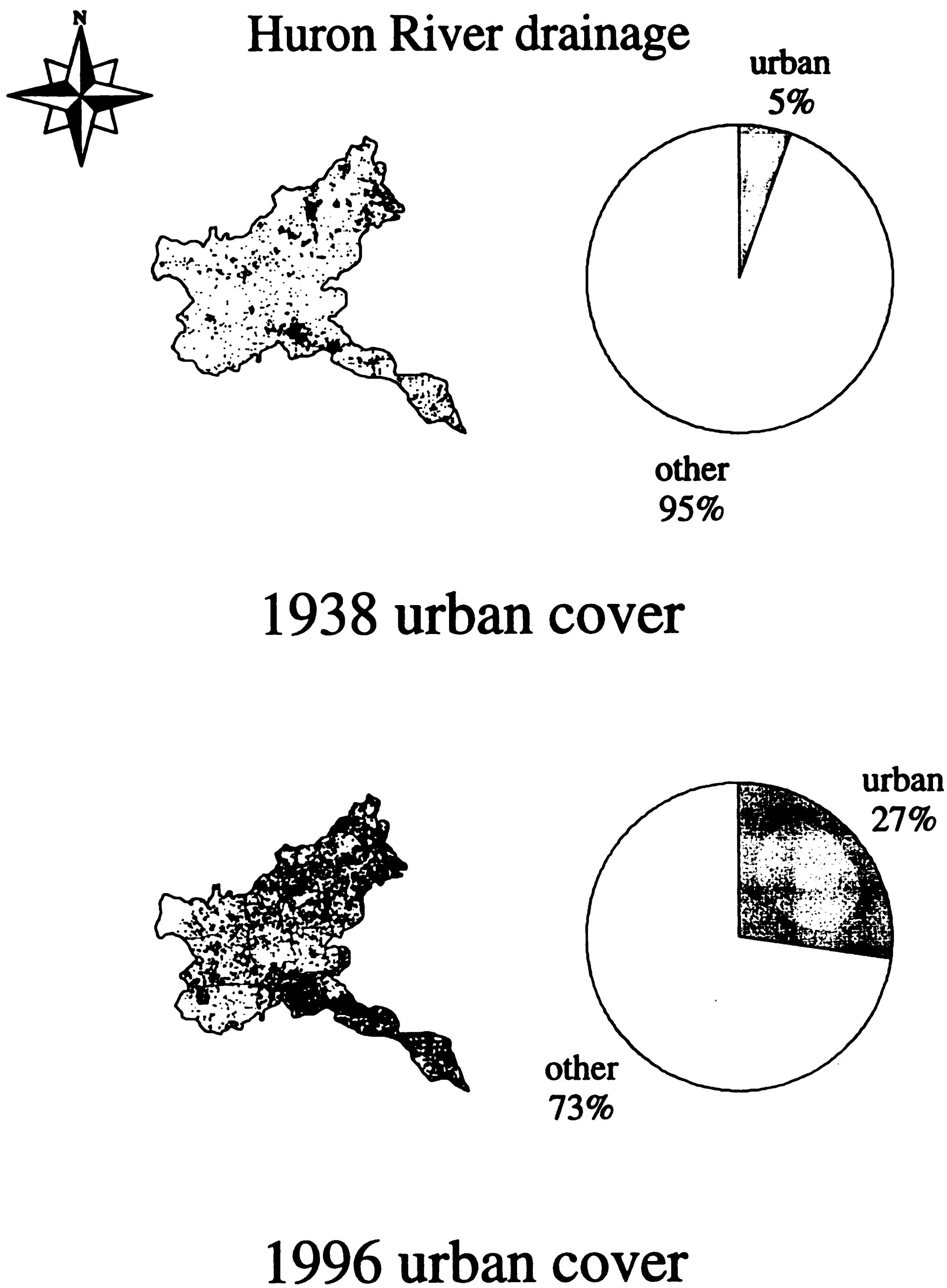

Figure 4. Basin-wide changes in the urban land cover observed within the Huron River watershed between 1938 and 1996. Urban lands shaded in black, all other land covers are white.

Table 1. Percent coverage of Mill Creek sub-drainage basin and percent change by land cover categories and year.

Land Cover	1938	1996	Change
urban	1.8%	9.1%	7.3% gain
agriculture	60.7%	52.8%	7.9% loss
nonforested	11.4%	13.6%	2.2% gain
forested	16.4%	14.9%	1.5% loss
water	2.2%	2.0%	0.2% loss
wetland	7.5%	7.5%	no change

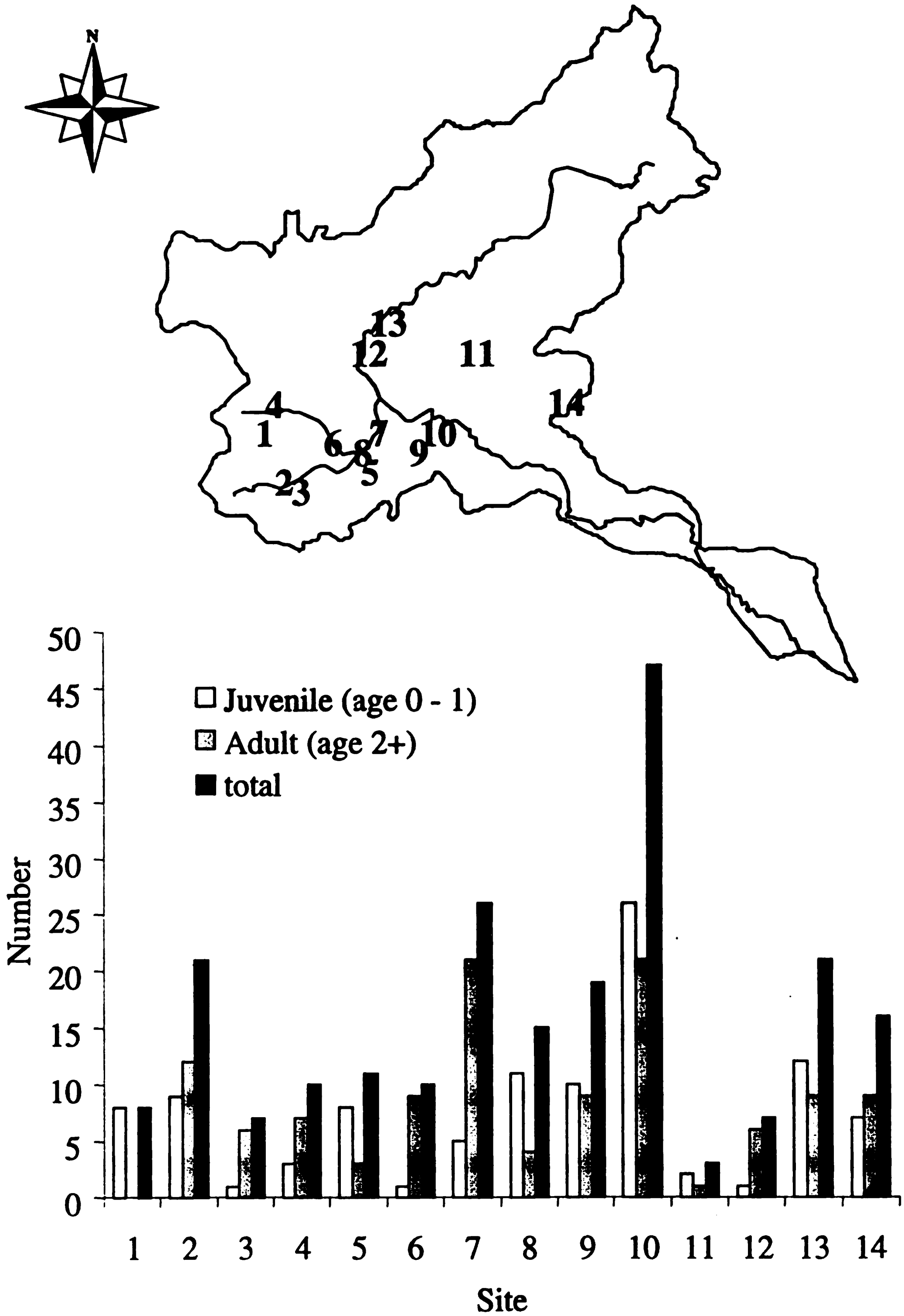

Figure 5. Location of fourteen sampling sites within the Huron River watershed where mottled sculpin were resampled in 1996.

in any way. Storage of the otolith in glycerin resulted in dramatic clearing after just a few days. A longer duration of storage in glycerin did not promote further clearing, but also did not appear to have any negative affects when making measurements of annuli distances for the back-calculation procedure. A simple linear regression of fish total length (mm) against otolith radius (mm) (N=221 fish) showed that the Y-intercept of the line describing that relationship was not significantly different from zero (P>0.05). Hence, back-calculated lengths at age were determined from the product of the ratio between otolith radius at age and otolith total radius times fish length at time of capture (Carlander 1981, Smale and Taylor 1987, Campana 1990, Francis 1990, Ricker 1992). The youngest mottled sculpin in our sample were in their first year, and the oldest individuals, based on reading of otoliths, were age seven. Mean lengths ranged from 41 to 109 mm among ages (Table 2).

A general linear model that included a categorical variable for site and an interaction term between site and the length of fish at the beginning of the 1996 growing season was developed to evaluate differences in mottled sculpin growth among the sites sampled. The model showed a significant relationship between annual incremental growth and the variables described (N=221, P<0.0001). However, neither the categorical site variable nor the interaction term between site and previous length were significant (P = 0.156 and 0.128 respectively). A reduced model that eliminated the interaction term was also evaluated, however the site variable was still not statistically significant (P=0.313). Because neither of these terms was significant in this model, it appears that growth was similar across sites. Thus, a simple linear regression model adequately describes the relationship between annual incremental growth and fish size at the

Table 2. Back-calculated length at age (mm) statistics for mottled sculpin collected (N = number collected, Max = maximum, Min = minimum, SD = standard deviation).

Age	N	Mean	Max	Min	SD
1	221	41	64	21	8.20
2	186	62	96	35	12.69
3	117	80	108	54	10.84
4	42	96	117	74	10.74
5	27	106	125	80	12.27
6	5	105	122	84	14.94
7	3	109	127	92	17.52

beginning of a growing season (N=221, P<0.0001, Figure 6). The linear model of mottled sculpin growth in the Huron River is:

$$I = -0.23L_0 + 31$$

In this model, I = annual incremental increase in fish length (mm) and L_0 = total length (mm) of a fish at the beginning of the growing season. The Y-intercept (31 mm) is the estimated length a fish will reach in its first year, and the slope (-0.23) describes the rate at which a fish approaches its estimated maximum length.

While these results did not indicate a difference in mottled sculpin growth among the sites sampled in the Huron River drainage, they do illustrate a key advantage to modeling mottled sculpin growth using the general linear model approach instead of more traditional methods (see: Von Bertalanffy 1938, Ricker 1975, 1979). Namely, that we can statistically compare growth patterns among different locations. It would also be possible, using these types of linear models, to incorporate other data (e.g., temperature, depth, width, or substrate composition) into the growth model relatively easily should the inclusion of such data be biologically sensible (Weisberg and Frie 1987).

Predictive ability of measured habitat parameters

The logistic regression using temperature (°C), width (cm), depth (cm), and percent coarse substrates (> 8 mm in diameter) as explanatory variables was unable to predict the presence or absence of mottled sculpin at a site. The SAS system provides three criteria for assessing model fit: 1) the Akaike Information Criterion (AIC), 2) the Schwartz Criterion (SC), and 3) the –2 Log Likelihood statistic (SAS Institute Inc. 1989). The –2 Log Likelihood statistic has a chi-square distribution under the null hypothesis

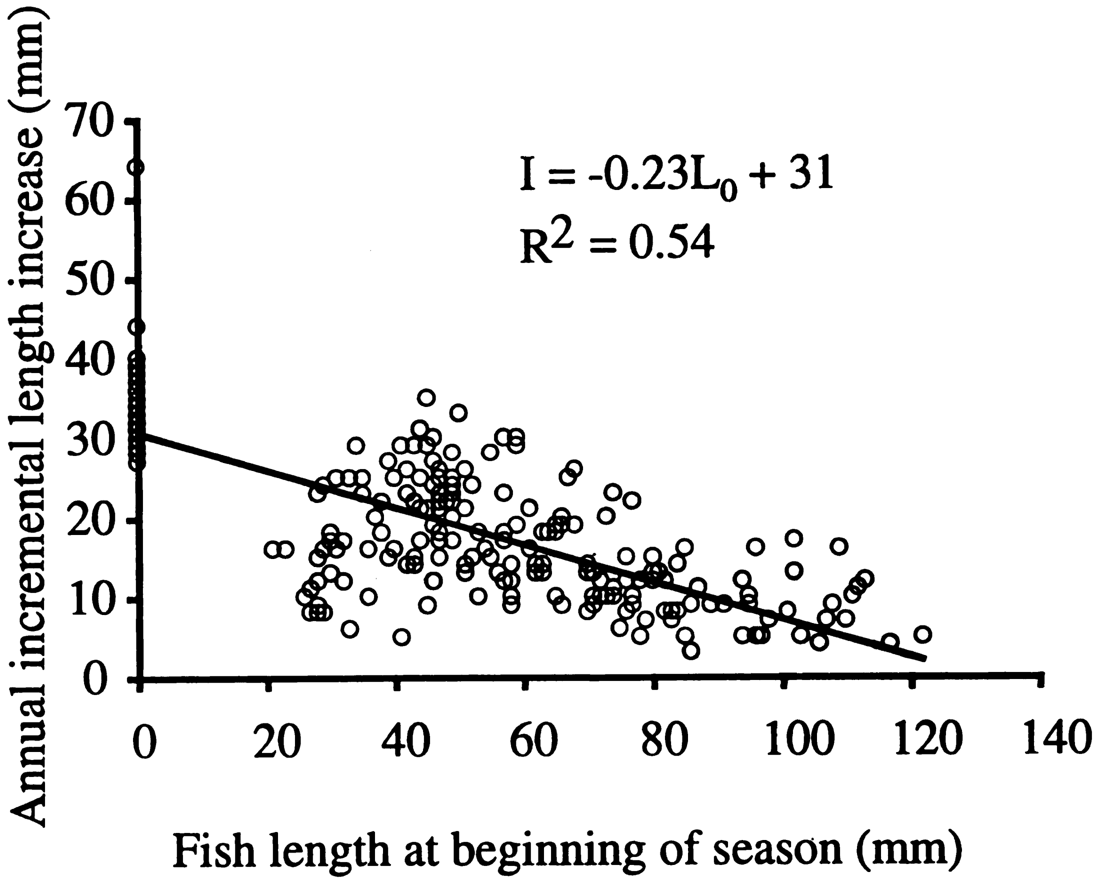

Figure 6. The simple linear regression model depicting mottled sculpin growth in the Huron River watershed.

that the effect of all the explanatory variables in the model are zero. The AIC and SC statistics give two different ways of adjusting the –2 Log Likelihood statistic for the number of terms in the model and the number of observations used. None of these statistics provided evidence of a significant model (P>0.05 in all cases, Table 3). Furthermore, none of the individual parameters had coefficient estimates that were significantly different from zero (P>0.05 in all cases, Table 4).

Because I was unable to detect any difference in the way mottled sculpin are currently growing among sites in the Huron River drainage or the ability of several on-site habitat parameters to predict the presence or absence of mottled sculpin, it may be that the occurrence and relative abundance of this species depends as much on the temporal variability, type and proximity of neighboring habitats as on the resources locally available at a given site. In his paper on source-sink dynamics and population regulation, Pulliam (1988) discussed the need to combine studies of local mechanisms controlling population regulation and species occurrence with "landscape" studies of the availability of habitat types on a broader scale.

In this study, five sites within the Mill Creek sub-drainage and near its confluence with the Huron River mainstem (i.e., sites 2, 3, 6, 7, and 10 – Figure 5) had the full compliment of ages observed. As such, the fish at these sites were typically larger than elsewhere. All other sites where mottled sculpin were recaptured in 1996 had only younger fish, ages 1 through 3, with the exception of three individual five-year-old fish found at two different sites. The relative abundance of mottled sculpin at the above listed five sites was also generally high when compared to the other sites sampled (Figure 5), although three sites on the periphery of the current range of mottled sculpin (i.e., sites 9,

Table 3. Model fit statistics for logistic regression used to determine if on-sight habitat variables could be used to predict mottled sculpin presence or absence.

Criterion[a]	Intercept only	Intercept and covariates	Pr > ChiSq[b]
AIC	89.229	89.010	0.0839
SC	91.729	101.509	0.1712
-2 Log Likelihood	87.229	79.010	0.2254

a. AIC = Akaike Information Criterian; SC = Schwartz Criterian; -2 Log Likelihood statistic

b. ChiSq = probability based on Chi-square distribution

Table 4. Analysis of maximum likelihood estimates of explanatory parameters used in logistic regression.

Parameter	DF[a]	Estimate	SE[b]	Pr > ChiSq[c]
Intercept	1	1.2882	1.8160	0.4781
Temperature	1	-0.0910	0.0965	0.3458
Width	1	-0.0012	0.0010	0.2357
Depth	1	0.0002	0.0080	0.9753
% coarse	1	-0.0059	0.0108	0.5841

a. DF = degrees of freedom

b. SE = standard error of the estimate

c. ChiSq = probability based on Chi-square distribution

13, and 14) also had an abundance of younger, smaller fish. These sites may represent what Pulliam (1988) described as "sink" habitats, where within-habitat reproduction is insufficient to balance local mortality. The abundance at sites on the edges of the current distribution of mottled sculpin may be dependent upon continual immigration from "source" habitats nearby, where there is a surplus of local reproduction that exceeds local mortality. Pulliam (1988) also argued that if limited reproduction occurred in these sink habitats along with continued immigration, that these sink habitats may actually support very large populations despite the obvious fact that they would eventually disappear without the influx of individuals from source habitats. In this sense, the "realized niche" of mottled sculpin within the drainage may actually be larger than the "fundamental Grinnellian niche" expanded on by James et al. (1984); a situation counter to the theoretical comparison of fundamental and realized niche sizes so elegantly proposed by Hutchinson (1958).

If the regulation of the mottled sculpin population within the Huron River drainage can accurately be described by source-sink dynamics, then the implications are important for future land development within the Mill Creek sub-drainage. Based on these data, the Mill Creek sub-drainage has undergone far less disturbance since 1938 than the rest of the Huron River watershed. The consequence of this is that Mill Creek represents a possible site for future development (i.e., a place where urbanization has not yet occurred). Should fisheries and land use managers misinterpret the relative abundance of a sensitive fish species like mottled sculpin in sink habitats, then the possibility of developing a sub-drainage that contains a relatively small source habitat could lead to local population extinction.

There is no way to be certain of the mechanisms causing the reduction in the distribution of mottled sculpin within the Huron River watershed, but the pattern of urban development, dam construction and loss of sites occupied by the species provides circumstantial evidence of an impact and warrants further investigation. It certainly would be difficult, if not impossible, to determine what the capacity of the Huron River was for mottled sculpin prior to the land cover changes that have occurred since 1938. But, as Rabeni and Sowa (1996) argued, the factors controlling the "livability" of the system are emergent properties from the broadest spatial scale. In this case, I conclude that urbanization at the watershed scale has had an effect on the ability of mottled sculpin to persist across a broad geographic range within the drainage.

Future research aimed at examining the relationship among mottled sculpin performance, population regulation and broad geographical patterns of land use at the edges of their diminishing range within the Huron River watershed would prove fruitful in clarifying the extent of the effect of human land use on fish success. I also believe that the influence of dam construction on source-sink dynamics and mottled sculpin survival would also be beneficial given results of my previous studies (Chapter 1). Clearly, the observed reduction in the range of mottled sculpin in the watershed between 1938 and 1996 suggests a loss of habitat necessary for their survival. However, determining the extent to which that habitat is a reflection of broader geographical influences still needs to be done. Future research would also benefit from a comparison of mottled sculpin growth in the Huron River with other stream systems that have been less impacted by human changes within the watershed.

Summary

Changes in the distribution of mottled sculpin, a fish species known to be sensitive to anthropogenic sources of fish habitat degradation shows that this population's distribution in 1996 was dramatically reduced from what it was in 1938. The reduced distribution of mottled sculpin within the watershed may be a response to human development within the drainage basin since 1938, or possibly even before that time.

A linear model of mottled sculpin growth significantly related the annual incremental increase in fish length to fish length at the beginning of the growing season ($P<0.0001$), but showed no statistically significant difference in fish growth rate across the species' current distribution in the watershed. What this means is that smaller or larger mottled sculpin found at any given site are not growing any differently than similar sized mottled sculpin at another site in this drainage basin.

Logistic regression on a suite of fish habitat parameters measured at each site failed to predict the presence or absence of mottled sculpin across their current range. Although this may reflect a choice of habitat measures that are inappropriate, I feel that the presence or absence of mottled sculpin at a site in the Huron River watershed is as dependent on the accessibility and quality of neighboring habitats as it is on proximate habitat measures. I believe that future work in meta-population analyses for this or other fish populations could result in major advances in our understanding of how fish populations relate to their habitat.

CHAPTER 3

THE EFFECT OF URBANIZATION ON THE HYDROLOGIC VARIABILITY OF THE HURON RIVER, MICHIGAN

Introduction

To this point, I have examined the spatial relationships among land cover, increasing urbanization and the fish community at several scales across the Huron River basin. In Chapters 1 and 2, I have shown that there have been significant reductions in the range and occurrence of many fish species in the Huron River. In this chapter, I will examine the effect of land cover change on the temporal variability of the hydrological regime of the Huron River in hopes of linking observed changes in land cover characteristics to the concurrent changes documented in the fish community.

The current paradigm among fisheries biologists is that urbanization of a streams watershed tends to result in the extirpation of fish species, loss of recreational fishing opportunities, groundwater depletion and reduced baseflow, increased frequency and intensity of flooding, and declines in water quality. This paradigm does not always rest on firm empirical evidence, however (Poff and Ward 1989). A growing body of work in community ecology suggests that large scale environmental factors, such as changes in land cover characteristics, may determine the structure of local biological communities (Ricklefs 1987, Roughgarden 1989, Ricklefs and Schluter 1993, Poff and Allen 1995). Much of this work suggests that it is the variability of critical physical components of ecosystems that determine the biological organization we observe. The importance of environmental variability in structuring biological communities has actually captured the interest of ecologists for a long time (Hutchinson 1961, Menge and Sutherland 1976, Wiens 1977, 1984, Connell 1978, Connell and Sousa 1983, Sousa 1984, Chesson 1986, Poff and Ward 1989), but stream ecologists seem to have become particularly interested in the regulation of community structure by temporal environmental variability (Poff and Ward 1989). This is due in part to the enormous variability often observed in lotic systems, especially with regards to streamflow. Arguably, variability in streamflow is one of the most important physical determinants of the suitability of stream ecosystems for fish because it shapes so many other aspects of fish habitat (e.g., habitat volume, current velocity, channel geomorphology, substrate type and stability, and the availability of resting, feeding, and reproductive habitats) (Hynes 1970).

Previous work has indicated that hydrological regime is an important constraint on the structure of biological communities in running waters. In their study of 34 midwestern streams, Poff and Allen (1995) demonstrated that hydrological factors played a significant role in determining fish assemblage. They hypothesized that hydrological alterations induced by climate change or anthropogenic disturbances (e.g., urbanization) could modify stream fish assemblages in the midwest. Other studies have also shown that extremes of flow and patterns of flow variability influence local fish community structure (Horwitz 1978, Meffe 1984, Coon 1987, Bain et al. 1988, Fausch and Bramblett 1991).

Flooding and unusually low flows affect the growth, reproductive success and survival of several life history stages of individual fish species in various ways (Toth et al. 1982, Schlosser 1985, Harvey 1987, and Nesler et al. 1988). Floods reconnect the stream channel laterally with the floodplain, and promote the exchange of sediment, woody debris, and other transportable materials. This material is often very important to the diversity of fish habitat and the productivity of both within-stream and floodplain components of the ecosystem (Sparks 1992, Toth 1995). Floods can also scour fine sediments from spawning gravels for salmonids thereby making these areas more suitable for successful reproduction (Beschta and Platts 1986), and can serve as environmental cues for the initiation of spawning (Nesler et al. 1988). However, floods have also been shown to cause both indirect and direct mortality for juvenile and adult fish (Schlosser 1985, Toth et al. 1982). The timing and duration of low flows can serve to isolate sensitive species from unfavorable water quality conditions during critical life history stages (Newman 1995). Prolonged low flows can however lead to the loss and fragmentation of habitat, disconnection of the stream channel from the floodplain, and reduced water quality for numerous fish species (Poff and Allen 1995).

Consequently, it seems that the maintenance of variability in flow regime can and does play an important role in the persistence of stream fish communities adapted to a particular regime. My goal in this chapter is to examine variability in the flow regime of the Huron River since the late 1930's, and to model the impact changes in land cover have had on that variability. The basic questions that need to be answered to accomplish this goal are first, has there been any change in stream flow of the Huron River since 1938, and second, to what extent does precipitation and land cover account for the observed discharge patterns for this river system. These models are intended to provide insight into the effect land cover changes have had on the fish community structure of the Huron River by virtue of disruption to the flow regime in the river, and by extension on fish habitat and the fish community.

To answer the above questions I used historical data on streamflow and precipitation for the Huron River watershed. First, I examined patterns in the variability of streamflow over the same time period that I had data describing changes in land cover and the fish community. I then combined quantitative measures of the changes in land cover over that time period (Chapter 1) with the observed streamflow data to model the impact land cover changes have had on the historical patterns of streamflow in the Huron River.

My expectations were: 1) that changes in land cover have increased the variability of streamflow in the Huron River since 1938, and 2) that changes in land cover have increased water yields in the Huron River since 1938. To evaluate my expectations, I had the following main objectives: 1) to quantify the variability in streamflow of the Huron River since 1938, 2) to quantify trends in the variability of streamflow of the Huron River since 1938, and 3) to model the effect of precipitation and land cover changes on the hydrologic variability of the Huron River since 1938.

Methods

Historical variability of the Huron River flow regime

In the first part of my analysis for this chapter I wanted to determine whether or not there had been any observable changes in the flow regime of the Huron River since 1938. To answer this question I split my examination of the historical patterns into two parts. I first wanted to simply describe the observed variability in flow since 1938. I then looked for patterns or any discernable trends in that variability over the period of record. I used several commonly applied methods to dissect the data for each of these objectives and answer the basic question. All analyses made use of the same hydrological and climate data series.

All hydrological data were acquired from a commercially available database (EarthInfo 1992) that consists of a digital compilation of the U.S. Geological Survey (USGS) daily value files. All data used in the following analyses and model development were drawn from the USGS-gauged site at Ann Arbor, Michigan. I chose this site because it had reliable long-term records of streamflow and because more than 75% of the watershed coverage is upstream of this site. The period of record used for all analyses and model development was from 1938 to 1992; each water year began on October 1 and ended on September 30. Precipitation data were acquired from the National Climate Data Center (NCDC) for the same time period, and consisted of an average of total precipitation (inches) recorded daily at the cities of Ann Arbor, Chelsea, Howell, Jackson, Milford, Pontiac, and Ypsilanti in the Huron River watershed.

I used a variety of methods to examine the flow patterns of the Huron River since 1938. I first computed and plotted the annual total discharge in cubic feet to examine variability over the entire period of record. I also examined the within and among year variation in daily flow by developing flow histories based on the long-term daily mean discharge records. These records were separated into three approximately equal intervals over the entire period of record and three-dimensional plots were constructed that had day of the water year on the x-axis, the year of record on the y-axis, and discharge (cfs) on the z-axis.

As discussed earlier, high and low flows are important in determining several components of fish habitat. Because of this, I developed high and low flow probability plots for Huron River. Probability plots show the percentage of time during a period of record when water flows exceed a given level. I used the recorded daily maximum and minimum flows from the entire period of record to develop these plots. After the annual maximum and minimum series were determined they were then ordered from highest to lowest. After ordering the data values, the largest value was given a rank of 1, the second highest value a rank of 2, and so on until all values were ranked with the lowest value having a rank equal to *N*, the total number of data points. A plotting position was then calculated using the Weibull method (Gordon et al. 1992). The Weibull method is the most commonly applied plotting position and is the method currently being used by the USGS. It is applicable for both annual and partial duration series (Dalrymple 1960). Construction of these probability plots then showed the largest flood (or conversely the largest of the low flow events in the annual minimum series) plotting near 0% (i.e., relatively little chance of that event ever being exceeded), and the smallest event in either series plotting near 100% (i.e., nearly all flows equal to or greater than these values).

To evaluate the relationship between observed precipitation and observed streamflow I plotted the annual values for each on the same page. This allowed me to explore if observed patterns in the variability of precipitation and discharge were similar over the period of record. I investigated the correlation between observed annual precipitation and observed annual discharge using linear regression. Finally, I developed a probability plot examining the likelihood of observing a high precipitation event in the Huron River watershed during the period of record using the same methods described above.

Trends in the variability of the Huron River flow regime

I used several measures to assess trends in the variability of streamflow over the period of record. I first computed coefficients of variation (CV) of daily flows for each year. The coefficient of variation is a useful measure for evaluating the overall variability in streamflow over the period of record (Poff and Ward 1989). The coefficient of variation of daily flow is a dimensionless index that represents the ratio of the mean daily flow over the period of record (in this case each year) to the standard deviation of daily flows, multiplied by 100 and expressed as a percent. I plotted the annual values along with a 10-year running mean of CV to investigate trends in the deviation of daily flows about their mean annual values since 1938. The 10-year running mean was an arbitrary choice, simply used to smooth the observed variability in CV and elucidate a pattern should one exist.

I also computed an index of flow stability that has previously been applied to Michigan rivers (Hay-Chmielewski et al. 1995). The index of flow stability is another dimensionless measure that represents the ratio of highest mean monthly flow to lowest mean monthly flow for each year. High ratios of these two numbers indicate unstable flows dominated by runoff. Low ratios indicate stable flows dominated by groundwater. In Michigan, values between 1.0 and 2.0 are indicative of stable groundwater-fed trout streams and values between 2.1 and 5.0 are considered good and representative of the State's better warmwater rivers (Hay-Chmielewski et al. 1995). I plotted the flow stability indices for each year over the period of record to evaluate trends in the stability of flows in the Huron River since 1938.

Changes in the annual yield of water from the Huron River might be expected given the increased urbanization in the watershed since 1938. I calculated annual yield as the ratio of the total discharge in cubic feet divided by the total precipitation in cubic feet (i.e., sum of the annual precipitation converted from inches to feet and multiplied by the area of the watershed), multiplied by 100 and expressed as a percent. I then plotted those annual yields along with a 10-year running mean to explore trends in yield over the period of record.

Finally, I examined trends in the probability plots for observed monthly average discharge (cfs). I again separated the period of record into three intervals (approximately 18 years for each period). Probability plots for each interval were calculated as described above and plotted on the same graph to evaluate changes in observed monthly average discharge over the entire period of record. I also calculated and plotted the probability of exceeding an observed monthly average precipitation event for each interval to determine if any observable trends in discharge could be attributed solely to changes in the precipitation patterns as opposed to changes in something else (e.g., land cover).

Modeling the contribution of precipitation and land cover to the Huron River flow regime

In the second part of my analysis for this chapter, I wanted to determine the extent land cover played in determining the observed pattern in discharge of the Huron River. To answer this question I developed a series of models that predicted patterns in discharge from observed patterns in precipitation, land cover characteristics, and different components of water storage within the watershed. Six different models were developed that increased in complexity from a very simple model to one that was much more detailed. Furthermore, each of these was applied to a full year time series and to a baseflow data series (defined throughout this chapter as the period between May 1 and Oct 31). The reason for using a baseflow data series was to evaluate if changes in land cover characteristics would produce a better signal in modeled discharge during that time of year when we would expect surface water runoff to be most responsive to land cover types (i.e., during the low flow period for the year). Some models were optimized with bounds on the runoff coefficients derived from the current literature, and some were optimized with the runoff coefficients unbounded. In all, 19 different models were developed that allowed me to examine both improvement in the fit of a given model (i.e., a reduction in the residuals produced by the fit of a model) and the relative contribution of different land cover coefficients to the improvement of model fit. The simplest model developed was based on annual discharge and precipitation data and treated all land cover in the same way. The most complex model developed made use of daily discharge and precipitation data, had both groundwater and surface storage components, and incorporated the observed changes in land cover since 1938. All models were developed in a spreadsheet and coefficients for all models were estimated using the nonlinear optimization routine applied by Microsoft Excel Solver®. Microsoft Excel Solver® uses the Generalized Reduced Gradient (GRG2) nonlinear optimization code developed by Leon Lasdon, University of Texas at Austin, and Allan Waren, Cleveland State University.

My simplest model of discharge makes use of the commonly applied "rational formula" (Morris and Fan 1997), and I will refer to it as the rational model throughout the remainder of this chapter. The rational model has the form:

$$Q = CIA$$

In this model, Q = discharge (ft^3/s), I = precipitation (ft), A = the river's drainage area (ft^2), and C = a dimensionless runoff coefficient. In this simple model, land cover characteristics are ignored, and all land cover is treated in the same way (i.e., a single runoff coefficient is estimated for the entire drainage basin). I also aggregated the discharge and precipitation data from daily values to annual values before developing this model. This model was optimized for both the full year and baseflow data series. The runoff coefficient was left unbounded in each case.

The next level of complexity I modeled was to include runoff coefficients for each land cover type included in the model. Land cover types included urban, agriculture, nonforested, forested, water, and wetlands. The area in each land cover category was determined for five different time steps or years since 1938 (Table 1). Land cover patterns were based on aerial photography from the late 1930s through the 1990s. Mapping resolution for these data is approximately 1 ha, with a minimum lateral dimension of 61 m, and all land cover patterns were digitally mapped and quantified using a geographic information system (ARC/INFO). I used a linear interpolation of these values to estimate the area of the different land cover categories for years between the five time steps. This provided best estimates of land cover areas in each category for each year between 1938 and 1992, which I then matched with the discharge and precipitation data to develop the models.

Discharge, precipitation, and land cover data were again all aggregated from daily values to annual values before developing these models. I optimized the model for both the full year and the baseflow data series, and with bounded and unbounded runoff

Table 1. Total areas in each land cover type for the five time steps in the period of record.

Land cover type	Year 1938	1957	1971[a]	1981	1992
Urban	1,621,502,678	2,064,553,834	619,842,804	2,283,685,741	2,725,820,482
Agriculture	7,739,740,116	7,353,461,319	7,535,443,513	6,208,220,810	5,950,566,696
Nonforested	3,337,703,978	3,073,587,799	4,130,058,380	4,376,384,789	4,050,236,143
Forested	3,779,342,358	4,191,315,160	4,378,636,264	3,900,811,049	3,951,453,601
Water	883,383,112	892,956,283	943,846,403	907,937,237	998,986,060
Wetland	1,904,604,393	1,690,402,239	1,658,449,271	1,589,237,009	1,589,213,651
Total	19,266,276,635	19,266,276,635	19,266,276,635	19,266,276,635	19,266,276,635

a. Land cover areas in 1971 reflect errors in aerial photography interpretation that were unable to be reconciled at this time. As such, interpolation of daily land cover characteristics did not make use of this time step.

coefficients. Bounds for all land cover runoff coefficients ranged from greater than 0.05 to less than 0.90 (Morris and Fan 1997). This annual model with runoff coefficients has the form:

$$Q = I(\beta_1 UB + \beta_2 AG + \beta_3 NF + \beta_4 FR + \beta_5 WT + \beta_6 WL)$$

In this model, Q = discharge (ft^3/s), I = precipitation (ft), UB = the river's drainage area in urban cover (ft^2), AG = the river's drainage area in agricultural cover (ft^2), NF = the river's drainage area in nonforested cover (ft^2), FR = the river's drainage area in forested cover (ft^2), WT = the river's drainage area in water cover (ft^2), WL = the river's drainage area in wetland cover (ft^2), and β_x = a dimensionless runoff coefficient for each of the land cover types.

The third level of complexity I incorporated into these hydrological models was to include a component for groundwater storage and a separate transfer coefficient from groundwater to discharge. The groundwater component was included to account for the relatively deep, slow movement of water through the soils that provides water to the stream channel even during periods of little or no precipitation. My intent was to improve the fit of the models by accounting for streamflow in the absence of precipitation and to better match the timing and peaks of the observed hydrograph more precisely. I again optimized these models for both the full year and the baseflow data series, and with bounded and unbounded runoff coefficients. Bounds for all land cover runoff coefficients ranged from greater than 0.05 to less than 0.90. Bounds for the transfer coefficient from groundwater to discharge were intentionally kept very liberal and ranged from greater than 0 to less than 0.95.

The next level of models was similar in structure to the previous model described, but made use of discharge, precipitation, and land cover data on a daily basis. I did this because the previous models were overly simplified in that they only allowed water (whether from surface runoff or groundwater storage) to move once each year. These new models allowed water to move more dynamically each day of the year for the entire period of record. My intent was to improve on the realism of the models and again to better match the timing and peaks of the observed hydrograph more precisely. As in the last series of models, bounds for all land cover runoff coefficients ranged from greater than 0.05 to less than 0.90, and bounds for the transfer coefficient from groundwater to discharge ranged from greater than 0 to less than 0.95.

The final level of complexity that I incorporated into these models was to account for depression storage, also with a separate runoff coefficient from depression storage to discharge. I accounted for all above ground storage within the drainage basin in this single component (i.e., both deep and shallow depressions). Both groundwater and depression storage had capacities and initial storage values that I allowed the model to optimize. These capacities were used to account for saturated overland flow when all land cover types act the same by shunting any accumulation from precipitation immediately to streamflow. These models also made use of all data on a daily basis. These models were optimized using both the full year and the baseflow data series, and with bounded and unbounded runoff coefficients. Bounds for all land cover runoff coefficients remained from greater than 0.05 to less than 0.90. Bounds for the transfer coefficient from groundwater to discharge and for the runoff from depression storage ranged from greater than 0 to less than 0.95. I compared the results of this complex model with the results from the rational model to see if the added complexities developed actually mirrored what we would expect given what we know about the hydrological cycle and movement of water through a landscape. All models were tested using an approximate general linear test to see if they differed significantly in their ability to predict streamflow (Neter and Wasserman 1974). I also examined how well this complex model matched the timing and peaks of the observed hydrograph for a period of years early in the data series (1938 through 1940), a period near the middle of the data series (1965 through 1967), and a period of time near the end of the data series (1990 through 1992). This allowed me to evaluate if the models performed better at any given time throughout the period of record and to speculate on the reason for any differences in model fit over that time frame.

I developed one final model that was fundamentally similar to the most complex model described above. The major difference in this model from the one just described is that I standardized the runoff coefficients to stay within a range similar to the values typically reported throughout the literature. I did this by first fitting the model as described above, and then assigning runoff coefficient values for each of the land cover types from the reported literature (Morris and Fan 1997). I then uniformly adjusted the land cover coefficients until the model most closely predicted the observed total water yield. In a sense this was like fitting the model by hand, a procedure that is generally used in practice. Once I had approximated the total water yield as best I could, I then allowed the model to optimize the transfer coefficients, the initial storage values and the capacities for depression and groundwater storage. The end result was that I produced a model that maintained the relative magnitude of the land cover coefficients from my most complex model, but that had coefficients that were more easily interpreted relative to the current state of knowledge. This was all accomplished with little expense to the sums-of-squares of the most complex model. I compared the resulting predictions of this standardized model with the predictions of the best-fit model using linear regression.

I developed the standardized model so that I could simulate the effects of changes in land cover in meaningful ways. By keeping land cover areas at their 1938 values for the entire data series, I was able to evaluate the impact of observed changes in land cover on the flow regime of the Huron River since that time using this model. I compared the predicted discharge under the observed changes in land cover since 1938 with the predicted discharge if land cover had not changed since that time using linear regression.

Land-use planners and developers estimate that urban land cover will increase within the Huron River watershed by at least 40% in the next ten to twenty years (Chapter 1). Using the standardized model, I simulated what the discharge patterns would look like if the entire watershed was urbanized and what that discharge pattern would look like if the entire watershed was forested. These simulations effectively bounded the variability I might expect to see predicted by the model at the extremes of land cover characteristics. I then simulated a 45% increase in urban cover over the next twenty years. I absorbed the losses to urban cover entirely from agricultural cover. This may be an over-simplification of the dynamics of land cover change for the next twenty years, but it is reflective of the nature of changes observed since 1938 throughout the watershed. Using a random number generator, I generated random values for daily precipitation based on the mean and standard deviation of the observed daily precipitation values for this simulation. I plotted the predicted discharge patterns under the observed patterns of change in land cover, the discharge patterns predicted for an entirely urbanized and forested watershed, and the simulated 45% increased urban cover on the same graph. This allowed me to evaluate any trends in the simulated pattern of discharge over the next twenty years relative to the models predictions under the other scenarios. Finally, I compared the simulated 45% increase in urban cover to the observed patterns in streamflow since 1938 to determine if any trends produced by the model were outside of the observed variability in the flow regime of the Huron River since that time.

Results and Discussion

Variability in Huron River flow regime 1938 - 1992

A plot of total discharge (ft^3) by year recorded at the Ann Arbor USGS gauge-site shows that there has been considerable variability in streamflow in the Huron River at this site since 1938 (Figure 1). The minimum total discharge of 3,825,792,000 ft^3 was observed in 1948, while the maximum total discharge of 28,043,107,200 ft^3 was recorded just two years later in 1950. Minimum values in the series appear to be higher after the mid-1960s, but no clear trend in the total annual discharge is discernable given the large amount of year to year variability in the record.

By separating the daily flow records at this site into three approximately equal time intervals between 1938 and 1992, I was able to examine the within and among year variation in the daily discharge patterns individually for each of those periods. The Huron River reportedly does not experience the same degree of seasonal variability in streamflow through the early part of the water year (October through May) that other more northern Michigan streams do because of the regular pattern of thawing and re

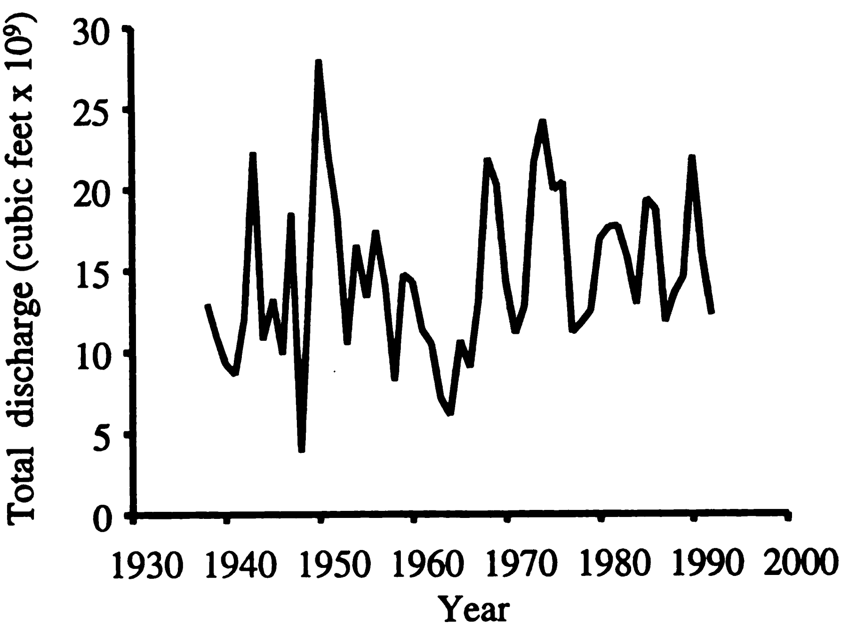

Figure 1. Observed total discharge at the Ann Arbor USGS gauged-site between 1938 and 1992.

-freezing that occurs in southern Michigan (Hay-Chmielewski et al. 1995). Plots of the daily discharge pattern for the years between 1938 and 1955 suggest that the Huron River had a seasonal discharge pattern dominated by snowmelt early in the water year, resulting in pronounced, seasonal runoff patterns (Figure 2). This pattern continued between 1956 and 1974, but the frequency and magnitude of the daily peaks during the snowmelt-dominated period began to diminish (Figure 3). Plots of the daily discharge patterns between 1975 and 1992 (Figure 4) reflect the stable pattern described by Hay-Chmielewski et al. (1995), but I will argue later that this evenly distributed pattern of high and low daily flows throughout the water year are as likely due to other anthropogenic causes as they are to the climate of southern Michigan.

Daily discharge patterns in the Huron River have been highly variable since 1938. Examination of the annual maxima and minima shows that flow at Ann Arbor gauge station has ranged from as low as 6 cfs to a high recording of 5,170 cfs. As discussed earlier, these high and low flow events often serve as ecological "bottlenecks" that present critical stresses and opportunities for many fish species (Poff and Ward 1989). I constructed probability plots for both the annual maximum and the annual minimum series in the Huron River since 1938. The probability of a high flow event between 5,000 cfs and 3,000 cfs diminishes quickly; the "typical" high flow event of 1,890 cfs is exceeded in about 50% of the years (Figure 5). The probability plot of low flow events diminishes at a much more gradual rate over the entire range of the annual minimum series, with typical low flow events below 69 cfs about 50% of the time (Figure 6).

All streamflow derives ultimately from precipitation, but at any time and in any place that precipitation is modified by some combination of climate, geology,

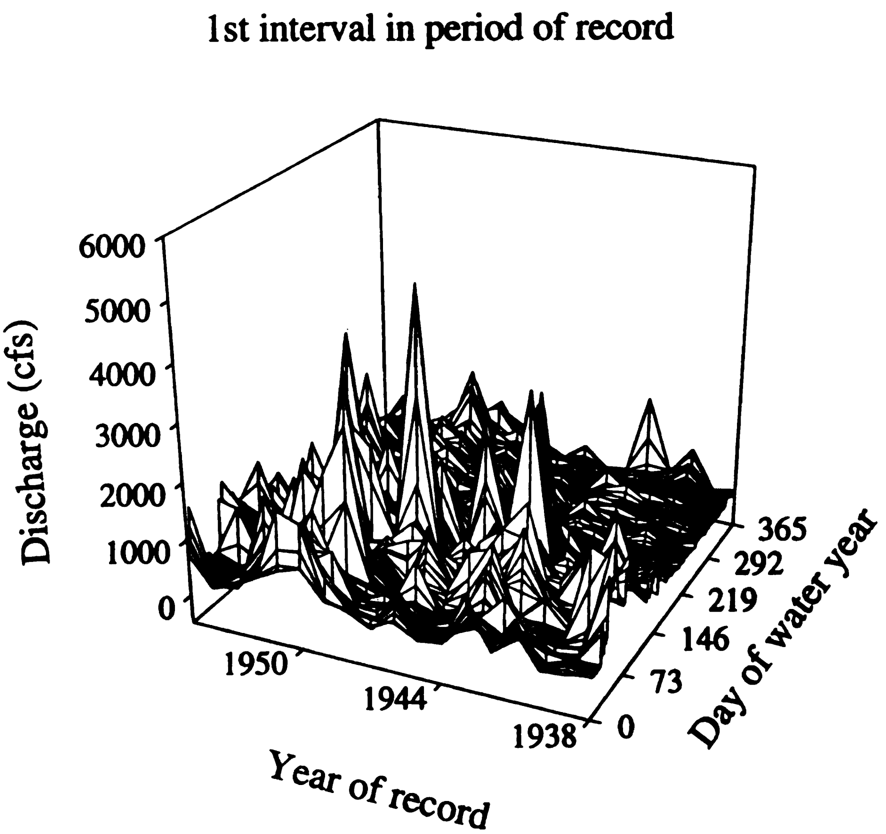

Figure 2. Observed daily discharge by day of the water year (October 1 through September 30) between 1938 and 1955.

2nd interval in period of record

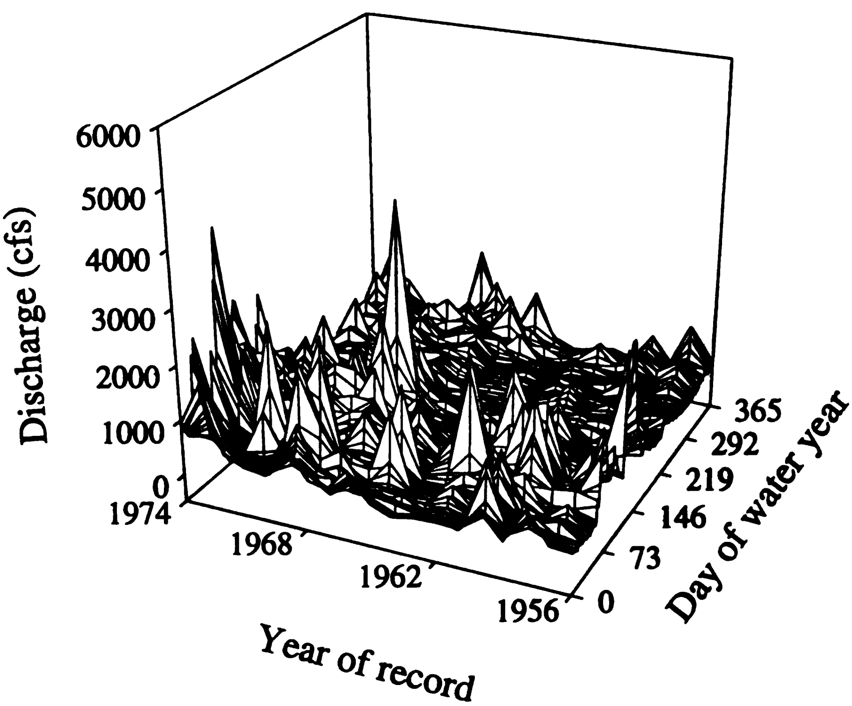

Figure 3. Observed daily discharge by day of the water year (October 1 through September 30) between 1956 and 1974.

3rd interval in period of record

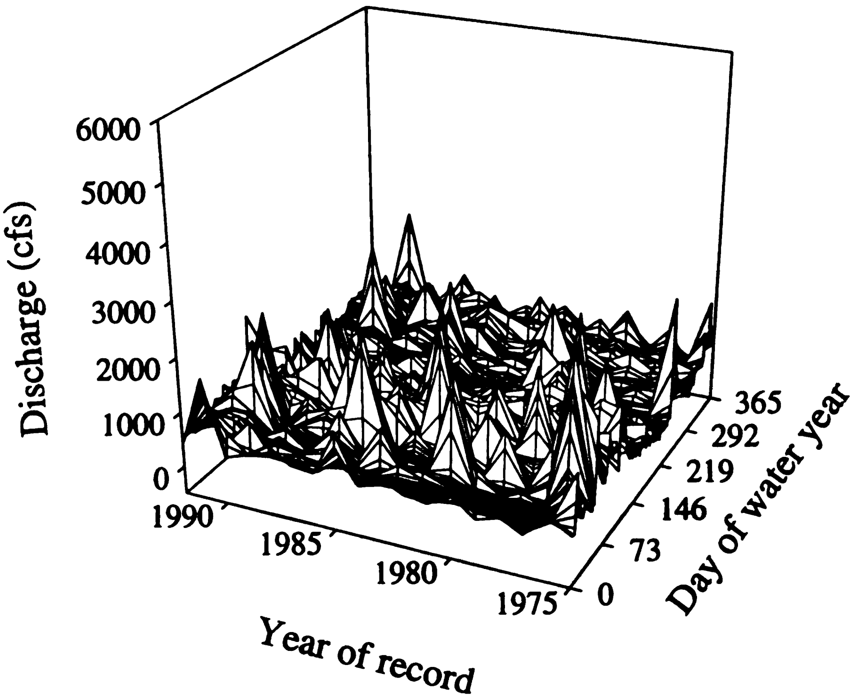

Figure 4. Observed daily discharge by day of the water year (October 1 through September 30) between 1975 and 1992.

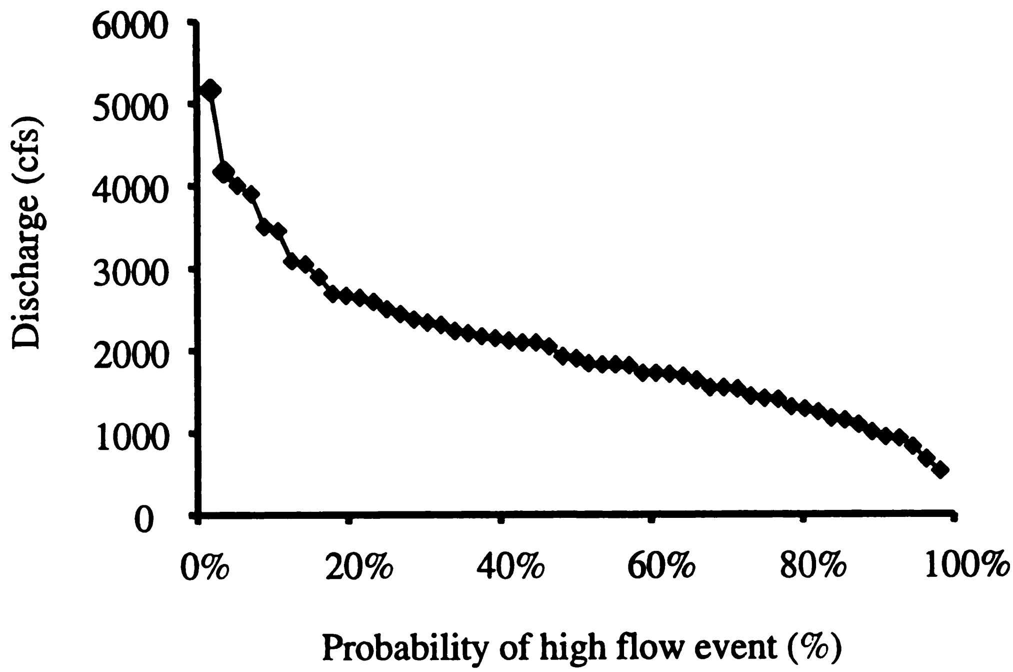

Figure 5. Probability of observing a high flow event in the Huron River. Based on the annual maximum series between 1938 and 1992.

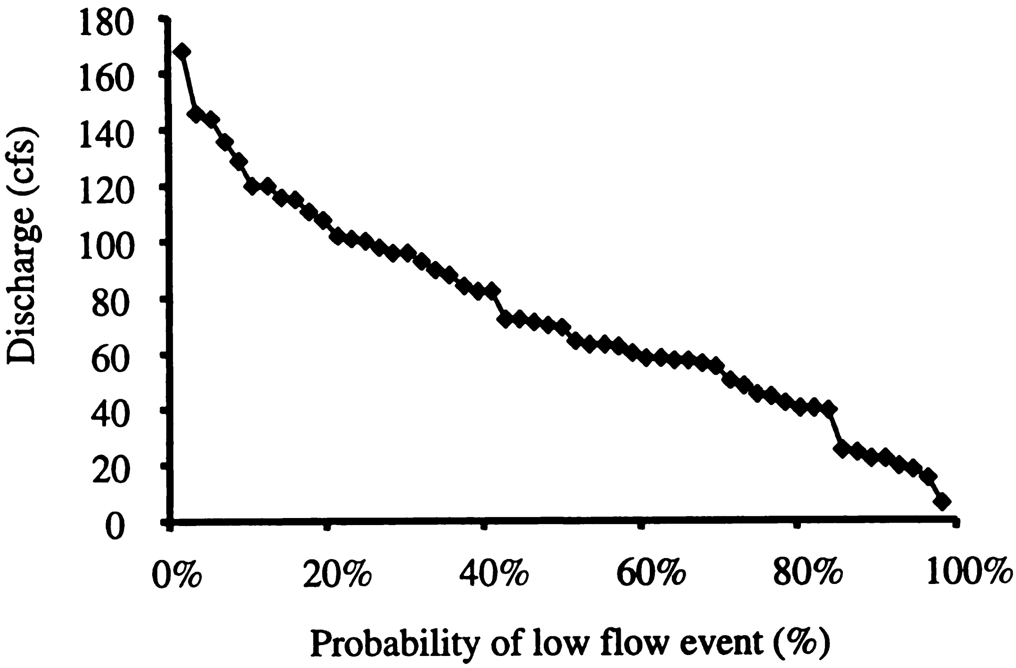

Figure 6. Probability of observing a low flow event in the Huron River. Based on the annual minimum series between 1938 and 1992.

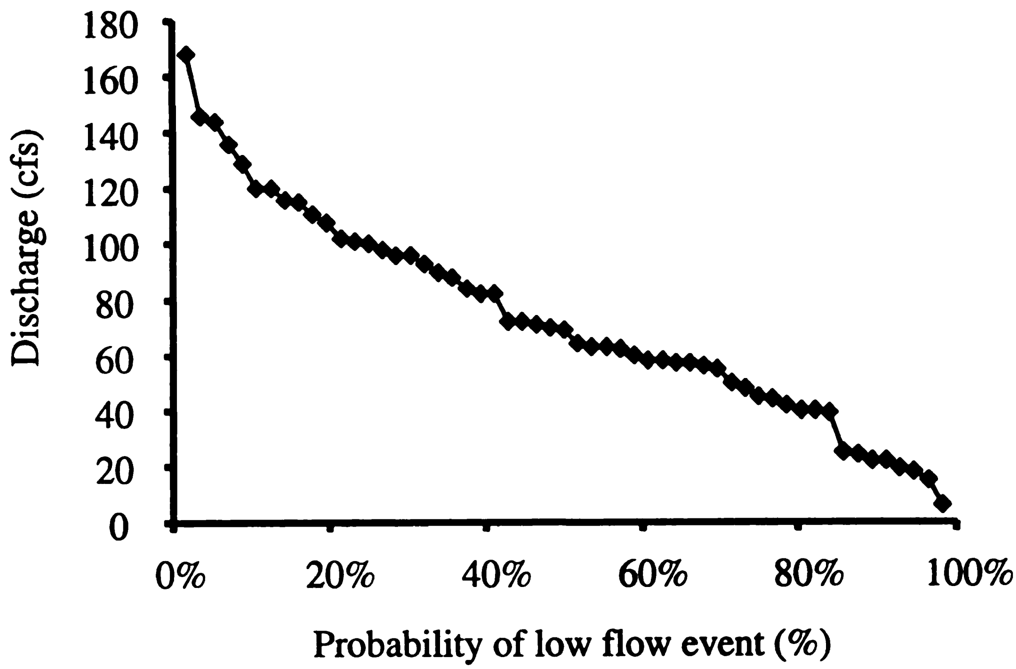

Figure 6. Probability of observing a low flow event in the Huron River. Based on the annual minimum series between 1938 and 1992.

topography, soils, and land cover characteristics (Poff et al. 1997). Streamflow in the Huron River is also closely linked to precipitation events. Examination of the annual plots of total precipitation (ft^3) and total discharge (ft^3) suggests that while high and low peaks in the two plots tend to track each other closely, the year to year variability in precipitation was less than that observed in streamflow (Figure 7). A linear regression of these two parameters resulted in a significant positive correlation ($R^2 = 0.31$), but there was considerable scatter in the data about the regression line (Figure 8). The probability plot of the annual maximum series of precipitation had a gradual decline from the highest observed events to the lowest observed in the series (Figure 9). This is indicative of a relatively stable pattern in precipitation since 1938, with these high events exceeding 1.37 inches about 50% of the time.

Trends in the variability of the Huron River flow regime

Because it may be the patterns of streamflow variability that sustains native biodiversity and maintains ecosystem integrity in rivers, I wanted to examine trends in the observed variability of streamflow in the Huron River since 1938. Based on previous studies, my expectation was that increased urbanization of the watershed since 1938 had likely produced a much more variable system since that time (Gordon et al. 1992).

I began my investigation of the trends in streamflow variability by calculating and plotting the annual coefficient of variation (CV) in daily flows along with a 10-year running mean of those values on the same graph. The annual CV values indicated substantial variability about the daily mean flow for any given year, but no clearly defined upward or downward trend was apparent (Figure 10). There does appear to be an

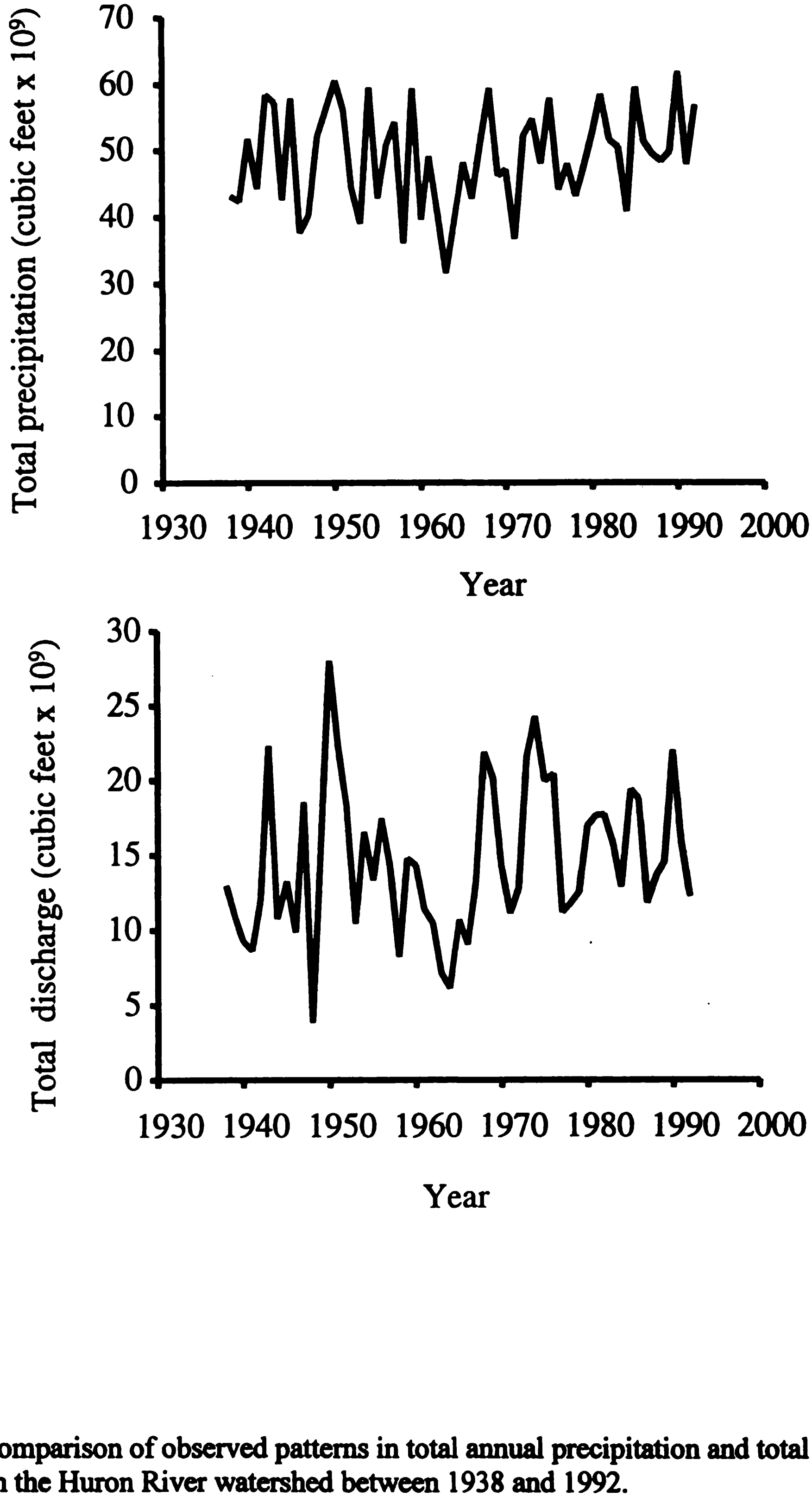

Figure 7. Comparison of observed patterns in total annual precipitation and total annual discharge in the Huron River watershed between 1938 and 1992.

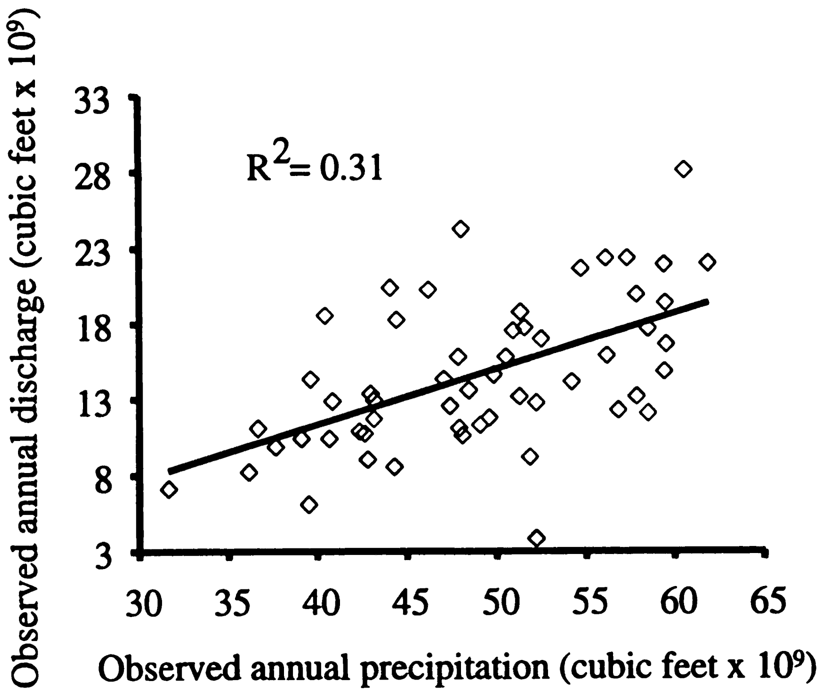

Figure 8. Results of linear regression of observed total annual precipitation and total annual discharge in the Huron River watershed between 1938 and 1992.

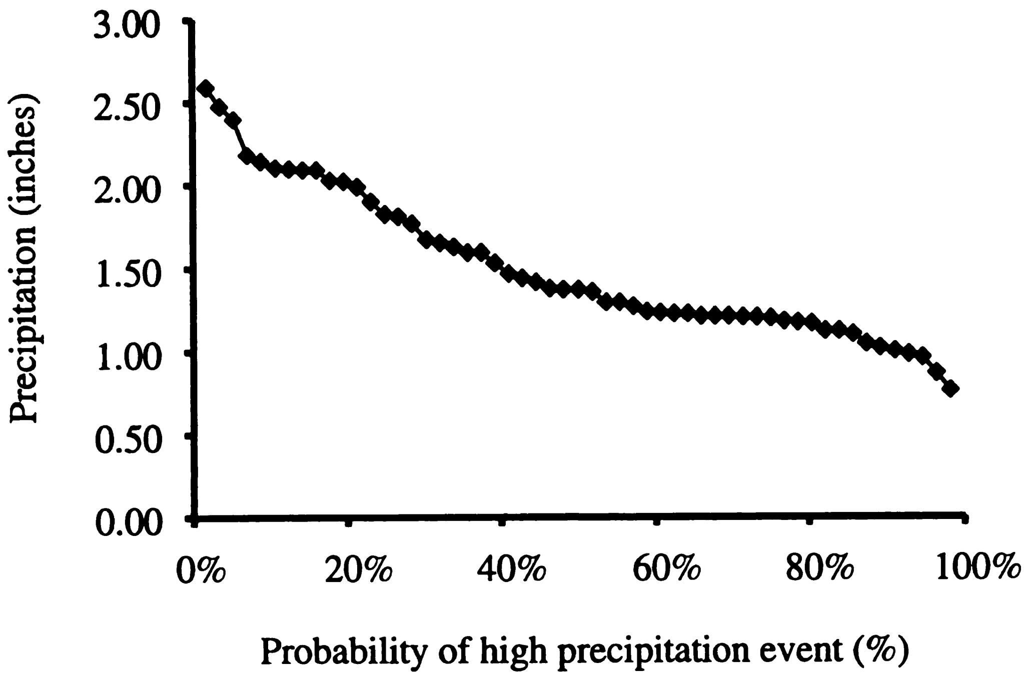

Figure 9. Probability of observing a high precipitation event in the Huron River watershed. Based on the annual maximum series between 1938 and 1992.

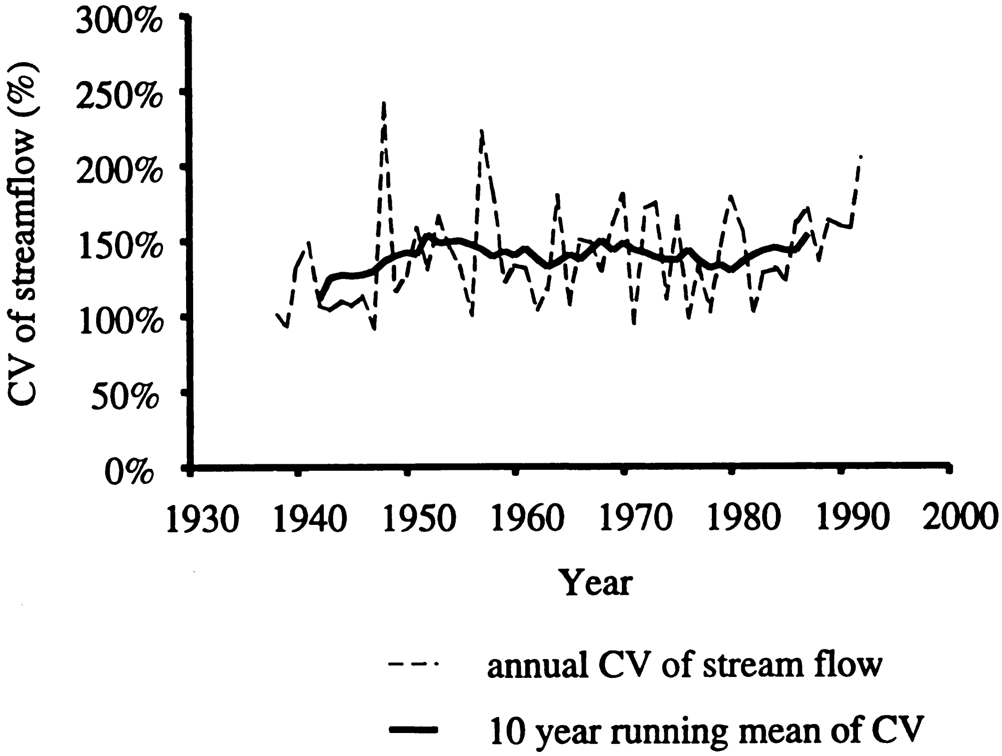

Figure 10. Observed pattern and 10-year running mean of the annual coefficient of variation (CV) of streamflow in the Huron River between 1938 and 1992.

increase in the CV values over the last two decades, but not outside of the range of variability observed in these values historically. Often, using a running mean of highly variable values will elucidate a pattern when one otherwise would be indistinguishable from the noise in a data set. In this case, the 10-year running mean showed no obvious trend in the overall variability of streamflow in the Huron River since 1938.

I also calculated an index of annual flow stability that has been used for other streams in Michigan (Hay-Chmielewski et al. 1995). By doing this, I was able to compare the stability of flow in the Huron River with other published reference points for the State of Michigan. Although there have been a few high spikes in the annual flow stability index since 1938 (Figure 11), the observed variability in the index was well within the bounds considered to be good for Michigan's warmwater streams (Hay-Chmielewski et al. 1995). Further, there does not appear to be a trend toward greater or lesser stability over the time series. The relative stability of the Huron River at Ann Arbor is surprising given the well documented flashiness (i.e., the rapid rate of change in flow) in tributaries upstream (Hay-Chmielewski et al. 1995). As water moves downstream within the Huron River watershed, I would expect streamflow at Ann Arbor to reflect the sum of flow generation and the routing processes occurring in all the flashy tributaries upstream. And yet, the stability index values at Ann Arbor are indicative of a stream more dominated by groundwater discharge than flashy runoff. This is counter to what I had expected given the increased urbanization of the watershed upstream of this site. I had expected to see less stable flows and an increase in the magnitude and frequency of the flashier, peak runoffs and a reduction in the levels of baseflow. These index values and my analysis of the daily discharge patterns since 1938 (Figures 2

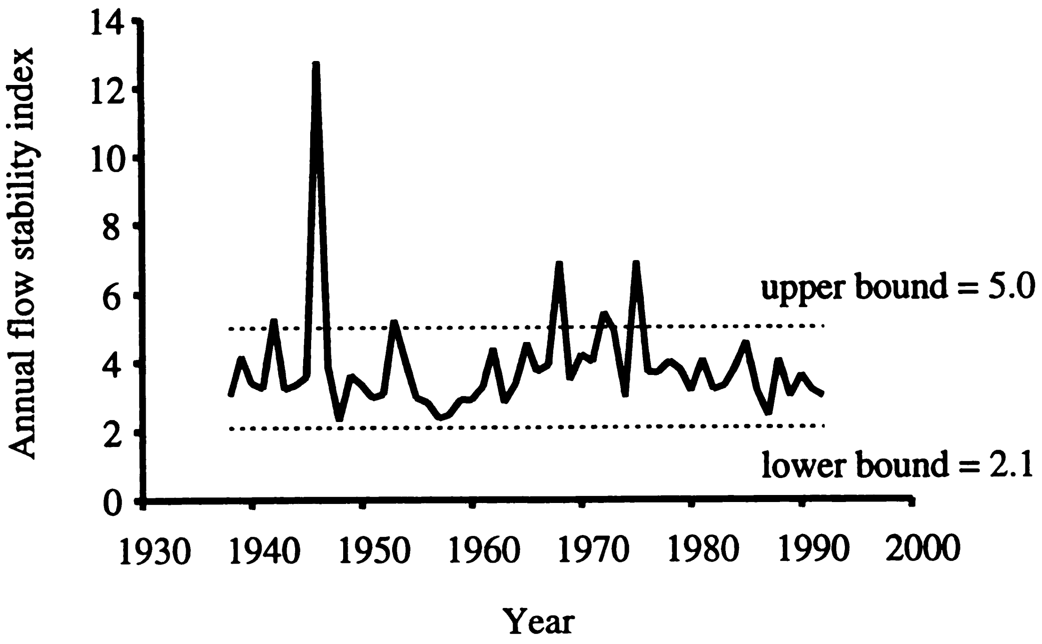

Figure 11. Observed pattern of the annual flow stability index in the Huron River between 1938 and 1992. Upper and lower bounds based on expected values for stable warmwater streams in Michigan.

through 4) suggest that streamflow at Ann Arbor is relatively stable compared to other systems throughout the State, and that the flashiness of flow at this site has diminished over time.

Annual water yields in the Huron River since 1938 also show considerable variability. However, plotting the 10-year running mean of yield values from 1938 to 1992 does not reveal a general upward trend, though there may be a slight increase in yield since about the mid-1960s (Figure 12). Interestingly, there is a trough in the 10-year running mean centered between the late 1950s to the early 1960s, indicating an overall reduction in water yields during this period. The overall trend (or lack thereof) in water yields mirrors what I have uncovered in my previous analyses.

Separating the streamflow data into the three time intervals used earlier, I was able to look for trends in the probability plots for monthly average discharge. Generally, there is a rapid decrease in the observed monthly average discharge from about 1,000 cfs to 600 cfs, with average monthly flows exceeding 416 cfs about 50% of the time (Figure 13). It appears that for the most recent interval (1974 through 1992) there has been a slight upward shift in the curve. This indicates that streamflow has become somewhat higher in recent years.

Treating the precipitation data in a similar way, I was able to also examine trends in the probability plots of exceeding monthly average precipitation events since 1938. This was important for determining if trends in streamflow were dominated by trends in precipitation. Precipitation gradually declines from high monthly average values of 0.12 inches to 0.05 inches, with average monthly precipitation exceeding 0.08 inches 50% of the time for the entire period (Figure 14). No obvious differences in the patterns exists

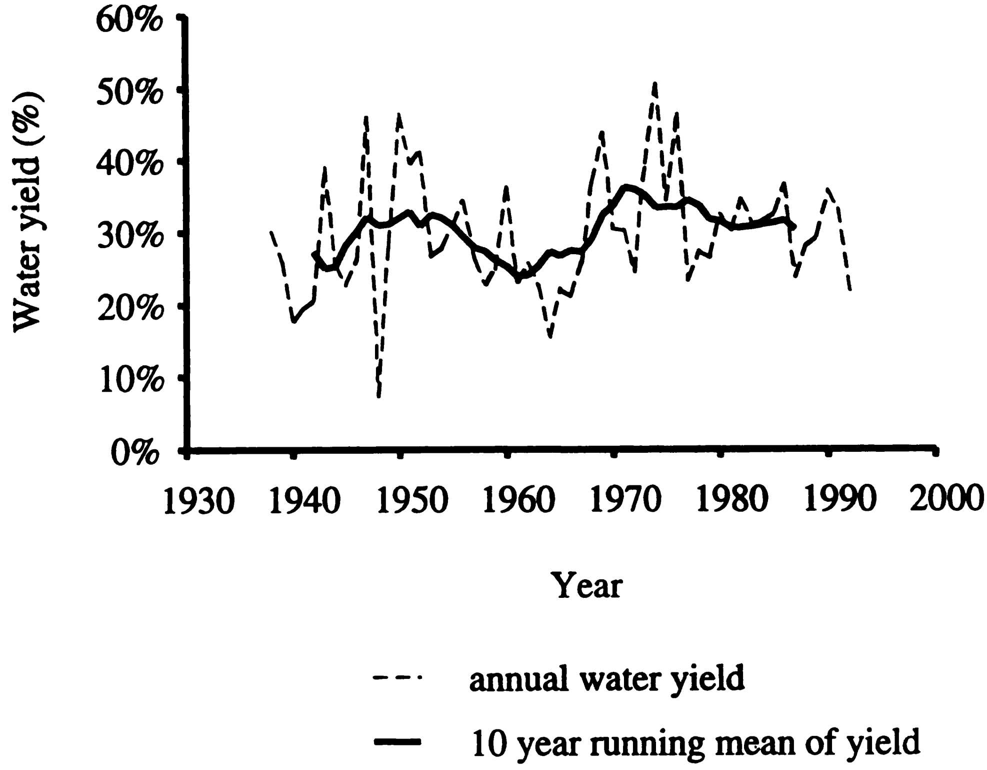

Figure 12. Observed pattern and 10-year running mean of the annual water yields in the Huron River between 1938 and 1992.

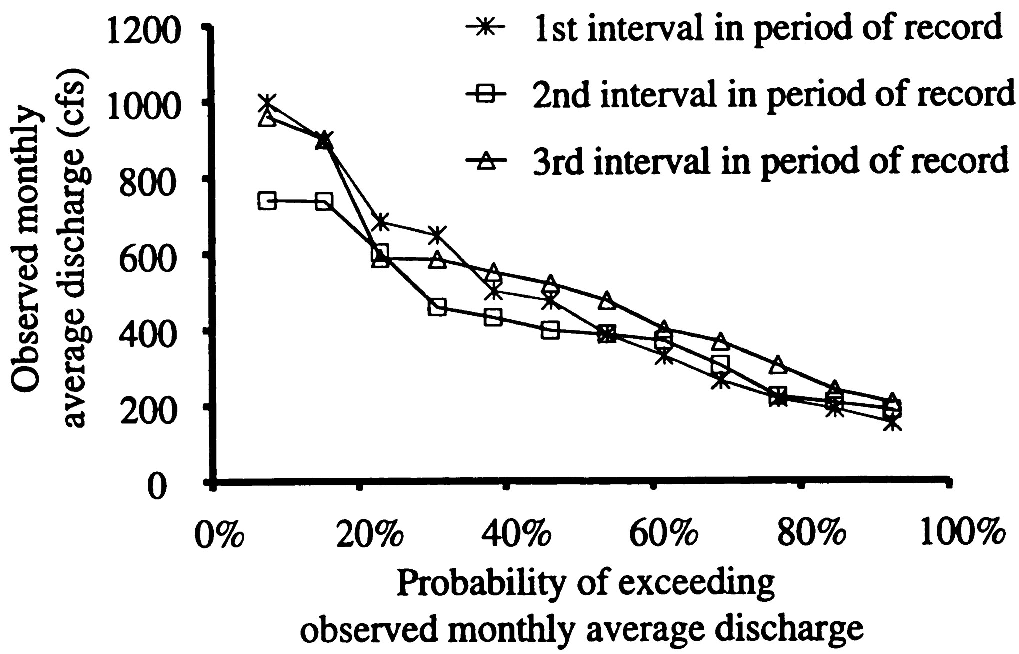

Figure 13. Probability of exceeding the observed monthly average discharge in the Huron River for the intervals 1938 to 1955 (1st interval in period of record), 1956 to 1974 (2nd interval in period of record), and 1975 to 1992 (3rd interval in period of record).

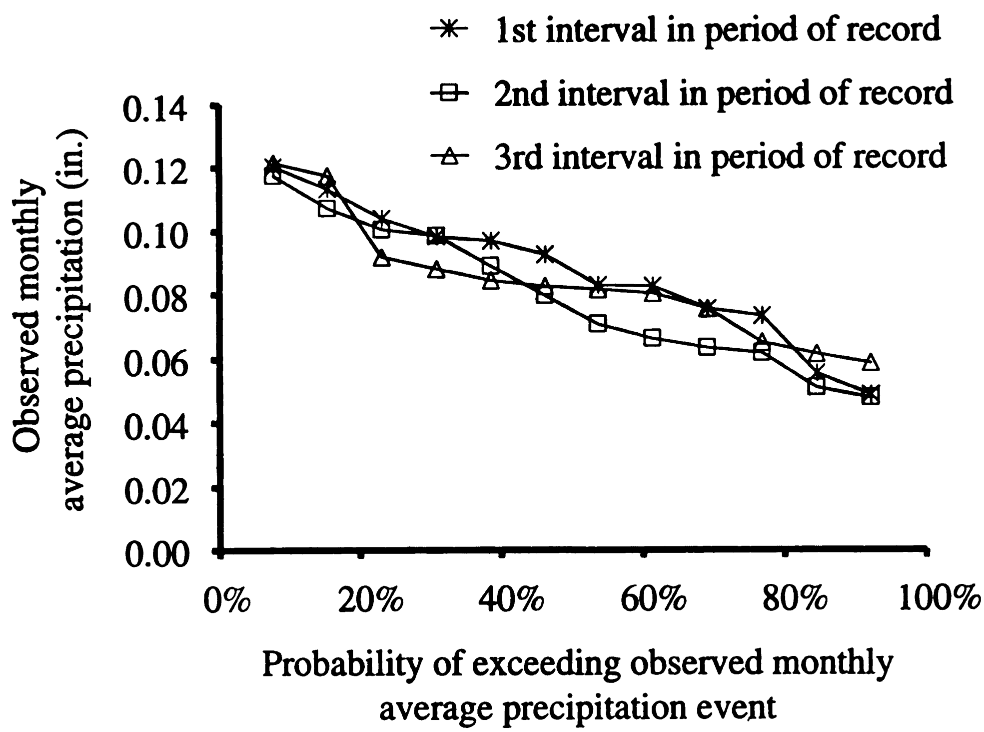

Figure 14. Probability of exceeding the observed monthly average precipitation event in the Huron River watershed for the intervals 1938 to 1955 (1st interval in period of record), 1956 to 1974 (2nd interval in period of record), and 1975 to 1992 (3rd interval in period of record).

among the three intervals suggesting that precipitation patterns have not changed considerably since 1938, and that both the trough in water yield observed between 1950 and 1970 and the generally higher flows since that time are due to other anthropogenic causes.

Modeling the contribution of precipitation and land cover to the Huron River flow regime

I developed a range of models to evaluate the extent to which precipitation and land cover characteristics defined the observed patterns of discharge in the Huron River. The simplest of these was the rational model of streamflow, which ignores land cover characteristics entirely (Morris and Fan 1997). The most complex model included components for groundwater storage and transfer to discharge, depression storage and transfer to discharge, all the observed changes in land cover characteristics since 1938, and was modeled for the baseflow (May through October) season only. This complex model resulted in the best fit to observed streamflow (Table 2), but total sums-of-squares values did not differ significantly (P>0.05) among any of the models developed. Sums-of-squares for models based on a full year time series are calculated using more observations than are models using the baseflow time series, hence values are not directly comparable between full year time series models and baseflow time series models because they are on different scales. Plotting results of the rational and "best-fit" model on the same page, relative to observed streamflow, shows graphically that these two models produce nearly equal discharge predictions (Figure 15). These results suggest that land cover characteristics may not be as important in determining streamflow in the Huron River as I had expected.

Table 2. Runoff coefficients and residual estimates for all models of Huron River streamflow developed.

Model constraints	DB	DS	GS	UB	AG	NF	FR	WT	WL	SSQ[b]
				Runoff coefficients[a]						
Rational model										
Full year unbounded	0.30									929,024,152
Baseflow unbounded	0.19									207,225,738
Annual model with runoff coefficients only										
Full year bounded				0.05	0.05	0.65	0.71	0.05	0.05	895,875,865
Full year unbounded				-1.52	-0.23	1.03	2.71	-0.90	-1.88	878,716,626
Baseflow bounded				0.05	0.10	0.27	0.42	0.05	0.05	205,826,631
Baseflow unbounded				-1.75	-0.16	0.81	2.19	-0.83	-1.52	200,269,188
Annual model with runoff coefficients and groundwater storage										
Full year bounded			0.2878	0.15	0.22	0.89	0.05	0.23	0.29	1,083,938,628
Full year unbounded			0.2799	-3.62	0.25	2.31	2.36	-1.48	-2.76	1,032,368,468
Baseflow bounded			0.1276	0.05	0.19	0.47	0.06	0.18	0.14	272,319,559
Baseflow unbounded			0.1245	-668.44	-502.91	-111.10	674.42	998.12	1008.48	268,503,753
Daily model with runoff coefficients and groundwater storage										
Full year bounded			0.0007	0.05	0.20	0.77	0.05	0.05	0.90	1,293,852,500
Full year unbounded			0.0005	-24.38	37.20	12.19	-41.18	256.92	-184.93	1,132,727,418
Baseflow bounded			0.0011	0.05	0.20	0.39	0.05	0.05	0.36	311,110,882
Baseflow unbounded			0.0009	-39.63	-24.56	-3.51	34.25	64.99	44.18	287,394,110
Daily model with runoff coefficients, groundwater and depression storage										
Full year bounded		0.2137	0.1034	0.05	0.31	0.55	0.05	0.05	0.30	1,035,780,284
Full year unbounded		0.2017	0.1070	-112.78	-89.51	-19.65	118.90	151.27	190.90	1,022,188,537
Baseflow bounded		0.5544	0.0672	0.05	0.21	0.23	0.05	0.25	0.17	197,848,378
Baseflow unbounded		0.5071	0.0676	-83.13	-61.24	-13.54	81.97	133.78	120.38	196,982,705
Standardized model										
Baseflow		0.5710	0.0678	0.23	0.17	0.15	0.10	0.20	0.18	198,369,232

a. Runoff coefficient abbreviations: DB = drainage basin; DS = depression storage; GS = groundwater storage; UB = urban; AG = agriculture; NF = nonforested; FR = forested; WT = water; WL = wetland.

b. SSQ = total sum of squares. All SSQ values were divided by 10^6 to facilitate model fitting procedures.

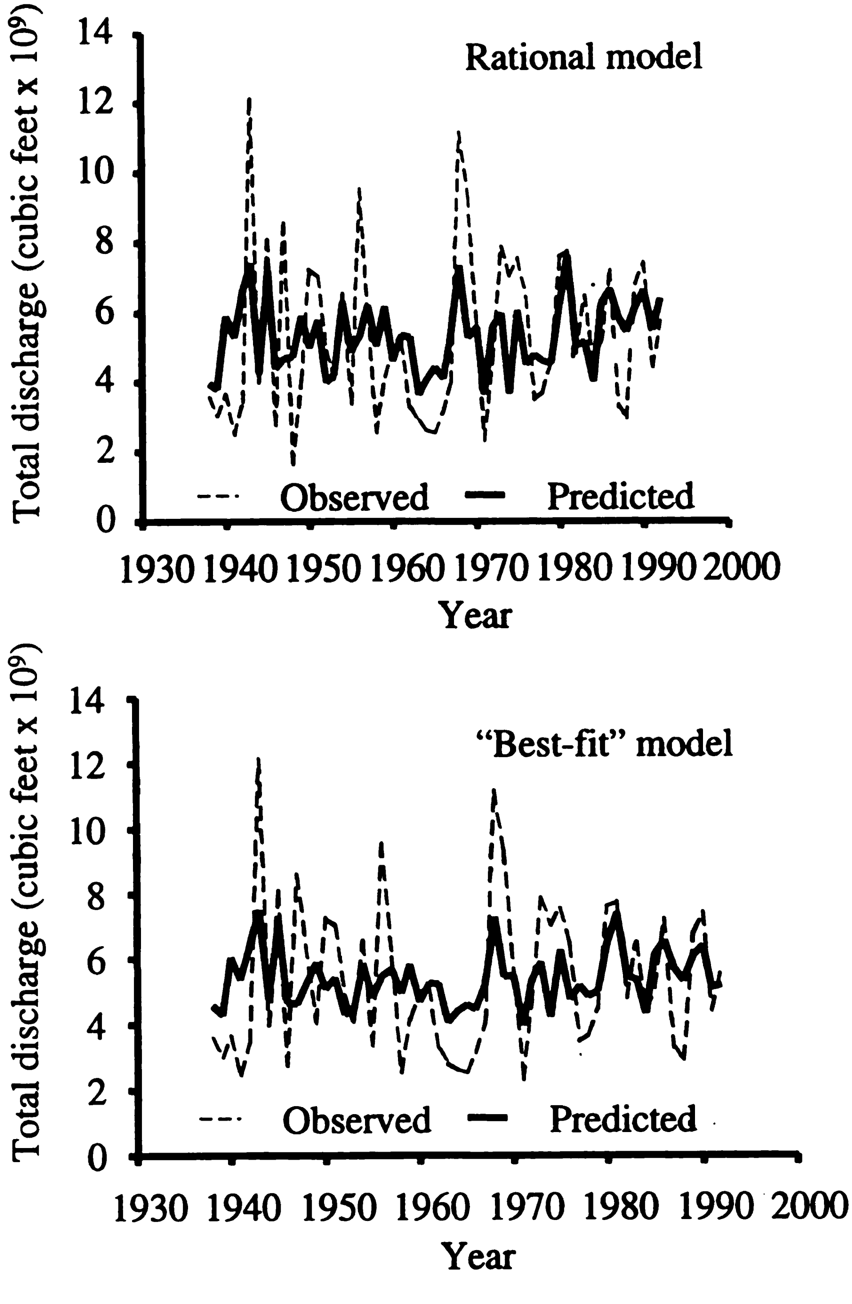

Figure 15. Comparison of the results from the rational and the best-fit models of predicted total discharge and observed total discharge in the Huron River between 1938 and 1992.

Using my best fitting model, I plotted predicted verses observed patterns in baseflow for several years early, near the middle, and at the end of the period of record (Figure 16). These plots showed that the model tended to over predict streamflow early in the data series, over-predicted flow to an even greater degree near the middle of the data series, and with the exception of a few peak flows, fit much better at the end of the data series. In general, this model does a relatively good job of predicting the observed patterns in streamflow since 1938. However, inclusion of land cover characteristics during that time of year when we would expect land cover to be an important determinant of stream flow (i.e., during the low flow period), does not greatly improve the models ability to predict the observed patterns in discharge. In fact, scrutiny of the predicted runoff coefficients for the different land cover categories indicates that these coefficients are too loosely defined by the contrast in the land cover data set to be of any real consequence to the models predictions (Table 2). Once again, these results suggest to me that changes in land cover characteristics in the Huron River watershed since 1938 have not influenced the observed variability in streamflow to a great degree.

Obviously, adding impermeable surfaces to a drainage basin will reduce the retention time of water moving through a watershed, and instead route it more quickly downstream, increasing the size and frequency of peak flows and reducing baseflow levels during dry periods. Many of the previously developed models of river hydrology treat this as a basic assumption (Morris and Fan 1997). In order to use my model to make predictions of the impact of projected increases in urban cover over the next twenty years, I needed to standardize my land cover runoff coefficients so that they reflected a similar basic assumption about impermeable surfaces (Table 2). Comparing results of

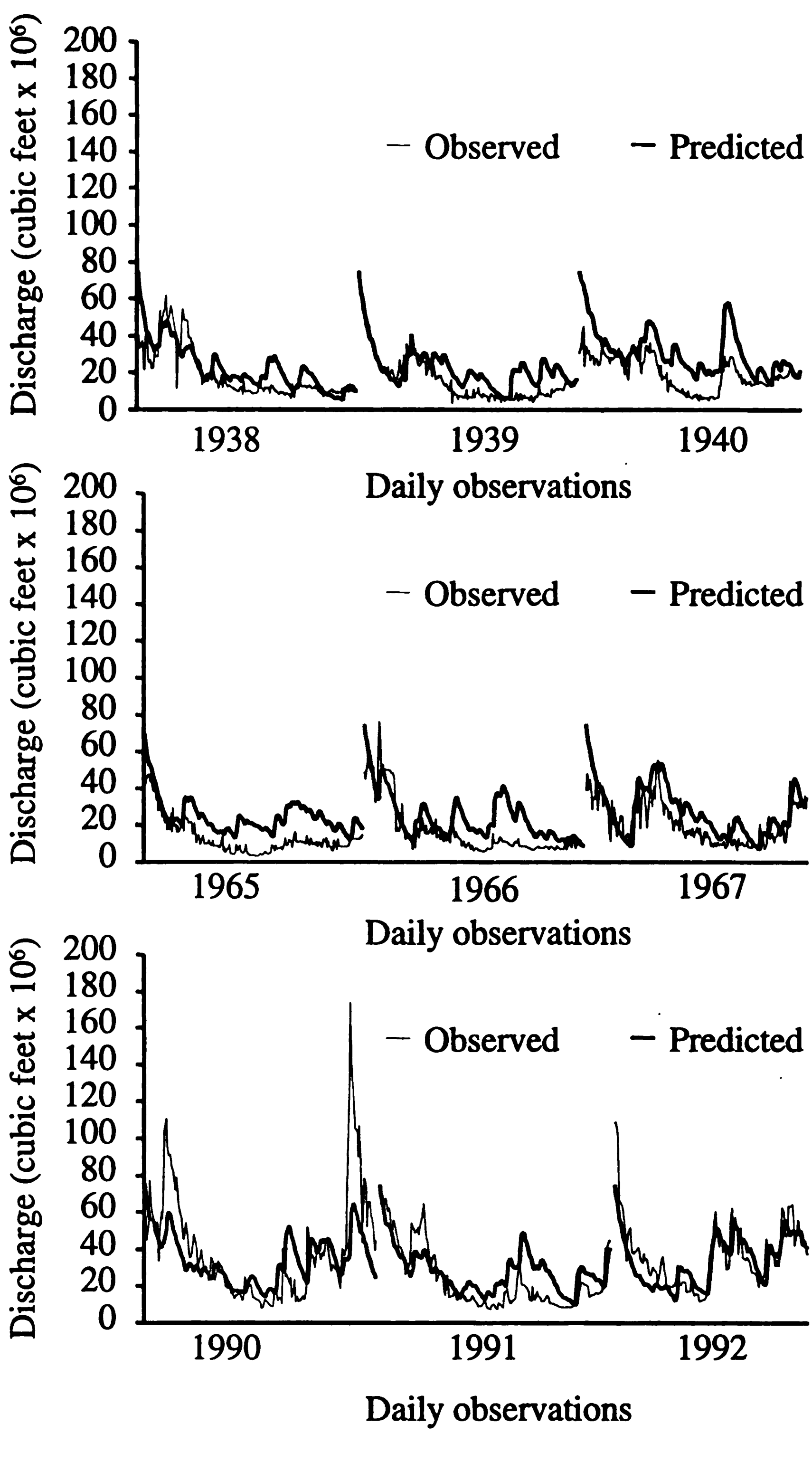

Figure 16. Comparison of the results from the best-fit model of predicted total discharge and observed total discharge in the Huron River for three different time sequences in the period of record.

this standardized model with my best fitting model show that there is no real difference in either model's ability to predict streamflow (Figure 17). Using the standardized model, I compared the predicted discharge if land cover had not changed since 1938 with the predicted discharge given the observed changes in land cover since that time. No appreciable difference exists between the predictions of the model under these two different scenarios (Figure 18). Results of this comparison further supported my conclusions that changes in land cover in the Huron River watershed since 1938 have not been a major factor defining streamflow, but the effects of projected increases in urbanization remained to be evaluated.

I simulated what the predicted pattern in streamflow would be if the entire watershed were urbanized or forested in order to bound the models predictions of streamflow variability between those extreme possibilities of land cover characteristics. I then simulated a 45% increase in urban cover over the next 20 years. The model predicts an increase in total discharge in the Huron River in response to increased urbanization over the next twenty years, with total discharge becoming more similar in pattern to what we might expect if the entire watershed were urbanized (Figure 19). However, that projected increase in discharge is not beyond the historical variability observed in streamflow since 1938, even though it appears to be trending upward (Figure 20).

Previous work suggests that for many rivers, land use, land cover, and especially urbanization are the primary causes of altered flow regimes (Poff et al. 1997). While this may be true, it appears that in the Huron River watershed, urbanization has not yet altered the variability in streamflow beyond what we might expect given the historical record. This is not to say that continued urbanization of the watershed will not have an impact,

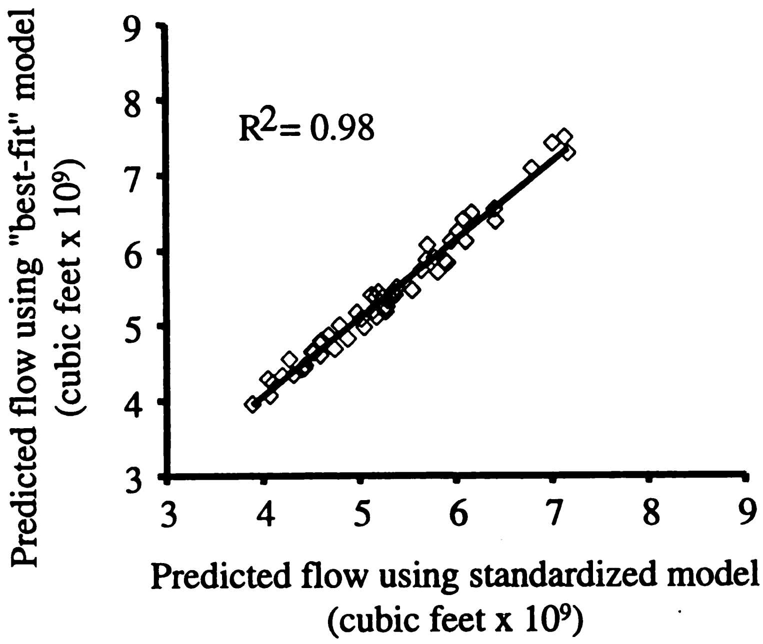

Figure 17. Results of linear regression of predicted flow in the Huron River using the standardized model and the best-fit model.

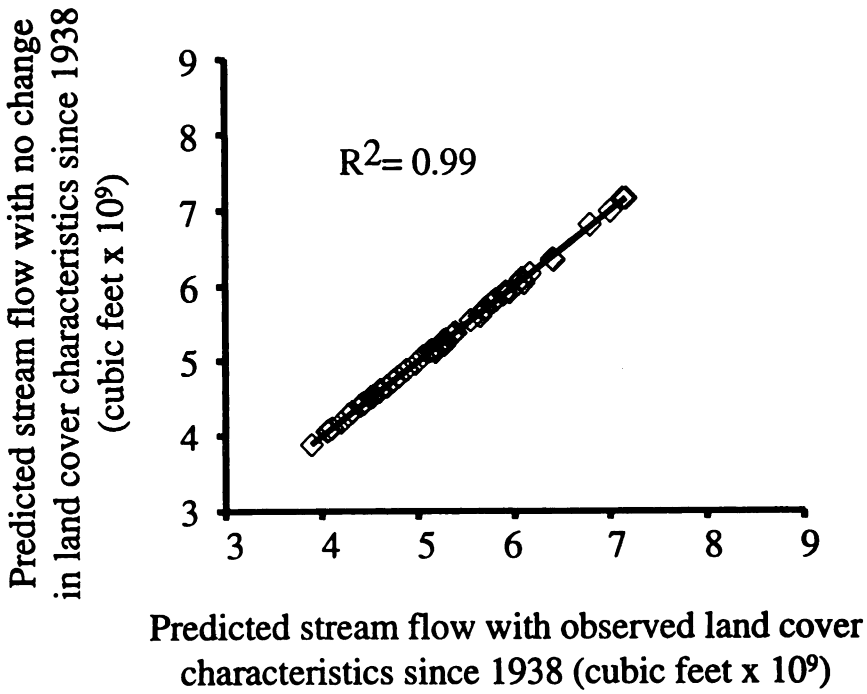

Figure 18. Results of linear regression of predicted flows in the Huron River with observed changes in land cover since 1938 and with no change in land cover since 1938. Predicted flow values were derived using the standardized model.

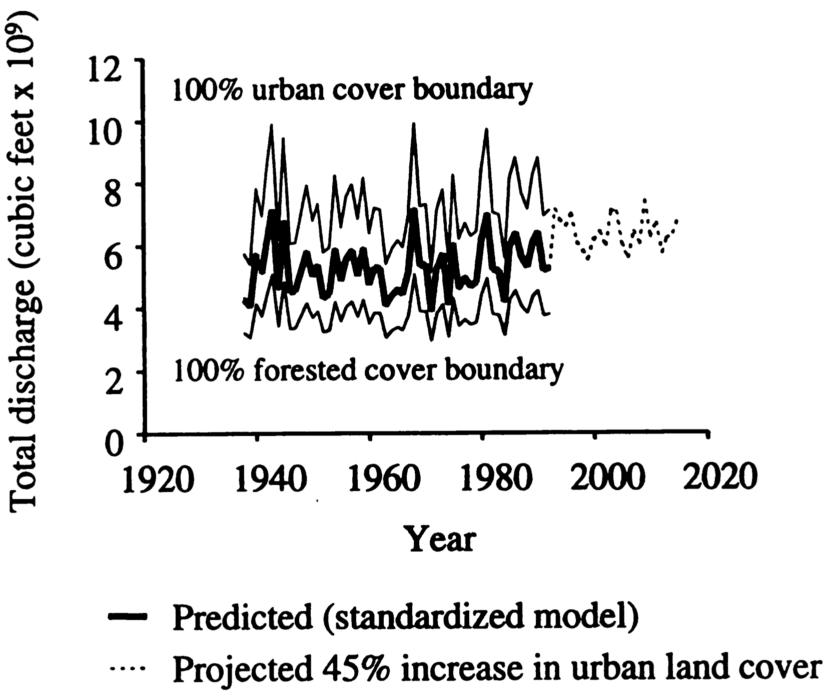

Figure 19. Predicted total discharge between 1938 and 1992, and projected discharge given 45% increase in urban cover between 1992 and 2015 using standardized model. Bounds on predicted discharge between 1938 and 1992 derived with simulations using 100% urban land cover (upper bound), and 100% forest land cover (lower bound).

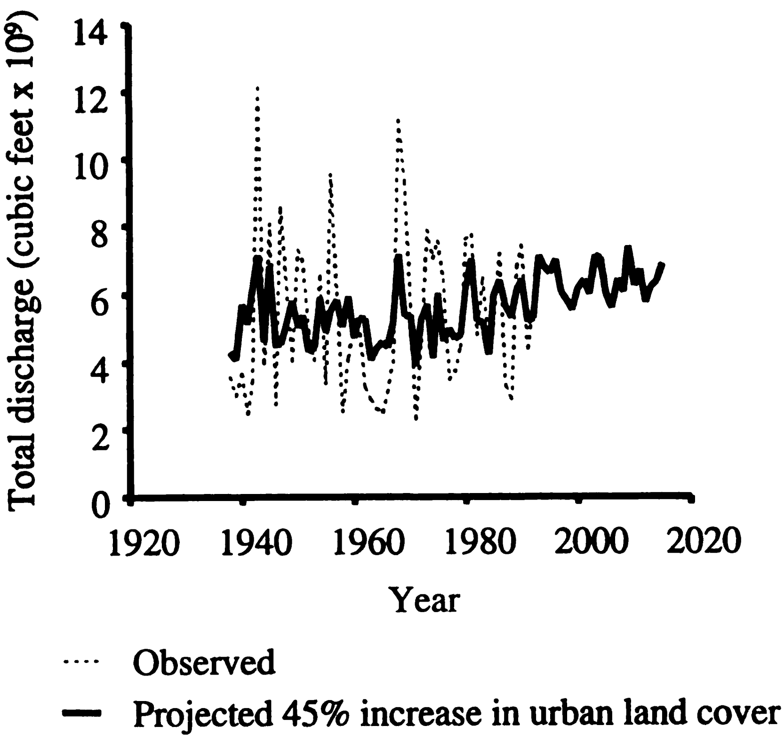

Figure 20. Predicted total discharge in the Huron River between 1938 and 2015 using projected 45% increase in urban land cover verses observed total discharge between 1938 and 1992.

only that the large degree of change in land cover characteristics since 1938 has not been enough to establish a strong signal in discharge to this point.

The hydrology of the Huron River appears to be more strongly affected by the geology of its basin. The surface geology of the watershed contains extensive deposits of end (or recessional) moraines formed during the retreat of the last glacier about 10,000 years ago (Hay-Chmielewski et al. 1995). These deposits in the upper basin are capable of retaining large amounts of groundwater. I believe that it is this groundwater reservoir that is responsible for the relatively stable trends observed in discharge since 1938, and consequently the lack of an effect attributable to increased urbanization.

Despite the strong influence of surface geology and groundwater on the hydrology of the Huron River, human land and water use impacts can not be entirely ignored. There are 99 dams on record in the Huron River basin. Dams are the most obvious modifiers of streamflow capturing both low and high flows thereby having the potential to reduce variability in a streams flow regime (Poff et al. 1997). Data on the location of 85 of the dams in the Huron River drainage basin are available, and dates of construction can be determined for 63 dams from the historical record (Chapter 1). I speculate that the construction of these dams, the commensurate storage of water over time as reservoirs filled, and increased surface water evaporation in the upper-basin have masked any changes to streamflow due to the influence of changing land cover since 1938. I believe the observed patterns in daily discharge (Figures 2 through 4) are at least in part the result of effects from increased dam construction. Between 1830 and 1950, twenty-nine dams are known to have been constructed within the Huron River drainage basin (Figure 21). Construction nearly doubled between 1951 and 1970, with another

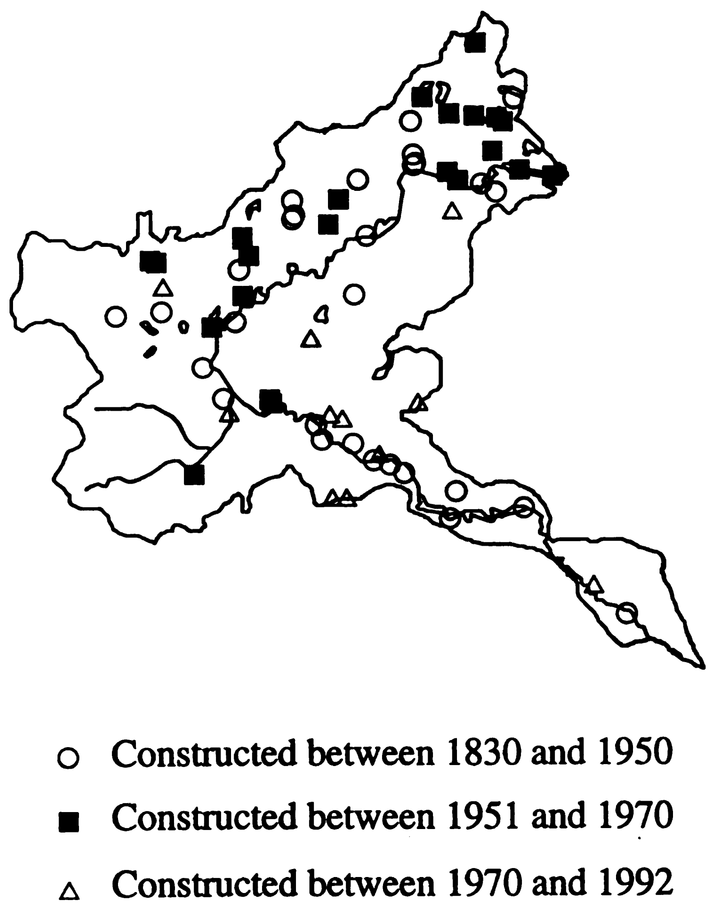

Figure 21. The location and date of dams constructed throughout the Huron River drainage basin for three different periods between 1830 and 1992.

twenty-three dams being completed, mostly in the headwaters of the upper basin (Figure 21). Since 1970, eleven new dams are known to have been constructed, many below the USGS-gauge in Ann Arbor (Figure 21), which would therefore not influence flow at Ann Arbor.

Furthermore, my previous analysis of water yield in the Huron River since 1938 indicates a reduction in yield between about 1950 and 1970, about the same time that a large increase in dam construction occurred. Variability in the observed yield was also reduced during this time period. Water yield ranged from 7 to 46 percent between 1938 and 1950, from 15 to 44 percent between 1951 and 1970, and from 22 to 50 percent between 1971 and 1992 (Figure 22). While there is no clear trend in the overall water yield since 1938, it does appear that yield has become somewhat less variable, and settled at a higher level in recent years compared to the late 1930s. Also, because my investigation of trends in precipitation since 1938 detected no distinguishable changes in that parameter since the late 1930s, changes in yield are most likely due to some other cause. I have been unable to demonstrate convincingly that land cover modified the delivery of incoming precipitation before it reached the stream channel to any large degree. As such, I feel that there is strong circumstantial evidence that dam construction has affected the flow regime of the Huron River to a greater degree than have changes in land cover since 1938.

Chapters 1 and 2 documented that there have been significant reductions in the range and occurrence of fish species in the Huron River. Human modification of the hydrological regime can and does lead to disruption of those processes important for forming fish habitat in streams. I do not believe that urbanization alone has altered the

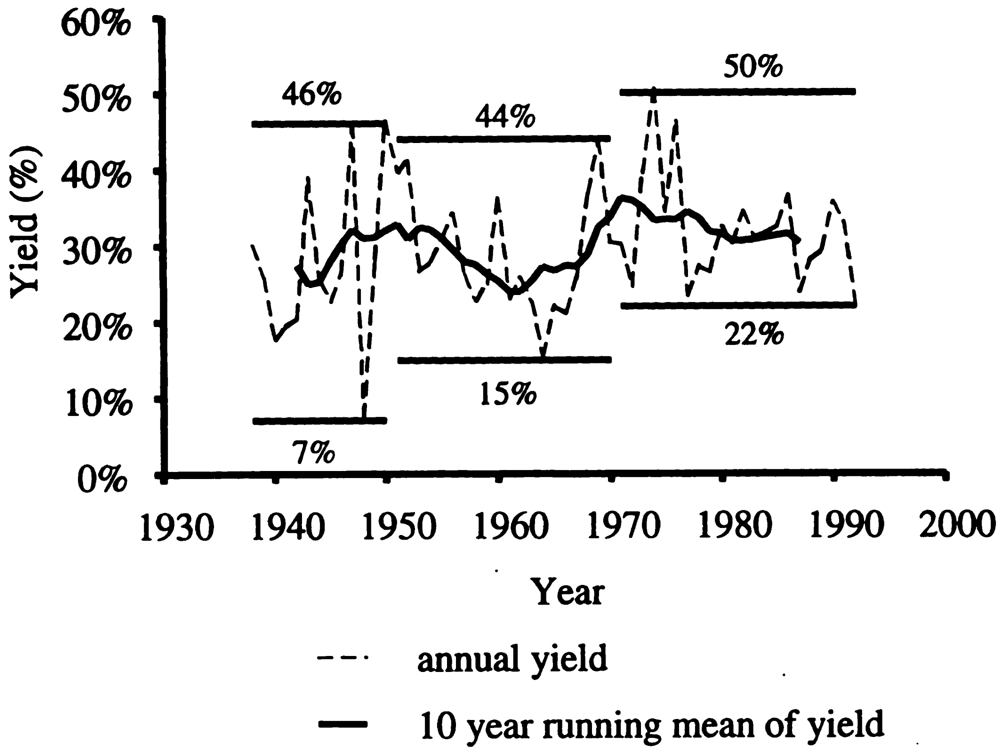

Figure 22. Changes in the variability of the observed pattern of annual water yields in the Huron River for three different intervals in the period of record including 1938 to 1950, 1951 to 1970, and 1971 to 1992.

flow regime of the Huron River enough to be considered the principle cause of the observed changes in the fish community since 1938. I do however believe that continued urbanization of the watershed will disrupt those processes important for forming fish habitat in the future given the results of my simulations of streamflow and the projected urbanization in this drainage basin. I also believe that the extensive damming of this watershed since 1938 has had a major impact on the flow regime of this river, along with urbanization, and subsequently has altered those processes important for forming fish habitat in concert with the observed changes in land cover. Dams have also likely had direct impacts on fish habitat through changes in sediment concentrations, altered levels of dissolved oxygen, modification of the benthos and the aquatic food web, and probably most importantly, fragmentation of historical fish habitat. Based on my research, I believe that modification to the patterns of hydrological variation and disturbance in the Huron River since 1938 have altered the habitat dynamics of this river and created new conditions to which the fish species may be poorly adapted.

Summary

Variability in streamflow often presents fish species with ecological "bottlenecks" representing critical stresses and opportunities for their survival. Evaluation of the historical hydrological regime of the Huron River since 1938 revealed a large amount of year-to-year variability in streamflow, with the general magnitude and frequency of high flow events in the daily records being reduced since that time. No trend was apparent in streamflow since 1938, and discharge appears to be stable in the Huron River relative to many other warmwater river systems in the State of Michigan. Water yields in the Huron

River have fluctuated since 1938, being less variable and somewhat higher in recent years than they were historically. Models evaluating the contribution of precipitation and land cover characteristics to the observed patterns in streamflow suggest that changes in land cover since 1938 have not had a major influence on the observed patterns of variability in streamflow. However, simulations based on projected increases in urban land covers suggest that discharge is likely to increase over the next twenty years. The lack of clear trends in discharge or water yield since 1938 suggests that changes in hydrology are not a major factor contributing to the observed losses of fish species in the watershed from 1938 to 1996.

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