Sustaining Minnesota's Lake Superior Tributaries in a Changing Climate

August 2016

Minnesota Department of Natural Resources

Natural Resources Research Institute, University of Minnesota Duluth

The Nature Conservancy

MNDNR

The Nature Conservancy
Protecting nature. Preserving life.™

UMD Natural Resources Research Institute
University of Minnesota Duluth
Driven to Discover

Acknowledgements

This study was made possible through the time and energy of the following people:

- William Bartsch, Natural Resources Research Institute, University of Minnesota Duluth
- Cliff Bentley, Minnesota Department of Natural Resources
- Kristen Blann, The Nature Conservancy
- Meijun Cai, Natural Resources Research Institute, University of Minnesota Duluth
- Jeremy Erickson, Natural Resources Research Institute, University of Minnesota Duluth
- Rachael Franks-Taylor, NOAA, Office for Coastal Management
- Ralph Garono, Natural Resources Research Institute, University of Minnesota Duluth
- William Herb, St. Anthony Falls Laboratory, University of Minnesota
- Tom Hollenhorst, US Environmental Protection Agency
- John Jereczek, Minnesota Department of Natural Resources
- Lucinda Johnson, Natural Resources Research Institute, University of Minnesota Duluth
- Clinton Little, Minnesota Department of Natural Resources (Minnesota's Lake Superior Coastal Program)
- Molly MacGregor, Minnesota Department of Natural Resources
- Hilarie Sorensen, Minnesota Sea Grant
- Amber Westerbur, Minnesota Department of Natural Resources (Minnesota's Lake Superior Coastal Program)
- Mark White, The Nature Conservancy

Funding for this project was received from NOAA's Office for Coastal Management via President Obama's Great Lakes Restoration Initiative. For more information on the Initiative and Action Plan go to www.glri.us.

Suggested Citation

Herb, W., K. Blann, L. Johnson, R. Garono, J. Jereczek, M. White and H. Sorensen. 2016. Sustaining Minnesota's Lake Superior Tributaries in a Changing Climate. Final Report to NOAA's Office for Coastal Management. mndnr.gov/eloha.

Table of Contents

Part I

Executive Summary

Part II

Module 1: Introduction

Module 2: Resource Manager Engagement

Module 3: Project Components and Supporting Data

Module 4: Hydrologic Stream Classification

Module 5: Hydrologic Models and Flow Statistics

Module 6: Projected Forest Cover Change

Module 7: Flow Ecology Relationships

Acronyms

Acronym	Definition
AFINCH	Analysis of Flows in Networks of Channels: A computer application that can be used to generate a time series of monthly flows at stream segments (flowlines) and water yields for catchments defined in the National Hydrography Dataset Plus (NHDplus) value-added attribute system.
BAU	Business As Usual
BIC	Bayesian Information Criterion
BFI	Baseflow Index
BMPs	Best management practices
BPJ	Best Professional Judgement
C-CAP	Coastal Change Analysis Program : A collection of land cover and land change products of coastal intertidal areas, wetlands, and adjacent uplands for the coastal U.S.
CCA	Canonical Correspondence Analysis
CMIP5	Coupled Model Intercomparison Project Phase 5
CO_2	Carbon dioxide
DEM	Digital Elevation Model
EFCs	Ecological Flow Conditions
ELT	Ecological Land Types
EPA	(U.S.) Environmental Protection Agency
EPT	EPT Index: The total number of distinct taxa within the groups Ephemeroptera, Plecoptera and Trichoptera.
EROM	Extended Unit Runoff Method
ET	Evapotranspiration
GCMs	Global Climate Models
GFDL	A global climate model output that represents a relatively cool, wet projected future climate.
Ha	Hectare
Hadley	A global climate model output that represents a relatively warm and dry projected future climate.
HSPF	Hydrologic Simulation Program—Fortran
HUC (Huc)	Hydrologic Unit Code
IBI	Index of Biological Integrity
km	Kilometers

Acronym	Definition
LANDIS-II	LANdscape DISturbance and Succession: A forest landscape simulation model
LiDAR	Light Detection and Ranging: A remote sensing method
m	Meter
mm	Millimeters
MNDNR (DNR)	Minnesota Department of Natural Resources
MPCA (PCA)	Minnesota Pollution Control Agency
NHD (NHDPlusV2; NHD+; NHDplus)	National Hydrography Data Set
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NRRI	Natural Resources Research Institute
NWI	National Wetland Inventory
NWS	National Weather Service
PCA	Principal Components Analysis
PET	Potential Evapotranspiration
ppm	parts per million
PRESS	Predicted Residual Error Sum of Squares
PRISM	Parameter-elevation Regressions on Independent Slopes Model
PWI	Public Waters Inventory
Q10	10% (high) flow: The daily streamflow rate that is exceeded on exactly 10% of the days.
Q90	90% (low) flow: The daily streamflow rate that is exceeded on exactly 90% of the days.
RCP	Representative Concentration Pathways: A set of greenhouse gas concentration and emissions pathways designed to support research on impacts and potential policy responses to climate change.
RD	Redundancy Analysis
RET	Reference Evapotranspiration
SGCN	Species of Greatest Conservation Need
SSURGO	NRCS Soil Survey Geographic (Database)
SWCD	Soil and Water Conservation Districts
TNC	The Nature Conservancy
USFS (Forest Service)	United States Forest Service

Acronym	Definition
USGS	United States Geological Survey

Forward

How will climate change affect Minnesota's Lake Superior tributaries? How can water resources managers in the area prepare for climate change, and protect the conditions that support fish and other aquatic life?

A partnership of agencies and academics dove into these questions and has developed an approach to defining and managing the ecological limits. This report details that research. It also helps to move the research into practice, providing management recommendations that can help protect fish and aquatic life into the future.

Using the Report

We all ask questions. Sometimes they call for a short answer and sometimes a long one. Regardless of where you are on that spectrum when it comes to Minnesota's Lake Superior tributaries and climate change, this report has something for you.

There are two parts to this report. The first section is the Executive Summary. It summarizes the entire project, including results and management recommendations. It will be helpful to resource managers looking for an overview of the project from start to finish. The second part is a series of modules, one for each portion of the project. These go into the all technical details. They will be helpful to those resource managers who would like to more thoroughly explore the research methods, data collection, modeling or other aspects of the project. They also will be useful to other researchers or professionals who want to know how something was done.

A companion to the report is the data. It is available at http://data.nrri.umn.edu/data/dataset/eloha.

Resource managers with some GIS expertise will also want to check out the management support tool in Module 2. The tool will help you decide which types of management actions are appropriate in certain places given what we know about today's conditions and how they may change in the future.

Executive Summary

Sustaining Minnesota's Lake Superior Tributaries in a Changing Climate

William Herb[1], Kristen Blann[2], Lucinda Johnson[3], Ralph Garono[4], John Jereczek[5], Mark White[6] and Hilarie Sorensen[7]

[1] St. Anthony Falls Laboratory, University of Minnesota, 2 3rd Ave S E, Minneapolis, MN 55414, (612) 624-5147, herb0003@umn.edu

[2] The Nature Conservancy, 40234 US 10, Cushing, MN 56443, (218) 330-9612, kblann@tnc.org

[3] Natural Resources Research Institute, University of Minnesota Duluth, 5013 Miller Trunk Hwy, Duluth, MN 55811, (218) 788-2651, ljohnson@d.umn.edu

[4] Natural Resources Research Institute, University of Minnesota Duluth, 5013 Miller Trunk Hwy, Duluth, MN 55811, (218) 720-4294, rjgarono@d.umn.edu

[5] Minnesota Department of Natural Resources, 525 S. Lake Ave, Duluth, MN 55802 (218) 302-3244, john.jereczek@state.mn.us

[6] The Nature Conservancy, 394 S Lake Ave, Duluth, MN 55802, (218) 727-6119, mark_white@tnc.org

[7] Minnesota Sea Grant, 31 W College St, Duluth, MN 55812, (218) 726-8106, seagr@d.umn.edu

Goals

This study explored the relationships between water quantity and the health of fish and invertebrates in Minnesota's Lake Superior tributaries. We sought to establish flow-ecology relationships between instream organisms (and communities) and hydrologic patterns for both current and future stream conditions through the use of interrelated models built with existing data. From there, we worked to determine both the direct effect of future climate change and the effect of future natural forest progression on stream hydrology and ecology.

Our ultimate goal is to use this research to inform and influence management. To that end, we identified a set of recommendations that are both scientifically credible and aimed at today's resource manager.

Purpose of this Study

Lake Superior tributaries in Minnesota have some of the most important cold-water trout habitat in the State, streams that are significant to the local economy. Area tributaries currently support naturalized populations of coho, chinook, pink salmon, steelhead, and brown trout, as well as reduced populations of native brook trout, the only salmonid truly native to these streams. Populations of cold-water species face limiting factors in this areas stream due to the area's bedrock geology including warm water temperatures, lack of suitable spawning and nursery habitat, and reduced stream connectivity. These factors coupled with low base flows and high storm flows makes these streams and the fish and other aquatic life that live there potentially vulnerable to climate change.

This study looks at how vulnerable these streams may be in the future. More importantly, it identifies management actions that can be taken today to maintain and enhance streams' natural resilience.

For more information about the context and significance of this project, refer to Module 1 – Introduction.

Project Components

Resource Manager Engagement

Because of the management focus, we consulted a wide range of resource managers throughout the course of the project. Our methods varied from one-on-one interviews with research staff and formal presentations in a symposium setting, to informal interactions at workshops. This layered approach was critical. The repeated presentations gave managers the opportunity to truly learn from our project team and their research. At the same time, we learned the importance of having information that could be easily understood and directly applicable to managers' everyday work.

Results

Resource managers expressed concerns about the impact of climate change on low flows, warming of cold-water streams and the potential impact of greater extremes in precipitation on in-stream communities of fish and invertebrates. They shared very specific information needs and priorities, including flow data, maps, and prioritization assistance among other things (Table 1).

Table 1. Priority topics articulated by resource managers and others during surveys, meetings and workshops.

Category	Topics of Interest and Needs
Flow Data	Flashiness index related to biological data (could help when working with private landowners) Models outputs (data) predicting: • peak flow • changes in stream flow (frequency and magnitude) • low flow (seasonal) • stream segment seasonal outlooks for flashiness
Prioritize Streams and Assistance	Need for help prioritizing where stream restoration happens that fits within approximately ten year planning cycles Prioritize areas that are predicted to have flow change due to land cover/development and climate change Focus on protecting streams that are likely to be in fairly good condition 'Prioritized, Targeted and Measurable' or PTM is the basis for local management decisions.
Maps (1:24,000 scale ideally)	Maps predicting changes in flow for cold-water streams over the next 30-50 years Forest change maps related to hydrological impacts Map of stream health and resilience for region and by stream segment Maps that include the kind of change anticipated Map of locations and timing of stream sections anticipated to reach critically low flows Map current conditions and future scenarios to show where change may occur Map catchments that are most flashy and anticipated to increase flashiness under climate scenarios
Other Priorities	Types of management activities that will address/ achieve solutions for climate change issues, e.g. forestry practices, land use/setbacks. Decision matrix for prioritization of culvert replacements/ upgrades. Land use and land cover (tree species, function of plant communities)-scale (parcel level base level) Projections of future land cover at the catchment level Identify gaps where additional data is needed, e.g. places where we need more gages Provide seasonal summaries and score by conditions and rank by season in terms of conditions for fish Stability of fish communities over time

For more information about the project's engagement activities, refer to Module 2 – Resource Manager Engagement.

Research

Approach

We approached this project's research in a series of steps, many building off the previous (Figure 1). Different models, modeling approaches and data were used throughout.

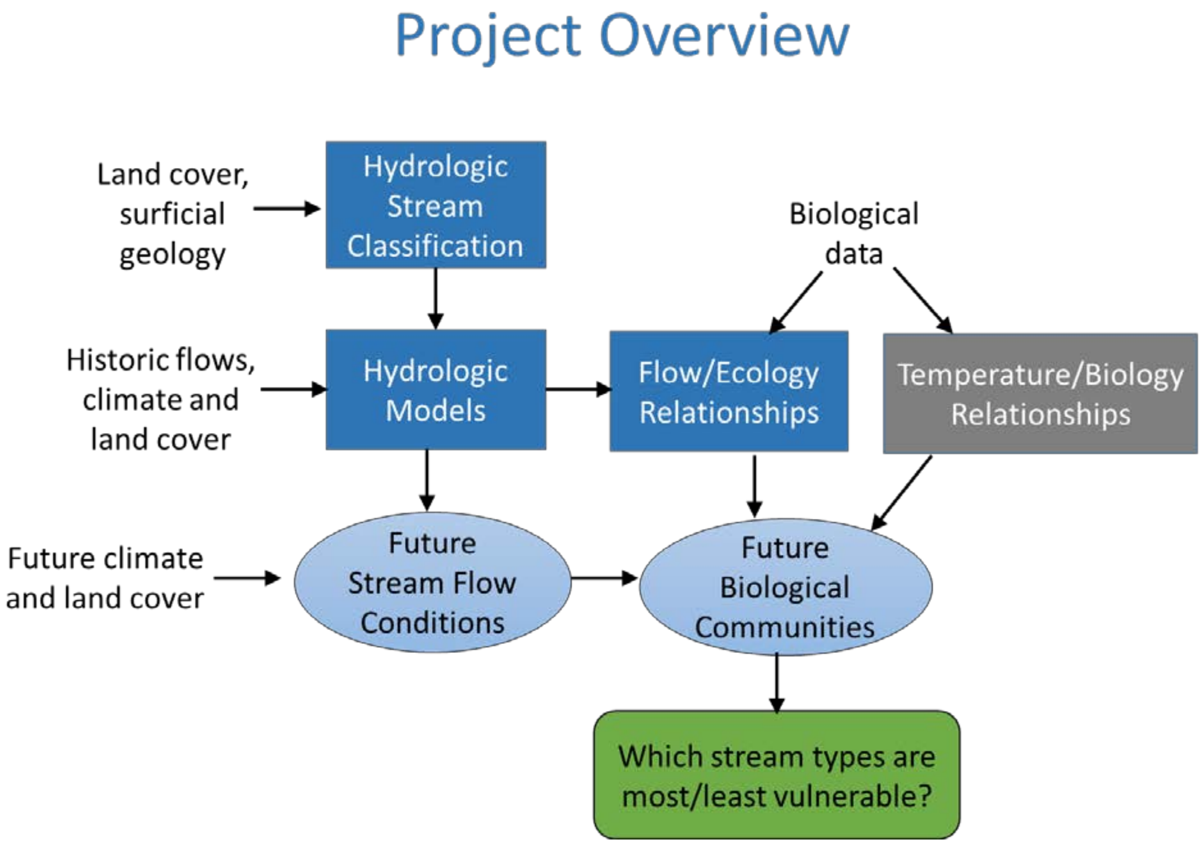
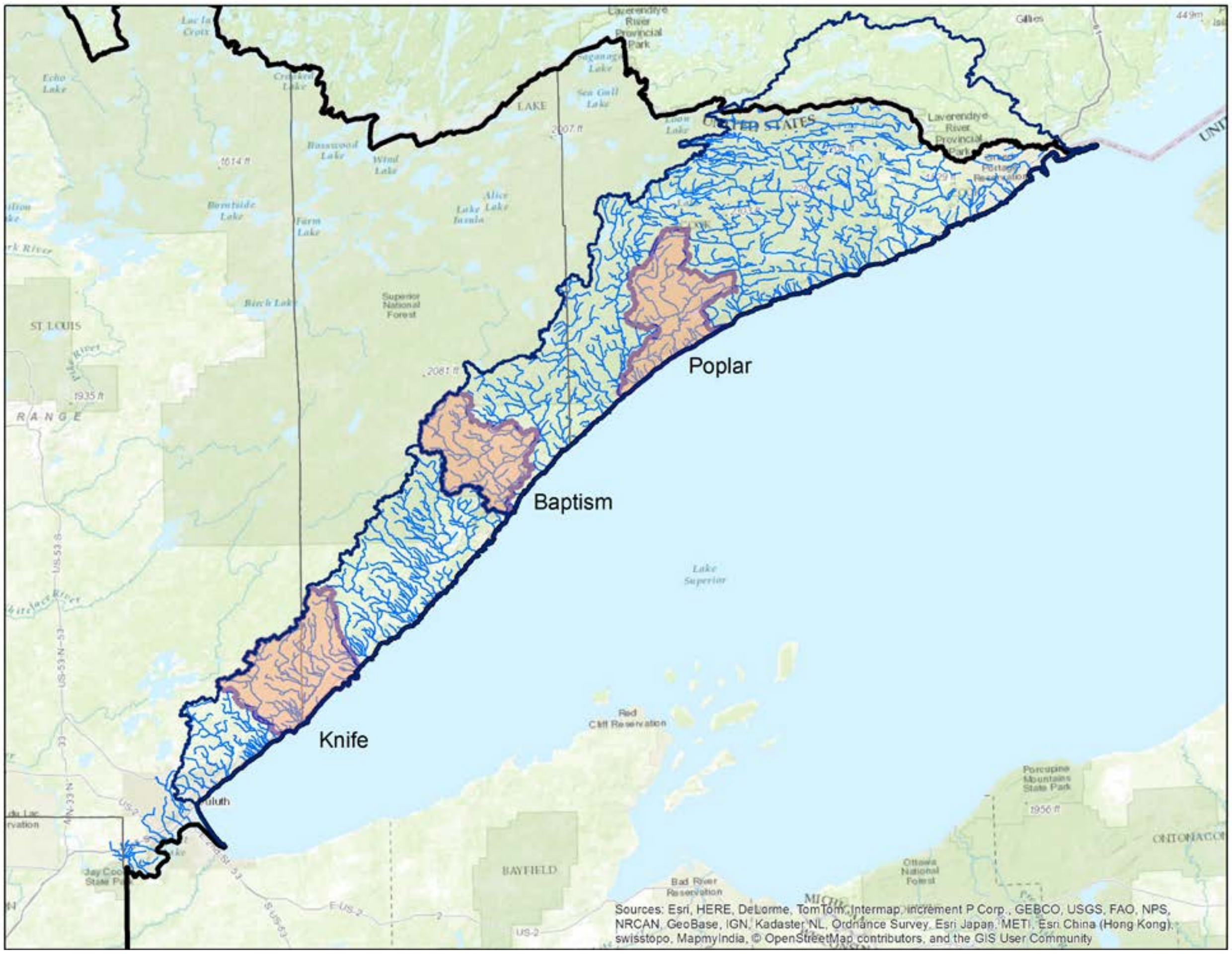


Figure 1. Project approach framework. This project focused on the link between flow and biological response; while termperature is also a very important factor in predicting biological response, it was outside the scope of this project.

First, we reviewed available data and identified data gaps. Through that process, we discovered a lack of historic flow data from stream gages. In an attempt to extrapolate hydrologic models to ungaged streams, we developed a hydrologic stream classification system. Based on the stream classification work, we chose the Baptism, Knife, and Poplar Rivers for detailed hydrologic modeling (Figure 2). They were chosen because they gave a good representation of the study region as a whole, and also had relatively long flow records.



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 2. Study area (region). The bold black line on the western edge of the Baptism River watershed marks the boundary between the study region's two main watersheds: Lake Superior – North and Lake Superior – South. The three intensively modeled watersheds (Knife, Baptism and Poplar) are noted in pink.

Next, we assembled detailed hydrologic models for the Baptism, Knife, and Poplar Rivers using the HSPF (Hydrological Simulation Program—Fortran) modeling package. HSPF was used to simulate a 20-year time series of daily streamflow and compute flow metrics (e.g., flow peak, flashiness, baseflow, flow duration, etc.) for each catchment (local drainage area), derived from the modified National Hydrography Dataset (NHDplusV2), in each of the three modeled watersheds. We ran the detailed hydrologic models for a series of historical and future scenarios, summarized in Table 2.

Table 2. Combinations of climate and land cover scenarios used in this study. Baseline climate and land cover scenarios represent the recent historical condition (1981-2000), while the future scenarios represent the period 2061-2080.

Land Cover Scenario

Climate Scenario	LANDIS 2000	LANDIS 2070LE	LANDIS 2070HE
Baseline	X	X	X
2070, GFDL	X	X	
2070, Hadley	X	X	

X = complete

Land Cover Scenarios
LANDIS 2000 = Current forest distribution used in LANDIS model
LANDIS 2070LE = LANDIS simulations for 2070, low emissions, modified silviculture with 60% reduction in clearcutting, which favors shade tolerant species (balsam fir, white spruce, sugar maple)
LANDIS 2070HE = LANDIS simulations for 2070, high emissions, business as usual forestry with short rotation clearcutting, which favors shade intolerant hardwoods (quaking aspen, paper birch)

Climate Scenarios
Baseline: Current Climate Conditions (1981-2000)
Warm/Dry: Hadley-CC365, 2060-2080
Cool/Wet: GFDL-ESM2G, 2060-2080

We reviewed several Global Climate Models (GCMs) and selected the Hadley GEM2-CC365 and GFDL-ESM2G GCMs to simulate temperature, precipitation, and evapotranspiration under the potential range of future conditions projected by these models. While both models project warmer and wetter future climate in the region, the Hadley model projects small increases in precipitation and large air temperature increases (+7 degrees Celsius), while the GFDL model projects relatively wet conditions with moderate air temperature increases (+3 degrees Celsius).

We used results from the LANDIS II forest simulation model to describe future land cover for 50-150 years into the future. Two future LANDIS scenarios were used: 2070LE, based on lower CO2 emissions and modified forest harvest practices, and 2070HE, based on higher CO2 emissions and business-as-usual forest harvest.

We also used empirical regression models (regression analysis). These models allowed us: (1) to extrapolate historical flow metrics to ungaged streams in the region, which enabled the flow-ecology relations to be established; and (2) to extrapolate future flow metrics derived from the HSPF models for the three selected watersheds to the set of all stream segments in the region. Relationships were then established between each of these flow metrics and catchment variables, such as the catchment storage, forest fraction, and surficial geology types.

Finally, the estimated flow metrics were related to biological data using several statistical techniques.

For more information about the data and methods used in this projects, refer to the accompanying project modules:

- Module 3 – Project Components and Supporting Data
- Module 4 – Hydrologic Stream Classification
- Module 5 – Hydrologic Models and Flow Statistics
- Module 6 – Projected Forest Cover Change
- Module 7 – Flow Ecology Relationships

Hydrological Model and Flow Statistics

Historical Flow Metrics

We calculated a set of flow metrics for each stream gaging site in the region. Regression analysis was then used to relate each metric to land cover, topographical, and soil variables over the region. These flow metrics included summer low flow (the lowest low), spring high flow (the highest high), the baseflow index (a measure of groundwater contribution to stream flow), and the flashiness index (a measure of how quickly flow changes in response to rainfall events). The regression equations were used to map each flow metric to a complete set of stream segments in the region (Figures 3-6). These estimated, regional flow metrics are a useful product alone, but also enabled the estimation of flow metrics at each biological sampling site, for the flow-ecology analysis.

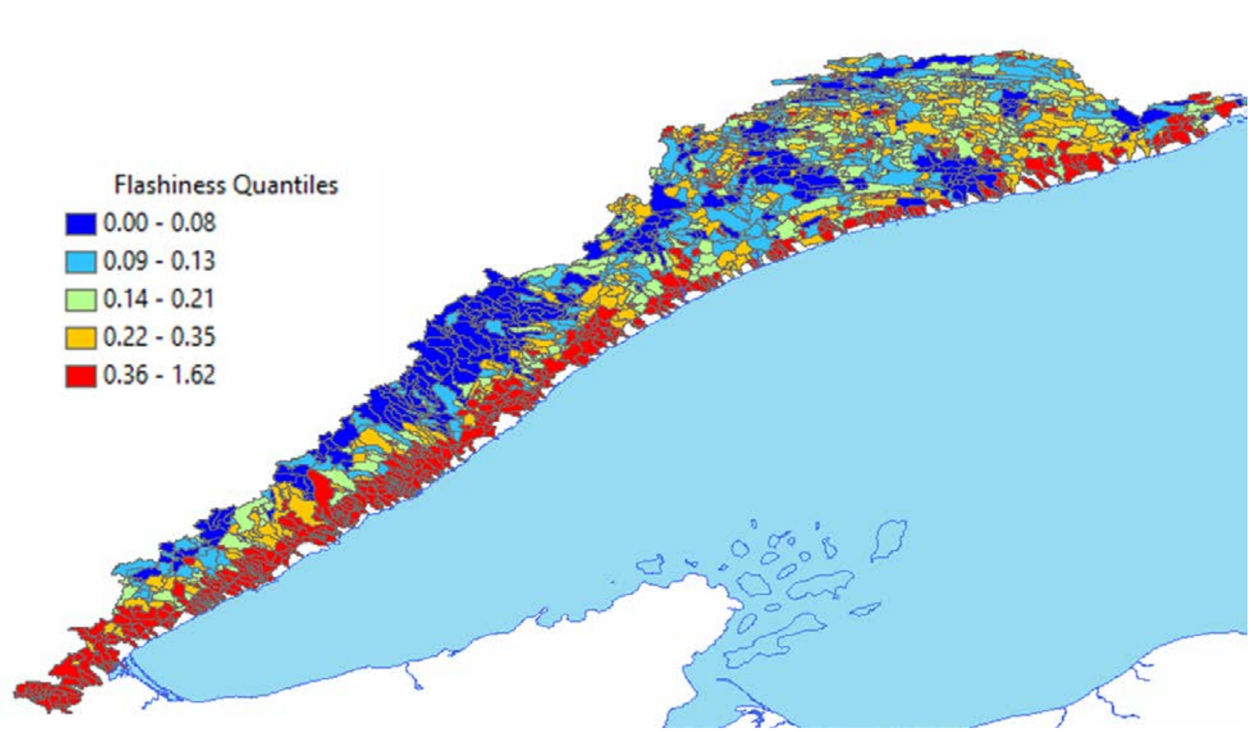


Figure 3. Distribution of the flashiness index over the study region. The flashiness index is a measure of the daily variability in flow normalized to the mean flow. The index is dimensionless.

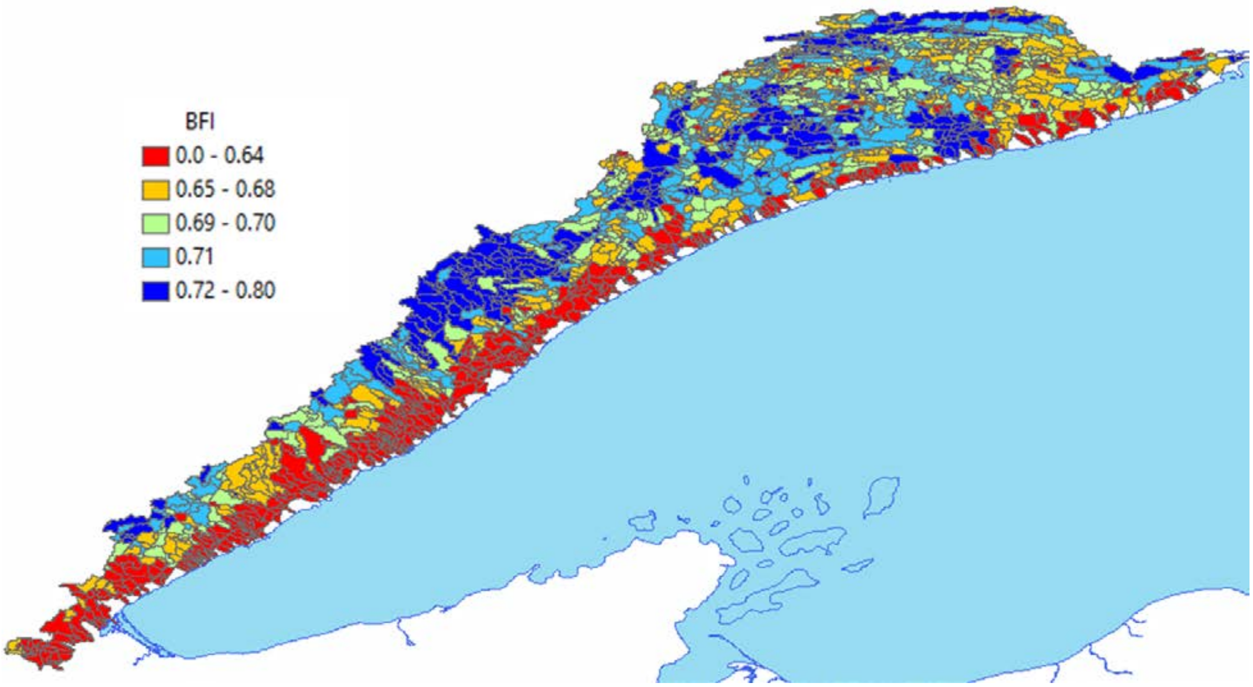


Figure 4. Distribution of the base flow index (BFI) over the study region. The base flow index is the fraction of total stream flow source from groundwater. The index is dimensionless.

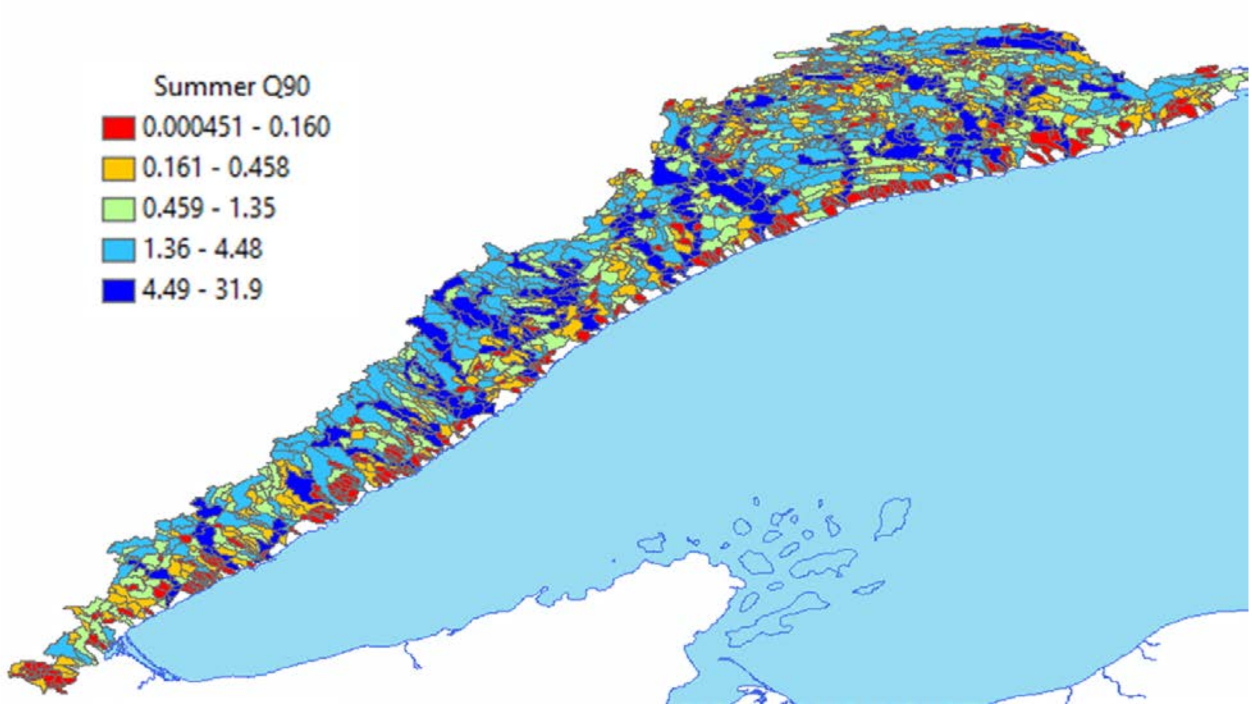


Figure 5. Distribution of summer low flow (Q90) over the study region, in units of cfs (cubic feet per second).

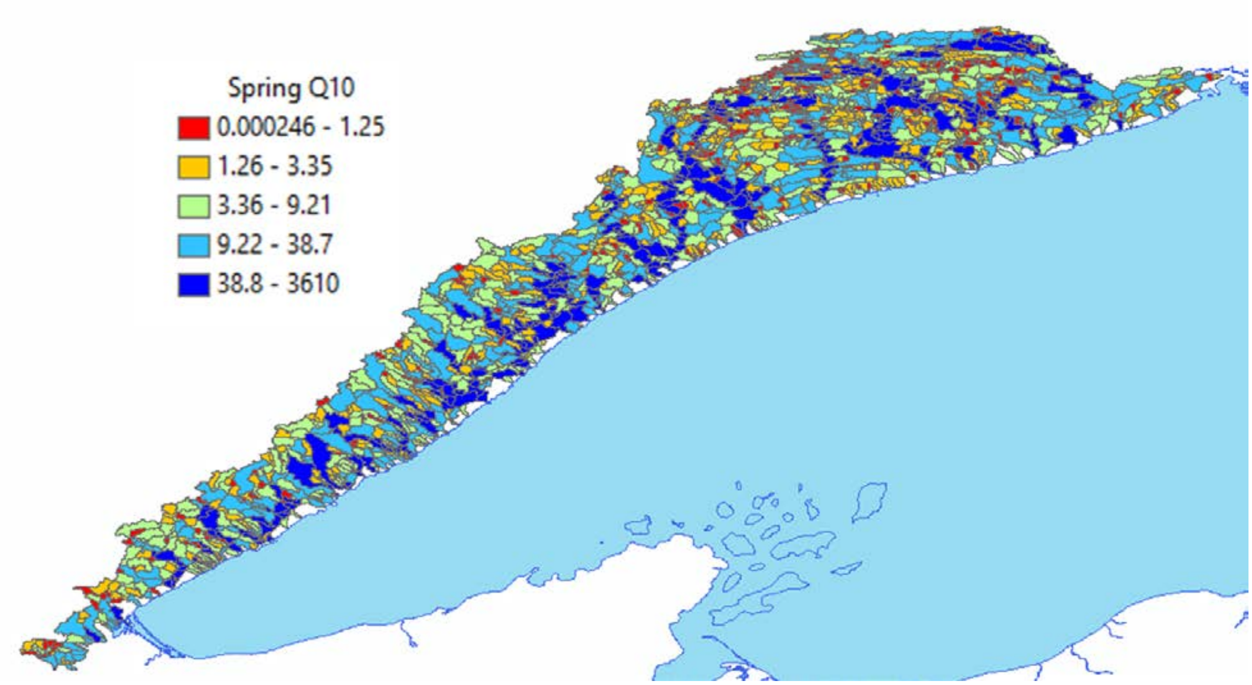


Figure 6. Distribution of spring high flow (Q10) over the study region, in units of cfs (cubic feet per second).

Current Climate and Flow Trends

To compare current regional climate trends to the trends indicated by the Global Climate Models, we performed trend analysis of historical precipitation and air temperature data from the Duluth, Two Harbors, and Grand Marais airports.

Results

- For the periods 1980 to 2015 and 1950 to 2015, **mean annual precipitation showed some increasing trends**, but these trends were not statistically significant. For the same period, **winter precipitation has a statistically significant increasing trend** of about 0.04 inches per year. **Decreasing trends in summer precipitation were visible**, but not statistically significant, because year-to-year variability is much higher than the long-term trend.

- **Mean annual air temperatures in the region appear to be trending upwards from 1980 to 2015** with increases of up to 1.4 °F over the period; however, these trends were not statistically significant. Expanding the analysis period to 1950-2015 produced statistically significant increases in mean annual air temperature of 2.0 to 2.8 °F. For the same period, winter air temperatures showed similar increases of 2.5 to 3.2 °F.

Summary of Future Scenarios in the HSPF Modeled Watersheds

We considered several future scenarios in this study: land cover changes, climate changes, and the combination of both land cover and climate change.

The HSPF models for the Baptism, Knife and Poplar rivers were run for both historical (1981-2000) and future conditions (2061-2080) as predicted by each of the selected climate models (GFDL, Hadley). It was necessary to run simulations for historical and future climate from each climate model to eliminate biases in the climate models (Table 3).

Table 3. Response of mean annual stream flow, Spring Q10 (high flow), and Summer Q90 (low flow) at the outlet of the Baptism, Knife, and Poplar rivers to four land cover and climate change scenarios.

Flow Variable	Stream	2070LE[1]	2070HE[2]	GFDL[3]	Hadley[4]	GFDL + 2070LE	Hadley + 2070LE
Mean Annual	Baptism	-3.6	-1.3	28.0	-17.6	24.7	-25.7
Mean Annual	Knife	-1.7	-0.60	32.0	-19.6	22.1	-22.4
Mean Annual	Poplar	-1.4	-0.14	31.9	-28.3	31.7	-30.2
Summer Low Flow (Q90)	Baptism	-13.8	-7.1	150	-94.7	188	-99.4
Summer Low Flow (Q90)	Knife	-7.3	-5.5	138	-83.7	128	-84.8
Summer Low Flow (Q90)	Poplar	-4.4	-1.0	112	-81.4	187	-80.5

Spring High Flow (Q10)	Baptism	-2.3	-0.85	18.8	-32.8	28.7	-17.8
Spring High Flow (Q10)	Knife	-1.8	-0.60	10.1	-45.1	32.1	-19.6
Spring High Flow (Q10)	Poplar	-1.4	-0.13	17.8	-43.7	32.0	-28.4

[1] Landis 2070LE = low emissions, modified forest management;
[2] Landis 2070HE = high emissions, business-as-usual forest harvest
[3] GFDL = cooler, wetter climate scenario
[4] Hadley = warmer, drier climate scenario

Results

- **The modeled land cover scenarios led to relatively modest projected changes in stream flow.** The projected flow responses are mainly driven by the transition of aspen to conifer in the region, and the corresponding assumptions made in how evapotranspiration, canopy interception, and shading change due to the conifer transition.

- **The projected flow response to climate change was driven mainly by the assumed differences in evapotranspiration rates between deciduous and coniferous forest.** More evapotranspiration monitoring could help test these assumptions.

- **The response of some flow metrics, such as summer low flow, to the 2070LE scenario was greater than the response of mean annual flow**.

- **The projected flow responses to climate change were much more substantial compared to the land cover change scenarios.**

- **The climate change scenarios projected substantial changes in the water budget of Minnesota's Lake Superior tributaries.** Overall, precipitation and evapotranspiration increased under both the low and high emission scenarios.

- **The response of seasonal flows to the climate change scenarios was substantial.** The GFDL climate scenario, with increased precipitation and moderate air temperature increases, gives higher mean flows in almost all months and the highest flows continue to be in April and May. The Hadley scenario, with little change in precipitation and very warm air temperatures, produces higher winter flows and lower spring flows. Mean summer flows decrease in August. Projected increases in winter flow were due to a combination of increased rainfall, increased snowfall, and increased snowmelt in December, January, and February.

- **Annual maximum flows (the highest flow each year) both increased in**

magnitude and shifted seasonally. The annual maximum flow was projected to increase significantly (20% to 50%), and the seasonal distribution of the annual maximum was projected to change, with more maxima occurring in the summer and fewer in the spring.

Regional Extrapolation and Generalization of HSPF Model Results

The HSPF model outputs give detailed information on historical and future flow metrics for the catchments in the Baptism, Knife, and Poplar river watersheds. The last step of the hydrologic analysis was then to extrapolate, where possible, the flow metric results to the rest of the study region. Relationships were explored between the modeled changes in flow for the future scenarios and catchment characteristics (e.g., hydrologic storage, forest cover types).

Results

- **Hydrologic storage and conifer fraction were found to be the most influential land cover variables in determining the degree of flow response to future scenarios.**
- **For the climate change scenarios, the response of summer low flow was tied to hydrologic storage (wetland and lake coverage fraction) within each catchment**. Increasing precipitation in the GFDL scenario appears to saturate hydrologic storage, so that there is less difference in spring high flow between catchments with more or less storage. For the Hadley scenario, with higher air temperatures but little increase in precipitation, the change in spring high flow was relatively constant across the study's three modeled watersheds, and was assumed to be constant over the region.
- **As air temperature increases, winter flows tend to increase, while spring, summer and autumn flows decrease.** In high storage catchments (catchments with many wetlands and/or lakes), increased evapotranspiration uses some of the available storage water, tending to reduce baseflows. In catchments with higher conifer fraction, the higher annual ET rates of conifers leads to lower streamflow.
- **For summer flows, more storage leads to higher baseflows**. For spring flows, storage becomes less effective with increasing precipitation as storage capacity is overwhelmed, so that spring flows in low and high storage watersheds become more similar.

For more information about the methods and results for this portion of the study, refer to the Module 5 – Hydrologic Models and Flow Statistics.

Projected Forest Cover Change

Forest Management and Climate Scenarios

We chose to project forest cover change using the LANDIS II model. We selected the LANDIS II model output because it provides spatially explicit maps of forest composition and age structure while incorporating management and climate change.

For the management scenarios, we bracketed the potential futures to understand sensitivity of hydrologic response to a full range of variability. We therefore selected scenarios that:

- Allocate the distribution of forest stand ages across the watersheds as uniformly as is warranted by forest types in those watersheds,
- "Bracket" the likely future trajectories under a warmer, ***drier*** future climate vs. a warmer, ***wetter*** future,
- Reflect a range of plausible forest management scenarios including: business-as-usual management focused on short rotation, even-aged forestry, and modified silviculture with longer rotations, higher retention, and more diverse species composition.

The business as usual (BAU) management prescriptions (cover type based rotation ages, average biomass removed) were derived from agency-specific management plans from the Superior National Forest, the Lake County Land Department, the St. Louis County Land Department, and the Minnesota Department of Natural Resources Forestry Division. Under BAU management, intensity and type of management varies substantially between agencies.

We compared the baseline scenario (year 2000) to forest change created by the different climate/ management scenarios across watersheds and between scenarios, to assess the extent to which watersheds that are currently similar experience similar transitions. Our analysis confirmed that this LANDIS output is appropriate for addressing questions about stream resilience.

For this analysis, we used two different climate scenarios. The A1FI-GFDL represents a significantly warmer and drier future compared to the B1-PCM model. Temperatures begin to diverge at approximately year 2045 and continue the trend through 2150. Precipitation is variable in both scenarios but is higher overall in the B1-PCM model. The combination of higher temperatures and less precipitation in the A1FI-GFDL compared to the moderate temperature increase and higher precipitation indicates that these two scenarios capture the "hot-dry" and "warm-wet" conditions.

These scenarios are different from those used in the hydrologic modeling. The GFDL and

Hadley projections were used because they captured a broader range of precipitation and temperature changes.

Results

Composition and Age Structure

- **In the low emissions-modified silviculture scenario conifer cover increased** from 29 to 46% while hardwoods decreased from 45 to 25%. LANDIS II results show a decline in aspen-birch even under current climate conditions under both the BAU or modified silviculture scenarios. Under the low emissions scenario, climate conditions remain within the tolerance ranges of boreal conifer species for the first 70 years but also probably contribute to the decrease in aspen-birch. The **proportion of young forest (0-15 years) decreased** from an average of 22% in the 2000 baseline to 11% in 2070 **under the low emissions-modified silviculture scenario**.

- **By 2070, under the high emission BAU scenario, hardwoods** (primarily aspen and birch) **decrease** from 45 to 37% **while conifers increase** from 29 to 33%. In this scenario by 2100, species composition changes with boreal conifers and hardwoods showing decreases while temperate species (white pine, oaks, sugar maple, red maple, basswood) show large increases.

- **During the relatively short time window (2000-2070) management has a much stronger influence on composition compared with climate.** However, by 2150 we see dramatic climate driven differences in composition, especially under the high emission scenarios with much lower proportions of boreal hardwoods and conifer. This management scenario maintained an average of 22% young forest, which is almost identical to baseline age conditions.

- **Results indicate that random harvest events did not create strong age structure differences among the study region's watersheds.** Age structure is largely a function of disturbance or management frequency and severity.

Alternative Views of Forest Change

- **The LANDIS II simulations show a relatively gradual shift from boreal to temperate species composition even under the high emissions scenario.** This will ultimately lead to a messy transition to an open savanna structure on drier sites and hardwood forest on mesic sites over the next 50-100 years.

Forest Management in a Warming Climate

- **Management will have a major influence on forest composition over the next 50-100 years.** Managing for "response diversity" ensures that a range of life history traits (e.g., tolerance of shade, drought, and fire) are represented in the suite of tree species.

- **Without climate-tolerant temperate species there is a greater risk of state change to savanna structure, which would likely have adverse impacts on ecological flows in Minnesota's Lake Superior tributaries.** Models and empirical data show that aspen and birch will decline regardless of management in a warming climate. Climate tolerant species include bur oak, red oak, northern pin oak, and basswood.

For more information about the methods and results for this portion of the study, refer to the Module 6 –Projected Forest Cover Change.

Flow Ecology Relationships

Flow ecology relationships were derived using existing fish and invertebrate data collected by Minnesota's state management agencies (primarily the Minnesota Pollution Control Agency (MPCA)). The objective of flow ecology analysis is ultimately to quantify the amount of change in ecological condition for a given change in one or more flow metrics so that acceptable limits of alteration can be defined. We used a variety of univariate and multivariate techniques to identify the flow metrics that explained variation in the presence/absence of fish and invertebrate taxa. We then used the Threshold Indicator Taxon Analysis (TITAN) to identify the community thresholds with respect to those metrics, which were derived from the regression-based flow models. We subsequently mapped the distribution of flow metrics by reach under current/historical flows. Reaches whose metrics fell above or below the break points corresponding to fish and invertebrate community thresholds were identified as vulnerable. These results, along with reach maps showing presence/absence of species with significant change points, suggest that fish community response to flow metrics may represent a combination of spatial distribution of reaches in relation to stream size, catchment position, and proximity to Lake Superior and other habitats.

Results

- **Flow metrics that most consistently were associated with biological responses were spring and summer high flows (Q10), summer low flows (Q90), and the flashiness index.**

- **10-40% of the study region's stream reaches are likely to experience significant community change thresholds for flow responses under the future**

modeled scenarios. Scenarios that result in large percentage increases in flows, especially seasonal high flow components (e.g., GFDL), are even more likely to "cross" community thresholds for fish and invertebrates than warmer, drier scenarios resulting in lower overall flows (e.g., Hadley). However, because of the interaction of temperature and flow this does not mean that streams will necessarily be less resilient overall in the case of wetter versus drier scenarios.

- **Fish and invertebrate species and communities exhibit coherent responses to flow metrics, especially spring high flows, summer low flows, and flashiness.**
- **There is evidence that future changes in flow are likely to drive changes in biological communities. Flow changes will interact with the likely temperature and habitat effects of climate and land cover change in ways we can anticipate but cannot empirically predict at this time.**
- **Overall, flow metrics explained less than 15% of variance in fish and macroinvertebrate response datasets in all multivariate analyses.** One possible reason for this result was the lack of temporal resolution in the biological data which likely masked the importance of seasonal and interannual variation, whereas clearly in many cases, it is seasonal and interannual variability in climate and flow regime that drives life history, behavioral and physiological adaptations. Fish and macroinvertebrate responses in multivariate analysis were similar across presence/absence, abundance, or trait-based metrics.
- **Both fish and invertebrate taxa exhibited significant community threshold responses to all flow metrics analyzed, especially the high flow component metrics**. However, individual species and taxa abundance occur across a wide range of high flow values.
- **Some taxa showed stronger responses and narrower ranges of high flow values than others.** For example, for fish, longnose dace and brook stickleback showed fairly strong responses to summer high flows across a narrow range of low values (< 50 cubic feet per second [cfs]). Longnose sucker also weighted strongly on summer high flows, but at a much higher value (nearly 300 cfs) and across a broader range of flows.
- **Fish community thresholds for summer low flows were observed, but were more variable.** For summer low flow, TITAN suggests a threshold value of 2.6 cfs for fish community response, with stream species such as fathead minnow, brook stickleback and pearl dace showing declining abundance above that threshold. This suggest an ability to maintain abundance even at very low baseflow values.

Longnose dace appears to have a strong positive relationship to a narrow range of summer low flows, showing increasing abundance at relatively low baseflow values of around 4 cfs. Several other species, including johnny darter, longnose sucker, and smallmouth bass also showed marginally significant "tolerant" response to increasing summer low flows.

- **For summer low flows, invertebrate community threshold for the sensitive indicator taxa appears at a value of around 2-2.3 cfs.**
- **Community responses for flashiness and high flow count were significant.** The flashiness index threshold for sensitive fish is ~0.15, with species such as Iowa darter, brook stickleback, central mudminnow, and even smallmouth bass showing a significant sensitivity to flashiness exceeding the community threshold value. Rainbow trout and fathead minnow however, both show tolerance for flashiness. For macroinvertebrate response, the threshold is 0.6 for tolerant indicator species and ~0.43 for sensitive indicator species.
- **Individual taxa responses to baseflow index are significant in many cases but show abundance scores across a wide range of baseflow index values.** For fish, the rainbow trout was the only robust indicator whose abundance declined with increasing values of the baseflow index. Most indicator species responded positively to increasing base flow, including brook trout, northern pike, yellow perch, smallmouth bass, central mudminnow, slimy sculpi, and Iowa darter, with increasing abundance above a relatively low threshold (change point) value of 0.44. For invertebrates, multiple taxa showed increasing abundance with increasing baseflow index, including *Chimarra*, Pisiidae, and *Nigronia*.
- **Brook trout showed a marginally significant negative response for spring high flows at very high values, as well as a marginally significant "tolerant" response to increasing base flow index at a value similar to the overall fish community threshold response (~0.4).** Overall brook trout did not exhibit a robust response to flow metrics.
- **In many cases, individual species have significant change points at flow values very different than the community threshold, consistent with their different habitat preferences and life histories.** Blacknose dace—a headwater stream species widespread in cool and coldwater streams—showed a moderately significant tolerance response for spring and summer high flows, flashiness, and high flow counts, but declined for baseflow index below 0.64. Slimy sculpin, smallmouth bass, and trout perch also showed a tolerant threshold response at much higher values for spring and summer high flows, whereas brook stickleback

and pearl dace showed a significant negative response at relatively low values (20-53 cfs).

For more information about the methods and results for this portion of the study, refer to the Module 7 –Flow Ecology.

Summary of Management Recommendations

Strategies for adapting to and mitigating for climate change impacts on stream biodiversity over the next decades are all about maintaining and enhancing the natural resilience of stream and riparian ecosystems. Protecting the healthiest systems is likely to be a more effective strategy than attempting to restore systems that are already degraded. We have identified key aspects of the flow regime to which the biological communities appear to respond: flashiness, spring and summer peak flow, and summer base flow. Each of these metrics represents a component of the flow regime with specific links to potential management actions:

1. **Protect base flows.** To improve stream resilience, managers need to protect base flows, particularly at low flows, especially against significant extraction at times when low flows are of concern. This might be accomplished through guidance regarding protective thresholds for total forest harvest or amount of impervious surface in a watershed, or protection criteria limiting withdrawals at minimum flows.

2. **Identify and protect the wetlands, vernal pools, floodplain soils, and other hydro-geologic features that store and transport subsurface flow contributions to base flow.**

3. **Identify and protect reaches serving as refugia, understand the sources and mechanisms of their baseflow and insure connectivity of these reaches within the system and to Lake Superior.**

4. **Manage and maintain riparian zones to keep forest cover/shade.** Buffers of mature riparian vegetation along the banks of small streams and tributaries can provide shade and other conditions to moderate the warming effects of climate change, at least within the range of a few degrees. Monitor for potential impacts of increased forest cover on low flows and temperature.

5. **Better understand the role of riparian tree species** (i.e., conifers), which may have an effect on water balance at low flows due to higher evapotranspiration. Boreal conifers (balsam fir, white spruce, black spruce, white cedar) are expected to persist longer on cool-moist sites and may have the most benefit in the riparian zones where they can provide shade and coarse wood inputs into streams.

6. **Restore or construct riparian buffers where necessary to provide adequate shade along existing cold and cool water streams, and/or manage heavy runoff of non-point source pollution and sediments with potentially more frequent and intense precipitation events.** Utilize LiDAR information to assess where riparian reforestation efforts are needed on high quality trout streams.

7. **Establish ecological buffers zones around natural features.**

8. **Ensure that wetlands identified as significant are protected.**

9. **For highly vulnerable streams: examine and adjust, where appropriate, management to reflect fluctuations in aquatic carrying capacities and shifting fish breeding and migration patterns association with climate change.** The main challenge to ecosystem response to climate change comes from warming temperatures and impacts from low flows, not high flows. Ultimately, the most resilient streams are likely to be the most thermally-resilient, not the most geomorphically-stable.

10. **Encourage stewardship groups to protect and rehabilitate aquatic habitat, riparian zones and wetlands.**

11. **Maintain and restore riparian and instream connectivity, including removing barriers where possible.**

12. **Build adaptive capacity by managing for healthy, high quality forests.** Healthy, high quality forests minimize the risk of large-scale abrupt changes and help avoid simultaneous major disturbances to streams at the scale of a connected stream network. In addition to managing forests for future climate, management should **include control of plant invaders, earthworms, insect pests, and deer populations to reduce the impact of these stressors**.

13. **Utilize the geophysical diversity inherent in the landscape.** There is significant variation in soils and topographic features in this region that can accommodate a variety of tree species.

14. **Manage for bur oak, red oak, northern pin oak and jack pine on drier upland sites on thin, coarse textured soils (the areas highest at risk for drought stress and forest loss)**. This will require planting, browse protection, and release for successful establishment.

15. **Increase temperate tree species tolerant of warmer-wetter or hotter-drier conditions: white pine, red oak, bur oak, white pine, basswood, yellow birch, sugar maple.** Models and empirical data show that aspen and birch will decline

regardless of management in a warming climate. Oak species have adaptive traits for water-use efficiency and also may have lower evapotranspiration rates than fast growing species such as aspen. Without climate tolerant species, there is a greater risk of state change to more open savanna structure which could likely have adverse impacts on ecological flows in Minnesota's Lake Superior tributaries. Recent work indicates that bur oak, red oak, and white pine sources from northern and central seed zones can establish on a variety of sites in northeastern Minnesota.

16. **Collaborate in establishing forest cover thresholds.** Fisheries managers should collaborate with foresters and land use planners to establish thresholds for minimum forest cover using historical or "range of natural variation" benchmarks to improve the chances of maintaining flow regimes within the range of natural variation to which stream systems have adapted. The desirable threshold for conifer cover ranges from 40-50%.

17. **Manage for mixed stands where conifers make up an average of 15-25% of basal area.** Conifer and hardwood proportion may have a significant effect on flow, especially summer flows, in a changing climate.

18. **Seek opportunities to coordinate watershed planning, infrastructure planning, mitigation/adaptation and disaster response with proactive stream and watershed restoration and management.** Use information about high and low flow metrics to design more resilient road crossings, bridges, culverts, especially where connectivity is needed to ensure organisms have access to key habitats.

19. **Expand stream gaging efforts.** We recommend that where possible, stream gages be maintained in operation over time to establish a historical record, winter flow data be collected, and further gages be deployed within strategically defined subcatchments to quantify flow throughout the basin.

20. **Collect groundwater data.** There is a critical need for groundwater data including the completion of groundwater maps for the region.

21. **Develop and maintain comprehensive biodiversity survey to more thoroughly characterize baseline conditions, against which future change can be effectively detected, managed and mitigated.** This includes more repeat sampling of biological communities over time and across a range of seasons and conditions.

22. **Develop and digitize historical biological data, where possible.**

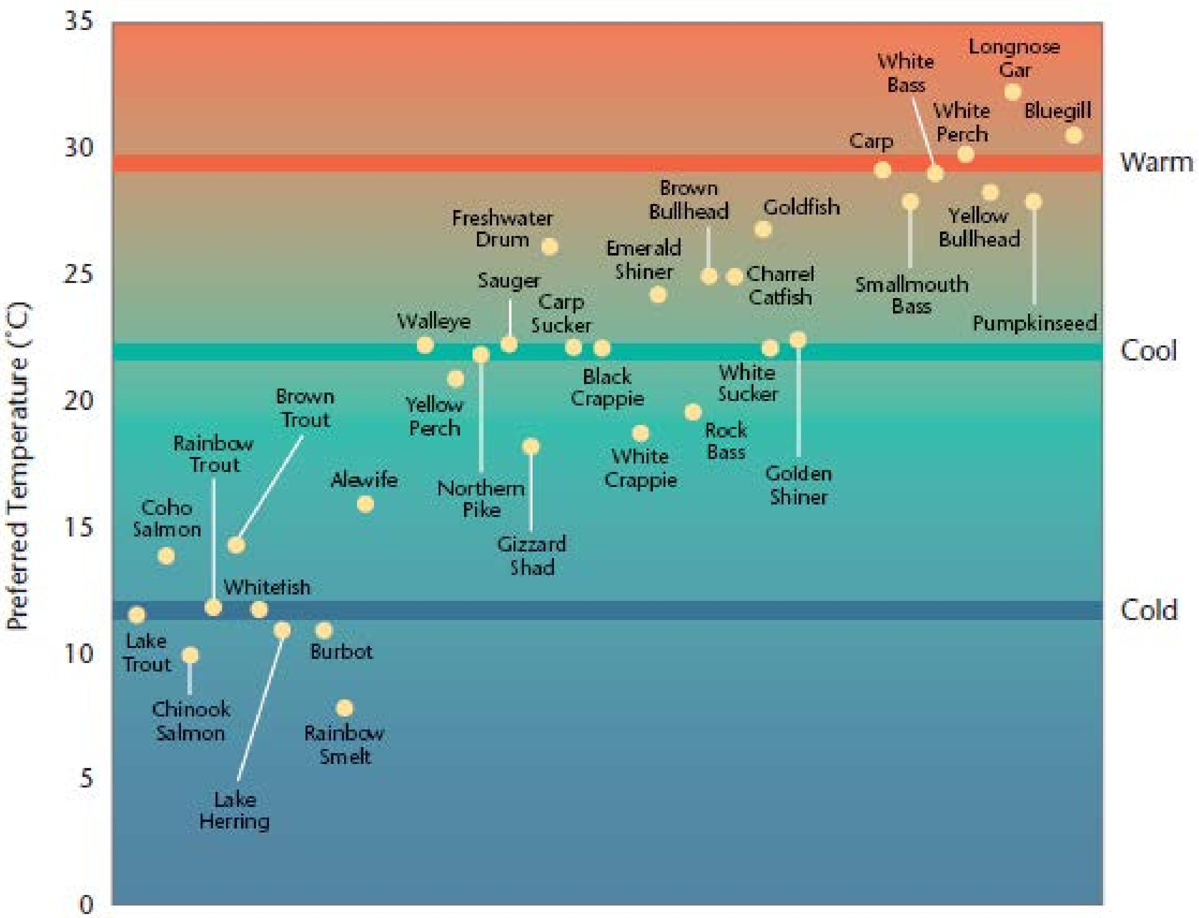
Module 1: Introduction

Climate change threatens to significantly alter freshwater ecosystem functions and services in many parts of the world, including along Minnesota's coast of Lake Superior, especially when coupled with land use changes and other human activities that impact natural systems. Together these alterations represent significant risks and impacts to local communities and economies. Identifying streams vulnerable to changing conditions and predicting the responses of stream communities to projected climate change is, therefore, an important scientific and management challenge.

Minnesota's Lake Superior Tributaries

Water quality, stream geomorphology, habitat availability, and aquatic species and communities are all affected by the natural patterns of variability in hydrology and flow in streams, rivers, lakes, and wetlands. The magnitude, timing, frequency, and rate of change of stream flows or water levels (i.e., hydrologic flow regimes) are key attributes governing the structure of native fish and aquatic communities (Poff et al. 1997). For example, along Minnesota's Lake Superior coast, stream discharge (the amount of water flowing through a cross-section of the stream at a given time) and water temperature are the major signals influencing the timing of the juvenile steelhead emigration. Significant alterations to natural patterns of hydrology inevitably alter the suitability of those systems for native aquatic biodiversity.

Lake Superior tributaries have some of the most important coldwater fisheries habitat in Minnesota: more than 150 designated trout streams of significance to the local economy. Many tributaries currently support naturalized populations of coho, chinook, and pink salmon, steelhead, and brown trout, as well as reduced populations of native brook trout, the only salmonid truly native to these streams (Figure 1.1).



Source: Based on information provided by Brian Shuter
Credit: Amanda Wait/DG Communications

Figure 1.1. Fish species thermal habitat preferences. [Reprinted from Kling et. al. (2003)]

Fish communities in the anadromous reaches of Minnesota's Lake Superior tributaries have already changed considerably since the early 19th century. Legacy forest harvest (Figure 1.2), development, overfishing, and introductions of other salmonids have resulted in vastly different fish communities today (Blankenheim 2014). Populations of coldwater fish species face multiple population limiting factors in Minnesota's Lake Superior tributaries including, erratic flow regimes, warm water temperatures, lack of suitable spawning and nursery habitat, and reduced stream connectivity.

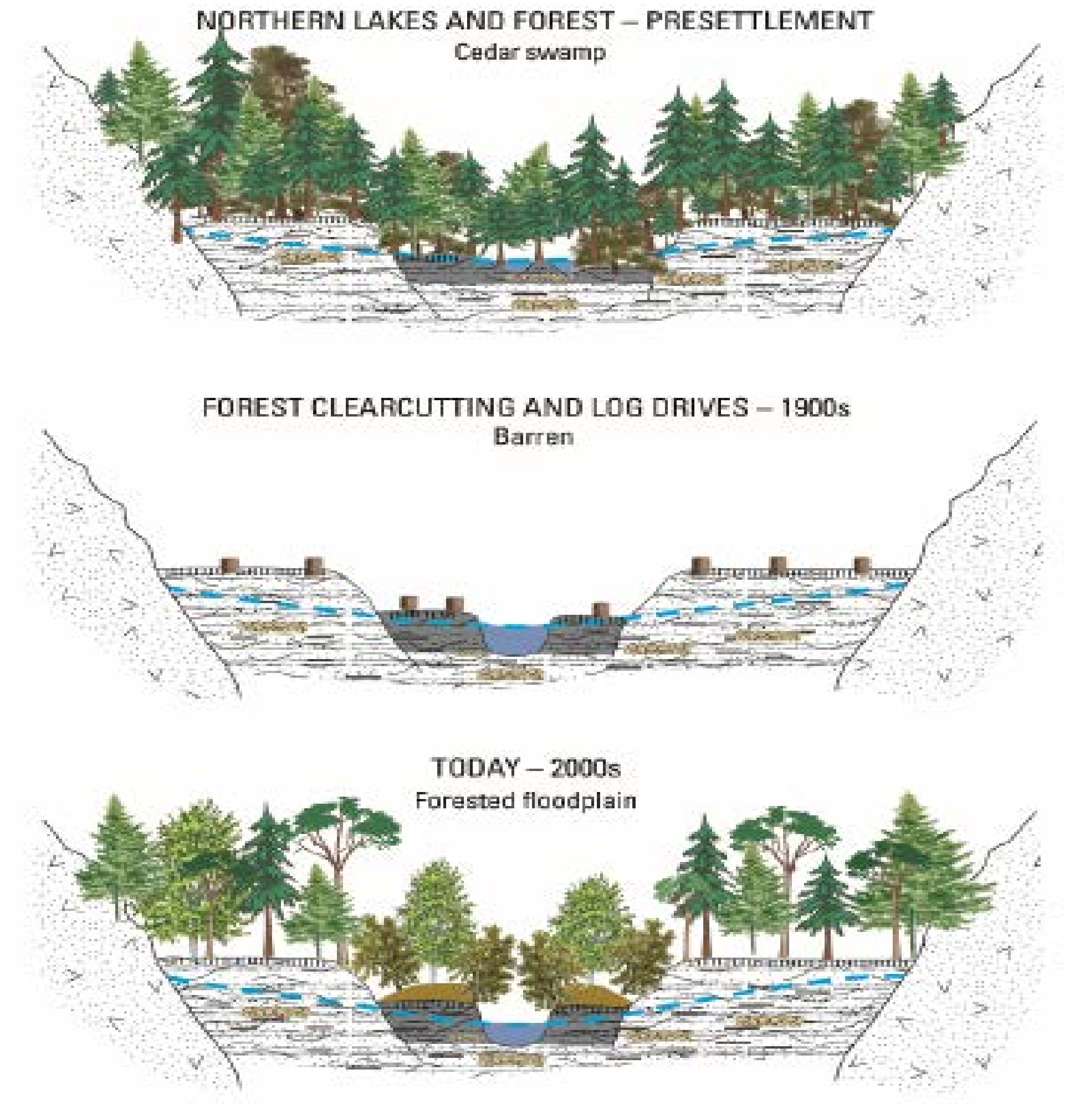


Figure 1.2. Historical changes in stream channels resulting from land use and management legacy. [Source: Fitzpatrick (2014) Lake Superior Stream Science Symposium]

Climate Change – What We Have Experienced So Far

In many ways, manifestation of climate change in the recent climate record for Minnesota's coast tracks changes being experienced across Minnesota and the Midwest. Annual temperatures between 1970 and 2000 increased more than 0.4°F per decade for the Midwest, with winter temperatures rising 0.9°F per decade (Kling et al. 2003; Hayhoe et al. 2010). Average temperature in Minnesota has increased 1°F to 2°F since the 1980s, after decades of essentially no change, and recent trends show a more steeply sloped upward trend, with projected increases of 2°F to 6°F by 2050 and 5°F to 10°F by 2100. (MN EQB. 2014.).

The trend has been especially noticeable on a seasonal basis, with winters warming more significantly than summer or annual average, and much higher minimum temperatures (seven of Minnesota's warmest years occurred in the last 15 years). Related trends include earlier arrival of spring and shorter duration of ice cover; greater frequency of tropical dew points (in July 2011, Moorhead, MN registered as the "hottest, most humid" spot on Earth, with a heat index above that of the Amazon jungle).

The Midwest overall has also experienced an increase in precipitation across all seasons of approximately 10% since 1900 (Minnesota Pollution Control Agency 2010). The frequency of heavy rain events (defined as occurring once per year during the past century) doubled since the early 1900s across the Midwest and Northeast (Kunkel et al. 1999). This has been true in Minnesota and the Great Lakes Region as well, which has experienced greater annual precipitation—more days with rain, more frequent heavy rains, and an apparent trend of increasing winter precipitation, with more winter precipitation as rain than snowfall (Kling et al. 2003; Figure 1.3). Since 2004 alone, Minnesota has had three "1,000-year" flash floods—in other words, three flash floods of a magnitude that, previous to those events, was estimated to have a probability of occurrence only once in a thousand years.

Increased Frequency of Heavy Rainfall Events in the Great Lakes Region

The next several decades will almost certainly see continued increases in heavy rainfall—perhaps doubling by 2100—with longer dry spells in between. The intensity of extreme rainfall events may also increase. Upgrading water control infrastructure based on historical frequencies of extreme events will thus be inadequate in a warming world, especially as more frequent downpours interact with more impervious surfaces.

Source:
Hayhoe and Wuebbles

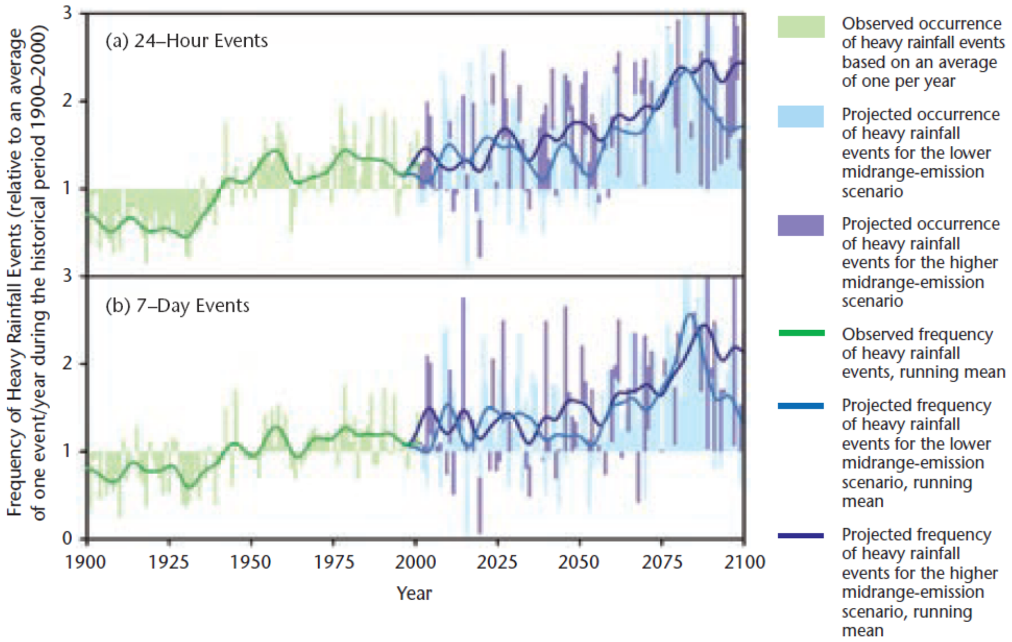


Figure 1.3. Increased frequency of heavy rainfall events in the Great Lakes Region. [Reprinted from Figure 14, page 41 of Kling et al. 2003]

Heavy downpours are now twice as frequent as they were a century ago (U.S. Global Change Research Program (USGCRP) 2009. *Global Climate Change Impacts in the United States: Midwest)*. Both summer and winter precipitation has been above average for the last three decades, the wettest period in a century. The Midwest has experienced two record-breaking floods in the past 15 years (USGCRP 2009). Average temperatures in the Midwest have risen in recent decades, with the largest increases in winter. There has also been a decrease in lake ice, including on the Great Lakes (Sharma and Magnuson 2014; Lynch et al 2016). Since the 1980s, large heat waves have become more frequent than any other time period in the last century, other than the Dust Bowl years of the 1930s. The observed patterns of temperature increases and precipitation changes are projected to continue, with larger changes expected under higher emissions scenarios.

In most watersheds, increased precipitation has translated as increased runoff. However, the proportion of hydrologic change that can be attributed to climate trends versus changes in land use has been debated. As we move further into the 21st century, there is a question of whether climate change will manifest in streams as more water, more erosion, and higher runoff, or will warmer temperatures drive greater evapotranspiration, increased drought frequency, water level declines and drought stress? Or will we experience both?

Warmer temperatures along with shorter periods of ice and snow cover can be expected to increase surface water temperatures in lakes and streams, and to result in less coldwater fish habitat. Recently, empirical stream temperature models were developed for Minnesota's Lake Superior tributaries by Johnson, Herb, and Cai (2013) showing that brook trout (*Salvelinus fontinalis*) are strongly negatively impacted by higher July mean temperature, positively affected by higher low flow, and to a lesser extent negatively associated with deciduous trees in riparian zone. The negative relationship between trout and deciduous trees in the riparian zone might be a surrogate for lower gradient landforms and less permeable soils in the southern portion of the study area. Their results also suggest that some streams are likely to be more resilient than others (Fig. 1.4). More accurate predictions of future trout distributions would require better projections of future forest cover and higher resolution vegetation and topography data to better map riparian conditions. Others have recommended that in addition to future forest cover, the impact of forest management policy and decisions also should be addressed, along with the role and influence of temporary impoundments, such as beaver dams.

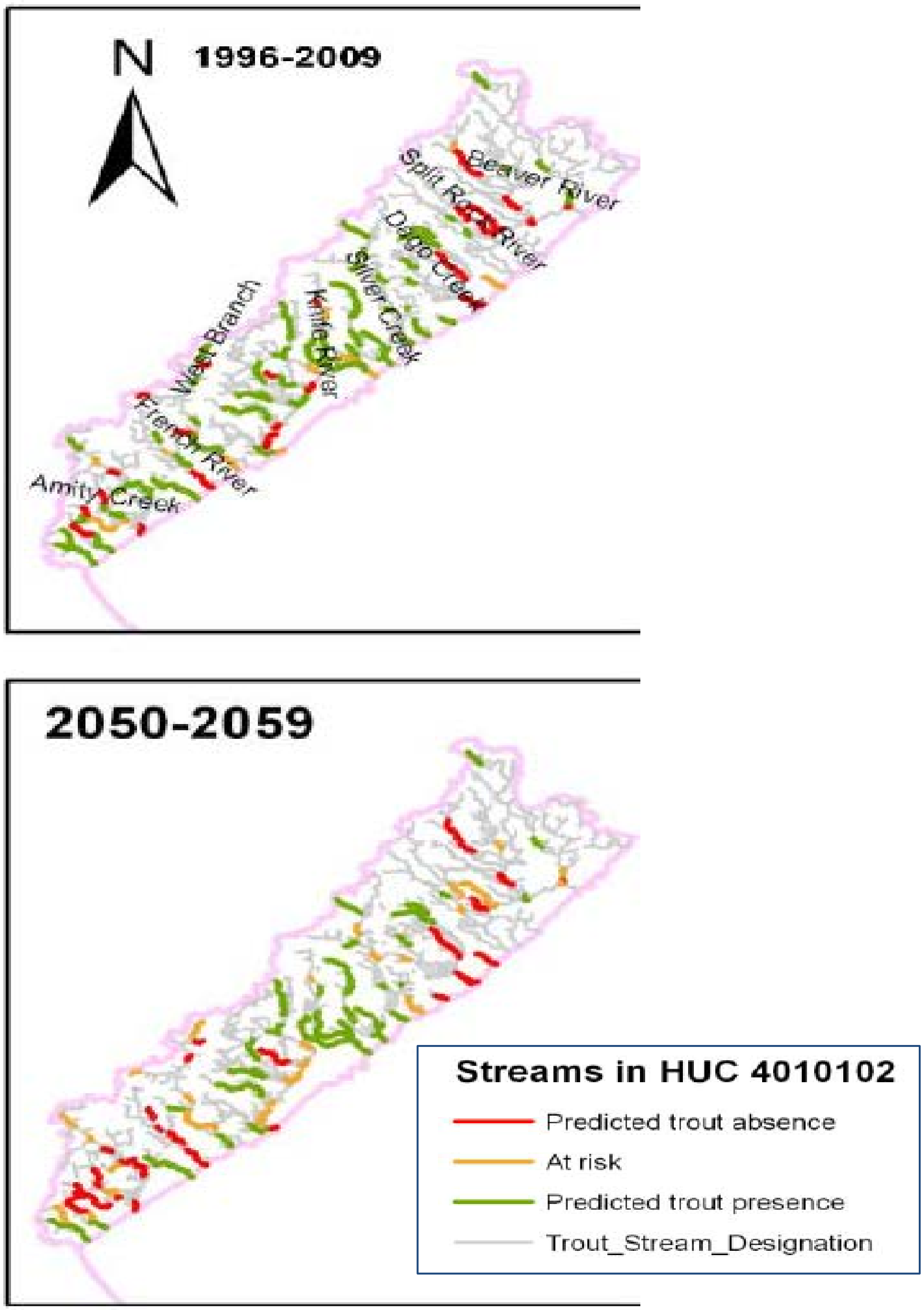


Figure 1.4. Predictions of future trout distributions in the Lake Superior – South watershed (HUC 4010102) [Source: Johnson et al. 2013]

A significant and relatively certain impact of climate change in Minnesota is a projected shift in precipitation from snowfall to rainfall (Kling et al. 2003, Johnson et al. 2013). While an increasing trend in precipitation leads to increasing streamflow, the increasing trend in spring and summer air temperature tends to reduce streamflow (by increasing evapotranspiration). Available streamflow records for Minnesota's Lake Superior tributaries suggest there may be a decreasing trend in mean annual flow and summer low flow, but the trends are not statistically significant. Historical precipitation data shows an increasing trend for total annual precipitation at Duluth and Two Harbors between 1900 and 2010, whereas Grand Marais and Grand Portage do not have a clear trend. Based on an analysis of daily precipitation totals, there is some indication of an increasing trend in the number of days in summer with high precipitation (10-20 cm). Both General Circulation Model (GCM) scenarios used by Johnson and colleagues (2013) projected overall increases in precipitation of about 15%, but differed with respect to the seasonal distribution of the precipitation changes. Future projections of streamflow based on the GCM output were equivocal, with the deterministic models projecting moderate increases in average stream flow and summer low flow, while the regression models suggested a moderate decrease in low flows. In Minnesota, the State Climatology Office (Blumenfeld, pers. comm.) cites the highest confidence in predictions regarding increased air temperature, increased annual precipitation, and increases in extreme storm events.

Climate Change and Flow Regimes

The flow regime characteristic of a particular river or stream is governed by the interaction of physical setting (catchment characteristics: primarily catchment area, topography, geomorphology, soil and groundwater, land use and land cover) with climate (rainfall, both the timing and amount, and temperature). Significant changes in climate or land cover can be expected to alter flow regimes. Because of the dominant influence of bedrock, Minnesota's Lake Superior tributaries are characterized by naturally low baseflows and high storm flows, and are often flashy and runoff dominated. Previous research has shown that maintaining baseflow is critical to support trout and other coldwater species in these streams (Huckins et al. 2008; Johnson et al. 2013). Because groundwater input is often naturally limited by the area's bedrock geology, stream thermal buffering capacity is naturally low, and baseflow is often partially supported by wetlands. Therefore, streamflows in Minnesota's Lake Superior tributaries are expected to be highly sensitive to both changes in air temperature and precipitation. However, because land use and land cover management can also influence canopy interception of precipitation, timing of runoff, evapotranspiration, groundwater recharge, shading, and overall water yield, there is potential for land use / land cover changes to either exacerbate or mitigate the impacts of changing climate.

Manifestations of changing climate are likely to be seen as changing patterns of precipitation, timing of snowmelt, temperature, and storm intensity (IPCC 2014). These changes are likely to affect stream ecosystems via altered streamflows and altered thermal regimes. For example, Wenger and colleagues (2011) used downscaled outputs from general circulation models coupled with a hydrologic model to forecast effects of altered flows and temperatures on sympatric trout in the interior western U.S. They found that increases in temperature combined with increased winter flood frequency were likely to result in habitat loss for nonnative brook trout and brown trout, whereas flow regime shifts that benefit rainbow trout may partially offset habitat loss due to temperature increases.

Climate change combined with land use change threatens to create significant alterations to stream ecosystems. Recent comprehensive, multi-stakeholder water-resource assessments and reports have identified significant unmet needs related to climate change adaptation, as well as gaps in the state's existing water appropriations and water-resource planning processes (Blann and Kendy 2012, Huff and Thomas 2014).

Land Cover and Forest Management Impacts on Flow Regime

Land use is a major driver of water quality, temperature, and flow response with the greatest changes resulting from conversion of natural lands to urban development (Poff et al 1997, Allan and Johnson 1997; Allan 2005). For example, stormwater runoff from roads and parking lots can cause Duluth trout streams to experience nighttime temperature spikes as great as 3 to 6^{o}C. Even moderate rain events can cause a 5 to 11 ^{o}F jump as water moves across warm asphalt (R. Axler, unpublished data). Trout in these more developed watersheds are already near the upper range of their temperature tolerance in the summer.

In many regions, land use activities --including timber harvest, livestock grazing, agriculture, and urbanization are recognized as primary causes of altered flow regimes. In the current study (and specifically for this report) we focus on forested land cover, due to the relatively low levels of urban development across the study area, and projections that suggest relatively little change in the future (EPA ICLUS 2014; MN State Demographic Center 2007).

A large body of research on the impacts of land cover and forest management on flow regimes has accumulated spanning multiple disciplines ranging from stream and watershed ecology, watershed management, geomorphology, and forest hydrology. Although the most extensive literature on the stream impacts of logging and forest harvest has developed in the western U.S., some significant long-term forest hydrology research programs have been conducted in forests of the Midwest and eastern United States, including long-term paired watershed studies at the Marcell Experimental Forest in northern Minnesota. The contribution of logging and the associated roads to the degradation of salmon streams in the Pacific Northwest, mainly through effects on runoff and sediment delivery, is well-documented (NAS 2008). Regardless, the high gradient forested watersheds along Minnesota's Lake Superior coast likely respond more similarly to forests in the mountain regions of the western U.S. and Appalachians than to the low gradient forest and peatland catchments of northern Minnesota, so we provide a brief summary of some major findings from those regions.

In mountainous watersheds of the western U.S., forest harvest on steep slopes has been associated with significant impacts to streamflow and long-term channel response (Keppeler et al. 2003). For example, in rainfall-dominated, forested watersheds of north coastal California, selective cutting of 65% of the timber volume in one watershed increased annual sediment loads as much as 331%. Clearcutting of half of a watershed basin resulted in storm peak increases of as much as 300%, but as basin wetness increased, percentage peak flow increases declined. Flow increases were explained by reduced transpiration and interception. Measurements suggested a return to pre-treatment flow conditions at around 12 years post-harvest. However, sediment yields have yet to recover (Keppeler et al. 2003).

In the Midwest, Verry (1987) similarly found that annual peak flows and total water yield increased following the clearcutting of a mature aspen forest in years 1-9 and year 14 of subsequent aspen regrowth. Maximum increases of 85, 117, and 88 mm / year occurred during the first 3 years of regrowth. Increases in streamflow volumes from snowmelt and early spring rains were minimal and more variable after harvest and regeneration. Most of the streamflow increases occurred during the leaf-on periods, but sporadic increases occurred during the fall-early winter recharge period for as long as 15 years after harvest. Increases in water yield were best explained by changes in aboveground biomass, but precipitation, especially during the leaf-on periods, improved the relationship. Increases in annual water yields became insignificant when aboveground biomass approached 57 tonnes / ha (17 percent of mature forest biomass at 14-15 years of age).

Large variability in stream flow is observed across experimental studies due to large year-to-year variability in watershed response due to climate that can often mask the portion contributed by land cover. But the impact on peak flows in any given year depends on the point of reference from within a watershed and how changes result in homogenization or heterogeneity of watershed response to climatic conditions. For example, research from the Marcell Experimental Forest (Verry et al. 1983; NAS 2008) has shown that peak flows could be reduced at a certain point downstream by a 50% aspen forest clearcut, by de-synchronizing snowmelt peaks, as compared with the mature forest hydrograph. However, with complete upland clearcut of the aspen, snowmelt occurred 4 days earlier watershed-wide, synchronizing and doubling the peak flow rate compared to mature forest conditions.

Impacts of land cover changes on flow regime are proportional, although not always linearly, to the proportion of the watershed and/or biomass affected. A 2008 National Academy of Sciences review of forest hydrology concluded that, for paired watershed experiments across experimental stations, first year water yield increases from cutting increases linearly with % basal area cut. Conversion of 40% or more of forested areas to open lands within a watershed can lead to as much as a doubling or tripling of annual, bankfull, and peak flows (Keppeler et al. 2003, Verry 2004, NAS 2008). Jones and Post (2003) also found both relative and absolute streamflow changes to be positively correlated with the age of the forest at the time it was cut.

Permanent land use conversion to open areas, or forest harvest (more than 1.5% of watershed area per year) can cause changes to hydrology that result from more rapid snowmelt or by more rapid delivery of rain. This, in turn, causes the bankfull flows that shape stream channels to double or triple (Fitzpatrick et al 1999). In North Fish Creek Basin near Ashland, Wisconsin, land conversion to agriculture at the turn of the last century caused (modeled) sediment yields to peak in 1928. Modeled sediment yields in 1991 were still double 2/3 of the pre-conversion yield (Fitzpatrick et al. 1999).

Forest cover changes from conifer to deciduous are known to alter hydrology as well. Numerous studies show that in general, converting conifers to hardwoods can increase discharge and water yield, both short and long-term (NAS 2008). Mao and Cherkauer (2009) analyzed change in hydrology from pre-settlement vegetation to current conditions in Wisconsin. They found that where land-use change was primarily from majority evergreen to majority deciduous forest, decreases of 5–10% in evapotranspiration and increases of 20–40% in total runoff were observed. Experimental studies measuring the impact of forest harvest on flow regimes generally find that water yields return to pre-treatment flow conditions in watersheds dominated by aspen, or other deciduous hardwoods, after 12-17 years (Verry 2004). However, harvest effects on seasonal flow responses in watersheds dominated by conifers may take 35 years or longer (Jones and Post 2004).

While in general changes in forest composition or management may have small effects on an annual or regional scale, seasonal effects and effects on specific ecological flow conditions (EFCs), such as summer low flows, may be important. Yu et al. (2010) used a simulation model to demonstrate impacts from two different forest harvesting techniques on long-term water yield in a Norway spruce forest. Comparing flow duration curves provides a potential means of gaining a greater understanding of the impact of vegetation on the distribution of daily flows (Brown et al. 2005). A study of watershed management practices in Arizona found that forest management and thinning had relatively small impacts on mean annual flows (0-3%), but that forest management practices designed to enhance seasonal streamflows could temporarily enhance seasonal runoff (Robles et al. 2014).

Long-term studies suggest that the effects of harvest on streamflow can be significant and long lasting. Verry and colleagues (Verry 2004, Anderson et al. 2006) have built a weight of evidence case that over an 80 year period of record, a differential pattern of changes in bankfull flow in two streams of northern Minnesota are due to the impacts of historical logging and the influence of local geology and vegetation. Trends in bankfull discharge in the Little Fork River were independent of the effects of annual precipitation and appeared to be driven largely by land cover. In an adjacent, similarly sized river, normalized bankfull flows are significantly lower, due to the latter watershed having a greater percentage of peatlands (that were never logged) which dampen flood flows and reduce flashiness, a greater number of headwater lakes providing more watershed storage, earlier and comparatively less historical logging, and less pasture / open land. A regional curve analysis indicated that the Little Fork River and its tributaries have approximately twice the water yield when compared to other area streams. The Little Fork is likely still recovering from the hydrological and geomorphic impacts associated with historical logging, from years of increased runoff (water yield) following initial harvest, as well as the geomorphic impact of using the river to transport logs.

Flow regime may also be impacted by altered surface-groundwater interactions, due to the interacting processes triggered by legacy land use and channel processes in the context of local geology and vegetation (Verry 2004). Permanent changes can affect stream physical conditions (channel processes, sediment transport) for a century or more (Knox 2001). For example, the downcutting and incision associated with increased peak and bankfull flows can result in hydrologic and physical disconnection of the floodplain from the stream and water table, resulting in loss or degradation of aquatic and riparian habitat. Overall, this body of research has highlighted the need to interpret current flow regimes, water quality and sedimentation problems in the context of past and present watershed hydrological processes and present and future stream channel responses (Fitzpatrick et al. 1999, Fitzpatrick 2014).

Climate variability often amplifies differences in hydrologic responses based on land cover and management. Long-term research at the Coweeta, North Carolina experimental forest found that converting deciduous hardwood stands to pine altered the streamflow response the most during years characterized by precipitation extremes (both low and high). Laird and colleagues (2011) concluded that harvest impacts to streamflows can be significant over long period of time, and explored whether different forest management strategies could potentially mitigate or exacerbate effects associated with climate change. Because streamflow responses varied between management treatments, forest management could potentially be used to mitigate climate change effects. However, a greater ability to predict the direction and magnitude of streamflow effects at different scales is needed.

Climate Change Impacts on Minnesota's Northern Forests and Land Cover

Climate change is expected to a major driver of change to Minnesota's northern forest over the next 1-2 centuries (Duveneck et al. 2014a, Handler et al. 2014). Because Northern Great Lakes forests are transitional to boreal forest to the north and temperate forest to the south they are expected to change dramatically in a warming climate. Minnesota's northern forest is a relatively young ecosystem (6000 years) that assembled with the retreat of the glaciers and Holocene warming (Davis and Shaw 2001, Davis et al. 2005). The current forest is dominated by tree species at the southern edge of their ranges including boreal conifers such as black and white spruce, jack pine, and balsam fir and boreal hardwoods such as quaking aspen and white birch (Handler et al. 2014). This region also includes species such as eastern white pine, sugar maple, red maple, yellow birch, basswood, red oak, and bur oak that are characteristic of north-temperate forests. These species are close to northern edge of their ranges and are expected to increase in abundance while boreal tree species decline as the climate warms (Ravenscroft et al. 2010, Handler et al. 2014; Figure 1.5).

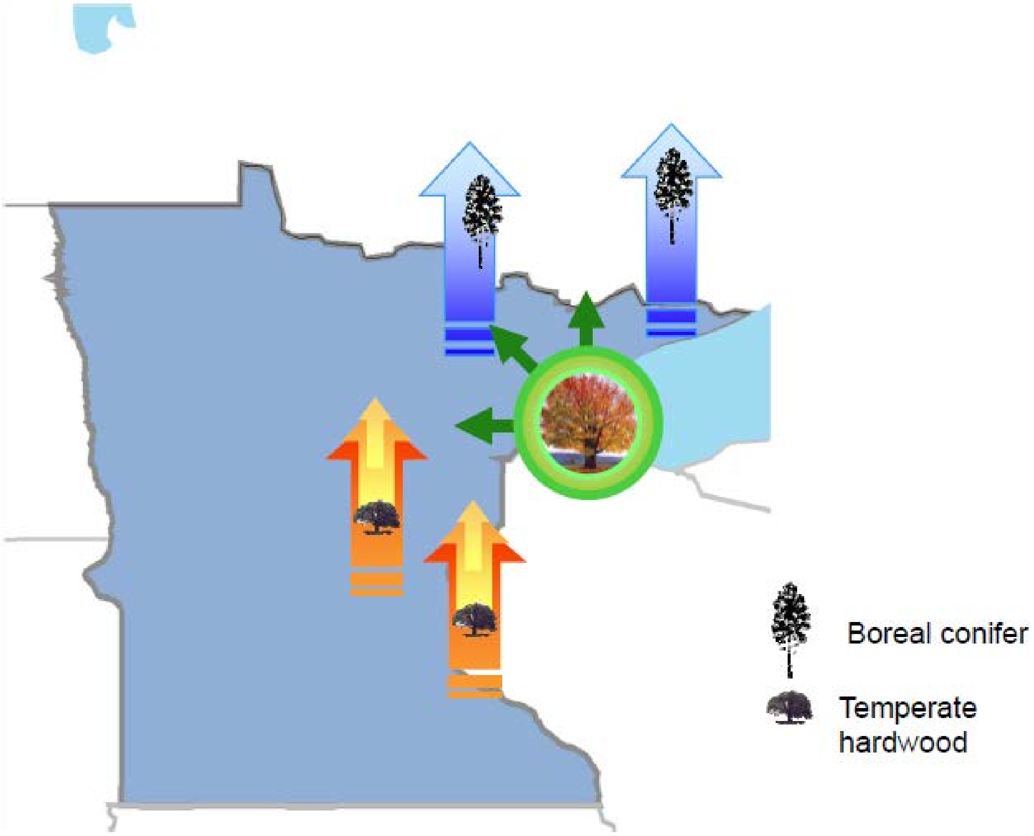


Figure 1.5. Anticipated migration of tree species in the western Great Lakes region. [Adapted with permission from R.M. Scheller]

A variety of modeling efforts (Prasad et al. 2007, Ravenscroft et al. 2010, Duveneck 2014a), as well as paleoecological studies (Davis and Shaw 2001) are consistent in projecting a northward shift in forest habitats due to climate change in the 21st century (Handler et al. 2014).

In general, habitat for temperate hardwood species (oaks, maples, basswood, yellow birch, black cherry, hickories) is expected to increase at the expense of boreal tree species (Prasad et al. 2007, Duveneck et al. 2014b; Figure 1.6). However, modeling works suggests that migration rates for many of these species may not be sufficient to keep up with rapid climate changes (Ravenscroft et al. 2010). Red maple is a temperate tree species that is already well-distributed in northern Minnesota which shows increased establishment and growth relative to boreal species, especially on warmer sites (Fisichelli et al. 2012).

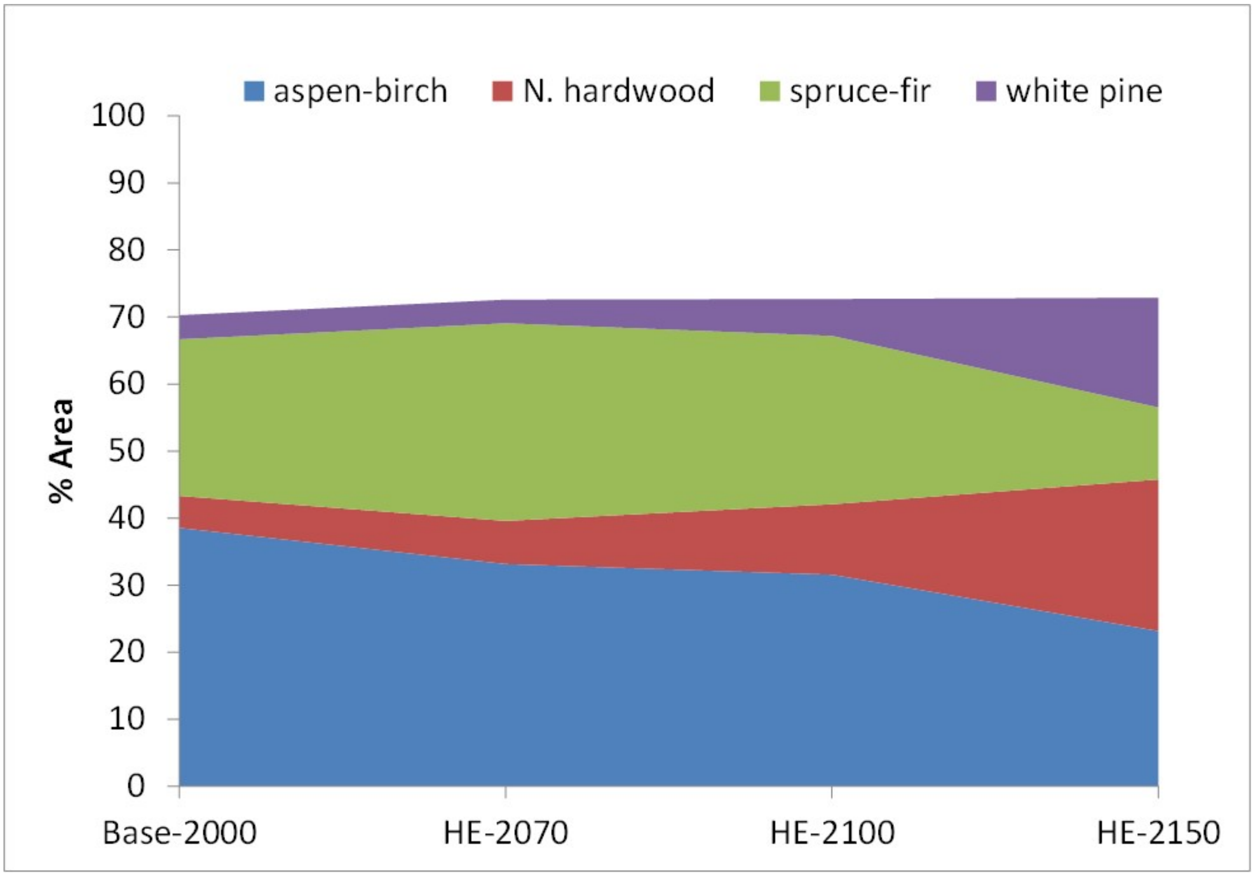


Figure 1.6. LANDIS II forest model projections for northeastern Minnesota based on high emissions (GFDL) and intensive (business as usual) forest management. [Adapted from Duveneck et al. 2014b]

The timescale of change is unclear. Migration rates, pests, disease, land use, natural disturbances and forest management will also impact forest health and composition in the 21st century (Handler et al. 2014). Insect infestations or wildfires may cause faster changes in forest types than suggested by climate models, or the long life expectancy and hardiness of some tree species may ameliorate the impacts of climate change on Lake Superior forests (Saunders et al., 2011). These changes have implications for hydrology of Minnesota's Lake Superior tributaries.

Climate Change and Flow Ecology

There is a growing body of research and evidence documenting freshwater community response to climate change (Isaak 2015). Research suggests that fish responses to climate change, although ongoing, are relatively gradual and may take decades to manifest. In

France, Comte and Grenouillet (2013) found systematic species shifts upstream/towards higher elevation, with mean shifts in range center of 13.7 m/decade and 0.6 km/ decade, respectively. Fish species displayed dispersal-driven expansions along the elevational gradient at their upper range limit (61.5 m/decade), while substantial range contractions at the lower limit (6.3 km /decade) were documented for most species along the upstream–downstream gradient. Despite being consistent with the geographic variation in climate change velocities, they suggested that the majority of stream fish have not shifted at a pace sufficient to track changing climate, in particular at the center of their ranges.

In the interior western U.S., Wenger and colleagues (2011) used downscaled general circulation models coupled with a hydrologic model to forecast effects of altered flows and temperatures on sympatric trout. They found that increases in temperature combined with increased winter flood frequency –when redds and emerging juveniles may be more vulnerable to high flows – are likely to result in habitat loss for nonnative brook trout and brown trout, whereas flow regime shifts that benefit rainbow trout may partially offset habitat loss due to temperature increases. Extreme flow events in winter can lead to scouring and washout of spawning redds and juvenile fish. At the same time, winter low flows may be as significant as summer low flows in terms of constraining fish habitat, since ice can degrade available habitat as well as result in ice scour or even dewatering of fall spawning redds.

Due to changing patterns of precipitation, timing of snowmelt, temperature, and storm intensity, climate change is likely to affect streams primarily via altered streamflow and altered thermal regimes. Behavioral and life history traits that represent adaptations to flow and thermal regimes may either mitigate or mask responses to changing climatic conditions. These adaptations, also known as “traits”, have been studied extensively for many species of fish and invertebrates, and there are now “trait” databases built on a solid foundation of empirical sources and studies (U.S. EPA 2012).

Poff et al. (2010) explored vulnerability of stream benthic communities to climate change using macroinvertebrate and environmental data from 279 reference-quality sites spanning 12 states in the western U.S., and suggested that reference sites in the western U.S. may be differentially vulnerable to future climate change due to the combination of traits-based sensitivity coupled with significant projected changes in temperature and runoff. Regression-tree analysis also showed that temperature and hydrologic variables mostly accounted for the differences in proportion of sensitivity traits across the sites. Vulnerability of sites to climate change was assessed by superimposing regional scale projections of late-21st-century temperature and runoff change on the spatial distribution of temperature- and runoff-sensitive assemblages. Stamp et al. (2010) found that at two sites with long-term data (> 14 years), thermal-preference metrics showed significant patterns that could be interpreted as being related to directional climate change. At these sites, coldwater taxa were negatively correlated with air temperature, and, when years were grouped into hottest- and coldest-year samples, were strongly reduced in the hottest-year samples. Results suggest that thermal-preference metrics show promise for application in a biomonitoring context to differentiate climate-related responses from other stressors.

Flow Ecology in Minnesota's Lake Superior Tributaries

How do current fish communities in Minnesota's Lake Superior tributaries currently relate to flow regimes? Overall, these tributaries have naturally low base flow and high storm flow. Previous research has shown that maintaining base flow is critical to support trout and other coldwater species in them. Because groundwater input is often naturally limited by the area's bedrock geology, stream thermal buffering capacity is naturally low. Flow alterations that affect the relative proportion of groundwater and surface water instream may significantly influence and alter stream temperatures, which can be especially important at certain times of year such as during summer heat waves and low flow events, as well as during winter low flow conditions (Figure 1.7).

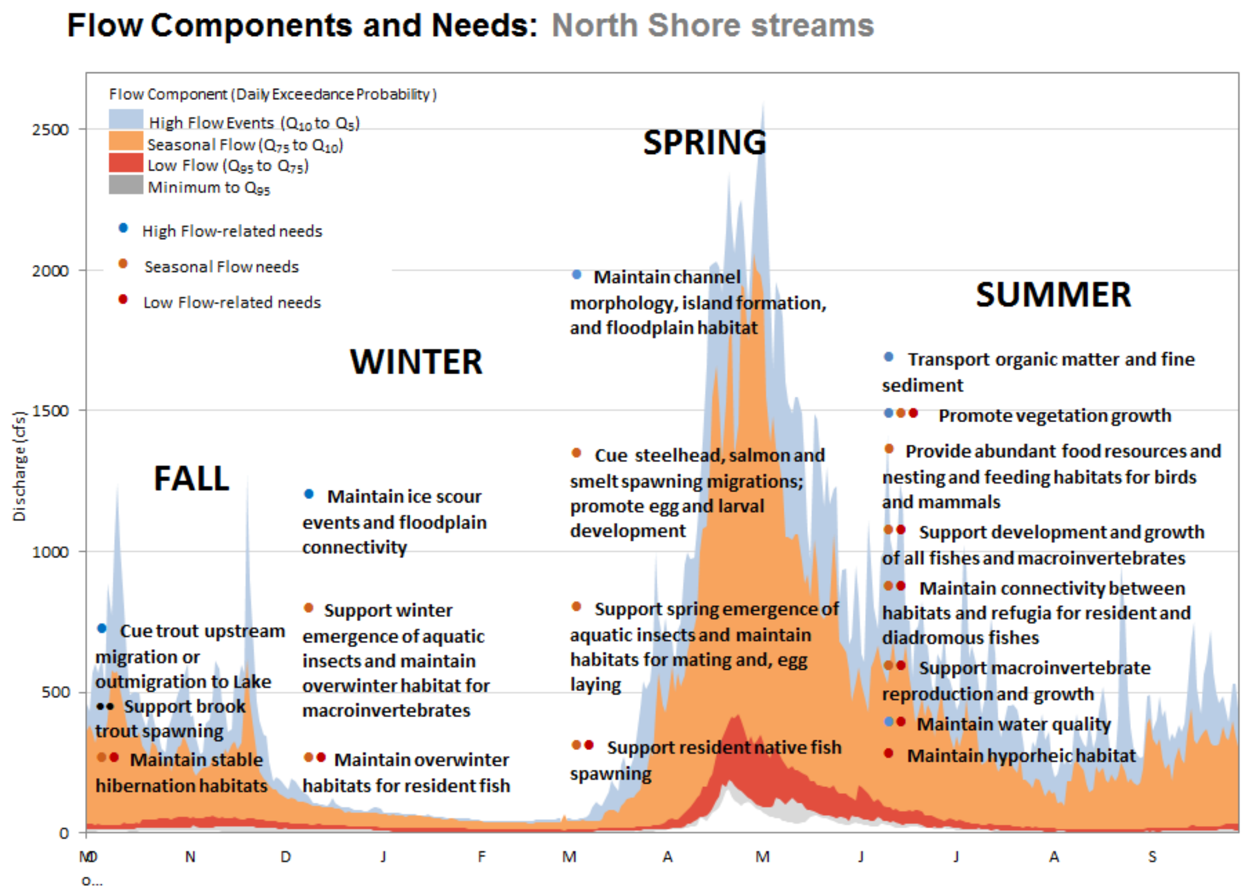


Figure 1.7. Example flow-ecology diagram for Minnesota's Lake Superior tributaries (referred to here as North Shore steams), based on the long-term historic daily statistics for the Baptism River near Beaver Bay.

Multiple studies have used both whole assemblages and individual species' traits to demonstrate altered hydrologic responses and declines in stream fish and biological community indicators as a percentage of "open" land (i.e., loss of mature forest cover resulting from forest harvest, natural disturbance, and/or development) in the watershed increases. Variation in fish response in particular was strongly related to watershed properties controlling hydrologic response, notably mature forest cover and percent watershed storage (Detenbeck et al. 2004, Brazner et al. 2004). Indicator Species Analysis suggested that the best indicator species of fragmentation and watershed storage were brook trout and slimy sculpin for least degraded forest conditions, and common shiners and mesottled sculpins (*Cottus bairdi)* for more degraded conditions (higher fragmentation). For third order streams, brown trout and salmon were significant indicators of lower watershed storage. Close et al. (1989) found that steelhead and Atlantic salmon preferred fast water habitats and avoided pools, whereas Chinook were typically found in deeper water, and responded to overhead cover, independent of measured low flow habitat variables.

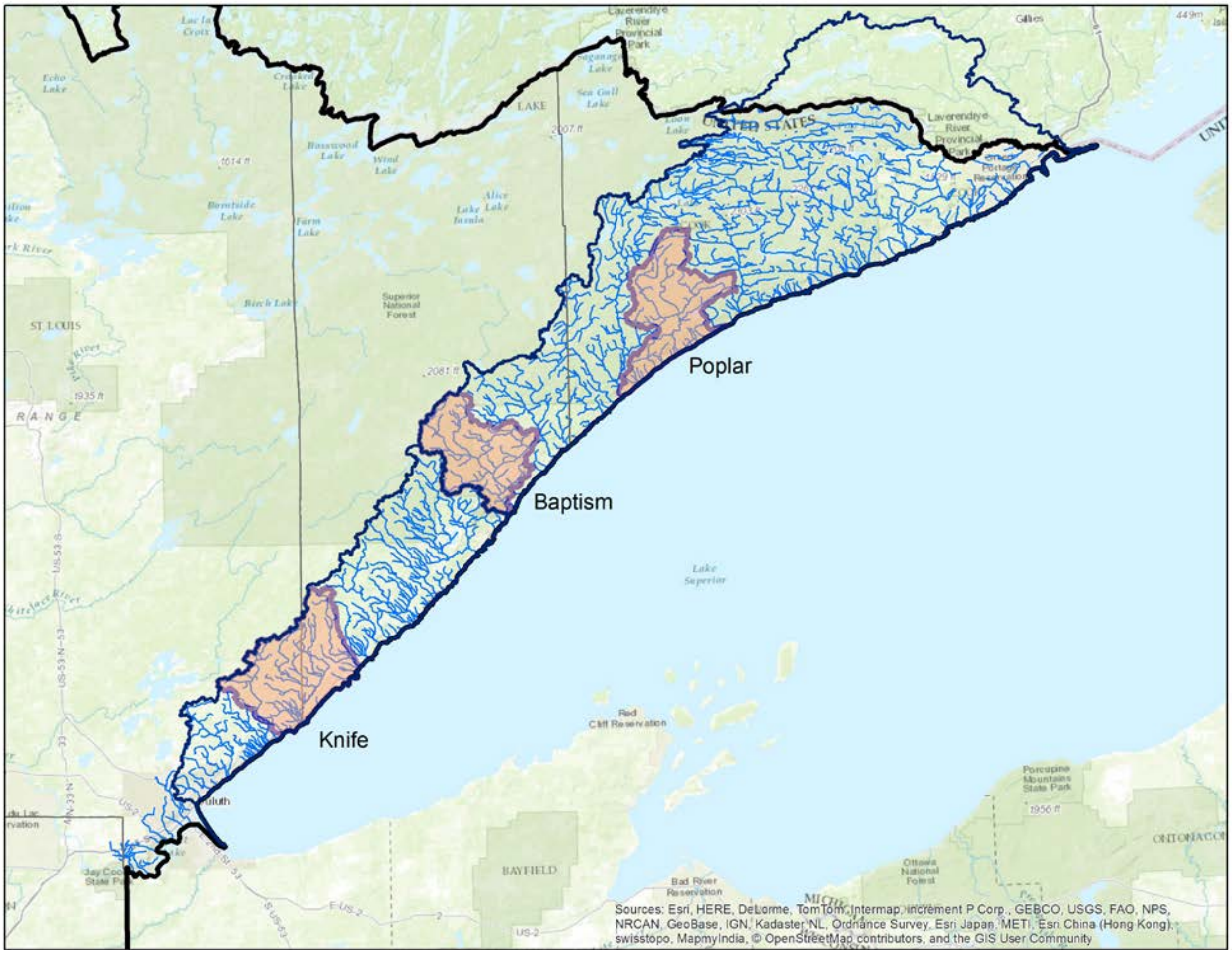
Trophic status indicators-- such as the proportion of predators or insectivores, or benthic feeders for fish, and shredders, filter-collectors, grazers, or predators for macroinvertebrates--are often used as a measure of community structure. Taxonomic and/or life history trait indicator metrics (e.g. feeding, reproduction, locomotion) are frequently included in fish indexes of biologic integrity (IBIs). For example, Brazner et al. (2004) included metrics of body shape and swimming speed for fish, as well as feeding, spawning, and habitat guilds, in evaluating response of fish assemblages to watershed hydrologic indicators in watersheds of Lake Superior (Table 1.1).

Table 1.1. Flow ecology target species groups of fish based on key life history traits and hydrological associations.

Group	Key Traits and Hydrological associations	Species
Coldwater, Headwater	Similar needs defined by temperature thresholds • Groundwater discharge areas serve as spawning habitats and maintain red conditions throughout winter • High seasonal flows keep redds sediment free • Scour events can flush eggs/larvae from redds • Low flows increase temperature and limit habitat quality and availability • Timing of spawning, rearing, and migration varies by species	Brook trout, brown trout, sculpins
Anadromous sport fish	Salmonid species that use lake habitats for adult growth and stream habitats for spawning and juvenile growth • High flow events remove sediment from spawning substrates • High flow events combined with temperature changes cue spawning runs • Higher flows increase connectivity between shallow spawning habitat and deeper downstream habitats	Salmon and steelhead
Riffle obligates	Small bodied, flow-velocity specialists who spend most of their life in riffle/run habitats • High to moderate velocity riffle and run habitats are limited by low flow periods	Longnose dace, blacknose dace, logperch, darters
Riffle associates	Species with moderate-sized home range that migrate in the spring to spawn and need access to, and connectivity between, riffle habitats • High flow events remove sediment from spawning substrates • High flow events combined with temperature changes cue spawning runs • Higher flows increase connectivity between shallow spawning habitat and deeper downstream habitats • Low flows can limit drift and limit survival of larvae	Redhorse, suckers, bass, walleye
Nest builders	Similar timing of flow needs (during nest building, spawning, and egg and larval development), but a diverse group in terms of nesting strategy (includes true nests, mound construction and ledge spawners) • High discharge events after spawning scour nests	Creek chub, sunfishes, smallmouth bass, johnny darter
Marsh spawners	Large-bodied fish that rely on spring flows to flood emergent vegetation for spawning • Rely on spring high flows to flood and maintain backwater marsh areas for spawning, egg and larval development, and swim up.	Northern Pike

Study Watersheds

Our study area or region included the Lake Superior – North (Hydrologic Unit Code (HUC) 04010101) and portions of the Lake Superior – South (HUC 04010102) watersheds in northeastern Minnesota (Figure 1.8). Intensive modeling (hydrologic) was conducted in the Knife, Baptism and Poplar River watersheds.



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 1.8. Study area (region). The bold black line on the western edge of the Baptism River watershed marks the boundary between the Lake Superior – North and Lake Superior – South watersheds. The three intensively modeled watersheds (Knife, Baptism and Poplar) are noted in pink.

Lake Superior – North

According to the Minnesota Pollution Control Agency:

> the Lake Superior North watershed covers 1,019,923 acres in the Northern Lakes and Forest ecoregion. Soils and subsurface geology are dominated by bedrock, glacial

> till complexes and unconsolidated glacial lake deposits of sand, gravels, clay and silt. Bedrock is complex in its evolution and contributes to the spectacular mountains and ridges that slope toward Lake Superior. Numerous streams flow through the bedrock cracks, forming waterfalls, cascades and rapids. Wetlands and lakes are found throughout the watershed. (Minnesota Pollution Control Agency, 2016a)
>
> Land use in the Lake Superior North watershed is a mix of smaller towns and commercial, resort and rural residential. Developed areas include the communities of Finland, Schroeder, Tofte, Lutsen, Grand Marais, Hovland and Grand Portage. Significant development is also located along Lake Superior's shoreline. Tourism and forest products are significant components of land use activity. Some commercial/industrial uses, such as marinas, shipping ports and taconite processing support, depend upon water resources. (Minnesota Pollution Control Agency, 2016a)
>
> The watershed is a source of exceptional water quality in many areas. Some streams do not meet water quality standards for beneficial uses such as aquatic recreation, drinking and swimming due to a turbidity impairment. In this watershed, turbidity is associated with suspended sediment. (Minnesota Pollution Control Agency, 2016a)

Two of the intensively modeled watersheds, the Poplar and Baptism Rivers, fall within the Lake Superior – North watershed.

Lake Superior – South

According to the Minnesota Pollution Control Agency:

> the Lake Superior South watershed is 402,371 acres in size. The watershed is located in the Northern Lakes and Forest Ecoregion. Soils and subsurface geology are dominated by bedrock, glacial till complexes, and erodible lake-laid clay soils. Bedrock is complex in its evolution and contributes to the spectacular mountains and ridges that slope toward Lake Superior. Numerous streams flow through the bedrock cracks forming waterfalls, cascades, and rapids. Lakes are found predominantly in the northeastern-most section. Major developed areas include the city of Duluth and towns of Two Harbors, Beaver Bay, and outskirts of Silver Bay. Significant development is also located along Lake Superior's shoreline. (Minnesota Pollution Control Agency, 2016b)
>
> Land use in the Lake Superior – South watershed is a mix of urban and commercial, resort and rural residential. Tourism and forest products are significant components of land-use activity. Some commercial/industrial uses, including marinas, shipping ports, and taconite processing support, utilize and/or depend upon water resources.

> (Minnesota Pollution Control Agency, 2016b)
>
> The watershed is a source of exceptional water quality in many lakes, streams and rivers. However, some streams do not meet water quality standards for beneficial uses such as aquatic recreation, drinking, and swimming due to excess levels of turbidity and bacteria (*E. coli*). Turbidity is associated with suspended sediment. Additional stressors such as elevated stream temperatures in recent summers and lack of persistent flow have become sources of concern for resource managers. (Minnesota Pollution Control Agency, 2016b)

One of the intensively modeled watersheds, the Knife River, falls in the Lake Superior – South watershed.

References

Allan, J.D., 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics*, 35(1), pp.257– 284.

Allan, J.D. & Johnson, L.B. (1997). Catchment-scale analysis of aquatic ecosystems. *Freshwater Biology*, 37, pp.107–111.

Anderson, J. et al., (2006). *Effect of Historical Logging on Geomorphology , Hydrology , and Water Quality in the Little Fork River Watershed. M*innesota Pollution Control Agency and Ellen River Partners: St Paul, MN.

Assel, R., Quinn, F., and Sellinger, C. (2004). Hydroclimatic Factors of the Recent Record Drop in Laurentian Great Lakes Water Levels. Bulletin of the American Meteorological Society, 85(8), 1143–1151.

Blankenheim, J. (2013). Status of Coaster Brook Trout in Minnesota Lake Superior Tributaries Report to Minnesota Department of Natural Resources.

Blann, K. and Kendy, E. (2012). *Developing Ecological Criteria for Sustainable Water Management in Minnesota*. The Nature Conservancy, Minneapolis, MN.

Brazner, J.C. et al. (2004). Landscape character and fish assemblage structure and function in western Lake Superior streams: general relationships and identification of thresholds. *Environmental Management*, 33(6), pp.855–875.

Brown, A.E. et al., 2005. A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology*, 310(1-4), pp.28–61. Available at: http://www.sciencedirect.com/science/article/pii/S0022169404005906 [Accessed July 14, 2014].

Close, T., Belford, D. & Anderson, C.S., (1989). *The Role of Low Flow Habitat and Interspecific Competition in Limiting Anadromous Parr Abundance in North Shore Streams.* Minnesota DNR Fisheries Investigational Report #398, Saint Paul, MN.

Comte, L. & Grenouillet, G., 2013. Do stream fish track climate change? Assessing distribution shifts in recent decades. *Ecography*, 36(11), pp.1236–1246.

Davis, M.B. and R.G. Shaw. (2001). Quaternary history of deciduous forests of eastern North America and Europe. Annals of the Missouri Botanical Garden. 70 (3): 550-563.

Davis, M.B., R.G. Shaw, J.R. Etterson (2005). Evolutionary responses to changing climate. *Ecology* 86(7): 1704-1714.

Detenbeck, N.E. et al. (2004). Region, landscape, and scale effects on Lake Superior tributary water quality. *Journal of the American Water Resources Association*, 55804, pp.705–720.

Duveneck, M.J. et al. (2014a). Climate change effects on northern Great Lake (USA) forests : A case for preserving diversity. *Ecoshpere*, 5(February), pp.1–26.

Duveneck, M.J., Scheller, R.M. & White, M. (2014b). Effects of alternative forest management on biomass and species diversity in the face of climate change in the northern Great Lakes region (USA). *Can J For Res*, 710(September 2013), pp.700–710.

Fisichelli, N., L. E. Frelich and P. B. Reich (2012). "Sapling growth responses to warmer temperatures 'cooled' by browse pressure." Global Change Biology **18**: 3455-3462.

Fitzpatrick, F., J. Knox, and H. Whitman. (1999). Effects of historical land-cover changes on flooding and sedimentation, North Fish Creek, Wisconsin. U.S. Geological Survey Water Resources Investigations Report 99-4083, 12 p.

Fitzpatrick, F. (2014). Diagnostic Geomorphic Methods for Understanding Future Stream Behavior of Lake Superior Streams – What Have We Learned in Two Decades? Lake Superior Stream Science Symposium. Duluth, MN.

Handler, S., Duveneck, M. J.; Iverson, L.; Peters, E.; Scheller, R. M.; Wythers, Kirk R.; Brandt, Leslie; Butler, P.; Janowiak, M.; Shannon, P. D.; Swanston, C.; Barrett, K.; Kolka, R.; McQuiston, C.; Palik, B.; Reich, P. B.; Turner, C.; White, Mark; Adams, C.; D'Amato, A.; Hagell, S.; Johnson, P.; Johnson, R.; Larson, M.; Matthews, S.; Montgomery, R.; Olson, S.; Peters, Matthew; Prasad, A.; Rajala, J.; Daley, J.; Davenport, Mae; Emery, Marla R.; Fehringer, David; Hoving, C. L.; Johnson, G.; Johnson, L.; Neitzel, D.; Rissman, A.; Rittenhouse, C.; Ziel, R. (2014). Minnesota Forest Ecosystem Vulnerability Assessment and Synthesis: A Report from the Northwoods Climate Change Response Framework Project. General Technical Report NRS-133. USDA, Forest Service, Northern Research Station. Newtown Square, PA. 228 p.
URL: http://www.treesearch.fs.fed.us/pubs/45939

Hayhoe, K., VanDorn, J., Croley, T., Schlegal, N., and Wuebbles, D. (2010). Regional Climate Change Projections for Chicago and the US Great Lakes. Journal of Great Lakes Research, 36, 7–21.

Huckins, C.J. et al., 2008. Ecology and Life History of Coaster Brook Trout and Potential Bottlenecks in Their Rehabilitation. *North American Journal of Fisheries Management*, 28(4), pp.1321–1342.

Huff, A. and A. Thomas. 2014. Lake Superior Climate Change Impacts and Adaptation. Prepared for the Lake Superior Lakewide Action and Management Plan – Superior Work Group. Available at https://www.epa.gov/greatlakes/lake-superior-climate-change-impacts-report.

IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds)]. IPCC, Geneva, Switzerland, 151 pp.

Isaak, Dan. (2015). Climate-Aquatics Blog Compendium. Accessed May 2016: http://www.fs.fed.us/rm/boise/AWAE/projects/stream_temp/stream_temperature_climate_aquatics_blog.html.

Johnson, L., Herb, W., and Cai, M. (2013). Assessing Impacts of Climate Change on Vulnerability of Brook Trout in Lake Superior's Tributary Streams of Minnesota. Report to Minnesota Department of Natural Resources.

Jones, Julia A., Post, D.A., 2004. Seasonal and successional streamflow response to forest cutting and regrowth in the northwest and eastern United States. *Water Resources Research*, 40(5), pp.1–19.

Keppeler, E.T., Lewis, J. & Lisle, T., 2003. Effects on Forest Management on Streamflow, Sediment Yield, and Erosion, Caspar Creek Experimental Watersheds. pp.1–6.

Kling, G., Hayhoe, K., L. Johnson, J. Magnuson, S. Polasky, S. Robinson, B. Shuter, M. Wander, D. Wuebbles, D. Zak, R. Lindroth, S. Moser, and M. Wilson. (2003). Confronting Climate Change in the Great Lakes Region. Union of Concerned Scientists, Cambridge, Massachusetts, and Ecological Society of America, Washington, D.C.

Kunkel, K., Andsager, K., & Easterling, D. (1999). Long-term Trends in Extreme Precipitation Events over the Conterminous United States and Canada. Journal of Climate, 12(1998), 2515–2527.

Laird, S.G. et al., 2011. Long-term Forest Management and Climate Effects on Streamflow. *Fourth Interagency Workshop on Research in the Watersheds*, (September), pp.26–30.

Lofgren, B., Quinn, F., Clites, A., Assel, R., Eberhardt, A., and Luukkonen, C. (2002). Evaluation of Potential Impacts on Great Lakes Water Resources Based on Climate Scenarios of Two GCMs. Journal of Great Lakes Research, 28(4), 537–554.

Lynch, A.J. et al. (2016). Climate Change Effects on North American Inland Fish Populations and Assemblages. *Fisheries*, 41(7), pp.346–361. Available at: http://www.tandfonline.com/doi/full/10.1080/03632415.2016.1186016. .

Mao, D. & Cherkauer, K. (2009). Impacts of land-use change on hydrologic responses in the Great Lakes region. *Journal of Hydrology*, 374(1-2), pp.71–82. Available at: http://dx.doi.org/10.1016/j.jhydrol.2009.06.016.

Minnesota Pollution Control Agency. (2010). Adapting to Climate Change in Minnesota. Report to Minnesota Pollution Control Agency.

Minnesota Pollution Control Agency. (2016a). Lake Superior – North. https://www.pca.state.mn.us/water/watersheds/lake-superior-north. [Accessed August 4, 2016].

Minnesota Pollution Control Agency. (2016b). Lake Superior – South https://www.pca.state.mn.us/water/watersheds/lake-superior-south#overview . [Accessed August 4, 2016].

Minnesota Environmental Quality Board (MN EQB). (2014). Minnesota and Climate Change: Our Tomorrow Starts Today. St. Paul, MN. URL: https://www.eqb.state.mn.us/sites/default/files/documents/EQB%20Climate%20Change%20Communications.pdf.

Minnesota State Demographic Center. (2007). Minnesota Minor Civil Division Extrapolated Population (city/township). Average of middle values of 4 methods, controlled to county projection. Accessed October 2007: https://mn.gov/admin/demography/

National Academy of Science. (2008). *Hydrologic Effects of a Changing Forest Landscape*, Washington, D.C.: National Academies Press.

Poff, N.L. et al. (1997). The natural flow regime - a paradigm for river conservation and restoration. *BioScience*, 47(11), pp.769–784. Available at: http://www.jstor.org/stable/1313099.

Poff, N.L. et al., 2010. Developing linkages between species traits and multiscaled environmental variation to explore vulnerability of stream benthic communities to climate change. *Journal of the North American Benthological Society*, 29(4), pp.1441–1458. Available at: http://www.bioone.org/doi/abs/10.1899/10-030.1. [Accessed December 30, 2014].

Prasad, A. M., L. R. Iverson, S. Matthews, and M. Peters. 2007. A climate change atlas for 134 forest tree species of the eastern United States [database]. Northern Research Station, USDA Forest Service, Delaware, OH. http://www.nrs.fs.fed.us/atlas/tree

Ravenscroft, C.R. et al., 2010. Forest restoration in a mixed-ownership landscape under climate change. *Ecological applications : a publication of the Ecological Society of America*, 20(2), pp.327–346. Available at: http://www.ncbi.nlm.nih.gov/pubmed/20405791.

Robles, M.D. et al., 2014. Effects of Climate Variability and Accelerated Forest Thinning on Watershed-Scale Runoff in Southwestern USA Ponderosa Pine Forests. *PLoS ONE*, 9(10), p.e111092. Available at: http://dx.plos.org/10.1371/journal.pone.0111092.

Saunders, S., D. Findlay, T. Easley, and T. Spencer. 2011. Great Lakes National Parks in Peril: The Threats of Climate Disruption. Rocky Mountain Climate Organization (RMCO) and National Resources Defense Council (NRDC). Available at http://www.rockymountainclimate.org/images/GreatLakesParksInPeril.pdf.

Sharma, S. & Magnuson, J.J., 2014. Oscillatory dynamics do not mask linear trends in the timing of ice breakup for Northern Hemisphere lakes from 1855 to 2004. *Climatic Change*, 124(4), pp.835–847.

Stamp, J.D. et al., 2010. Use of thermal preference metrics to examine state biomonitoring data for climate change effects. *Journal of the North American Benthological Society*, 29(4), pp.1410–1423.

U.S. Environmental Protection Agency (U.S. EPA). (2012). *Freshwater Biological Traits Database, Final Report 2012*, Accessed December 2014: https://cfpub.epa.gov/ncea/global/recordisplay.cfm?deid=241813.

U.S. Environmental Protection Agency (U.S. EPA). (2014). Integrated Climate and Land-Use Scenarios (ICLUS). URL: https://www.epa.gov/iclus

U.S. Global Change Research Program (USGCRP 2009). *Global Climate Change Impacts in the United States: Midwest.* URL: https://nca2009.globalchange.gov/midwest/index.html

Verry, E.S. (1987). The effect of aspen harvest and growth on water yield in Minnesota. *Forest Hydrology and Watershed Management, IAHS Publ. no 167*, (August), pp.553–562.

Verry, E.S. (2004). Land fragmentation and impacts to streams and fish in the central and upper Midwest. In G. C. Ice & J. D. Stednick, eds. *Lessons for Watershed Research in the Future: A Century of Forest and Wildland Watershed Lessons.* Bethesda, Maryland, pp. 129–154.

Verry, E.S., J.S. Lewis, and K.N. Brooks. (1983). Aspen clearcutting increases snowmelt and stormflow peaks in North Central Minnesota. *Water Resources Bulletin* 19(1):59-67.

Wenger, S.J. et al., 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, 108(34), pp.14175–14180.

Yu, X. et al., 2013. Modeling the long term water yield effects of forest management in a Norway spruce forest. *Hydrological Sciences Journal*, (July).

Module 2: Resource Manager Engagement

Introduction

Natural resource managers and decision makers want to know how to apply developing science about climate change to their work. They understand that the potential effects of changing climate can be anticipated, addressed, and hopefully, mitigated, through best management techniques. They have an idea about what changes are likely to come – based on their observation of increased precipitation and warmer temperatures generally.

Scientists and researchers in the Lake Superior basin want to see their research applied to real world problems. Therefore, we convened managers and researchers to develop scientifically credible management recommendations to help address changing climate conditions on Minnesota's Lake Superior tributaries.

These techniques can protect ecological and human resources. Many of these techniques are known and established through best management practices. However, the potential changes are uncertain and the ecological effects are unknown. Moreover, land use changes affect human values. It was important to managers that any management actions be credible, defensible and understandable. Science does not rest until all information is challenged. Yet, managers want answers – fast. Reconciling these two world views was an important challenge to the success of this project.

Minnesota's coastal area is large geographically, but low in population. There is significant public land ownership. There is also private land ownership. The private lands are subject to local rules and practices, but administration is not necessarily consistent.

Public lands are managed through administering agencies at the federal, state and local level. Those agencies have adopted organizational or institutional approaches to dealing with climate change.

However, private land ownership is a component of the land base that is also affected by climate change. Natural resource managers at the state and federal level have to engage local government managers to prepare for the anticipated changes.

Land use is managed by counties, through state law that provides that authority to county governments on private lands. In Minnesota, state agencies administer regulations affecting water quality and shoreline conditions. The Minnesota Board of Water and Soil Resources (BWSR) administers county soil and water conservation districts (SWCDs) which work with private landowners on wetlands, erosion and water planning.

Methods

Two core advisors were part of this project: researchers who would explore the ecological limits of hydrologic alteration, and managers whose work can help maintain stream resiliency. Many of the participants in either community knew each other at the start of the project. This helped us with the central task of reconciling the uncertainty of science with the manager's need for action.

We used formal and informal methods to define the area of inquiry for the project. First, we asked managers to identify what information about Lake Superior tributaries would be most useful to them. We did an informal survey and a workshop to identify knowledge needs.

Then, we recruited scientists to help us develop that information.

Finally, we reconvened the managers to review what we have learned and then to help us craft management recommendations that are based on the new science.

The first step in gathering information was to ask natural resource managers about their understanding of flow information, climate and land use change, and their ideas about implications for management, in a survey in summer of 2015.

This was an informal or qualitative survey of selected managers conducted by Minnesota Sea Grant. Managers selected for interviews were drawn from local governments, especially SWCDs in the three counties located in the study area. SWCDs work with private landowners for voluntary conservation activities. Private land owners rely on district managers for guidance and advice on addressing conservation issues on their property. It was important to understand the kinds of questions that managers are asked to answer and the challenges they face.

Managers were identified by Minnesota Sea Grant staff and confirmed with the project leadership team. Interviewees included:

- Soil and water conservation district managers and technicians from Cook and Lake counties (six individuals);
- Naturalist and board member of local scientific education center (one individual);

- Minnesota Department of Natural Resources fisheries specialists from the Duluth, Grand Marais and Finland area offices (six individuals);
- Minnesota Department of Natural Resources St. Louis River, Lake Superior and coastal program specialists (five individuals), and
- Minnesota Pollution Control Agency watershed specialists (two individuals).

These 20 individuals were interviewed for about twenty minutes each, in person and over the telephone. They were asked about their understanding of the following topics:

- Anecdotal and informal observations about climate conditions, especially stream flow, extreme storms or weather events, winter temperatures and ice cover and land use trends;
- How climate change could affect their management actions;
- Local understanding of the relationship between climate change and land use; and
- Tools or resources that they would like to help with their work.

Results were compiled and discussed with the project team. Unfortunately, the actual comments from stakeholders were not compiled in a report. Instead, the project team used the ideas to organize a workshop to bring together researchers and managers to identify how the research could support management. This workshop was held at Tettegouche State Park in September 2015. The goals of the workshop were:

- Connect participant needs with the project
- Identify needs and process for going from concept to tool
- Engage stakeholders on review of interim products
- Identify additional data needs, management needs, research needs and a path forward.

The workshop was organized in two parts:

1. Report of underlying assumptions and hypotheses guiding the research, especially an understanding of the concept of ecological limits of flow, relationship of flow to the fish life cycle, and the possible scenarios for climate changes; and
2. Small group exploration of how these issues affect management and strategies to adapt management accordingly.

In January 2016, the project team presented work to date at the biannual Lake Superior Watershed Stream Science Symposium at the University of Minnesota – Duluth. This is a professional conference with more than 150 managers, researchers and citizens in attendance. All research results were presented to date.

The stakeholder group was reconvened in May 2016 and reviewed final results. We were not able to develop a set of specific management recommendations at that workshop.

Results & Findings

Overview

This project used three approaches to working with resource managers and others:

- One-on-one interviews with research staff;
- Formal presentations in a symposium setting, and
- Informal interactions in a workshop setting.

These three approaches provided benefits to resource managers. For example, the one-on-one interviews provided the opportunity for open-ended observations about the connection between research and science. The formal and informal presentations of research – at the symposium and in the workshops – provided opportunities to learn and critique research. And, finally, the interaction portion of the workshop provided informed feedback about how the research would provide managers critical information.

We think that it was important to provide this layered approach. The science is difficult and it can be challenged by elected officials who have authority over local decision makers. Repeated presentations gave managers the opportunity to truly learn from the researchers, and several managers challenged the researchers to provide information that could be easily understood by decision-makers.

We also found that researchers are bound by the practices of science and are not necessarily comfortable applying results to actions. In the long run, it was the managers who could conceptualize research findings in terms of action.

Specific Results

2015 Survey

The 2015 survey gathered initial ideas from 20 area natural resource managers about the impact of climate change on land use, types of information they need for planning for maintaining desired conditions, and how best to share project information, outputs and products. Respondents reported on current planning mechanisms to address climate change, anticipated local impacts from a changing climate on natural resources and features, importance of different types of information related to a changing climate as it relates to stakeholder roles and responsibilities, anticipated land use changes in the study area, and preferred methods of sharing project information with stakeholders throughout the course of the study.

Nearly two-thirds of the managers said that climate change would likely result in increases in air temperatures, water and stream temperatures, runoff, flooding, storm intensity, shifts in geographic ranges of plant and animal species and algal blooms.

About half the respondents said that coastal water quality would likely decrease, while about one-third said that the amount of precipitation, especially snow, would likely decrease.

Local natural resource managers manage land use in riparian areas. When asked to rank the importance of climate change information to their work, they stated that information about changes to lake levels and shoreline changes were very important. They also said that understanding local climate change predictions was very important to their work.

Local land use actions can directly affect the riparian area of a stream or lake, affecting the ability of the water body to attenuate high flows or sustain base flow through periods of low water. The survey results helped the project team delve deeper into the connections between management and the stream flow work.

September 2015 Workshop

During the September 2015 workshop, resource managers identified real-time decision making that could promote stream resilience and minimize impacts of climate change. These actions ranged from direct management efforts, such as culvert sizing, and included actions that require a longer time frame, such as land use planning, floodplain planning and management, and habitat and water use planning and management. The distinction between immediate actions and long term planning was an important finding. Stakeholders stated that the scale of most climate change research tended to be extremely long term – up to 100 years. That is useful for overall forest, floodplain, and habitat management, they said. However, shorter-term projections in ten-year increments at the catchment scale are more applicable to managers work, as it is tied to the actions of local private property owners and associated permitting and decision making frameworks, as well as the very short-term funding cycles supporting local and state governments.

During the workshop, stakeholders were asked to identify and rank several types of project information by perceived importance to their work. The following list includes the top types of information as identified at the September 2015 workshop:

- Maps of predicted cold-water streams: 30-50 years into the future (with confidence interval)
- Priority areas to implement best management practices (BMPs)
- List of the best types of BMPs to implement on streams/watersheds and stream

types (classifications)

- Map of stream health and resilience as a whole and by segment
- Types of management activities that will address/achieve solutions for climate change issues
- Decision matrix for prioritization of culvert replacements/upgrades, stream restoration, etc. with inclusion of "value" of the watershed
- Models that predict increases in peak flow (eg. 100 year recurrence) to aid in decision-making such as culvert sizing
- Maps depicting forest changes incorporated related to hydrological impacts
- Three-dimensional map/image of stream channel/corridor/flood plain
- Predicted changes in stream flow (frequency and magnitude)
- Prioritization of riparian areas for ecological function and use

Minnesota Lake Superior Watershed Stream Science Symposium

Formal presentations of project research were featured at the Minnesota Lake Superior Watershed Stream Science Symposium in January 2016. In addition to the project participants, more than 150 other individuals from the region participated and learned about research on ecological limits of hydrologic alternation. Research identified stressors and threats as well as broad scale management strategies were identified and captured in the symposium proceedings (http://www.lrcd.org/uploads/1/6/4/0/16405852/proceedingsii.6.pdf).

Individual Meetings

Following the Symposium, key participants from SWCDs, the Minnesota BWSR, Minnesota Pollution Control Agency (MPCA), Minnesota Department of Natural Resources (MNDNR) hydrologists, fisheries specialists and stream restoration staff, as well as representatives of the natural resources division of the Fond du Lac Band of Ojibwe were scheduled to participate in individual meetings with project team members to learn about and provide input on specific project outputs to identify how project information/products could be directly applied to their work. Managers reiterated again their main flow concerns: flashiness and extreme low flows at the catchment level. They also expressed interest in maps and decision support tools to help identify particularly vulnerable stream segments under changing conditions and guidance on stream prioritization in the face of climate and land use change.

Summary of Results

Resource managers expressed concerns about the impact of climate change on low flows, warming of cold-water streams and the potential impact of greater extremes in precipitation on in-stream communities of fish and invertebrates. They shared very specific information needs and priorities, including flow data, maps, and prioritization assistance among other things (Table 1).

Table 1. Priority topics articulated by resource managers and others during surveys, meetings and workshops.

Category	Topics of Interest and Needs
Flow Data	Flashiness index related to biological data (could help when working with private landowners) Models outputs (data) predicting: • peak flow • changes in stream flow (frequency and magnitude) • low flow (seasonal) • stream segment seasonal outlooks for flashiness
Prioritize Streams and Assistance	Need for help prioritizing where stream restoration happens that fits within approximately ten year planning cycles Prioritize areas that are predicted to have flow change due to land cover/development and climate change Focus on protecting streams that are likely to be in fairly good condition 'Prioritized, Targeted and Measurable' or PTM is the basis for local management decisions.
Maps (1:24,000 scale ideally)	Maps predicting changes in flow for cold-water streams over the next 30-50 years Forest change maps related to hydrological impacts Map of stream health and resilience for region and by stream segment Maps that include the kind of change anticipated Map of locations and timing of stream sections anticipated to reach critically low flows Map current conditions and future scenarios to show where change may occur Map catchments that are most flashy and anticipated to increase flashiness under climate scenarios
Other Priorities	Types of management activities that will address/ achieve solutions for climate change issues, e.g. forestry practices, land use/setbacks. Decision matrix for prioritization of culvert replacements/ upgrades. Land use and land cover (tree species, function of plant communities)-scale (parcel level base level) Projections of future land cover at the catchment level Identify gaps where additional data is needed, e.g. places where we need more gages Provide seasonal summaries and score by conditions and rank by season in terms of conditions for fish Stability of fish communities over time

Conclusions

What have we learned?

Resource managers have a critical role in the determining the future of Minnesota's Lake Superior tributaries and a desire to take the necessary steps to respond to changing climate conditions. They have information needs and priorities that if met can lead to better management.

Management Recommendations

Strategies for adapting to and mitigating for climate change impacts on stream biodiversity over the next decades are all about maintaining and enhancing the natural resilience of stream and riparian ecosystems. Protecting the healthiest systems is likely to be a more effective strategy than attempting to restore systems that are already degraded.

One way to approach this is through the use of our management support tool (Appendix 2-I). The tool is an aid in deciding which types of management actions are appropriate in certain places given what we know about current stream conditions and how they may change in the future. It is a direct output of this project and marries the project's research and the natural resource managers' needs.

For More Information

Contact John Jereczek (218-302-3244; john.jereczek@state.mn.us) with questions about the project's engagement efforts or the management support tool.

References

Social Science Tools for Coastal Programs: Introduction to Survey Design and Delivery. NOAA Office for Coastal Management. 2009.

Social Science Tools for Coastal Programs: Introduction to Conducting Focus Groups. NOAA Office for Coastal Management. 2009.

Appendix 2-I: Management Decision Tool

Introduction

The research conducted for "Sustaining Minnesota's Tributaries in a Changing Climate" indicates that three flow metrics are most consistently associated with biological responses: (1) spring and summer high flows (Q10); (2) summer low flows (Q90); and (3) the flashiness index.

The "Sustaining Minnesota's Tributaries in a Changing Climate" project generated these flow metrics across the area. Available are:

- Future and current spring high flow and summer low flow for the entire Lake Superior-North and –South watersheds.
- Flashiness for all watersheds for the current time period only.
- Future summer high flows for the Knife, Baptism and Poplar river watersheds.

How to use

Locate a watershed of concern in the "Management Decision Guidance" ArcGIS Map Package available at http://data.nrri.umn.edu/data/dataset/eloha. Determine from the GIS data the modeled conditions for Flashiness, Spring High Flow, and Summer Low Flow. Using the grids below identify the color category and check the column on the right. Add the columns together to get an overall score. This then relates to the management recommendations table. Ecological flow criteria have been established for "sustainability boundaries" for flow alteration. Overall, protecting the healthiest systems is likely to be a more effective strategy than attempting to restore systems that are already degraded.

For more details on these criteria, refer to the Flow Ecology Module (Module 7) in "Sustaining Minnesota's Tributaries in a Changing Climate" available at www.mndnr.gov/eloha.

Modeled Conditions

Current	Flashiness	Low	Medium	High
0	0	0	0	0

R Y B

Modeled Conditions +

Change in High	Spring High	Medium	High
0	0	0	0

R B

Current Modeled Conditions +

Change in Low	Summer Low	Low	Medium	High
0	0	0	0	0

R Y B

Total = R____x 3 + Y_____x 2, B____ x 1

Total = ________________

Management Recommendations Score

- **Score of 3 – Preservation**
  Continue existing appropriate management actions along with protection
- **Score of 4-6 – Adaptive Management**
  Implement intensive management actions
- **Score of 7-9 – Re-evaluate**
  Consider reassessment of management objectives for future conditions

Preservation Management Objectives

- Identify and protect reaches serving as refugia, understand the sources and mechanisms of their baseflow and insure connectivity of these reaches within the system and to Lake Superior.
- Ensure that wetlands identified as significant are protected.
- Identify and protect the wetlands, vernal pools, floodplain soils, and other hydro-geologic features that store and transport subsurface flow contributions to base flow.
- Establish ecological buffers zones around natural features.

Adaptation Management Objectives

- Protect base flows. To improve stream resilience, managers need to protect base flows, particularly at low flows, especially against significant extraction at times when low flows are of concern. This might be accomplished through guidance regarding protective thresholds for total forest harvest or amount of impervious surface in a watershed, or protection criteria limiting withdrawals at minimum flows.
- Manage and maintain riparian zones to keep forest cover/shade. Buffers of mature riparian vegetation along the banks of small streams and tributaries can provide shade and other conditions to moderate the warming effects of climate change, at least within the range of a few degrees. Monitor for potential impacts of increased forest cover on low flows and temperature.
- Better understand the role of riparian tree species (i.e., conifers), which may have an effect on water balance at low flows due to higher evapotranspiration. Boreal conifers (balsam fir, white spruce, black spruce, white cedar) are expected to persist longer on cool-moist sites and may have the most benefit in the riparian zones where they can provide shade and coarse wood inputs into streams.
- Restore or construct riparian buffers where necessary to provide adequate shade along existing cold and cool water streams, and/or manage heavy runoff of non-point source pollution and sediments with potentially more frequent and intense precipitation events. Utilize LiDAR information to assess where riparian reforestation efforts are needed on high quality trout streams.
- Establish ecological buffers zones around natural features.
- Encourage stewardship groups to protect and rehabilitate aquatic habitat, riparian zones and wetlands.
- Maintain and restore riparian and instream connectivity, including removing barriers where possible.
- Build adaptive capacity by managing for healthy, high quality forests. Healthy, high quality forests minimize the risk of large-scale abrupt changes and help avoid simultaneous major disturbances to streams at the scale of a connected stream network. In addition to managing forests for future climate, management should include control of plant invaders, earthworms, insect pests, and deer populations to reduce the impact of these stressors.
- Utilize the geophysical diversity inherent in the landscape. There is significant variation in soils and topographic features in this region that can accommodate a variety of tree species.
- Manage for bur oak, red oak, northern pin oak and jack pine on drier upland sites on thin, coarse textured soils (the areas highest at risk for drought stress and forest loss). This will require planting, browse protection, and release for successful establishment.
- Increase temperate tree species tolerant of warmer-wetter or hotter-drier conditions: white pine, red oak, bur oak, white pine, basswood, yellow birch, sugar maple. Models and empirical data show that aspen and birch will decline regardless of management in a warming climate. Oak species have adaptive traits for water-use efficiency and also may have lower evapotranspiration rates than fast growing species such as aspen. Without climate tolerant species, there is a greater risk of state change to more open savanna structure which could likely

have adverse impacts on ecological flows in Minnesota's Lake Superior tributaries. Recent work indicates that bur oak, red oak, and white pine sources from northern and central seed zones can establish on a variety of sites in northeastern Minnesota.

- Collaborate in establishing forest cover thresholds. Fisheries managers should collaborate with foresters and land use planners to establish thresholds for minimum forest cover using historical or "range of natural variation" benchmarks to improve the chances of maintaining flow regimes within the range of natural variation to which stream systems have adapted. The desirable threshold for conifer cover ranges from 40-50%.
- Manage for mixed stands where conifers make up an average of 15-25% of basal area. Conifer and hardwood proportion may have a significant effect on flow, especially summer flows, in a changing climate.
- Seek opportunities to coordinate watershed planning, infrastructure planning, mitigation/adaptation and disaster response with proactive stream and watershed restoration and management. Use information about high and low flow metrics to design more resilient road crossings, bridges, culverts, especially where connectivity is needed to ensure organisms have access to key habitats.
- Expand stream gaging efforts. We recommend that where possible, stream gages be maintained in operation over time to establish a historical record, winter flow data be collected, and further gages be deployed within strategically defined subcatchments to quantify flow throughout the basin.
- Collect groundwater data. There is a critical need for groundwater data including the completion of groundwater maps for the region.
- Develop and maintain comprehensive biodiversity survey to more thoroughly characterize baseline conditions, against which future change can be effectively detected, managed and mitigated. This includes more repeat sampling of biological communities over time and across a range of seasons and conditions.
- Develop and digitize historical biological data, where possible.

Re-evaluate Management Objectives:

For highly vulnerable streams: examine and adjust, where appropriate, management to reflect fluctuations in aquatic carrying capacities and shifting fish breeding and migration patterns association with climate change. The main challenge to ecosystem response to climate change comes from warming temperatures and impacts from low flows, not high flows. Ultimately, the most resilient streams are likely to be the most thermally-resilient, not the most geomorphically-stable.

Module 3: Project Components and Supporting Data

Introduction

Module 3 provides a descriptive overview of the components (i.e., models and analyses) and how those components related to one another over the course of the project. It also provides our record of the review of existing data, their suitability for this project, and the identification of data gaps, which ultimately shaped the outcome of this project.

This study explored the relationships between water quantity and the health of fish and invertebrates in Minnesota's Lake Superior tributaries. We sought to establish flow-ecology relationships between instream organisms (and communities) and hydrologic patterns for both current and future stream conditions through the use of interrelated models built with existing data. From there, we worked to determine both the direct effect of future climate change and the effect of future natural forest progression on stream hydrology and ecology. We used the results to develop recommendations that will help resource managers in stream management and restoration, land and water use planning and climate adaptation activities.

We used a number of different models and datasets throughout this project. The term 'model' refers to the HSPF (Hydrological Simulation Program –Fortran) hydrologic model, Global Climate Change Models (GCMs), LANDIS (a forest landscape simulation model described in Module 6), and statistical models (e.g., used for classification and regressions). The term 'data' refers to different types of data used in the project, including spatial (e.g., a GIS data layer) or biological data (i.e., organisms sampled at a specific place and time).

In addition to developing our own models, this project made use of existing models developed by others to predict future conditions. For example, the LANDIS models, used to describe future land cover, and various GCMs were developed by others. We used output from these models to examine how climate change would affect Minnesota's Lake Superior tributaries.

Since this project relied exclusively on existing data sets, an early step in this project was data review and evaluation. Rationale is also provided for each selection and methodological decision.

Project Components

Conceptual Model

A conceptual model is a simplified representation of a complex system or process. In our case, we used a conceptual model to communicate with our team and others the major components of the project and their connections.

Briefly, our approach was to develop detailed hydrologic models for three Lake Superior tributaries that computationally describe flow metrics (e.g., peak flows, base flows, duration, etc.) at each point along a stream network. Modeled flow metrics took into account a wide range of variables (Figure 3.1). The models were calibrated to accurately mimic patterns measured at real-world stream gages. These models are also used to project future flow conditions, based on climate and land cover change scenarios. We expected that model development would be limited by the availability of stream gage data; therefore, considerable attention was given to selecting the three watersheds for detailed modeling. For the purpose of relating flow metrics of the modeled watersheds to areas in the remaining unmodeled watersheds, a hydrologic stream classification was developed; stream catchment classes were expected to be used to relate flow metrics from modeled streams to unmodeled streams that share similar characteristics. In addition to the hydrologic stream classification, we developed a series of empirical models to predict flow metrics from catchment characteristics, in order to estimate flow metrics at the biological sampling points. Finally, the estimated flow metrics were related to biological data using several statistical techniques.

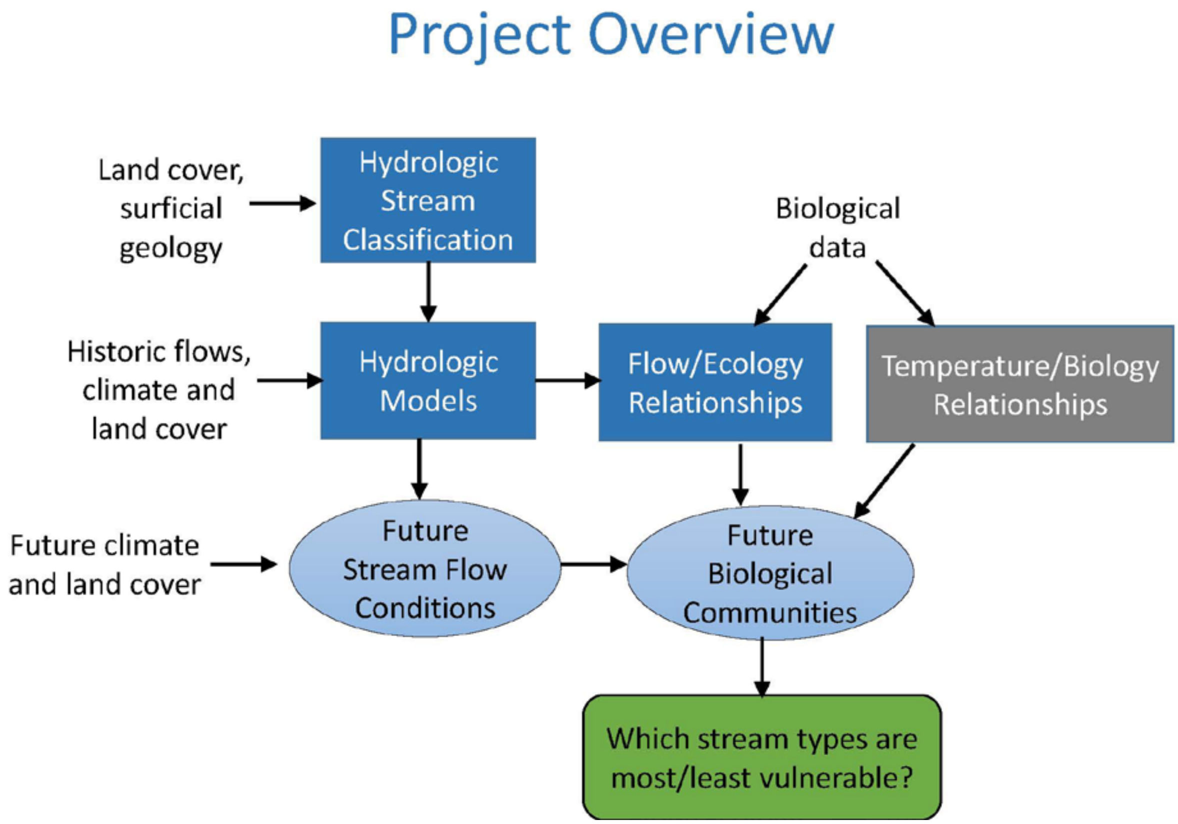


Figure 3.1. A conceptual model of the project components and their linkages of this project.

Data Review

Numerous data sources were compiled and considered for use in this project; what follows is a discussion of the datasets that we reviewed as inputs to various analyses or models and the results of that evaluation (whether the dataset was selected for use and why).

Most of the project's data sets were spatial data. We considered the date of acquisition, resolution, spatial coverage, and other qualitative characteristics (e.g., availability of metadata) in our data evaluation. Several key data sets were identified early in the project. Availability of these data ultimately determined the target watersheds for which detailed hydrologic models would be developed and the type of hydrologic modeling tool selected.

Key data sets identified include: hydrography (a digital representation of the stream network); stream discharge (stream flow data measured at stream gage locations); soils (soil types with information on soil permeability, etc.); climate (temperature and precipitation); and biological responses (Table 3.1).

Table 3.1. Anticipated data needs and potential data sources and availability. These data are generally required during the hydrological modeling development. Many of these data needs are shown, in a general sense, in Figure 3.1.

Data Need	**Description**	**Sources**	**Status**
Precipitation	Historical precipitation data	NOAA Weather Stations and MnGAGE Network	in-hand
Air Temp	Historical air temperature data	NOAA Weather Stations and MnGAGE Network	in-hand
Stream Flow	Historical stream flow data	MPCA/DNR Cooperative Stream Gages	in-hand
Evapotranspiration	Observed Evapotranspiration for different forest cover types	Ameriflux Network	in-hand
Land Cover	Land cover data sets: impervious surfaces, vegetation types, wetlands	National Land Cover Database (NLCD) 2001, 2006, 2011, & Coastal Change Analysis Program (C-CAP) 1985, 1996, 2001, 2006, 2010 National Wetlands Inventory Walter et al., NRRI Forest Reclassification	in-hand

Table 3.1 (continued). Anticipated data needs and potential data sources and availability. These data are generally required during the hydrological modeling development. Many of these data needs are shown, in a general sense, in Figure 3.1.

Data Need	**Description**	**Sources**	**Status**
Soils	Soil and surficial geology data	SSURGO Soils STATSGO Soils USGS Surficial Geology Superior National Forest Soils DNR Ecological Subsections	in-hand
Topography	LiDAR-based digital elevation maps	Minnesota Geospatial Information Office	in-hand
Hydrography	Stream and catchment network	National Hydrography Data Set (NHDplus V2)	in-hand
Groundwater			not yet mapped for northeast Minnesota
Future Land Cover	Modeled future land cover, particularly forest cover change in response to climate change	Landis, PNet	available through Mark White, TNC
Future Precipitation	Projected precipitation from downscaled GCMs	USGS/Hostetler dynamic downscaled climate University of Wisconsin Statistical downscaled climate	in-hand
Future Temp	Projected future air temperature from downscaled GCMs	Bureau of Reclamation statistical downscaled climate	
Future Temp	Projected future air temperature from downscaled GCMs	Katherine Hayhoe statistical downscaled climate	1/16 degree; 1/8 degree (expected but not available in time for this study)
Future Temp	Projected future air temperature from downscaled GCMs	University of Idaho MACA downscaled climate	In-hand (selected as the primary source)
Biological Data	Fish and invertebrate field surveys	Various sources; MPCA, MDNR, Bell Museum,	in-hand at TNC

Hydrography

We evaluated several different hydrography layers. Hydrography is a digital representation of a stream network. In our evaluation, we considered the following criteria: (1) uniform and complete spatial coverage of the area of interest; (2) sufficient spatial resolution (~1:24,000) of stream segments and associated catchments; and (3) embedded attributes that would facilitate the stream segment classification portion of this study (Figure 3.1). Figure 3.2 illustrates the difference in four different hydrography layers available for the Knife River. We selected the NHDplusV2 layer for this project because it was a nationally available data set that described tributaries in the area of interest in sufficient detail for this project. NHDplusV2 also has associated stream channel and catchment attributes that were used in the hydrologic classification.

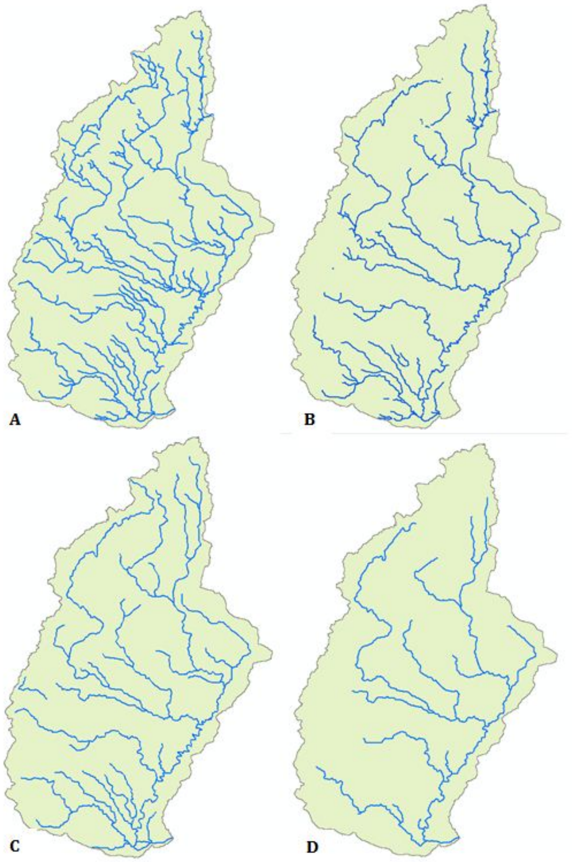


Figure 3.2. A comparison of four different hydrography layers for the Knife River watershed. A: DNR 24K stream segments, B: DNR 24K stream segments perennial only, C: NHDplusV2 stream segments, and D: Hydrological Simulation Program – Fortran (HSPF) stream segments. Notice a few unconnected segments in images B and C. These segments were edited prior to our analysis.

Stream Discharge

Our selection of watersheds to be modeled was based primarily upon data availability and a desire to represent different hydrologic regime types within the study area. One key data set was stream discharge. Stream discharge is measured by stream gages which are maintained by different organizations over different durations.

We summarized available stream discharge data for 16 area streams (Table 3.3) and narrowed the list of potential watersheds to be modeled to the Amity, Baptism, Beaver, French, Knife, Pigeon, Poplar, Sucker, and Talmadge, based on factors such as flow record length, soil data availability (Figure 3.3), and biological data availability (Table 3.5).

Table 3.3. Summary of available stream discharge data for Minnesota's Lake Superior tributaries.

Stream	Watershed Area (km^2)	First year of data	Number of years, total	Number of years, 1985-2014	Source	SSURGO Coverage
Amity	43	2002	8	8	1	Yes
Baptism	356	1928	68	16	1	Yes
Beaver	316	2011	3	3	1	Partial
Brule	686	2002	8	8	1	No
Chester	18	2003	10	10	3	Yes
French	51	1994	16	16	2	Yes
French Tributary	24	2003	1	1	1	Yes
Kingsbury	24	2003	9	9	3	Yes
Knife	225	1974	41	30	1	Yes
Knife Tributary	37	2004	5	5	1	Yes
Miller	30	1992	5	5	1	Yes
Pigeon	1579	1921	94	30	1	No
Poplar	295	2002	13	13	1	No
Sucker	98	2001	11	11	1	Yes
Talmadge	15	2001	8	8	1	Yes
Tischer	19	2003	10	10	3	Yes

Sources: 1=Minnesota Department of Natural Resources (MNDNR)/Minnesota Pollution Control Agency (MPCA) cooperative stream gaging; 2=MNDNR; 3=Lakesuperiorstreams.org. Most data are daily time step. The lakesuperiorstreams.org data and the most recent few years of the MNDNR/MPCA cooperative sites have 15 minute time steps.

Soils

Soils data were also important in our modeling effort (Figure 3.1). A uniform soils data set was not available for the area of interest (Table 3.3, Figure 3.3).

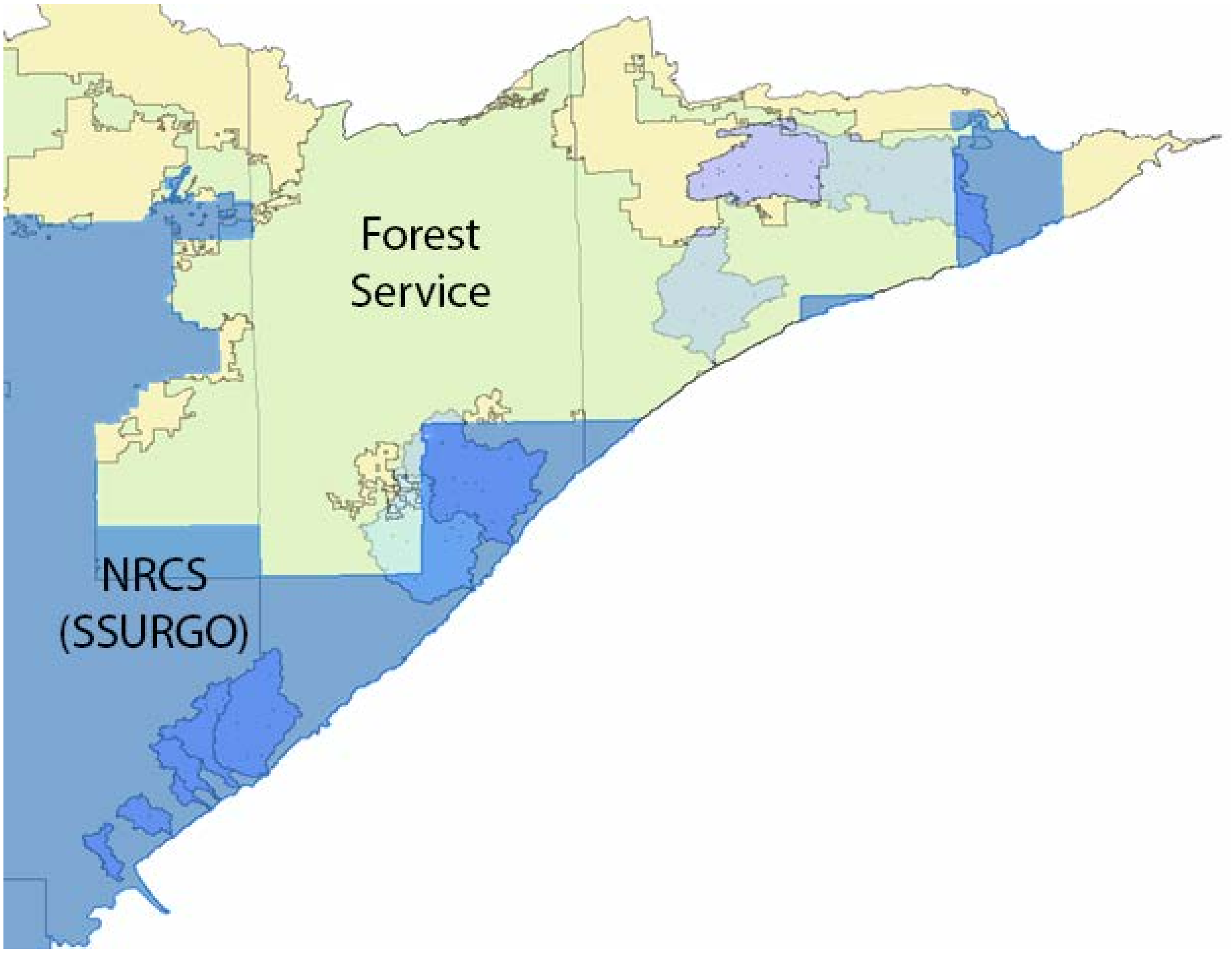


Figure 3.3. Comparison of the spatial extent of available soil data from two sources: United States Forest Service (Forest Service) and Natural Resources Conservation Service (NRCS).

Climate

Precipitation and temperature data were also important components of the hydrologic model. We incorporated hourly data from National Weather Service stations (Figure 3.4) into the model. Daily precipitation data from a local high-density network (http://climate.umn.edu/ hidradius/radius_new.asp) often produced stronger correlations between simulated and actual stream flow. Figure 3.4 shows the locations of available climate data in our study area. In addition to precipitation data, evapotranspiration was also important. Evapotranspiration (ET) accounts for about 50% of the water budget; therefore, our modeling approach needed to be able to accurately model present and future evapotranspiration and its seasonal variation. We anticipated the need to account for changes in the ET patterns as the forest type changes under different climate scenarios. Flux data measured or Ameriflux sites near Ashland, Wisconsin were used to help set ET rates for different forest cover types.

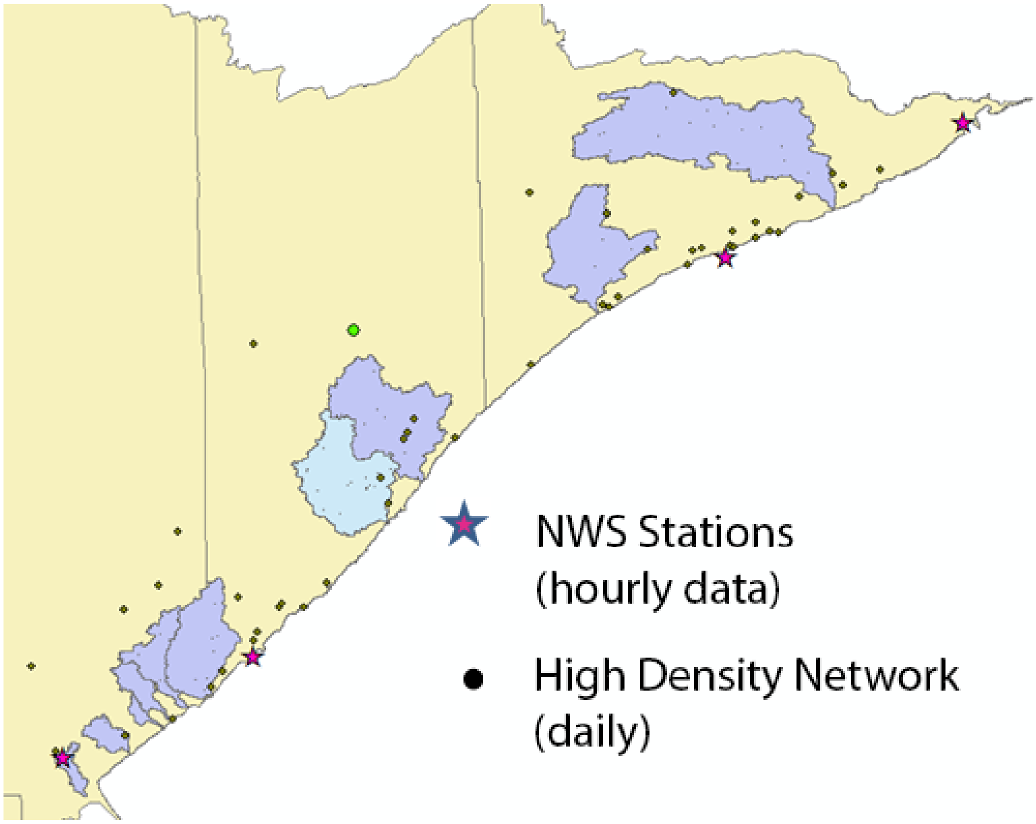


Figure 3.4. Location of climate data sources in our study area.

Biological Data

One of the goals of this project was to relate flow metrics from the future landscape and stream network to changes in instream fauna. Ultimately, these findings helped us identify catchments and stream segments that were either resistant or resilient to change due to changing climate and land use.

To get there, we first quantified relationships between current flow metrics and instream fauna, and then predicted how potential future flow conditions could affect the biota. The types and location of existing biological data sets were important in setting up this study and, indeed, influenced the final selection of study watersheds for hydrologic modeling.

We evaluated several biological databases compiled by state agencies that routinely survey stream organisms (fish and invertebrates) as part of comprehensive management, stream or watershed assessment programs (Table 3.4). These data were important in deriving the flow-ecology relationships described above. We were looking for data collected during the same period for which our hydrologic models were developed (i.e., recent data). The goal was to relate modeled flow metrics, for both current and future conditions, to patterns in the biological communities.

Table 3.4. Summary of evaluated biological datasets and databases.

Name	**Scope**	**Source**	**Description**
MPCA Biological Monitoring Data	Full study area	Minnesota Pollution Control Agency (MPCA)	• 411 unique sample sites that match 228 unique NHDplusV2 reaches for the study area. • 66 HUC (Hydrologic Unit Code) 2s, 15 Huc10s • 5 different fish classes. However, nearly all the Lake Superior tributaries are classified “11”, “Northern coldwater”, with a few classified as “6”, “northern headwater”
Fishes of Minnesota Data	Full study area	Minnesota Department of Natural Resources (MNDNR)	• 23,701 observations for the Lake Superior drainage • 10,374 records come from the two Lake Superior Huc8s • 153 sites had data from more than 3 years. • 547 unique reaches (NHDplusV2 reaches)

Table 3.4 (continued). Summary of evaluated biological datasets and databases.

Name	Scope	Source	Description
Fishes of Minnesota Data	By time period for the Amity, Talmadge, French, Knife and Baptism Rivers	MNDNR	• 1928 unique site IDs/data sources (of which ~ 19 are off-shore trawls). o 1376 stream, 552 lakes • 883 unique site IDs for DNR only, o 385 lake, 498 stream site IDs o 260 stream reaches (NHDplusV2), 312 lake features (NHDplusV2) • Of the 260 stream reaches (COMID), 99 had more than 1 year of data (58 have 2 years, 22 have 3 years, and 19 have > 3)
Bell Museum Fishes of Minnesota Data	By time period for the Amity, Talmadge, French, Knife and Baptism Rivers	Bell Museum	• 308 unique site IDs that match PCA North Shore only (streams) • 397 lakes, 660 streams by NHDplusV2 reach (COMID) • 1800 records • 18,771 records where catch > 1 individual fish
MPCA Access Database of Biological Data	By time period for the Amity, Talmadge, French, Knife and Baptism Rivers	MPCA Environmental Analysis and Outcomes Division (John Sandberg)	Complete dataset used by MPCA to assess biological condition for surface water, for use in calculating Index of Biological Integrity values (IBIs) and 10 year watershed monitoring and planning cycle as required under Clean Water Act.

The MPCA Access database was particularly robust and easily summarized by the date of observation and type and location of data (Figures 3.5, 3.6 and Tables 3.4 and 3.5).

Table 3.4. Summary of the total number of biological observations for the study area sorted by year.

Year	# Fish Observations	# Invertebrate Observations
1967-1968	36	-
1980-1985	51	-
1986-1990	86	-
1991-1995	119	-
1996-2000	211	131
2001-2005	32	5
2006-2010	164	151
2011-2014	178	193
Total	877	480

Table 3.5. Summary of the available biological data for the original candidate study watersheds (5), sorted by year. [Source: MPCA Access database of Biological Data]

Year	**Amity** Fish Obs	**Amity** Invert Obs	**Baptism** Fish Obs	**Baptism** Invert Obs	**French** Fish Obs	**French** Invert Obs	**Knife** Fish Obs	**Knife** Invert Obs	**Talmadge** Fish Obs	**Talmadge** Invert Obs
1967-1968	-	-	-	-	-	-	-	-	-	-
1980-1985	-	-	2	-	-	-	-	-	-	-
1986-1990	-	-	19	-	-	-	-	-	-	-
1991-1995	-	-	6	-	-	-	13	-	-	-
1996-2000	4	4	6	5	1	1	1	1	-	-
2001-2005	-	-	-	-	-	-	2	-	-	-
2006-2010	-	-	1	1	-	-	1	1	-	-
2011-2014	2	3	7	9	2	2	12	13	8	3
Total	6	7	41	15	3	3	29	15	8	3

Some of the observation locations for the Baptism and Knife fell on small tributary streams with different names; however, these sites fall in the NHDplusV2 watershed delineations for these streams. Note that due to a paucity of data for the Amity, French, and Talmadge, a sixth stream, the Poplar, was considered and ultimately selected as a watershed to model.

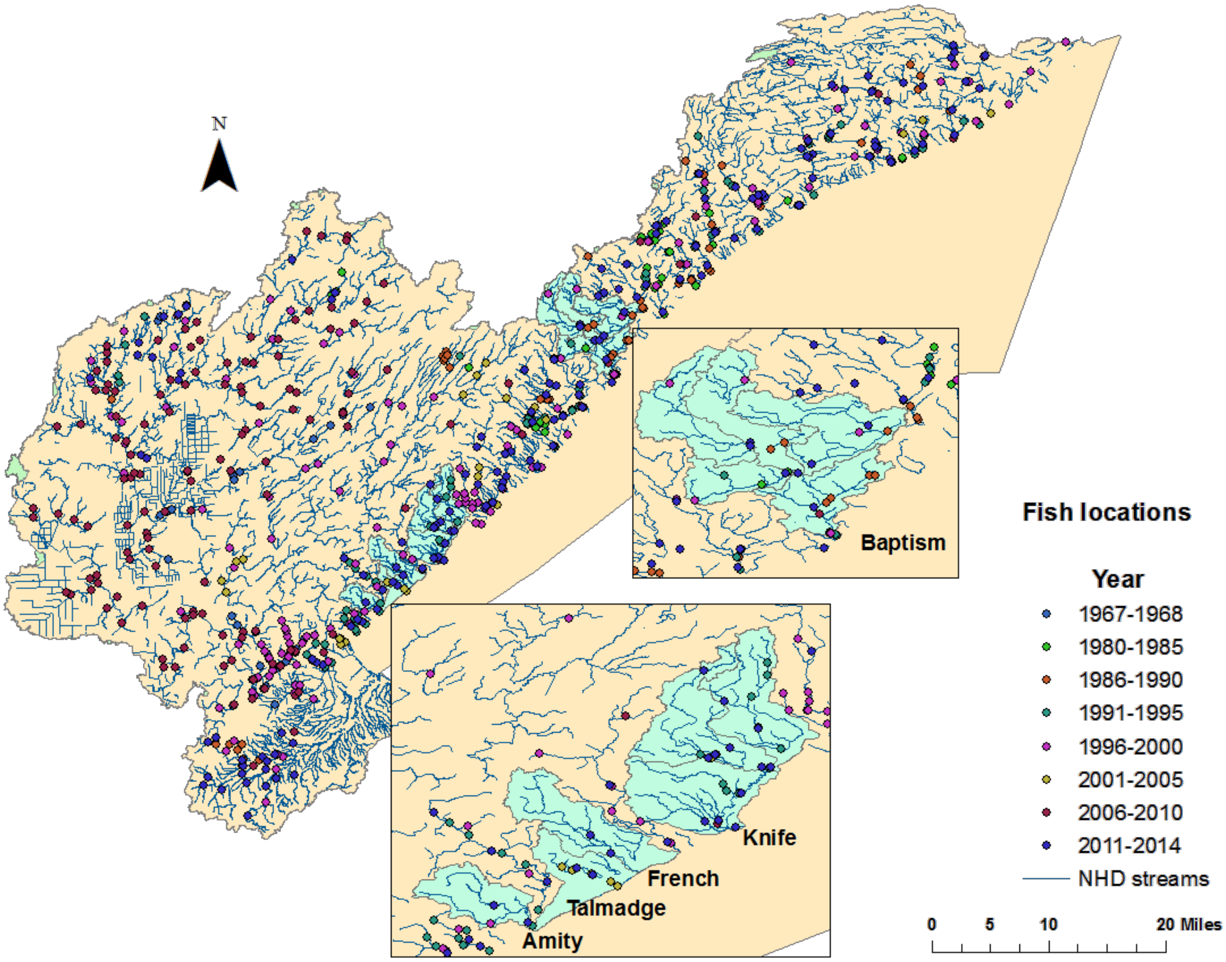


Figure 3.5. All of the fish observation locations with the candidate study watersheds highlighted in the insets. The data were sorted by year. The watershed and stream delineations were from the NHDplusV2 dataset. The observation locations were queried from the MPCA Access database.

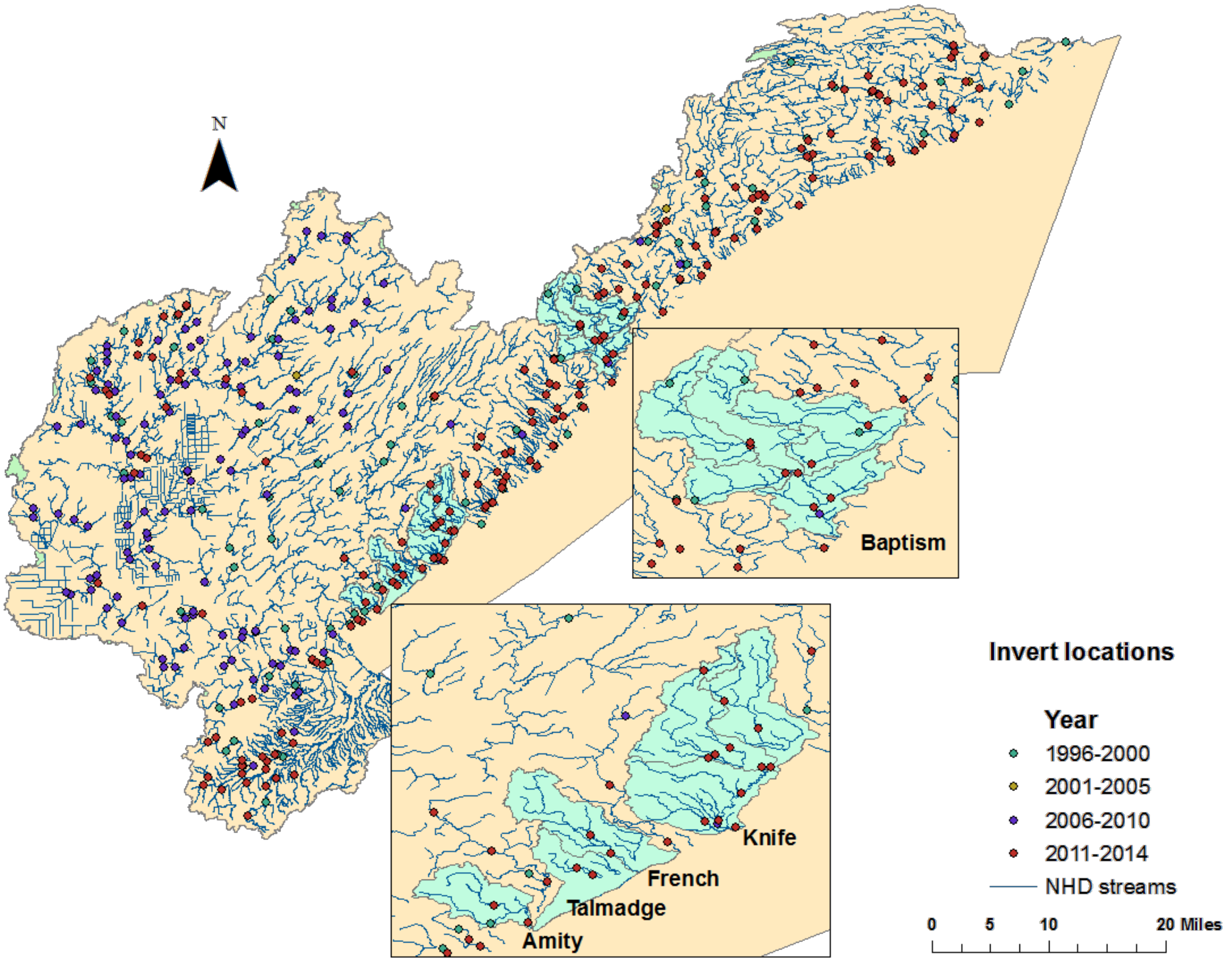


Figure 3.6. All of the invertebrate observation locations with the candidate study watersheds highlighted in the insets. The data were sorted by year. The watershed and stream delineations were from the NHDplusV2 dataset. The observation locations were queried from the MPCA Access database.

Hydrologic Modeling

The purpose of developing a hydrologic model was two-fold. First, a calibrated hydrologic model enabled predictions of historical stream flows in ungaged catchments in order to help develop flow-ecology relationships. Second, we used hydrologic models, in conjunction with climate model projections, to project future stream flow conditions under future climate change scenarios.

Lake Superior tributaries can differ greatly in their flow regimes due to significant differences in the amount of surface storage and groundwater influence. Ideally, this project would have developed calibrated hydrologic models for all of the major tributaries.

The hydrologic models could then have been parameterized with variables predicted by climate change models. Data limitations and available resources precluded us from taking this approach. Instead, we parameterized hydrologic models for three of the tributaries and then related stream flow metrics generated by those models to other stream segments / catchments within the study area through a series of statistical models (Figure 3.1). To more accurately predict flow in ungaged streams, we developed a hydrologic classification system to identify streams with similar flow regimes and a then tested a series of regression models, which statistically related catchment characteristics to flow metrics.

HSPF Models

We modeled three watersheds: the Knife, Baptism, and the Poplar Rivers. These watersheds were selected, after much discussion, on the basis of available data and the types of hydrologic regimes that were expected to be represented (based on geology, land use/ land cover, and experience with these areas). We modeled the three watersheds in detail using a physics-based hydrologic modeling package (HSPF, Hydrologic Simulation Program-- Fortran). HSPF provided detailed flow information on the three representative watersheds. HSPF generated flow statistics for present and future climate, based on continuous, multi-year, year-round simulations at hourly time steps. In addition, we developed regional stream flow models for particular parameters, in conjunction with hydrologic stream classifications (Figure 3.1).

The HSPF model included both surface and groundwater components. It was used to model both open water season and winter snow accumulation/melting. The main inputs to the HSPF models were (1) hydrography (stream and catchment drainage network, slopes), (2) land cover (impervious, forest), (3) soils data (soil water storage, infiltration rates), and (4) climate and potential evapotranspiration.

HSPF produced (1) continuous hourly stream flow rate at any point in the drainage network and (2) other hydrologic data, as needed (e.g., infiltration rates, surface runoff and groundwater contributions, soil moisture).

Hydrologic Stream Classification

We used a combination of Best Professional Judgment (BPJ), based on previous research, and multivariate statistical analyses in the hydrologic stream classification. We considered several variables (Table 3.6). We also considered existing aquatic classification systems appropriate to our region based on the following criteria:

- Ecological Subsection
    - North Shore Highlands subsection

    - Border Lakes / Laurentian Uplands
        - Till plain, morainal, or bedrock land type association (valley type)
- Size and Connectivity
    - Directly connected to Lake Superior
        - Small, mainstem tributaries reaches directly connected to Lake Superior
        - Larger, mainstem stream reaches directly connected to Lake Superior
    - Headwater reaches
        - Storage/surface water dominated
        - High drainage density / low storage
    - Baseflow dominated perennial coldwater reaches
    - Wetland/surface water influenced reaches

Table 3.6. Proposed GIS variables and rationale for inclusion in the development of a hydrologic classification.

GIS Variable	Rationale
Wetland / Hydric Soils/ Floodplain Area	Water storage, attenuation of peak flows
Area-Weighted Impervious Surface	Water storage, peak flows, index of urbanization
Area-Weighted of Slope Classes/ Isochrones	Peak flow, time of travel
Area-Weighted Forest Cover	Water storage, peak flows, ET
Area-Weighted Deciduous Cover	Water storage, peak flows, ET
Area-Weighted Coniferous Cover	Water storage, peak flows, ET
Area-Weighted Open Area	Water storage, peak flows, ET
Area-Weighted Developed	Water storage, peak flows
Area-Weighted Surficial Geology	Link to ground water, water storage, peak flows
Contributing Area/ Area-Weighted Flow Accumulation	Flow duration, peak flows
Stream Density	Peak flows
*Area-Weighted Aspect/ Hill Shading	ET, snow melt
*No. Road Crossings/ Culverts	Impede flow
Area-Weighted Soils	Influence permeability, runoff
*Precipitation	Source of stream flow
**Stream Slope / Gradient	Habitat
**Length-Weighted Confinement	Transport vs depositional reach
**Length-Weighted Stream Shading	Temperature, biological covariate
**Length-Weighted Pools/ Riffles/ Glides	Habitat
**Length-Weighted Bank Erosion	Habitat, peak flows

* Indicates data not included in the classification analyses.
**Habitat-scale data are not available for the study area in sufficient detail to allow them to be incorporated into the classification.
Climate data (i.e., precipitation) were not included in the classification due to the relatively homogeneous nature of the data for the study region. See Table 4.2 for a list of the final variables included in the classification analysis.

Deriving Hydrologic Classification and Covariates of Biological Response Variables, including Data Sources

The following section describes data sources for catchment and flowline characteristics and the methodologies we proposed for deriving variables that could potentially be used for deriving a hydrologic stream classification. Included below also are variables that are covariates of biological responses. Many of these variables listed below can be derived from attributes within the NHDplusV2 data layer. The NHDplusV2 User's Guide summarizes many of these variables at both the immediate flowline and catchment levels as well as the upstream flow accumulated level (Figure 3.7). The flow accumulated level refers to the area upstream of the downstream node of each flowline. Conceptually, flow accumulation can be thought of the area which drains through each position (e.g., cell) on the landscape. Thus, ridge top areas have low flow accumulation values and stream areas have high values. Most of the variables were summarized at the immediate flowline or catchment level using ArcMap tools, and at the flow accumulated level using the NHDplusV2 flow accumulation tool. We used the NHDplusV2 flow accumulation tool to summarize the upstream area for the downstream point of each NHDplusV2 flowline.

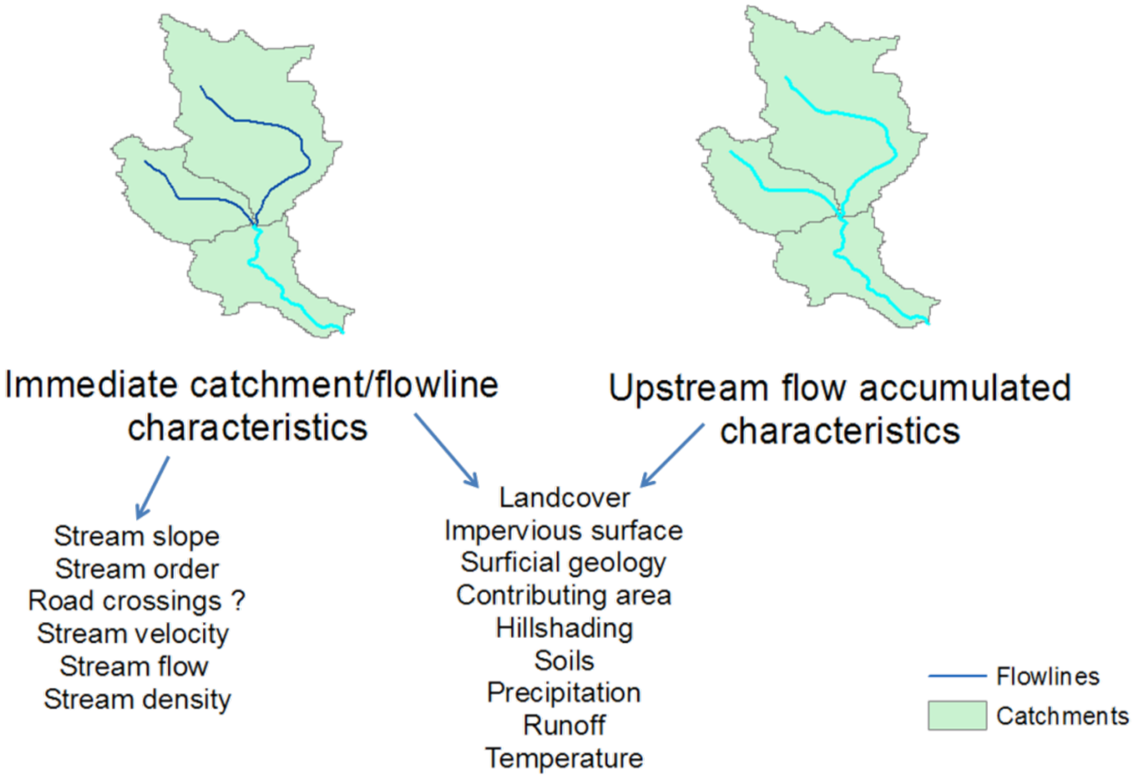


Figure 3.7. Example of stream flowline and catchment variables contained within NHDplusV2. The variables can be summarized at the immediate catchment/flowline level or the flow accumulated level. The flow accumulated level refers to the area upstream of the downstream node of each flowline and represents the area that drains through a particular positon on the landscape (see text).

Some of the NHDplusV2 flow accumulated attributes were summarized as total upstream accumulation and divergence-routed accumulation. Divergence refers to the minor (smaller) and major (main) stream paths when a stream splits into at least two paths as it flows downstream (braided channel). The divergence method assigns a portion of the flow accumulation to each stem so that the sum is 100 percent of the flow accumulation. In areas where there is no additional knowledge about the divergence, NHDplusV2 defaults down the main stem. Divergent paths that do not connect back to the main stem are not considered.

The following data sets were considered in the development of the hydrologic classification system or its validation / verification because of their inclusion in a previous classification or a hypothesized connection to flow. Additional biological response covariates are also listed below. Table 3.7 lists the final data sets included in the analyses.

Wetlands/Hydric Soils/Floodplain Area

Area-Weighted Wetland Type

National Wetland Inventory (NWI): The NWI includes wetlands that were large enough to be identifiable by type (minimum mapping unit from 1.0 – 3.0 acres). Wetlands identified from photo-interpretation of air photos from 1974-1988.

Coastal Change Analysis Program (C-CAP): The C-CAP land cover maps were developed from Landsat Thematic Mapper imagery from 1985-2010. C-CAP data are used as the land cover coastal expression for the NLCD.

Floodplain area: derived from the intersection of NHDplusV2 Flowlines with NWI Cowardin polygons.

Area-Weighted Soils

Hydric and/or partially hydric from SSURGO and ELT datasets were important components of the hydrologic classification. SSURGO soils classifications were used where available; ELT or STATSGO soils data were used to supplement locations with missing SSURGO data.

NRCS Soil Survey Geographic (SSURGO): The SSURGO soils data covers most of the Lake Superior Basin. However, the study areas that fall within the Superior National Forest only have soil classifications provided by the Forest Service (USFS).

USFS Superior National Forest Ecological Land Types (ELT): Some soil classifications such as hydric soils classifications and drainage classifications can be deduced from the ELT descriptions. This process has already been done for the Minnesota wetland restoration prioritization tool project. The data can either be summarized by NHDplusV2 catchment or flowline. Summaries could be produced for total wetland area or by area of specific wetland types. For example, if we were interested in wetlands that were within a certain distance of each flowline, we could then have summarized wetland types within a buffered distance from the flowline.

Land Use / Land Cover

The National Land Cover Dataset (2011 NLCD) classifications was summarized for the NHDplusV2 catchments and flowlines (streams) as area weighted attributes.

Area-Weighted Impervious Surface

The area-weighted impervious surface summaries for the NHDplusV2 catchments were calculated using the 2011 NLCD impervious surface layer and the tools tabulate areas, zonal statistics, or a zonal statistics script. In addition, upstream flow accumulated percent impervious surface were calculated for the NHDplusV2 flowlines using the NHDplusV2 flow accumulation tool.

Area-Weighted Forest Cover

The NLCD 2011 forest cover classes include: [41, Deciduous], [42, Evergreen], and [43, Mixed Forest].

Area-Weighted Developed

The NLCD 2011developed classes included: [21, Developed open space], [22, Developed low intensity], [23, Developed medium intensity], [24, Developed high intensity]. The Barren land classification [31, Barren Land], included bedrock, strip mines, gravel pits and other accumulations of earthen material and has been included as development in the past.

Area-Weighted Open Spaces

We considered the following NLCD 2011open spaces classes: perennial non-forest classes ([52, Shrub scrub], [71, Grassland/herbaceous], [81, Pasture/hay], [82, Cultivated crops]) and wetlands ([90, Woody wetlands], [95, Emergent herbaceous wetlands]). Catchment and flowline summaries similar to the other land cover categories were calculated.

Road Crossings/Culverts

We considered the GLAHF (Great Lakes Aquatic Habitat Framework) culvert and road crossing data due to their impact on stream flow; however, these anthropogenic features were not included in the development of the classification due to the incomplete nature of the data set.

Geology / Topography / Geomorphology

Area-Weighted Surficial Geology

Area-weighted surficial geology was calculated for the NHDplusV2 catchments using zonal statistics, tabulate areas, or a zonal statistics script. The surficial geology layers reviewed included the USGS Ecosystems Mapping Surficial Lithology layer and the SSURGO soils surface texture.

Area-Weighted Slope Classes/Isochrones

Mean slopes were calculated from the 10 m DEM (digital elevation model) using the ArcMap tools. LiDAR DEM data were also readily available (at NRRI) for the arrowhead region of Minnesota.

Stream Slope/Gradient

NHDplusV2 Flowline elevation and slope are included in the attribute table. The table includes the following attributes for the NHDplusV2 Flowlines: MAXELEVRAW, maximum flowline elevation (unsmoothed) (cm); MINELEVRAW, minimum flowline elevation (unsmoothed)(cm); MAXELESMO, maximum flowline elevation (smoothed) (cm); MINELEVSMO, minimum flowline elevation (unsmoothed)(cm); SLOPE, slope of flow line (meters/meters) based on smoothed slope elevation; and SLOPELENKM, The length of the flowline, used to calculate the slope.

Area-Weighted Aspect/Hill Shading

The NHDplusV2 has a shaded relief grid calculated from the NED 30 m DEM. In addition, hillshade can be easily calculated from a DEM using ArcMap tools.

Catchment Area/Contributing Area/Area-Weighted Flow Accumulation

Catchment area, cumulative area for the farthest downstream endpoint of each flowline and flow accumulation is included in the NHDplusV2 attribute table.

Watershed Boundary Dataset (WND)

The WBD watershed areas were also available in the NHDplusV2 dataset. The WBD provides Hydrological Units for each drainage area. The NHD catchments align with the WBD delineations.

Stream Density

Stream density (km/km2) was estimated for each NHDplusV2 catchments by dividing the total NHDPlusV2 flowline length in each catchment by the catchment area. The flowlines were classified as artificial path, canal/ditch, coastline, connector, pipeline (one location), or stream/river. Flowlines classified as coastline were removed prior to the stream density calculation.

Channel Type

Channel types were found in the NHDArea attribute table and included: Area to be

Submerged, BayInlet, Bridge, CanalDitch, DamWeir, Flume, Foreshore, Hazard Zone, Lock Chamber, Inundation Area, Rapids, SeaOcean, Special Use Zone, Spillway, StreamRiver, Submerged Stream, Wash, Water IntakeOutflow, and Area of Complex Channels. The area, length, and elevation of the feature were also found in the attribute table. We also considered other channel type classifications such as the Montgomery-Buffington Channel Classification.

Hydrology

Stream Order/Watershed Size/Mean Flow

Strahler stream order can be found in the attribute table PlusFlowlineVAA. The table includes the following attributes: STREAMORDE, Modified Strahler Stream Order and STREAMLEVE, Stream level classifications (1: streams that terminate on a coastline and can include large or small streams, 2: streams that flow north or south and are categorized as main streams, and 3: streams that flow east or west and are categorized as tributary streams).

Mean Flow

Mean annual and mean monthly flow statistics for each NHD Flowline were estimated in the Extended Unit Runoff Method (EROM) attribute tables. These data can be used either to help classify the catchments or to help verify the classification. All the flow estimates and velocity estimates were presented in cfs and fps respectively.
The table names include the month (EROM01001, January) for locating the monthly averages. The annual average flow and velocity table is labeled as EROM_MA0001. The tables include the following attributes: V0001E Gage adjusted stream velocity estimate; Q0001E Gage adjusted stream flow estimate; V0001C Reference gage stream velocity estimate; and Q0001C Reference gage stream flow estimate. The Q0001E flow estimates are considered the most accurate because they are corrected with actual gages. The Q0001C are considered the next best estimates.

In addition to the EROM for estimating flow, we also considered the Vogel method. This method is only applicable for flowlines that have drainage area ranges that fall within the min and max ranges for the Vogel Coefficients table. The Vogel flow and velocity estimates are located in the attribute table and the attribute table has the attributes: MAFlowV, Mean Annual Flow (cfs) at the downstream node of the flowline using the Vogel Method; MAVelV, Mean Annual Velocity (fps) at the bottom of the flowline using the Jobson Method (1996) with MAFlowV.

Perennial/Intermittent Hydrology

The perennial or intermittent hydrology classification was determined for each flowline based on its attribute (FCODE) in the flowline attribute table.

Baseflow Component/Ratio of Low Flow: High Flow

The ratio of low flow to high flow was estimated from the mean monthly flows in the EROM tables.

Lake/Wetland Influence

The NHDplusV2 has a water bodies layer that was used to identify streams with lake influence. We considered using GIS to identify water bodies (DNR, Public Water Inventory (PWI)) and wetlands (NWI, PWI) that overlap the NHD flowlines or to select wetlands and water bodies within a certain buffered distance.

Upstream Headwater Storage

Headwater flowlines can be identified using the attribute NHDplusV2 table PlusFlow.

Miscellaneous Covariates

Precipitation

Mean monthly and annual rainfall was summarized for the NHDplusV2 catchments. In addition, mean monthly and annual flow accumulated precipitation was summarized for the NHDplusV2 flowlines. The precipitation values were estimated using the Parameter-elevation Regressions on Independent Slopes Model data (PRISM) (www.prismclimate.org) and precipitation data from 1971-2000.

Temperature

Temperature values were estimated using the Parameter-elevation Regressions on Independent Slopes Model data (PRISM) (www.prismclimate.org) and temperature data from 1971-2000.

Table 3.7. Initial variables extracted for both reach-scale catchments and flow- accumulated catchment property datasets. Input variables are similar to those used in other hydrologic classifications.

Variable group	**Variables**	**Map sources**
Area	Area	NHDplusV2 attribute
Groundwater recharge	Groundwater recharge	USGS MPCA groundwater recharge
Slope	Slope	NED 30 m (NHDplus)
Stream density	Stream density	NHDPlusV2 flow lines (except coastlines)
Floodplain	% floodplain	Intersection of NHD Flowlines with NWI Cowardin polygons
Impervious area	% impervious area	NLCD 2011 % impervious surface summaries
Soil drainage type	9 variables, % drainage type	SSURGO NSF STATSGO data
Hydric soil type	4 variables, % hydric type	SSURGO NSF STATSGO data
Land cover type	6 variables, % land cover type	NLCD 2011
Sedimentary type	12 variables, % sedimentary type	MNDNR sedimentary associations
Wetland type	10 variables, % wetland type	National Wetlands Inventory (NWI)

Flow Ecology Relationships

Univariate and Multivariate Statistical Techniques

We used a variety of univariate and multivariate statistical techniques including linear regression, Redundancy Analysis (RDA), Canonical Correspondence Analysis (CCA), and Random Forests to explore the relationships between biological assemblages and environmental drivers, including flow metrics. Results from these analyses allowed us to identify specific flow metrics that most influence the presence and abundance of fish and invertebrate species in the study area streams.

Multivariate statistical approaches were used to discover relationships between indicator and stressor datasets, as well as to allow for some degree of variance partitioning in order to determine the most prevalent and significant relationships. We used principal components analysis (PCA) to explore fish, invertebrate, and flow datasets, and to identify subsets of variables representing the dominant axes of variation in each dataset. In each case, multiple individual variables are highly correlated, and PCA helped identify subsets of variables for use in subsequent analyses. We conducted exploratory analysis using PCA to identify dominant gradients of variation in the fish and invertebrate datasets as well as to select subsets of metrics used in the MPCA invertebrate IBI for coldwater and northern high gradient stream classes. CCA was conducted on the community data and RDA on the fish trait data. For the flow metrics, the most correlated environmental flow components were those representing flow magnitude. Based on these analyses, the following subset of flow metrics was selected for evaluating biological community responses to flow metrics: baseflow index (BFI); high flow count (HC) or flashiness (Flash); low flow count (LC); and either maximum (MAX), summer (SUM_Q10), or spring high flows (SPR_Q10); as well as summer low flow (SUM_Q90).

All CCA and RDA ordination analyses were performed using R software – including the vegan package – or SAS 9.3. Ordination results are presented as graphs (biplots) depicting the scores of response and predictor variables on the first two ordination axes which account for the majority of variance explained. The length of the arrows in the biplot represents the strength of a variable's influence on the respective axes. The species-environment correlation represents the multiple correlations between the site scores that are weighted averages of the species scores and the site scores that are a linear combination of the environmental variables. For a detailed description of these techniques and an explanation of interpreting biplots see McCune et al. (2002).

TITAN Analysis

Different taxa respond to stressors or other predictor variables at different values. Threshold Indicator Taxa ANalysis (TITAN) is an analytical approach for understanding threshold responses to environmental gradients by identifying synchronous changes in the distribution of multiple taxa at the level of the whole community (King and Baker 2010). In other words, TITAN can be used to identify transition points (or zones of rapid change) in biological communities' response to small, continuous increases in a stressor (Biastoch 2015), where there are multiple biological variables being evaluated in response to a single environmental variable. Individual taxa responses also are shown. We used the fish and invertebrate species abundance datasets to evaluate whether there were threshold responses to flow in the study area's biological communities. Details of the TITAN method can be found in Baker and King (2010).

Conclusions

Data Gaps

The following data gaps and data limitations have been noted following our data review.

1. **Stream gage** data did not exist for all streams in the study area. Nor did the gages have overlapping periods of records (Table 3.3) or winter flow records. Availability of stream gage data affected our choice of streams to be modeled, as described above.

2. We selected the **NHDplusV2 hydrography** for this study to represent the streams network. Several modifications, however, were necessary to make it suitable for this study (see Figure 3.2).

3. Uniform **soils data** did not exist for the entire study area (Figure 3.3). Availability of soils data also affected our choice of streams to be modeled and limited interpretation of results.

4. A source for **groundwater** data was not identified, which limited our modeling effort. In the absence of groundwater data we used best professional judgment to derive information about potential for groundwater infiltration and other metrics reflecting groundwater influence on base flow, in particular.

5. Lack of available **biological data** also limited the scope of our statistical analyses.

For More Information

Contact John Jereczek (218-302-3244; john.jereczek@state.mn.us) or Ralph Garono (218-720-4294; rjgarono@d.umn.edu) with questions about the project components and supporting data.

References

King, R. S., & Baker, M. E. (2010). Considerations for analyzing ecological community thresholds in response to anthropogenic environmental gradients. *Journal of the North American Benthological Society*, *29*(3), 998–1008. doi:10.1899/09-144.1

Biastoch, R. (2015). Threshold Indicator Taxa Analysis (TITAN) – a potential tool for ecological management? SOSMART Spring Meeting.

Module 4: Hydrologic Stream Classification

Purpose

Flow and water temperature are strong drivers of environmental conditions that control habitat and biotic communities in north temperate streams (Allan and Castillo 2007). Previous work to assess the impacts of future flow and temperature in Lake Superior tributaries was hampered by the paucity of long term flow records across this region (Johnson et al. 2013). One recommendation of that study was the development of a hydrologic stream classification system that would allow model results to be extrapolated across the regions to streams with similar landscape characteristics. We developed a hydrologic stream classification system for Minnesota's Lake Superior tributaries with four goals in mind: 1) reduce the amount of unexplained variation across river types to produce the best possible predictive models; 2) identify a discrete number of river types with similar characteristics to enable empirical models to be extrapolated beyond the locations with known data; 3) to inform the selection of watersheds for which highly detailed hydrologic models (HSPF) were employed, and 4) to assist in the analysis of flow-ecology relations for fish and invertebrates.

Methods

We employed the deductive method of classification (Olden et al. 2011) due to the relatively small region encompassed by the study area, and the paucity of stream gage data, which prevented direct classification based on streamflow metrics. In addition, due to the small size and the relatively homogeneous nature of climate across the region, climatic variables were not included in the classification; rather, major drivers of flow, including land cover, soils, topography and geology were employed for this exercise. Experts in the field of hydrologic classification verified this approach (A. James, pers. comm.; I. Creed, pers. comm.).

The following steps were employed to arrive at a hydrologic stream classification for Minnesota's Lake Superior tributaries, informed by protocols described in Olden et al. (2011):

1) Data were assembled (Table 4.1) and pretreated to reduce redundancy and reduce the number of potential variables (Table 4.2).

2) Data were summarized across two spatial scales, for local reach-scale catchments and for the upstream catchment associated with each reach-scale catchment (= flow accumulated catchment) based on the National Hydrography Dataset (NHDplus v2).

3) A cluster analysis was conducted to identify a discrete number of river types, followed by a Principle Components Analysis (PCA) to evaluate the overlap among the types. Stream types were mapped and visually assessed for whether existing knowledge of stream types was consistent with statistically-derived classes. The goal was to identify the minimum number of classes that would allow a statistically robust analysis.

Table 4.1. Proposed GIS variables and rationale for inclusion in a statistical analysis.

GIS Variable	Rationale
Wetland / Hydric Soils/ Floodplain Area	Water storage, attenuation of peak flows
Area-Weighted Impervious Surface	Water storage, peak flows, index of urbanization
Area-Weighted of Slope Classes/ Isochrones	Peak flow, time of travel
Area-Weighted Forest Cover	Water storage, peak flows, ET
Area-Weighted Deciduous Cover	Water storage, peak flows, ET
Area-Weighted Coniferous Cover	Water storage, peak flows, ET
Area-Weighted Open Area	Water storage, peak flows, ET
Area-Weighted Developed	Water storage, peak flows
Area-Weighted Surficial Geology	Link to ground water, water storage, peak flows
Contributing Area/ Area-Weighted Flow Accumulation	Flow duration, peak flows
Stream Density	Peak flows
*Area-Weighted Aspect/ Hill Shading	ET, snow melt
*No. Road Crossings/ Culverts	Impede flow
Area-Weighted Soils	Influence permeability, runoff
*Precipitation	Source of stream flow
**Stream Slope / Gradient	Habitat
**Length-Weighted Confinement	Transport vs depositional reach
**Length-Weighted Stream Shading	Temperature, biological covariate
**Length-Weighted Pools/ Riffles/ Glides	Habitat
**Length-Weighted Bank Erosion	Habitat, peak flows

* Indicates data not included in the classification analyses.
**Habitat-scale data are not available for the study area in sufficient detail to allow them to be incorporated into the classification.
Climate data (i.e., precipitation) were not included in the classification due to the relatively homogeneous nature of the data for the study region. See Table 4.2 for a list of the final variables included in the classification analysis.

Table 4.2. Summary of the final selected variables. For details regarding the selection and methods for selecting final input variables see Table 6 in Cai et al. 2015.

Variable group	Variables	Description
Area	Area	Catchment area
Groundwater recharge	Rechrg_avg	Groundwater recharge
Slope	Slope_mean	Mean slope
Stream density	StreamDens	Stream density
Floodplain	Fld_pln_pc	floodplain area weighted percent
Impervious area	Avg_impervious	The area weighted mean percent impervious surface value
Soil drainage types	drain_1P	Very poorly drained area weighed percent
Soil drainage types	Drain_2P	Well drained area weighed percent
Soil drainage types	Drain_4P	Moderately well drained area weighed percent
Soil drainage types	Drain_58P	Somewhat excessively drained + excessively well drained area
Soil drainage types	Drain_6P	Poorly drained area weighed percent
Soil drainage types	Drain_7P	Somewhat poorly drained area weighed percent
Hydric soil types	All_hydrP	all hydric
Hydric soil types	Par_hydrP	partially hydric
Hydric soil types	No_hydrP	non-hydric
Land types	ForestPct	Total forest percent, includes deciduous, evergreen, and mixed forest
Land types	DevPct	Developed area, includes open, low, medium, and high intensity development
Land types	NonForPct	Perennial non-forest, includes shrub scrub, grassland herbaceous, pasture, and cultivated crops
Land types	WtlndPct	Wetland area, includes woody wetlands and emergent herbaceous wetlands
Land types	ForDecPct	Deciduous forest area weighted percent for each catchment
Land types	ForEgPct	Evergreen forest area weighted percent for each catchment
Surficial sedimentary types	sed_gP	Igneous percent
Surficial sedimentary types	sed_tP	Till Plain percent
Surficial sedimentary types	sed_iP	Ice Contact percent
Surficial sedimentary types	sed_almP	Alluvium + Lacustrine + Metamorphic
Surficial sedimentary types	sed_opsxP	Outwash + Peat + Supraglacial Drift Complex + Undifferentiated

Table 4.2 (continued). Summary of the final selected variables. For details regarding the selection and methods for selecting final input variables see Table 6 in Cai et al. 2015.

Variable group	**Variables**	**Description**
Wetland types	NWI_1P	Seasonally flooded basin or flat (percent)
Wetland types	NWI_24P	Wet meadow + deep marsh
Wetland types	NWI_3P	Shallow marsh (percent)
Wetland types	NWI_5P	Shallow open water (percent)
Wetland types	NWI_6P	Shrub swamp (percent)
Wetland types	NWI_7P	Wooded swamp (percent)
Wetland types	NWI_8P	Bogs (percent)
Wetland types	NWI_90P	Riverine systems (percent)

All data for 35 variables were transformed by either log10 (x+1) (variables of area, groundwater recharge, slope and stream density) or by arcsin square root (all other 31 variables) to normalize data. Catchments were classified by cluster analysis and principal components analysis (PCA). Agglomerative (Ward Method) procedures were employed for the cluster analysis, and group separation was determined based on their Euclidean distances (see Wolock et al. 2004). The standard deviations of all 35 variables from catchments in each group defined by cluster analysis were used to generate dispersion ellipses in PCA plots. We examined overlap in ellipses of the standard deviations. Non-overlapping ellipses indicated significant differences among clusters.

Cluster analysis and PCA were performed based on 2, 3, 4, 5, 6, 7, 8, 9, and 10 clusters. The final choice for the classification was made following further analyses of existing physical and biological data. Detailed methods used for derivation of these two classifications can be found in the revised report: Cai et al. (2015).

Results & Findings

Two classification systems were ultimately developed: one based on 4 classes, the other based on 10 classes.

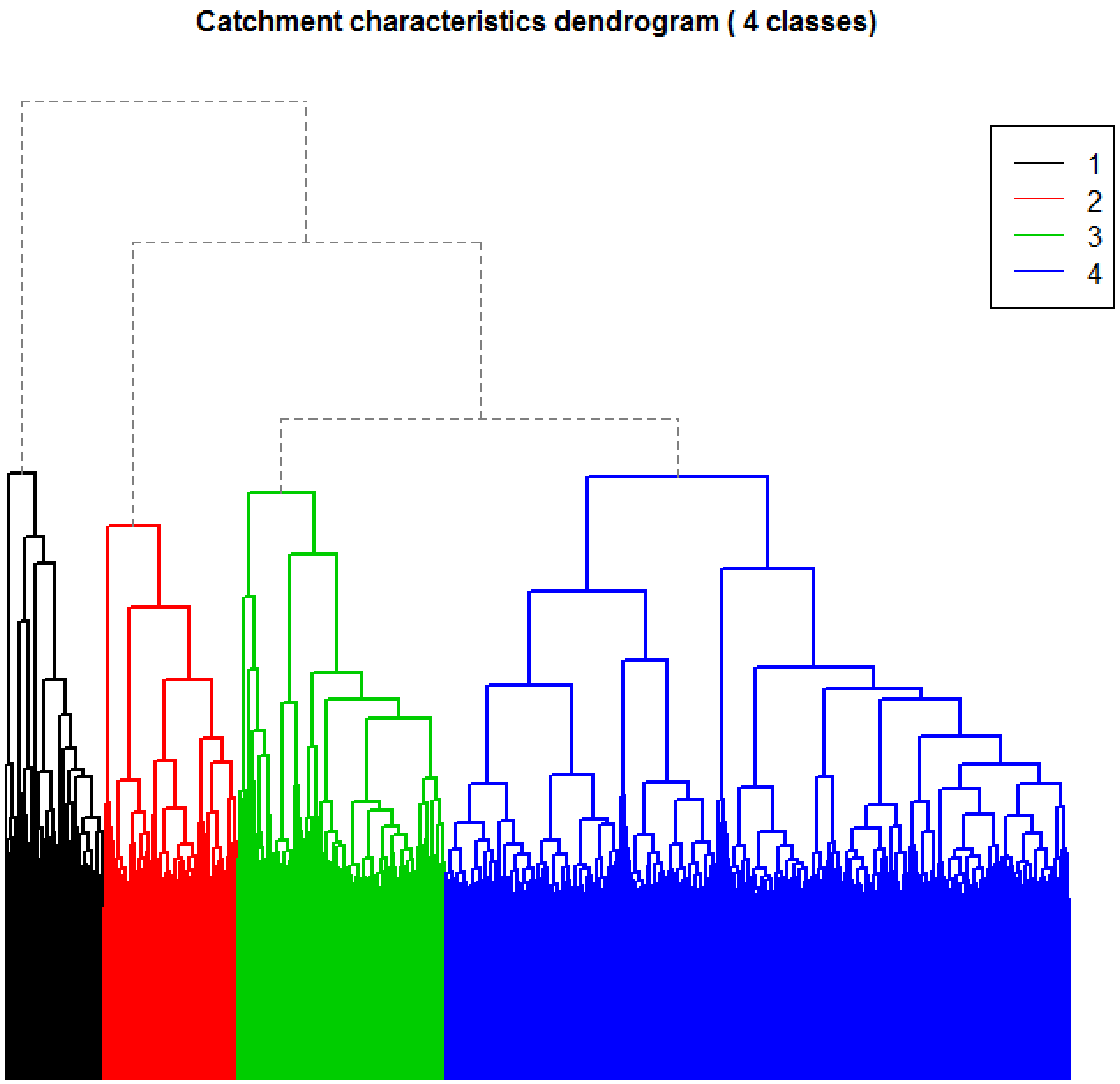


Figure 4.1a. Dendrogram for local catchment properties based on 4 clusters derived from cluster analysis using Ward method. The group colors in dendrogram are consistent to the group colors in PCA plot (Figure 4.1b) and the map in Figure 4.2. Stream classes derived from cluster analyses were separated largely on the basis of the amount and type of surface water in the catchment, the amount of baseflow, and flashiness.

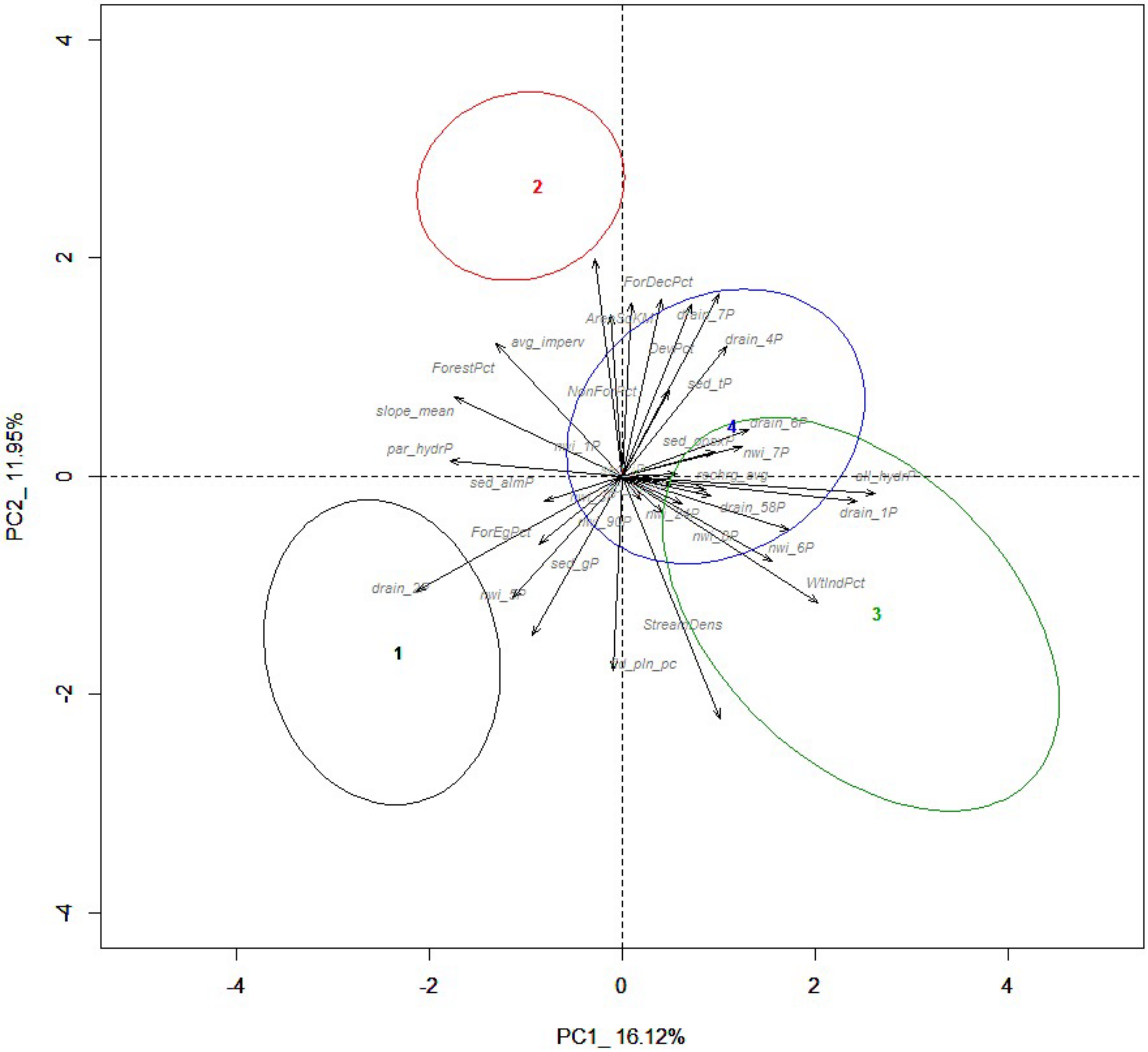


Figure 4.2b. PCA plots for local catchment properties based on 4 clusters derived from cluster analysis using Ward method. Ellipses in PCA plot represent the standard deviations of all studied catchment property variables from catchments in each group defined in dendrogram. The group colors are consistent to the map in Figure 4.2. Stream classes derived from cluster analyses were separated largely on the basis of the amount and type of surface water in the catchment, the amount of baseflow, and flashiness.

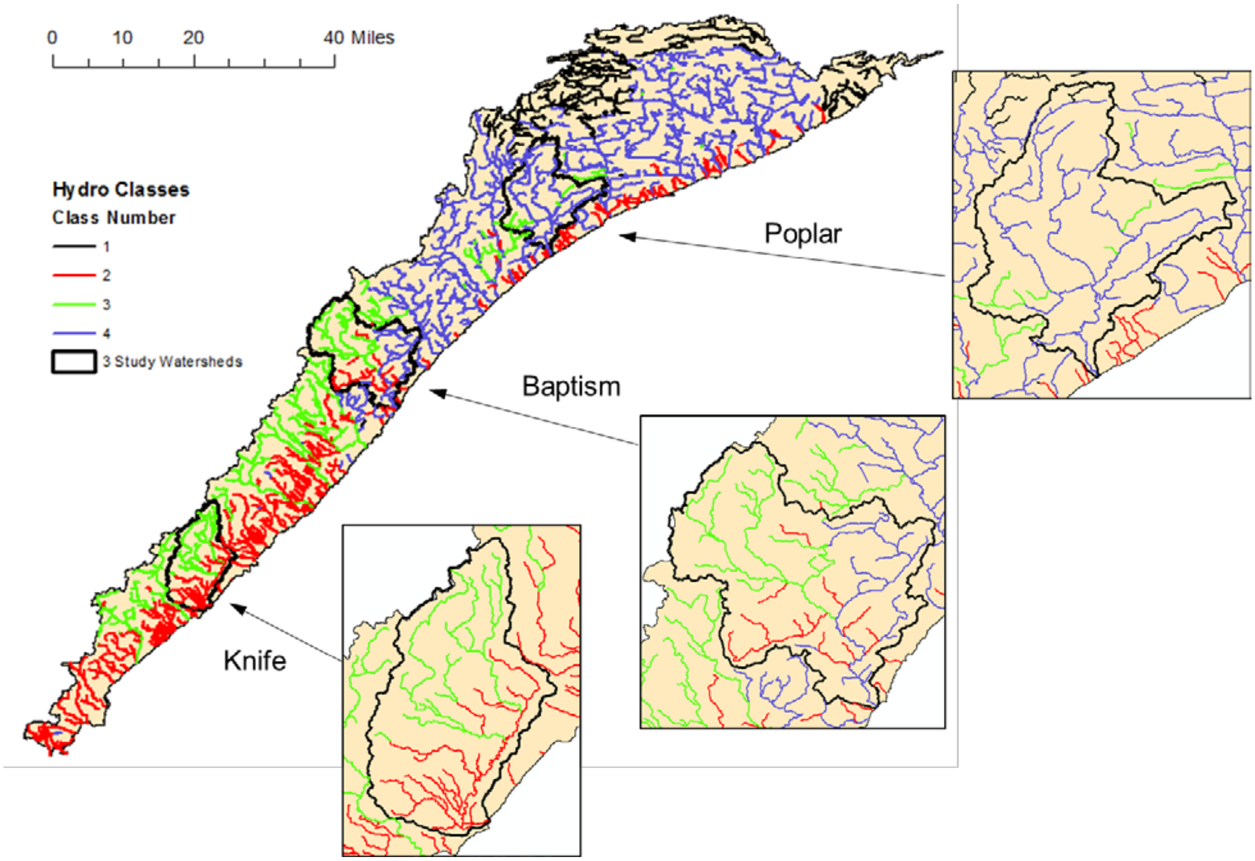


Figure 4.2. Stream reaches classified based on 4 classes and flow-accumulated catchment characteristics, with the 3 case-study watersheds detailed (Knife, Baptism, and Poplar Rivers).

Class Descriptions

Stream classes falling within the 4-class grouping and flow accumulated catchment characteristics (Figures 4.1a, 4.1b, and 4.2) are distinguished largely on the basis of soil drainage class, dominant cover types, stream branching pattern and floodplain area (Table 4.3). Catchments that fall within class 1 are found in the far northern reaches of the study area and are characterized by well drained soils, shallow open water, and igneous rock. Catchments that fall in class 2 are typically found below the escarpment and closer to the Lake Superior stream outlets and are characterized by steeper slopes with more deciduous forests. Much of the development occurs along Lake Superior and not surprisingly these catchments are characterized by higher percent impervious. Catchments that fall within class 3 are typically found higher in the watersheds and many cases above the escarpment. These catchments generally have flatter terrain and more headwater branching and not surprisingly are classified by larger floodplain areas, higher stream densities, and higher wetland areas. Classes derived from local catchments varied only slightly from those associated with flow-accumulated catchments (Table 4.3).

Analysis of the stream flow statistics by stream class suggested that the class 2 streams, which dominate the southern half of the region, had lower baseflow per unit catchment area and higher flashiness, indicating lower hydrologic storage. Class 3 and 4 streams were found to have fairly similar flow statistics, suggesting comparable amounts of hydrologic storage in these classes. However, hydrologic storage may come from different sources, with class 3 streams likely depending on wetland storage, and class 4 streams more dependent on lakes.

Table 4.3. Predominant catchment characteristics associated with each of the four stream classes based on correlations with PCA axes. Local catchments are associated with discrete reaches; flow accumulated catchments include upstream drainage areas.

Associated Cluster	Local Catchments Characteristics	Flow Accumulated Area Characteristics
1	Well drained soils	Well drained areas
1	Shallow open water	Shallow open water
1	Igneous percent	Igneous percent
1	NA	Groundwater recharge
2	Slope	Percent impervious
2	Forest	Deciduous forest
2	Catchment Area	Till plain
2	Percent Impervious	Somewhat poorly drained soils
3	Wetland area	Outwash, Peat, Supraglacial Drift Comp.
3	Stream density	Moderately well drained soils
3	Very poorly drained soils	Very poorly drained soils
3	All hydric soils	All hydric soils
4	Percent developed land use	Bogs
4	Moderately well drained soils	Total catchment area
4	Somewhat poorly drained soils	Not hydric soils
4	Deciduous forest	Flood plain area

Following this formulation of the hydrologic classification system, the results were presented to area managers in the form of maps depicting the geographic distribution of the clusters. The intent was to assess whether the distribution of stream types was reflected by the manager's experience and impressions, i.e., a "best professional judgment" evaluation. Managers generally agreed that the distribution of classes reflected distinct flow regimes; however, they felt that four classes were insufficient to be truly useful, and they requested a more granular approach be considered. Further analyses were conducted to further discriminate flow classes within the two most diverse clusters (classes) for streams grouped in class 2 and class 4. The classification for subclasses was again performed using cluster analysis and principal components analysis (Figures 4.4a, 4.4b, 4.5a, 4.5b & 4.6). Table 4.4 summarizes the number of streams for each class and each sub-class. Each of the primary classes was subsequently found to have four natural subclasses.

Table 4.4. Number of streams grouped into each class and subclass.

Class No.	Total	Sub-class 1	Sub-class 2	Sub-class 3	Sub-class 4
1	742				
2	413	186	57	86	84
3	318				
4	1345	287	371	346	341

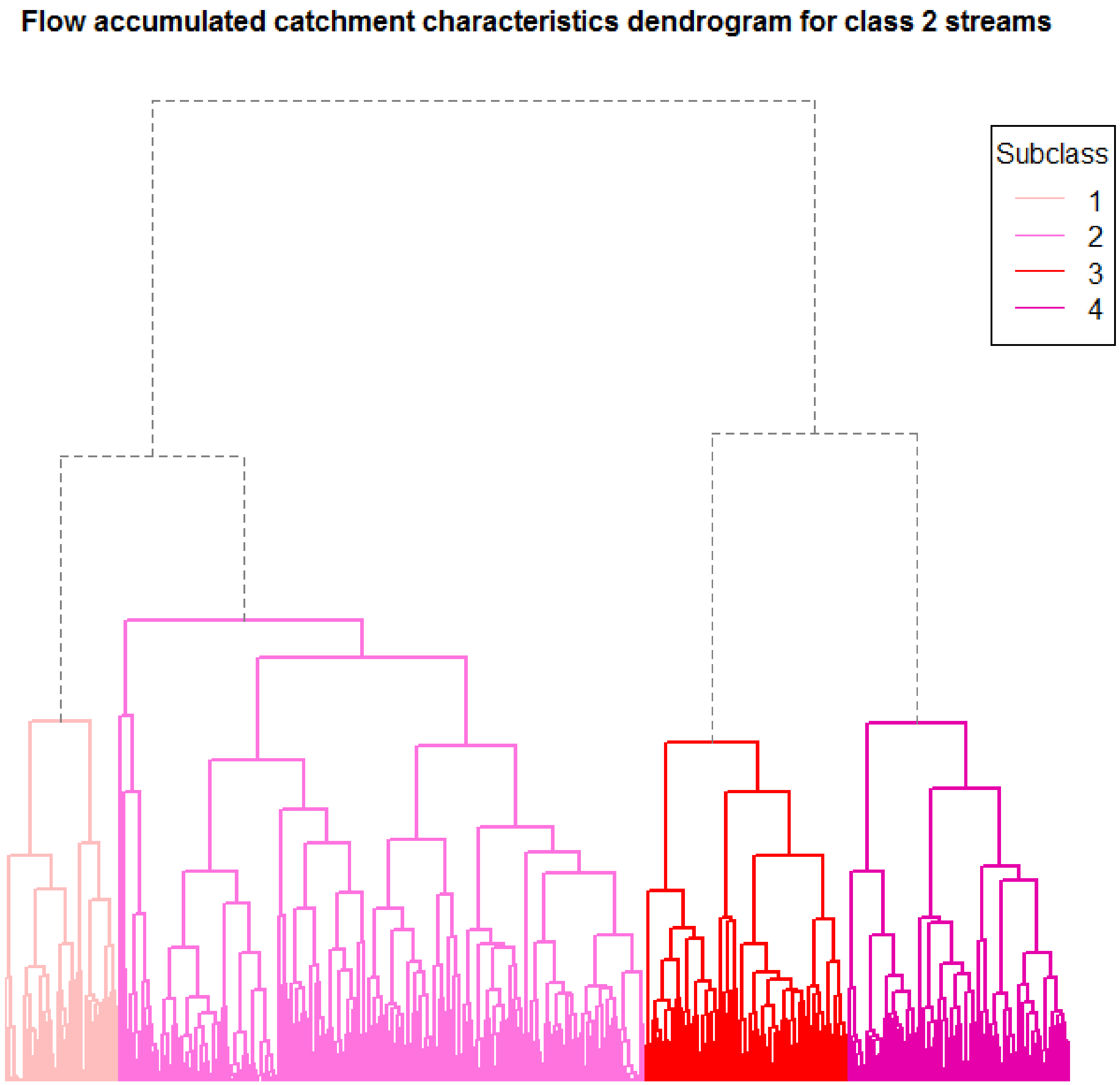


Figure 4.4a. Cluster dendrogram for class 2 streams.

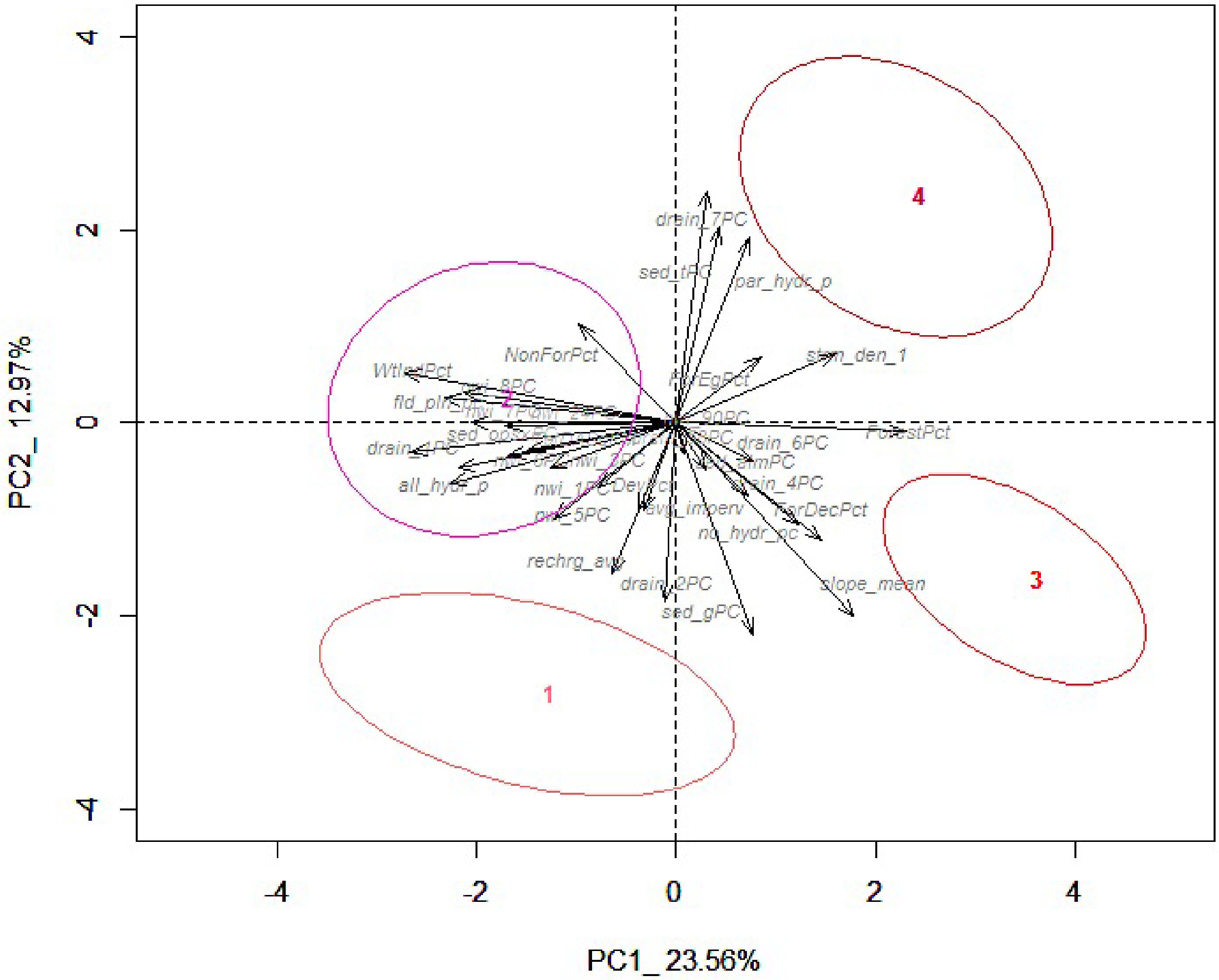


Figure 4.4b. PCA plots for class 2 streams.

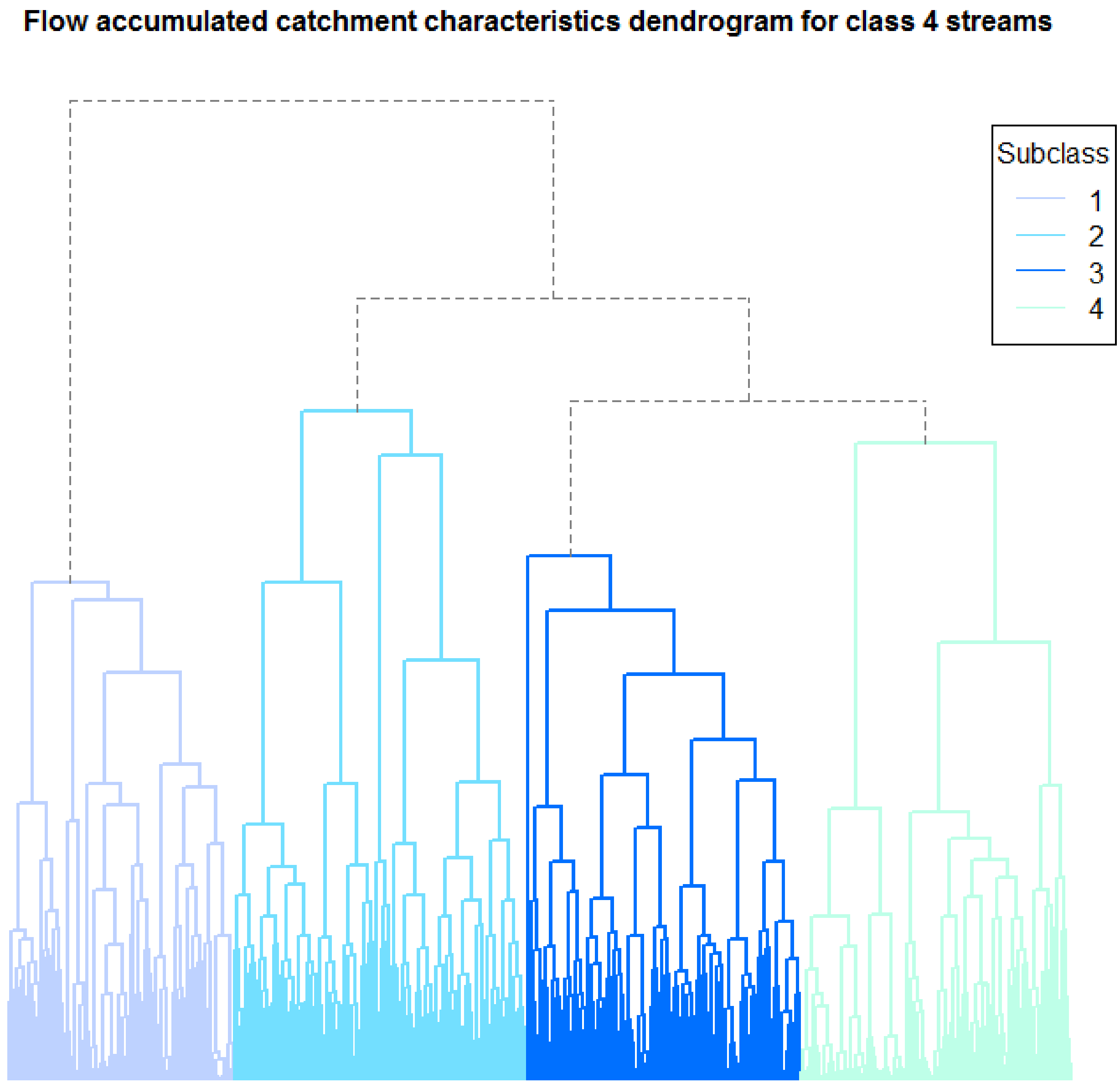


Figure 4.5a. Dendrogram for class 4 streams.

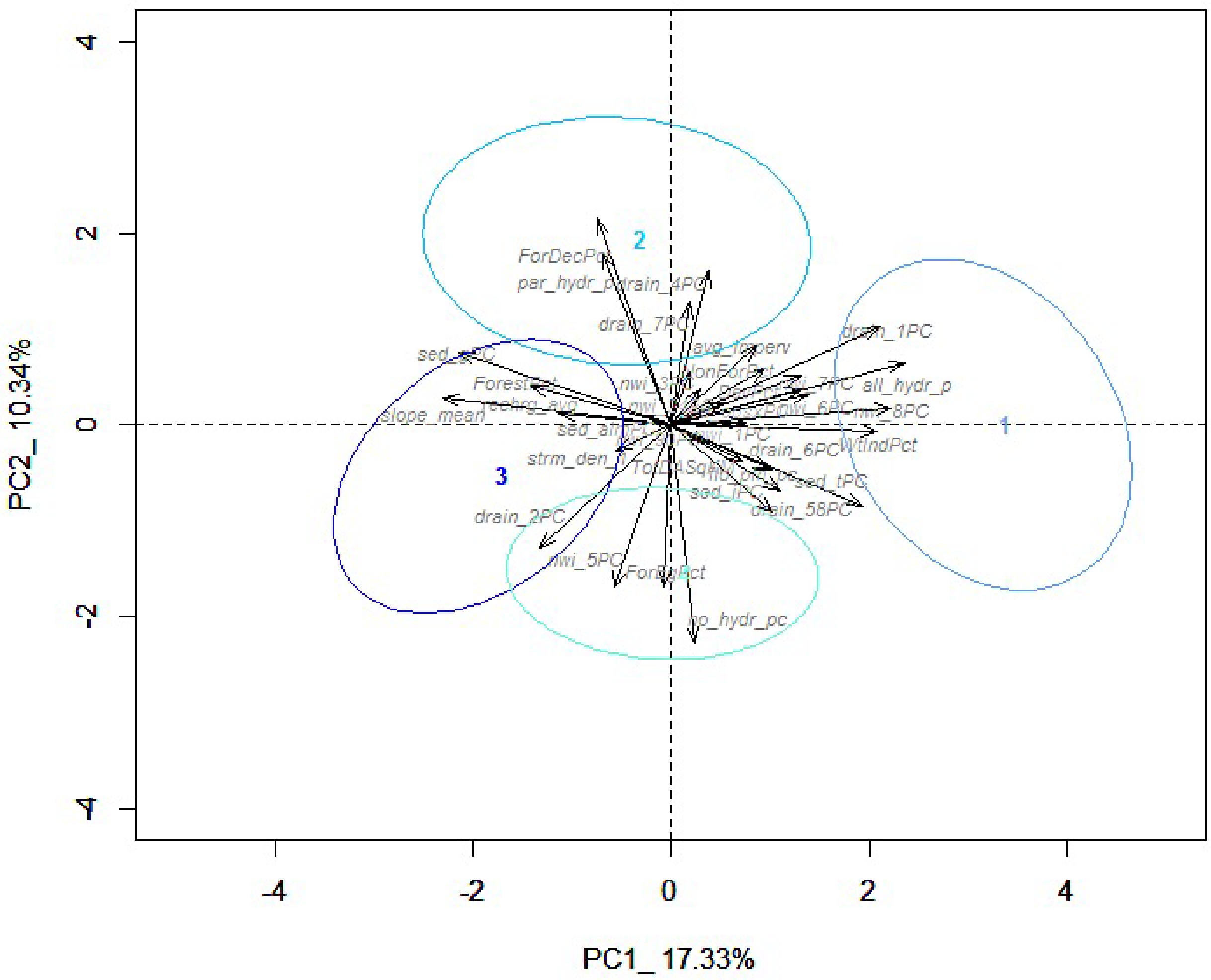


Figure 4.5b. PCA plots for class 4 streams.

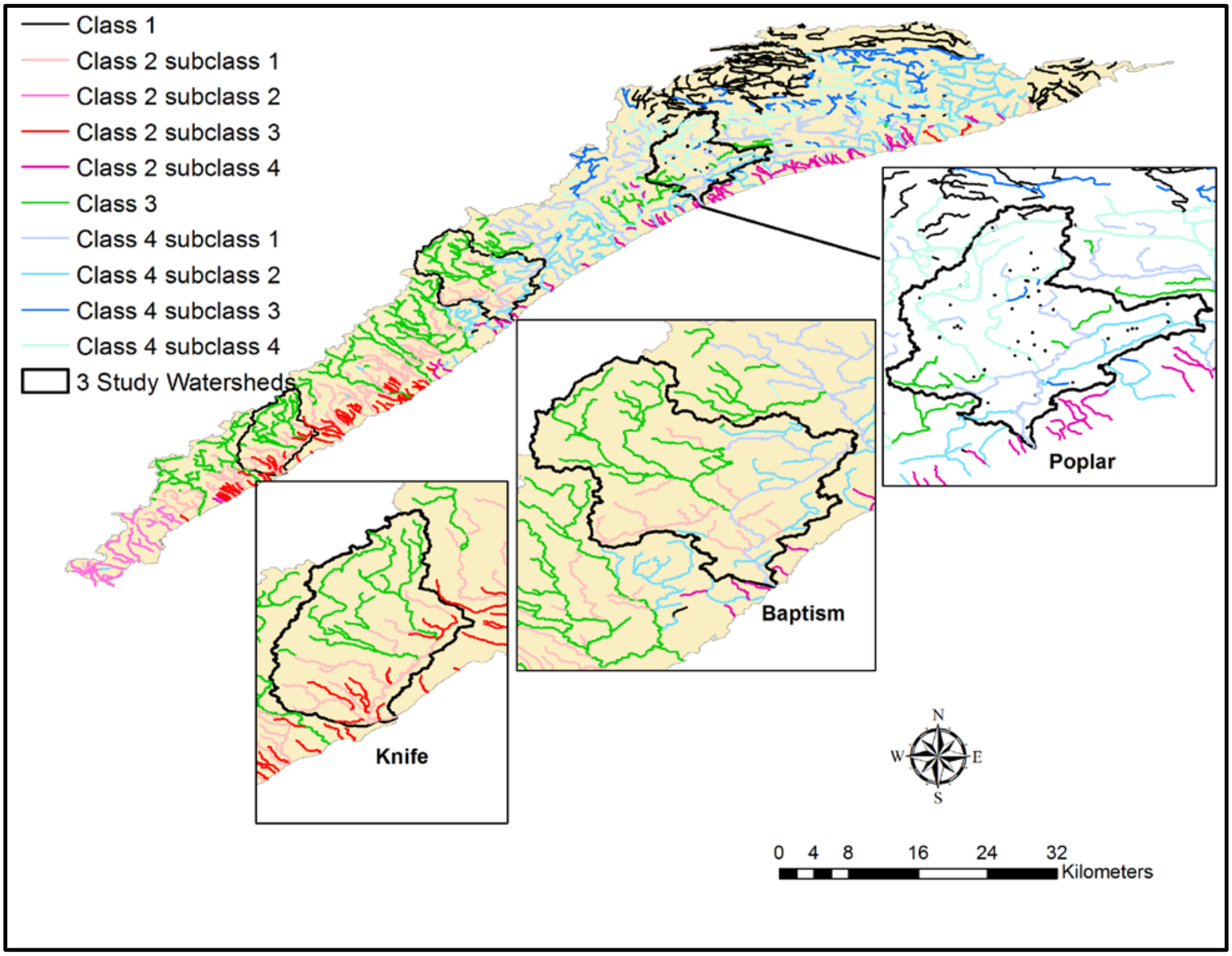


Figure 4.6. North shore streams depicting the primary classes (1-4) and subclasses for class 2 and class 4 streams. Colors in the map match the colors used in dendrogram and PCA plots in Figures 4.1 and 4.2.

Characteristics of catchments within each sub-clusters are summarized in Table 4.5. The class 2 catchments were further divided into four sub-clusters, including inland wetland region, southern urban area, south nearshore partially poorly drained area, and north nearshore area dominated by deciduous forest and non-hydric soil. The four sub-classes of class 4 streams are characterized as: rich in wetland for sub-class 1 streams, dominant impervious area in sub-class 2 area, large proportion of igneous sedimentary for sub-class 3 region, and evergreen forest in sub-class 4 area.

Table 4.5. Dominant variables for each sub-cluster of cluster 2 and cluster 4 streams.

Subcluster	Cluster 2 streams	Cluster 4 streams
1	Wetland, all hydric soil, wooded swamp, bogs, very poorly drained area	Wetland, all hydric soil, very poorly drained area, till plain sedimentary
2	Impervious area, developed area, well drained area, igneous sedimentary	Impervious area, deciduous forest, developed, partially hydric soil, shallow marsh, somewhat poorly drained area
3	Evergreen forest, partially hydric soil, somewhat poorly drained area, till plain sedimentary	Proportion of igneous sedimentary
4	Deciduous forest, non-hydric soil, steep slope, moderately week drained area	Evergreen forest

Hydrologic Characteristics

Preliminary evaluation of the stream classes (clusters) was performed to assess whether stream clusters have observably different hydrologic properties. This evaluation was based on the flashiness index, which describes the rate of change of streamflow in response to rainfall events, and is an indicator of characteristics such as the amount of hydrologic storage and impervious surfaces in a watershed. The flashiness index can be calculated from observed stream flow time series. For this project, the method given by Baker et al. (2004) was used to calculate a flashiness index for each available stream gaging site in the study region, as summarized in Table 4.6. The available stream gage records include representation of 3 of the 4 classes within the 4 class system for accumulated catchments (Figure 4.7). Although smaller watersheds tend to be more flashy than larger watersheds, there is also variability in flashiness within watersheds of similar size (Figure 4.7, Table 4.6), presumably due to variations in land cover, surficial geology, and topography.

Table 4.6. Summary of 15 gaged Lake Superior tributaries, including total area, the class numbers based on the 4-class system (Figure 4.2) and flashiness index calculated from Baker et al. (2004). Note that the flashiness index was a reliable factor separating the three classes, with class 2 streams exhibiting higher flashiness than classes 3 and 4.

Name	Area (km^2)	Class #	Flashiness Index
Brule	686	4	0.12
Poplar	295	4	0.15
Beaver	316	3	0.23
Baptism	356	4	0.25
Knife AP	37	3	0.26
Sucker	98	3	0.31
French Tributary	24	3	0.33
French	51	2	0.36
Chester	18.4	2	0.52
Knife	225	2	0.55
Kingsbury	24	2	0.58
Talmadge	15	2	0.59
Amity	43	2	0.63
Miller	30	2	0.66
Tischer	19	2	0.71

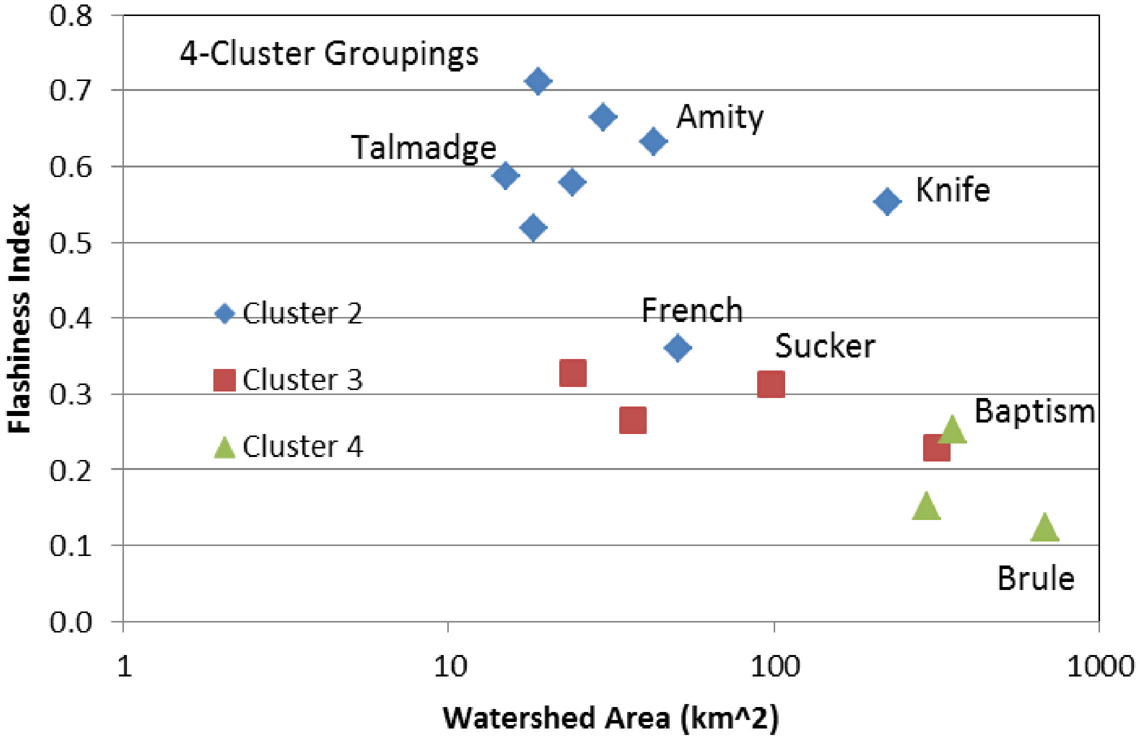


Figure 4.7. Flashiness index (Baker et al. 2004) versus catchment size for 15 gaged Lake Superior streams with the 4-class system based on the flow-accumulated properties of each stream indicated with symbols. Note that no flashiness index is available for the Class 1 grouping due to lack of gage data for any streams in that class.

Application of the Hydrologic Classification for Flow Metric Calculations

The hydrologic classification system was envisioned as one possible approach for extrapolating model results for historic flow conditions to similar ungaged streams across the study area. This strategy for estimating flow statistics in ungaged streams used the calibrated HSPF models for the Baptism, Knife, and Poplar Rivers as their basis. The hypothesis for this strategy is that each HSPF model represents one or more stream classes, and therefore that flow statistics from each model can be scaled up and down with catchment area to estimate flow in ungaged catchments. A related assumption is that the HSPF model outputs for stream segments of different classes will have measurably different flow statistics. Each of the three HSPF models includes stream segments from multiple stream classes. In practice, we found that conventional regression models using landscape variables representing geology, land cover and soil characteristics captured the majority of the factors influencing flow and the stream classification was not useful in those predictions. [Module 5 contains details regarding the application of HSPF and regression models for predicting stream flow.]

Conclusion

What have we learned?

Flow data are incomplete across time and space within our study area making it difficult to implement hydrologic models across the study area. This component of the project sought to create a hydrologic classification system that would allow us to extrapolate our findings to predict flows and related ecological changes in streams that were lacking sufficient data to be directly modeled. A hydrologic classification system was developed using physical variables known to be associated with drivers of flow, including soil types, Quaternary geology, and land cover following the approach of Olden et al. (2011). Two levels of classifications were considered: one with four classes, one with ten classes. These classes were mapped and vetted to assess whether stream types were consistent with manager's experience and impressions. Managers felt that the four stream classes represented distinct stream types; however, they did not feel that four stream classes were useful to inform their management activities.

Flow metrics derived from HSPF models and regression models were not sufficiently different across the clusters to enable us to use the stream classes for predictions of flow-ecology relationships. Due to the coarse resolution of some of the data underlying the stream classification system (e.g., Quaternary geology, soils), the resulting stream classes are not sufficiently resolved to serve as surrogates for flow regime; therefore, this stream classification system is not recommended for use outside this project.

Management Recommendations

Because the intent of the hydrologic classification system is to extend the relevance of this study's findings, no direct management recommendations resulted from this aspect of the project; however, since the classification did not provide that intended benefit, our team suggests several actions managers might consider related to filling key data gaps. Most significantly, insufficient flow data, both across the study area and within individual catchments, are a significant impediment for accurately measuring ecohydrologic relationships, due to the poor predictive power of regression-based models. We recommend that, where possible, stream gages be maintained in operation over time to establish an historical record, winter flow data be collected, and further gages be deployed within strategically defined catchments to quantify flow throughout the basin. In addition, there is a critical need for groundwater data including the completion of groundwater maps for the region.

For More Information

Contact Lucinda Johnson (218-788-2651; ljohnson@d.umn.edu) with questions about the hydrologic stream classification work.

References

Allan, J.D. and M.M. Castillo. 2007. Stream Ecology. Springer. 436 pp.

Cai et al. 2015. A classification of north shore tributary streams for us in predicting ecohydrologic conditions. Technical Report for NOAA (revised July 6, 2016).

Creed, I. personal communication. University of Western Ontario

Baker, D.B., R.P. Richards, T.T. Loftus, and J.W. Kramer, 2004. A New Flashiness Index: Characteristics and Applications to Midwestern Rivers and Streams. Journal of the American Water Resources Association (JAWRA) 40(2):503-522.

Garono, R.J., W. Herb, K. Blann, J. Erickson, L. Johnson, and J. Jereczek. 2015. A Hydrologic Classification of North Shore Tributary Streams: Data Framework and Key Decisions: Data Framework and Key Decisions. Technical Report for NOAA. 27 pages.

James, A. personal communication. Nipissing University.

Olden, J. D., Kennard, M. J., and Pusey, B. J. 2011. A framework for hydrologic classification with a review of methodologies and applications in ecohydrology. Ecohydrology. DOI: 10.1002/eco.251

Module 5: Hydrologic Models and Flow Statistics

Purpose

The flow regime characteristic of a particular river or stream is governed by the interaction of physical setting (catchment characteristics: primarily catchment area, topography, geomorphology, soil and groundwater, land use and land cover) with climate (rainfall, both the timing and amount, and temperature). Significant changes in climate or land cover can be expected to alter flow regimes. Because of the dominant influence of bedrock, Minnesota's Lake Superior tributaries are characterized by naturally low base flows and high storm flows, and are often flashy and runoff dominated. Because groundwater input is often naturally limited by the area's bedrock geology, stream thermal buffering capacity is naturally low, and base flow is often partially supported by wetlands. Therefore, flows in Minnesota's Lake Superior tributaries are expected to be highly sensitive to both changes in air temperature and precipitation. However, because land use and land cover management can also influence water yields and runoff dynamics, there is potential for land cover changes to either exacerbate or mitigate the impacts of changing climate. Hydrologic models give the opportunity to sort out the physical differences between streams in a region, and determine the responses of streams to changes in climate and land cover.

There has been significant effort since 1990 by the Minnesota Pollution Control Agency (MPCA) and the Minnesota Department of Natural Resources (MNDNR) to add stream flow gaging stations to Minnesota's Lake Superior tributaries (MN DNR 2016), which give valuable insights on the hydrology of these systems. Limitations of the available flow data include a lack of gages on lower order tributaries, very limited winter flow data, and short/discontinuous records. In general, stream flow data were not available at biological sampling sites, so that the available gaging data limited our ability to perform standardized flow-ecology analyses. Given the two year time frame of this project, hydrologic models were the only means to estimate stream flow metrics for the ungaged catchments in the study region.

The hydrologic models used in this study served two main purposes: to extrapolate the stream gaging data to ungaged catchments for the flow-ecology analyses, and to determine the response of stream flow to projected climate and land cover changes.

Methods

Hydrologic models have been used extensively to study the impacts of climate and land cover change on stream flow regimes. For example, Wenger and colleagues (2011) used downscaled outputs from general circulation models coupled with a hydrologic model to forecast effects of altered flows and temperatures on sympatric trout in the interior western U.S.

Unique features of the present study include a relatively small study area, and a need to model stream flow regimes for relatively small catchments (e.g., a few square kilometers), land cover changes mainly driven by forest management, rather than urbanization, and relatively little water management and appropriation (e.g., dams, reservoirs, and irrigation).

Two types of hydrologic models were used in this study:

1) Conventional hydrologic (rainfall runoff) models were assembled and calibrated for three key watersheds in the study region representing a range of flow conditions, and used to project future stream flow conditions for several future climate and land cover scenarios. Where possible, the future stream flow projections from the three study watersheds were then generalized for the region.
2) Empirical regression models were developed to relate historical stream flow metrics to land cover, soils, and surficial geology parameters, and were then used to spatially extrapolate historical stream flow data from gaging stations to ungaged watersheds in the study region.

HSPF Rainfall Runoff Models

Hydrologic Model Selection

There were several considerations in selecting a hydrologic modeling package for this project. Priority was given to modeling packages more commonly used and more freely available to give more useful end products and to make the modeling products more transparent. The relatively undeveloped study region was a major factor in model selection, making models focused on urbanized watersheds (e.g., SWMM) and agricultural watersheds (e.g., SWAT) less useful for this study. The HSPF (Hydrological Simulation Program – Fortran) model (Imhoff et al. 1997) was selected based on both the capability of the model and its increased usage for hydrologic and water quality characterization by, for example, the Minnesota Pollution Control Agency. HSPF includes all of the basic hydrologic processes important to this study, including precipitation, canopy interception, surface runoff, evapotranspiration, infiltration, interflow, base flow, snow accumulation and melting, and channel routing. The HSPF modeling package can be linked to the Environmental Protection Agency (EPA) Basins package, which provides a GIS environment to assemble the various spatial information needed as model inputs, and to generate the HSPF input files in the appropriate format. HSPF version 3.0 was used in this study, with pre- and post-processing support using Basins version 4.1.

Study Watershed Selection

The watershed selection process for HSPF modeling work used the following considerations:

1) Only gaged watersheds were considered, to enable model calibration and verification. Preference was given to watersheds with longer flow records, such as the Knife and Baptism rivers.

2) To enable the best representation of the study region with a limited number of watershed models, the team developed a stream classification (see Module 4). Gaged watersheds were placed in their respective stream classification clusters, and an analysis was performed to determine the distance of each gaged watershed, in parameter space, from the medoid (centroid in parameter space) of the classification cluster. The gaged watersheds were then ranked in terms of how well they represent a "typical" watershed in each classification cluster.

The Knife and Baptism rivers were initially selected for HSPF models, based on their long flow records. Based on the hydrologic classification analysis, the Knife River is a good representative of the cluster that dominates the Lake Superior - South watershed (Hydrologic Unit Code (HUC) 04010102) of the study region. The Poplar River was found to be a good representative of the Lake Superior - North watershed (HUC 04010101), with small lakes occupying a substantial fraction of the watershed area. The Baptism River, the third study watershed, represents a transitional area between the southern and northern watersheds, with relatively high wetland coverage. The location and size of the three study watersheds are shown in Figure 5.1.

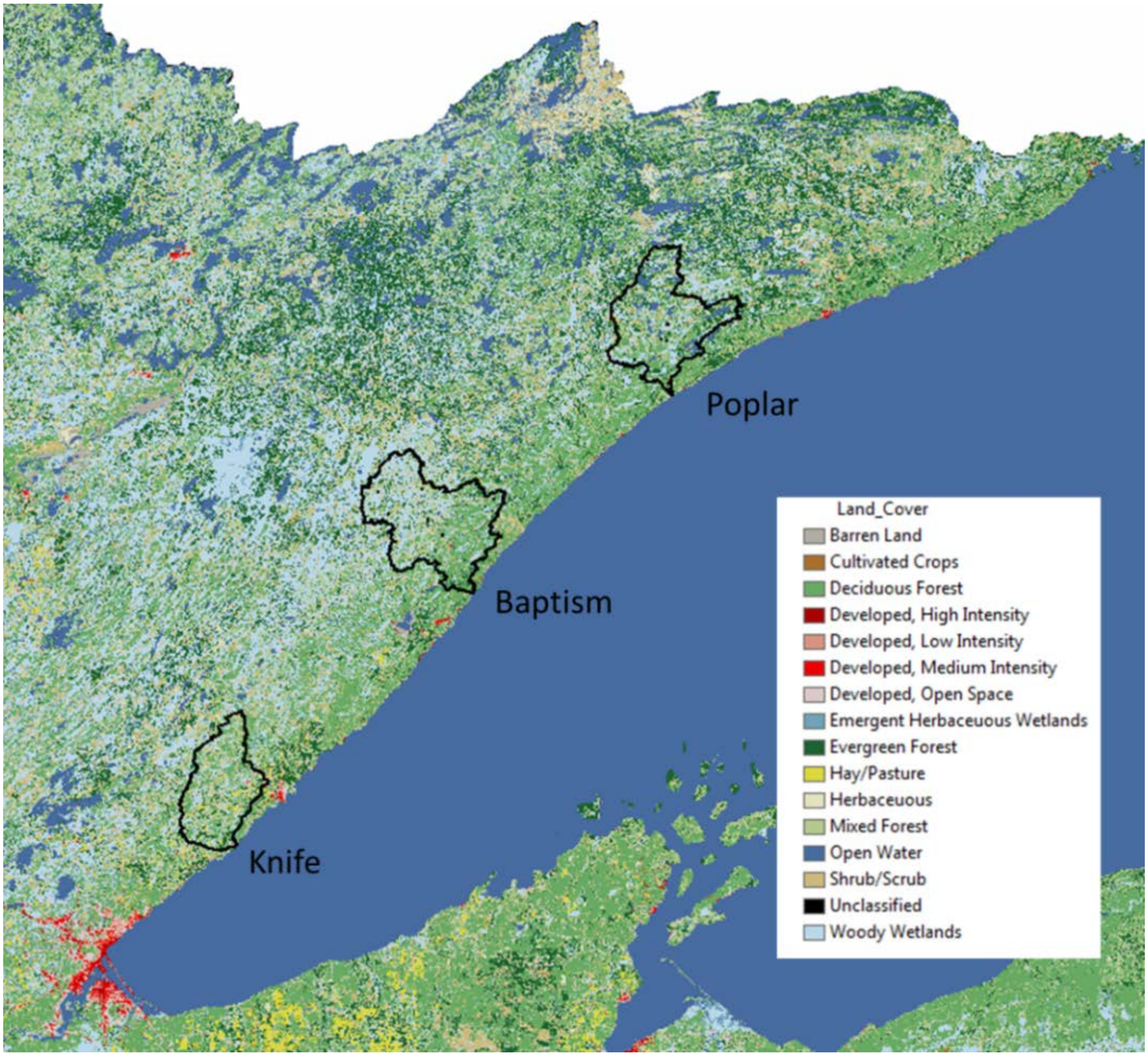


Figure 5.1. The NLCD 2011 Land Cover Data for the study region, with the three study watersheds superimposed. The NLCD land cover fractions for the three study watersheds are summarized in Table 5.1.

HSPF Model Assembly

The NHDPlus version 2 hydrography database (NHDplusV2; McKay et al. 2012) was used to establish the drainage network of catchments and stream channels for the modeling work. Useful features of the NHDplusV2 hydrography includes good spatial detail, stream segment and catchment layers with 1:1 correspondence, and a number of spatial and hydrologic attributes from other studies (Horizon Systems, 2015). Minor modifications to the NHDplusV2 stream and catchment network were made to eliminate looping channel networks, and to eliminate some of the very small catchments (< 0.01 km^2). The catchments for the three study watersheds are shown in Figure 5.2. NHDplusV2 data on stream segment length, connectivity, channel slope, and catchment area were used in setting up the HSPF models.

Setting the parameters in the HSPF model controlling hydrologic storage was a key part of the model assembly and calibration process. Soil water storage was set based on the available water capacity data in the Natural Resources Conservation Service's SSURGO soils data set (Soil Survey 2016). SSURGO data was also used to specify infiltration rates. Three (3) meter resolution LiDAR data was used to quantify depressional storage over the region. Wetlands were not treated as an explicit land cover or as discrete storage nodes, but rather were implicitly incorporated as an adjustment in the distributed surface storage in each sub-catchment. In the Poplar river model, lakes were treated as discrete storage nodes in the stream network. The outlet characteristics of each lake were estimated based on 1 m LiDAR data (outlet stream elevation and width).

The stream network was determined directly from the NHDplusV2 line work. The bankfull width and depth of each stream segment was estimated based on power law relationships to the upstream catchment area, using relationships given in the Basins user manual. For example, bankfull width = $c1 \cdot (area)^{n1}$, where c1and n1 are empirical constants. The impervious fraction in each catchment is the only land cover information that is used directly in the model, which were obtained from the 2011 NLCD (National Land Cover Database) impervious layer. Forest and other land cover data are used to derive evapotranspiration rates, canopy interception, and forest shading parameters used in the snowmelt calculations. The NLCD land cover data for the three study watersheds are summarized in Table 5.1.

Table 5.1. Summary of NHDplusV2 hydrography and NLCD land use characteristics for the three study watersheds.

Description	**Baptism**	**Knife**	**Poplar**
Total catchment area (sq. km)	356	225	295
County	Lake	St. Louis/Lake	Cook
Number of years of flow data	68	41	13
Number of sub-catchments	76	77	111
NLCD 2011 Classes, % of area	-	-	-
11. Open Water	1.0	0.3	7.4
21. Developed, Open Space	1.7	2.3	2.0
22. Developed, Low Intensity	0.3	0.4	0.1
23. Developed, Medium Intensity	0.0	0.1	0.0
24. Developed, High Intensity	0.0	0.0	0.0
31. Barren Land (Rock/Sand/Clay)	0.0	0.3	0.0
41. Deciduous Forest	26.0	26.2	21.9
42. Evergreen Forest	11.0	11.9	18.9
43. Mixed Forest	18.6	25.3	19.6
52. Shrub/Scrub	6.8	8.0	5.7
71. Grassland/Herbaceous	0.8	1.0	0.6
81. Pasture/Hay	0.0	3.3	0.0
82. Cultivated Crops	0.0	0.1	0.0
90. Woody Wetlands	32.9	19.3	23.7
95. Emergent Herbaceous Wetlands	0.8	1.4	0.2

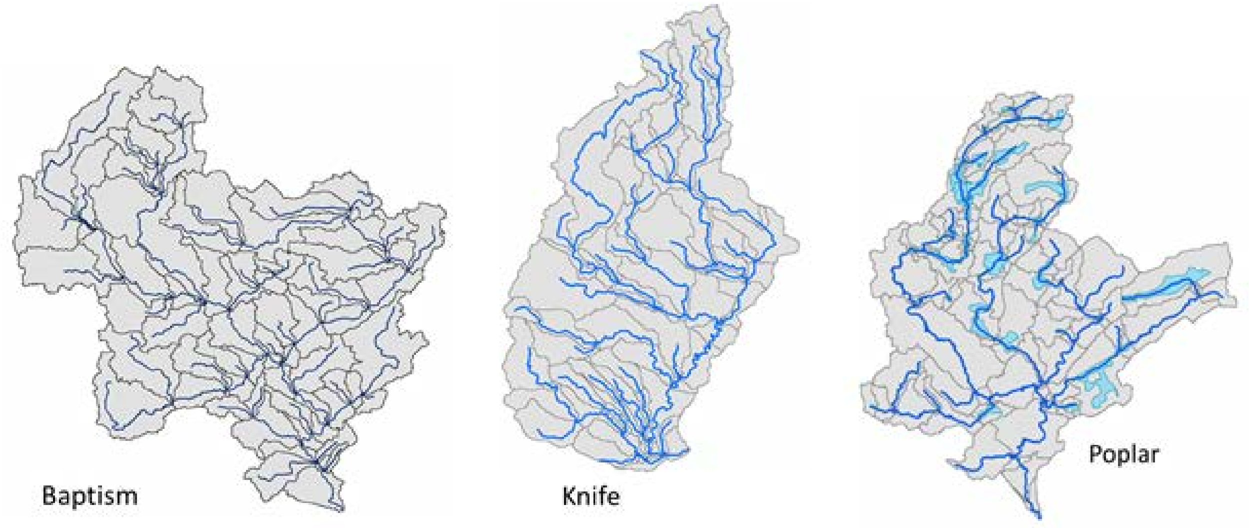


Figure 5.2. HSPF model catchments and stream channels for the three study watersheds, based on the NHDplusV2 hydrography. The NHDplusV2 lakes (33 in total) are also shown in the Poplar River watershed. The relative sizes of the three watersheds are not to scale. The number of sub-catchments (and stream segments) for the Baptism, Knife, and Poplar river models is 76, 77, and 111, respectively.

Evapotranspiration and Canopy Interception Estimates

Determining historical and future rates of evapotranspiration (ET) was a crucial component of the hydrologic modeling process, since ET consumes about 50% of annual precipitation in the region. ET is typically estimated in hydrologic models using the following process:

1) The reference evapotranspiration (RET) is calculated using available ET models, or is estimated from pan evaporation measurements. Reference ET represents the ET that can be expected from a well-watered area of grass, and depends only on weather.

2) Based on land cover (vegetation type), a seasonally-varying crop coefficient is applied to RET, to give potential evapotranspiration (PET).

3) Based on available soil moisture, actual evapotranspiration is estimated at hourly to daily time steps.

The HSPF modeling package has no means to calculate RET internally, so either RET or PET is supplied as an external input, along with the associated climate data. RET was calculated using the Hamon method (Hamon 1961) for earlier model runs, and the ASCE Penman-Monteith model (Walter et al. 2000) for final model runs. The Hamon model estimates RET based on air temperature and hours of daylight, whereas the Penman-Monteith model also uses solar radiation, humidity, and wind speed to estimate RET. RET was calculated as a daily time series based on either historical climate data or projected future climate data.

The ASCE model, which takes into account changes in humidity, projected that increased humidity tends to buffer increases in ET with air temperature. For the warmer, drier climate scenario (Hadley), the projected increase in RET was 50% based on the Hamon model and 34% based on the ASCE model. For the cooler, wetter climate scenario (GFDL), the projected increase in RET was 17% based on the Hamon model and 4% based on the ASCE model.

For this study, an important component of ET was to determine how ET may change with forest cover changes, e.g., transition of aspen to conifer. Studies from the Western U.S. have shown that a forest transition from aspen to conifer leads to a reduction in annual catchment runoff (stream flow per area) of up to 7 inches, about 30% of the annual runoff (Gifford et al. 1983). More local to the study region, long term measurements of ET and runoff from catchments in the Marcell Experimental Forest in North-Central Minnesota demonstrated a 17% (±8%) reduction in runoff for aspen-conifer transitions, which is attributed to 1) a longer growing season for conifers and 2) higher basal (stem) area (Shannon 2011). Estimates of seasonal ET from this study (Figure 5.3) were used as a basis to set the crop coefficients for each sub-catchment, based on the relative coverage of aspen and conifer forest. As a result, the potential evapotranspiration within each catchment was set based on a reference evapotranspiration (dependent on the climate scenario) multiplied by a crop coefficient (dependent on the land cover scenario).

Related to evapotranspiration, canopy interception is another important forest variable to consider in hydrologic studies. Precipitation (rain or snow) that is intercepted by the tree canopy can be lost back to the atmosphere due to either evaporation or sublimation. Leaf area is a good predictor of canopy storage, but needle-like leaves have been shown to retain more water per unit area compared to broad leaves (Keim et al. 2006). Evergreen forests have been shown to have higher canopy interception compared to aspen, particularly for snowfall (Nisbet 2005, Storck et al. 2002).

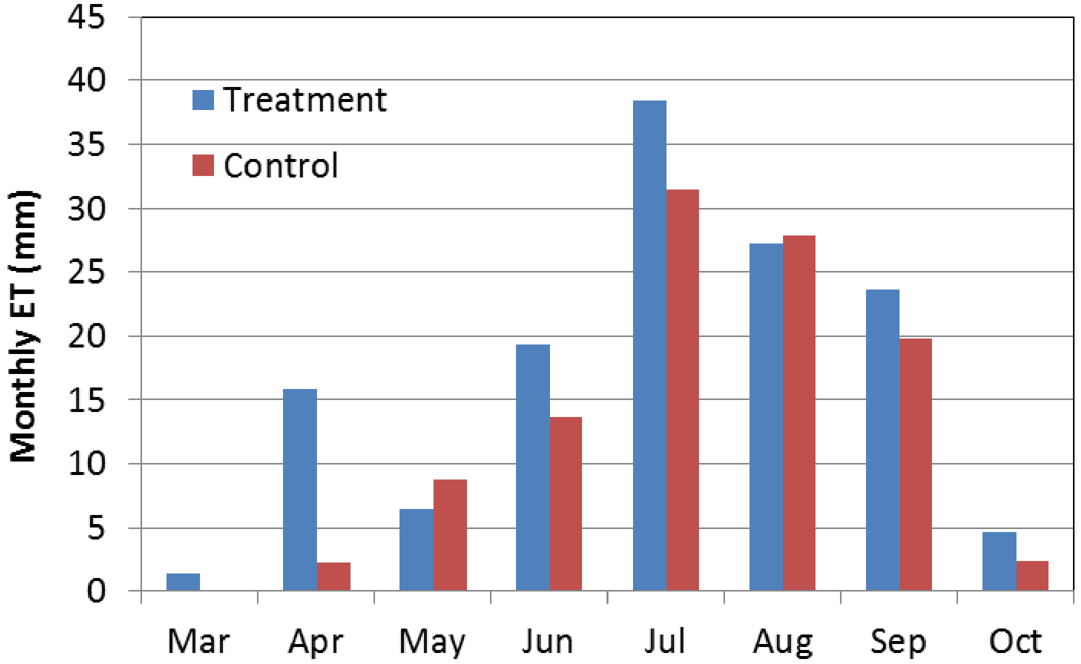


Figure 5.3. Measured monthly ET for the treatment (conifer) and control (aspen) catchments in the Marcell Experimental Forest, adapted from Shannon 2011.

HSPF Model Calibration

The three HSPF models were calibrated based on available flow gaging and climate data (Table 5.2). The calibration process included 1) adjusting evapotranspiration coefficients to achieve the correct water balance (mean annual flow), 2) adjusting snowmelt parameters to match winter and spring flows, 3) and adjusting groundwater recession coefficients and lake outlet rating curves (Poplar only) to match the observed low flow distribution in each watershed. The lake outlet rating curve relates the flow rate through a lake outlet to the water elevation, and determines how quickly water is released from a lake. The Nash-Sutcliffe coefficients for the predicted daily flows were in the acceptable range of 0.40 to 0.45 for the three watersheds (Motovilov et al. 1999). The Nash and Sutcliffe coefficient (E) compares the sum-squared differences between the predicted (P_i) and observed (O_i) values to the variance of the observed values:

$$E = 1 - \frac{\sum (O_i - P_i)^2}{\sum (O_i - \overline{O})^2}$$

where $\overline{O}$ is the mean observed flow. More importantly, the HSPF models were capable of reproducing the observed flow-duration curves and the inter-annual variability of summer low flows and spring high flows. Representative examples of simulated and observed flow duration curves and inter-annual variability are given in Figures 5.4 and 5.5, respectively, for the Baptism River.

Figure 5.4 gives typical results for the HSPF model calibration, including simulated and observed flow duration curves and monthly average flows for the Baptism River. The statistics of low, medium, and high flows are well represented. There are higher discrepancies for very low flows (e.g., 99th percentile exceedance), which is partially due to missing precipitation data from the weather records. August mean flows are over-predicted by the model, indicating that the evapotranspiration rate used in the model may be too low in late summer. Figure 5.5 plots simulated vs. observed annual mean flow, summer low flow, and spring high flow for the Knife River. Mean annual flow, summer low flow, and spring high flow are predicted with $r^2 > 0.50$, implying that the year-year variability of flow is largely captured by the HSPF model. Results for the Knife are compared to the other two watersheds in Table 5.3. The prediction of spring high flow in the Baptism watershed was relatively poor ($r^2=0.23$), implying an issue with modeled snow accumulation and melting predictions in the Baptism.

Table 5.2. Summary of flow and precipitation records used for the three HSPF models.

Watershed	Available Flow Record	Best Precipitation Station	Available Precipitation Record
Baptism	1928-	Isabella, MN	1926-
Knife	1974-2014	Two Harbors	2002- (hourly) 1897- (daily)
Poplar	2002-2014	Tofte	1948-

Table 5.3. Summary of fits (r^2) for HSPF simulated vs. observed annual mean flow, summer low flow, and spring high flow for the three study watersheds.

Watershed	r^2, Mean Annual Flow	r^2, Summer Low Flow	r^2, Spring High Flow
Baptism	0.58	0.78	0.23
Knife	0.83	0.55	0.61
Poplar	0.48	0.58	0.64

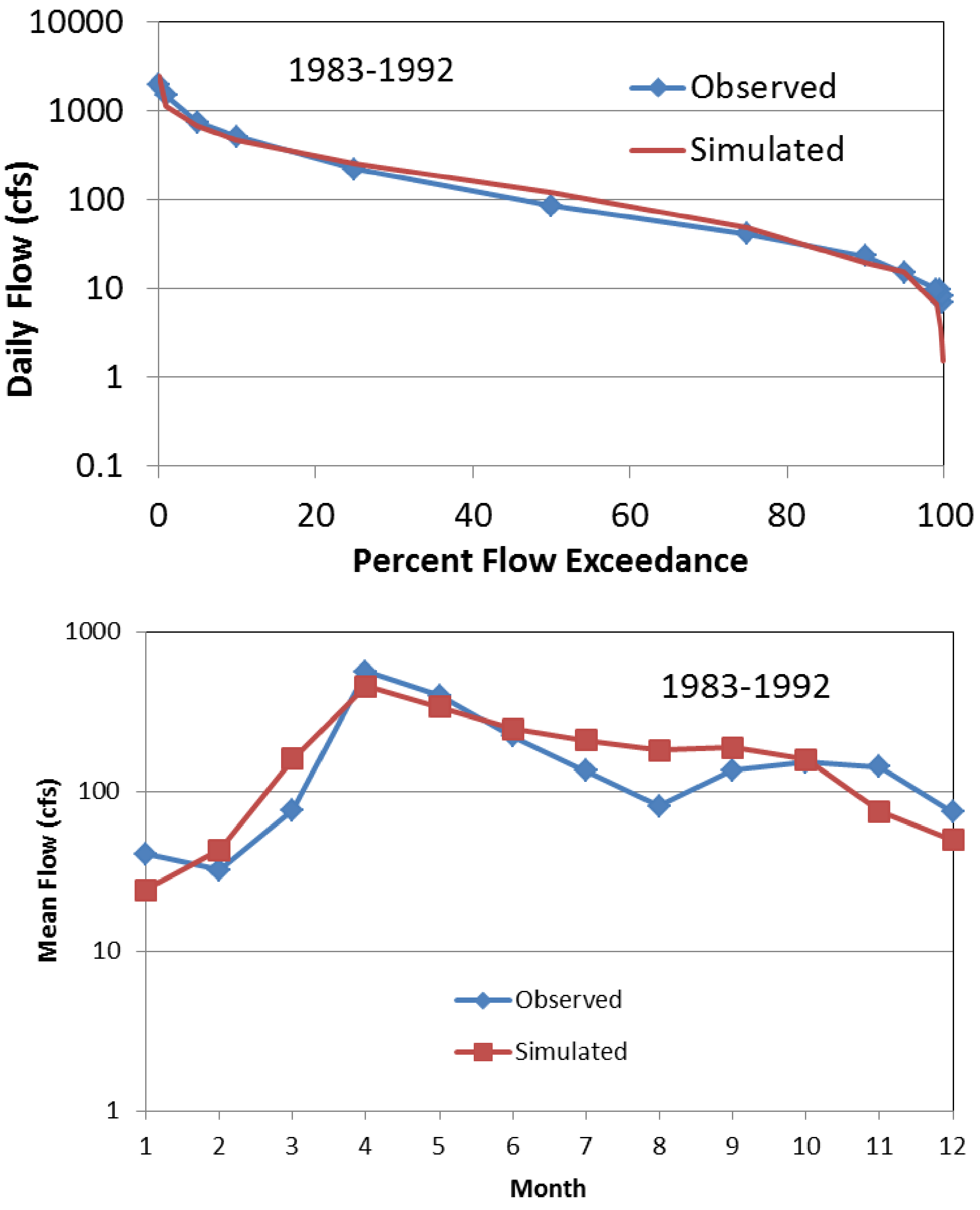


Figure 5.4. Simulated and observed flow exceedance (upper panel) and mean monthly flows (lower panel) for the Baptism River, 1983-1992.

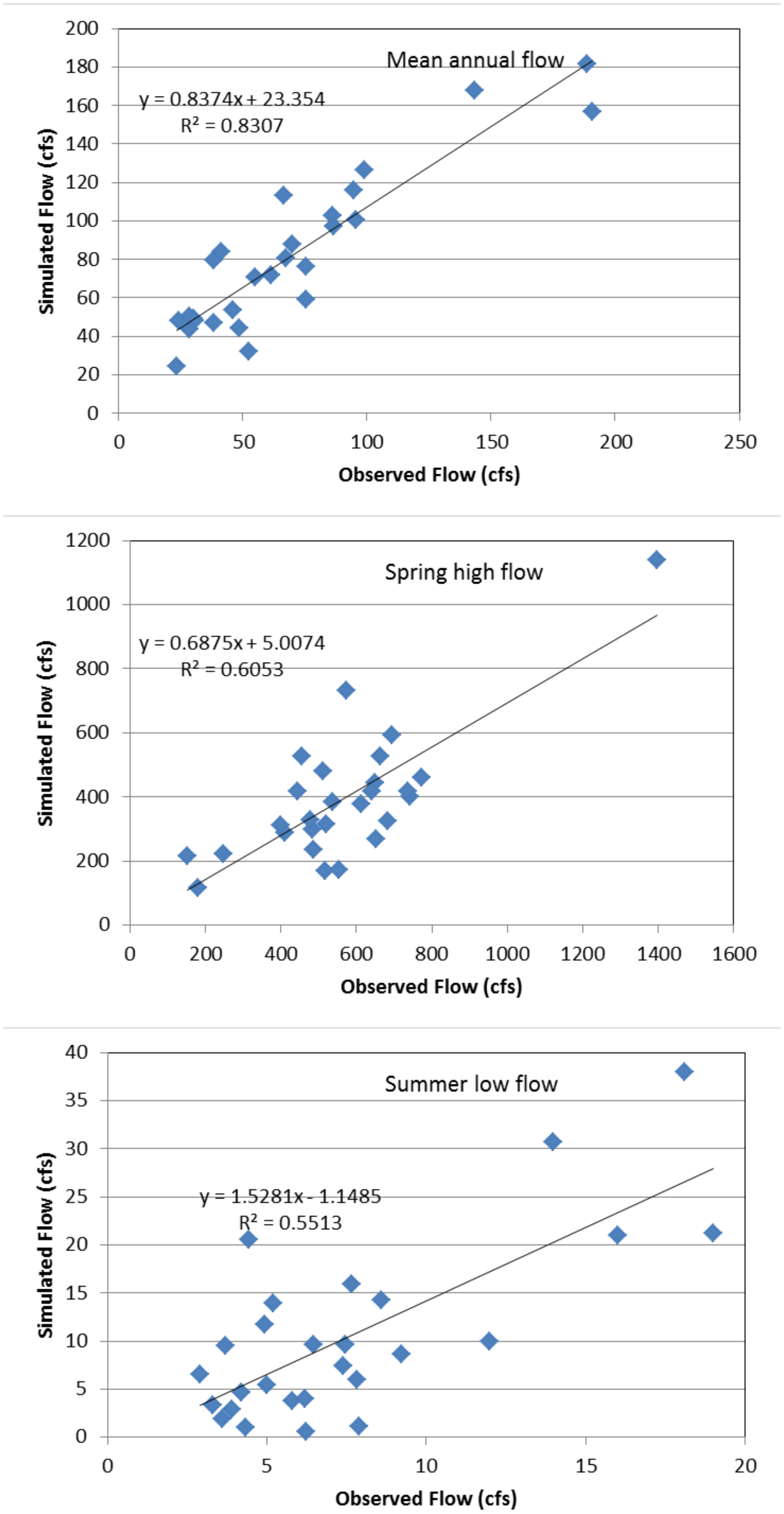


Figure 5.5. Simulated and observed mean annual flow, spring high flow, and summer low flow in the Knife River, 1983-2009. Spring high flow is the flow exceeded 10% of the time in March, April, and May; summer low flow is the flow exceeded 90% of the time in June, July and August.

Climate Scenario Selection and Assembly

In order to model predicted flow responses to climate change, we first needed to select appropriate global climate models (GCMs) and downscaled GCM data for the region, and disaggregating the daily climate to hourly values for input to the HSPF models. We used the most recent GCM model ensembles available, CMIP5 (Coupled Model Intercomparison Project Phase 5; Taylor et al. 2012), and chose the RCP (Representative Concentration Pathways) 8.5 emissions scenario, which yields the highest greenhouse gas emissions based on assumptions about population and income growth with rates of technology development (Riahi 2011). Under the RCP 8.5 scenario, global carbon dioxide concentrations exceed 1200 parts per million (ppm) by 2100. For comparison, pre-industrial carbon dioxide concentrations were in the range of 280-300 ppm, and current values recently surpassed 400 ppm. The projected changes in precipitation and air temperature for the CMIP5 climate model ensemble under the RCP 8.5 scenario vary substantially between GCM models. For the study region, mean annual air temperature increases 2.8 to 7.4 °C, and mean precipitation changes from -2.8% to +22% over the 20 GCM models. To emphasize climate variability in the open water season, we examined the changes in air temperature and precipitation for May through October (Figure 5.6). For purposes of evaluating the response of stream flow to seasonal shifts in mean air temperature and precipitation, we selected two GCM outputs from the CMIP5 GCM ensemble to represent a relatively warm and dry scenario (Hadley GEM2-CC365), and a relatively cool, wet projected future climate (GFDL-ESM2G).

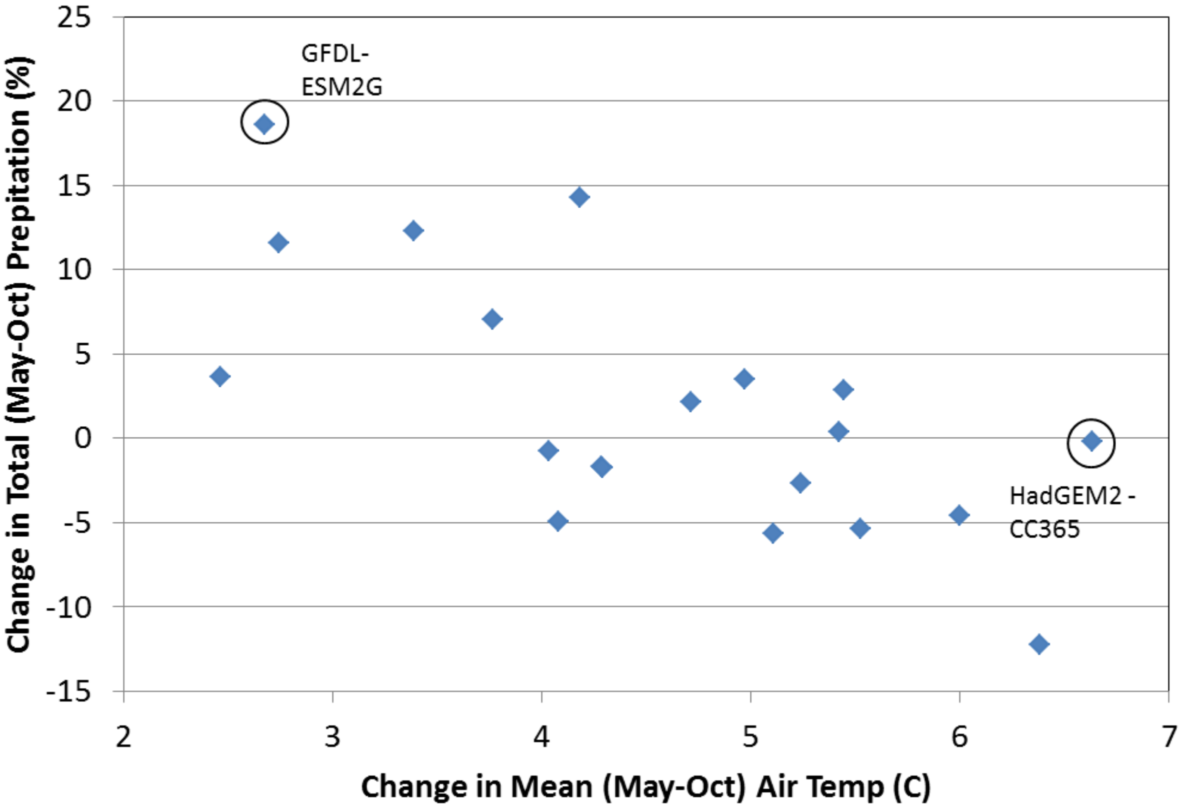


Figure 5.6. Change in mean precipitation vs. change in mean air temperature for May-October, for the Baptism River (Isabella, MN), based on 20 GCMs between the periods 1981-00 to 2061-80, for an ensemble of models from the IPCC Fifth Assessment (CMIP5), RCP 8.5 scenario. The two circled and labeled points are the GCMs that were used in the climate change response analysis (GFDL and Hadley). The changes illustrated here are representative of the study area.

To better capture the temporal and spatial variability of projected future climate, we used downscaled climate projections. For the study region, multiple sources of statistically downscaled GCM data are available with daily time step and 1/8° to 1/16° spatial resolution. We selected the 1/16° University of Idaho statistically downscaled data set (Abatzoglou et al. 2012), mainly because it includes projections for humidity, solar radiation and wind speed, in addition to precipitation and air temperature. These extra variables enabled the use of more advanced snowmelt and evapotranspiration models. Daily time series of precipitation and minimum and maximum air temperature were downloaded from the MACA web site (http://maca.northwestknowledge.net/) for the GFDL and Hadley GCMs in the period 2060-2081, with the RCP 8.5 concentration scenario, and for a historical period 1981-2000. The projected monthly changes in air temperature and precipitation for the two models are summarized in Table 5.4, for the Baptism River watershed. Climate data were downloaded for three points, near the centroid of the three study watersheds (Baptism, Knife, Poplar), to capture any climate gradients over the region. The daily data were disaggregated to hourly data for input to the HSPF models; for simulating daily average stream flow, the disaggregation tools that are integrated into the Basins package were found to be adequate. Corresponding potential evapotranspiration values were calculated based on data from each climate time series, using the methods described in Methods: Evapotranspiration and Canopy Interception Estimates.

Table 5.4. Projected changes in mean monthly precipitation for the Baptism watershed from the historical period (1981-2000) to the future period (2061-2080) for the 2 GCMs used in this portion of the study (GFDL and Hadley). The changes listed below were taken from a node within the Baptism River, and are representative for the study area.

Month	GFDL-ESM2G (GFLD) Change in Mean Air Temperature (°C)	GFDL-ESM2G (GFLD) Change in Mean Precipitation (%)	Hadley GEM2-CC365 (Hadley) Change in Mean Air Temperature (°C)	Hadley GEM2-CC365 (Hadley) Change in Mean Precipitation (%)
Jan	5.2	17.7	8.2	29.4
Feb	5.2	-10.1	8.9	20.7
Mar	4.4	61.3	5.1	36.1
Apr	2.0	66.3	4.2	30.1
May	2.1	35.2	4.9	7.4
Jun	1.9	28.3	4.7	-4.3
Jul	2.0	28.1	7.3	-23.6
Aug	3.4	5.3	7.3	-41.2
Sep	3.3	9.2	7.2	-11.6
Oct	3.3	1.1	7.0	12.5
Nov	3.8	3.8	6.1	47.4
Dec	3.3	16.0	9.0	46.2

Historical Climate Trend Analysis

To provide some context for the future climate scenarios, and to better relate these scenarios to current climate trends, a limited trend analysis study was performed on historical climate data from several National Weather Service stations in the study region, including Duluth International Airport and regional airports at Two Harbors, Grand Marais, and Grand Portage. Most of the analyses used monthly air temperature and precipitation data. Precipitation and air temperature data were obtained for the full record of each station from the cli-MATE web site (http://mrcc.isws.illinois.edu/CLIMATE/). Gridded monthly precipitation data were also obtained from Minnesota DNR State Climatology

Office (http://www.dnr.state.mn.us/climate/historical/monthly.html). Visual inspection of trends over the entire climate record was performed using LOWESS trendlines (locally weighted scatterplot smoothing) and 10-year moving averages. 10-year moving averages are helpful for identifying climate periodicity and trends (Seeley 2012). The Mann-Kendall trend test (Burn and Elnur 2002) was used to identify the statistical significance of the annual and seasonal precipitation trends over several time periods, including 1900-2015 and 1980-2015. The Mann-Kendall tau parameter varies from -1 to 1 for negative to positive trends. The closer the tau value is to 1 (or -1), the stronger is the likelihood that a trend exists. The significance (p-values) of the trends was also calculated - a p-value less than 0.05 (95% confidence interval) was used as a criterion for a statistically significant trend.

Stream Flow Sensitivity to Land Cover and Climate Change

The calibrated HSPF models were used to project the response of regional stream flow to land cover and climate change. A preliminary sensitivity analysis identified which land cover and climate variables cause the least and most change in stream flow. Several scenario analyses were then run, to find the response of stream flow to projected changes in forest cover and to future climate (from the downscaled GCM data).

The first sensitivity analysis focused on variables associated with land cover change; in particular, forest transition. Three variables in the HSPF model associated with forest cover were analyzed: 1) evapotranspiration rates, 2) canopy interception, and 3) winter shading. Based on a literature review discussed earlier, the values for each of these variables were adjusted by an amount and direction approximating a transition from a deciduous-dominated forest to a coniferous-dominated forest. The daily potential evaporation values were uniformly increased by 10%. Canopy interception is an internal parameter in the HSPF model that sets the maximum available canopy storage, by month. For the sensitivity analysis, these values were uniformly increased in 50%. Finally, HSPF has an internal parameter that sets a level of canopy shading over snow cover, which influences the snow melt simulation dynamics. This parameter was increased uniformly by 50%. The HSPF model was run over a 32-year period (1983-2014) for each of these changes, individually, and some basic stream statistics were compiled, as summarized in the results section.

A second sensitivity analysis was performed to examine the response of simulated stream flow to the air temperature and precipitation changes associated with the two selected GCMs (GFDL and Hadley). Flow at the Baptism River was simulated using the HSPF model from 1981-2000 to 2061-2080. Future climate, in this case, was the historical climate modified with monthly increments from the GFDL ESM2G and Hadley GEM2 CC365 GCMs, as given in Table 5.4. This is a relatively straightforward process, using the monthly summaries of projected climate change to adjust the historical climate record:

$T_f = T_h + \Delta T_j$
$P_f = P_h * \Delta P_j$

where T_f and P_f are the future values of hourly temperature and precipitation, T_h and P_h are the historical values of hourly temperature and precipitation, ΔT_j is the monthly temperature increment for month j, and ΔP_j is the monthly precipitation multiplier for month j. In addition to air temperature and precipitation, a corresponding change in evapotranspiration (ET) was calculated based on the projected changes in air temperature, using the Hamon model (Hamon 1961). This approach for adjusting historical climate time series with future changes has been widely used in previous climate change studies, particularly before downscaled GCM data were readily available.

Climate and Land Cover Scenario Analysis

The sensitivity studies previously were used to analyze the hydrologic impact of spatially uniform changes in individual climate and land cover variables. This section describes the scenario analyses, where the spatially complex outputs of climate and land cover models were applied to the hydrologic models to determine a projected response to these possible scenarios. See Module 6 for a full description of the land cover data and forest change models and results.

Selection of final future land use and climate scenarios for flow modeling was based in part on the environmental flow components (EFCs) shown to have the strongest relationship to in-stream biological communities. Empirical relationships between current EFCs and patterns in in-stream biota (fish and invertebrates) suggest that the most important EFCs are base flow index (BFI), flashiness (FLASH), high and low flow counts (HC, EC), as well as summer low flow (SUM_Q90), and either spring or summer high flow magnitude (SPR_Q10 or SUM_Q10) (see Module 7 for a more complete description). Mean, 10th percentile and 90th percentile flows are all highly correlated with catchment area. Extrapolating from the literature we could expect greatly reduced summer and autumn low flows associated with increased ET under the drier warmer climate scenario.

Example forest maps for historical and future conditions were derived from LANDIS II (Scheller and Mladenoff 2005) model results and are given in Figure 5.7. The more detailed LANDIS forest classes were aggregated to aspen/birch, coniferous, and deciduous species. Aspen/birch was maintained as a separate class from other deciduous (maple, oak, etc.) to give the option of setting separate ET coefficients; however, the current results assume the same coefficients for all deciduous species. Non-forest classes in the aggregated system include water, wetland, and general non-forest (grass, shrub). LANDIS II forest maps were available for historical conditions and two future forest cover scenarios in 2070, under a low CO_2 emissions and a high CO_2 emissions scenario.

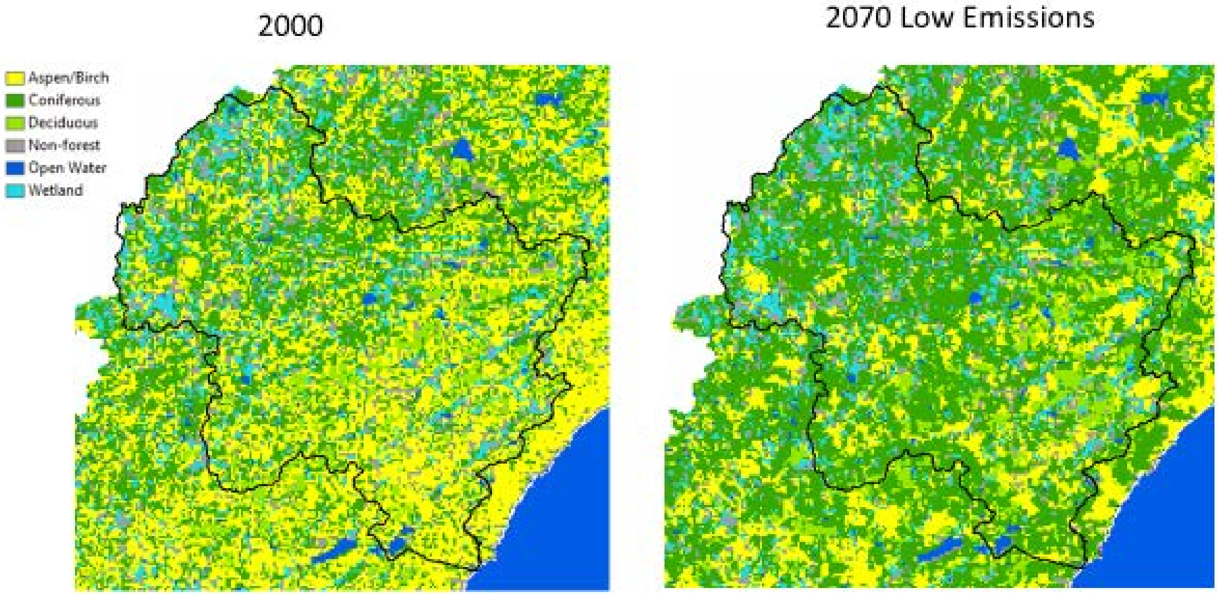


Figure 5.7. Example maps of LANDIS II forest cover maps for historical (2000) and future conditions (2070LE), in the region of the Baptism River watershed.

Future Flow Simulations

The HSPF models for the Baptism, Knife and Poplar rivers were run for the set of scenarios summarized in Table 5.5. The climate models used for the scenario analyses (GFDL, Hadley) are described earlier. For each scenario, the HSPF models were run for both historical (1981-2000) and future conditions (2061-2080), to help remove climate model biases. For example, at Two Harbors, Minnesota, the GDFL and Hadley models give mean annual precipitation of 28.5 and 29.4 inches, respectively, for the period 1981-2000, whereas the observed mean annual precipitation at the Two Harbors airport was 31.6 inches for the same period. Future flow projections for different scenarios are therefore characterized in terms of changes in flow parameters, rather than in terms of absolute values of future flow. For flow-ecology analysis, future flow conditions were calculated for each scenario as follows:

$$Q90_i = Q90_0 \cdot (100+\Delta Q90_i)/100$$

where $Q90_i$ is the future 90 percentile (Q90) flow for the i^{th} scenario, $Q90_0$ is the historical Q90 flow, and $\Delta Q90_i$ is the % change in Q90 calculated for the i^{th} scenario. This example calculation was performed for all flow variables, all reaches, and all scenarios.

Summary of Future Scenarios

We elected to choose the emissions scenarios and GCMS for the hydrologic analysis independently from the GCMs used in the LANDIS model runs. The two GCMs used in the LANDIS model were one generation old (CMIP3), and did not give a very good range of changes in air temperature and precipitation (cool/wet vs. warm/dry). It turned out that the LANDIS run using a low emissions scenario gave more forest response, because it was also associated with a modified forest management scheme. For the time frame of the study period (to 2070), the forest management strategy was found to be more important (in determining the forest response) than the climate scenario. The LANDIS 2070LE scenario was therefore emphasized in the hydrologic analysis, because it represented a larger forest response.

Table 5.5. Combinations of climate and land cover scenarios used in this study. Baseline climate and land cover scenarios represent the recent historical condition (1981-2000), while the future scenarios represent the period 2061-2080.

Climate Scenario	LANDIS 2000 Land Cover Scenario	LANDIS 2070LE Land Cover Scenario	LANDIS 2070HE Land Cover Scenario
Baseline	X	X	X
2070, GFDL	X	X	-
2070, Hadley	X	X	-

X = complete

Land Cover Scenarios

LANDIS 2000 = Current forest distribution used in LANDIS model

LANDIS 2070LE = LANDIS simulations for 2070, low emissions, modified silviculture with 60% reduction in clearcutting, which favors shade tolerant species (balsam fir, white spruce, sugar maple)

LANDIS 2070HE = LANDIS simulations for 2070, high emissions, business as usual forestry with short rotation clearcutting, which favors shade intolerant hardwoods (quaking aspen, paper birch)

Climate Scenarios (all CMIP5 RCP 8.5)

Baseline: Current Climate Conditions (1981-2000)

Warm/Dry: Hadley-CC365, 2060-2080

Cool/Wet: GFDL-ESM2G, 2060-2080

Regional regression models for stream flow statistics

One of the main challenges of this project was to estimate relevant flow variables in ungaged streams in the region, based on flow at a limited number of gaging stations. There have been several previous efforts to estimate stream flow variables in the Great Lakes basin. The US Geological Survey (USGS) has compiled empirical models for peak stream flows for many regions of the country, including Minnesota (Lorenz et al. 2009). For the

Superior Northshore region, the derived regression equations for peak flow included only two predictor variables: drainage area and percent lake area. The application of the AFINCH (Analysis of Flows in Networks of Channels) model for the Great Lakes region (Luukkonen et al. 2015) used air temperature and precipitation, percent forest, stream order, surficial geology (coarse end and ground moraines), hydric soils, and mean elevation as predictor variables for estimating monthly mean flows. Regional regression equations have been used for regional predictions of flow regimes in ungaged rivers in Michigan, Wisconsin, and Illinois (Seelbach et al. 2011). Regression equations for April high flow, August low flow, and mean annual flow were developed using ordinary least square regression analysis. Significant predictor variables included catchment area, precipitation, slope, surficial geology types, developed fraction, and agriculture fraction.

In this study, three methods for estimating flow statistics in ungaged watersheds were evaluated: 1) regional regression models, 2) regression models specific to each stream class, and 3) estimates of flow statistics by stream class, based on the HSPF models for the Baptism, Knife, and Poplar rivers.

Much of the work described in this section is closely tied to the stream classification system, summarized here and described in detail in Module 4. A hydrologic classification of the stream segments and catchments in the study region was created based on the NHDplusV2 hydrography, for the purpose of identifying streams with similar hydrologic regimes. Principal component analysis and cluster analysis were used to classify streams based on land cover, surficial geology, and soil attributes of the accumulated catchments. Several classifications were created with different numbers of clusters (classes); the 4-class system was used as a basis for several analyses of flow statistics given in this report.

While the stream classification system did capture some differences between southern and northern portions of the study region, the regional regression models (method 2) were found to give the best estimates of variability of flow metrics between the gaged catchments.

Flow Metrics

The list of stream gaging data used in the regression analysis is summarized in Table 5.6 and Figure 5.8. The flow data are a co-operative effort by the Minnesota DNR, the MPCA, and the USGS, and are quality controlled by these organizations. All available flow data from 1980 to the present was used, but omitting data rated as "poor". Most data are available as daily average flow, with some hourly flows available more recently. Any hourly flow data were averaged to obtain daily average flow. Based on previous ecological flow studies (Richter and et al. 1996; DePhilip and Moberg 2010, 2013; Poff and Zimmerman 2010), a list of the preliminary dependent flow parameters (flow metrics) calculated for each gaging site included seasonal low, high, and median flows, monthly median flows, annual high and low flows, high and low flow frequency, and flashiness and base flow indices. Flashiness is the measure of how quickly stream flow responds to rainfall events, and was quantified in this study as the mean change in flow between days divided by the mean flow (Baker et al. 2004). The base flow index measures the fraction of stream flow due to groundwater, and was quantified in this study using methods given by Nathan and McMahon (1990). We chose these flow metrics because they are easy to calculate, commonly used, and integrate several aspects of the flow regime, including frequency, duration, and magnitude.

Table 5.6. Summary of stream discharge data for tributaries used in the flow analysis study.

Stream	Catchment Area (km²)	First year of data	Number of years, total
Amity[1]	43	2002	8
Baptism[2]	356	1928	68
Beaver[2]	316	2011	3
Brule[2]	686	2002	8
French[3]	51	1994	16
Knife[2]	225	1974	41
Knife Tributary[2]	37	2004	5
Miller[2]	30	1992	5
Poplar[2]	295	2002	13
Sucker[2]	98	2001	11
Talmadge[2]	15	2001	8

1. Lake Superior Streams (http://www.lakesuperiorstreams.org/)
2. DNR/MPCA Cooperative Stream Gaging (http://www.dnr.state.mn.us/waters/csg/index.html)
3. Minnesota DNR, French River Hatchery ((218) 525-0867)

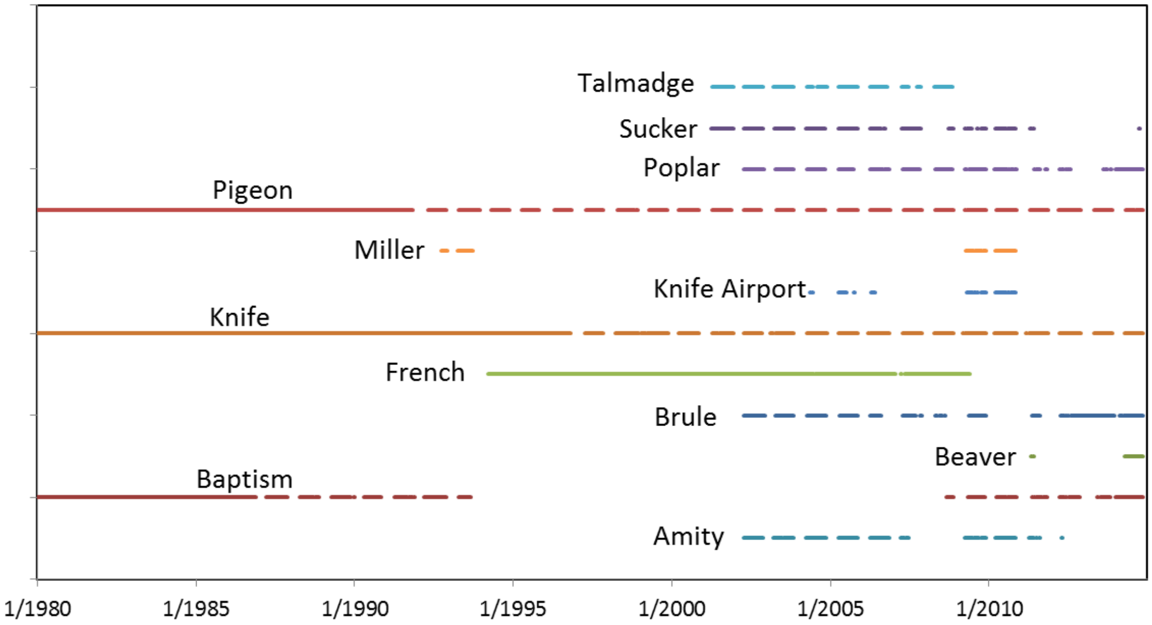


Figure 5.8. Summary of available stream gage data in the study region for 1980 through 2014. Solid lines indicate year-round flow data were available, while dashed lines indicate missing data, usually in winter.

Regression Analysis

The regression analysis was performed for each flow variable using stepwise regression in program ‘R’ (R Core Team, 2012). The predictor (independent) variables considered in the analysis are summarized in Table 5.7. The ‘R’ Leaps package was used to select the best 3-variable regression model, based on adjusted R^2 and BIC (Bayesian information criterion) statistic. If one or more the variables in the 3-variable regression had a significance less than P=0.05, the best 2-variable model was then determined. The PRESS (predicted residual error sum of squares) and predictive R^2 statistics were calculated, to estimate the predictive power of the regression relationships outside of the available data set using bootstrapping techniques (Lorenz et al. 2009, Allen 1974).

The best regression relationships were obtained using a log transform of the independent variables and the dependent flow variables with units of flow. For fractional variables that vary from 0 to 1, a value of 0.01 was added to all values to avoid issues with the logarithm of zero. The dimensionless dependent variables (base flow and flashiness coefficients) were not transformed. A typical regression relationship was of the form:

$$\log(QXX) = c0 + c1\cdot \log(Area) + c2\cdot \log(LC1) + c3\cdot \log(LC2)$$

where QXX is the flow variable of interest, Area is catchment area, LC1 and LC2 are land cover variables such as wetland fraction, c1-c3 are the fit coefficients, and log() denotes the natural log function. For all variables with units of flow, catchment area was a significant variable, and in most cases, the dominant variable. Catchment wetland fraction, the fraction of one surficial geology type (Clayey Till Ground Moraine), forest fraction, developed fraction, depressional storage, and slope were also significant for some flow variables. The complete set of regression equations is given in Appendix 5-I. Interestingly, while the surficial geology type was a significant predictor, soil properties such as hydric fraction and drainage class were generally not significant. This may reflect the lack of a complete SSURGO soils database for the region. While significant predictions were found for most of the flow variables considered, many of the variables are highly correlated to each other, suggesting redundancy (Appendix 5-I). Nonetheless, the set of variables was maintained for completeness, and to provide a larger set of variables for the flow-ecology analysis.

The distribution of some of the key flow predictor parameters for the gaged catchment set (used to develop the regression equations) and the full catchment set for the region are summarized in Figure 5.9. Compared to the gaged catchment set, the full catchment set has more small catchments. These smaller catchments can have relatively high fractions of the predictor variables, such as the clayey till surficial geology type. This, in turn, lead to unrealistic predicted values of some of the flow variables for the full catchment set, such as base flow index. As a correction, limits were set on the predicted value of base flow index (0 to 1) and flashiness index (>0).

Table 5.7 Independent variable list.

Variable group	Variables	Description
Area	Area	Catchment area
Slope	Slope	Mean catchment slope
Stream density	StreamDens	Stream density
Impervious area	Impervious	The area weighted mean percent impervious surface value
Climate	Ta	30-year mean annual air temperature
Climate	Pr	30-year mean annual precipitation
Soil drainage type	Drain	Scale of 1 to 7, from very poorly drained to excessively drained
Hydrologic storage	Depressional Storage	Mean depressional storage per unit area, derived from the 3 m DEM.
Hydric soil types	Hydric	Percent hydric, area weighted
Vegetation types	All Forest	Total forest percent, includes deciduous, evergreen, and mixed forest
Vegetation types	Develop	Developed area, includes open, low, medium, and high intensity development
Vegetation types	NonForest	Perennial non-forest, includes shrub scrub, grassland herbaceous, pasture, and cultivated crops
Vegetation types	Wetland	Wetland area, includes woody wetlands and emergent herbaceous wetlands
Vegetation types	Dec Forest	Deciduous forest area weighted percent for each catchment
Vegetation types	Ever Forest	Evergreen forest area weighted percent for each catchment
Surficial geology types	SLTGM	Sandy Loamy Till, Ground Moraine
Surficial geology types	SLTEM	Sandy Loamy Till, End Moraine
Surficial geology types	CTGM	Clayey Till, Ground Moraine
Surficial geology types	OSG	Outwash Sand and Gravel
Surficial geology types	OS	Outwash Sand
Surficial geology types	LSC	Lake Silt and Clay

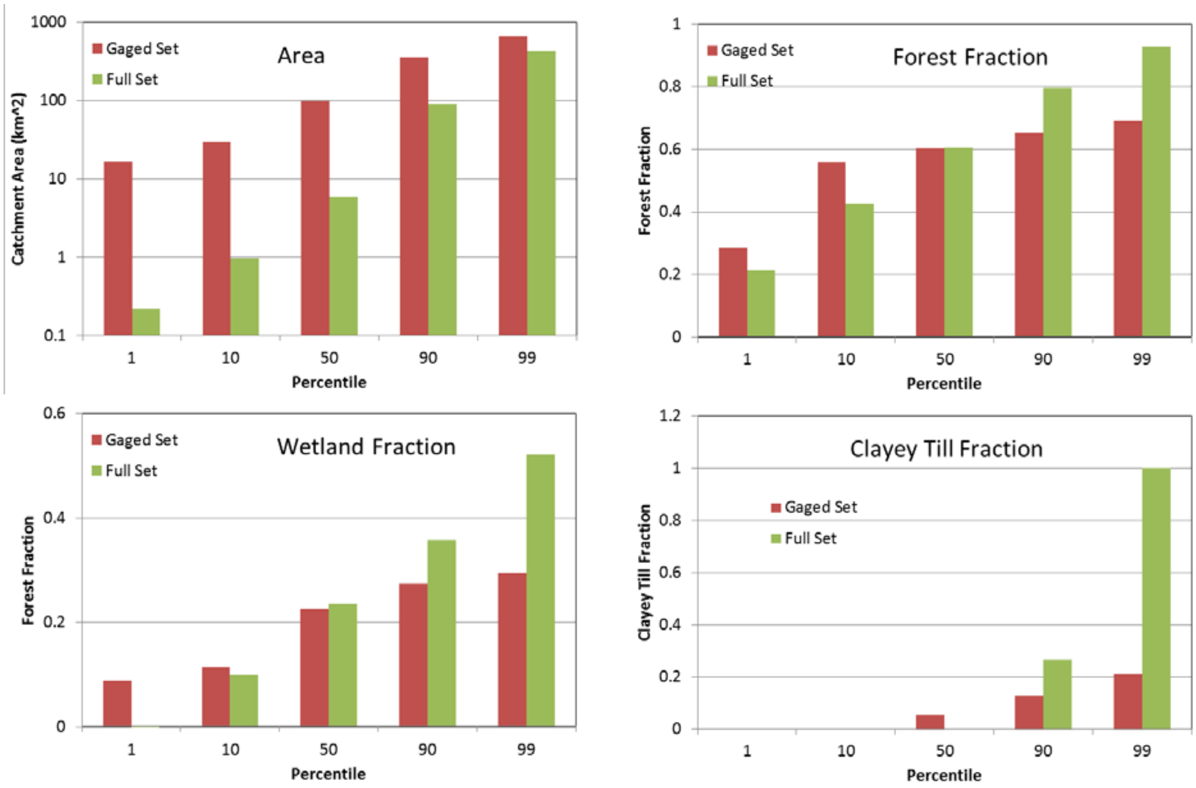


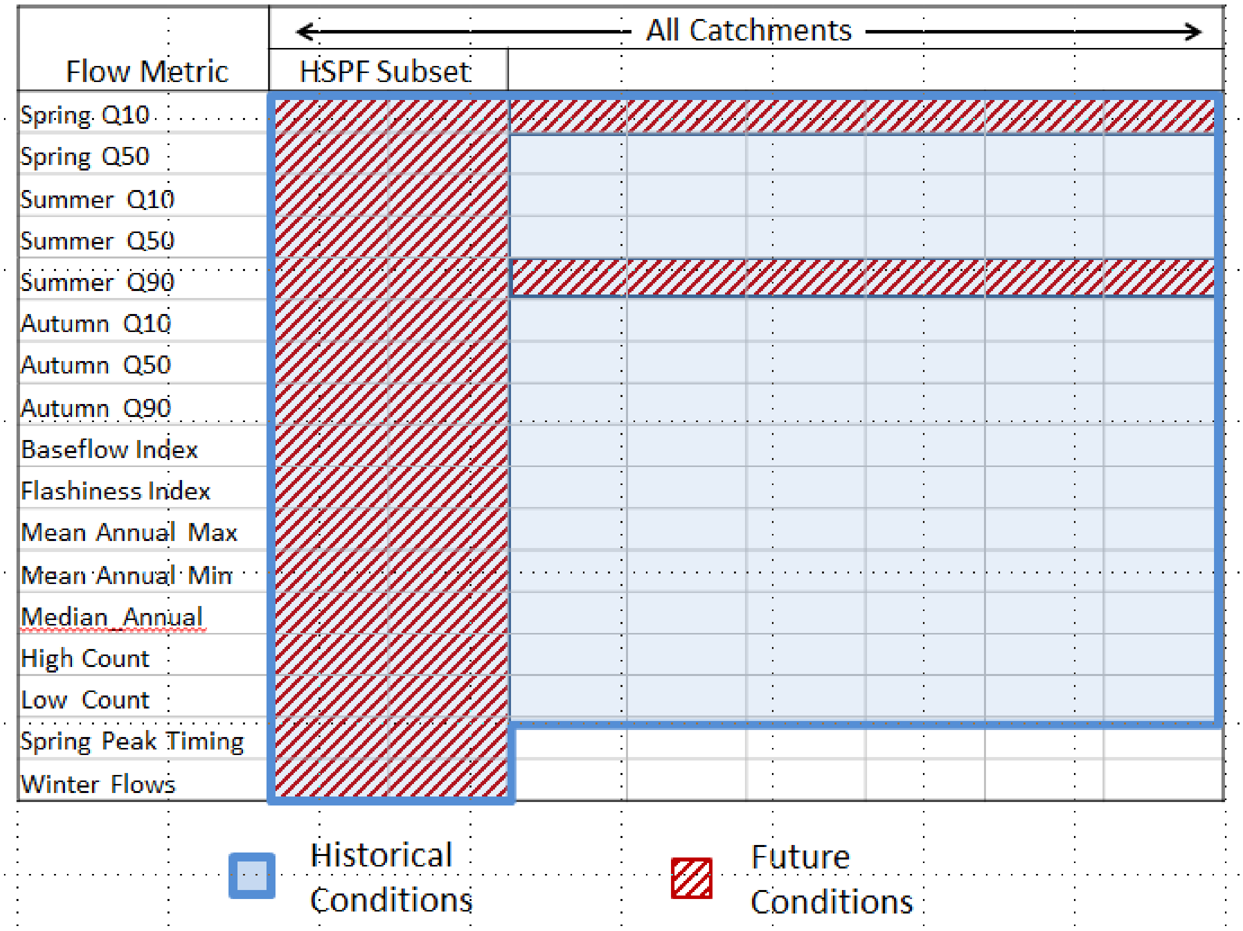
Figure 5.9. Distribution of select predictor variables (catchment area, forest fraction, wetland fraction, and clayey till fraction for the gaged catchment set and the full catchment set).

Results & Findings

The methods described above were used to generate regional stream flow metrics for historical and future time periods, as summarized in Table 5.8.

- A relatively complete set of stream flow metrics was generated for the historical time period, for all catchments in the study region.
- A complete set of stream flow metrics was generated for the future scenarios, for the subset of catchments modeled with HSPF (the Baptism, Knife, Poplar rivers and their sub-catchments).
- Two flow metrics (spring high flow, summer low flow) were extrapolated to all catchments for the future scenarios, based on the HSPF model results.

Table 5.8. Summary of modeled flow metrics for the historical time period and future scenarios. Areas of the table filled with solid blue correspond to flow metrics available for historical conditions, while areas with diagonal line fill represent flow metrics available for both historical and future conditions.



Flow Metric	HSPF Subset	All Catchments
Spring Q10	▨	▨
Spring Q50	▨	🟦
Summer Q10	▨	🟦
Summer Q50	▨	🟦
Summer Q90	▨	▨
Autumn Q10	▨	🟦
Autumn Q50	▨	🟦
Autumn Q90	▨	🟦
Baseflow Index	▨	🟦
Flashiness Index	▨	🟦
Mean Annual Max	▨	🟦
Mean Annual Min	▨	🟦
Median Annual	▨	🟦
High Count	▨	🟦
Low Count	▨	🟦
Spring Peak Timing	▨	
Winter Flows	▨	

🟦 Historical Conditions

▨ Future Conditions

Historical Stream Flow Metrics

Regression models were used to produce an extensive set of stream flow metrics for the historical time period (1981-2000). These flow metrics are mapped to the NHDplusV2 catchments in the study region. There are many ways to analyze and display the flow metric data to answer specific questions. Examples of these spatial data are given in Figures 5.10 and 5.11. The spatial distribution of the flashiness index and the base flow index are very similar, with areas of high flashiness corresponding to low base flow (Figure 5.10). Many of the catchments close to Lake Superior are relatively flashy, due to more coverage of clay soils and less hydrologic storage. The distribution of summer low flow (Figure 5.11) looks somewhat different, because a flow quantity scales up and down with catchment area.

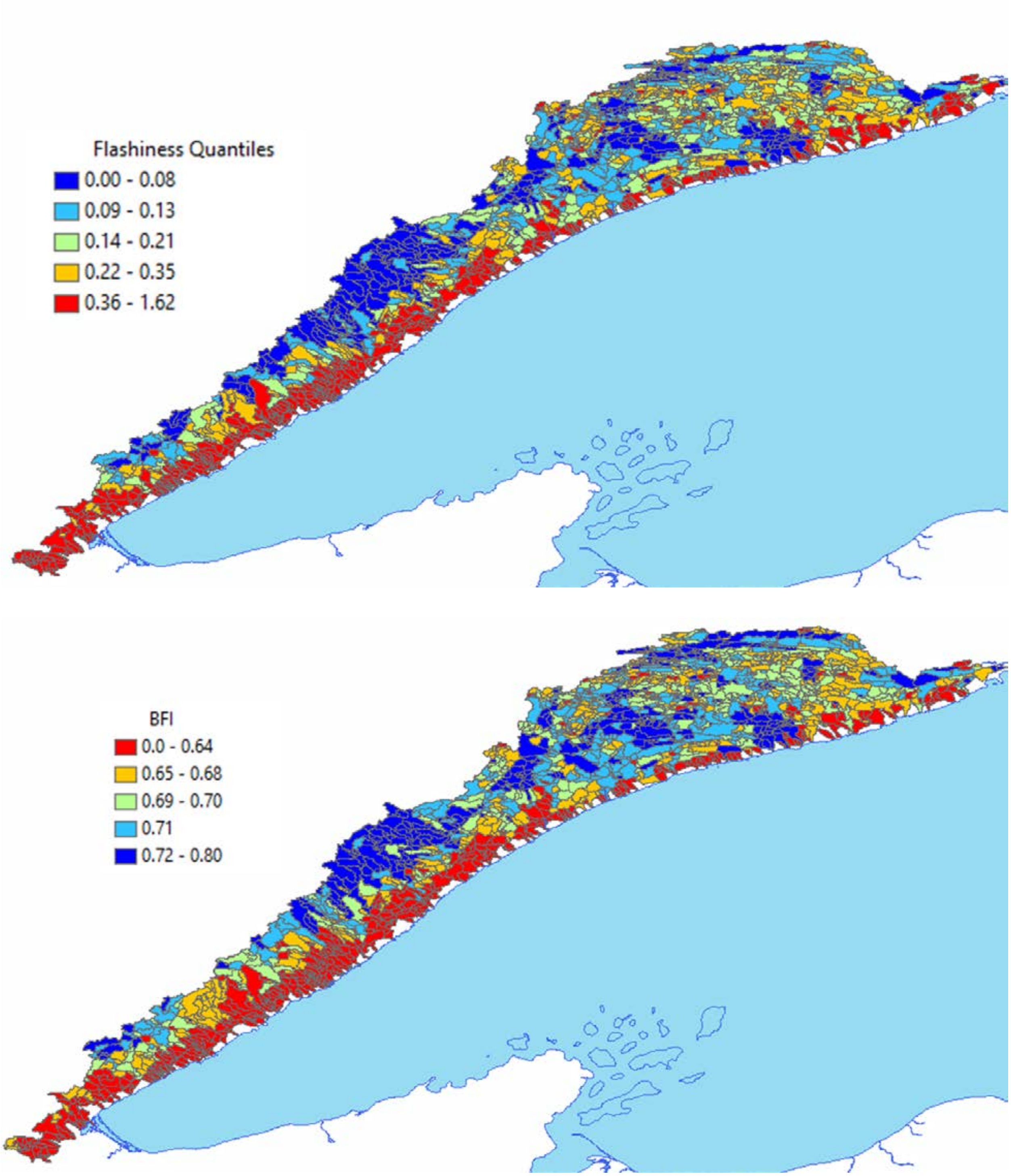


Figure 5.10. Distribution of the flashiness index and the base flow index (BFI) over the study region. The flashiness index is a measure of the daily variability in flow normalized to the mean flow, while the base flow index is the fraction of total stream flow sources from groundwater. Both indices are dimensionless. Note that high flashiness corresponds to low base flow index.

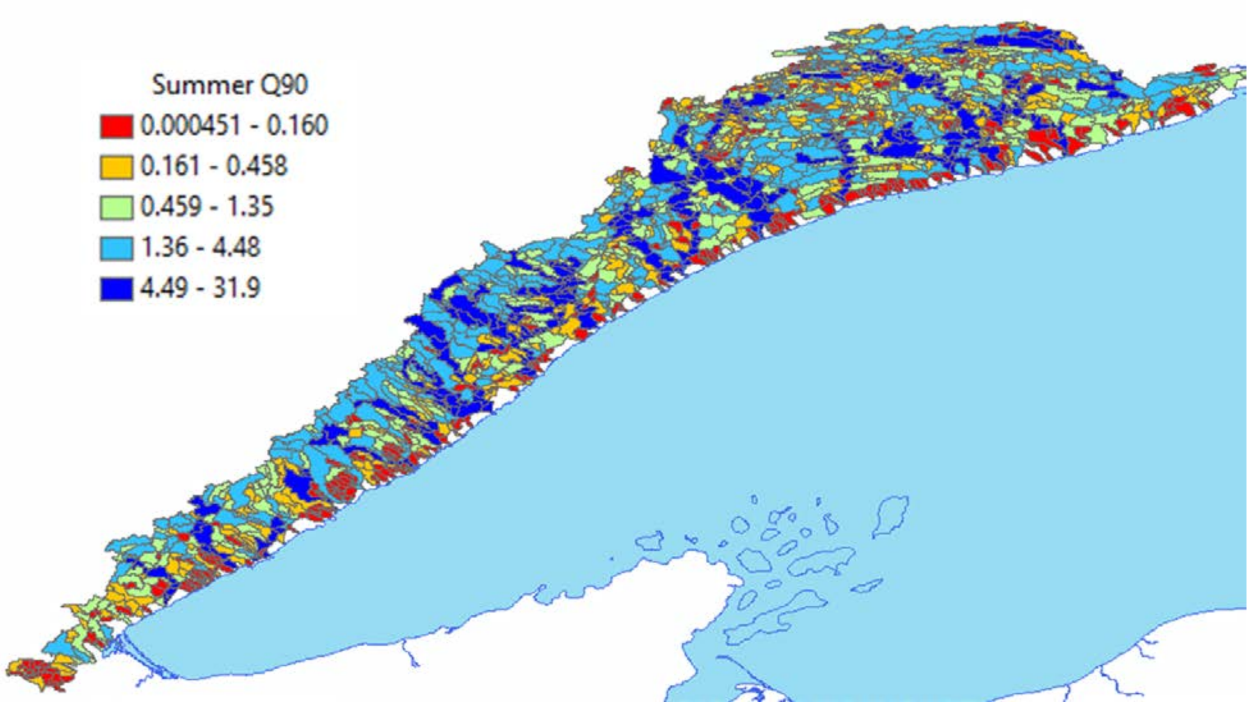


Figure 5.11. Distribution of summer low flow (Q90) over the study region, in units of cfs (cubic feet per second).

Sensitivity Analysis: Response of stream flow to changes in forest type, air temperature, and precipitation

The sensitivity analysis was performed for the Baptism River, as representative watershed for the study region. Table 5.9 gives the mean monthly stream flow for the nominal (current) model results, and for each of the change scenarios, while Table 5.10 gives the sensitivity of seasonal high and low flow statistics. The mean monthly flows were most sensitive to the change in evapotranspiration (ET), although ET was only increased by 10%. As expected, an increase in ET led to decreases in stream flow, with the greatest decrease occurring in September (-16.2%). Summer and autumn low flow both decrease markedly (22%) with the increase in ET (Table 5.10). A 50% increase in canopy interception led to increases in evaporation losses and decreases in summer mean flows of up to 7.4% and a 35% decrease in summer low flow. There was little change in winter flows associated with the change in canopy interception, however, HSPF does not take into account canopy interception (or evaporation/sublimation) for snowfall. Finally, an increase of 50% in snow shading (forest shading in winter) led to a 19% increase in mean March flow, as more snow was retained over winter, but only a 2.7% increase in spring peak flow (Q10). This suggests that rainfall, rather than snowmelt, may be the main driver of spring peak flows.

Table 5.9. Simulated mean monthly flows for the Baptism River model, and % change in monthly mean flows for 1) 10% increase in ET, 2) 50% increase in canopy interception, and 3) 50% increase in shading.

Month	Nominal Mean (cfs)	% Change in Flow +10% ET	% Change in Flow +50% Canopy Interception	% Change in Flow +50% Shade
Jan	34.7	-7.8	3.3	-1.5
Feb	52.7	-6.8	2.9	-8.2
Mar	131.2	-6.7	2.7	-16.2
Apr	417.2	-5.3	2.0	-4.1
May	349.0	-5.6	0.3	12.6
Jun	194.5	-8.4	-4.2	1.8
Jul	174.2	-9.9	-6.1	0.3
Aug	114.8	-13.6	-7.4	0.2
Sep	140.1	-16.2	-3.2	0.2
Oct	176.2	-14.0	0.8	0.1
Nov	109.6	-11.3	3.1	-0.7
Dec	63.6	-8.1	3.2	-1.6

Table 5.10. Simulated change (%) for the Baptism River in seasonal mean, summer low flow (Q90), and spring high flow (Q10) for a 1) 10% increase in ET, 2) 50% increase in canopy interception (CI), and 3) 50% increase in shading (Sh).

Season	+10% ET Mean	+10% ET Q90	+10% ET Q10	+50% CI Mean	+50% CI Q90	+50 % CI Q10	+50% Sh Mean	+50 % Sh Q90	+50% Sh Q10
Winter	-7.6	-10.9	-7.0	3.1	4.3	3.1	-3.8	0.2	-10.9
Spring	-5.7	-7.2	-3.9	1.4	1.5	1.8	-0.2	-2.9	2.7
Summer	-10.2	-21.7	-9.3	-5.7	-35.4	-2.9	0.9	2.1	1.2
Autumn	-14.0	-22.2	-11.6	0.1	-10.0	1.3	0.0	0.8	-0.1

Sensitivity of Stream Flow to Changes in Air Temperature and Precipitation

In general, the response of stream flow to climate variables was stronger than the response to forest cover variables. Table 5.11 and Figure 5.12 give the monthly flow changes for changes in precipitation, ET, and air temperature individually and the combination of all changes together. It is evident that 1) projected changes in individual climate variables may have opposite effects on stream flow and 2) the projected changes in flow vary substantially over the season, with increases in air temperature leading to substantial increases in winter flows, and increases in summer precipitation (for the GFDL projections) leading to increased summer flows, despite increased ET. As with the land cover variables, seasonal low flows are more sensitive to climate variables changes compared to the seasonal mean flows (Table 5.12).

Overall, the flow metrics predicted using the regression equations were not well differentiated by stream class. Figure 5.13 gives examples of the distributions of low flow variables, including summer low (Q90), autumn Q90, mean annual minimum flow, and the base flow index. Class 2 catchments, which dominate the southern HUC 8 of the region, are differentiated as having lower base flow index and Q90, however, the other 3 classes are not well differentiated.

Table 5.11. Simulated change in mean monthly flows from the historical period (1981-2000) to the future period (2061-2080) for the Baptism River model run with downscaled climate time series from the GFDL and Hadley models.

Month	Nominal Mean (cfs)	% Change in Flow GFDL	% Change in Flow Hadley
Jan	34.7	36.1	94.9
Feb	52.7	127.0	35.6
Mar	131.2	79.8	23.8
Apr	417.2	-2.6	-46.6
May	349.0	21.4	-50.6
Jun	194.5	22.4	-34.9
Jul	174.2	35.7	-39.7
Aug	114.8	20.6	-83.8
Sep	140.1	0.2	-78.3
Oct	176.2	-15.3	-67.8
Nov	109.6	3.3	-17.8
Dec	63.6	64.4	63.6

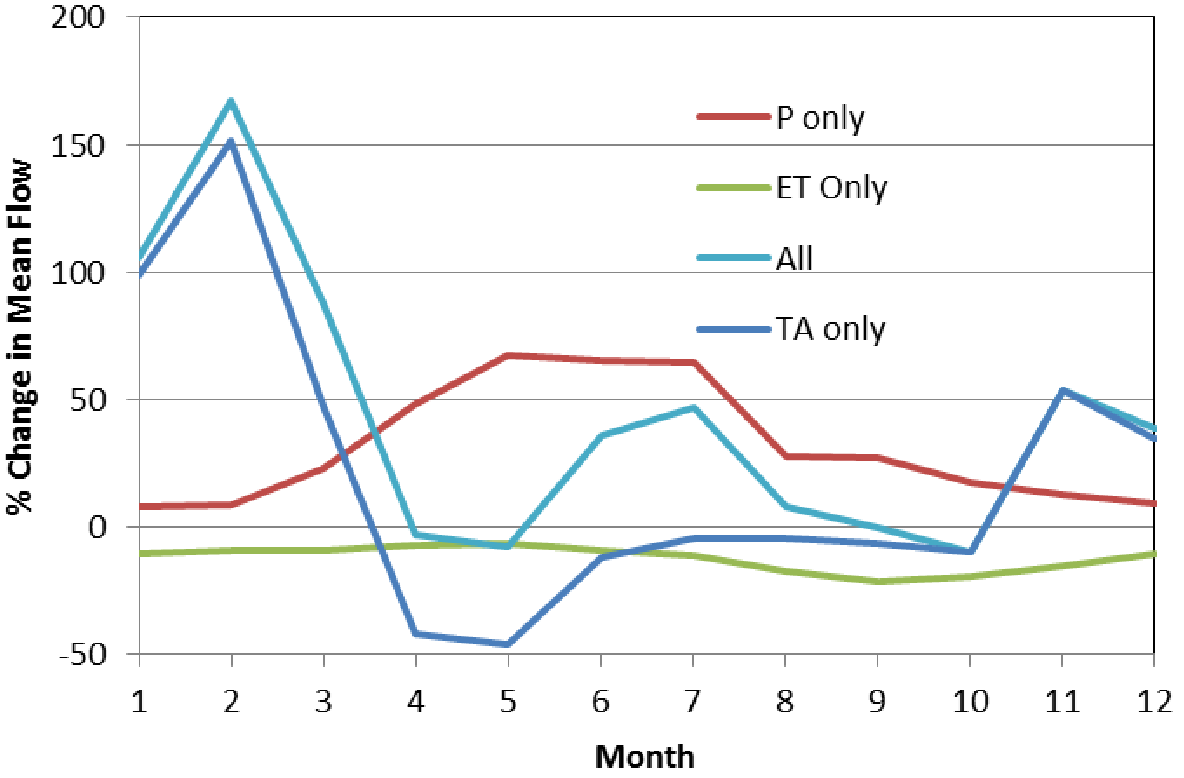


Figure 5.12. Projected future changes in mean monthly flow at the Baptism River outlet from 1981-2000 to 2061-2080, based on the HSPF model run with historical climate and future climate. Future climate, in this case, was the historical climate modified with monthly increments from the GFDL CC365 GCM. Results are given for changes in precipitation, ET, and air temperature individually and the combination of all changes together.

Table 5.12. Simulated change in seasonal flow statistics for the historical period (1981-2000) to the future period (2061-2080) for the Baptism River model for 1) monthly temperature changes (ΔT), 2) monthly precipitation changes (ΔP), and 3) the combined effects of temperature and precipitation, using climate change inputs from GCM 1.

Season	**Seasonal Mean: Nominal 1981-2000 (cfs)**	**Seasonal Mean: % Change GFDL**	**Seasonal Mean: % Change Hadley**	**Seasonal Q90: Nominal 1981-2000 (cfs)**	**Seasonal Q90: % Change GFDL**	**Seasonal Q90: % Change Hadley**	**Seasonal Q10: Nominal 1981-2000 (cfs)**	**Seasonal Q10: % Change GFDL**	**Seasonal Q10: % Change Hadley**
Winter	36.8	76.6	60.8	20.6	31.3	-44.3	55.4	123.3	104.4
Spring	246.2	18.2	-36.8	36.5	46.1	-51.8	589.6	3.6	-30.6
Summer	105.7	25.8	-48.8	11.5	123.0	-100.0	199.3	31.3	-35.8
Autumn	130.3	-5.3	-54.5	15.4	54.4	-100.0	279.1	-9.3	-45.4

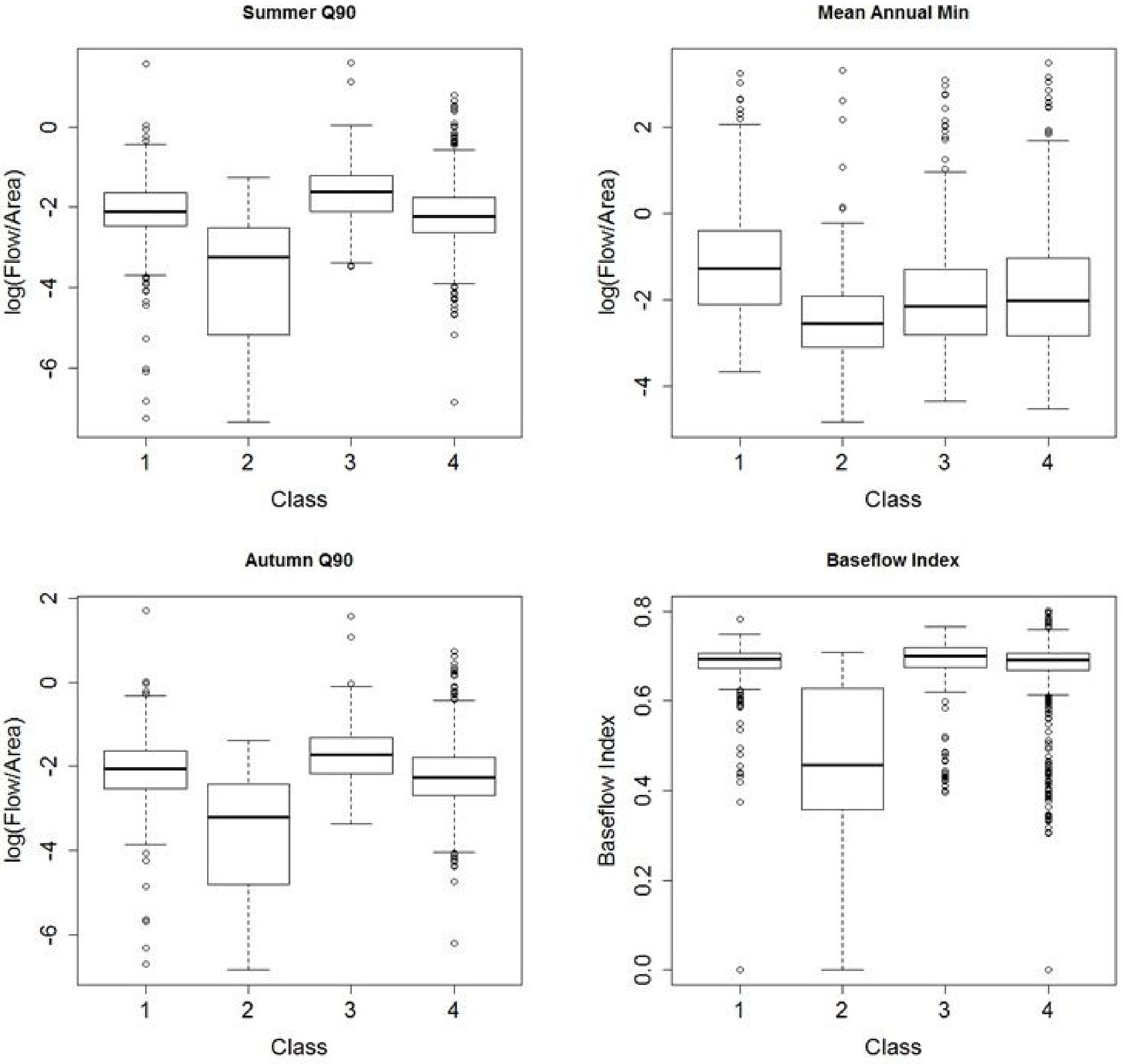


Figure 5.13. Box plots of normalized summer Q90 (low flow), normalized mean annual minimum flow, normalized autumn Q90, and base flow index, by stream class, for the 4-class system. Annual minimum, summer Q90, and autumn Q90 are normalized to catchment area.

Response to Land Cover Change Scenarios (2070LE, 2070HE)

The LANDIS land cover scenarios led to relatively modest projected changes in stream flow. The projected flow responses are mainly driven by the transition of aspen to conifer in the region, and the corresponding assumptions made in how evapotranspiration, canopy interception, and shading change due to the conifer transition (see methods section).

The 2070LE scenario gave a larger response than the 2070HE scenario (Table 5.13), because the LANDIS results for 2070LE showed greater shifts from aspen to conifers, mainly due to the modified forest management used in this scenario. For the 2070LE scenario, the response of mean annual flow was -3.6%, -1.8%, and -1.4% at the outlet of the Baptism, Knife, and Poplar rivers, respectively, with the (-) sign indicating a reduction in flow in the future. However, larger changes in mean annual flow ranging from +2% to -4.5% were predicted at the sub-catchment scale, where projected forest changes were more dramatic. The greater range of flow changes for smaller catchments is illustrated for the Baptism River and its sub-catchments in Figure 5.14.

The response of some flow metrics, such as summer low flow (Q90), to the 2070LE scenario was greater than the response of mean annual flow (Table 5.13), with changes of -14%, -7%, and -4% at the outlet of the Baptism, Knife, and Poplar rivers, respectively, and changes at the sub-catchment scale ranging from -17.5% to 4.8% (Figure 5.14). However, spring high flow (Q10) changed relatively little for the 2070LE scenario, with the major catchments decreasing about 2% (Table 5.13), and changes at the sub-catchment level on the order of ±4%.

Table 5.13. Response of mean annual stream flow, Spring Q10 (high flow), and Summer Q90 (low flow) at the outlet of the Baptism, Knife, and Poplar rivers to four land cover and climate change scenarios.

Flow Variable	Stream	2070LE[1]	2070HE[2]	GFDL[3]	Hadley[4]	GFDL + 2070LE	Hadley + 2070LE
Mean Annual	Baptism	-3.6	-1.3	28.0	-17.6	24.7	-25.7
Mean Annual	Knife	-1.7	-0.60	32.0	-19.6	22.1	-22.4
Mean Annual	Poplar	-1.4	-0.14	31.9	-28.3	31.7	-30.2
Summer Low Flow (Q90)	Baptism	-13.8	-7.1	150	-94.7	188	-99.4
Summer Low Flow (Q90)	Knife	-7.3	-5.5	138	-83.7	128	-84.8
Summer Low Flow (Q90)	Poplar	-4.4	-1.0	112	-81.4	187	-80.5
Spring High Flow (Q10)	Baptism	-2.3	-0.85	18.8	-32.8	28.7	-17.8
Spring High Flow (Q10)	Knife	-1.8	-0.60	10.1	-45.1	32.1	-19.6
Spring High Flow (Q10)	Poplar	-1.4	-0.13	17.8	-43.7	32.0	-28.4

[1] Landis 2070LE = low emissions, modified forest management;
[2] Landis 2070HE = high emissions, business-as-usual forest harvest
[3] GFDL = cooler, wetter climate scenario
[4] Hadley = warmer, drier climate scenario

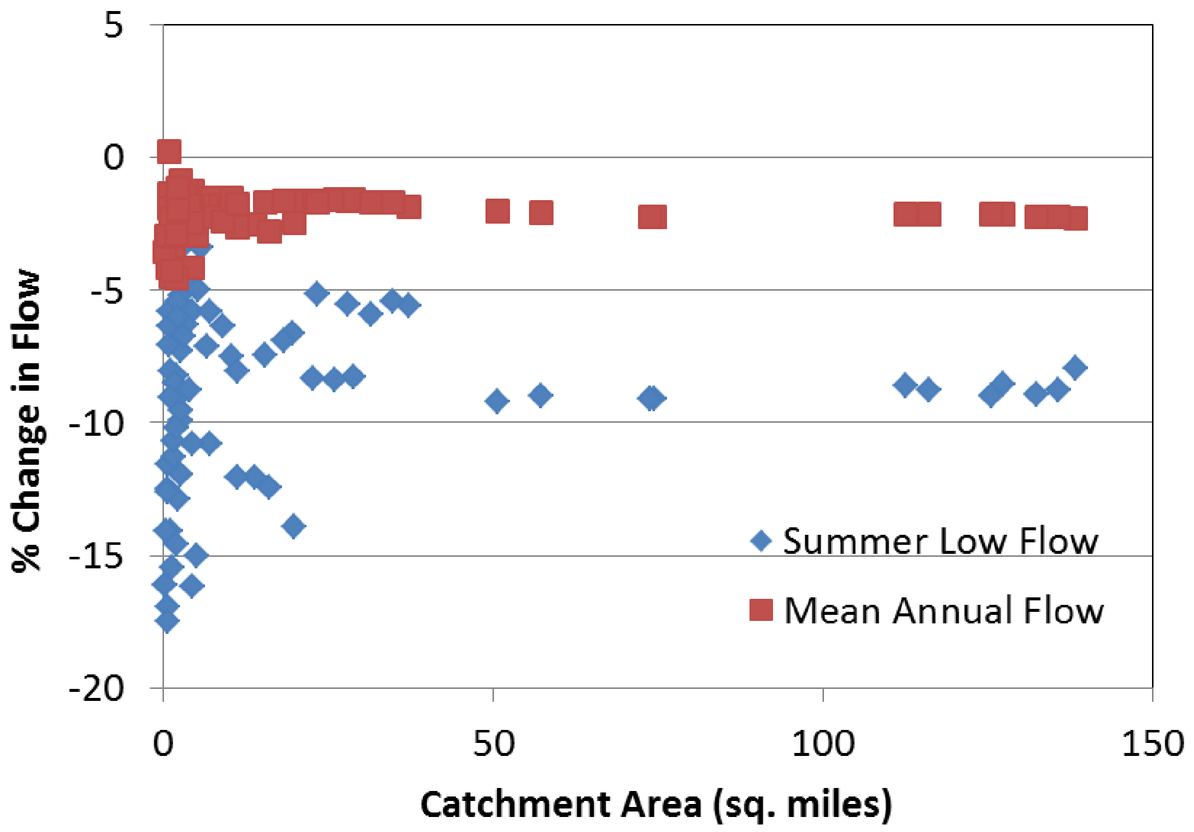


Figure 5.14. Simulated flow response to the Landis 2070LE scenario: % Change in mean annual flow and summer low flow (Q90) versus catchment area for all sub-catchments of the Baptism River.

Response to Climate Scenarios (GFDL, Hadley)

Simulations were made for the climate changes alone and for climate change in combination with the LANDIS 2070LE scenario. From Table 5.13, it is apparent that the response to climate change tends to dominate the response to the LANDIS land cover changes. To keep the complex responses as simple as possible, we focused most of the climate response interpretation on the cases with climate change only, keeping land cover fixed.

Annual and Seasonal Changes

The climate change scenarios projected substantial changes in the water budget of Minnesota's Lake Superior tributaries. Overall, precipitation increased 22-23% for the GFDL (cool, wet) climate scenario, and 8-11% for the Hadley (warm, dry) climate scenario (Table 5.14). Driven by air temperature changes, evapotranspiration increased about 15%

for the GFDL scenario and 30-44% for the Hadley scenario. Total runoff increased 29-32% for the GFDL model, and decreased 22-40% for the Hadley (warm, dry) scenario. The changes in the water budget for the Poplar River are also shown graphically in Figure 5.15.

The GFDL scenario, with increased precipitation, gives higher mean flows in almost all months (Figure 5.16), including mid-winter and mid-summer. For both present and future conditions, time shift is evident in the spring flow peak between the Knife and Poplar rivers, due to the north-south gradient in air temperature in the region. Under the GFDL scenario, the highest flows continue to be in April in the Knife and Baptism rivers and in May in the Poplar River.

The Hadley scenario produces more drastic shifts in the seasonal flow patterns, with higher winter flows and lower spring flows (Figure 5.16) in both the southern and northern portion of the region. Mean summer flows decrease, including 65-70% reduction in mean August flow due to a combination of decreased precipitation and increased ET. The mechanisms behind the shift in flow from spring to winter are explored in Figure 5.17 for the Baptism River, which summarizes changes in rainfall and snowmelt for the Hadley scenario. Increases in winter flow are due to a combination of increased rainfall, increased snowfall, and increased snowmelt in December, January, and February.

Table 5.14. Summary of projected changes in the annual water budget for the Baptism, Knife, and Poplar rivers.

River Name	Water Budget	% Change, GFDL	% Change, Hadley
Baptism	Precipitation	+22.1	+8.4
Baptism	Evapotranspiration	+15.1	+29.5
Baptism	Runoff	+28.7	-21.7
Knife	Precipitation	+23.1	+11.2
Knife	Evapotranspiration	+15.1	+35.4
Knife	Runoff	+32.1	-24.4
Poplar	Precipitation	+23.7	+8.9
Poplar	Evapotranspiration	+15.4	+44.0
Poplar	Runoff	+32.0	-39.6

Projected Changes in Flow Metrics for the Climate Scenarios

Table 5.8 summarizes the flow metrics that were calculated for the HSPF catchments (Baptism, Knife, Poplar) for present and future conditions. Results for spring high flow (Q10) and summer low flow (Q90) are described here. Compared to the land cover scenarios, the climate change scenarios produced much more substantial changes in the stream flow metrics, which follow seasonal patterns similar to the monthly mean flows.

The relatively wet and cool GFDL scenario resulted in increased summer Q90 of 112% to 150% at the river outlets. At the sub-catchment scale, summer Q90 flows increased up to 200% (excluding outliers), with some stream segments with very small flows in current conditions increasing substantially. In contrast, the warm/dry Hadley scenario resulted in drastic reductions of 81% to 95% in summer Q90 (Table 5.13), implying the possibility of crossing ecological low flow thresholds in many smaller streams. For example, summer low flows often represent a habitat "bottleneck" for coldwater species, in terms of total suitable wetted aquatic habitat (see Module 7).

Projected changes in spring high flows (Q10) were less drastic compared to summer low flows. At the major catchment outlets, spring high flow increased 10-19% under the GFDL scenario and decreased 33-45% under the Hadley scenario (Table 5.13). At the sub-catchment scale, Q10 increased up to 45% under the GFDL scenario and decreased up to 54% under the Hadley scenario (not shown). The decrease in spring flows in the Hadley scenario is due to an overall shift in snowmelt to the winter months, discussed in the previous section.

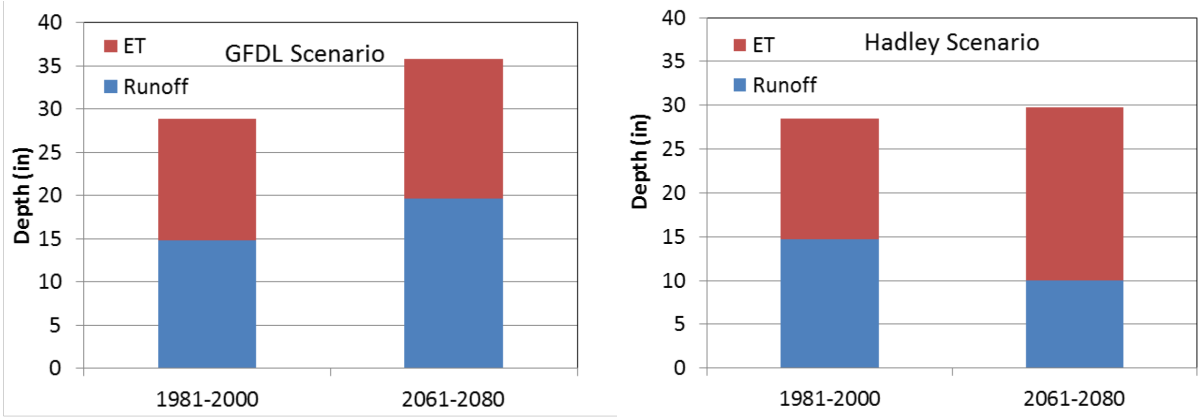


Figure 5.15. Changes in the water budget for the Poplar River from the historical period (1981-2000) to the future period (2061-2080). The total height of each column represents the annual precipitation depth, in inches. Stream runoff is stream flow per unit area, summed over a year.

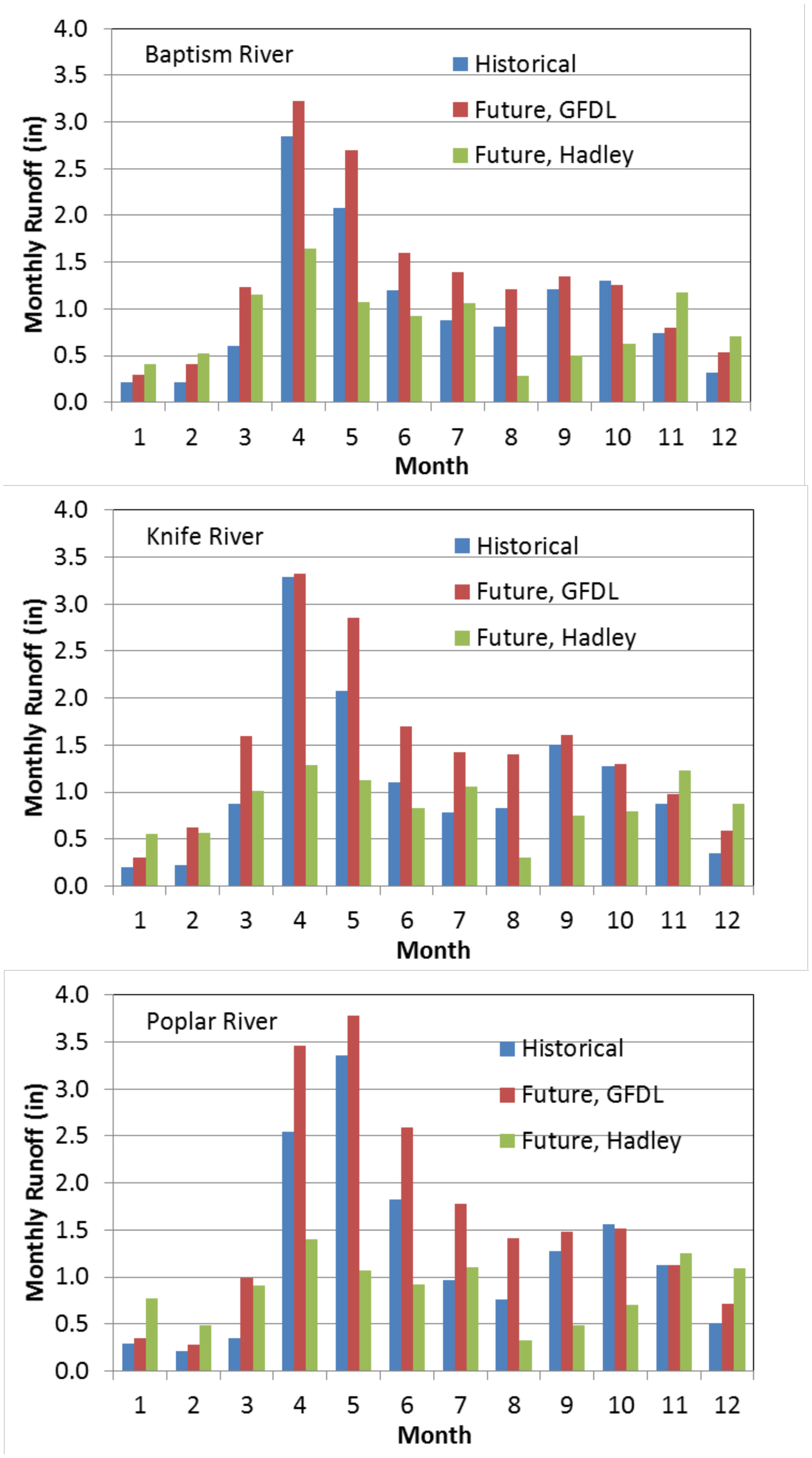


Figure 5.16. Simulated historical and future monthly mean flows in the Baptism, Knife and Poplar rivers, for historical conditions and future conditions under the cooler, wetter (GFDL) climate scenario.

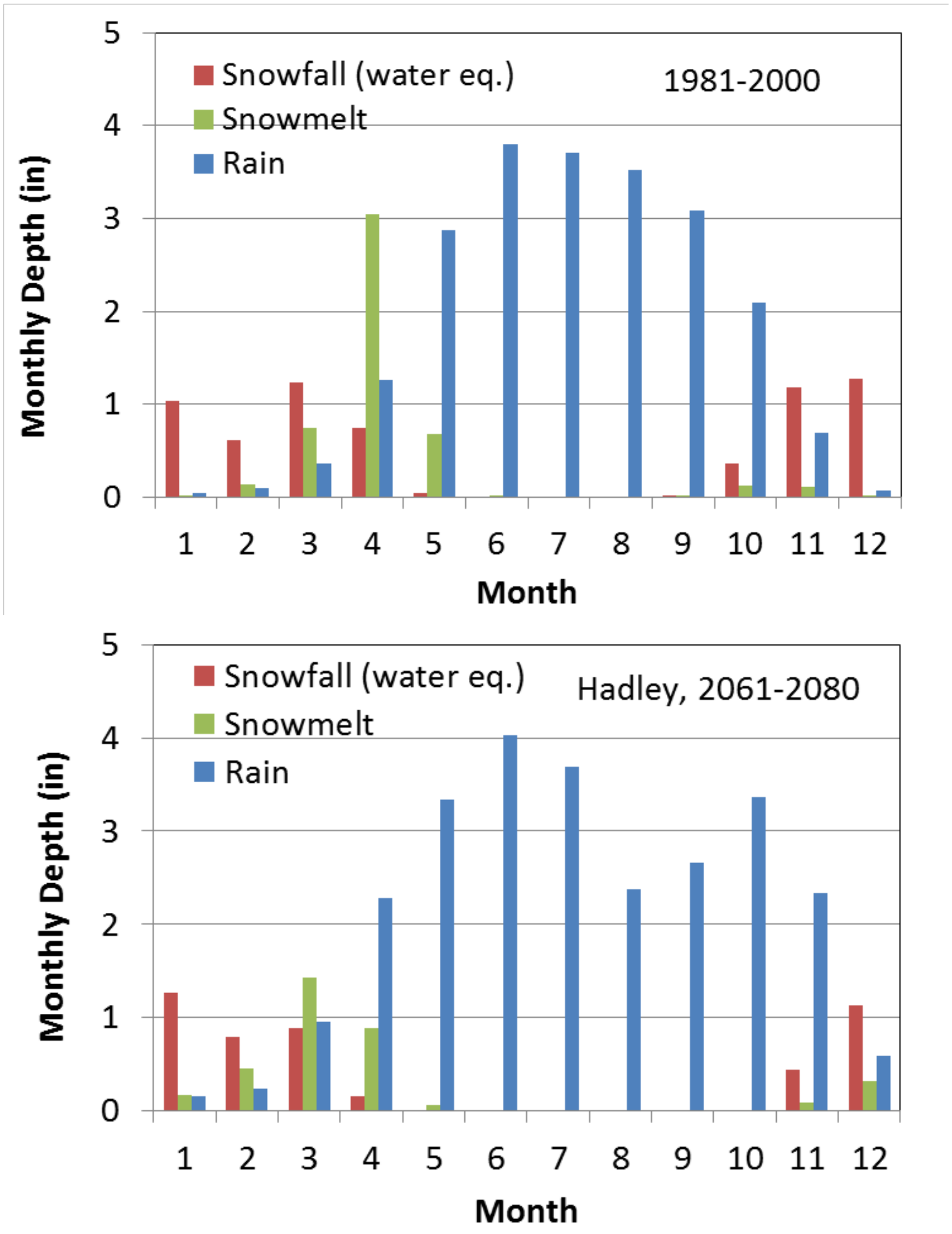


Figure 5.17. Monthly summaries of monthly snowfall, rainfall, and snowmelt for the Baptism River, under historical conditions and future conditions for the warmer, drier (Hadley) climate scenario.

Changes in Annual and Seasonal Maximum Flows

The HSPF time series for the Knife River was analyzed to characterize the timing and conditions for seasonal and annual maximum flows, where maximum flows are defined as the highest daily flow for each year (or season) in the 20-year flow simulation record.

Questions to address in this analysis included:

- What conditions (rainfall vs. snowmelt) lead to seasonal and annual maximum flows?
- How will seasonal and annual maximum flows change in the future, based on the climate scenarios?

The analysis included the HSPF simulated daily flows for the Knife River, the precipitation data used as input, and the simulated values of daily snowmelt. Climate data for both historical (1981-2000) and future (2061-2080) conditions were taken from the GCM model outputs (GFDL and Hadley). Maximum flows were plotted against 1) the precipitation and snowmelt occurring on the day of the maximum and 2) the precipitation and snowmelt occurring on the day of the maximum plus varying numbers of antecedent days. In general, the best predictor of daily maximum flow was the sum of the precipitation and snowmelt occurring on the day of the maximum.

Figure 5.18 gives examples of relationships found between maximum flows, precipitation, and snowmelt for present and future conditions under the cooler, wetter (GFDL) climate scenario, for the Knife River. Table 5.15 summarizes the mean contributions of precipitation and snowmelt to flow maxima determined from these analyses. Note the significant change in winter maximum flows, with more contribution of snowmelt in the future. Also note that for historical conditions, the GFDL and Hadley climate data give similar, but not identical results, due to imperfect climate model simulation. Based on the HSPF simulations, typical spring maximum flows are a combination of snowmelt and rainfall, with rainfall contributing about 70% of the flow for historical conditions, and 95% for future conditions (both future scenarios).

The distribution of annual maximum flows changes under both climate scenarios. Under the cooler, wetter (GFDL) climate scenario, both annual (Figure 5.19) and spring (Figure 5.20) maximum flows increase markedly. Under the warmer, drier (Hadley) climate scenario, there is an increase in the number of years in which maximum flow would be expected to be less than 500 cfs. The seasonal distribution of the month of the annual maximum flow also changes substantially under the Hadley scenario (Figure 5.21), with more annual maxima occurring in the summer and autumn in the future. The median annual maximum flow is projected to increase 54% under the cooler, wetter (GFDL) climate scenario and 21% under the warmer, drier (Hadley) scenario.

The median time of the spring maximum flow was predicted to shift under the GFDL and Hadley scenarios, but in opposite directions. Under the wetter GFDL scenario, the median date of spring high flow shifted from April 20 to April 7 by the 2061-2080 timeframe.

Under the relatively dry, warm Hadley scenario, the median date of spring high flow shifted from April 13 to April 21 by the 2061-2080 timeframe. Again, because the climate models do not perfectly simulate historical conditions, the change from present to future should be emphasized. Since both climate scenarios predict reduced contribution of snowmelt to spring high flows, the opposite shifts in high flow timing are likely due to the differing shifts in seasonal precipitation patterns, with March and April experiencing greater increases in precipitation for the GFDL scenario compared to the Hadley scenario (Figure 5.22).

Table 5.15. Summary of rainfall and snowmelt contribution to maximum daily flows in the Knife River both seasonally and annually, where maximum flow is the highest daily average flow in each year over the 20-year record. The values given are the mean values for the 20-year record. For winter maximum flows, including antecedent moisture (precipitation and snowmelt in days prior to the max flow) improved the prediction of flow magnitude.

GFDL Scenario

Season	Historical (1981-2000) Rainfall (inches)	Historical (1981-2000) Snowmelt (inches)	Future (2061-2080) Rainfall (inches)	Future (2061-2080) Snowmelt (inches)	Number of Antecedent Days
Winter	0.52	0.12	0.58	0.43	5
Spring	0.67	0.28	1.07	0.07	0
Summer	1.00	0.0	1.62	0.0	0
Autumn	1.16	0.01	1.33	0.0	0
Annual	1.29	0.18	1.91	0.03	0

Hadley Scenario

Season	Historical (1981-2000) Rainfall (inches)	Historical (1981-2000) Snowmelt (inches)	Future (2061-2080) Rainfall (inches)	Future (2061-2080) Snowmelt (inches)	Number of Antecedent Days
Winter	0.42	0.18	1.13	0.23	5
Spring	1.05	0.28	0.86	0.05	0
Summer	1.05	0.0	0.92	0.0	0
Autumn	0.90	0.0	1.00	0.0	0
Annual	1.12	0.2	1.60	0.01	0

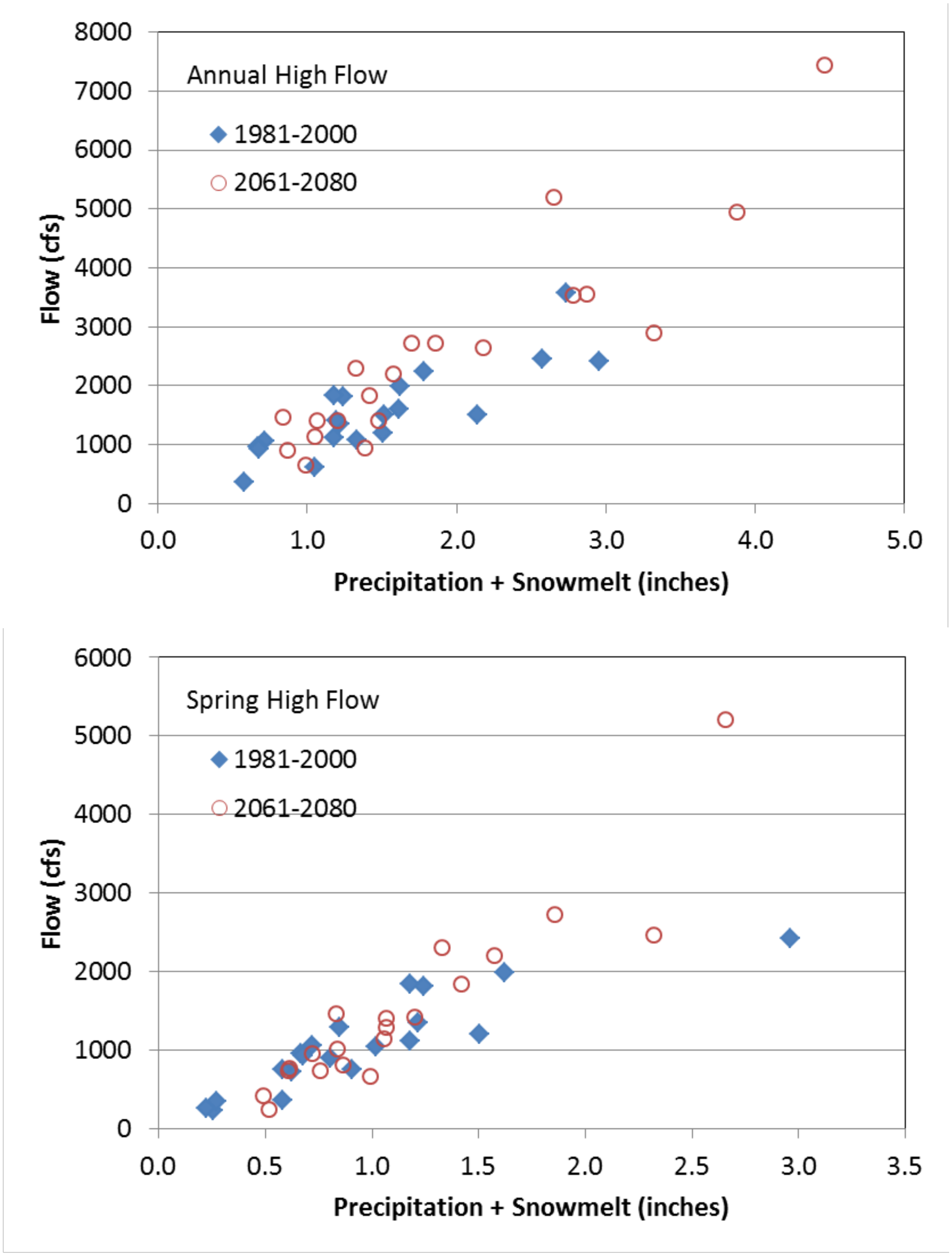


Figure 5.18. Relationships of simulated annual high flow and spring high flow to the preceding total precipitation and snowmelt, for the Knife River and the cooler, wetter (GFDL) climate scenario.

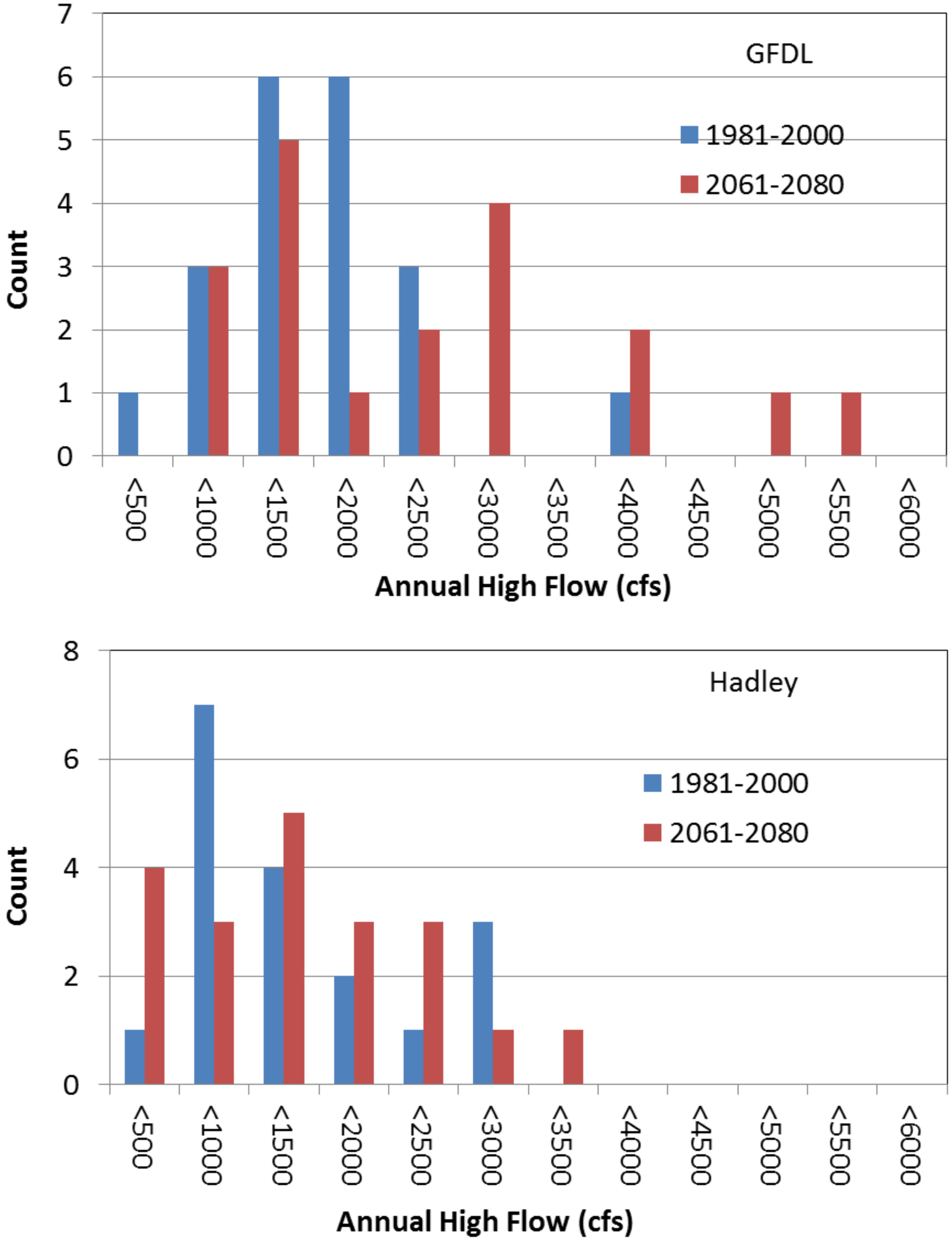


Figure 5.19. Histogram of simulated annual high flows for historical (1981-2000) and future (2061-2070) climate, for the Knife River under the cooler, wetter (GFDL) and warmer, drier (Hadley) climate scenarios. Note that for historical conditions, the GFDL and Hadley climate data give somewhat different distributions of annual high flow.

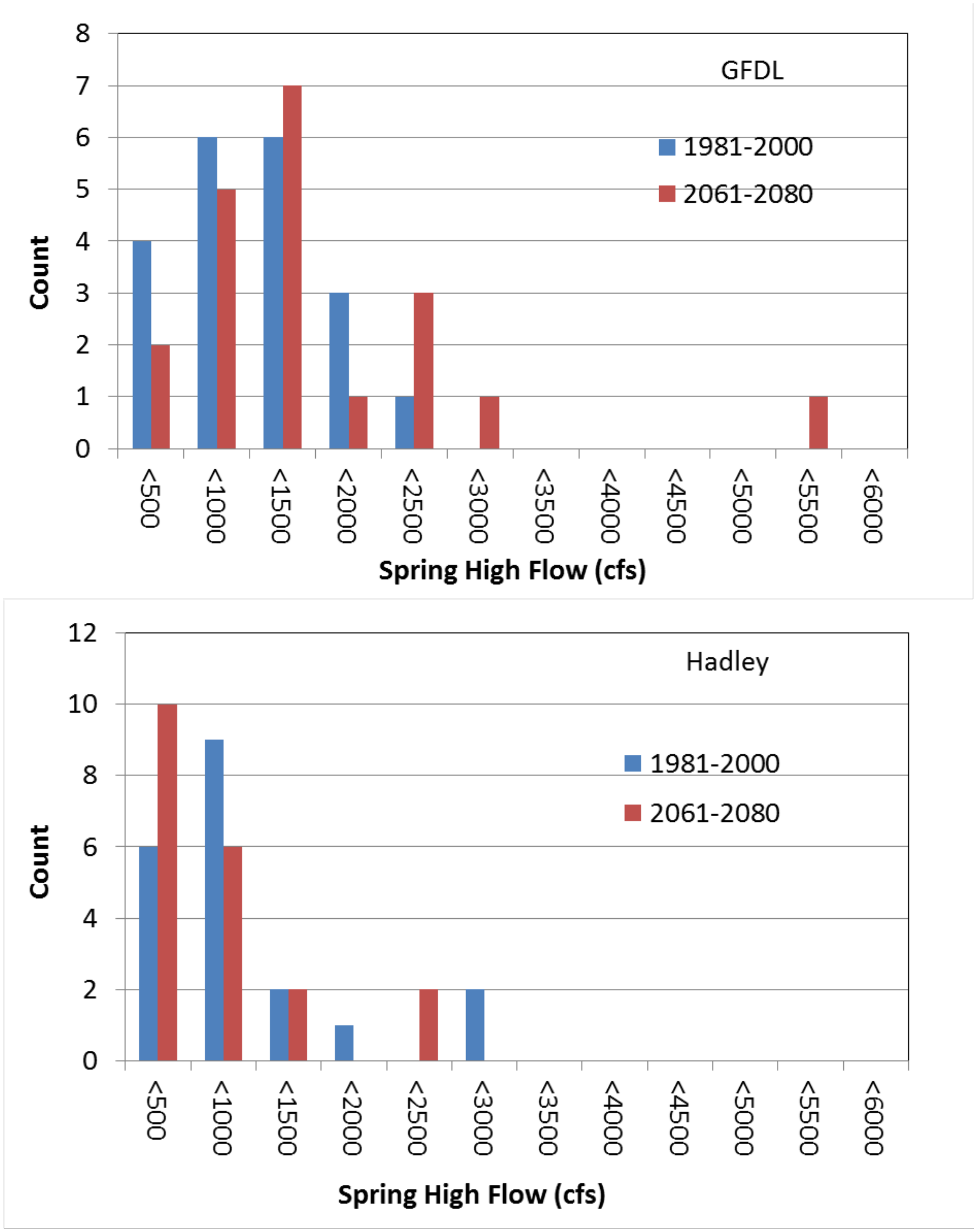


Figure 5.20. Histogram of simulated spring high flows for historical (1981-2000) and future (2061-2070) climate, for the Knife River under the cooler, wetter (GFDL) and warmer, drier (Hadley) climate scenarios.

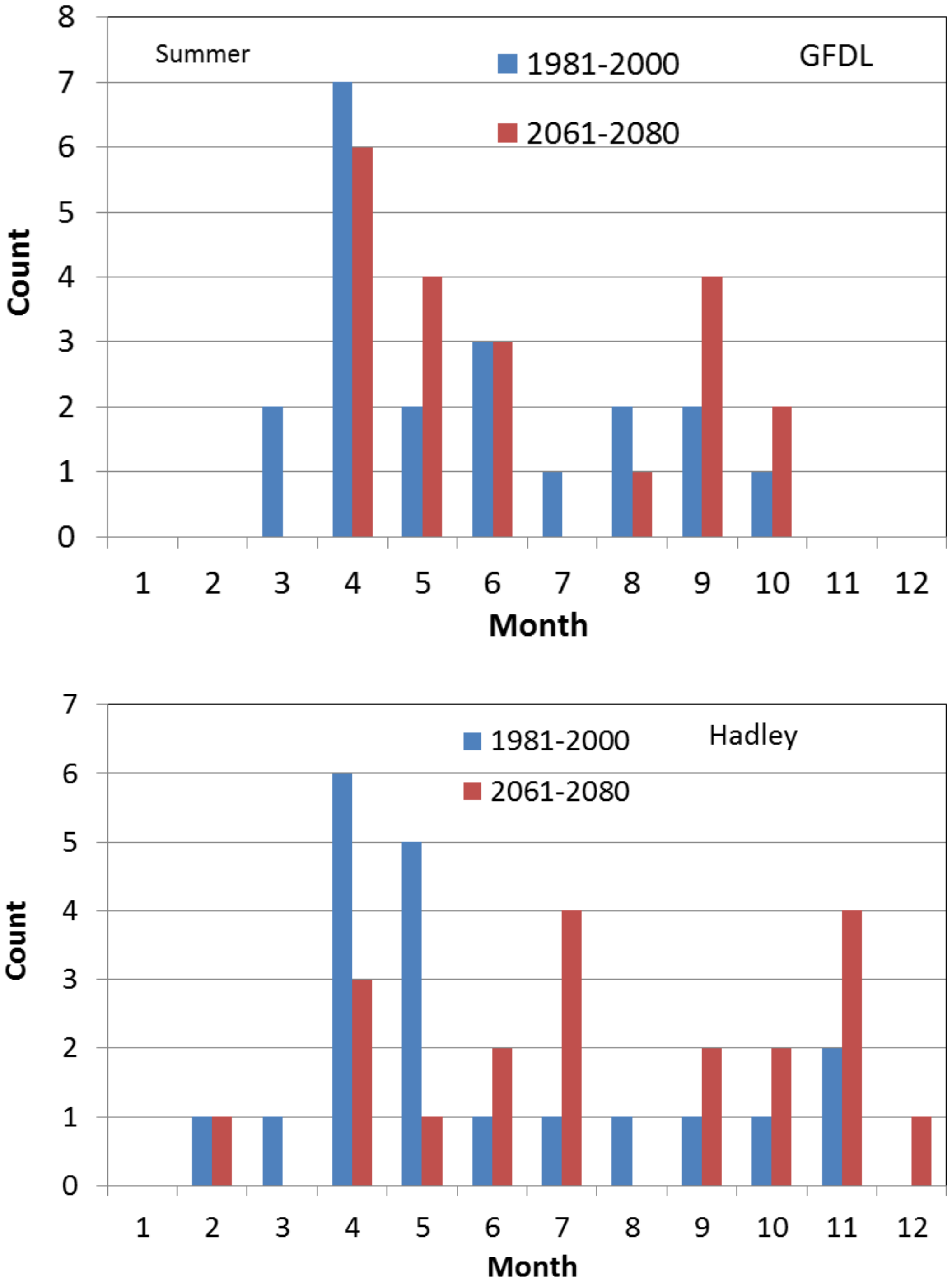


Figure 5.21. Histogram of the month in which annual high flows occurred for historical (1981-2000) and future (2061-2080) climate, for the Knife River under the cooler, wetter (GFDL) and warmer, drier (Hadley) climate scenarios.

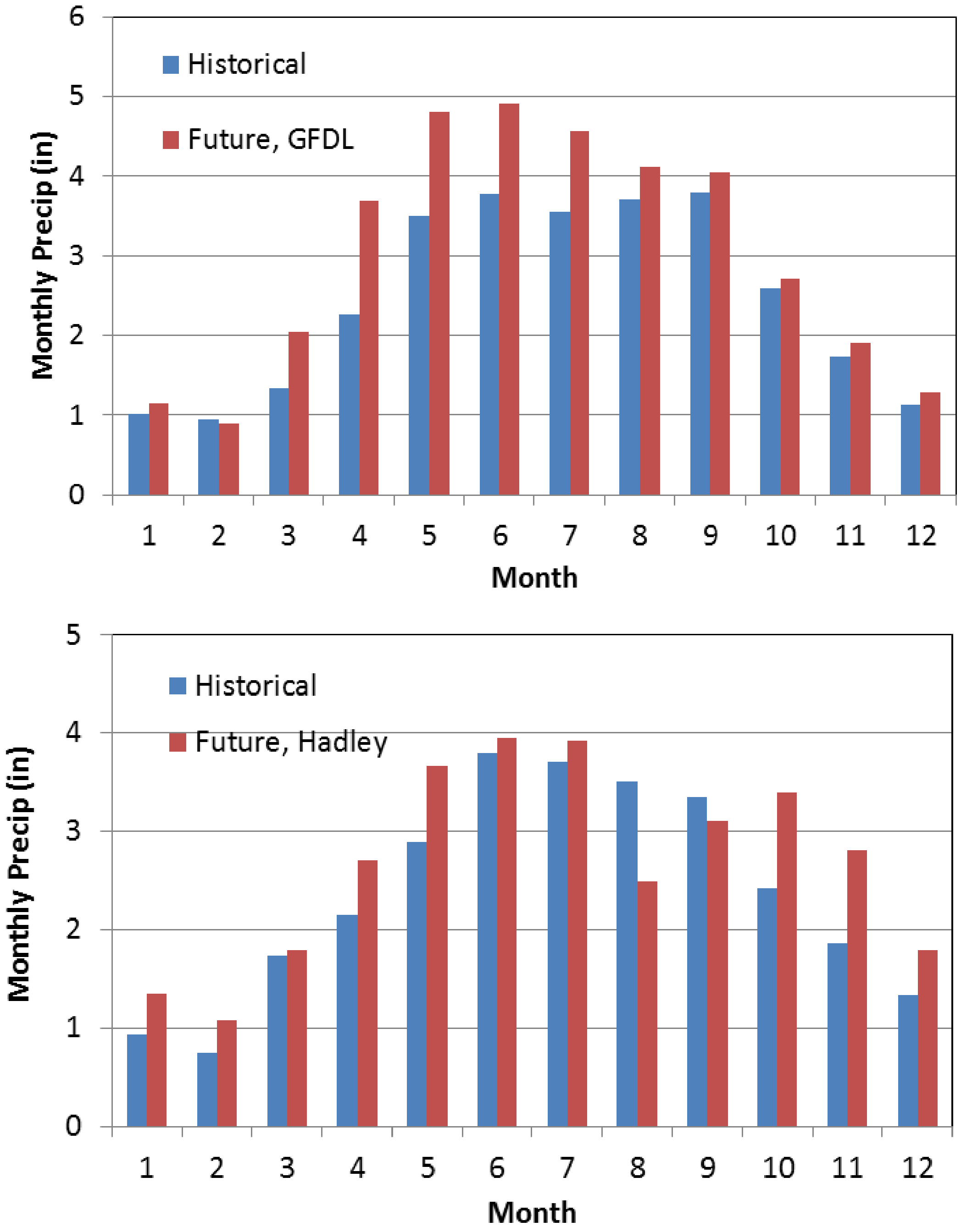


Figure 5.22. Present and future distributions of monthly average precipitation for the cooler, wetter (GFDL) and warmer, drier (Hadley) climate scenarios.

Regional Extrapolation of HSPF Model Results

The HSPF models give detailed information on flow metrics for the sub-catchments in the Baptism, Knife, and Poplar river watersheds. The last step of the hydrologic analysis was then to extrapolate, where possible, the flow metric results to the rest of the study region. The original plan was to use the stream classification as a basis for this extrapolation, however, the stream classes were not found to give sufficiently distinct flow metrics. Figure 5.23 gives an example of the response of flow metrics to the climate scenarios, summarized by stream class. As a result, other relationships were sought to relate modeled flow metrics to land cover and soils parameters. Emphasis was placed on the spring high flow and summer low flow metrics, and several cases were identified:

1) For the LANDIS 2070LE scenario, the response of summer low flow was closely tied to the change in conifer fraction within each sub-catchment (Figure 5.24). Spring high flow changed relatively little in the LANDIS scenarios (<5%).

2) For the climate change scenarios, the response of summer low flow (Q90) was tied to hydrologic storage (wetland and lake coverage fraction) within each sub-catchment. However, most of the variability was driven by the sub-catchments of the Poplar, where changes in lake storage caused changes in summer low flow. Interestingly, lake storage seems to be susceptible to increases in ET, with average summer lake levels dropping about 4” under the warm, dry (Hadley) climate scenario, leading to decreases in lake outlet flow.

3) For the cooler, wetter (GFDL) climate scenario, spring high flow was tied to hydrologic storage, while for the warmer, drier (Hadley) climate scenario, the change in spring high flow was relatively constant across the modeled watersheds. Increasing precipitation in the GFDL scenario appears to saturate hydrologic storage, so that there is less difference in spring high flow between catchments with more or less storage.

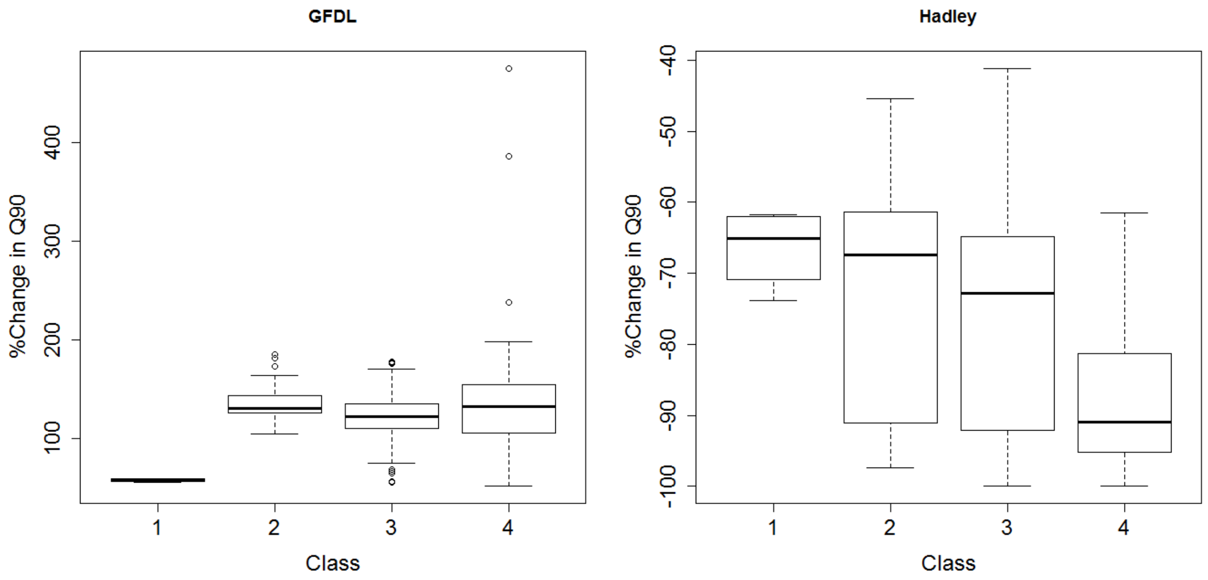


Figure 5.23. Change in summer low flow, by stream class, for the HSPF catchments in response to the cooler, wetter (GFDL) and warmer, drier (Hadley) climate scenarios.

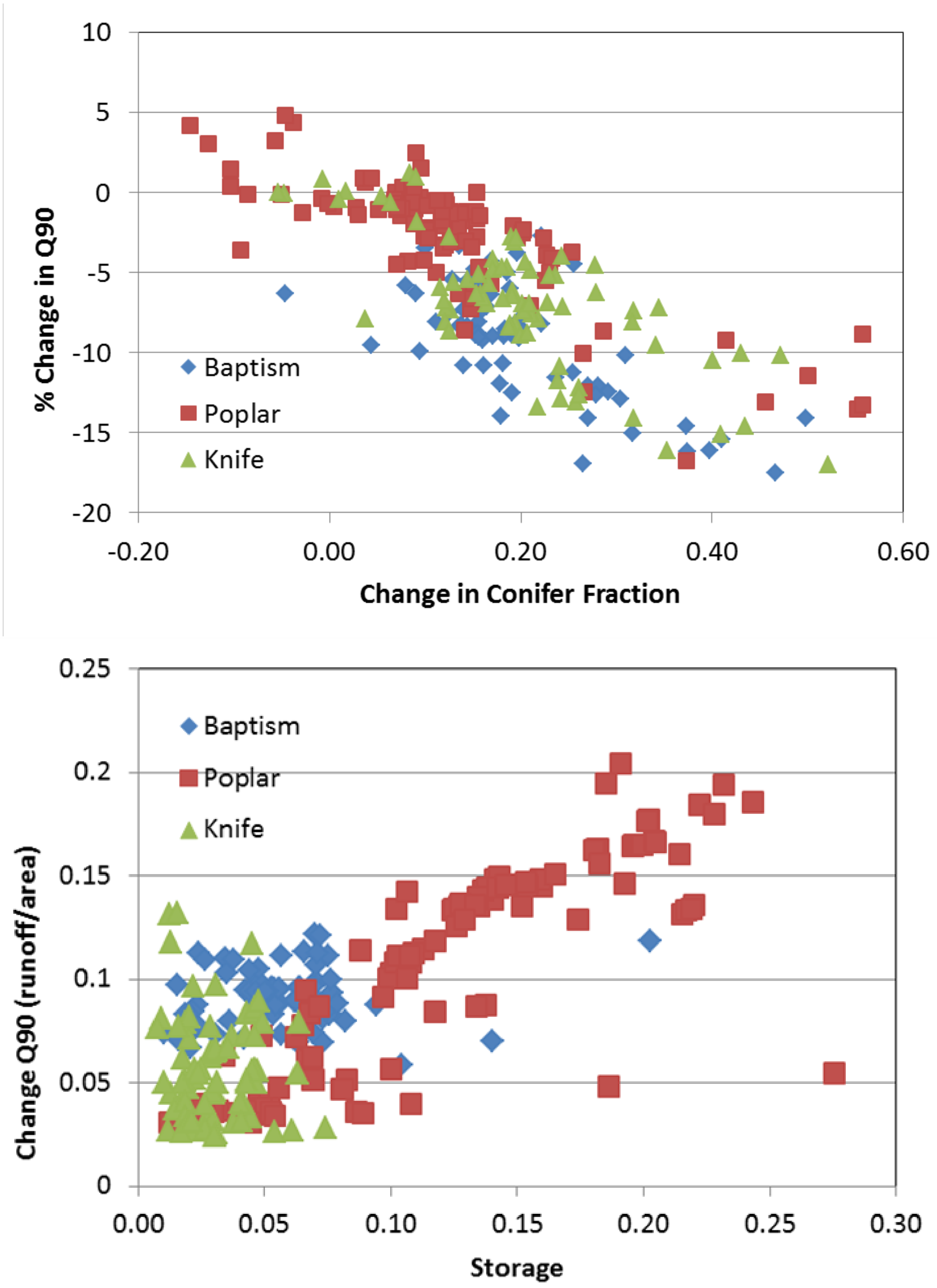


Figure 5.24. Simulated change in summer low flow vs. change in conifer fraction, for the low emissions, modified forest management (LANDIS 2070LE) scenario (upper panel) and vs. catchment storage for the cooler, wetter (GFDL) scenario (lower panel). Both panels give data for the Baptism, Poplar, and Knife rivers.

Current Climate and Flow Trends

Regional Air Temperature Trends

Mean annual air temperatures in the region are trending upwards from 1950 (Figure 5.25, Table 5.16), with statistically significant trends of 0.030 °F to 0.044 °F per year. Shorter terms trends, e.g., for 1980, are not statistically significant (Table 5.16), due to high year-year variability and decadal-scale oscillations. For the same period, winter air temperatures also had a significant upward trend of 0.037 to 0.05 °F per year.

Comparing air temperature trends in the historical and GCM projections, both the GFDL and Hadley GCMs project a continuation of moderate, but persistent, increasing trends in mean annual air temperature (Figure 5.26) of 0.07 °F/year and 0.14°F/year for the GFDL and Hadley models respectively. Historical and projected trends in winter air temperatures are slightly higher, with increasing trends of 0.09 °F/year and 0.17 °F/year for the GFDL and Hadley models respectively. The results shown for Two Harbors are typical for the region.

Regional Precipitation Trends

For the period of record (1900-2015), mean annual precipitation showed positive, statistically significant trends at the Duluth and Two Harbors stations, but only a weak trend at Grand Marais (Table 5.16, Figure 5.27). Shorter term, increasing trends may exist after 1980, but are difficult to quantify because of oscillations in the record. However, winter precipitation had a statistically significant upward trend over both 1900-2015 and 1980-2015 (Table 5.16, Figure 5.28). Summer precipitation has no significant trends (Table 5.16, Figure 5.29).

Comparing precipitation trends in the historical and GCM projections, the cooler, wetter (GFDL) GCM projects a continuation of moderate, but persistent, increasing trends in annual and summer precipitation, whereas the warmer, drier (Hadley) model shows annual precipitation to nearly level off at current levels, and summer precipitation to decrease by about 3 inches towards the end of the century (Figure 5.30). Both GCMs follow the current, increasing trends of winter precipitation to mid-century, but the Hadley model, with warmer air temperatures, projects an increasing trend towards the end of the century.

Regional Flow Trends

There are very few continuous flow records in the region that are long enough for trend analysis. In a previous study (Johnson et al. 2013), no statistically significant trends were found in the flow records of the Knife, Baptism, and Pigeon rivers. However, plotting mean annual flow and mean annual precipitation with 10 year moving averages show stream flow responds quite dramatically to decadal scale fluctuations in precipitation. This is very apparent in the relatively long record of the Pigeon River and the Grand Portage weather station (Figure 5.31).

Table 5.16. Tau and p-values from the Mann-Kendall trend test for annual and seasonal precipitation and air temperature over the period 1980-2015 in Duluth, Two Harbors, and Grand Marais. Highlighted cells indicate statistically significant trends for a 95% confidence interval.

Variable	**Period**	**Duluth**	**Two Harbors**	**Grand Marais**
Annual Precipitation	1980-2015	0.043 (0.72)	-0.022 (0.85)	-0.035 (0.77)
Annual Precipitation	1900-2015	0.244 (<0.001)	0.237 (<0.001)	0.066 (0.29)
Winter Precipitation	1980-2015	0.244 (0.037)	0.234 (0.047)	0.218 (0.064)
Winter Precipitation	1900-2015	0.136 (0.031)	0.229 (<0.001)	-0.070 (0.27)
Spring Precipitation	1980-2015	0.14 (0.23)	0.20 (0.088)	0.191 (0.10)
Summer Precipitation	1980-2015	0.0016 (1)	-0.141 (0.23)	-0.125 (0.288)
Autumn Precipitation	1980-2015	-0.194 (0.099)	-0.219 (0.062)	-0.194 (0.099)
Annual Air Temp	1980-2015	0.125 (0.34)	0.0108 (0.95)	0.104 (0.42)
Annual Air Temp	1950-2015	0.293 (0.002)	0.171 (0.063)	0.207 (0.025)
Winter Air Temp	1980-2015	0.032 (0.80)	0.038 (0.77)	-0.075 (0.54)
Winter Air Temp	1950-2015	0.158 (0.068)	0.177 (0.039)	0.115 (0.182)
Spring Air Temp	1980-2015	-0.154 (0.22)	-0.237 (0.054)	-0.106 (0.39)
Summer Air Temp	1980-2015	0.225 (0.056)	0.043 (0.72)	0.172 (0.14)
Autumn Air Temp	1980-2015	0.338 (0.005)	0.218 (0.073)	0.188 (0.123)

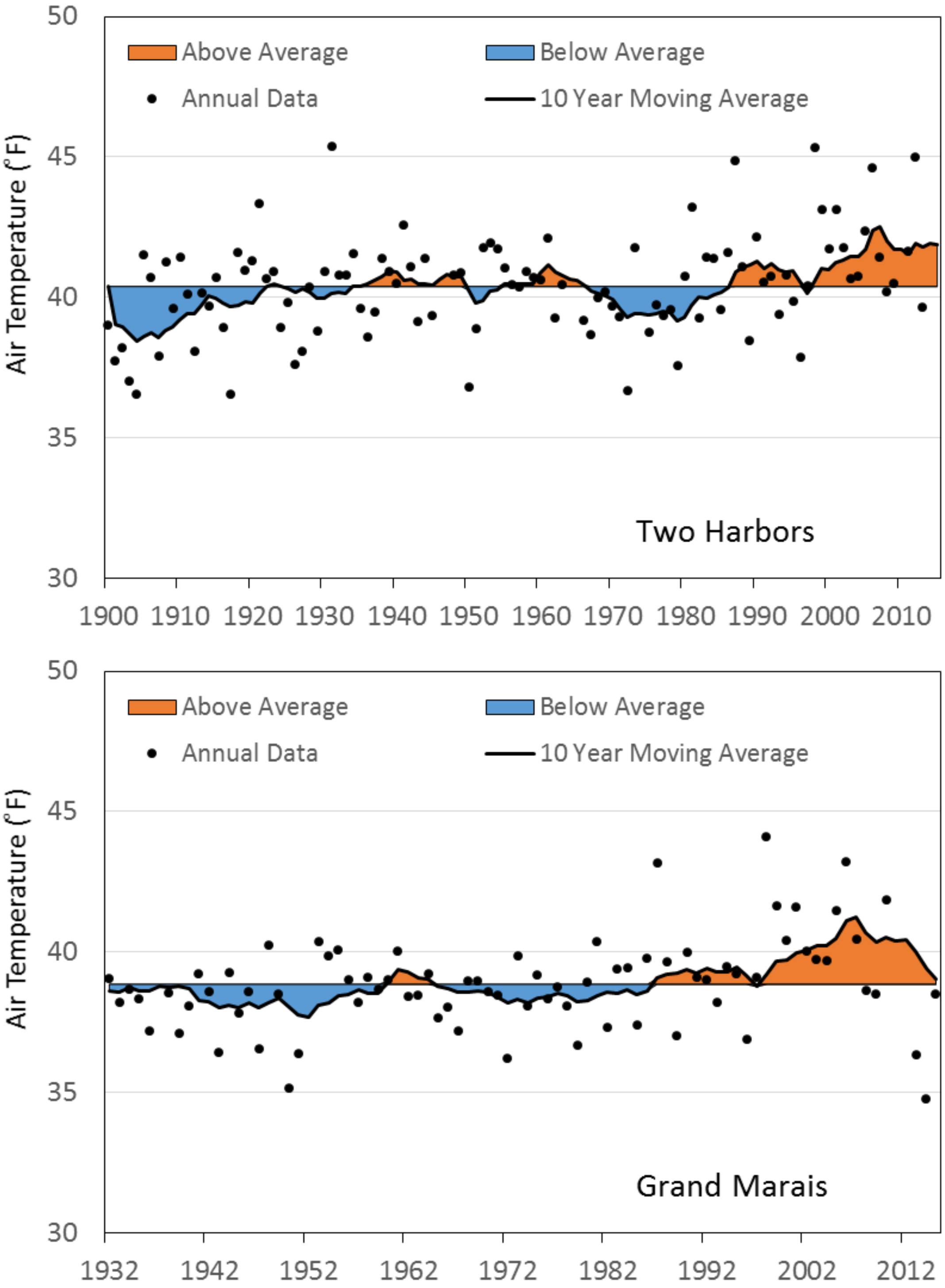


Figure 5.25. Time series of mean annual air temperature at Two Harbors and Grand Marais, with 10 year moving average curves. The coloration indicates sections of the record that are above and below the mean over the entire record. Two Harbors, MN and Grand Marais, MN are close to the Knife and Poplar rivers, respectively.

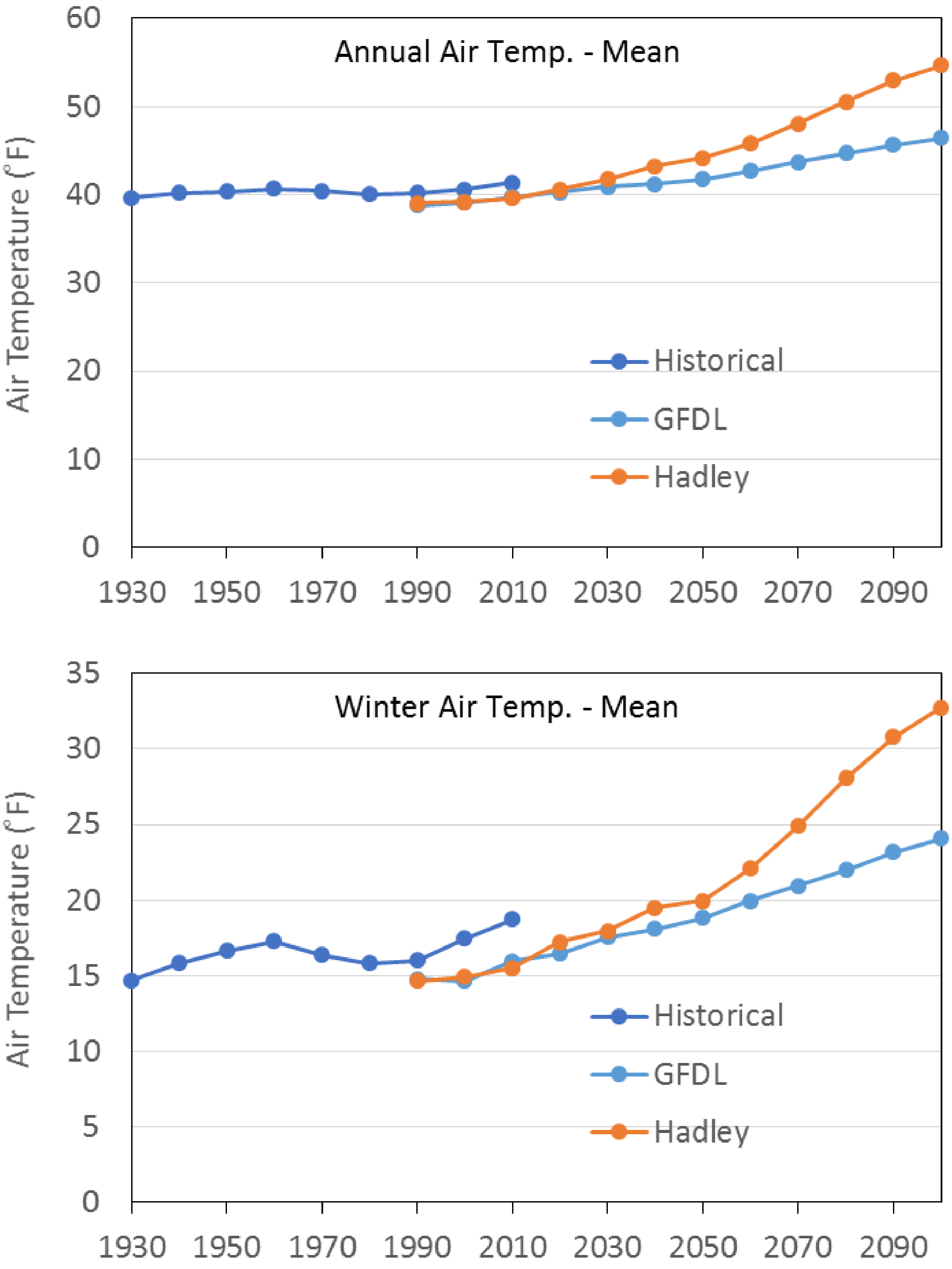


Figure 5.26. Mean annual air temperature and mean winter air temperature for historical data and future projections at Two Harbors, MN. Each point is a 30 year mean, calculated at 10 year increments. The offset between the historical and GCM values is due to model bias.

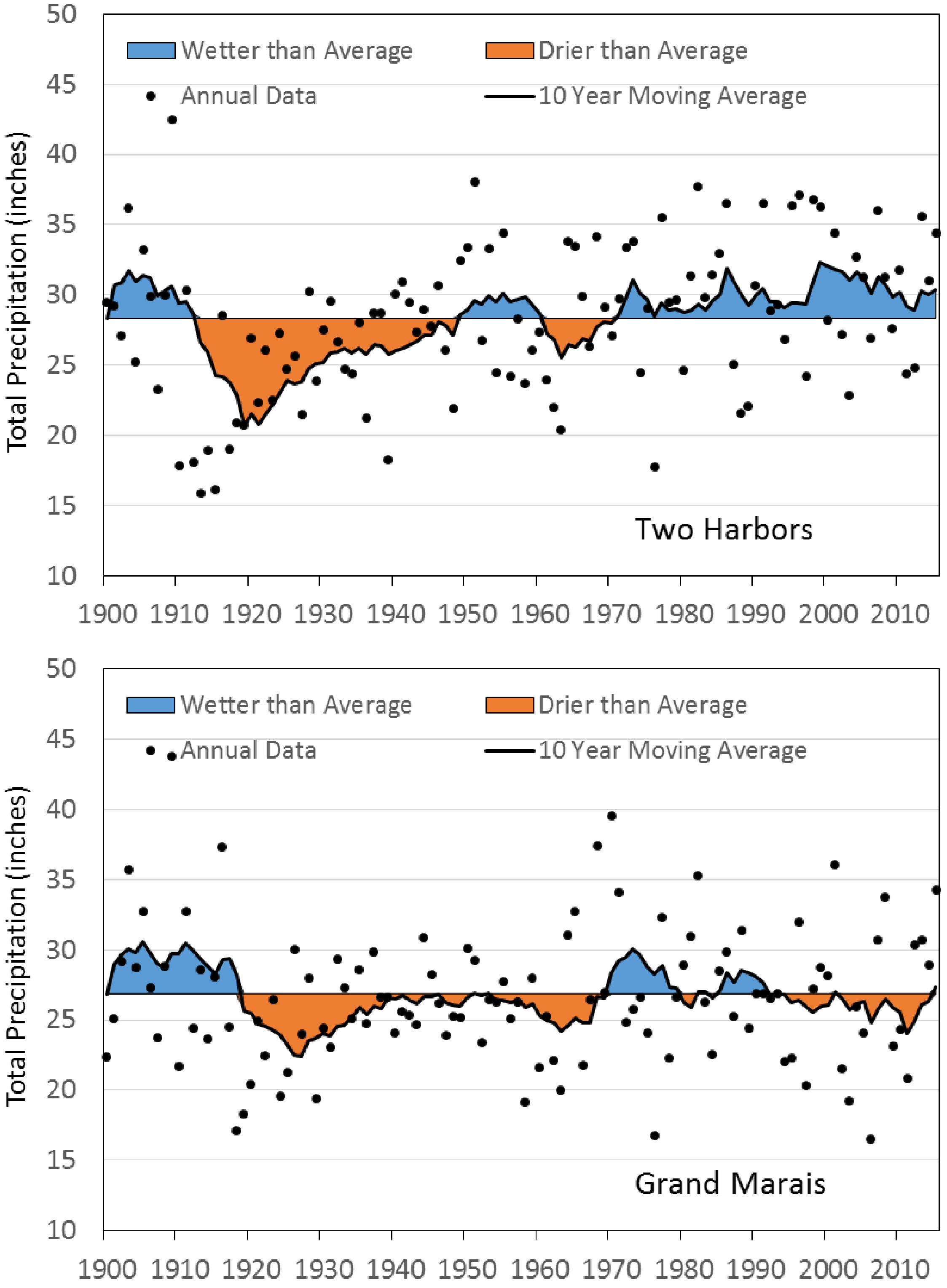


Figure 5.27. Time series of total annual precipitation at Two Harbors and Grand Marais, with 10 year moving average curves. The coloration indicates sections of the record that are above and below the mean over the entire record.

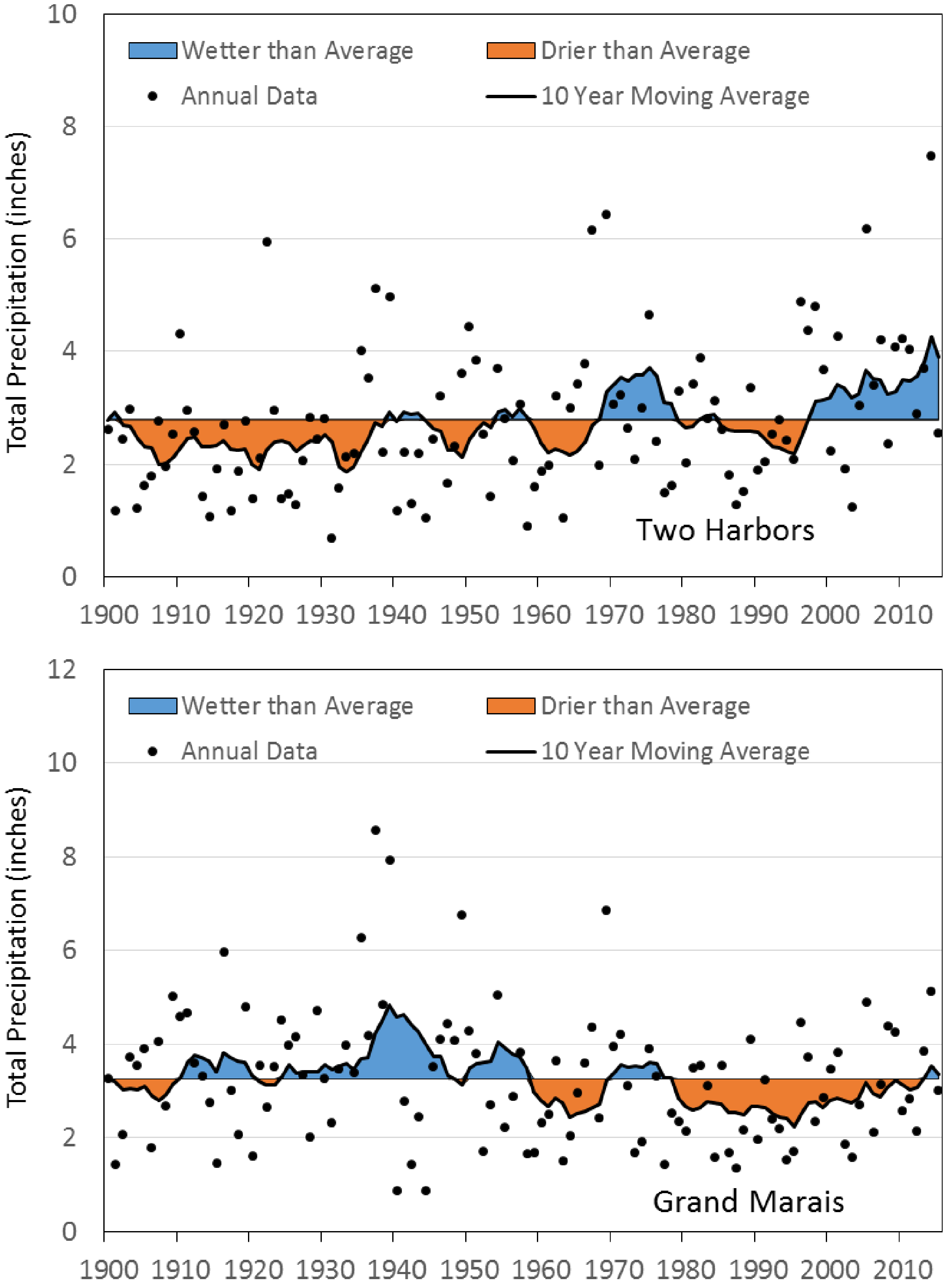


Figure 5.28. Time series of total winter precipitation (December, January, February) at Two Harbors and Grand Marais, with 10 year moving average curves. The coloration indicates sections of the record that are above and below the mean over the entire record.

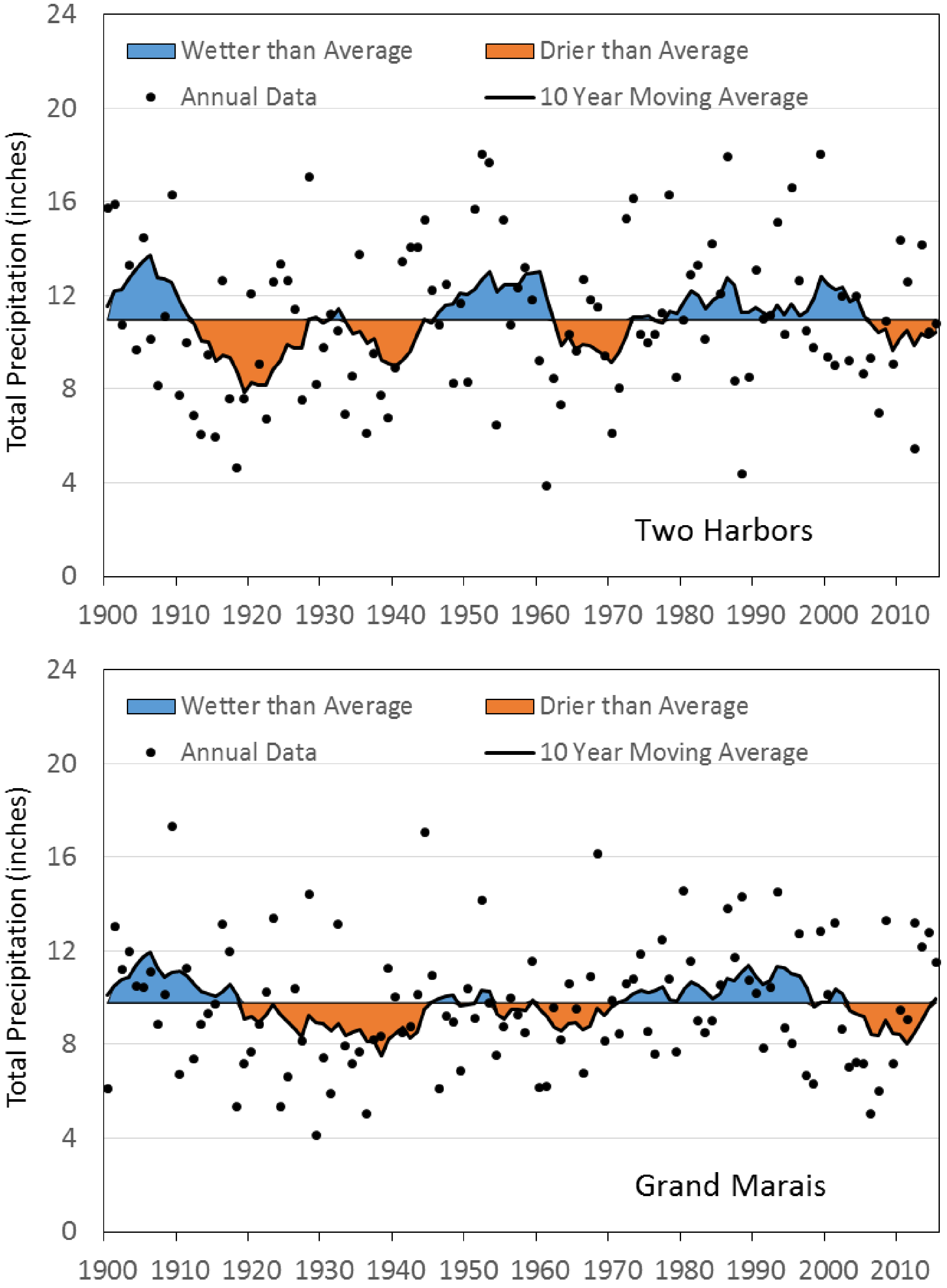


Figure 5.29. Time series of total summer precipitation (June, July, August) at Two Harbors and Grand Marais, with 10 year moving average curves. The coloration indicates sections of the record that are above and below the mean over the entire record.

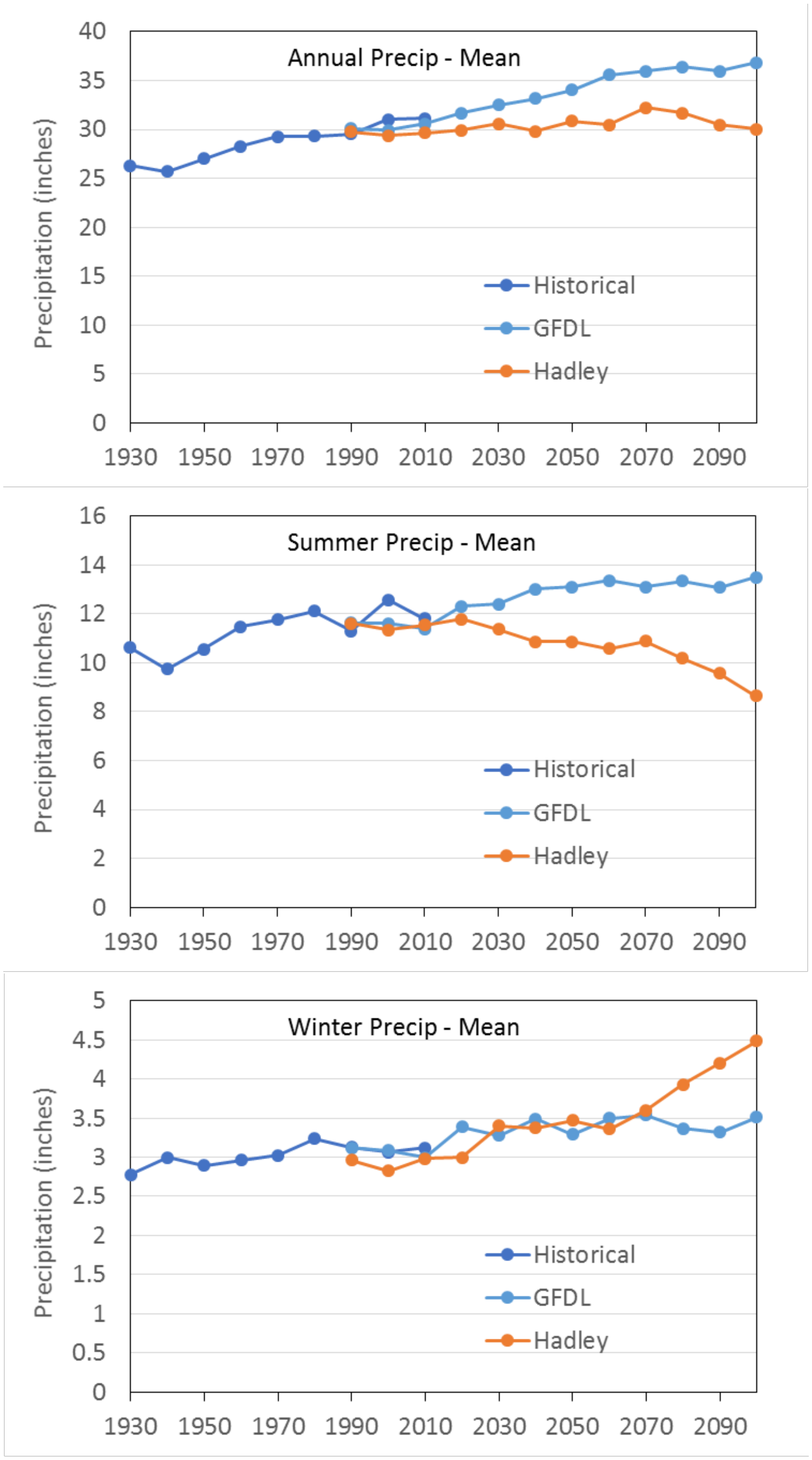


Figure 5.30. Mean annual, mean summer, and mean winter precipitation for historical data and future projections at Two Harbors, MN, near the Knife River. Each point is a 30-year mean, calculated at 10-year increments.

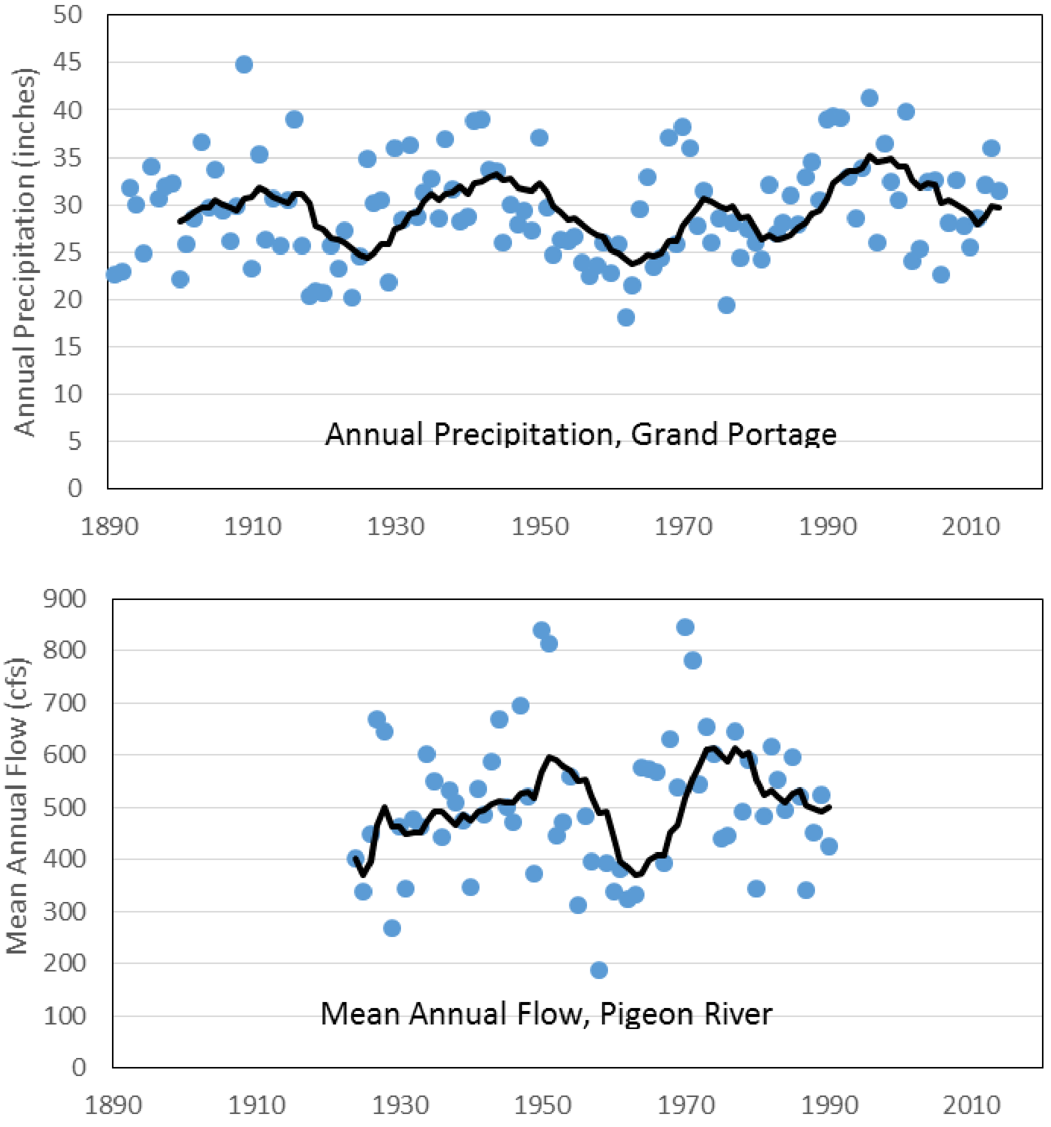


Figure 5.31. Time series of total annual precipitation at Grand Portage and mean annual flow in the Pigeon River, with 10 year moving average curves. Flow data in the Pigeon are given only for years with complete records.

Conclusions

What have we learned?

1. Projected Response of Regional Stream flow to Climate Change

- The water budget of Minnesota’s Lake Superior tributaries is determined by the balance of annual precipitation against evapotranspiration losses from forests and wetlands, and evaporation from lakes within the watershed. Under the GFDL climate scenario (cooler, wetter), increases in annual precipitation more than offset increases in evapotranspiration, resulting in a 30% increase in mean annual flow to 2070. Under the Hadley climate scenario (warmer, dryer), annual precipitation is relatively constant, and substantial increases in evapotranspiration result in a 20% reduction in mean annual flow.

- Simulated winter stream flow is projected to increase under both climate scenarios, due to a combination of increased snowfall and melting, and increased rainfall. Summer and autumn stream flow is projected to decrease under the Hadley scenario, due to a combination of increased evapotranspiration and reduced precipitation.

- Low flows, and in particular, summer low flows, were found to be more sensitive to changes in climate than seasonal mean and annual mean flow.

- The annual maximum flow was found to increase significantly (20% to 50%), and the seasonal distribution of the annual maximum is projected to change, with more maxima occurring in the summer and fewer in the spring. The ability to project changes in high flows is limited by both the temporal (daily time step) and spatial (about 6 km) resolution of the downscaled climate projections used in this study. This study did not take into account potential changes in hourly rainfall intensity and the spatial extent and uniformity of individual storm events, both of which could further affect peak stream flow.

- The timing of spring high flows was found to be driven both by the timing of snow melt and the changes in seasonal precipitation patterns. As a result, simulations using the two GCMs gave differing results, with shifts in the timing of the median spring high flow to either shift earlier or later by a week or two.

2. Response of Regional Stream Flow to Land Cover Change

With the exception of the Duluth area, we expect land cover change in the region to be driven by forest change. For one of the two land cover scenarios considered in this study (low CO_2 emissions, low-intensity forest management), there is a significant shift from aspen to conifers by 2070. Based on published data on evapotranspiration, we expect conifer forests to have higher water usage and lower water yields (stream flow per area). A catchment that transitions from aspen to conifer may experience lower mean annual flows and lower summer flows. However, the modeled flow responses to land cover changes are lower in magnitude than the projected climate responses, and are relatively uncertain, because evapotranspiration data for different forest types are not available within the study region.

3. Hydrologic Storage

Hydrologic storage is probably the most important variable that differentiates stream flow characteristics over the region. In the Lake Superior-North watershed (Hydrologic Unit Code (HUC) 04010101), lakes are an important source of hydrologic storage, while wetlands and soil storage are important in the Lake Superior-South (HUC 04010102) watershed. Catchments with more storage have higher base flow and lower flashiness. However, as air temperature increases in the future, some of the stored water in high storage watersheds is lost to evapotranspiration. As a result, base flows in high storage watersheds may be pulled down to levels closer to levels in low storage watersheds. Minnesota Lake Superior tributaries with little deep groundwater storage may be more prone to increased evaporation losses in the future, because most of the hydrologic storage is available for evapotranspiration.

4. Historical Climate Trends

Mean annual air temperatures in the region are trending upwards from 1950, with statistically significant trends of 0.030 to 0.044 ^{o}F per year. Shorter terms trends (after 1980) are not statistically significant, due to high year-year variability and decadal-scale oscillations. Winter air temperatures have an upward trend of 0.037 to 0.050 ^{o}F per year over the period1950-2015, but this trend is only significant at Two Harbors.

For the period of record (1900-2015), mean annual precipitation has a positive, statistically significant trend at the Duluth and Two Harbors stations, but little or no trend at Grand Marais. Shorter term, increasing trends may exist after 1980, but are difficult to quantify because of decadal-scale oscillations in the record. However, winter precipitation has a statistically significant upward trend over both 1900-2015 and 1980-2015. Summer precipitation has no significant trends.

Management Recommendations

1. Expand stream gaging efforts. We recommend that where possible, stream gages be maintained in operation over time to establish an historical record, winter flow data be collected, and further gages be deployed within strategically defined sub-catchments to quantify flow throughout the basin.

2. Collect groundwater data. There is a critical need for groundwater data including the completion of groundwater maps for the region. Local areas with significant base flow from groundwater may be less vulnerable to changes in air temperature and evaporation, because deeper groundwater is more insulated from air temperature changes, and is less available for evapotranspiration.

3. Protect base flow sources. To improve stream resilience, managers need to protect base flow sources. Specifically, wetlands, lakes, and local aquifers that act as base flow sources need to be protected against significant water appropriation at times when low flows are of concern. Strategies for protecting and enhancing wetlands and lakes sources need to consider how the source is connected to stream channel – hydraulically isolated wetlands may reduce, rather than increase, base flow, by increasing overall evaporation.

4. Better understand the role of riparian tree species (i.e., conifers), which may have an effect on water balance at low flows due to higher evapotranspiration.

5. Manage for healthy, high quality forests, minimizing the risk of large-scale abrupt changes to avoid simultaneous major disturbances to streams at the scale a connected stream network. In addition to managing forests for future climate, management should include control of plant invaders, earthworms, insect pests, and deer populations to reduce the impact of these stressors.

6. Seek opportunities to coordinate watershed planning, infrastructure planning, mitigation/adaptation and disaster response with proactive stream and watershed restoration and management. Use information about high and low flow metrics to design more resilient road crossings, bridges, and culverts.

For More Information

Contact William Herb (612-624-5147; herb0003@umn.edu) with questions about the project's hydrologic models and flow statistics.

References

Abatzoglou, J. T., & Brown, T. J. (2012). A comparison of statistical downscaling methods suited for wildfire applications. International Journal of Climatology, 32(5), 772-780.

Allen, D. M. (1974), The Relationship Between Variable Selection and Data Augmentation and a Method for Prediction, Technometrics, 16, 125–127.Apse, C., M. DePhillip, J. Zimmerman, and M. P. Smith. 2008. Developing instream flow criteria to support ecologically sustainable water resource planning and management. The Nature Conservancy, Harrisburg, PA.

Baker, D. B., Richards, R. P., Loftus, T. T., & Kramer, J. W. (2004). A New Flashiness Index : Characteristics and Applications To Midwestern Rivers And Streams. Journal of the American Water Resources Association, 44883(03095), 503–522.

Burn, D.H., Elnur, M.A.H., 2002. Detection of hydrologic trends and variability. Journal of Hydrology 255, 107-122.

DePhilip, M. and T. Moberg. 2010. Ecosystem flow recommendations for the Susquehanna River Basin. The Nature Conservancy, Harrisburg, PA.

Gifford, G. F., Humphries, W., & Jaynes, R. A. (1983). A preliminary quantification of the impacts of aspen to conifer succession on water yield within the Colorado River Basin (a process aggravating the salt pollution problem).

Hamon, W.R. 1961. "Estimating Potential Evapotranspiration," Journal of the Hydraulics Division, ASCE. 87(HY3):107-120.

Horizon Systems, 2015. http://www.horizon-systems.com/NHDPlus/applications.php

Imhoff, J. C., Kittle Jr, J. L., Donigian Jr, A. S., and Johanson, R. C. (1997). Hydrological simulation program--Fortran: User's manual for version 11. Athens, GA: US Environmental Protection Agency, National Exposure Research Laboratory.

Johnson, L. B., Herb, W., & Cai, M. (2013). Assessing Impacts of Climate Change on Vulnerability of Brook Trout in Lake Superior's Tributary Streams of Minnesota. Report to Minnesota Department of Natural Resources.

Keim, R. F., Skaugset, A& Weiler, M. (2006). Storage of water on vegetation under simulated rainfall of varying intensity. *Advances in Water Resources*, 29(7), 974-986.

Lorenz, D.L., Sanocki, C.A., and Kocian, M.J., 2009, Techniques for estimating the magnitude and frequency of peak flows on Small Streams in Minnesota based on data through water year 2005: U.S. Geological Survey Scientific Investigations Report 2009–5250, 54 p.

Luukkonen, C. L., Holtschlag, D. J., Reeves, H. W., Hoard, C. J., & Fuller, L. M. (2015). Estimation of monthly water yields and flows for 1951-2012 for the United States portion of the Great Lakes Basin with AFINCH (No. 2014-5192). US Geological Survey.

McKay, L., Bondelid, T., Dewald, T., Johnston, J., Moore, R., and Rea, A. (2012). NHDPlus Version 2: User Guide.

MN DNR, 2016. http://www.dnr.state.mn.us/waters/csg/index.html

Motovilov, Y. G., L. Gottschalk, K. England, and A. Rodhe. 1999. Validation of distributed hydrological model against spatial observations. Agric. Forest Meteorology 98-99: 257-277.

Nathan, R.J. and McMahon, T.A. (1990). Evaluation of automated techniques for base

flow and recession analysis. *Water Resources Research* 26(7): 1465-1473.

Nisbet, T. (2005). *Water use by trees*. Edinburgh: Forestry Commission

Olden, J. D., & Poff, N. L. (2003). Redundancy and the choice of hydrologic indices for characterizing streamflow regimes. *River Research and Applications*, *19*(2), 101–121.

Poff, N. L., & Zimmerman, J. K. H. (2010). Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology*, *55*(1), 194–205. Retrieved from http://doi.wiley.com/10.1111/j.1365-2427.2009.02272.x

R Core Team (2012). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Riahi, K., Krey, V., Rao, S., Chirkov, V., Fischer, G., Kolp, P., ... & Rafai, P. (2011). RCP-8.5: exploring the consequence of high emission trajectories. Climatic Change, 10, 1007.

Richter, B. D., Baumgartner, J. V., Powell, J., & Braun, D. P. (1996). A method for assessing hydrologic alteration within ecosystems. *Conservation Biology*, *10*(4), 1163–1174. doi:10.1046/j.1523-1739.1996.10041163.x

Seelbach, P. W., Hinz, L. C., Wiley, M. J., & Cooper, A. R. (2011). Use of multiple linear regression to estimate flow regimes for all rivers across Illinois, Michigan, and Wisconsin. Fisheries Research Rep, 2095, 1-35.

Seeley, M. (2012). Climate Trends and Climate Change in Minnesota: a Review. Presentation at the American Society of Agricultural and Biological Engineers in Minnesota, January 20, 2012. Available at http://climate.umn.edu/seeley/

Scheller, R. M., & Mladenoff, D. J. (2005). A spatially interactive simulation of climate change, harvesting, wind, and tree species migration and projected changes to forest composition and biomass in northern Wisconsin, USA. *Global Change Biology*, *11*(2), 307–321. doi:10.1111/j.1365-2486.2005.00906.x

Shannon, J. (2011). Canopy Transpiration and Water Yield Changes Following Forest Canopy Conversion in Northern Minnesota (Doctoral dissertation, University of Minnesota).

Soil Survey Staff 2015. Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database. Available online at http://sdmdataaccess.nrcs.usda.gov/.

Storck, P., Lettenmaier, D. P., & Bolton, S. M. (2002). Measurement of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. Water Resources Research, 38(11), 5-1.

Taylor, J. M., Fisher, W. L., Klein, D., Apse, C., Kendy, E., Schuler, G., … Crabtree, D. T. (2013). *Flow Recommendations for the Tributaries of the Great Lakes in New York and Pennsylvania*. The Nature Conservancy, Rochester, NY.

Walter, Ivan A., Richard G. Allen, Ronald Elliott, M. E. Jensen, D. Itenfisu, B. Mecham, T. A. Howell et al. (2000). ASCE's standardized reference evapotranspiration equation." In Proc. of the Watershed Management 2000 Conference, June. 2000.

Wenger, S. J., Isaak, D. J., Luce, C. H., Neville, H. M., Fausch, K. D., Dunham, J. B., … Williams, J. E. (2011). Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. *Proceedings of the National Academy of Sciences of the United States of America*, *108*(34), 14175–14180. doi:10.1073/pnas.1103097108

Hydrologic Models and Flow Statistics Appendix (Appendix 5-I)

Regional Regression Equations for Flow Metrics

Table 5-I.1. Summary of the fit coefficients as determined in Eq. 1 for 18 flow variables. All regression equations use log transformations of the dependent and independent variables, except for Base flow Index, Flashiness Index, High Count, and Low Count, which use untransformed variables. High and low flow events were based on thresholds of 7X the median annual flow and 0.05X of the mean annual flow, respectively (Olden and Poff 2003).

Flow Variable	Regression Equation	Adjust. R^2	Predict. R^2
Spring 7Q10	-14.75 + 1.15·Area + 0.28·CTGM + 0.90·All Forest	0.97	0.95
Spring 1Q10	13.78 + 1.04·Area	0.92	0.90
Spring 7Q50	-16.77 + 1.13·Area	0.89	0.86
Summer 7Q10	-13.57 + 0.97·Area	0.98	0.98
Summer 1Q10	-15.18 + 1.05·Area	0.95	0.93
Summer 7Q50	-10.46 + 1.15·Area + 1.19·Wetland	0.98	0.97
Summer 7Q90	-9.95 + 0.78·Area + 1.70·Wetland	0.85	0.75
Autumn 7Q10	-8.71+ 0.73·Area + 0.56·Wetland	0.97	0.95
Autumn 1Q10	-12.40 + 0.89·Area	0.84	0.79
Autumn 7Q50	-13.40 + 0.70·Area – 1.69·All Forest – 0.70·Develop	0.98	0.92
Autumn 7Q90	-9.51 + 0.73·Area + 1.53·Wetland	0.84	0.74
Base flow Index	0.55 + 0.068·Wetland - 0.056·CTGMl + 0.014·Conifer	0.92	0.91
Flashiness Index	0.25 – 0.31·Wetland + 0.073·CTGM + 0.05·Develop	0.94	0.93
Mean Ann. Max	-6.44 + 0.78·Area + 0.34·CTGM + 0.37·Conifer	0.93	0.93
Mean Ann. Min	-10.28 + 0.67·Area – 0.89·Develop + 0.90·Depress Storage	0.92	0.91
Median Ann.	-15.14 + 0.98·Wetland – 0.40·Develop + 0.31·Depress Storage	0.98	0.97
High Count	0.096 + 0.0036·CTGM + 0.023·All Forest + 0.017·Develop	0.90	0.89
Low Count	-0.02 + 0.0047CTGM - 0.0052·Depress Storage + 0.015·Slope	0.64	0.62

Table 5-I.2. Summary of the correlation coefficients between the flow variables.

	Spr 1Q10	**Spr 7Q50**	**Spr 7Q10**	**Sum 1Q10**	**Sum 7Q90**	**Sum 7Q50**	**Sum 7Q10**	**Aut 1Q10**	**Aut 7Q90**	**Aut 7Q50**	**Aut 7Q10**	**BFI**	**Flash**	**High Count**	**Low Count**	**Mean Max**	**Mean Min**
Spr 1Q10	1.00	0.94	0.99	0.94	0.94	0.89	0.94	0.73	0.93	0.94	0.87	0.18	-0.62	-0.51	0.07	0.82	0.81
Spr 7Q50	0.94	1.00	0.95	0.84	0.88	0.78	0.87	0.54	0.90	0.86	0.71	0.10	-0.56	-0.48	-0.07	0.68	0.94
Spr 7Q10	0.99	0.95	1.00	0.96	0.94	0.88	0.95	0.74	0.94	0.94	0.85	0.15	-0.58	-0.48	0.08	0.85	0.79
Sum 1Q10	0.94	0.84	0.96	1.00	0.93	0.95	0.98	0.83	0.92	0.98	0.93	0.33	-0.65	-0.53	0.09	0.89	0.63
Sum 7Q90	0.94	0.88	0.94	0.93	1.00	0.95	0.97	0.61	0.99	0.96	0.83	0.41	-0.69	-0.59	-0.15	0.72	0.70
Sum 7Q50	0.89	0.78	0.88	0.95	0.95	1.00	0.97	0.71	0.93	0.98	0.92	0.55	-0.76	-0.63	-0.06	0.73	0.60
Sum 7Q10	0.94	0.87	0.95	0.98	0.97	0.97	1.00	0.71	0.97	0.99	0.89	0.41	-0.70	-0.57	-0.04	0.80	0.68
Aut 1Q10	0.73	0.54	0.74	0.83	0.61	0.71	0.71	1.00	0.58	0.75	0.90	0.18	-0.54	-0.42	0.39	0.92	0.36
Aut 7Q90	0.93	0.90	0.94	0.92	0.99	0.93	0.97	0.58	1.00	0.96	0.80	0.41	-0.69	-0.59	-0.19	0.71	0.73
Aut 7Q50	0.94	0.86	0.94	0.98	0.96	0.98	0.99	0.75	0.96	1.00	0.92	0.46	-0.76	-0.63	-0.06	0.79	0.68
Aut 7Q10	0.87	0.71	0.85	0.93	0.83	0.92	0.89	0.90	0.80	0.92	1.00	0.41	-0.74	-0.61	0.18	0.83	0.55
BFI	0.18	0.10	0.15	0.33	0.41	0.55	0.41	0.18	0.41	0.46	0.41	1.00	-0.81	-0.75	-0.56	0.03	0.05
Flash	-0.62	-0.56	-0.58	-0.65	-0.69	-0.76	-0.70	-0.54	-0.69	-0.76	-0.74	-0.81	1.00	0.93	0.38	-0.41	-0.52
High Count	-0.51	-0.48	-0.48	-0.53	-0.59	-0.63	-0.57	-0.42	-0.59	-0.63	-0.61	-0.75	0.93	1.00	0.35	-0.32	-0.46
Low Count	0.07	-0.07	0.08	0.09	-0.15	-0.06	-0.04	0.39	-0.19	-0.06	0.18	-0.56	0.38	0.35	1.00	0.38	-0.15
Mean Max	0.82	0.68	0.85	0.89	0.72	0.73	0.80	0.92	0.71	0.79	0.83	0.03	-0.41	-0.32	0.38	1.00	0.44
Mean Min	0.81	0.94	0.79	0.63	0.70	0.60	0.68	0.36	0.73	0.68	0.55	0.05	-0.52	-0.46	-0.15	0.44	1.00

Module 6: Projected Forest Cover Change

Purpose

Our overall objective in examining forest change during the next 50-70 years was to link land cover change to ecological flows in a changing climate over a time span useful to land managers. By combining land cover shifts and climate change we could examine the relative influence of each of these factors on different stream flow metrics. The LANDIS II model output provided high resolution (2 hectares (ha)) vegetation maps at different periods under different greenhouse gas and management scenarios. The resulting vegetation maps were then used to provide land cover inputs required for the HSPF ((Hydrologic Simulation Program—Fortran) model for each of the three study watersheds.

Methods

Projected forest cover change

Forest cover change was projected using the LANDIS II model. LANDIS II is a spatially dynamic forest simulation model based on tree species life history traits (e.g. shade tolerance, drought tolerance, seed production, longevity) that incorporates seed dispersal, natural disturbance, management, soil properties, and climate (Scheller and Mladenoff 2005). LANDIS II can model large landscapes (10^6 ha) at high spatial resolution (1 ha) at time scales of decades to centuries and time steps ranging from annual to decadal. LANDIS II has been used extensively in northern Great Lakes forests. Species life history attributes, disturbance parameters, management prescriptions, and understanding of the influence of climate on tree growth have all been refined and improved over the last decade (Scheller and Mladenoff 2005, Ravenscroft et al. 2010, Duveneck et al. 2014). We selected the LANDIS II model output because it provides spatially explicit maps of forest composition and age structure while incorporating management and climate change.

LANDIS II does have important limitations. The version we used does not model the influences of CO^2 enrichment, nitrogen deposition, deer browse, non-native earthworms, forest insects and diseases, and hydrologic changes on wet forest systems. However, LANDIS II provided the best option for understanding the relative influence of climate and management on regional species composition trends.

Selection of Forest Change Scenarios for Modeling

A major objective of this project is to connect models and tools for understanding stream vulnerability and resilience in the face of climate and land use change to land managers and decision makers. Based on input from managers, we have selected medium range projections of 50-70 years, which corresponds to a time frame meaningful and significant to current resource managers within their careers, and falls within the range of time projected to be important for Minnesota's coldwater species. We recognize that the selection of a medium-time range presents a tradeoff between the relatively small climate-driven changes to forest composition, relative to the magnitude of impacts of near-term forest management decisions and policies. A next step should involve examining forest management effects over a longer time horizon (2070-2150) as the influence of climate on species composition increases.

Duveneck et al. (2014a, 2014b) modeled northeastern Minnesota future land cover under a changing climate using the LANDIS II model. The model projected change in forest composition and biomass over 150 years (2000-2150) using three climate scenarios; current (PRISM-1969-1999), low emissions (PCM-B1) and high emissions (GFDL-A1FI) along with two management scenarios. Business as usual management (BAU) emulated the short rotation even-aged forestry that is currently practiced in northern Minnesota (Table 6.1). Modified silviculture emphasized higher tree retention and longer rotations with a 60% decrease in even-aged management.

Table 6.1. Landis II management scenarios derived from Duveneck et al. 2014b. Business as usual management (BAU) was derived from current agency management plans: PNIF (private non-industrial forest), USDA-FS (USDA Forest Service) MN DNR & CO (Minnesota Department of Natural Resources and County Land Departments, PIF (Private Industrial Forest).

	BAU landscape treated per 5-year time step (%) **PNIF**	**BAU landscape treated per 5-year time step (%)** **USDA-FS**	**BAU landscape treated per 5-year time step (%)** **MN DNR & CO**	**BAU landscape treated per 5-year time step (%)** **PIF**	**BAU planted species after harvest**	**Modified silviculture adjustment** **Change in treated area per time step**	**Modified silviculture adjustment** **Species planted**
Aspen clearcut	2.81	4.41	6.80	6.30	White spruce, white pine and red pine	-40	Removed white spruce
Upland spruce clearcut	1.61	1.99	1.66	0.19		-10	
Jack pine clearcut	0.18	0.29	0.18		Jack pine and red pine	-10	Removed jack pine
Northern hardwood shelterwood			0.60			-100	
Northern hardwood clearcut						25	
Northern hardwood patch cut						0	Added northern hardwoods and oak species
Oak shelterwood	0.09	0.08	0.10	0.10		-10	Added oak species
Red pine clearcut	0.12	0.23	0.13	0.08	Red pine and white spruce	-10	Removed white spruce
White pine clearcut	0.09	0.09	0.08	0.07	White pine	-10	

Together, these scenarios provided a useful range of greenhouse gas emissions and management options for the purpose of examining potential forest change. Because we only had the capacity to model a limited number of future scenarios, we identified priority criteria for selecting forest change scenarios, and matched them to appropriate climate projections.

In characterizing baseline forest conditions, we considered factors including forest age, composition, and spatial configuration, since these variables influence the interception, infiltration, storage and seasonal patterns of evapotranspiration and runoff. In the process of exploring the sensitivity of stream hydrology to a range of forest composition and condition, we determined that these parameters will most directly influence stream flow and thus used them to calibrate the watershed HSPF models. As a result, important aspects of scenario selection included the proportion of forest age classes (0-15 years vs. more mature, closed canopy forest types), composition (deciduous vs. coniferous), and soil hydrology (wet forest vs. upland).

We selected future forest land cover and management scenarios that are based on landscape and biophysical potential and realistic management scenarios. For the management scenarios, we bracketed the potential climate futures to understand sensitivity of hydrologic response to a full range of variability. We therefore selected scenarios that:

- Allocate the distribution of forest stand ages across the watersheds as uniformly as is warranted by forest types in those watersheds
- “Bracket” the likely future trajectories under a warmer, ***drier*** future climate vs. under a warmer, ***wetter*** future (Figure 6.1),
- Reflect a range of plausible forest management scenarios including: business-as-usual management focused on short rotation, even-aged forestry, and modified silviculture with longer rotations, higher retention, and more diverse species composition (Table 6.1).

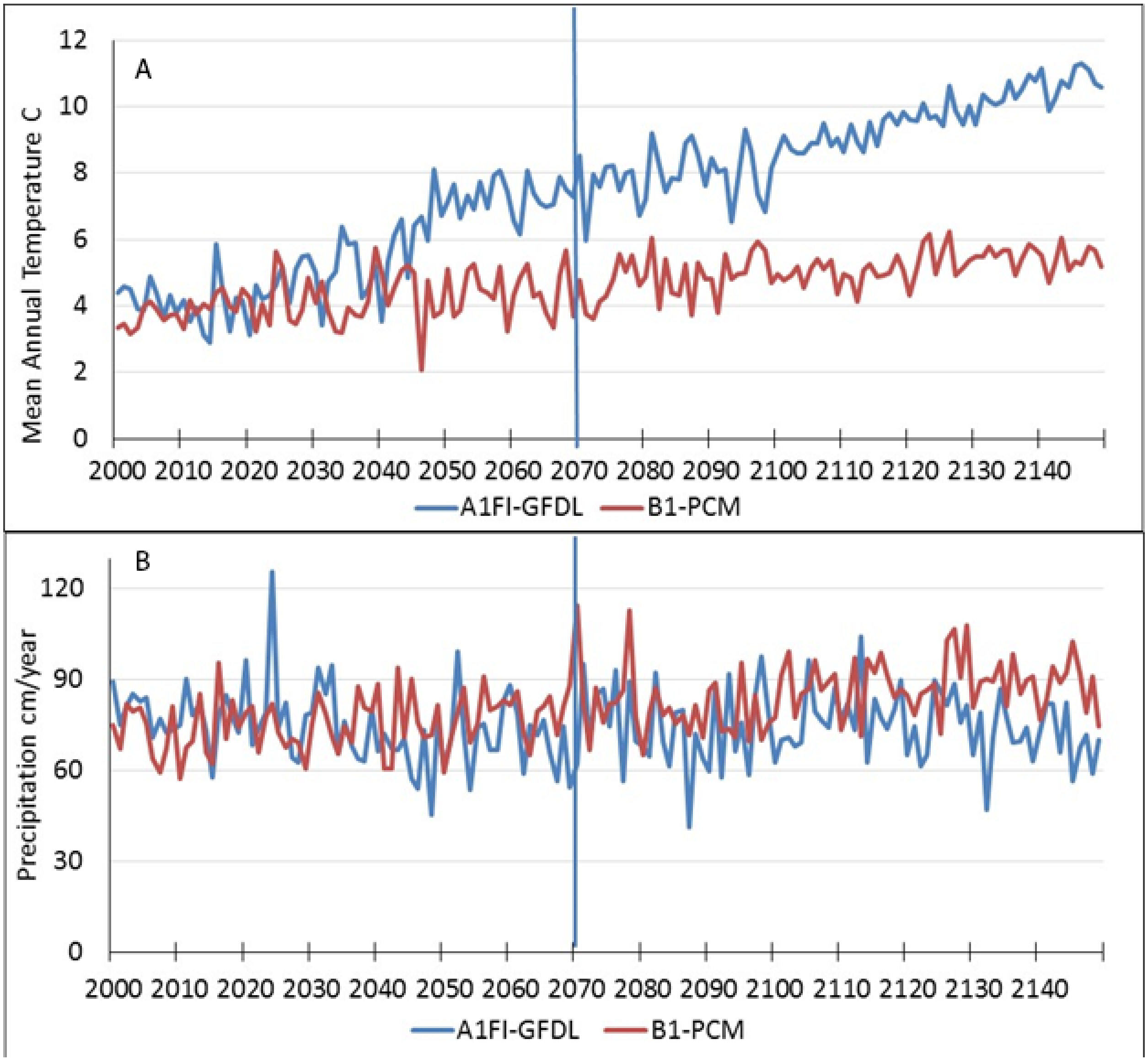


Figure 6.1. Mean annual temperature (A) and annual precipitation (B) from A1FI-GFDL and B1-PCM climate models used in the Landis II simulations.

In order to select scenarios, we interpreted what the B1 and A1FI models used in the LANDIS II forest model represented in terms of warmer-drier or warmer-wetter climate. We further considered how forest stand age was distributed across the watersheds under each of the two management scenarios; this helped ensure that, for watersheds with similar forest composition, our modeled scenarios would not be significantly biased in the event one watershed had randomly been subject to a large recent harvest and the other had not.

Management Scenarios

The BAU management prescriptions (cover type rotation ages, and average biomass removed) were derived from agency-specific management plans from the Superior National Forest, the Lake County Land Department, the St. Louis County Land Department, and the Minnesota Department of Natural Resources Forestry Division. Under BAU management, intensity and type of management varies substantially between agencies. Lake County, St. Louis County, and private industrial forest had a substantially higher rate of clear-cut management compared to the USDA Forest Service (Superior National Forest) and non-industrial private landowners. The modified silviculture scenario resulted in an average reduction in harvested biomass of 60% and shifted management towards higher retention and less even-aged management (Table 6.1).

The baseline scenario (year 2000) was compared to the 2070 forest change created by the different climate/management scenarios across watersheds and between scenarios, to assess the extent to which watersheds that are currently similar experience comparable transitions. The conifer-hardwood shifts from 2000 to 2070 followed a similar trajectory in each climate-management scenario for watersheds that were similar in composition in 2000 (Figures 6.4, 6.5). This indicates that the cover type based management prescriptions (Table 6.1) were applied consistently across the study region. The consistent responses to management and climate for similar watersheds indicate that the hydrological modeling results for the three study watershed could be reasonably applied to other watersheds with comparable geophysical and cover type characteristics.

Climate Scenarios

The A1FI-GFDL represents a significantly warmer and drier future compared to the B1-PCM model. Temperatures begin to diverge at approximately year 2045 and continue the trend through 2150. Precipitation is variable in both scenarios but is higher overall in the B1-PCM model. The combination of higher temperatures and less precipitation in the A1FI compared to the moderate temperature increase and higher precipitation indicates that these two scenarios capture the “warm-dry” and “warm-wet” conditions.

Combined Climate-Management Scenarios

We selected the following LANDIS climate-management scenarios in order to maximize the range of climate conditions and management prescriptions:

- Baseline (year 2000 land cover data) which reflects current forest composition and age structure
- Future (2070) high emissions (A1FI GFDL) business as usual (BAU) management

scenario emphasizing short rotation, even-aged management (Table 6.1). This scenario results in intensive management that favors early successional boreal hardwoods (quaking aspen, paper birch) but in a hotter-drier future that would select against boreal species. Age structure in this scenario averaged 20-25% of the upland landscape in young forest.

- Future (2070) low emissions (B1 PCM) modified silviculture with longer rotations, higher retention levels with an emphasis on higher species diversity (Table 6.1). The 60% reduction in clear-cutting and in a slightly warmer-wetter future favors shade tolerant species including boreal conifers. This scenario maintains an average of 8-12% of the upland landscape in young forest.

Data Preparation

We clipped each of the three forest data sets to the HUC (hydrologic unit code) 8 watershed boundary. Because LANDIS II does not model wetlands, wetland types (forested wetland, shrub-herb wetland) and open water were added from a satellite derived land cover classification (Wolter and White 2002). To derive forest age structure, we used above ground biomass (ABG) to classify each pixel into three classes: young, mid-seral, and mature. ABG varies with age and is a strong indicator of vegetation density and ABG influences through-fall, interception, and evapotranspiration. We used age-biomass relationships derived from 2000s era Forest Inventory and Analysis (FIA) data (Miles et. al. 2001). For this analysis we used 1500 FIA plots from the larger LANDIS study area in northeastern Minnesota (Ravenscroft et al. 2010) to determine age-ABG relationships. As LANDIS ABG output is calibrated to FIA plot data, we derived the following age-ABG classes from the FIA analysis: young forest (0-15 years, < 3800 gms/m^2), mid-seral (16-50 years, 3800-8000 gms/m^2) and mature (> 50 years, > 8000 gms/m^2). The resulting map for each classification included a cover type and age/ABG class. These were used as inputs for the HSPF model.

The LANDIS II baseline forest cover for year 2000 and modeled output used a detailed classification system and includes forest types based on species abundance in each pixel (Table 6.2) (Ravenscroft et al. 2010). The LANDIS baseline data set (Duveneck et al. 2014) was developed from a Landsat TM species-level forest classification (Wolter and White 2002) dating from 1995-2000. For HSPF modeling purposes, forest types were reclassified to hardwood and conifer.

Table 6.2. LANDIS baseline forest classification and percent area for the year 2000 for the three study watersheds.

Cover type	Baptism	Knife	Poplar
Aspen-birch	37.3	50.6	33.5
N. hardwood	6.5	2.6	3.5
Non forest	10.9	10.5	8.4
Oak	1.2	1.4	1.1
Red-jack pine	1.2	0.5	2.5
Spruce-fir	18.2	20.9	23.6
White pine	0.3	0.3	0.6
Total forest	64.7	76.3	64.8

Results & Findings

Composition

Over the 70-year simulation period there were substantial differences in forest composition between the climate-management scenarios. In the low emissions-modified silviculture scenario conifer cover increased from 29 to 46% while hardwoods decreased from 45 to 25% (Figure 6.2). This is largely due to the shift in management resulting in a 60% decrease in even-aged management. The overall decrease in harvest intensity along with the shift towards thinning and group selection altered the light environment and favored shade tolerant boreal conifers (balsam fir, white spruce, black spruce, white cedar) over shade intolerant boreal hardwoods. LANDIS II results show a decline in aspen-birch even under current climate conditions under the BAU or modified silviculture scenarios. Under the low emissions scenario, climate conditions remain within the tolerance ranges of boreal conifer species over the first 70 years but also probably contribute to the decrease in aspen-birch (Figures 6.2, 6.4) (Duveneck et al. 2014b).

Under the high emission BAU scenario, hardwoods (primarily aspen and birch) decrease from 45 to 37% while conifers increase from 29 to 33% (Figures 6.2, 6.5). Boreal hardwoods decrease even under BAU management due to the substantial temperature increase (Figure 6.1), which leads to lower productivity and a competitive disadvantage with other species more tolerant of warmer temperatures. By 2100 in the high emissions-BAU scenario, boreal conifers and hardwoods show strong decrease while temperate species (white pine, oaks, sugar maple, red maple, basswood) have large increases (Figure 6.3). During the relatively short time window (2000-2070) management has a much stronger influence on composition compared with climate. However, by 2150 we see dramatic climate driven differences in composition, especially under the high emission scenarios with much lower proportions of boreal hardwoods and conifer (Figure 6.3).

While this indicates that current composition could be maintained over the next 50-70 years, it also suggests that adaptation work could begin now as way to establish seed sources of climate tolerant species (e.g. bur oak, red oak, northern pin oak, white oak, white pine) so that they are poised to replace boreal species when their regeneration begins to fail. Given the level of uncertainty in climate and forest change, increasing climate tolerant species now is an insurance policy against more rapid and dramatic forest change.

Forest change showed substantial spatial variation across the HUC 8 region (Figures 6.4, 6.5). Under the low emissions scenario, conifer abundance showed higher increases in the southern watersheds where baseline values were low. Under the high emissions scenario conifer abundance showed a similar pattern, but with much smaller increases.

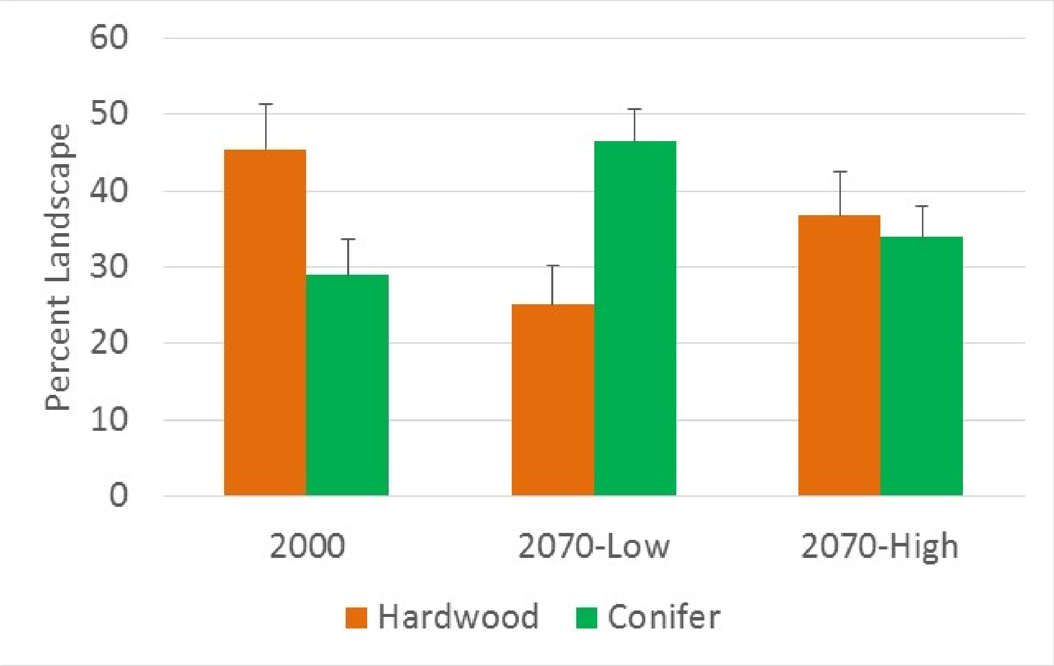


Figure 6.2. Average percent of hardwood and conifer dominated forest for baseline (2000) and low and high emissions scenarios for HUC 10 watersheds. Error bars represent 95% confidence intervals.

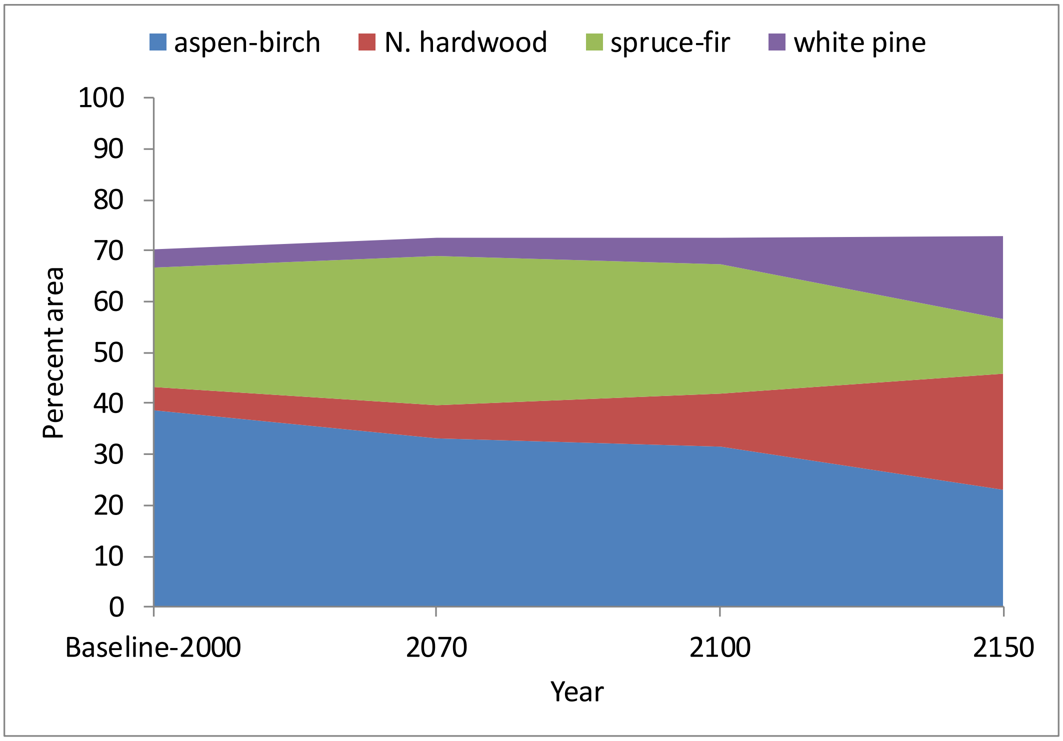


Figure 6.3. Percent of landscape for major forest types under high emissions, BAU forest management scenario 2000-2150.

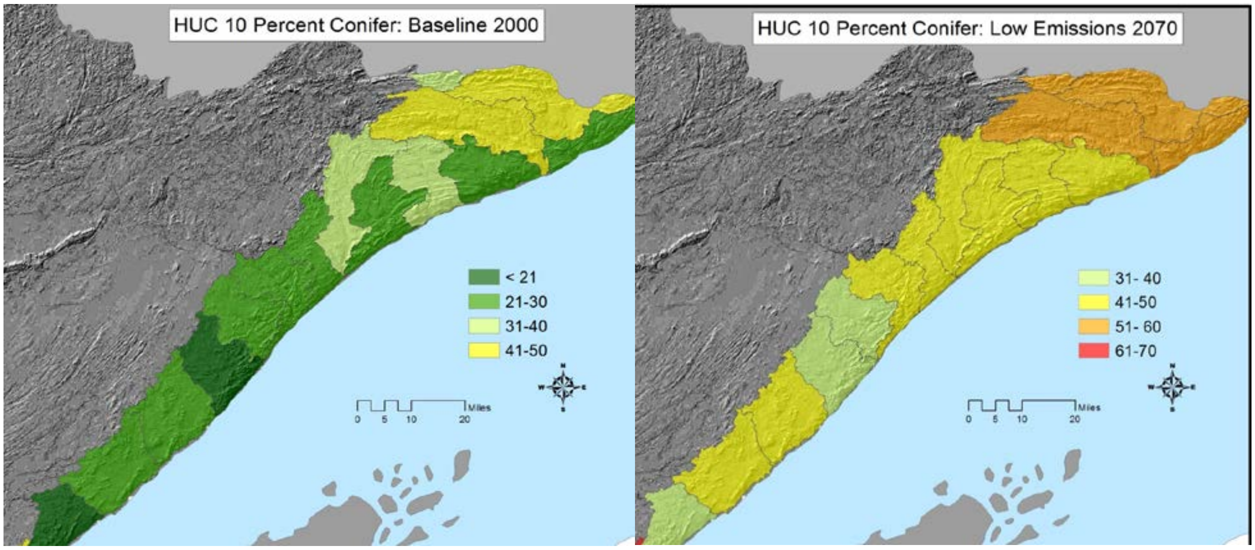


Figure 6.4. The spatial distribution (percent conifer cover) in low emissions scenarios from 2000 to 2070 for 1 HUC 10 watersheds.

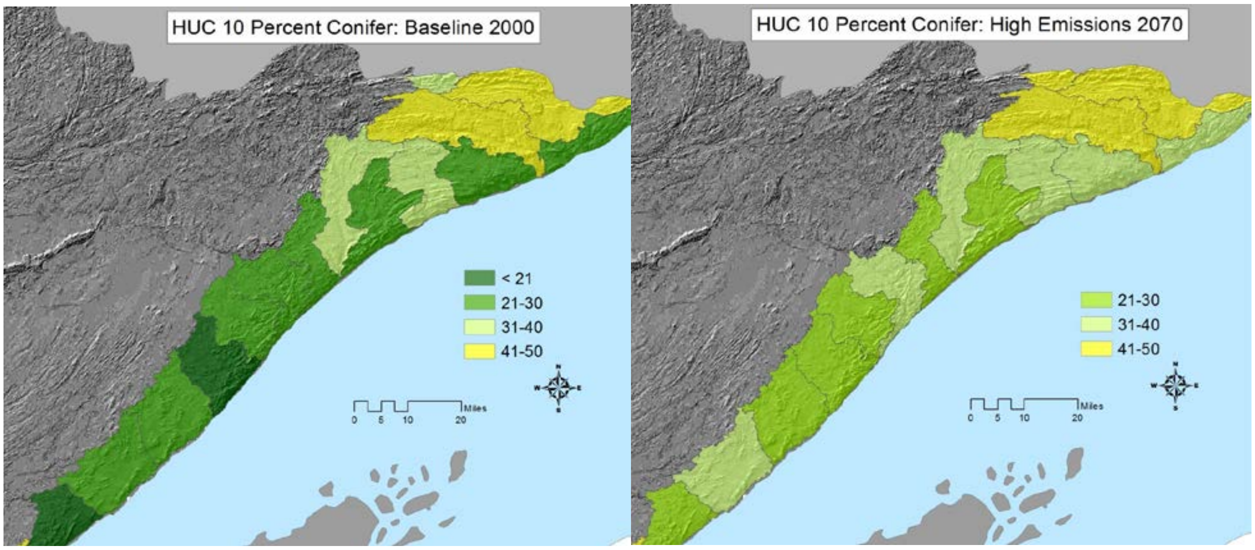


Figure 6.5. The spatial distribution (percent conifer cover) in high emissions scenarios from 2000 to 2070 for HUC 10 watersheds.

Age Structure

Age structure is largely a function of disturbance or management frequency and severity. Under the low emissions-modified silviculture scenario, the proportion of young forest (0-15 years) decreases from an average of 22% in the 2000 baseline to 11% in 2070 (Figure 6.6). The 60% decrease in even-aged management drives the decrease in young forest. The high emissions-BAU management system scenario also shows 22% for young forest, indicating this management scenario is accurately capturing BAU forest management. Thresholds for young forest area impacts on peak flows may be in the 50% range for small watersheds this region (< 2.5 Km^2) (Verry 2004). Peak flows from either rainfall or snowmelt increase dramatically once the 50% young forest-open land threshold is exceeded. While there is some variability in young forest proportion, 95% confidence intervals indicate relatively minor variation in HUC 10 watersheds (Figure 6.6). Under these management scenarios HUC 10 watersheds are not likely to experience high peak flows due to high proportions of young forest or open land. However, more extreme forest loss due to large disturbances and or tree regeneration failure could lead to higher proportions of young forest/open lands in some watersheds, increasing the risk for high peak flow periods.

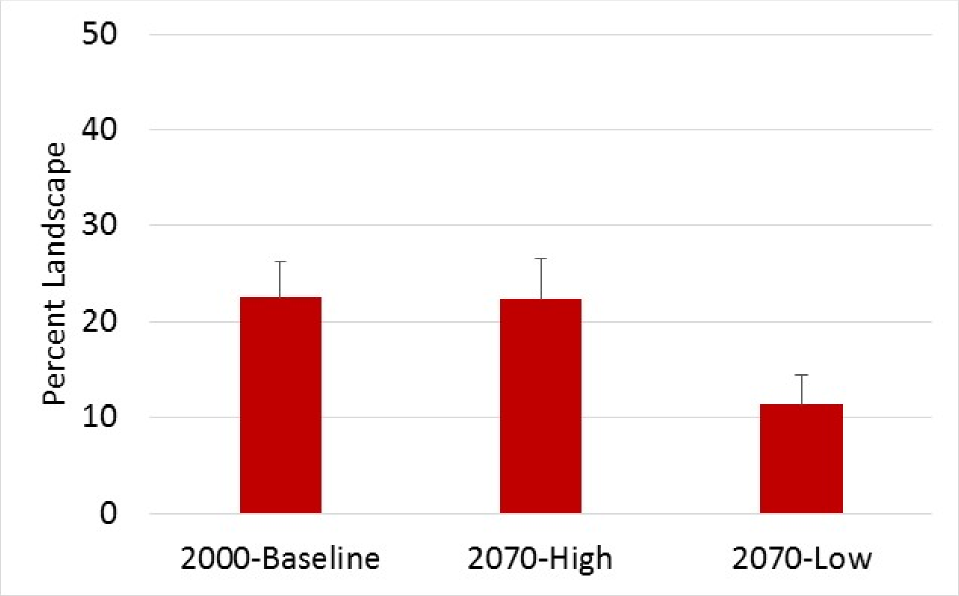


Figure 6.6. Average percent of young forest (0-15 years) for baseline (2000) and low and high emissions scenarios for HUC 10 watersheds. Error bars represent 95% confidence intervals.

Alternative Views of Forest Change

The LANDIS II simulations show a relatively gradual shift from boreal to north-temperate species composition. LANDIS is limited as it does not account for the impacts of deer browse, invasive plant species, insects and disease and potential interactions between these and other factors. Frelich and Reich (2010) predict that the combination of drought, catastrophic wind and wildfire, insect pest outbreaks, deer browse impacts, and invasive plants will amplify the influence of warmer temperatures. This will ultimately lead to a transition to savanna on drier sites and forest on mesic sites over the next 50-100 years. There are relatively large areas of the north shore highlands where paper birch is dying off and there is little tree regeneration. The lack of regeneration may be due to both intense browse pressure from white-tailed deer and dense grass layer that inhibits seedling establishment.

We mapped drought stress risk within the HUC 8 study area using the Natural Resources Conservation Service (NRCS) SSURGO (Soil Survey Geographic Database) data on available water supply in the top 1.5 meters (m) of the soil profile (Figure 6.7). The risk of forest loss, or a shift to more open canopy conditions and lower productivity, may vary greatly across this landscape. At present, much of the landscape may be buffered from drought stress and forest loss. However, as warming increases over time, a much greater proportion of the landscape may be vulnerable to changes in structure and loss of productivity (Frelich and Reich 2010). Novel species assemblages and vegetation structures may occur over time which may give rise to altered and novel hydrological regimes in these watersheds.

Given the level of uncertainty of forest and hydrologic change, proactive forest management may be one of the best tools for maintaining the ecological integrity of these linked land-water systems.

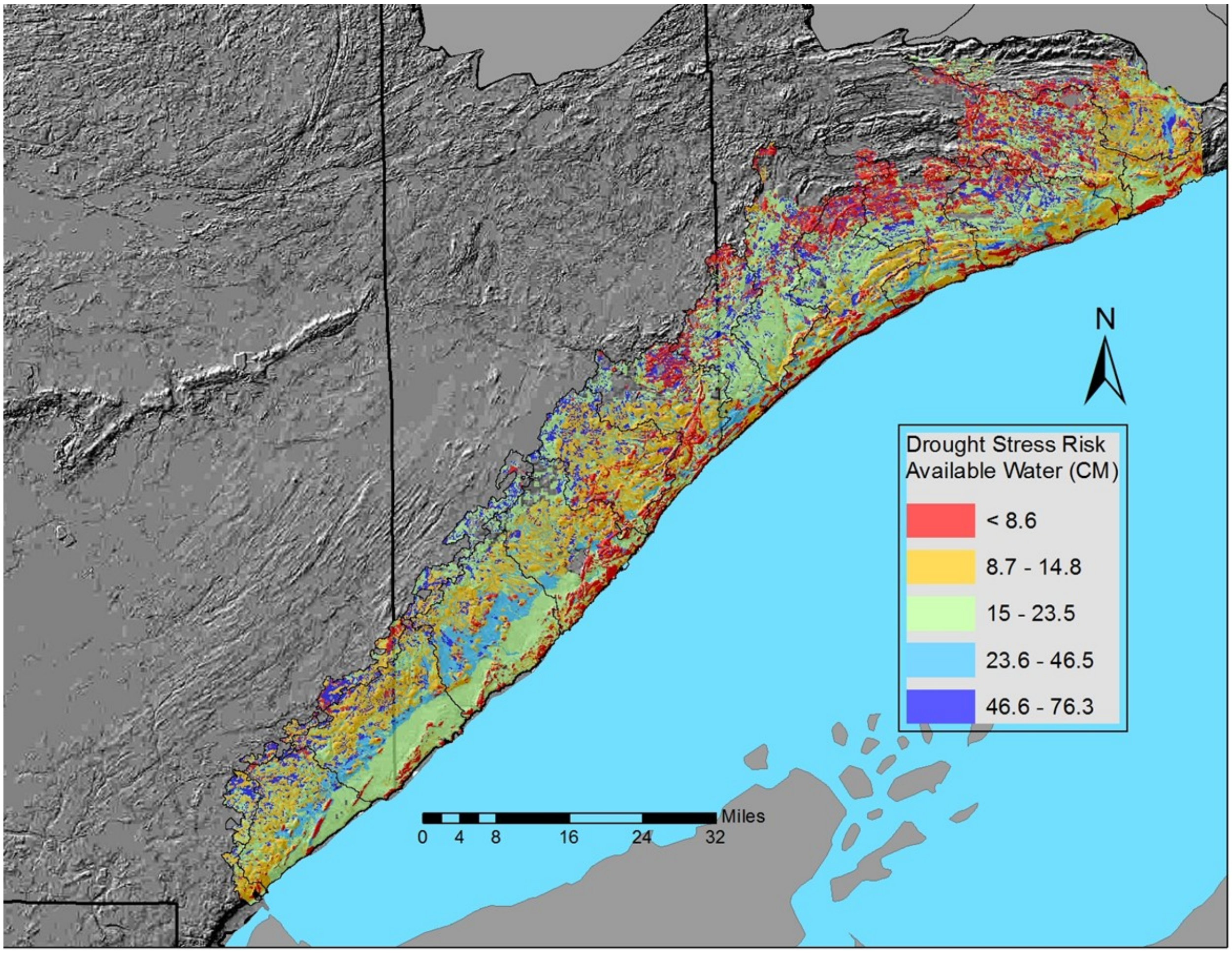


Figure 6.7. Drought stress risk derived from SSURGO. Areas with values of less than 8.6 cm are considered high risk for drought stress.

Conclusions

What have we learned?

- Modeling results indicate that over the next 50-70 years, management will have a greater influence than climate on forest composition. A scenario that pairs a high-emissions climate with business as usual (BAU) forest management emphasizing short-rotation even-age forestry would generally maintain current age structure, although hardwoods would experience a slight decline with a corresponding increase in conifer cover over the next 50-70 years. Low emissions paired with a 60% reduction in clear-cutting would lead to significant increases in conifer cover and higher levels of mature forest. After 2070, boreal hardwoods (aspen, paper birch) and conifers (white spruce, black spruce, balsam fir) decrease substantially as temperate species increase (basswood, red oak, bur oak, white pine).

- The low emissions scenario seems to be very unlikely at this point in time as measured greenhouse gas emissions are closely tracking the highest scenarios: A1FI and RCP 8.5. We should be aware that given the trajectory of greenhouse gas emissions, forest change may proceed more rapidly than indicated by models.

- Because conifers have higher annual evapotranspiration rates relative to hardwood trees, increased conifer cover in some watersheds could lead to decreased summer low flows.

- While there is general agreement on differences in evapotranspiration for conifers vs hardwoods, we lack sufficient and definitive empirical data on evapotranspiration for different species of conifer and hardwoods. This kind of data could increase the accuracy of modeled stream flow projections as forest composition changes. This in turn would increase our understanding of the role of forest management in influencing water flow.

- The strong influence of management over the next 50-70 years suggests that we have an opportunity shape forest composition and age structure in Lake Superior tributary watersheds in ways that can promote the health and function of both streams and forests.

Management Recommendations

- Management will have major influence on composition over the next 50-70 years. This is our opportunity to build adaptive capacity (the ability to respond to changing condition and maintain function) (D'Amato et al. 2011) into our forest systems. Managing for "response diversity" (*sensu* Elmqvist et al. 2003) ensures that a range of life history traits (e.g. tolerance of shade, drought, and fire) are represented in the suite of tree species. Having a variety of life history traits (e.g. shade tolerance, drought tolerance, seed production) confers an ability to respond favorably to new environmental conditions in a changing climate, thereby allowing the forest to maintain key ecosystem functions. Structural complexity (variation in tree sizes, heights, canopy openings, standing dead and downed wood) is also important for maintaining habitat, productivity, and adaptive capacity (D'Amato et al. 2011).

- Increase temperate tree species tolerant of warmer-wetter or hotter-drier conditions: white pine, red oak, bur oak, white pine, basswood, yellow birch, sugar maple. Models and empirical data show that aspen and birch will decline regardless of management in a warming climate. Oak species have adaptive traits for water-use efficiency and also may have lower evapotranspiration rates than fast growing species such as aspen. Without climate tolerant temperate species, there is a greater risk of state change to more open savanna structure which could likely have adverse impacts on ecological flows in Minnesota's Lake Superior tributaries. Recent work indicates that bur oak, red oak, and white pine sourced from northern and central seed zones can establish on a variety of sites in northeastern Minnesota.

- Utilize the geophysical diversity inherent in the landscape: soil, landform, topography can support a broad range of tree species now and into the future. For planting, this means careful consideration of tree species silvics and life history traits and how they relate to local site conditions (soil texture, depth, drainage, slope position, aspect). The native plant community classification (MN DNR 2003) is based on vegetation composition, soil properties, and landform associations and has well-defined silvicultural options (http://www.dnr.state.mn.us/forestry/ecs_silv/interpretations.html) as well as tools (http://files.dnr.state.mn.us/forestry/ecssilviculture/treetables.pdf) to help select appropriate tree species under warming climate conditions.

- However, because of possible rapid warming, consider managing for tree species that may not be listed as a component of current native plant communities, but are more tolerant of warmer conditions (e.g. northern pin oak, bur oak in fire dependent forests). This could also include tree species not currently present in the region that grow well in warmer climates (e.g. swamp white oak, black cherry, bitternut hickory) (Handler et al. 2014).

- Drier upland sites on thin, coarse textured soil are at highest risk for drought stress and forest loss: consider managing for bur oak, red oak, northern pin oak and jack pine. This will require planting, browse protection, and release from competition with understory vegetation for a greater likelihood of successful establishment.

- Conifer and hardwood proportion may have a significant effect on flow in a changing climate. HSPF results suggest that high proportions of conifers could lead to decreased summer flows due to higher evapotranspiration rates. The threshold for conifer cover ranges from 40-50%. Managing for mixed stands where conifers make up and average of 15-25% of basal area may limit the negative effect on summer flows. Temperate hardwood species such as bur oak and red oak are better adapted for warmer-drier conditions than aspen and birch and have greater water use efficiency. The shift from boreal to temperate hardwoods may also alter seasonal flow characteristics.

- Boreal conifers: balsam fir, white spruce, black spruce, white cedar, are expected to persist longer on cool-moist sites and may have the most benefit in the riparian zone where they can provide shade and coarse wood inputs into streams.
- Deer and earthworms may favor boreal species on cool-moist sites due to selective browsing on temperate hardwoods and mineral soil seedbeds created by earthworms (Fisichelli et al. 2012, Frelich et al. 2012, White 2012). However, earthworm activity may lead to warmer soil temperatures by removing insulating leaf litter and increasing soil bulk density which could limit growth and establishment of boreal tree species (Frelich personal communication). High deer densities in the region will be a continuing challenge to establishing diverse forest stands. Fencing planted seedlings and mechanical or herbicide release are effective management methods, but are also costly, limiting the amount of acres we can restore.

For More Information

Contact Mark White (218-727-6119; mark_white@tnc.org) with questions about the projected forest cover changes in the study area.

References

D'Amato, A. W., J. B. Bradford, S. Fraver and B. J. Palik. 2011. Forest management for mitigation and adaptation to climate change: Insights from long-term silviculture experiments. Forest Ecology and Management 262: 803-816.

Duveneck, M. J., Scheller, R.M. White. M.A., Handler, S.D, and C. Ravenscroft 2014a. Cimate change effects on northern Great Lake USA forests: A case for preserving diversity. Ecosphere 52: 23.

Duveneck, M. J., R. M. Scheller and M. A. White 2014b. Effects of alternative forest management on biomass and species diversity in the face of climate change in the northern Great Lakes region USA. Canadian Journal of Forest Research 447: 700-710.

Elmqvist, T., Folke, C., Nyström, M., Peterson, G., Bengtsson, J., Walker, B., and Norberg, J. 2003. Response diversity, ecosystem change, and resilience. Frontiers in Ecology and the Environment 19: 488-494.

Fisichelli, N., L. E. Frelich and P. B. Reich 2012. Sapling growth responses to warmer temperatures 'cooled' by browse pressure. Global Change Biology 18: 3455-3462.

Frelich, L. E., R. O. Peterson, M. Dovciak, P. Reich, J. Vucetich and N. Eisenhauer 2012. Trophic cascades, invasive species and body-size hierarchies interactively modulate climate change responses of ecotonal temperate-boreal forest. Philosophical Transactions: Biological Sciences 367: 2955-2961.

Frelich, L. E. and P. B. Reich 2010. Will environmental changes reinforce the impact of global warming on the prairie–forest border of central North America? Frontiers in Ecology and the Environment 87: 371-378.

Handler, Stephen; Duveneck, Matthew J.; Iverson, Louis; Peters, Emily; Scheller, Robert M.; Wythers, Kirk R.; Brandt, Leslie; Butler, Patricia; Janowiak, Maria; Shannon, P. Danielle; Swanston, Chris; Barrett, Kelly; Kolka, Randy; McQuiston, Casey; Palik, Brian; Reich, Peter B.; Turner, Clarence; White, Mark; Adams, Cheryl; D'Amato, Anthony; Hagell, Suzanne; Johnson, Patricia; Johnson, Rosemary; Larson, Mike; Matthews, Stephen; Montgomery, Rebecca; Olson, Steve; Peters, Matthew; Prasad, Anantha; Rajala, Jack; Daley, Jad; Davenport, Mae; Emery, Marla R.; Fehringer, David; Hoving, Christopher L.; Johnson, Gary; Johnson, Lucinda; Neitzel, David; Rissman, Adena; Rittenhouse, Chadwick; Ziel, Robert. 2014. Minnesota forest ecosystem vulnerability assessment and synthesis: a report from the Northwoods Climate Change Response Framework project. Gen. Tech. Rep. NRS-133. Newtown Square, PA; U.S. Department of Agriculture, Forest Service, Northern Research Station. 228

Miles, P.D., Brand G.J., Alerich, C.L., Bednar, L.S., Woudenberg, S.W., Glover, J.F., and Ezzel, E.N. The Forest Iventory and Analysis Database: Database description and user's manual. USDA Forest Service. North Central Research Station. GTR-218

MN DNR 2003. Field guide to the native plant communities of Minnesota: The Laurentian mixed forest province. Ecological Land Classification Program, Minnesota Biological Survey, and the Natural Heritage and Nongame Research Program. Minnesota Department of Natural Resources, St. Paul, MN. 352 p

Ravenscroft, C., R. M. Scheller, D. J. Mladenoff and M. A. White 2010. Forest restoration in a mixed ownership landscape under climate change. Ecological Applications 202: 327-346.

Scheller, R. M. and D. J. Mladenoff 2005. A spatially interactive simulation of the effects of climate change, harvesting, wind, and tree species migration on the forest composition, and biomass in northern Wisconsin, USA. Global change biology 11: 307-321.

Verry, E.S. 2004. Land Fragmentation to streams and fish in the central and upper Midwest. In: *Lessons for Watershed Research in the Future; A Century of Forest and Watershed Lessons,* ed. G.G. Ice and J.D. Stednick. Bethesda, MD: Society of American Foresters, pp. 129-154.

White, M. A. 2012. Long-term effects of deer browsing: Composition, structure and productivity in a northeastern Minnesota old-growth forest. Forest Ecology and Management 269: 222-228.

Wolter, P. T. and M. A. White 2002. Recent forest cover type transitions and landscape structural changes in northeast Minnesota, USA. Landscape Ecology 17: 133-155.

Module 7: Flow Ecology Relationships

Purpose

Resource managers working on Minnesota's coast recognize the need to understand the potential impact of changing flows for fisheries and watershed management. We set out to explore potential future response of streams to climate and land cover change to aid managers in land and water use planning, stream management and restoration, and climate adaptation activities that improve stream resilience. Specifically, we conducted an analysis of flow-ecology relationships to understand how current stream fish and invertebrate communities relate to existing flow regimes, and to assess vulnerability of native fish and other in-stream fauna to future flow alterations.

Fisheries managers in particular are interested in specific aspects of the flow regime, especially as it relates to extreme events that are stressful for trout and other instream biota. Managers recognize the need to understand current flow extremes, such as summer low flow magnitude and patterns and "flashiness," (i.e., rapid changes in flow in response to precipitation) as well as how future climate and land use may affect these measures. For example, summer low flows often represent a habitat "bottleneck" particularly for coldwater species, in terms of total wetted aquatic habitat that is suitable in terms of temperature, dissolved oxygen, and other important components of stream habitat. Understanding how instream biological communities relate to current and historical flow regimes is necessary to understand how streams may respond to future climate and land cover changes. Freshwater communities are already responding to climate change; fish responses to climate change so far appear to be gradual and may take decades to fully manifest (Comte and Grenouillet 2013). Fish communities in Minnesota's Lake Superior tributaries have already changed considerably since the early 19th century; legacy forest harvest, development, overfishing, and introductions of other salmonids have resulted in vastly different fish communities today (Blankenheim 2013). Today's coldwater species face a suite of potentially population-limiting factors including erratic flow regimes, warm water temperatures, lack of suitable spawning and nursery habitat, and reduced stream connectivity.

The effort to develop empirical relationships between flow metrics and in-stream biota was intended to inform predictions of the response of in-stream communities to future flows further influenced by changing climate and land use. To best frame the flow-ecology component of the overall study and make the best use of the limited biological and flow data that was available we developed a series of hypotheses based on the literature and our best professional judgment. We hypothesized that (1) there are significant natural differences in hydrologic response between stream types in the region (primarily based on extent of groundwater contributions); and (2) some stream types will be more robust than others to climate change.

Analysis of flow/biology relationships were conducted using existing biological data with respect to current (historic) flows, climate, and land cover; results were then used to inform predictions about how biological communities are likely to respond to future streamflow conditions. Future streamflow conditions are based on modeled future climate and land cover scenarios described in Modules 5 and 6 of this series.

Methods

To evaluate ecological relationships to current/existing flow conditions, we used available biological datasets for the Lake Superior coast of Minnesota from the Minnesota Department of Natural Resources (MNDNR) and Minnesota Pollution Control Agency (MPCA). We reviewed flow-ecology hypotheses developed for the study region under a previous planning effort that was structured based on the "Ecological Limits of Hydrologic Alteration (ELOHA)" framework (Blann and Kendy 2012). However, constraints on which metrics (characterizing flow predictor and biological response) could be derived from available datasets limited the number of hypotheses that could be effectively tested.

Fish and invertebrate species were selected for analysis largely based on adequate distribution across the study reaches (present at more than 4% and 10% of reaches respectively). Metrics (describing specific attributes of the fish and invertebrate communities) were selected based on sensitivity to flow alteration or flow-related disturbance, representative or inclusive of aquatic species of interest to stakeholders, or representative of stream types and stream dependent biota along the Minnesota's Lake Superior coast. Collectively, the metrics are intended to illustrate how streams are currently, or might in the future, be affected by flow alterations.

Flow metrics identified in flow-ecology hypotheses may either characterize natural components of the flow regime, or serve as indicators of the degree of alteration. All components of the natural flow regime are potentially ecologically important (Bunn and Arthington 2002, Poff et al. 2010a). The objective of flow ecology analysis is ultimately to quantify the amount of change in ecological condition for a given change in one or more flow metrics so that acceptable limits of alteration can be defined. However, an understanding of baseline or reference flows is needed in order to provide a baseline for assessing alteration.

Characterizing Biological Communities (Fish and Aquatic Macroinvertebrates)

We used the extensive dataset developed by the Minnesota Pollution Control Agency (MPCA) as part of its biological monitoring and assessment used to support condition assessment under the Clean Water Act (Niemela and Sandberg 2010, MPCA 2014). The MPCA biological monitoring program measures physical, chemical, and biological conditions in rivers and streams using an integrated approach that combines measures of fish and invertebrate community characteristics along with physical habitat assessments and water chemistry analyses. The MPCA uses fish and invertebrates to assess stream health and to evaluate whether waterbodies are meeting designated aquatic life use standards under the Clean Water Act, serving as an indicator that integrates watershed conditions over time.

Fish presence/absence and abundance

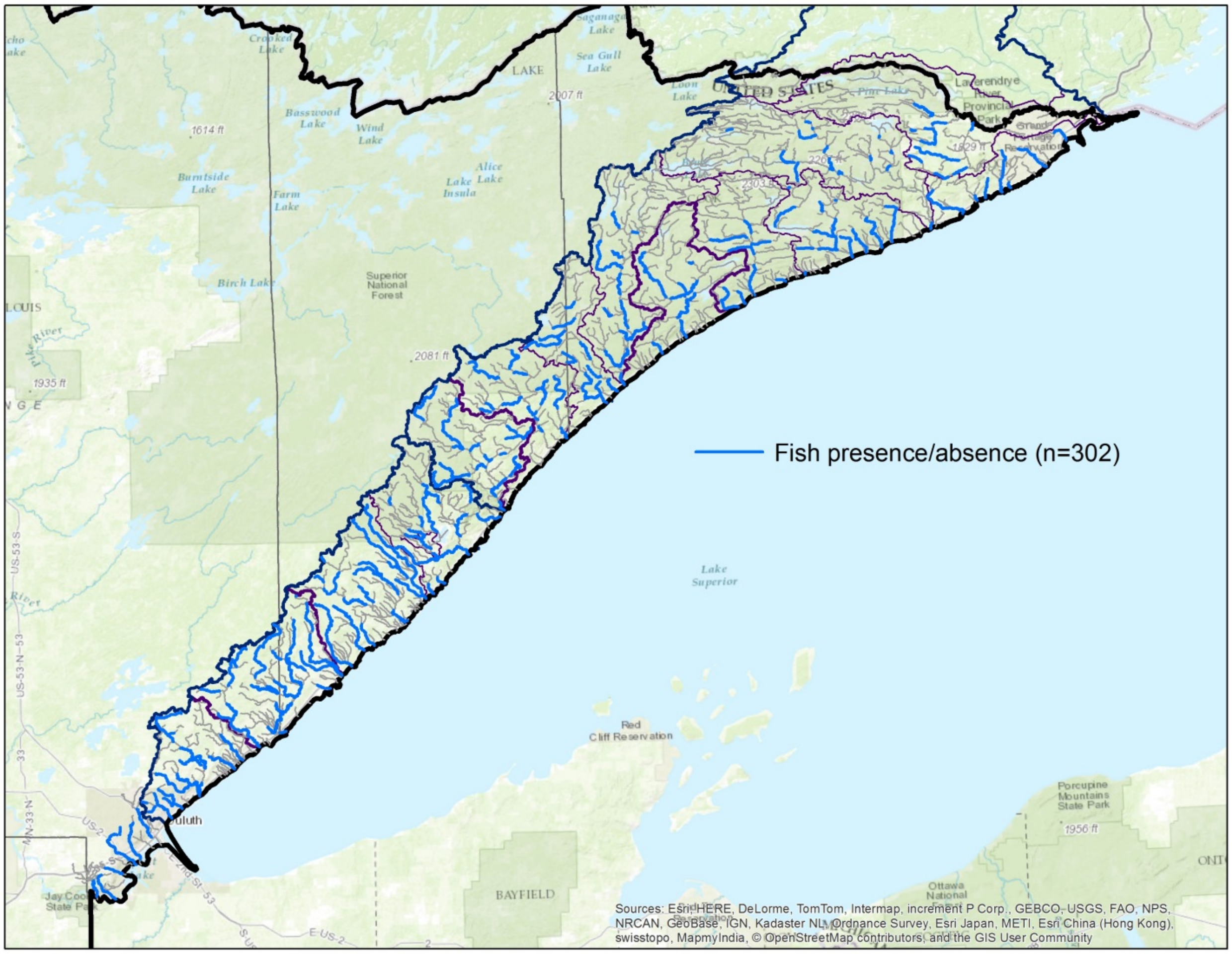
For fish presence/absence, we were able to supplement the MPCA sample size with other sources of data from a comprehensive "Fishes of Minnesota" dataset developed and maintained by Minnesota DNR Fishes of Minnesota (FOM) Mapper.[1] Fishes of Minnesota is a large, historical collection of fish data combined from various sources, including Minnesota and Wisconsin Departments of Natural Resources, Minnesota Pollution Control Agency, James Ford Bell Museum of Natural History, U.S. Fish and Wildlife Service, U.S. Geological Survey, Excel Energy/Minnesota Power and private consultants that has recently been developed by the MNDNR into an online mapping tool with options for interactive download. Because FOM records have been collected over a long time period and over many different surveys using a variety of sampling methods, comparisons of population abundance among surveys or waterbodies are inappropriate. However, we considered Fishes of Minnesota generally reliable with respect to inferring species presence over the period of time corresponding to our flow data.

Our compiled fish presence/absence dataset ultimately included presence/absence data for a total of 302 stream reaches: 247 reaches with fish data from the MPCA biological monitoring dataset (1980-2013), plus an additional 55 reaches with fish surveys adequate to assess presence/absence, conducted after 1983, from the Fishes of Minnesota dataset. Module 3 contains a detailed description of the available biological datasets that we

---

[1] http://www.dnr.state.mn.us/maps/fom/index.html

reviewed. From the total list of species, we included species present at 10 or more reaches (> 4%; Figure 7.1; Table 7.1). Metrics known to be linked to flow are listed in Table 7.2. Because the MPCA has a standardized and consistent method of data collection and reporting, we also were able to use the MPCA dataset to calculate abundance for each species collected at the MPCA reaches, yielding a sample size of 233 reaches with abundance data averaged across all sites and years (1983-2014; Appendix 7-III.)



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 7.1. Location of fish presence/absence data for the study area. Purple lines represent 10-digit Hydrologic Unit Code (HUC) boundaries for modeled watersheds (Module 5). Light gray lines represent stream reaches for which usable fish survey data were not available. Lake Superior-North and South, the two HUC-8 watersheds, are outlined in dark blue. County boundaries are shown in dark gray, while the thick black line is the Canada-Minnesota border.

Table 7.1 Fish species by frequency of occurrence by reach over the entire study period.

Abbrev	Common name	Scientific name	Reaches	%
CRC	Creek chub	*Semotilus atromaculatus*	228	76%
BND	Blacknose dace	*Rhinichthys atratulus*	195	65%
BKT	Brook trout	*Salvelinus fontinalis*	182	61%
LND	Longnose dace	*Rhinichthys cataractae*	171	57%
WTS	White sucker	*Catostomus commersoni*	157	52%
CNM	Central mudminnow	*Umbra limi*	130	43%
BST	Brook stickleback	*Culaea inconstans*	127	42%
RBT	Rainbow trout	*Oncorhynchus mykiss*	102	34%
CSH	Common shiner	*Luxilus cornutus*	98	33%
MTS	Mottled sculpin	*Cottus bairdii*	88	29%
NRD	Northern redbelly dace	*Phoxinus eos*	68	23%
PRD	Pearl dace	*Margariscus margarita*	66	22%
FND	Finescale dace	*Chrosomus neogaeus*	61	20%
FHM	Fathead minnow	*Pimephales promelas*	60	20%
SMS	Slimy sculpin	*Cottus cognatus*	53	18%
JND	Johnny darter	*Etheostoma nigrum*	42	14%
BNT	Brown trout	*Salmo trutta*	37	12%
YEP	Yellow perch	*Perca flavescens*	36	12%
NOP	Northern pike	*Esox lucius*	34	11%
LKC	Lake chub	*Couesius plumbeus*	34	11%
IOD	Iowa darter	*Etheostoma exile*	31	10%
BUB	Burbot	*Lota lota*	30	10%
SMB	Smallmouth bass	*Micropterus dolomieu*	27	9%
CHS	Chinook salmon	*Oncorhynchus tshawytscha*	22	7%
PMK	Pumpkinseed	*Lepomis gibbosus*	21	7%
LNS	Longnose sucker	*Catostomus catostomus*	21	7%
BNS	Blacknose shiner	*Notropis heterolepis*	21	7%
WAE	Walleye	*Sander vitreus*	12	4%
TRP	Trout perch	*Percopsis omiscomaycus*	12	4%
BLG	Bluegill	*Lepomis macrochirus*	9	3%
LGP	Logperch	*Percina caprodes*	8	3%

Fish IBI Metrics

To assess stream condition, MPCA quantifies the results of biological surveys by developing a biological index commonly referred to as an index of biological integrity or IBI (Karr 1981, MPCA 2014). Because of the role of flow regime in structuring overall stream habitat conditions, we included in this analysis the set of indicator metrics used by the MPCA for stream biological assessments, based on the IBI for the northern coldwater and high gradient stream classes (Table 7.2; MPCA 2014).

For the northern coldwater and high gradient stream classes that represent the majority of Minnesota's Lake Superior tributaries, metrics that have a positive relationship with IBI score—i.e., positively correlated with stream health—include coldwater species richness, percent of the community consisting of coldwater and coolwater taxa and individuals, percent sensitive coldwater individuals, and percent headwater individuals. Metrics that have a negative relationship with IBI score—i.e., positively correlated with stressors or anthropogenic disturbance—include the percent of pioneer species or taxa, percent tolerant individuals, non lithophilic nesters (i.e.. fish that do not broadcast spawn, but construct nests in benthic substrates and exhibit nest-guarding behavior), percent omnivorous taxa, and percent of individuals belonging to the perciformes (includes perches, sunfish, and bass; see MPCA 2014 for further definitions).

Additional Indicator Metrics Potentially Sensitive to Flow or Flow-related Disturbance

Certain traits or adaptations of fish and invertebrate taxa may also be expected to respond to flow alteration or variation in flow regime. We identified a set of indicator metrics for each of the fish and invertebrate datasets based on relative abundance of individuals and taxa with similar life history traits or adaptations potentially sensitive to flow as reflected in flow ecology hypotheses (Table 7.3). Metrics are derived by calculating the relative abundance of individuals and/or taxa sharing similar traits. Traits and preferences potentially responsive to flow identified in the literature include tolerance to siltation, flow specialist or riffle species, general substrate preference (e.g., coarse, fine, sand), and marsh spawners (which take advantage of floodplain habitats during spring high flows).   "Sport" fish include all managed fisheries that are maintained by MNDNR stocking programs. "Anadromous" specifically includes managed, introduced lake-run ("anadromous") salmon. Species/taxa membership was assigned based on a traits database maintained by MPCA (Sandberg, pers. comm.), supplemented with traits from Brazner et al. (2004) and Freeman and Marcinek (2006). Although salmon are of significant interest to stakeholders and managers, they occur relatively infrequently in our study sample in part because most biological sampling is conducted in mid-summer, when sampling will miss seasonal habitat use of streams by nonresident fish, such as that exhibited by migrating salmon in fall and spring. Rainbow smelt (*Osmerus mordax*) are another non-native anadromous species that typically migrates into tributary streams in mid- to late April, when the water instream warms to above about 40 °C. Smelt became very popular with anglers during the large spring "smelt runs" of the 1960s and 1970s. However, smelt do not occur in our sample.

Table 7.2. Flow ecology target species groups of fish based on key life history traits.

Group	**Key Traits and Hydrological Associations**	**Species**
Headwater (HDW)	Similar needs defined by temperature thresholds • Groundwater discharge areas serve as spawning habitats and maintain red conditions throughout winter • High seasonal flows keep redds sediment free • Scour events can flush eggs/larvae from redds • Low flows increase temperature and limit habitat quality and availability • Timing of spawning, rearing, and migration varies by species	Sculpins, pearl dace and redbelly dace, brook stickleback
Anadromous sport fish	Salmonid species that use lake habitats for adult growth and stream habitats for spawning and juvenile growth • High flow events remove sediment from spawning substrates • High flow events combined with temperature changes cue spawning runs • Higher flows increase connectivity between shallow spawning habitat and deeper downstream habitats	Salmon and steelhead
Riffle obligates and associates	Small bodied, flow-velocity specialists that spend most of their life in riffle/run habitats • High to moderate velocity riffle and run habitats are limited by low flow periods Species with moderate-sized home range that migrate in the spring to spawn and need access to, and connectivity between, riffle habitats • High flow events remove sediment from spawning substrates • High flow events combined with temperature changes cue spawning runs • Higher flows increase connectivity between shallow spawning habitat and deeper downstream habitats • Low flows can limit drift and limit survival of larvae	Longnose dace, blacknose dace, logperch, darters Redhorse, suckers, bass, walleye
Nest builders	Similar timing of flow needs (during nest building, spawning, and egg and larval development), but a diverse group in terms of nesting strategy (includes true nests, mound construction and ledge spawners) • High discharge events after spawning scour nests	Creek chub, sunfishes, smallmouth bass, johnny darter
Marsh spawners	Large-bodied fish that rely on spring flows to flood emergent vegetation for spawning • Rely on spring high flows to flood and maintain backwater marsh areas for spawning, egg and larval development, and swim up.	Northern Pike

Table 7.3 Community metrics hypothesized to be responsive to flow

Fish IBI Metrics for northern coldwater streams

Name	Description
Coldwater	Taxa richness of coldwater species
Intolerant Coldwater_Pct	Relative abundance (%) of individuals considered Intolerant in coldwater streams
Sensitive Coldwater_TxPct	Relative abundance (%) of species considered Sensitive in coldwater
Tolerant Coldwater_Pct	Relative abundance (%) of individuals considered Tolerant in coldwater streams
Non Lithophilic Nester_Pct	Relative abundance (%) of non-lithophilic, nest-guarding individuals
Omnivore_TxPct	Relative abundance (%) of omnivorous species
Pioneer_TxPct	Relative abundance (%) of pioneer species
Perciformes_Pct	Relative abundance (%) of Perciformid individuals

Additional metrics explored for potential flow responses

Name	Description
Coldtxpct	% of species classified as coldwater
Cooltxpct	% of species classified as coolwater
Headwater	% of species considered headwater species
Pioneer	% of species considered pioneer species
Coarse	% of species preferring coarse substrate
Riffle	% of species considered riffle habitat obligate or associate
Sport	% of species considered sport/game fish
Silt tolerant	% of species classified as silt tolerant
Anadromous	% of individuals that are anadromous

Aquatic Macroinvertebrates

A total of 509 invertebrate taxa were present in the 160 reaches sampled by MPCA for invertebrates within our study area. This value represents an underestimate of total species richness, as the majority of specimens were only identified to genus and some groups (e.g., Chironomidae) were only identified to higher taxonomic levels such as order or family. Metrics were calculated based on the occurrence within the full dataset. Since many taxa were relatively uncommon, we retained only taxa present at 10% of more of the sites for Threshold Indicator ANalysis (TITAN, further described below) (n=131; Appendix Table 7-IV). The most frequently encountered taxa in the basin belonged to the midge family Chironomidae (order Diptera), as well as the beetle family Elmidae (order Coleoptera). Caddisflies (order Trichoptera) were also well represented. Along with the orders Ephemeroptera (Mayflies) and Plecoptera (Stoneflies), the Trichoptera generally include many genera considered relatively intolerant of pollution or disturbance. A commonly used metric in bioassessment studies is based on the relative abundance of taxa from these three insect orders, i.e., EPT taxa.

Macroinvertebrate Metrics

The MPCA also has developed and selected a set of indicator metrics based on macroinvertebrates for use in stream biological assessments, based on the IBI for the northern coldwater and high gradient stream classes (Feist and Asmus, 2014; Table 7.4). In addition to the MPCA's macroinvertebrate IBI metrics, we generated additional invertebrate metrics (Table 7.5) based on seven categories of macroinvertebrate traits expected to be correlated with hydrologic or related disturbance by Poff et al. (2010b). We queried the U.S. Environmental Protection Agency (EPA) Freshwater Traits database (U.S. EPA 2012) and identified these seven categories of traits linked to >300 of 500 taxa in the MPCA database (see Appendix Table 7-V). Metrics were derived based on both the percent of individuals as well as the percent of taxa sampled with each of those traits, and mean values calculated by reach across all years.

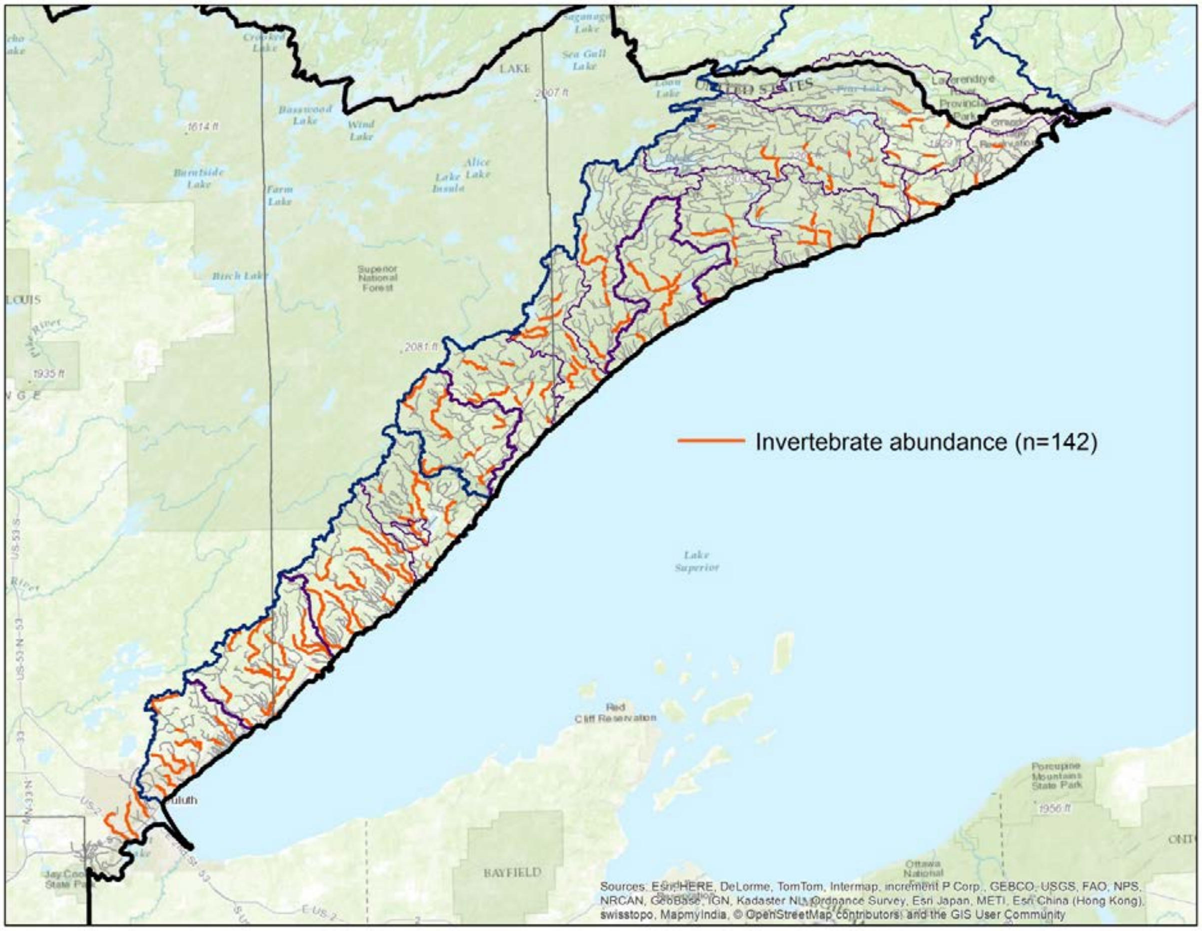


Figure 7.2. Location of reaches sampled for macroinvertebrate abundance. Purple lines represent 10-digit Hydrologic Unit Code (HUC) boundaries with the darkest lines showing modeled watersheds (Module 5). Light gray lines represent stream reaches for which usable fish survey data were not available. Lake Superior-North and South, the two HUC-8 watersheds, are outlined in dark blue. County boundaries are shown in dark grey, while the thick black line is the Canada-Minnesota border.

Table 7.4. Invertebrate indicator metrics* used by MPCA for northern coldwater macroinvertebrate index of biological integrity (M-IBI).

Variable Name	Description
Collector_gathererPct	% collector-gatherer
HBI	Hilsenhoff biotic index
NonInsectTxPct	% non-insect taxa
VeryTolerantChTxPct	% very tolerant taxa
DomFiveCHPct	% dominance of the five most abundant taxa
IntolerantChTxPct	Intolerant taxa richness
LongLivedChTxPct	% long-lived taxa
OdonataChTxPct	% Odonata (O)
POETChTxPct	% Ephemeroptera(E) + Plecoptera(P) + Trichoptera(T)- + Odonata (O)
PredatorChTxPct	Predator taxa
ClimberChTxPct	Climber taxa
ClingerChTxPct	Clinger taxa
OPT2	O, P, and T taxa

*Metrics represent functional feeding traits, life history characteristics, and behavioral characteristics. These are described in detail at https://www.epa.gov/national-aquatic-resource-surveys/wadeable-streams-assessment)

Table 7.5. Macroinvertebrate traits hypothesized to be sensitive to hydrologic/flow disturbance. Voltinism refers to number of generations per year; rheophily refers to preferred flow regime. Metrics are described in detail at https://www.epa.gov/national-aquatic-resource-surveys/wadeable-streams-assessment.

Trait	Description	Variable names (bold)
Female dispersal	Categorized as high (.1 km flight before laying eggs) and low (. 1 km)	**Female disp**ersal (1=high, 0=other)
Desiccation resistance	Categorized as absent or present.	**Desicc**ation Stage (1/0)
Voltinism states	Categorized as multivoltine (.1 reproductive generation/y), univoltine (1), and semivoltine (,1).	**Multivoltine** **Bivoltine** **Univoltine**
Occurrence in drift states	Rare (catastrophic drift only), common (typically observed in drift), and abundant (dominant in drift samples).	**No drift** (1 for rare, else 0)
Thermal tolerance states	Cold stenothermal, cool/ warm eurythermal, and warm eurythermal.	**Cold, coldcool, warm**
Rheophily states	Erosional obligate, depositional obligate, and both erosional and depositional.	**Eros**ional **Depo**sitional
Habit	Burrower, climber, sprawler, clinger, and swimmer (or skater) Poff et al. (2006b)	**Burrow**ing **Climber** **Clinger** **Swimmer**

Flow Ecology Analysis Methods

We used a variety of univariate and multivariate statistical techniques including linear regression, Redundancy Analysis (RDA), Canonical Correspondence Analysis (CCA), and Random Forests to explore the relationships between biological assemblages and environmental drivers, including flow metrics. Results from these analyses allowed us to identify specific flow metrics that most influence the presence and abundance of fish and invertebrate species in the study area streams.

Multivariate statistical approaches were used to discover relationships between indicator and stressor datasets, as well as to allow for some degree of variance partitioning in order to determine the most prevalent and significant relationships. We used principal components analysis (PCA) to explore fish, invertebrate, and flow datasets, and to identify subsets of variables representing the dominant axes of variation in each dataset. In each case, multiple individual variables are highly correlated, and PCA helped identify subsets of variables for use in subsequent analyses. We conducted exploratory analysis using PCA to identify dominant gradients of variation in the fish and invertebrate datasets as well as to select subsets of metrics used in the MPCA invertebrate IBI for coldwater and northern high gradient stream classes. CCA was conducted on the community data and RDA on the fish trait data. For the flow metrics, the most correlated environmental flow components were those representing flow magnitude. Based on these analyses, the following subset of flow metrics was selected for evaluating biological community responses to flow metrics: baseflow index (BFI); high flow count (HC) or flashiness (Flash); low flow count (LC); and either maximum (MAX), summer (SUM_Q10), or spring high flows (SPR_Q10); as well as summer low flow (SUM_Q90). These flow metrics are described in detail in Module 5.

All CCA and RDA ordination analyses were performed using R software – including the vegan package – or SAS 9.3. Ordination results are presented as graphs (biplots) depicting the scores of response and predictor variables on the first two ordination axes which account for the majority of variance explained. The length of the arrows in the biplot represents the strength of a variable's influence on the respective axes. The species-environment correlation represents the multiple correlations between the site scores that are weighted averages of the species scores and the site scores that are a linear combination of the environmental variables. For a detailed description of these techniques and an explanation of interpreting biplots see McCune et al. (2002).

TITAN Analysis

Different taxa respond to stressors or other predictor variables at different values. Threshold Indicator Taxa ANalysis (TITAN) is an analytical approach for understanding threshold responses to environmental gradients by identifying synchronous changes in the distribution of multiple taxa at the level of the whole community (King and Baker 2010). In other words, TITAN can be used to identify transition points (or zones of rapid change) in biological communities' response to small, continuous increases in a stressor (Biastoch 2015), where there are multiple biological variables being evaluated in response to a single environmental variable. Individual taxa responses also are shown. We used the fish and invertebrate species abundance datasets to evaluate whether there were threshold responses to flow in Minnesota's Lake Superior tributaries' biological communities.

Details of the TITAN method can be found in Baker and King (2010). Briefly, TITAN splits sample units into two groups at the value of a predictor variable that maximizes association of each taxon with one side of the partition. Association is measured by taxon abundances weighted by their occurrence in each partition (Dufrêne and Legendre 1997) and standardized as z-scores to facilitate cross-taxon comparison via permutation of samples along the predictor. TITAN distinguishes declining (sensitive, z-) and increasing (tolerant, z+) taxa and tracks the cumulative responses of increasing and decreasing taxa in the community. Bootstrapping is used to identify reliable threshold indicator taxa and the uncertainty around the location. We used the TITAN2 package in the freely available R software package to conduct the analysis.

Anticipating Biological Response under Future Flows: Defining Vulnerability and Resilience

Characterizing Resilience

A goal of this project was to develop models to characterize streams in terms of their resilience or vulnerability to climate and flow changes to help managers prioritize the healthiest and most resistant and resilient streams for protection, identify management criteria most likely to maintain or enhance stream resilience, and more efficiently target limited resources. Ecosystem resilience has been defined as "the ability of an ecosystem to retain essential processes and support native diversity in the face of disturbances or expected shifts in ambient conditions" (Anderson et al. 2013, modified from Gunderson 2000). Resilient stream systems are those that will support a full spectrum of biodiversity and maintain their functional integrity even as species compositions and hydrologic properties change in response to shifts in ambient conditions due to climate change; resilience can largely be characterized by factors such as connectivity, water quality, instream flow regime, link to groundwater, and geophysical settings (Rieman and Isaak 2010, Palmer et al. 2009, Benner et al. 2014). Many climate change vulnerability assessments have noted that with respect to freshwater ecosystems, resilience is likely to be correlated with specific physical properties as well as condition characteristics, with those streams experiencing the least amount of cumulative stress—i.e. the healthiest and most functional systems currently—in most cases better positioned to cope with additional stresses imposed by changing climate.

Our analysis focused on characterizing existing and potential magnitude of future hydrologic response at the reach scale, which can be viewed as an important physical characteristic influencing resilience. For the purposes of this analysis, we limit the definition of vulnerability and resilience to signify, "as influenced by changes to the flow regime." "Vulnerable" reaches are those where changes in flow regime are predicted or anticipated to trigger significant changes in biological community response, whereas "resilient" reaches are those where changes in flows are not expected to be significant and/or where they are unlikely to result in significant changes to biological community composition. We used two methods for characterizing vulnerable reaches: 1) based on biological response thresholds to flow, and 2) based on a "sustainability boundary" determined by comparison of current to predicted future flow.

Community thresholds detected in TITAN

We used biological thresholds with respect to flow metrics to identify vulnerability, focusing especially on flashiness, peak flows during spring and summer, and summer base flow. Community thresholds were identified for "sensitive" taxa (whose abundance declines as a particular condition changes), or "tolerant" taxa (whose abundance increase with changing conditions), thereby helping to identify particular reaches whose fish or invertebrate communities were most likely to change as a result of changing flow conditions. We compared baseline flows to future flows in modeled reaches for each of the four climate and land cover scenarios described in Module 5. For each of the community thresholds identified in TITAN, we calculate the number and percentage of reaches where the change from baseline flows to future flows crossed the community threshold value. (i.e., future spring peak flow, etc.) Reaches exceeding such a threshold are hypothesized to be "vulnerable."

Percent change based on presumptive "sustainability boundaries"

In the extensive literature on ELOHA, there is an emerging convention in the establishment of ecological flow criteria proposing "sustainability boundaries" for flow alteration of 5-10% for critical low flow magnitude, frequency, and duration, and 11-20% for other environmental flow components (Richter et al. 2011). Therefore, for the modeled set of study reaches (e.g., Poplar, Baptism, and Knife rivers), we also characterized "vulnerability" based on the number of flow metrics for each reach where these sustainability boundaries are exceeded, comparing current or baseline flow values to the corresponding flow metrics under the future land cover and climate scenario. For each scenario, we characterized the percent of reaches where:

- Summer low flow (SUM_Q90) or baseflow index (BFI) decreases by > 5% or 10%, respectively
- Any seasonal magnitude changes in high, low, or seasonal flow metrics (+/-) by ≥ 20% (e.g., spring high flows (SPR_Q10) or median flows (AUT_Q50))
- Frequency of high or low flow events (high flow count (HC) or low flow counts (LC)), or flashiness (FLASH) changes (+/-) by more than 10%

Reaches where one or more flow metrics exceed these percent change thresholds are proposed as potentially "vulnerable." Due to the sparse flow that can be linked to the biology data for areas outside the three intensively modeled catchments, we do not show or discuss the vulnerability estimates outside of these catchments.

RESULTS

Ecological Relationships to Flow

Minnesota's Lake Superior tributaries support a moderately diverse fish fauna with at least 49 stream species recorded as extant since 1983 in the Fishes of Minnesota database, including 42 native stream species, 6 species of introduced salmonids[2] (Coho, Pink, Chinook, and Atlantic salmon, plus brown trout and rainbow trout), and one hybrid (lake trout / brook trout cross). Several less common species are generally associated with lake habitats rather than streams. With the exception of the lake chub (*Couesius plumbeus*), which is designated of "special concern" by the state of Minnesota, there are no fish species listed as threatened or endangered or species of greatest conservation need (SGCN) found in the study area, though several are present in Lake Superior or neighboring drainages (e.g., St. Louis River). Flow metrics that most consistently were associated with biological

---

[2] Few coho and chinook salmon reproduce successfully in Minnesota's Lake Superior tributaries. MNDNR maintains a put-grow-take chinook stocking program; fingerlings are stocked and grow into large adults, which are caught by boaters and stream anglers. Spotty runs of chinook and fewer cohoes (which are only planted by the Michigan DNR) enter the tributaries to spawn in the fall--but most just go through the motions, which likely accounts for their only occasional presence in summer stream surveys.

responses were spring and summer peak flows (Q10), summer low flow (Q90), and the flashiness index.

Exploratory Analysis and Key Variables (Multivariate Analysis)

Many of the variables in the predictor (flow and catchment) as well as response (fish and macroinvertebrate) datasets are highly correlated. Principal components analysis (PCA) was used to identify the subset of predictor and response variables in each dataset that explained the dominant gradients and axes of variability.

Fish and macroinvertebrate responses in PCA were similar across presence/absence, abundance, or trait-based metrics. For fish presence/absence, relatively commonly encountered species such as blacknose dace (BND), common shiners (CSH), and mottled sculpin (MTS) loaded more positively on Axis 1. Axis 2 separated cool water species of relatively larger streams or lake- or wetland- connected habitats, such as smallmouth bass (SMB), yellow perch (YEP), and northern pike (NOP), from headwater or smaller stream species such as pearl dace (PRD), northern redbelly dace (NRD), and brook stickleback (BST).

Canonical Correspondence Analysis (CCA) using the fish presence/absence data and flow metrics as environmental variables (Figure 7.3) shows that the first two canonical axes explain about 5.5% of the variance in the fish community, or a total of 7% for all axes. Axis 1 reflects a gradient of higher spring and summer flows (both high and low flows), while Axis 2 reflects a gradient between higher baseflow index versus higher flashiness and low flow counts. These flow variables therefore account for the majority of explained variance in the fish community. Individual fish species have relatively weak loadings on these axes, with most species clustered around the center of the biplot; the strongest relationship occurs between smallmouth bass and higher flows. The colored ellipses represent the scores of the individual stream classes (based on the 4-class stream classification system). These primarily distinguish between stream class 4 and 2, with class 4 representing streams with slightly higher and more stable flows relative to class 2 (see Module 4 for an explanation of the hydrologic classification system referred to here).

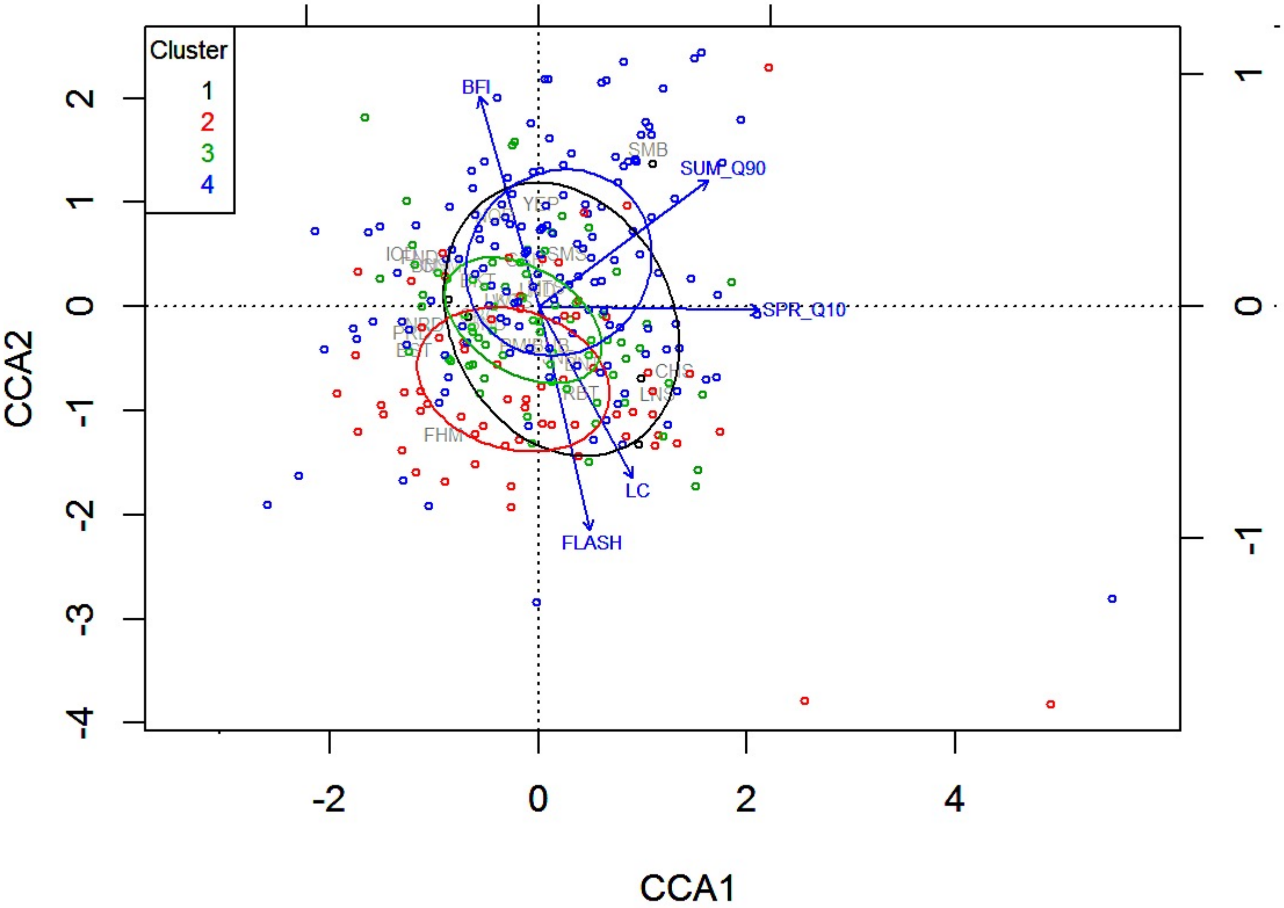


Figure 7.3. Canonical Correspondence Analysis (CCA) of fish presence/absence in response to flow metrics including flashiness index, spring peak flow, summer low flow and base flow index.

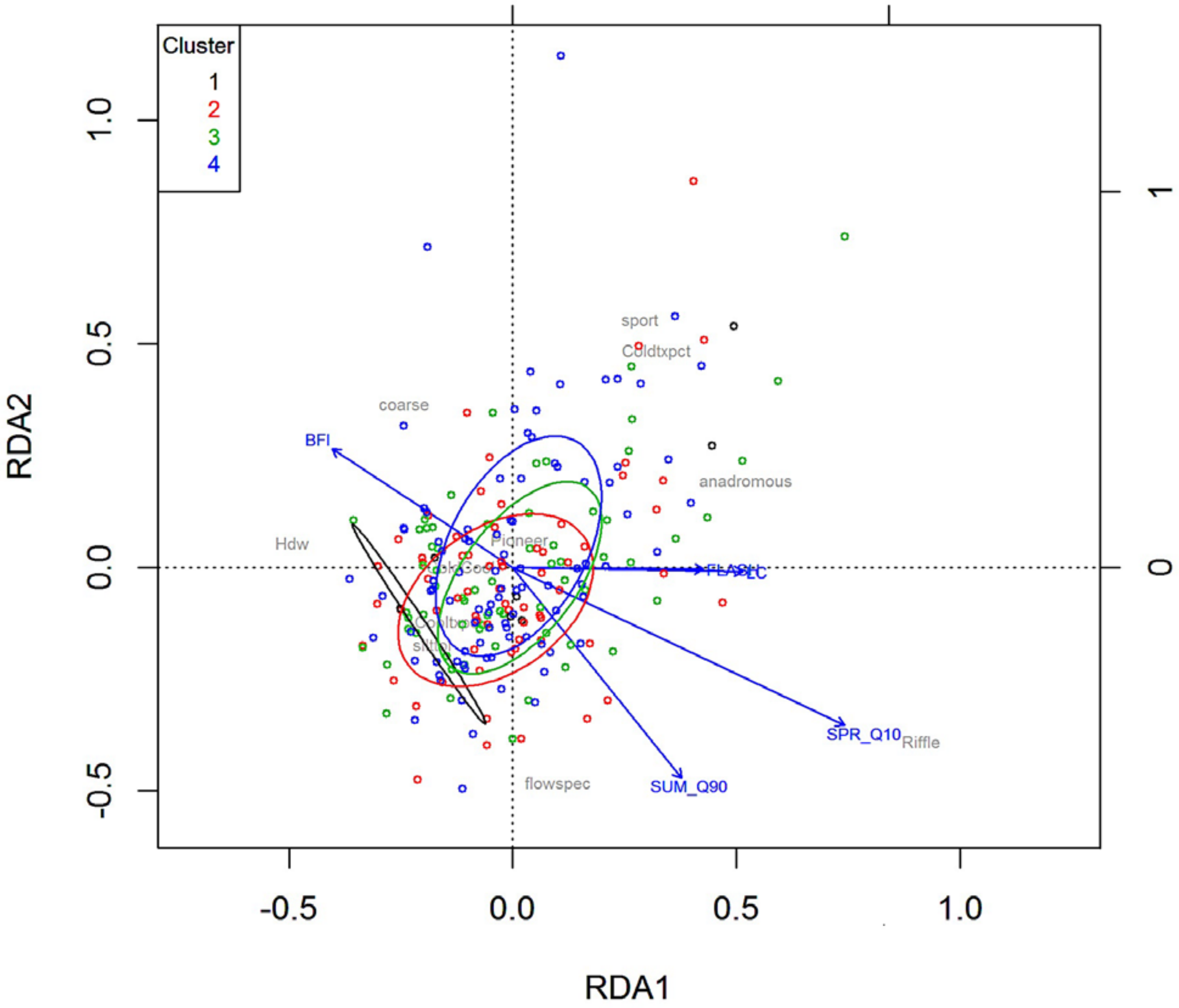


Figure 7.4. Redundancy Analysis (RDA) using fish life history metrics and flow metrics including summer low flow, spring high flow, baseflow index, high flow count, low flow count, and flashiness index. Variance explained by the first two axes is 10%.

A Redundancy Analysis (RDA) using the fish life history metrics and flow metrics as environmental variables explains a slightly greater percentage of the variance, with the first two axes of the ordination explaining 10% of the variance in the metrics (Figure 7.4). Anadromous fish (i.e., salmon), are associated with higher stream flashiness on Axis 1. Riffle species are associated with both larger high flow and flashiness on Axis 1; flow specialists are slightly associated with higher summer low flows. Headwater (Hdw) taxa and preference for coarse substrate are associated with lower flows and higher baseflow index. There is almost no separation of the stream classes in this analysis.

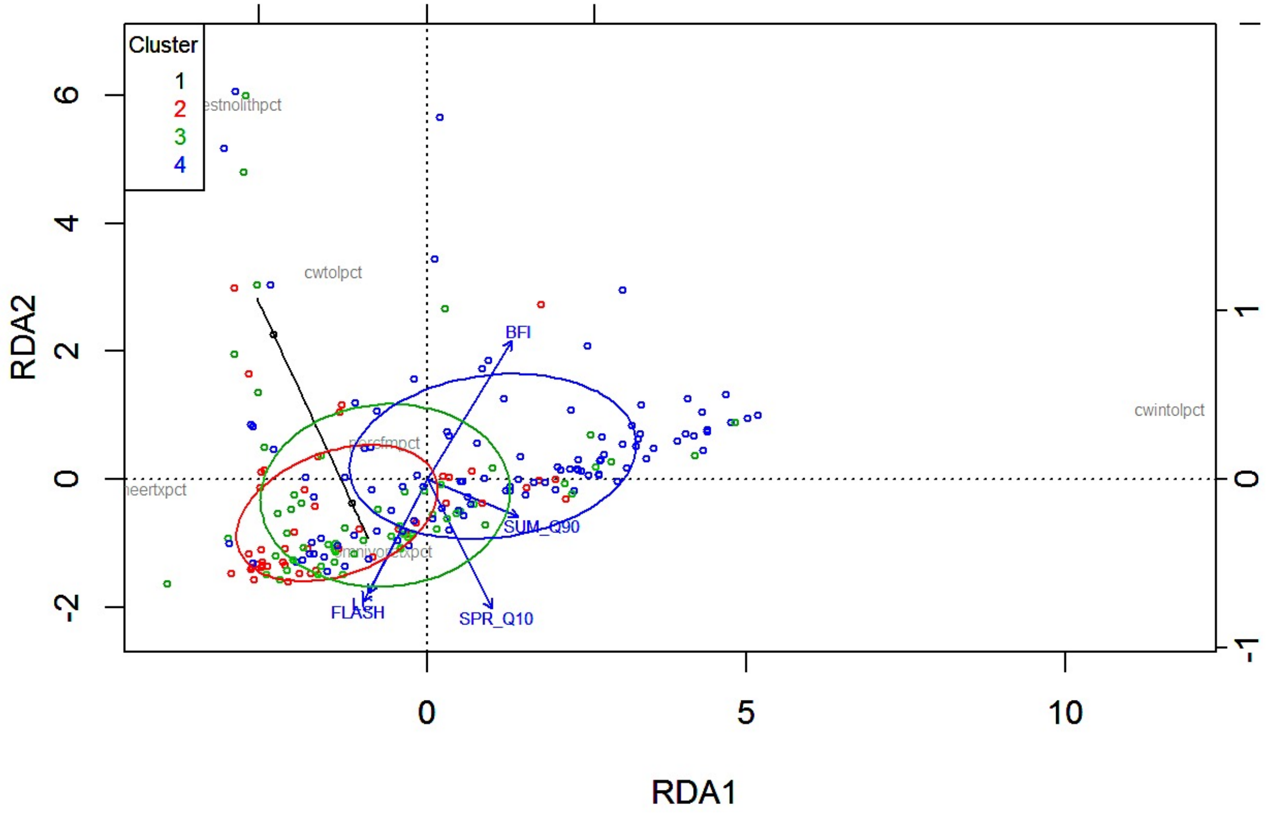


Figure 7.5. RDA of MPCA fish IBI metrics in response to flow metrics including flashiness index, low flow count, summer low flow, spring peak flow, and base flow index. Variance explained by the first two axes is 12%.

Flow metrics explain 12% of the variance in fish IBI metrics (Figure 7.5). Percent of taxa that are coldwater sensitive, which includes rainbow trout, are associated with higher spring high flows. Percent of taxa that are pioneer taxa–which is negatively related to the IBI—relates to lower summer low flows, higher spring flows, and flashiness. Percent pioneer taxa are associated with stream class 3 and lower overall flows. Percent coldwater intolerant are associated with higher baseflow index and higher summer low flows.

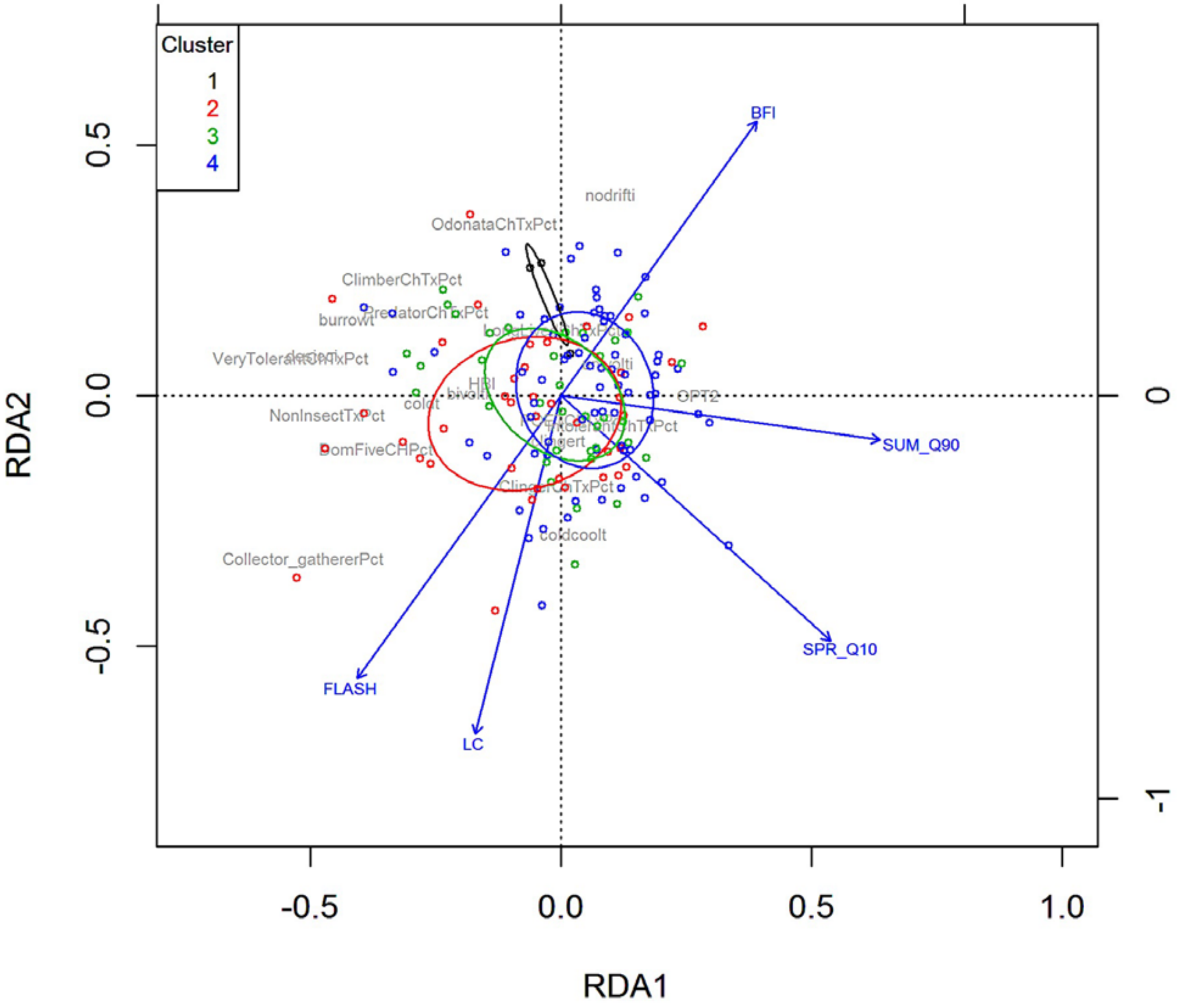


Figure 7.6. RDA of MPCA macroinvertebrate IBI metrics in response to flow metrics including flashiness index, low flow count, spring peak flow, summer low flow, and base flow index. The first two axes explain just 7% of the variance in macroinvertebrate metrics.

RDA of the MPCA invertebrate IBI invertebrate metrics in response to flow explains < 7% of the variance in the response (Figure 7.6). The combination of the first 2 axes show some separation between reaches with higher baseflow index (BFI) from flashier reaches with higher low flow counts, the latter slightly more characteristic of stream class 2. Tolerant and collector-gatherer taxa are associated with the flashier streams, whereas Odonate taxa (dragonflies) as well as percent of individuals rarely occurring in drift are associated with higher baseflow index.

Further Multivariate Analyses

Results of the CCA were used to identify the fish and invertebrate taxa that were most strongly associated with flow metrics. Although the total variation in the community data was not well explained by the flow metrics, some taxa (as described above) were found to be strongly correlated with distinct components of the flow regime. We subsequently conducted a Random Forest analysis using all flow metrics and the strongest responding taxa to confirm these relationships (data not shown). In summary, we sought to confirm that the flow metrics identified in the CCA were among the most important explanatory variables for a given taxon response. Finally, linear regression models were also developed to assess the strength and form of these relationships (e.g., linear, polynomial, wedge, etc). Based on this weight of evidence we then conducted a series of analyses to identify the community thresholds to establish a baseline from which to identify vulnerability to changing flow regimes.

Evaluating Threshold Response to Flow Metrics - TITAN results

Using the subset of flow metrics selected from the multivariate analyses described above (SPR_Q10, SUM_Q10, SUM_Q90, FLASH, HC, LC, and BFI), we identified community thresholds in both fish and invertebrate abundance using TITAN (Baker and King 2009). Community thresholds are the flow values beyond which both fish and invertebrates exhibit a marked change in abundance (Tables 7.6 – 7.8; Figures 7.7—7.20). In each figure, the top panel shows the sum(z) across flow statistics, and the lower panel shows significant indicator taxa. In the upper panel, TITAN sum(z-) and sum(z+) values correspond to taxon-specific change points (xi) along the gradient. Peaks in sum(z-) correspond to locations along the gradient where synchronous declines of taxa occur (i.e., community threshold). Solid and dashed lines represent the cumulative frequency distribution of change points (c.p.) among 500 bootstrap replicates for sum(z-) and sum(z+), respectively. In the lower panel of each figure, significant (purity (i.e., consistent direction) § 0.8, reliability (consistent magnitude) § 0.8, p ƒ 0.05) indicator taxa are plotted in increasing order with respect to their observed change point. Solid symbols correspond to negative (z-) indicator taxa (those that decline with respect to the gradient), whereas open symbols correspond to positive (z+) indicator taxa (those whose abundance increases along the gradient). Symbols are sized in proportion to magnitude of the response (z scores). Horizontal lines overlapping each symbol represent 5th and 95th percentiles among 500 bootstrap replicates.

Significant community thresholds as well as individual species and taxa change points with respect to flow metrics are summarized in Tables 7.6—7.8. Table 7.6 summarizes the community threshold flow values for both fish and macroinvertebrate taxa. Table 7.7

summarizes individual change point values for significant negative and positive indicator taxa from the fish data for each flow metric. Table 7.8 summarizes individual change points for significant negative and positive indicator taxa from the invertebrate data for each flow metric.

Both fish and invertebrate taxa exhibited strong community threshold responses to the high flow component metrics, SPR_Q10 and SUM_Q10 (Figures 7.7 – 7.9); however, some individual species and taxa abundance are distributed across a wide range of high flow values. For example, for fish, longnose dace (LND) and brook stickleback (BST) seemed to show fairly strong change points with respect to summer high flows across a narrow band of low values, < 50 cfs (Figure 7.9). Longnose sucker (LNS) also had a strongly significant change point for summer Q10, but at a much higher value (nearly 300 cfs) and across a wide confidence interval. Although these biological responses to high flow are significant, the climate models disagree in terms of their predictions; the warmer, drier (Hadley) climate model predicts large decreases in spring peak flows (32.8 – 45.1%) in the future, but the cooler, wetter (GFDL) climate model predicts only a modest increase (10.1- 18.8 %) (see Module 5, Table 5.13).

There are also significant community thresholds for summer low flows (Figure 7.11). Table 7.6 shows a threshold value of 2.6 cfs for the fish community response to summer low flow (SUM_Q90), with stream species such as fathead minnow (FHM), brook stickleback (BST) and pearl dace (PRD) showing declining abundance above that threshold (Figure 7.11). Longnose dace (LND), a riffle specialist of small, fast streams, appears to have a significant change point at a narrow range of summer low flows, showing increasing abundance at relatively low baseflow values of around 4 cfs (Figure 7.11). For invertebrates, the community threshold for the sensitive indicator taxa appears at a value of around 2 cfs (Figure 7.12). The Hadley prediction for summer baseflow (Q90) shows a strong decline of between 81.4 to 94.7%, while the GFDL predicts a 112-150% increase in base flow (see Module 5, Table 5.13).

TITAN fish and invertebrate community responses for flashiness (FLASH) and high flow count (HC) were also significant (Figures 7.13-7.16). The flashiness indicator threshold for sensitive fish is 0.15 (Table 7.6), with species such as Iowa darter (IOD), brook stickleback (BST), central mudminnow (CNM), and even smallmouth bass (SMB) showing significant negative change points (Figure 7.13). Rainbow trout (RBT) and fathead minnow (FHM), however, both show tolerance for flashiness, with relatively wide confidence intervals across the flashiness gradient. For macroinvertebrate response, the threshold is 0.6 for tolerant indicator species and 0.43 for sensitive indicator species (Table7.6).

Individual taxa responses to the low flow count and baseflow index (BFI) are significant in many cases but show change points across a wide range of BFI values (Figures 7.17-7.20). For BFI significant change points are shown for taxa whose abundance increases with along the BFI gradient. Most fish species showed increasing response to higher BFI values; brook trout (BKT), northern pike (NOP), yellow perch (YEP), smallmouth bass (SMB), central mudminnow (CNM), slimy sculpin (SMS), and Iowa darter (IOD) are identified as positive indicator taxa for BFI (Figure 7.19). We would expect coolwater and coldwater taxa to respond positively, at least initially, to increases in proportion of flow contributed by baseflow. However, rainbow trout (RBT) was a "sensitive" indicator species with a significant declining change point for BFI at ~0.45, although the confidence interval is also large. For invertebrates, multiple taxa showed increasing abundance with increasing BFI, including *Chimarra*, Pisiidae, and *Nigronia* (Figure 7.20).

Brook trout also appear to be rather tolerant of a broad range of flow conditions with a wide confidence interval displayed for all flow metrics except spring Q10. Blacknose dace—a headwater stream species widespread in cool and coldwater streams—showed significant positive response for spring and summer high flows (Figure 7.7, 7.9), flashiness (Figure 7.13), and high flow counts (Figure 7.15). Slimy sculpin, smallmouth bass, and trout perch increase in abundance and presence along gradients of both spring and summer high flows whereas brook stickleback and pearl dace declined along those gradients (Figure 7.7, 7.9). For summer low flows brook stickleback, pearl dace, and fathead minnow declined in abundance and presence, while johnny darter, longnose dace, and smallmouth bass increased along those flow gradients (Figure 7.11).

To help visualize this response, we generated a few example maps showing flow metrics with significant community threshold responses. The maps display flow metric values by reach across the study area, using break points for the color legend corresponding to significant z+ and z- community threshold values (Figures 7.21-7.25). We also display an overlay showing presence/absence of example species that showed significant threshold responses on those metrics. For additional description see the figure legends.

Table 7.6. Threshold indicator taxa analysis (TITAN) community level results for fish and macroinvertebrates.

Flow metric / Community		Change point (c.p.)	5% - 95% confidence interval
Fish - Spring high flow (SPR_Q10) (cfs)	sumz-	33	10 - 180
Fish - Spring high flow (SPR_Q10) (cfs)	sumz+	69	40 - 128
Inverts - Spring high flow (SPR_Q10) (cfs)	sumz-	33	25 - 43
Inverts - Spring high flow (SPR_Q10) (cfs)	sumz+	61	34 - 983
Fish - Summer high flow (SUM_Q10) (cfs)	sumz-	21	13 - 26
Fish - Summer high flow (SUM_Q10) (cfs)	sumz+	42	21 – 43
Inverts - Summer high flow (SUM_Q10) (cfs)	sumz-	21	15 - 26
Inverts - Summer high flow (SUM_Q10) (cfs)	sumz+	42	21 - 43
Fish - Summer low flow (SUM_Q90) (cfs)	sumz-	2.6	0.25 - 13
Fish - Summer low flow (SUM_Q90) (cfs)	sumz+	7.4	6.8 - 16
Inverts - Summer low flow (SUM_Q90) (cfs)	sumz-	2.3	0.3 - 6.0
Inverts - Summer low flow (SUM_Q90) (cfs)	sumz+	7.8	2.8- 8.7
Fish - Flashiness (FLASH)	sumz-	0.15	0.09- 0.23
Fish - Flashiness (FLASH)	sumz+	0.42	0.33 - 0.61
Inverts - Flashiness (FLASH)	sumz-	0.41	0 - 0.5
Inverts - Flashiness (FLASH)	sumz+	0.45	0.26 - 0.64
Fish - Baseflow index (BFI)	sumz-	0.45	0.42 - 0.67
Fish - Baseflow index (BFI)	sumz+	0.7	0.68 - 0.70
Inverts - Baseflow index (BFI)	sumz-	0.62	0.42 - 0.69
Inverts - Baseflow index (BFI)	sumz+	0.69	0.44 - 0.70
Fish - High flow count (HC)	sumz-	0.2	0 - 3.8
Fish - High flow count (HC)	sumz+	10	4.2 - 14
Inverts- High flow count (HC)	sumz-	2.0	0.2 - 6.6
Inverts- High flow count (HC)	sumz+	9.8	4.6 - 13
Fish - Low flow count (LC)	sumz-	0	0 - 1
Fish - Low flow count (LC)	sumz+	0	0 - 7
Inverts - - Low flow count (LC)	sumz-	0.41	0 - 2.8
Inverts - - Low flow count (LC)	sumz+	3.9	2.8 - 11

Table 7.7. TITAN fish abundance individual species change points for each flow metric for species showing significant individual effects.

Common Name	Code	*	SPR_ Q10	z-score	Sum Q10	z-score	Sum Q90	z-score	FLASH	z-score	BFI	z-score	LC	z-score	HC	z-score
Blacknose dace	BND	z(-)	-	-	-	-	-	-	-	-	0.64	5	-	-	-	-
Blacknose dace	BND	z(+)	13	5.0	8.2	5.0	-	-	0.42	7.0	-	-	-	-	8.6	6.0
Blacknose shiner	BNS	z(-)	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Brook stickleback	BST	z(-)	34	7.9	20	13.0	2.7	6.0	-	-	-	-	-	-	0.2	6.0
Brook trout	BKT	z(-)	281	5.1	-	-	-	-	-	-	-	-	-	-	-	-
Brook trout	BKT	z(+)	-	-	-	-	-	-	-	-	0.44	6	-	-	-	-
Brown trout	BNT	z(+)	-	-	26	-	-	-	-	-	-	-	-	-	-	-
Burbot	BUB	z(+)	-	-	40	-	-	-	-	-	-	-	-	-	-	-
Central mudminnow	CNM	z(-)	13	5.6	-	-	-	-	0.155	6.0	-	-	0.17	6.0	2	6.0
Central mudminnow	CNM	z(+)	-	-	-	-	-	-	-	-	0.7	7	-	-	-	-
Chinook salmon	CHS	z(+)	1015	14	212	6.0	28	6.0	-	-	-	-	-	-	-	-
Common shiner	CSH	z(+)	-	-	11	-	-	-	-	-	-	-	-	-	-	-
Creek chub	CRC	z(+)	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Fathead minnow	FHM	z(-)	-	-	-	-	0.26	7	-	-	-	-	-	-	-	-
Fathead minnow	FHM	z(+)	-	-	-	-	-	-	0.61	6	-	-	-	-	14	13
Finescale dace	FND	z(-)	-	-	-	-	-	-	-	-	-	-	0	-	0.5	5.0
Iowa darter	IOD	z(-)	10	6.1	-	-	-	-	0	7.0	-	-	-	-	-	-
Iowa darter	IOD	z(+)	-	-	-	-	-	-	-	-	0.71	6	-	-	-	-
Johnny darter	JND	z(-)	-	-	-	-	-	-	-	-	0.46	6	-	-	-	-
Johnny darter	JND	z(+)	115	6.3	-	6.0	4.8	5.0	0.46	6.0	-	-	-	-	9.8	6.0
Longnose dace	LND	z(+)	27	13.4	31	16.0	3.8	15.0	-	-	-	-	-	-	-	-
Longnose sucker	LNS	z(+)	449	9.7	288	14.0	24	12.0	-	-	-	-	-	-	-	-
Mottled sculpin	MTS	z(+)	-	-	-	-	6.1	3.0	-	-	-	-	-	-	-	-
Northern pike	NOP	z(-)	-	-	-	-	-	-	-	-	-	-	-	-	3.4	4.9
Northern pike	NOP	z(+)	-	-	-	-	7.6	-	-	-	0.67	5	-	-	-	-
Northern redbelly dace	NRD	z(-)	-	-	-	-	-	-	-	-	-	-	-	-	0	-
Pearl dace	PRD	z(-)	53	5.6	25	5.6	2.6	6.0	-	-	-	-	-	-	-	-
Rainbow trout	RBT	z(-)	-	-	-	-	-	-	-	-	0.45	11	-	-	-	-
Rainbow trout	RBT	z(+)	20	6.7	25	-	-	-	0.32	9.0	-	-	3	9.0	4.6	10.0
Slimy sculpin	SMS	z(+)	100	5.6	84	6.0	12	-	-	-	6	0.7	-	-	-	-
Smallmouth bass	SMB	z(-)	-	-	-	-	-	-	0.23	6	-	-	-	-	3.3	6
Smallmouth bass	SMB	z(+)	169	8.0	151	12.0	14	11.0	-	-	-	-	-	-	-	-
Trout perch	TRP	z(+)	428	14.5	122	10.0	8.7	9.0	-	-	-	-	-	-	-	-
Walleye	WAE	z(+)	851	9.3	288	12.0	16	9.0	-	-	-	-	7.2	6.0	-	-
White sucker	WTS	z(+)	-	-	16	5.0	1.4	6.0	-	-	-	-	-	-	-	-
Yellow perch	YEP	z(-)	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Yellow perch	YEP	z(+)	-	-	-	-	7.6	-	-	-	0.7	5.0	-	-	-	-

*z(-) = Decreasing indicator taxa; z(+) = Increasing indicator taxa

Table 7.8. TITAN invertebrate abundance individual species change points for each flow metric for species showing significant individual effects

Order	Family	Taxa (Genus/family)	abbrev	ind	SPR Q10	SUM Q10	SUM Q90	FLASH	BFI	HC	LC
Annelida	Oligochaeta		oligo	z-	-	-	-	-	0.61	11.61	-
Astigmata	-	Acari (mites and ticks)	acari	z-	-	-	-	-	0.61	7.53	0.72
Astigmata	-	-	acari	z+	-	-	-	0.41	-	-	-
Branchiobdellida	-	*Hirudinea*	leech	z-	10	12	-	-	-	-	-
Coleoptera	Elmidae (riffle beetles)	*Dubiraphia*	dubir	z-		21	-	-	-	-	-
Coleoptera	Elmidae	*Optioservus*	optio	z-	-	-	1.2	-	-	-	-
Coleoptera	Elmidae	*Stenelmis*	sten	z+	422	186	9.8	-	-	-	-
Coleoptera	Elmidae	-	elmid	z-	-	23	-	-	-	-	-
Diptera	Athericidae	*Atherix*	atherix	z+	-	13	-	-	-	-	-
Diptera	Ceratopogonidae	*Bezzia*	bezzia	z-	7	4	0.5	-	-	-	-
Diptera	Ceratopogonidae	-	ceratop	z-	6	10	0.3	-	-	-	-
Diptera	Chironomidae	*Brillia*	brillia	z-	34	19	1.9	-	-	13.03	-
Diptera	Chironomidae	*Cladotanytarsus*	clado	z-	-	-	-	-	0.54	4.85	-
Diptera	Chironomidae	*Conchapelopia*	concha	z-	-	-	-	-	-	-	0.32
Diptera	Chironomidae	*Corynoneura*	cory	z-	27	21	2.0	-	-	-	-
Diptera	Chironomidae	*Cricotopus*	crico	z-	-	-	-	-	0.44	8.37	0.59
Diptera	Chironomidae	*Dicrotendipes*	dicro	z-	-	-	-	-	0.61	8.84	-
Diptera	Chironomidae	*Eukiefferiella*	eukie	z-	-	-	-	-	-	-	0.32
Diptera	Chironomidae	*Limnophyes*	limnoph	z-	20	21	2.0	-	-	-	-
Diptera	Chironomidae	*Paramerina*	paramer	z-	-	-	2.3	-	0.68	-	-
Diptera	Chironomidae	*Phaenopsectra*	phaeno	z-	-	-	-	-	-	10.92	-
Diptera	Chironomidae	*Procladius*	proclad	z-	27	20	-	-	-	-	-
Diptera	Chironomidae	*Sublettea*	sublet	z-	-	-	-	-	0.4	-	0.52
Diptera	Chironomidae	-	clado	z+	911	-	-	0.48	-	-	-
Diptera	Chironomidae	-	crico	z+	72	-	-	-	-	-	-
Diptera	Chironomidae	-	dicro	z+	-	-	-	0.39	-	-	-
Diptera	Chironomidae	*Lopescladius*	lopes	z+	72	30	3.6	-	-	-	-
Diptera	Chironomidae	*Paramerina*	paramer	z+	-	-	-	0.48	-	-	-
Diptera	Chironomidae	*Sublettea*	sublet	z+	178	43	-	-	-	-	-
Diptera	Dixidae	*Dixella*	dixid	z-	11	10	1.9	-	-	-	-
Diptera	Dolichopodidae	-	dolo	z-	-	-	-	0.46	-	-	-
Diptera	Empididae	-	empid	z-	-	-	-	0.19	-	-	-

Order	Family	Taxa (Genus/family)	abbrev	ind	SPR Q10	SUM Q10	SUM Q90	FLASH	BFI	HC	LC
Diptera	Empididae	-	empid	z+	-	-	-	-	0.68	-	-
Diptera	Empididae	*Hemerodromia*	hemero	z+	-	-	-	-	0.7	-	-
Diptera	Limoniidae	*Antocha*	antoch	z-	-	-	-	-	0.43	8.25	-
Diptera	Limoniidae	-	antoch	z+	-	-	-	0.14	-	-	-
Diptera	Limoniidae	*Hexatoma*	hexatoma	z+	-	37	-	-	-	-	-
Diptera	Pediciidae	*Dicranota*	dicra	z-	69	31	1.1	-	0.68	13.03	-
Diptera	Pediciidae	-	dicra	z+	-	-	-	0.64	-	-	-
Diptera	Tabanidae	-	taban	z-	-	24	-	-	-	-	-
Diptera	Tipulidae	*Tipula*	tipula	z-	11	12	1.2	-	-	-	-
Ephemeroptera	Aeshnidae	*Aeshna*	aeshna	z-	-	21	2.3	-	-	-	-
Ephemeroptera	Aeshnidae	-	aeshnid	z-	35	-	-	-	-	-	-
Ephemeroptera	Baetidae	*Acentrella*	acentrella	z-	-	-	-	-	0.44	2.46	0.24
Ephemeroptera	Baetidae	-	baetid	z-	-	-	-	-	-	2.21	-
Ephemeroptera	Baetidae	*Baetis*	baetis	z-	-	-	-	-	-	2.21	-
Ephemeroptera	Baetidae	*Procloeon*	proclo	z-	-	-	-	-	0.41	7.81	0.24
Ephemeroptera	Baetidae	-	acentrella	z+	34	26	6.8	-	-	-	-
Ephemeroptera	Baetidae	*Procloeon*	proclo	z+	-	-	-	0.46	-	-	-
Ephemeroptera	Ephemerellidae	-	ephellid	z+	-	-	-	-	0.72	-	-
Ephemeroptera	Ephemerellidae	*Ephemerella*	ephemerella	z+	-	-	-	-	0.46	-	-
Ephemeroptera	Ephemeridae	*Hexagenia*	hexa	z+	-	37	-	-	-	-	-
Ephemeroptera	Heptageniidae	*Leucrocuta*	leucro	z-	-	-	-	-	-	7.14	0.35
Ephemeroptera	Heptageniidae	*Rhithrogena*	rhith	z-	-	-	-	-	-	-	0.94
Ephemeroptera	Heptageniidae	*Epeorus*	epeorus	z+	34	31	7.8	-	-	-	-
Ephemeroptera	Heptageniidae	-	hepta	z+	13	20	4.8	-	-	-	-
Ephemeroptera	Heptageniidae	*Leucrocuta*	leucro	z+	-	-	-	0.52	-	-	-
Ephemeroptera	Heptageniidae	*Rhithrogena*	rhith	z+	61	124	15.7	-	-	-	-
Ephemeroptera	Isonychiidae	*Isonychia*	isonych	z-	-	-	-	-	0.43	8.19	0.12
Ephemeroptera	Isonychiidae	-	isonych	z+	672	44	6.5	0.36	-	-	-
Ephemeroptera	Limnephilidae	-	limne	z-	38	21	-	-	-	-	-
Hygrophila	Physidae	*Physa*	physa	z+	-	-	-	0.64	-	-	-
Hymenopterans	Apidae	*Ferrissia*	ferris	z-	-	-	-	-	-	12.88	-
Megaloptera	Corydalidae	*Nigronia*	nigro	z-	-	-	-	0.2	-	-	-
Megaloptera	Corydalidae	*Nigronia*	nigro	z+	-	30	3.9	-	0.69	3.11	-
Odonata	Corduliidae	-	corduli	z-	27	10	2.9	-	-	-	-
Odonata	Corduliidae	*Somatochlora*	somato	z-	12	15	1.8	-	-	-	-
Odonata	Gomphidae	-	gomph	z+	34	19	3.8	-	-	-	-

Order	Family	Taxa (Genus/family)	abbrev	ind	SPR Q10	SUM Q10	SUM Q90	FLASH	BFI	HC	LC
Odonata	Gomphidae	*Ophiogomphus*	ophio	z+	38	44	7.8	-	-	-	-
Plecoptera	Leuctridae	-	leuctrid	z+	-	-	-	0.71	-	-	-
Plecoptera	Perlidae	*Acroneuria*	acro	z+	61	49	8.8	-	-	-	-
Plecoptera	Pteronarcyidae	*Pteronarcys*	ptero	z+	64	22	8.9	-	-	-	-
Trichoptera	Brachycentridae	*Brachycentrus*	brach	z+	-	218	-	-	-	-	-
Trichoptera	Goeridae	*Goera*	goera	z-	-	15	1.8	-	0.69	-	-
Trichoptera	Goeridae	-	goera	z+	-	-	-	0.7	-	-	-
Trichoptera	helicopsychidae	*Helicopsyche*	helico	z-	-	-	-	-	0.43	8.37	-
Trichoptera	helicopsychidae	-	helico	z+	281	36	-	-	-	-	-
Trichoptera	Hydropsychidae	*Cheumatopsyche*	cheuma	z-	-	-	-	-	0.64	8.84	0.93
Trichoptera	Hydropsychidae	*Hydropsyche*	hydropsych	z-	27	-	-	-	-	-	-
Trichoptera	Hydropsychidae	*Ceratopsyche*	cera	z+	34	21	7.7	-	-	-	-
Trichoptera	Hydropsychidae	-	cheuma	z+	-	-	-	0.38	-	-	-
Trichoptera	Leptoceridae	-	leptoc	z-	-	46	-	-	-	-	-
Trichoptera	Leptoceridae	*Mystacides*	mysta	z-	-	33	6.9	-	-	-	-
Trichoptera	Philopotamidae	*Chimarra*	chim	z-	-	-	-	0.18	-	-	-
Trichoptera	Philopotamidae	-	chim	z+	-	50	8.5	-	0.7	3.3	-
Trichoptera	Polycentropodidae	*Polycentropus*	polycent	z-	-	-	0.4	-	-	-	-
Veneroida	Pisidiiae	-	pisid	z-	-	-	-	0.18	-	-	-
Veneroida	Pisidiiae	-	pisid	z+	-	-	-	-	0.69	3.15	-

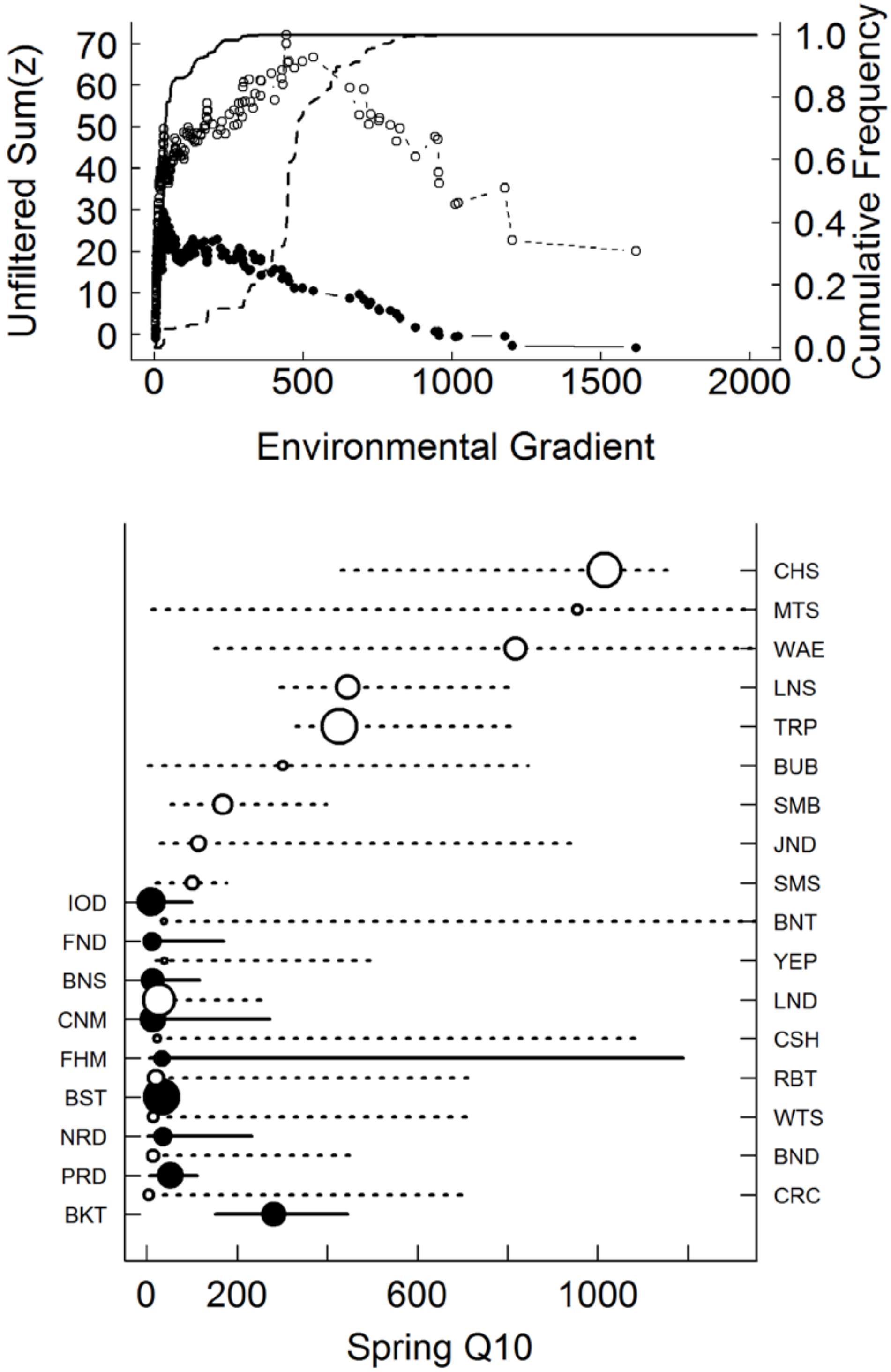


Figure 7.7. Threshold Indicator Taxa ANalysis (TITAN; Baker and King 2010) of fish community response to spring high flows (SPR_Q10) (n = 231). The community threshold for declining taxa occurs at ~33 cfs (90% confidence interval (C.I.) of 10-180 cfs); for positive taxa, at ~69 cfs (C.I. 40-128 cfs).

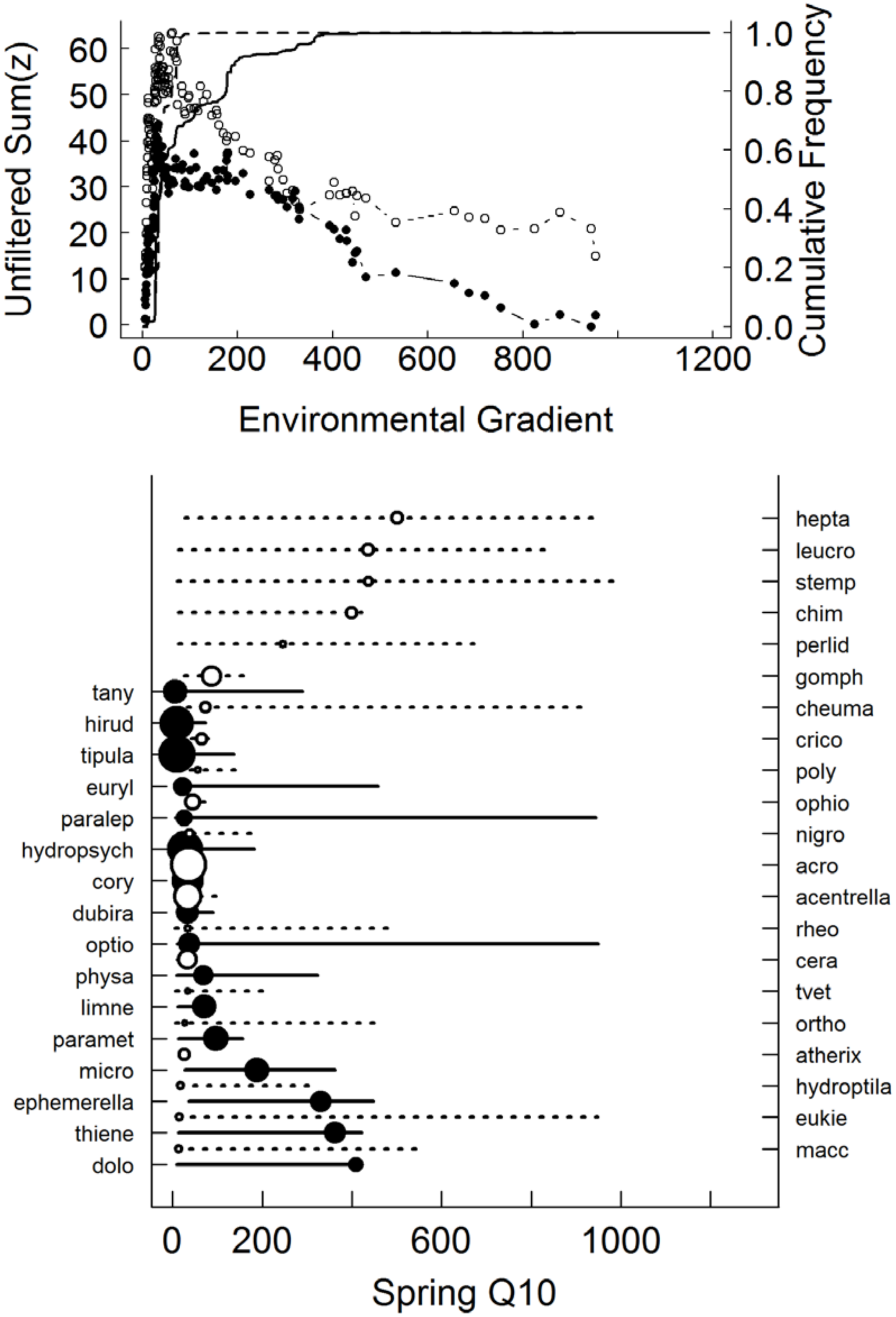


Figure 7.8. TITAN for macroinvertebrate community response to spring high flows (SPR_Q10) (n = 156). The community threshold for declining taxa occurs at ~33 cfs (C.I. 25-43 cfs); for positive taxa, at ~61 cfs (C.I. 34-983 cfs).

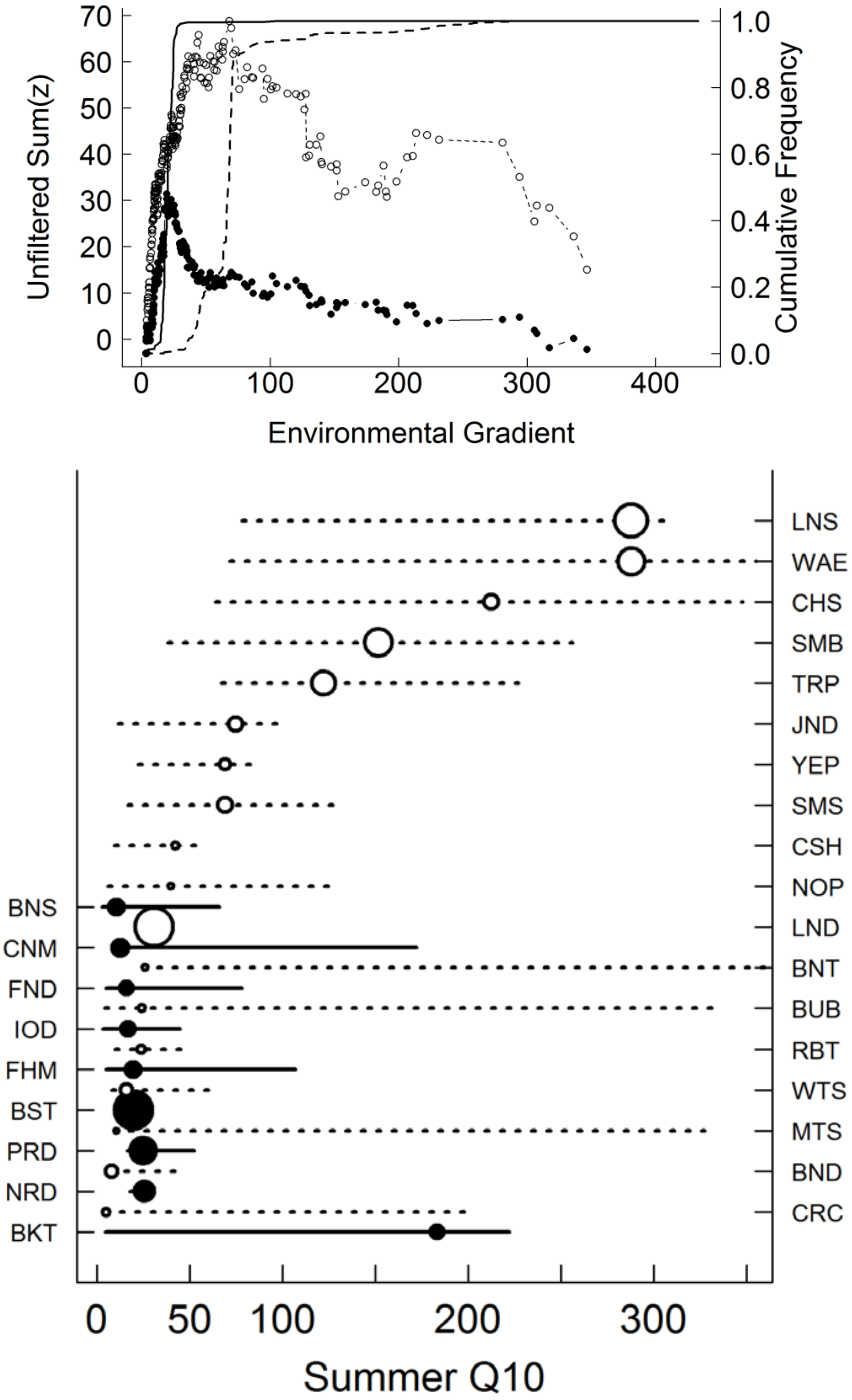


Figure 7.9. TITAN for fish community response to summer high flows (SUM_Q10). The community threshold for declining taxa occurs at ~21 cfs (C.I. 13-26 cfs); for positive taxa, at ~42 cfs (C.I. 21-43 cfs).

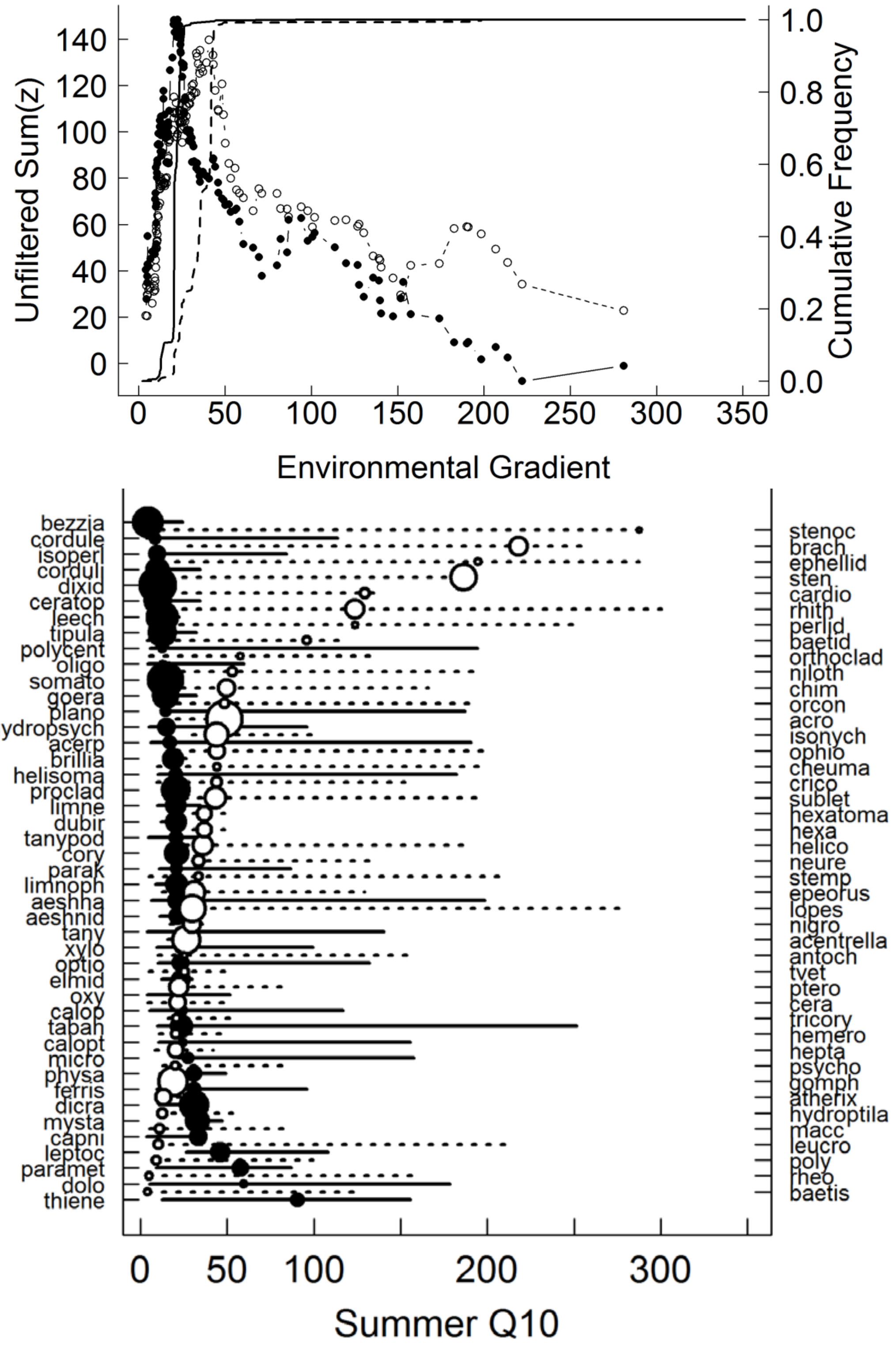


Figure 7.10. TITAN for invertebrate community response to summer high flows (SUM_Q10). The community threshold for declining taxa occurs at ~23 cfs (C.I. 13-26 cfs); for positive taxa, at ~42 cfs (C.I. 20-43 cfs).

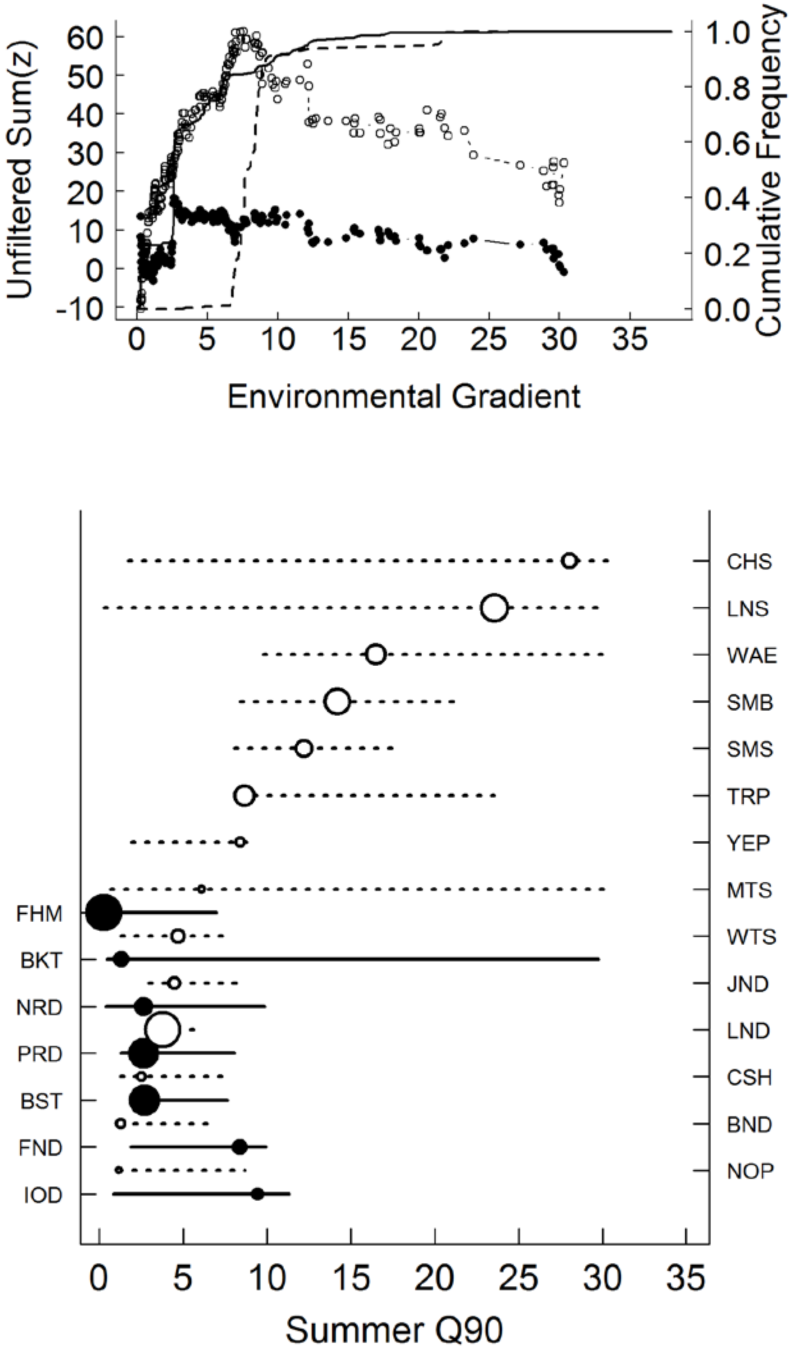


Figure 7.11. TITAN for fish community response to summer low flow (SUM_Q90). The community threshold for declining taxa peaks at ~2.6 (90% CI 0.25-13); for positive taxa, the peak is at ~7.4 cfs (C.I. 6.8-16 cfs). Only pearl dace (PRD), brook stickleback (BST), and longnose dace (LND) show both strong response and a narrow range of values for the 90% confidence interval.

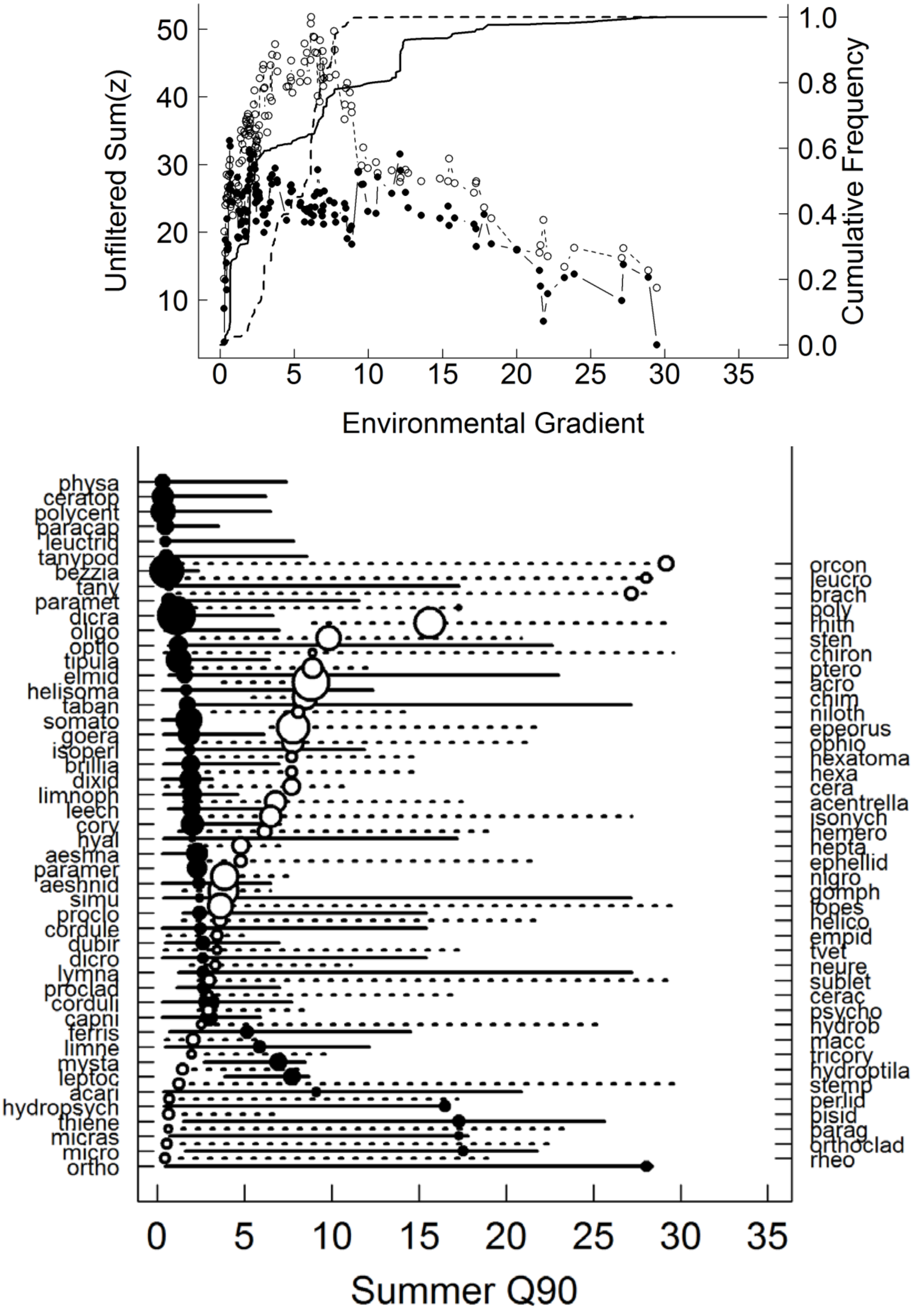


Figure 7.12. TITAN of macroinvertebrate community response to summer low flow (n = 156). The most significant change point (c.p.) for negative indicator taxa occurs at 2.3 cfs (0.36-6.0 cfs); for positive taxa at 7.7 (C.I. 2.8-8.7 cfs).

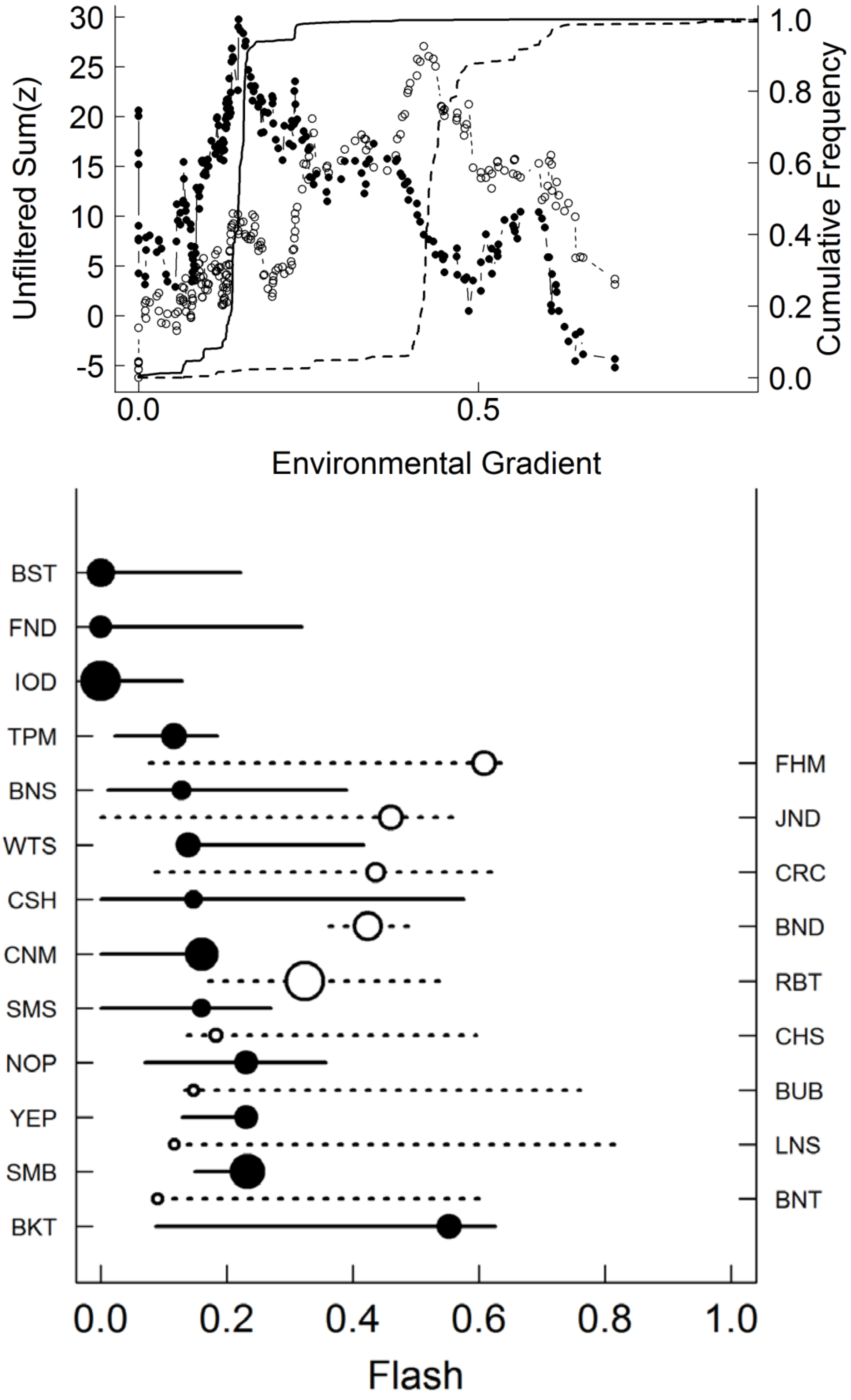


Figure 7.13. TITAN of fish community response to flashiness (defined as flow that increases and decreases rapidly with precipitation; n = 231). The threshold for declining indicator taxa occurs at ~0.15 (C.I. 0.09-0.23), with smallmouth bass (SMB) and Iowa darter (IOD) showing the strongest response. For positive taxa, the peak occurs at 0.42 (C.I. 0.33-0.61).

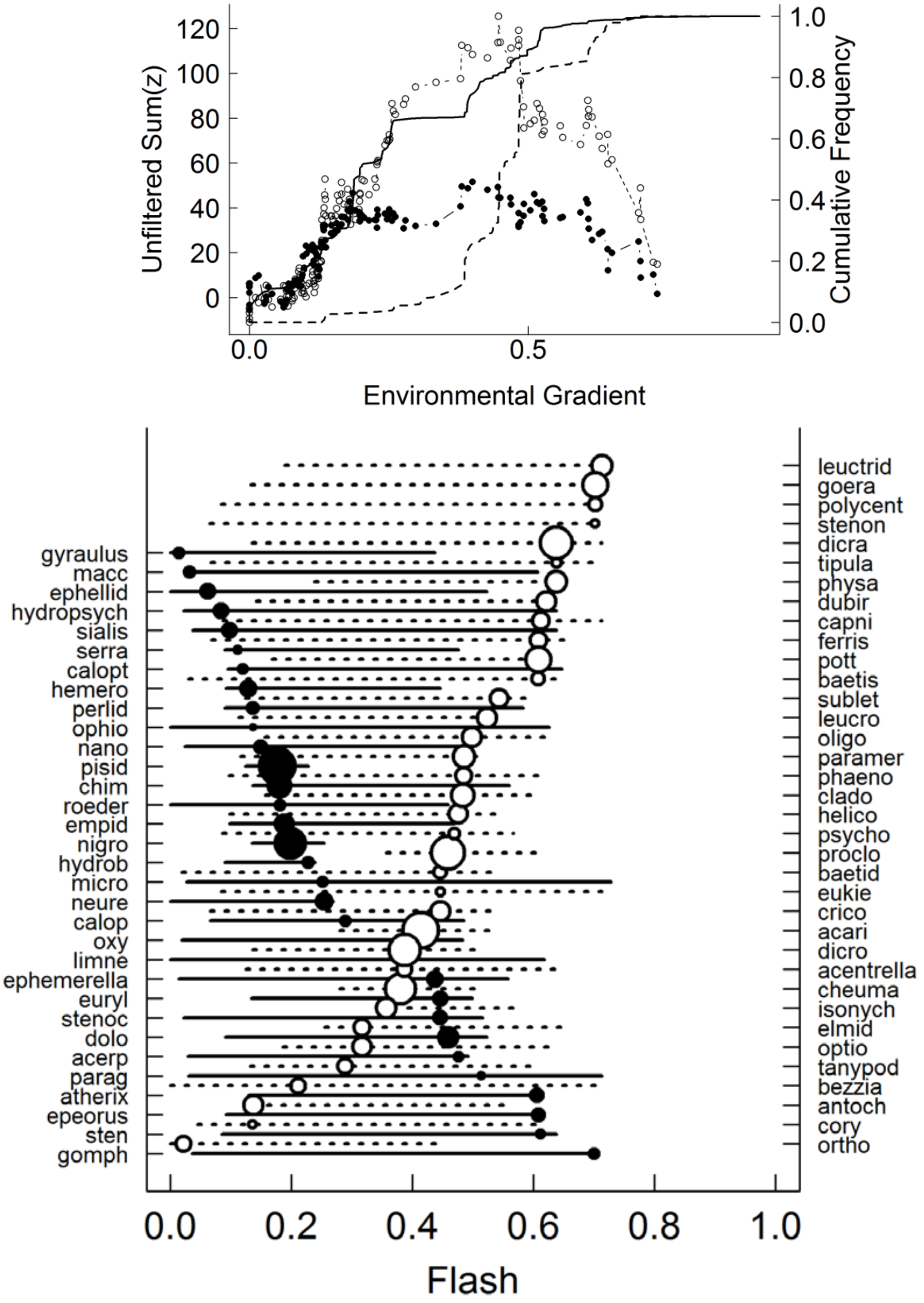


Figure 7.14. TITAN of macroinvertebrate community response to Flashiness (n = 156). The threshold for declining (sensitive) taxa occurs at ~0.41 (C.I. 0-0.5), and for positive indicator taxa at 0.45 (C.I. 0.26-0.64). Confidence intervals suggest the response is not highly specific.

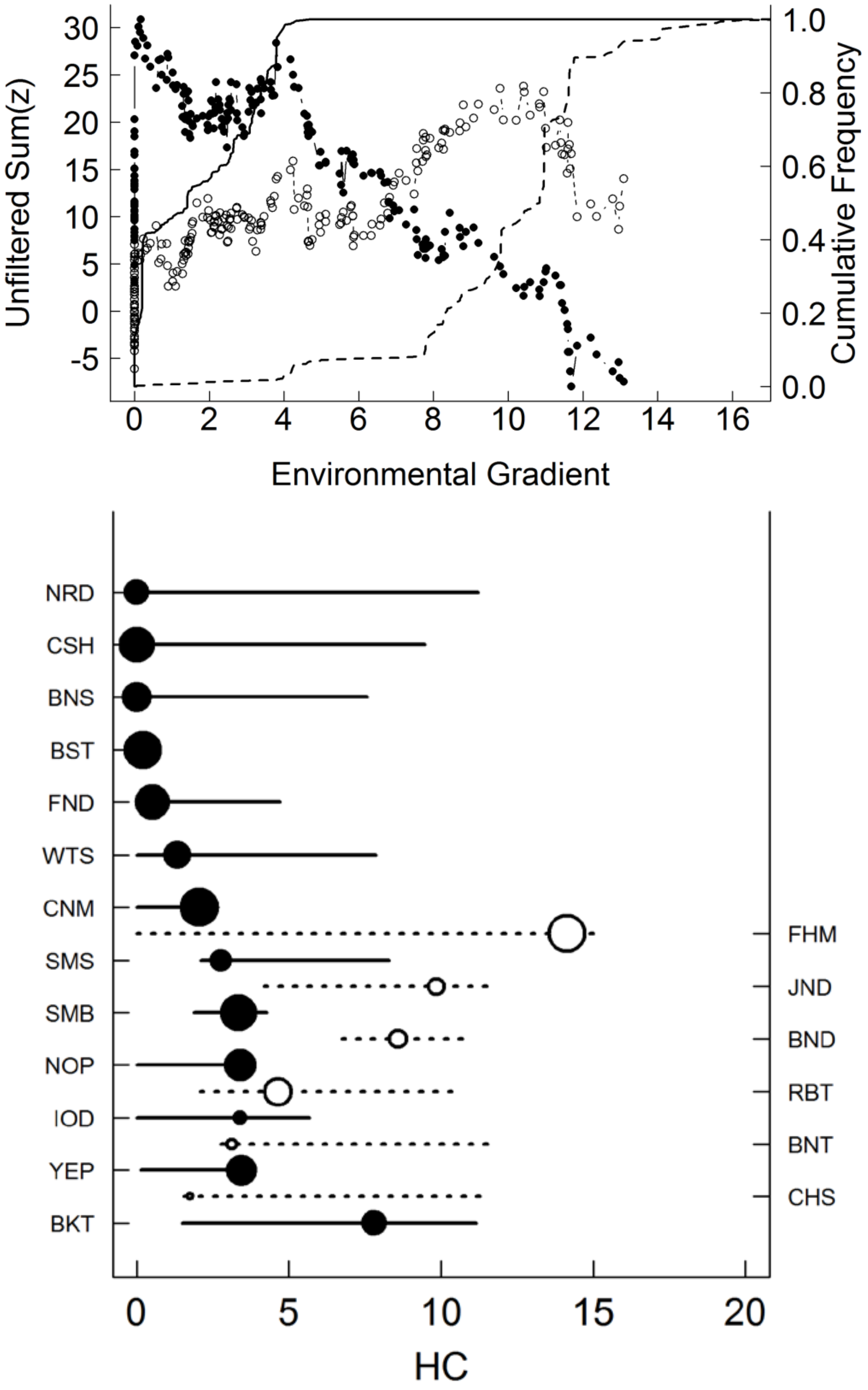


Figure 7.15. TITAN of fish response to High Flow Count (HC) shows a peak community threshold at 0.2 for negative indicator taxa, and at ~10 for tolerant taxa. Brook stickleback and smallmouth bass both show strong magnitude response combined with a narrower confidence interval.

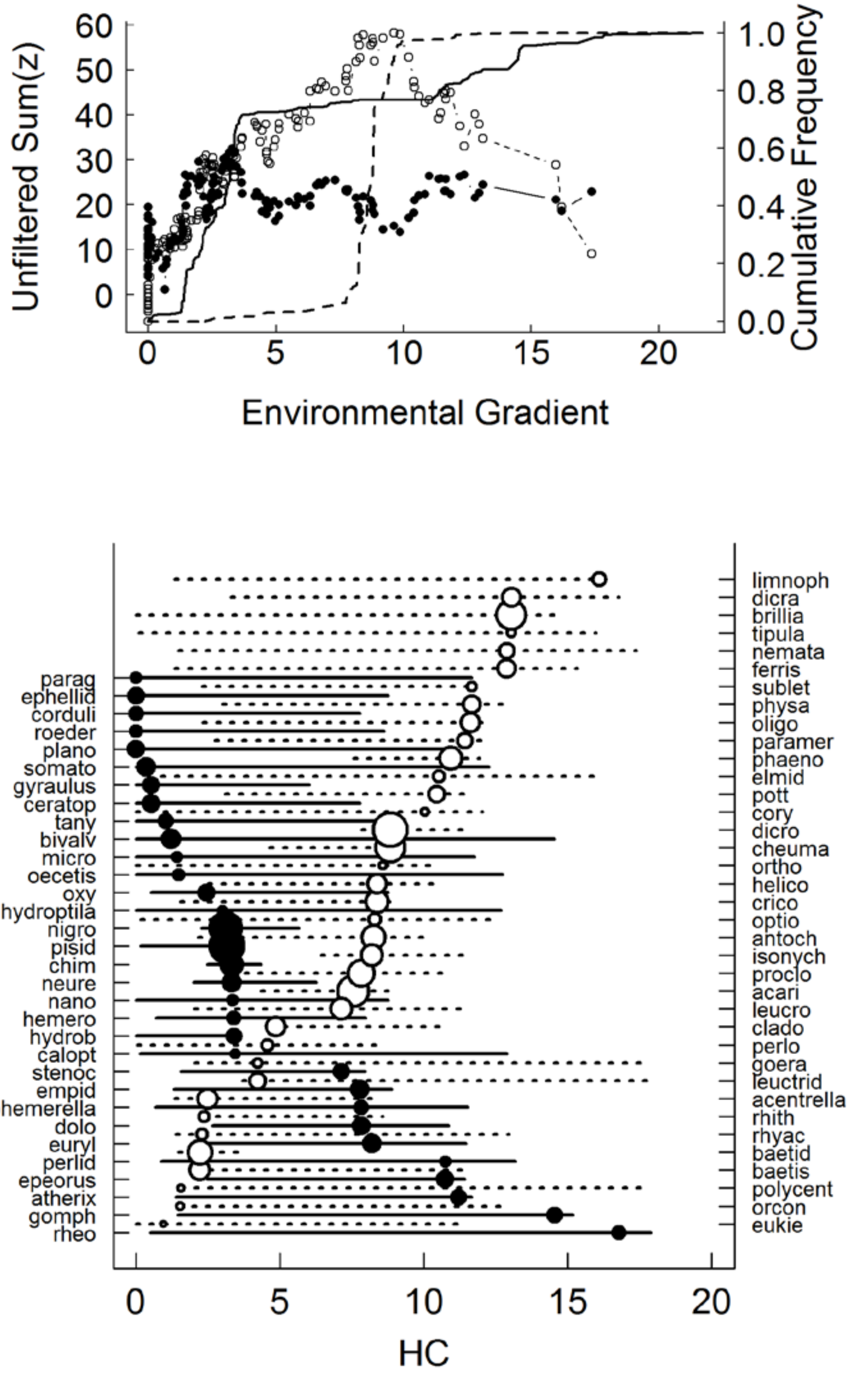


Figure 7.16. Community threshold for invertebrate communities for High Flow Count (HC). The community threshold occurs at around 2 events for declining taxa and ~9.7 for positive indicator taxa. Individual taxa showing narrow range of response and strong change points are listed in Tables 7.6-7.8.

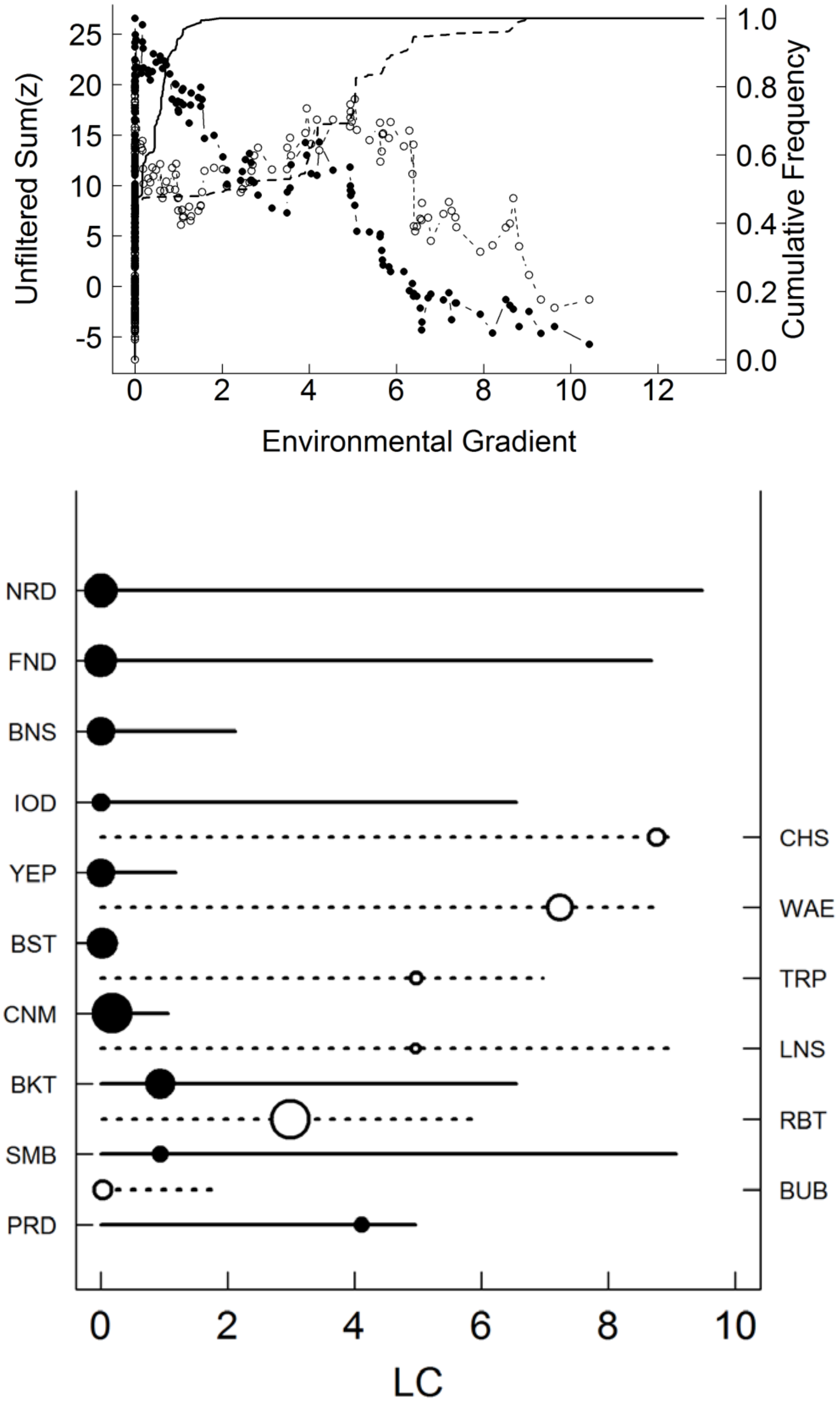


Figure 7.17. Community threshold for Low Flow Counts occur near zero with wide range of counts for most sensitive taxa: blacknose shiner, brook stickleback, yellow perch, and central mudminnow are strong indicator taxa that decline as the low flow events increase. There is no single community threshold for tolerant taxa.

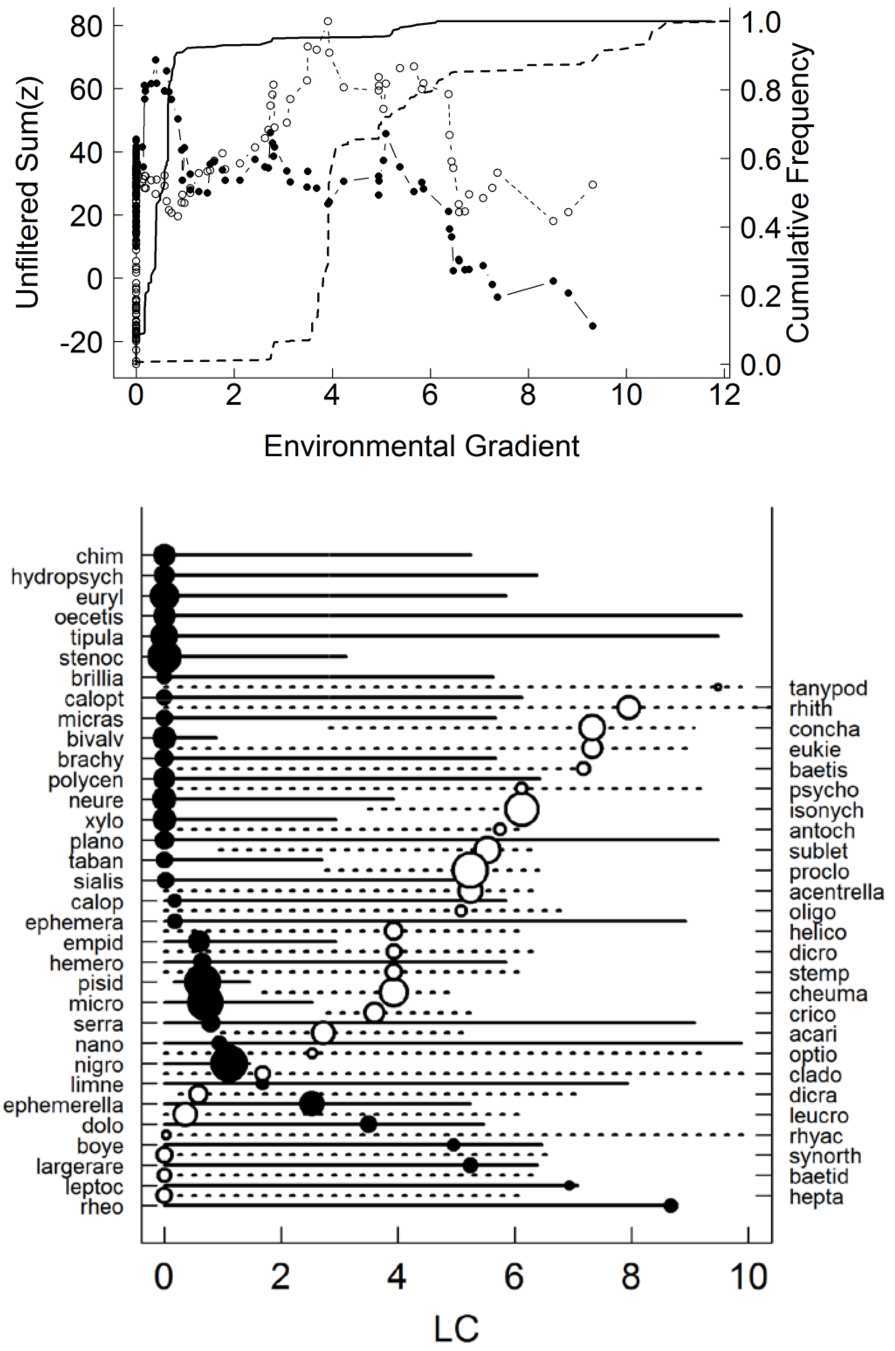


Figure 7.18. For low flow count, the invertebrate community threshold is < 1 for declining (sensitive) taxa (LC= 0.4).

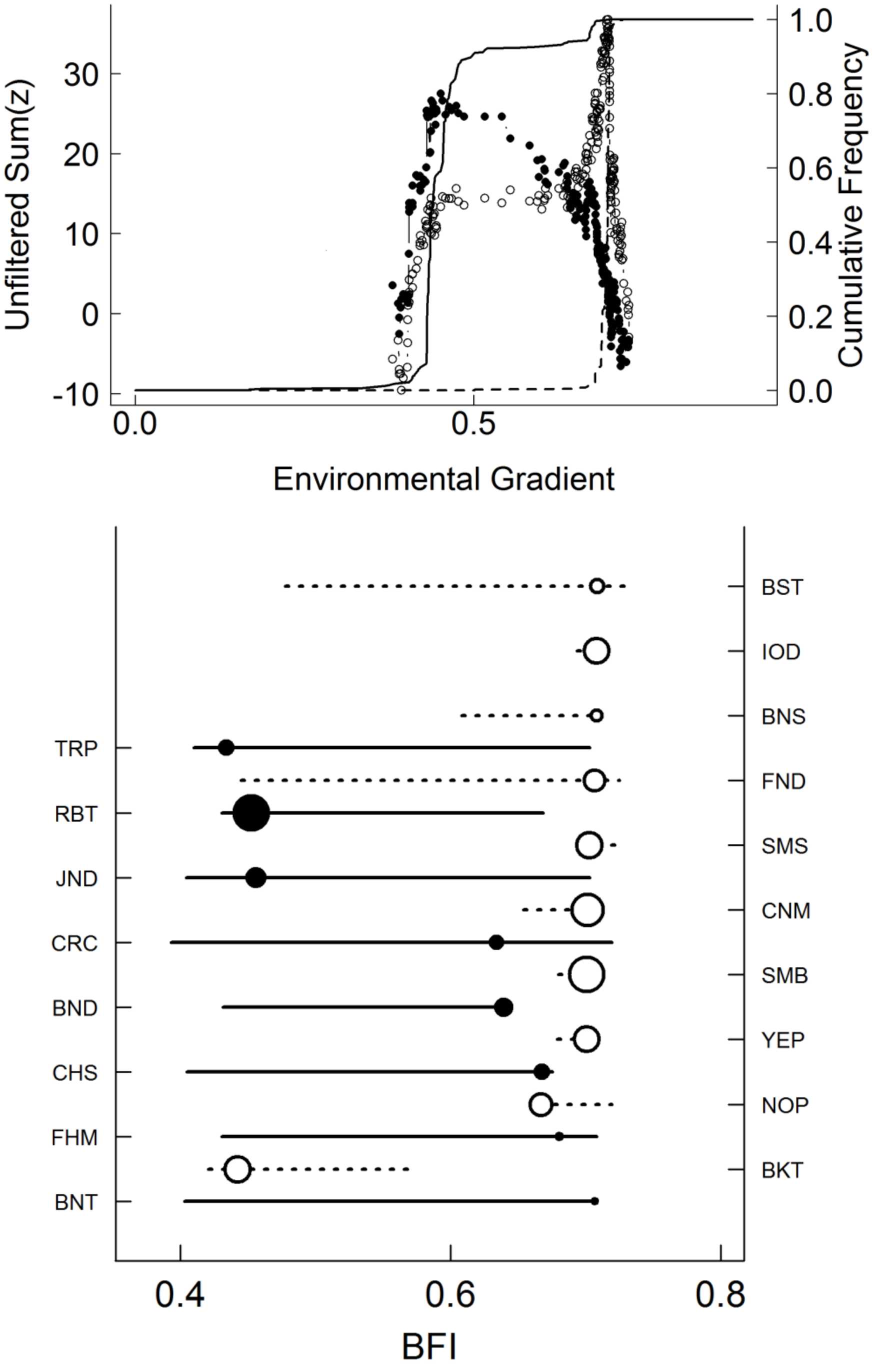


Figure 7.19. TITAN for fish community response to baseflow index (BFI). The community threshold for declining taxa is at 0.45 (0.42-0.67), with the strongest response shown by rainbow trout (RBT) (individual z value at ~0.45). Positive taxa show a fairly tight response with a community threshold at 0.70 and a narrow 90% C.I. (0.68-0.71). Brook trout (BKT) show a fairly strong positive response with a change point at 0.44.

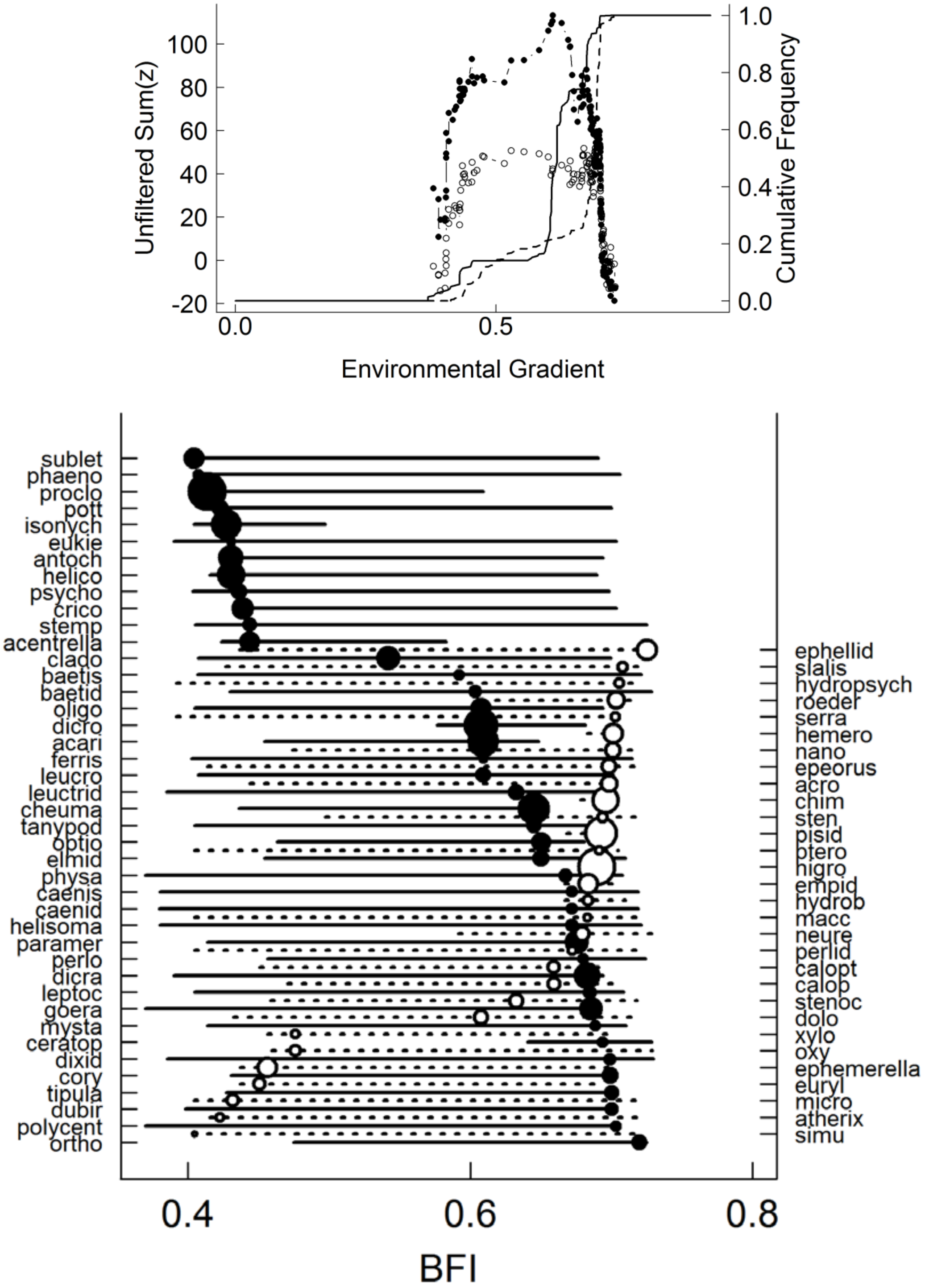


Figure 7.20. TITAN for invertebrate community response to baseflow index (BFI). The community threshold for declining taxa is at 0.62 (0.43-0.69). Positive taxa show a fairly tight response with a community threshold at 0.69 (C.I. 0.44- 0.70).

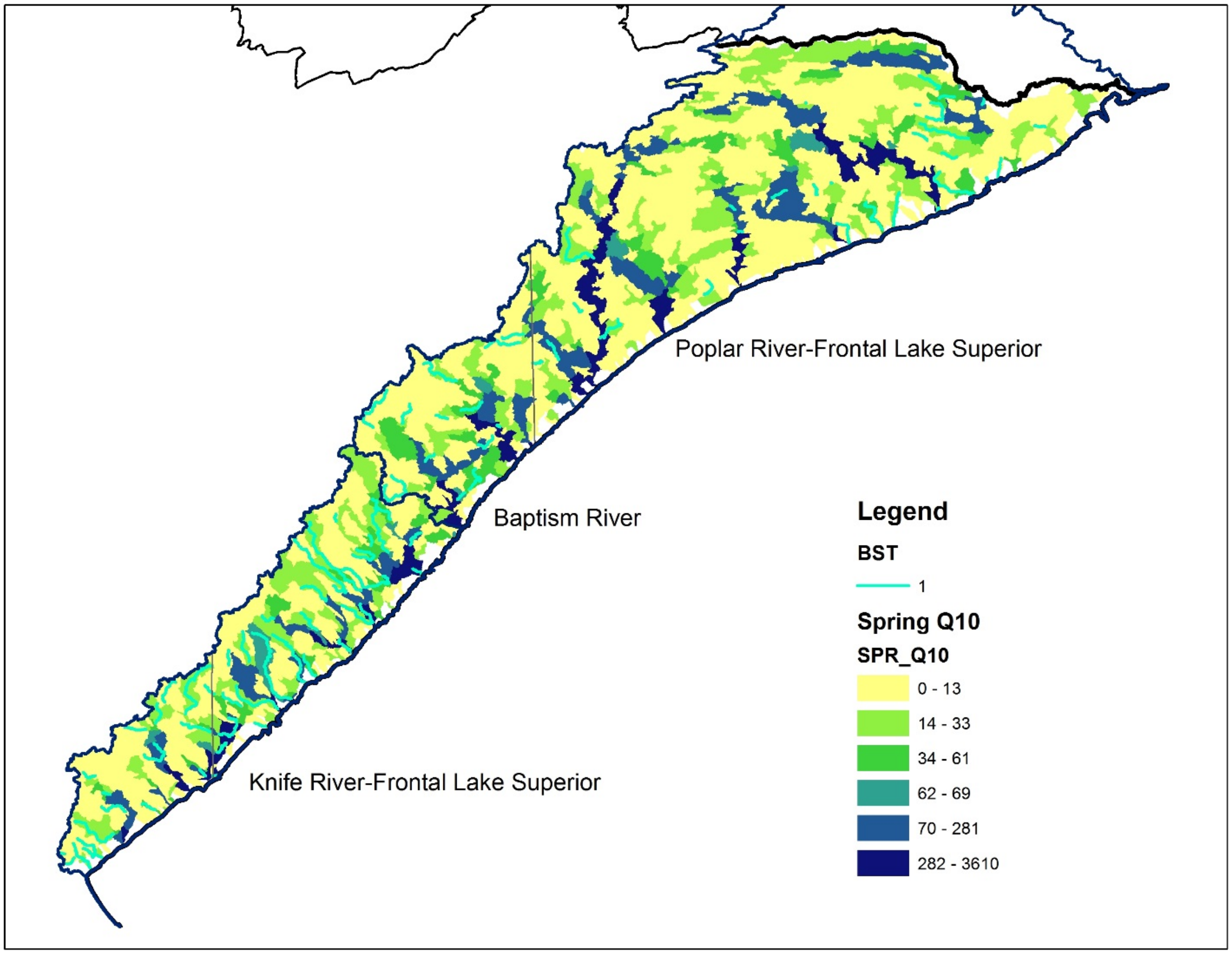


Figure 7.20. Brook stickleback (BST) presence/absence in relation to spring high flow (SPR_Q10) empirical model estimates under current, historical climate. Legend color breaks correspond to TITAN community thresholds (see Table 7.6). The change point for Brook stickleback (BST) --34-- is similar to the community threshold for sensitive fish and invertebrates (light green to dark green transition). The community threshold for "tolerant" invertebrate taxa is 61, for "tolerant" fish at 69 (light blue to dark blue). Brook trout show a positive z-score at 281. Central mudminnow and Iowa darter show a declining threshold at 10-13 cfs (yellow to green transition).

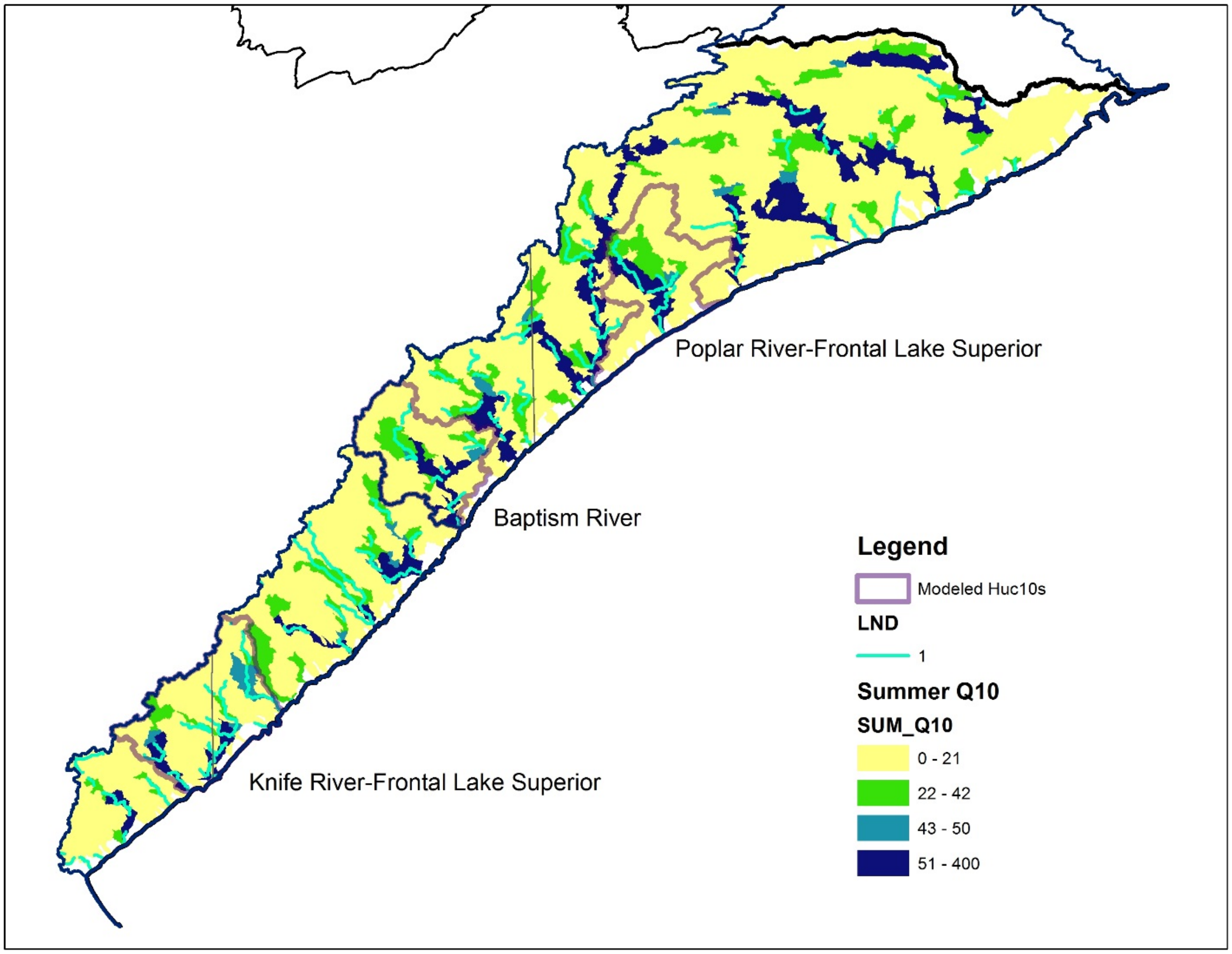


Figure 7.22. Longnose dace (LND) presence/absence shown in relation to summer high flow (SUM_Q10), empirical model under the current/historical conditions. The TITAN community threshold for declining fish and macroinvertebrates is ~21 cfs (yellow to green transition); for increasing taxa, ~42 cfs (see Table 7.6).

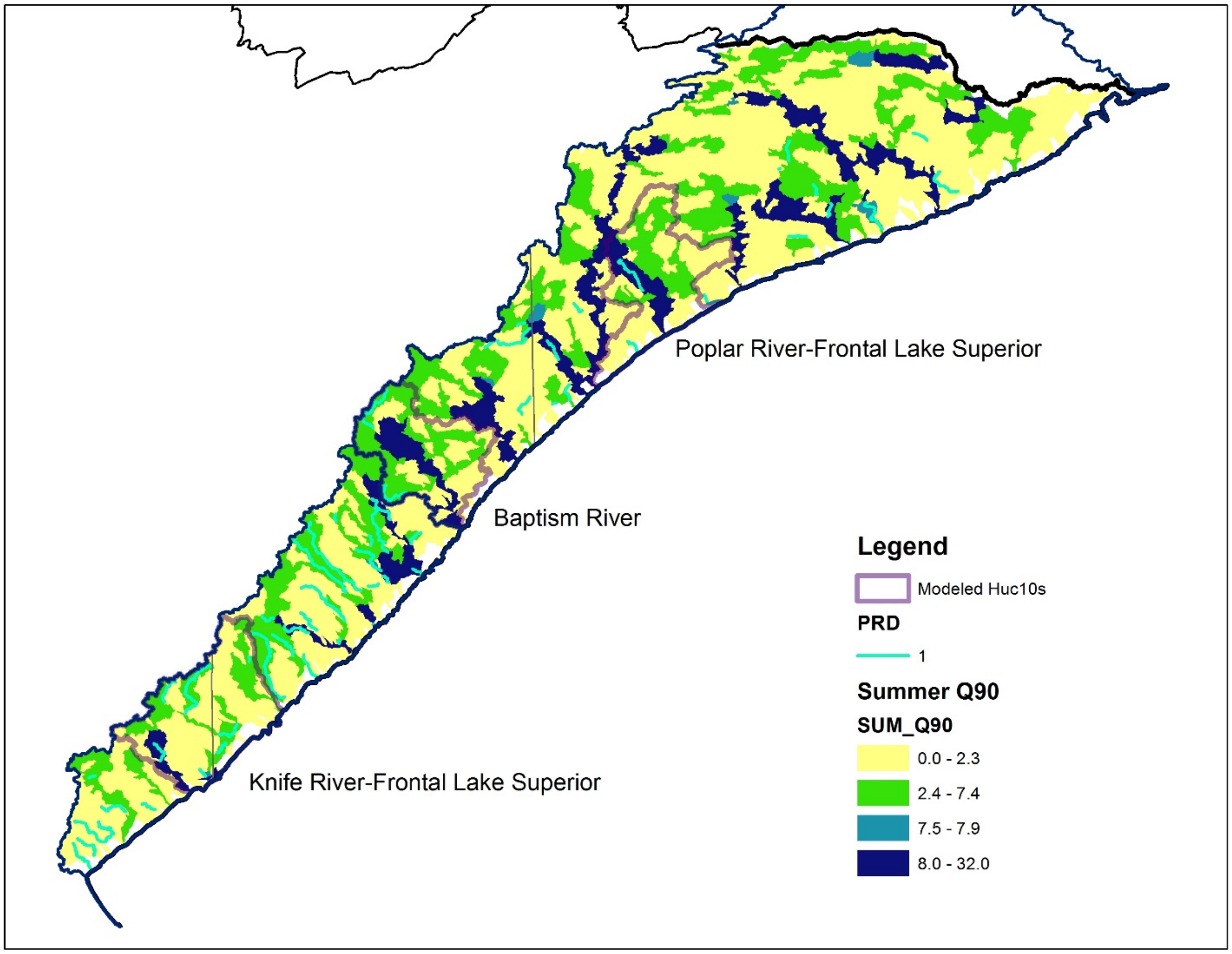


Figure 7.23. Pearl dace (PRD) presence/absence shown in relation to summer low flow (SUM_Q90), empirical model under current, historical climate. Legend color breaks correspond in part to TITAN community thresholds (see Table 7.6). Pearl dace and brook stickleback, both species of smaller streams, decline at low flows above 2.6, close to the overall community threshold. Fathead minnow (FHM), which had a significant negative change point at 0.26 cfs, is one of the most tolerant, generalist species in both warmwater and coldwater streams of the upper Midwest, suggesting it dominates in streams with very low summer low flows. Numerous other taxa had positive threshold responses at higher values of summer low flow (see Tables 7.7 and 7.8).

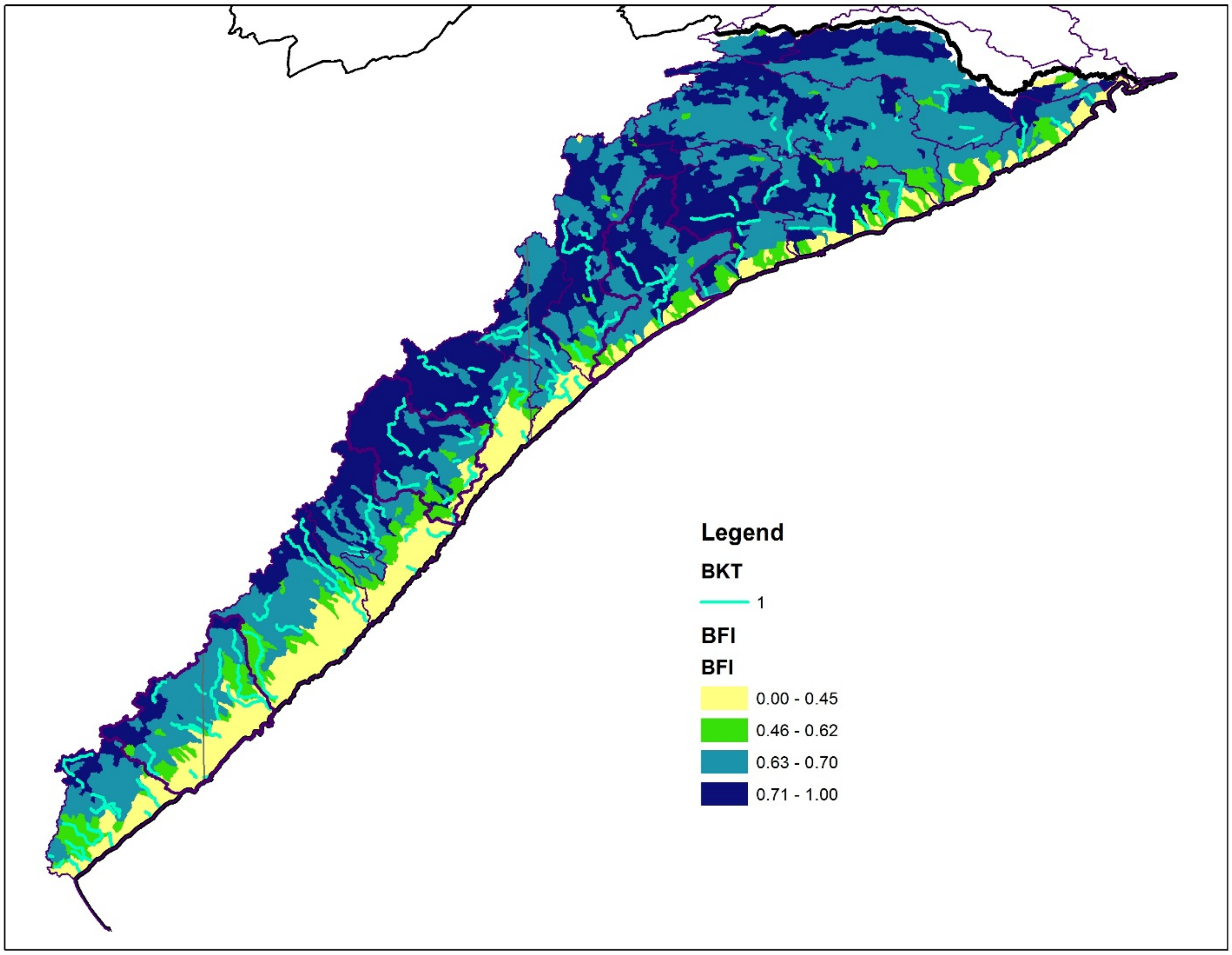


Figure 7.24. Brook trout presence/absence shown in relation to baseflow index (BFI), empirical model under the current/historical conditions. Legend color breaks correspond to TITAN community thresholds (see Table 7.6). Species that show a positive threshold response for higher values of baseflow index, which is highest in the most upstream reaches of the study area catchments, include central mudminnow, yellow perch, and smallmouth bass. These are species often associated with lake and wetland habitats that are also more prevalent in upstream catchments.

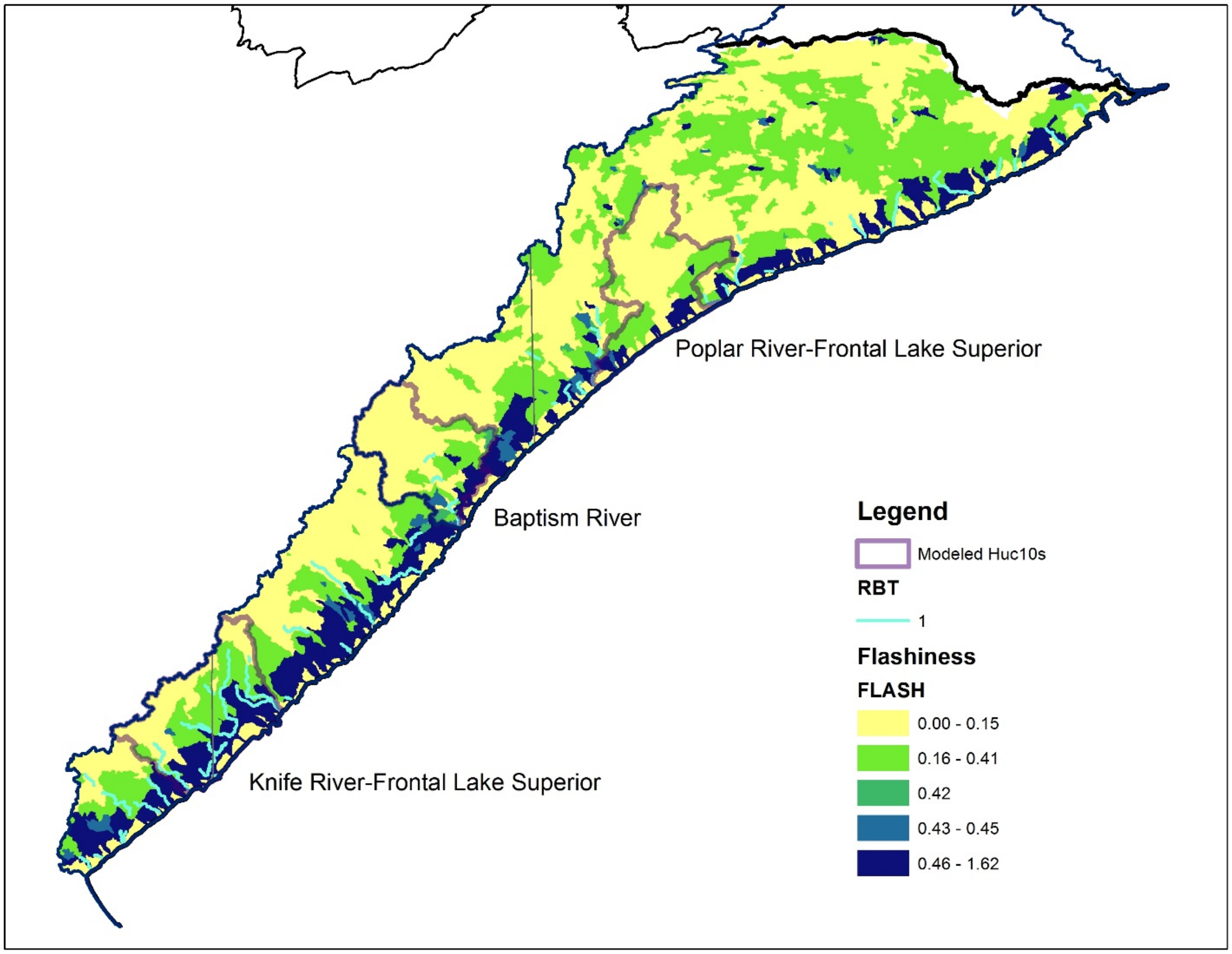


Figure 7.25. Rainbow trout (RBT) presence/absence overlaid with empirical estimates of flashiness under current, historical climate. The community threshold for flashiness is around 0.15 for sensitive species and 0.42 for increasing taxa (Table 7.6). RBT are "tolerant" for flashiness, with an individually significant positive change point at 0.32 (Table 7.7). Iowa darter, central mudminnow, and smallmouth bass are sensitive to flashiness, which is highest in Lake Superior-South and for streams closest to Lake Superior (crossing the escarpment).

Anticipating Biological Response under Future Flows

Community thresholds detected in TITAN

We compared baseline flows to modeled future flows for each of the four climate and land cover scenarios, and calculated the number of reaches where the change from baseline flows to future flows crosses a predicted community threshold value for any of the flow metrics. For negative indicator taxa, we identified where flow metrics under the baseline scenario do not exceed the threshold, but do exceed it under the modeled scenario. For positive taxa thresholds, we identified reaches where the reverse is true. Under the future land cover scenarios (high and low emissions scenarios), less than 10% of reaches, and usually a smaller percentage than that, cross a threshold between the baseline and modelled scenario for any given flow metric. However, under the cooler, wetter (GFDL) climate scenario, nearly 1/3 of reaches cross a fish (30%) or macroinvertebrate (28%) community threshold for declining indicator taxa due to increases in both high and low flows. For the warmer, drier (Hadley) climate scenario, 17% of reaches cross the fish community threshold for declining indicator species for flashiness, and 18% of reaches cross a fish community threshold for increasing taxa for one or more flow metrics--in other words, under the baseline scenario, the flow statistic exceeds the community threshold for those taxa, whereas in the future modeled scenario, it does not. For macroinvertebrate taxa, three climate scenarios – low emissions, high emissions, and Hadley—result in flow alterations that cross thresholds for declining taxa affecting about 10% of reaches. The GFDL scenario affects more than 1/3 of modeled reaches. Under the Hadley scenario, the decrease in high flow counts results in a threshold potentially affecting 100% of reaches; however, this threshold response is associated with the high flow count threshold, which has extremely wide confidence intervals for both community and individual taxa response.

Table 7.9 summarizes for the three modeled watersheds the number of reaches that cross thresholds under the different scenarios for each flow metric.

Table 7.9. Count of reaches where current versus future flows cross TITAN community thresholds.

	Scenario	SPR Q10	SUM Q10	SUM Q90	BFI	FLASH	HC	LC	ANY
Fish									
Z- (negative)									
Count	HE	-	-	-	-	-	-	-	0
Percent	HE	-	-	-	-	-	-	-	0%
Count	LE	-	-	-	-	7	-	-	7
Percent	LE	-	-	-	-	2%	-	-	2%
Count	GFDL	5	19	77	-	20	-	-	102
Percent	GFDL	1%	6%	23%		6%	-	-	30%
Count	Hadley	-	-	-	-	56	-	-	56
Percent	Hadley	-	-	-	-	17%	-	-	17%
Z+ (positive)									
Count	HE	-	-	1	4	-	2	-	7
Percent	HE	-	-	0%	1%	-	1%	-	2%
Count	LE	2	0	1	-	-	2	0	5
Percent	LE	1%	-	-	-	-	1%	-	1%
Count	GFDL	1	-	-	17	-	-	-	18
Percent	GFDL		-	-	5%	-	-	-	5%
Count	Hadley	24	26	16	1	6	2	-	59
Percent	Hadley	7%	8%	5%	0%	2%	1%	-	18%
Macroinvertebrates									
Z- (negative)									
Count	HE	-	-	-	-	3	33	-	36
Percent	HE	-	-	-	-	1	10%	-	11%
Count	LE	-	-	-	-	-	34	-	34
Percent	LE	-	-	2%	1%	-	10%	-	10%
Count	GFDL	5	19	79	4	18	19	1	115
Percent	GFDL	1%	6%	24%	1%	5%	6%	0%	34%
Count	Hadley	-	-	0	13	3	0	22	38
Percent	Hadley	-	-	0%	4%	1%	0%	7%	11%
Z+ (positive)									
Count	HE	-	-	-	-	-	-	-	1
Percent	HE	-	-	-	-	-	-	-	
Count	LE	-	-	-	-	-	-	-	1
Percent	LE	-	-	-	-	-	-	-	
Count	GFDL	1	-	8	-	-	-	6	15
Percent	GFDL	0%	-	2%	-	-		2%	4%
Count	Hadley	19	26	16	-	10	332	0	334
Percent	Hadley	6%	8%	5%	-	3%	99%	-	100%

Percent change based on presumptive "sustainability boundaries"

The percentage of reaches that experience significant flow regime changes using presumptive sustainability boundaries from the literature is even greater than those identified using community threshold values. Table 7.10 shows percent of the reaches where the difference between baseline and modelled future flows exceeds the magnitude proposed as a "sustainability boundary" for each of the key flow metrics. Under the warmer, drier Hadley model scenario, for example, 99% of reaches experience a 5% or greater decline in summer low flows, and nearly 100% of reaches have summer low flow declines of 10% or greater. 69% of reaches experience a 20% or greater decline in one or more flow metric. More importantly, essentially all reaches experience a more than 20% reduction in spring and summer peak flows.

Increased flows also exceed presumptive sustainability boundaries for percent change. Under the cooler, wetter GFDL scenario, 100% of reaches experience more than a 20% increase in summer peak flow magnitudes, and one-third of reaches experience more than a 20% increase in spring peak flows.

Table 7.10. Percent of reaches (n=335) potentially exceeding "sustainability boundaries" for key flow metrics between the baseline and four modeled future land cover and climate scenarios.

Predicted change:	% Change from baseline flow to: HE	% Change from baseline flow to: LE	% Change from baseline flow to: GFDL	% Change from baseline flow to: Hadley
20% increase (any flow metric)	1%	1%	53%	8%
20% decrease (any flow metric)	2%	1%	7%	69%
20% increase (SPR_Q10)	0%	0%	34%	0%
20% increase (SUM_Q10)	0%	0%	100%	0%
20% decrease (SPR_Q10)	0%	0%	0%	100%
20% decrease (SUM_Q10)	0%	0%	0%	99%
5% SUM_Q90 decrease	45%	67%	0%	99%
5% AUT Q90 decrease	24%	72%	3%	99%
5% decrease in BFI	0%	0%	27%	1%
10% increase in FLASH, HC, or LC	8%	8%	49%	47%
10% SUM_Q90 decrease	13%	39%	0%	99%
10% AUT_Q90 decrease	9%	30%	1%	99%

Overall results suggest that Minnesota's Lake Superior tributary reaches are likely to experience significant community changes under our future modeled scenarios.

Discussion

Overall, our analysis shows potentially dramatic changes to stream flow regimes under some climate and land cover scenarios. However, the relationship between flow metrics and biological response is not highly predictive. Community "thresholds" identified in TITAN, although significant, do not appear to enable robust characterization of resilience and vulnerability across the entire set of reaches. Minnesota's Lake Superior tributaries are similar with respect to physiography, landform, climate, and topography, and it is possible there is less variation in stream types with respect to flow across our study region than we hypothesized, an observation that would be supported by our inability to develop a clean hydrologic classification.

Our lack of ability to predict the fish assemblages based on flow conditions alone suggests that these communities may be composed of generalists with respect to their adaptation to flow and possibly to temperature. Minnesota's Lake Superior tributary fish communities are likely already somewhat adapted to high inherent variability with respect to flow and habitat variables controlled by flow. Alternatively, it is possible that the set of flow metrics we analyzed, representing long-term average flow conditions, does not capture key drivers of variability in fish and macroinvertebrate communities in Minnesota's Lake Superior tributaries since much of the flow variability occurs season-to-season and year-to year, nuance that is not fully represented in the long-term average.

Biological community response to current flows

Overall, flow metrics derived empirically for Minnesota's Lake Superior tributary reaches, extrapolating from HSPF models, explained less than 10% of variance in stream fish and macroinvertebrate response, whether we were looking at presence/absence, abundance, or community metrics. There are a number of potential reasons why our results did not provide stronger evidence of stream community response to flow regime. Flow metrics designed to characterize the natural flow regime do not necessarily provide direct indicators of other important variables known to influence stream biological composition, such as temperature, instream cover, and longitudinal connectivity, even to the extent that these variables are structured or mediated by flow regime. It is also possible that at the scale of the relatively homogeneous study area, variation in flow regime is not a dominant ecological gradient. Nevertheless, given expected changes in future climate as well as potentially major changes in land cover, our own results and the weight of evidence from previous studies suggest that changes in flow regimes will likely interact with temperature to impact instream biological communities. Johnson et al. (2013), for example, successfully predicted the presence of brook trout for Minnesota's Lake Superior tributaries as a function of baseflow, July mean temperature, and absence of deciduous vegetation in the riparian zone (a variable found to be closely related to differences in surficial geology across the study region).

Another major reason for the low proportion of variance explained in species/taxa assemblages may stem from the fact that we are averaging both flows and biological response over multiple decades, whereas clearly in many cases, it is seasonal and interannual variability in climate and flow regime that drives life history, behavioral and physiological adaptations (Rose 2000). Many studies document significant variation in reproduction, growth, and recruitment (year class strength) in response to interannual variability in flow and habitat conditions for trout and other managed fisheries. For example, for a brook trout population in Massachusetts, Xu and colleagues (2010) found that variation related to temperature and flow conditions occurred within seasons and years relative to other years. That is, growth was fast during the spring if it was relatively warm, but slow if it was relatively cold; whereas relatively warmer temperatures in the summer and fall meant less growth. Similarly, relatively higher flows were good for growth during spring, summer, and fall, but “bad” during the winter. Ayllón et al (2014) found that trout from rivers with highly variable flow and more frequent, longer, and stronger extreme flow events were more willing to occupy positions in high-velocity habitats but also showed stronger pattern of habitat use selection for velocity refuges than trout from more stable environments. Shifts in habitat selection patterns across years differing in flow conditions were markedly stronger in rivers with higher extreme flows and flow variability. We were unfortunately unable at this time to explore these and related hypotheses with existing biological datasets. For the MPCA dataset, less than 15% of reaches have been sampled repeatedly over three or more years. Furthermore, nearly all sampling has been done in the months of June, July, and August, when important habitat use related to migratory life histories (e.g., fall or spring run migrations to/from Lake Superior or inland lakes) is likely to be overlooked. For example, Blankenheim (2013) found increased abundance, especially for larger coaster brook trout in 2013, compared with 1997 and 2002. However, fish were sampled in October and November, and more than 50% of fish sampled were sampled at water temperatures below 4.2°C (40°F). They suggested that brook trout tend to enter streams to spawn late in the fall when water temperatures are cold.

We also found flow metrics explained a small but significant percentage of variance in the fish and invertebrate tolerance metrics that are used by the MN Pollution Control Agency (MPCA) to assess stream condition. Although we expected to see a relationship between flow metrics and those IBI metrics that are indicative of or associated with hydrologic disturbance, IBI metrics are designed to reflect a gradient of disturbance rather than baseline habitat conditions.

At the same time, it is very likely that the effects of temperature and flow are confounded and cannot be separated using the current data. An ongoing study by Johnson, Herb, and others may provide further data to tease apart these relationships.

In addition to high interannual variation and interaction effects between climate and population dynamics, Rose (2000) noted other challenges to establishing clear quantitative or empirical relationships between fish populations and environmental quality including community interactions, sublethal effects, overgeneralization across spatial scales, and cumulative and legacy effects of multiple stressors.

Anticipated responses to future flow changes

Overall, our analysis of fish and invertebrate community response to recent flow regimes suggests that many taxa exhibit significant threshold responses, although most occur across a wide range of flow conditions. Minnesota's Lake Superior tributary communities may remain relatively resilient over the next 50-100 years, at least with respect to flow. However, under more extreme scenarios such as the warmer, drier Hadley model scenario, we can expect significant reshuffling of fish and invertebrate communities towards those species and taxa more tolerant of extremes, including decreased summer low flows, lower spring and summer flows, and increased frequency of extreme events. Further, as the frequency of intense storms increases, flashiness will become more commonplace in this system. Hadley model scenarios shows a large decline in August flows which certainly is likely to exacerbate warming in streams already marginal for cold- or coolwater species based on thermal conditions. Highly reduced future spring flows and overall reduced variability in seasonal flows could definitely trigger some broader ecological changes, beyond the temperature and low flow impacts in summer.

Under the low emissions with modified forest management scenario, summer low flows are actually predicted to decrease by a greater percentage relative to the baseline than other scenarios. Under the cooler, wetter scenario, increased overall flows could benefit species tolerant of flashiness such as rainbow trout, provided there is sufficient connectivity in the system. Increased baseflow index could also benefit taxa that responded to baseflow, including brook trout. Overall, however, the majority of scenarios result in reduced summer low flows or increased frequency of high and low flow events, which will compound the effects of increased temperature and will likely reduce the extent of reaches supporting coldwater species.

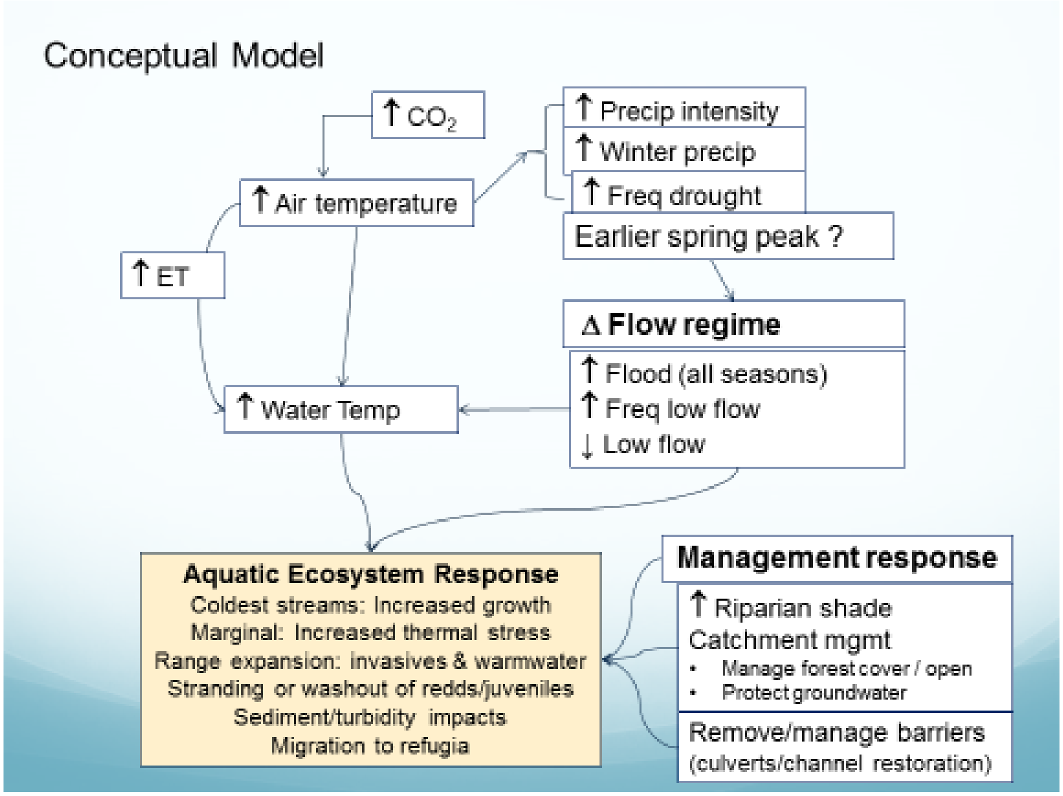


Figure 7.26. A conceptual model of aquatic ecosystem response to potential future flow regime changes.

Figure 7.26 presents a conceptual model of how aquatic ecosystems may respond to potential future flow regime changes. Increased CO_2 emissions lead to larger predicted increases in air temperature and evapotranspiration, which in turn leads directly to increased water temperature. At the same time, increased precipitation intensity, winter precipitation, and frequency of drought, as well as changes in timing of spring flows will drive changes in streamflow regimes, including potential increases in flood magnitude and frequency, increased frequency of low flows, decreased magnitude of low flows, and potential changes in the timing and duration of high and low flow events to which existing stream biological communities are adapted. Although increased temperature may lead to increased productivity in some of the coldest streams, many Minnesota Lake Superior tributaries are already marginal for coldwater species during summer and winter because of the dependence on surface water for flow. These streams may see increased thermal stress for cold and coolwater adapted species, and expansion of transitional and warmwater tolerant species.

Our four modeled scenarios do not just differ in magnitude, but are often inconsistent even with respect to the direction of change. This result underscores the enormous uncertainty still surrounding attempts to predict the direction and magnitude of climate change impacts. For example, the warmer, drier Hadley model scenario predicts significant decreases in summer baseflows, while the cooler, wetter GFDL climate scenario predicts increases. Thus an important take-home message is that managers should still hedge their bets in terms of selecting strategies that are "no regrets" – in other words strategies least likely to fail under realized conditions of either increased and/or decreased flows.

Conclusions

What have we learned?

We found that metrics that characterize aspects of the flow regime explain a small but significant percentage of variation in fish and invertebrate community composition and abundance. Although current flow metrics were not highly predictive, it is likely that future changes in flow will influence changes in biological communities, and therefore, would likely compound the temperature and habitat effects of climate and land cover change.

Fish and invertebrate species and communities exhibit coherent responses to flow metrics, especially spring high flows, summer low flows, and flashiness. **Both fish and invertebrate taxa exhibited significant community threshold responses to all flow metrics analyzed, especially the flashiness index, and low and high flow metrics**. Specifically, 10-40% of Minnesota Lake Superior tributary reaches are likely to experience significant community change thresholds (i.e., signifying either abrupt increases or decreases in abundance and distribution in response to changes in the flow regime) under our future modeled scenarios. Such changes in community composition can have significant effects on the food web and ecological functions of streams, making them less resilient to future change. Scenarios that result in large percentage increases in flows, especially seasonal high flow components, are even more likely to "cross" community thresholds for fish and invertebrates than warmer, drier scenarios resulting in lower overall flows. However, because of the interaction of temperature and flow, reaches may be more vulnerable to thermal changes under scenarios of reduced flows, even if they do not experience flow thresholds.

Management Recommendations

- Because the biota appears to be responding to extremes, future climate predictions should include not only annual and seasonal estimates, but also frequency and severity of extreme weather events.

- The link between past and present hydrologic processes and stream channel responses must be better understood to anticipate changes in erosion and sedimentation rates which profoundly influence instream habitat and influence flow-ecology relationships.

- Enhance current biodiversity surveys to better characterize baseline conditions to better inform management options. In particular, there is a need for better spatial and temporal coverage of sample sites, as well as enhanced population data to capture effects of extreme events (e.g., including both low and high flows).

- Additional information on baseline ecosystem processes, (e.g., production, decomposition, food web responses) are needed to better inform our understanding of the mechanisms underlying climate responses and factors that influence resilience.

- Enhance the accessibility and discoverability of existing data records by digitizing paper files and increasing accessibility to existing digital data.

There is growing consensus that future management of salmonids, especially in Minnesota's Lake Superior tributaries must include a strong emphasis on watershed management. As the frequency and severity of extreme weather events increases, there is a need to understand the likely range of event frequencies in order to guide adaptation and mitigation decisions around infrastructure, land use management, and forest harvest. Being able to anticipate conditions based on seasonal weather outlooks or trends (i.e., which sections of streams are anticipated to reach critically low flows and when, likelihood of severe winter impacts, and/or the likely magnitude of peak events in response to different storm forecasts) would be of value to managers so they can consider those outlooks and ensure that management actions have the intended results in spite of these weather events. There is a need to understand connections between past and present watershed hydrological processes and present and future stream channel response (Fitzpatrick 2014). Erosion or sedimentation problems may be displaced in both time and space from the original source, as hydrologic disturbances caused by weather events, land use change, or dams may migrate longitudinally (upstream or downstream) and may take decades or more to stabilize.

We need to continue to develop and maintain comprehensive biodiversity surveys to more thoroughly characterize baseline conditions, against which future change can be effectively detected, managed, and mitigated. This includes more repeat sampling of biological communities over time and across a range of seasons and conditions. We currently lack sufficient biological response data to fully understand how seasonal and temporal variability in flow characteristics relate to seasonal and interannual variation in habitat use, reproduction, recruitment, and abundance. Understanding which species, life history stages, communities, or features are most vulnerable to flow changes can help determine the necessary scale of management. Further data on ecosystem processes would also be useful to provide a more complete understanding of the underlying mechanisms driving biological responses to climate-related drivers. In this project, we were unable to characterize reproduction, year class strength, and recruitment, even for managed fishery resources such as trout and salmon, using existing datasets. Many state agencies have for many decades periodically conducted stream fish and other biological sampling, yet these data and monitoring results are often stored as paper records and have not been compiled digitally. In many cases, it may be feasible that these data could be compiled and entered into digital databases. We suggest that the development and digitization of historical biological data, where possible, represents an important opportunity to address gaps and limitations of this study, even if expanded monitoring or sampling is infeasible.

For More Information

Contact Kristen Blann (218-330-9612; kblann@tnc.org) or Lucinda Johnson (218-788-2651; ljohnson@d.umn.edu) with questions about the flow ecology relationships.

References

Anderson, M. & A. O. Sheldon, C. Apse, A. A. Bowden, A. R. Barnett, B. Beaty, C. Burns, D. Crabtree, D. Bechtel, J. Higgins, J. Royte, J. Dunscomb, P.Marangelo. (2013). *Assessing Freshwater Ecosystems for their Resilience to Climate Change*, The Nature Conservancy. URL: http://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/edc/Documents/FW_resilience_report_11_2013_distribute.docx

Armanini, D. G., Monk, W. a., Tenenbaum, D. E., Peters, D. L., & Baird, D. J. (2012). Influence of runoff regime type on a macroinvertebrate-based flow index in rivers of British Columbia (Canada). *Ecohydrology*, *5*(4), 414–423. doi:10.1002/eco.234

Ayllón, D., Nicola, G. G., Parra, I., Elvira, B., & Almodóvar, A. (2014). Spatio-temporal habitat selection shifts in brown trout populations under contrasting natural flow regimes. *Ecohydrology*, *7*(2), 569–579. doi:10.1002/eco.1379

Baker, M. E., & King, R. S. (2010). A new method for detecting and interpreting biodiversity and ecological community thresholds. *Methods in Ecology and Evolution*, *1*, 25–37.

Benner, R, Barnett, A, Olivero, A, et al. (2014). *North Carolina's Freshwater Resilience*. The Nature Conservancy: Durham, North Carolina. URL: https://www.conservationgateway.org/ConservationByGeography/NorthAmerica/UnitedStates/edc/Documents/ED_TNC_NC_FreshwaterResilience.pdf

Biastoch, R. (2015). Threshold Indicator Taxa Analysis (TITAN) – a potential tool for ecological management? SOSMART Spring Meeting.

Blankenheim, J. (2013). *Status of coaster brook trout in Minnesota Lake Superior tributaries* (Vol. 31). Minnesota Department of Natural Resources Report F13AF00322. Duluth, MN.

Blann, K., & Kendy, E. (2012). *Developing Ecological Criteria for Sustainable Water Management In Minnesota*. The Nature Conservancy, Minneapolis, Minnesota.

Brazner, J. C., Tanner, D. K., Detenbeck, N. E., Batterman, S. L., Stark, S. L., Jagger, L. a., & Snarski, V. M. (2004). Landscape Character and Fish Assemblage Structure and Function in Western Lake Superior Streams: General Relationships and Identification of Thresholds. *Environmental Management*, *33*(6), 855–875.

Breiman, L. and A. Cutler. (2016). Random Forests. https://www.stat.berkeley.edu/~breiman/RandomForests/cc_home.htm. Cited on June 9, 2016

Bunn, S. E., & Arthington, A. H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, *30*(4), 492–507. doi:10.1007/s00267-002-2737-0

Comte, L. & Grenouillet, G., (2013). Do stream fish track climate change? Assessing distribution shifts in recent decades. *Ecography*, 36(11), pp.1236–1246.

Detenbeck, N. E., Elonen, C. M., Taylor, D. L., Anderson, L. E., Jicha, T. M., & Batterman, S. L. (2003). Effects of hydrogeomorphic region, catchment storage and mature forest on baseflow and snowmelt stream water quality in second-order Lake Superior Basin tributaries. *Freshwater Biology*, *48*, 912–927.

Detenbeck, N. E., Elonen, C. M., Taylor, D. L., Anderson, L. E., Jicha, T. M., & Batterman, S. L. (2004). Region, Landscape, and Scale Effects on Lake Superior Tributary Water Quality. *Journal of the American Water Resources Association*, *55804*, 705–720.

Dodds, W. K., W. H. Clements, K. Gido, R. H. Hilderbrand, and R. S. King. (2010). Thresholds, breakpoints, and nonlinearity in freshwaters as related to management*. Journal of the North American Benthological Society* 29:998-997.

Dufrêne, M., and P. Legendre. (1997). Species assemblages and indicator species: the need for a flexible asymmetrical approach. *Ecological Monographs* 67:345–366.

Feist, M., & Asmus, B. (2014). Development of a Macroinvertebrate- Based Index of Biological Integrity for Minnesota's Rivers and Streams, (June). Minnesota Pollution Control Agency.

Fitzpatrick, F. (2014). Diagnostic Geomorphic Methods for Understanding Future Behavior of Lake Superior Streams: *What Have We Learned in Two Decades?* MN Lake Superior Watershed Stream Science Symposium, Duluth, MN. January 7, 2014. URL: http://www.lrcd.org/uploads/1/6/4/0/16405852/fitzpatrick_geomorphology.pdf

Freeman, M.C. & Marcinek, P. A, (2006). Fish assemblage responses to water withdrawals and water supply reservoirs in Piedmont streams. *Environmental management*, 38(3), pp.435–50. Available at: http://www.ncbi.nlm.nih.gov/pubmed/16688514 [Accessed November 30, 2014].

Gunderson, L.H., (2000). Ecological resilience — in theory and application. Annual Review of Ecology and Systematics 31:425-439.

Herb, W. R., Johnson, L. B., Jacobson, P. C., & Stefan, H. G. (2014). Projecting cold-water fish habitat in lakes of the glacial lakes region under changing land use and climate regimes. *Canadian Journal of Fisheries and Aquatic Sciences*, *1348*(April), 1334–1348.

Herb, W., L. Johnson, R. Garono, K. Blann, M. Cai, J. Erickson, J. Jereczek. (2015) Assembly and Calibration of Hydrologic Models for North Shore Tributary Streams. Report to NOAA. Task Order ID: Criteria for Land and Water Management to Sustain Healthy Aquatic Ecosystems in a Changing Climate - NCNP0000-14-01372 from NOAA's Office for Coastal Management, U.S. Department of Commerce.

Isaak, D. J., & Rieman, B. E. (2013). Stream isotherm shifts from climate change and implications for distributions of ectothermic organisms. *Global Change Biology*, *19*(3), 742–751. doi:10.1111/gcb.12073

Johnson, L. B., Herb, W., & Cai, M. (2013). Assessing Impacts of Climate Change on Vulnerability of Brook Trout in Lake Superior's Tributary Streams of Minnesota. Report to Minnesota Department of Natural Resources.

Johnson, L.B., C. Richards, G.E. Host and J.W. Arthur. (1997). Landscape influences on water chemistry in Midwestern stream ecosystems. Freshwater Biology 37:193-208.

Karr, J.R. (1981). Assessment of biotic integrity using fish communities. *Fisheries* 6: 21-27.

King, R. S., & Baker, M. E. (2010). Considerations for analyzing ecological community thresholds in response to anthropogenic environmental gradients. *Journal of the North American Benthological Society*, *29*(3), 998–1008. doi:10.1899/09-144.1

Kling, G. W., Hayhoe, K., & L.B. Johnson, J.J. Magnuson, S. Polasky, S.K. Robinson, B.J. Shuter, M.M. Wander, D.J. Wuebbles, D.R. Zak, R.L. Lindroth, S.C. Moser, and M. L. W. (2003). *Confronting Climate Change in the Great Lakes Region*. Washington, D.C.

Leigh, C., Stewart-Koster, B., Sheldon, F., & Burford, M. A. (2012). Understanding multiple ecological responses to anthropogenic disturbance: rivers and potential flow regime change. *Ecological Applications*, *22*(1), 250–263. doi:10.1890/11-0963.1

Minnesota Pollution Control Agency. (2014). *Development of a Fish-Based Index of Biological Integrity for Minnesota's Rivers and Streams*. Contributing authors: John Sandberg, Scott Niemela. Minnesota Pollution Control Agency, Environmental Analysis and Outcomes Division, St. Paul, MN.

McCune, B., J. B. Grace and D. L. Urban. Analysis of Ecological Communities. 2002. MjM Software Design.

Palmer, M., Lettenmaier, D., Poff, N. L., Postel, S., Richter, B., & Warner, R. (2009). Climate Change and River Ecosystems: Protection and Adaptation Options. *Environmental Management*, *44*(6), 1053–1068. doi:10.1007/s00267-009-9329-1

Pastor, J. (2016). The Forests of the Lake Superior Watershed and Climate Change: In Transition to What and When? Lake Superior Stream Science Symposium, Jan 6-7, 2016, Duluth, MN.

Poff, N. L., & Zimmerman, J. K. H. (2010). Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology*, *55*(1), 194–205. doi:10.1111/j.1365-2427.2009.02272.x

Poff, N. L., Pyne, M. I., Bledsoe, B. P., Cuhaciyan, C. C., & Carlisle, D. M. (2010). Developing linkages between species traits and multiscaled environmental variation to explore vulnerability of stream benthic communities to climate change. *Journal of the North American Benthological Society*, *29*(4), 1441–1458. doi:10.1899/10-030.1

Poff, N.L., J.D. Allan, M. B. Bain, J.R. Karr, K.L. Prestegaard, B. Richter, R. Sparks, and J. Stromberg. (1997). The natural flow regime: a new paradigm for riverine conservation and restoration. *BioScience* 47:769-784

Richter, B. D., Davis, M. M., Apse, C., & Konrad, C. (2011). A presumptive standard for environmental flow protection. *River Research and Applications*. doi:10.1002/rra

Rieman, B. E., & Isaak, D. J. (2010). Climate Change, Aquatic Ecosystems, and Fishes in the Rocky Mountain West: Implications and Alternatives for Management. *United States Department of Agriculture Forest Service. Rocky Mountain Research Station. General Technical Report*, *250*(November), 46. Retrieved from http://www.regions.noaa.gov/western/pdfs/library/2010_USFW_Climate_Change_Aquatic_Ecosystems_and_Fishes.pdf

Rose, K., (2000). Why are Quantitative Relationships between Environmental Quality and Fish Populations so Elusive ? *Ecological Applications*, 10(2), pp.367–385.

Seavy, N. E., Golet, G. H., Griggs, F., Howell, C. A., Kelsey, R., Small, S. L.,J. Viers, Weigand, J. F. (2009). Why Climate Change Makes Riparian Restoration More Important than Ever : Recommendations for Practice and Research. *Ecological Restoration*, *27*(September), 1543–4079.

Shellberg, J. G., Bolton, S. M., & Montgomery, D. R. (2010). Hydrogeomorphic effects on bedload scour in bull char (*Salvelinus confluentus*) spawning habitat, western Washington, USA. *Canadian Journal of Fisheries and Aquatic Sciences*, *67*(4), 626–640. doi:10.1139/F10-007

U.S. Environmental Protection Agency (EPA). (2012) Freshwater Traits Database. Global Change Research Program, National Center for Environmental Assessment, Washington, DC; EPA/600/R-11/038F. Available from the National Technical Information Service, Springfield, VA, and online at http://www.epa.gov/ncea

U.S. Global Change Research Program. (2009). *Global Climate Change Impacts in the United States: Midwest*. Cambridge, Massachusetts: Cambridge University Press.

Wikipedia. (2016). https://en.wikipedia.org/wiki/Canonical_correspondence_analysis. Cited on June 9, 2016.

Xu et al. (2010). Context-specific influence of water temperature on brook trout growth rates in the field. *Freshwater Biology* 55:2253-2264.

Flow Ecology Relationships Appendices

7-I. Fish species occurrence in study reaches by frequency of and mean abundance

7-II. List of fish species by MPCA northern stream IBI metric classification

7-III. List of fish species by additional metrics derived based on potential flow sensitivity

7-IV. List of aquatic macroinvertebrate taxa by frequency of occurrence

7-V. List of aquatic macroinvertebrate taxa by potentially flow sensitive traits

Appendix 7-I. Fish species occurrence in study reaches by frequency of and mean abundance.

Obs	Code	Common Name	Scientific Name	N=233	Mean Abundance (n=233)
1	CRC	creek chub	*Semotilus atromaculatus*	185	29
2	BND	blacknose dace	*Rhinichthys atratulus*	158	64
3	BKT	brook trout	*Salvelinus fontinalis*	155	21
4	LND	longnose dace	*Rhinichthys cataractae*	138	35
5	WTS	white sucker	*Catostomus commersonii*	125	10
6	CNM	central mudminnow	*Umbra limi*	99	8
7	BST	brook stickleback	*Culaea inconstans*	89	19
8	RBT	rainbow trout	*Oncorhynchus mykiss*	78	35
9	MTS	mottled sculpin	*Cottus bairdii*	78	8
10	CSH	common shiner	*Luxilus cornutus*	76	21
11	NRD	northern redbelly dace	*Phoxinus eos*	64	23
12	PRD	pearl dace	*Margariscus margarita*	63	11
13	FND	finescale dace	*Phoxinus neogaeus*	60	11
14	SMS	slimy sculpin	*Cottus cognatus*	38	14
15	FHM	fathead minnow	*Pimephales promelas*	35	11
16	JND	johnny darter	*Etheostoma nigrum*	31	11
17	BNT	brown trout	*Salmo trutta*	28	6
18	NOP	northern pike	*Esox lucius*	27	2
19	LKC	lake chub	*Couesius plumbeus*	34	-
20	IOD	Iowa darter	*Etheostoma exile*	27	4
21	BUB	burbot	*Lota lota*	24	4
22	SMB	smallmouth bass	*Micropterus dolomieu*	22	2
23	YEP	yellow perch	*Perca flavescens*	25	6
24	BNS	blacknose shiner	*Notropis heterolepis*	20	4
25	LNS	longnose sucker	*Catostomus catostomus*	13	2
26	PMK	pumpkinseed	*Lepomis gibbosus*	13	3
27	WAE	walleye	*Sander vitreus*	10	2
28	CHS	chinook salmon	*Oncorhynchus tschawtscha*	9	4
29	TRP	trout-perch	*Percopsis omiscomaycus*	7	44
30	TPM	tadpole madtom	*Noturus gyrinus*	5	5
31	BLB	black bullhead	*Ameirus melas*	4	2
32	BLG	bluegill	*Lepomis macrochirus*	4	7
33	RKB	rock bass	*Ambloplites rupestris*	4	1
34	ATS	Atlantic salmon	*Salmo salar*	3	12
35	BNM	bluntnose minnow	*Pimephales notatus*	1	4
36	COS	coho salmon	*Oncorhynchus kisutch*	1	3
37	PKS	pink salmon	*Oncorhynchus gorbuscha*	1	1
38	GSF	green sunfish	*Lepomis cynaellus*	1	1
39	SEL	sea lamprey	*Petromyzon marinus*	1	1
40	TST	threespine stickleback	*Gasterosteus aculeatus*	-	-
41	BLC	black crappie	*Pomoxis nigromaculatus*	-	-
42	BRM	brassy minnow	*Hybognathus hankinsoni*	-	-
43	EMS	emerald shiner	*Notropis atherinoides*	-	-
44	GOS	golden shiner	*Notemigonus crysoleucas*	-	-

Appendix 7- II. List of fish species by MPCA northern stream IBI metric classification.

CNCode	Scientific name	Common Name	CWIntolerant	CWSensitive	CWTol	NestNoLith	Pioneer	Percfm
BLB	*Ameiurus melas*	black bullhead	0	0	1	0	0	0
LNS	*Catostomus catostomus*	longnose sucker	1	1	0	0	0	0
FND	*Chrosomus neogaeus*	finescale dace	0	1	0	0	0	0
MTS	*Cottus bairdii*	mottled sculpin	0	1	0	0	0	0
SMS	*Cottus cognatus*	slimy sculpin	1	1	0	0	0	0
LKC	*Couesius plumbeus*	lake chub	1	1	0	0	0	0
BST	*Culaea inconstans*	brook stickleback	0	0	0	1	0	0
CAP	*Cyprinus carpio*	common carp	0	0	1	0	0	0
IOD	*Etheostoma exile*	Iowa darter	0	0	0	0	0	1
JND	*Etheostoma nigrum*	johnny darter	0	0	0	1	1	1
NBL	*Ichthyomyzon fossor*	northern brook lamprey	1	1	0	0	0	0
GSF	*Lepomis cyanellus*	green sunfish	0	0	1	1	1	1
PMK	*Lepomis gibbosus*	pumpkinseed	0	0	0	1	0	1
BLG	*Lepomis macrochirus*	bluegill	0	0	0	1	0	1
CSH	*Luxilus cornutus*	common shiner	0	0	0	0	0	0
PRD	*Margariscus margarita*	pearl dace	0	1	0	0	0	0
SMB	*Micropterus dolomieu*	smallmouth bass	0	0	0	1	0	1
BNS	*Notropis heterolepis*	blacknose shiner	0	0	0	0	0	0
TPM	*Noturus gyrinus*	tadpole madtom	0	0	0	1	0	0
RBT	*Oncorhynchus mykiss*	rainbow trout (steelhead)	0	1	0	0	0	0
YEP	*Perca flavescens*	yellow perch	0	0	0	0	0	1
LGP	*Percina caprodes*	logperch	0	0	0	0	0	1
FHM	*Pimephales promelas*	fathead minnow	0	0	1	1	1	0
BND	*Rhinichthys atratulus*	blacknose dace	0	0	0	0	0	0
LND	*Rhinichthys cataractae*	longnose dace	1	1	0	0	0	0
BNT	*Salmo trutta*	brown trout	0	1	0	0	0	0
BKT	*Salvelinus fontinalis*	brook trout	1	1	0	0	0	0
WAE	*Sander vitreus*	walleye	0	0	0	0	0	1
CRC	*Semotilus atromaculatus*	creek chub	0	0	0	0	1	0

CNCode	Scientific name	Common Name	CWIntolerant	CWSensitive	CWTol	NestNoLith	Pioneer	Percfm
CNM	*Umbra limi*	central mudminnow	0	0	1	0	0	0

Appendix 7-III. List of fish species by additional metrics derived based on potential flow sensitivity.

CNCode	Scientific name	Common Name	Cold	Cool	Hdw	Riffle	flowspec	silttol	coarse	sport	anadromous
LNS	*Catostomus catostomus*	longnose sucker	0	1	0	0	0	0	1	0	0
WTS	*Catostomus commersonii*	white sucker	0	1	0	1	0	1	0	0	0
FND	*Chrosomus neogaeus*	finescale dace	0	1	1	0	0	0	0	0	0
MTS	*Cottus bairdii*	mottled sculpin	1	0	1	1	0	0	1	0	0
SMS	*Cottus cognatus*	slimy sculpin	1	0	1	1	0	0	1	0	0
LKC	*Couesius plumbeus*	lake chub	0	1	0	0	0	0	0	0	0
BST	*Culaea inconstans*	brook stickleback	0	1	1	0	0	0	0	0	0
NOP	*Esox lucius*	northern pike	0	1	0	0	0	0	0	0	0
IOD	*Etheostoma exile*	Iowa darter	0	1	0	0	1	0	0	0	0
JND	*Etheostoma nigrum*	johnny darter	0	1	0	0	1	1	0	0	0
NBL	*Ichthyomyzon fossor*	northern brook lamprey	0	1	0	1	0	0	0	0	0
BLG	*Lepomis macrochirus*	bluegill	0	0	0	0	0	1	0	0	0
BUB	*Lota lota*	burbot	0	1	0	0	0	0	1	0	0
CSH	*Luxilus cornutus*	common shiner	0	1	0	0	0	0	0	0	0
PRD	*Margariscus margarita*	pearl dace	0	1	1	0	0	0	0	0	0
SMB	*Micropterus dolomieu*	smallmouth bass	0	0	0	0	1	0	1	0	0
BNS	*Notropis heterolepis*	blacknose shiner	0	1	0	0	1	0	0	0	0
PKS	*Oncorhynchus gorbuscha*	pink salmon	1	0	0	0	0	0	0	1	1
COS	*Oncorhynchus kisutch*	coho salmon	1	0	0	0	0	0	1	1	1
RBT	*Oncorhynchus mykiss*	rainbow trout (steelhead)	1	0	0	1	0	0	1	1	1
CHS	*Oncorhynchus tshawytscha*	chinook salmon	1	0	0	0	0	0	0	1	1
YEP	*Perca flavescens*	yellow perch	0	1	0	0	0	0	0	0	0
LGP	*Percina caprodes*	logperch	0	1	0	0	1	0	0	0	0
TRP	*Percopsis omiscomaycus*	trout-perch	0	1	0	0	0	0	0	0	0
NRD	*Phoxinus eos*	northern redbelly dace	1	0	1	0	0	0	0	0	0
FND	*Phoxinus neogaeus*	finescale dace	0	1	0	0	0	0	0	0	0
FHM	*Pimephales promelas*	fathead minnow	0	0	0	0	0	1	0	0	0
BND	*Rhinichthys atratulus*	blacknose dace	0	1	1	0	1	0	0	0	0
LND	*Rhinichthys cataractae*	longnose dace	0	1	0	1	1	0	0	0	0

CNCode	Scientific name	Common Name	Cold	Cool	Hdw	Riffle	flowspec	silttol	coarse	sport	anadromous
ATS	*Salmo salar*	Atlantic salmon	1	0	0	1	0	0	0	1	1
BNT	*Salmo trutta*	brown trout	1	0	0	0	0	0	1	1	0
BKT	*Salvelinus fontinalis*	brook trout	1	0	0	0	0	0	0	1	0
WAE	*Sander vitreus*	walleye	0	1	0	0	0	0	0	0	0
CRC	*Semotilus atromaculatus*	creek chub	0	1	0	0	0	0	0	0	0
CNM	*Umbra limi*	central mudminnow	0	1	0	0	0	1	0	0	0

Appendix 7-IV. List of macroinvertebrate taxa by frequency of occurrence.

Obs	Taxa	Family / order	Count	Percent
1	Ceratopsyche	Hydropsychidae / Trichoptera (caddis)	149	93%
2	Polypedilum	Chironomidae / Diptera	146	91%
3	Baetidae	Baetidae / Ephemeroptera (mayfly)	140	88%
4	Optioservus	Elmidae / Coleoptera	139	87%
5	Tvetenia	Chironomidae / Diptera	138	86%
6	Lepidostoma	Lepidostomatidae / Trichoptera	132	83%
7	Thienemannimyia Gr.	Chironomidae / Diptera	130	81%
8	Rheotanytarsus	Chironomidae / Diptera	126	79%
9	Simulium	Simuliidae / Diptera	126	79%
10	Acari	Astigmata (mites and ticks)	120	75%
11	Glossosomatidae	Glossosomatidae / Trichoptera (caddis)	117	73%
12	Cricotopus	Chironomidae / Diptera	115	72%
13	Orthocladiinae	Chironomidae / Diptera	113	71%
14	Acroneuria	Perlidae / Plecoptera (stonefly)	110	69%
15	Oligochaeta	Annelida (worm)	109	68%
16	Chimarra	Philopotamidae / Trichoptera	107	67%
17	Microtendipes	Chironomidae / Diptera	104	65%
18	Cheumatopsyche	Hydropsychidae / Trichoptera (caddis)	103	64%
19	Stempellinella	Chironomidae / Diptera	99	62%
20	Eukiefferiella	Chironomidae / Diptera	98	61%
21	Tanytarsus	Chironomidae / Diptera	97	61%
22	Hydropsychidae	Hydropsychidae / Trichoptera	95	59%
23	Parametriocnemus	Chironomidae / Diptera	95	59%
24	Oecetis	Leptoceridae / Trichoptera	94	59%
25	Acentrella	Baetidae / Ephemeroptera (mayfly)	93	58%
26	Micropsectra	Chironomidae / Diptera	93	58%
27	Gomphidae	Gomphidae / Odonata	89	56%
28	Maccaffertium	/ Ephemeroptera	89	56%
29	Paraleptophlebia	Leptophlebiidae / Ephemeroptera	89	56%
30	Atherix	Athericidae / Diptera	86	54%
31	Physa	Physidae / Hygrophila (mollusk)	86	54%
32	Boyeria	Aeshnidae / Odonata	85	53%
33	Dolophilodes	Philopotamidae / Trichoptera	84	53%
34	Hemerodromia	Empididae / Diptera	83	52%
35	Paragnetina	Perlidae / Plecoptera (stonefly)	79	49%
36	Perlidae	Perlidae / Plecoptera (stonefly)	78	49%
37	Ephemerella	Ephemerellidae / Ephemeroptera	76	48%
38	Leucrocuta	Heptageniidae/ Ephemeroptera	75	47%
39	Epeorus	Heptageniidae/ Ephemeroptera	74	46%

Obs	Taxa	Family / order	Count	Percent
40	Ferrissia	Apidae / Hymenopterans	74	46%
41	Pisidiidae	Pisidiidae / Veneroida (mollusk)	71	44%
42	Thienemanniella	Chironomidae / Diptera	71	44%
43	Eurylophella	Ephemerellidae / Ephemeroptera	70	44%
44	Hydroptila	Hydroptilidae / Trichoptera	69	43%
45	Nigronia	Corydalidae / Megaloptera	68	43%
46	Heptageniidae	Heptageniidae/ Ephemeroptera	65	41%
47	Corynoneura	Chironomidae / Diptera	64	40%
48	Stenelmis	Elmidae / Coleoptera	63	39%
49	Ophiogomphus	Gomphidae / Odonata	62	39%
50	Pteronarcys	Chironomidae / Diptera	59	37%
51	Hirudinea	Branchiobdellida (leeches)	57	36%
52	Tanypodinae	Chironomidae / Diptera	57	36%
53	Leptophlebiidae	Leptophlebiidae / Ephemeroptera	56	35%
54	Acerpenna	Baetidae / Ephemeroptera	53	33%
55	Limnephilidae	Limnephilidae / Trichoptera	53	33%
56	Calopteryx	Calopterygidae / Odonata	52	33%
57	Stenonema	Heptageniidae / Ephemeroptera	52	33%
58	Micrasema	Brachycentridae / Trichoptera	51	32%
59	Antocha	Limoniidae / Diptera	50	31%
60	Baetidae	Baetidae / Ephemeroptera	49	31%
61	Caenis	Caenidae / Ephemeroptera	49	31%
62	Rheocricotopus	Chironomidae / Diptera	49	31%
63	Stenochironomus	Chironomidae / Diptera	48	30%
64	Tanytarsini	Chironomidae / Diptera	47	29%
65	Hyalella	Hyallelidae / Amphipoda	47	29%
66	Tipula	Tipulidae / Diptera	47	29%
67	Nanocladius	Chironomidae / Diptera	45	28%
68	Dubiraphia	Elmidae / Coleoptera	45	28%
69	Chironomini	Chironomidae / Diptera	42	26%
70	Gyraulus	Planorbidae / Hygrophila	41	26%
71	Polycentropus	Polycentropodidae / Trichoptera	41	26%
72	Ephemerellidae	Ephemerellidae / Ephemeroptera	40	25%
73	Helicopsyche	helicopsychidae / Trichoptera	39	24%
74	Oxyethira	Hydroptilidae / Trichoptera	39	24%
75	Leuctridae	Leuctridae / Plecoptera	39	24%
76	Brillia	Chironomidae / Diptera	38	24%
77	Dicrotendipes	Chironomidae / Diptera	38	24%
78	Paratanytarsus	Chironomidae / Diptera	38	24%
79	Mystacides	Leptoceridae / Trichoptera	37	23%
80	Ceraclea	Polycentropodidae / Trichoptera	37	23%

Obs	Taxa	Family / order	Count	Percent
81	Parakiefferiella	Chironomidae / Diptera	36	23%
82	Helisoma	Planorbidae / Mollusc	36	23%
83	Rhyacophila	Rhyacophilidae / Trichoptera	36	23%
84	Cordulegaster	Cordulegastridae / Odonata	35	22%
85	Perlodidae	Perlodidae / Plecoptera	34	21%
86	Ablabesmyia	Chironomidae / Diptera	33	21%
87	Stempellina	Chironomidae / Diptera	33	21%
88	Hydroptilidae	Hydroptilidae / Trichoptera	33	21%
89	Calopterygidae	Calopterygidae / Odonata	32	20%
90	Orconectes	Cambaridae / Crayfish	29	18%
91	Dicranota	Pediciidae / Diptera	29	18%
92	Aeshna	Aeshnidae / Odonata	28	18%
93	Procloeon	Baetidae / Ephemeroptera	27	17%
94	Bezzia	Ceratopogonidae / Diptera	27	17%
95	Lopescladius	Chironomidae / Diptera	27	17%
96	Hydatophylax	Limnephilidae / Trichoptera	27	17%
97	Brachycentrus	Brachycentridae / Trichoptera	26	16%
98	Procladius	Chironomidae / Diptera	26	16%
99	Isonychia	Isonychiidae / Ephemeroptera	26	16%
100	Tricorythodes	Leptohyphidae / Ephemeroptera	26	16%
101	Bivalvia	/	26	16%
102	Phaenopsectra	Chironomidae / Diptera	25	16%
103	Polycentropodidae	Polycentropodidae / Trichoptera	25	16%
104	Sialis	Sialidae / Megaloptera	25	16%
105	Capniidae	Capniidae / Plecoptera	24	15%
106	Neureclipsis	Polycentropodidae / Trichoptera	24	15%
107	Leptoceridae	Leptoceridae / Trichoptera	23	14%
108	Ceratopogoninae	Ceratopogonidae / Diptera	22	14%
109	Cardiocladius	Chironomidae / Diptera	22	14%
110	Conchapelopia	Chironomidae / Diptera	22	14%
111	Somatochlora	Corduliidae / Odonata	22	14%
112	Rhithrogena	Heptageniidae / Ephemeroptera	22	14%
113	Nilothauma	Chironomidae / Diptera	21	13%
114	Orthocladius (Sympos	Chironomidae / Diptera	21	13%
115	Synorthocladius	Chironomidae / Diptera	21	13%
116	Nemata	Draconematidae / Nematoda	21	13%
117	Roederiodes	Empididae / Diptera	21	13%
118	Hexatoma	Limoniidae / Diptera	21	13%
119	Limnophyes	Chironomidae / Diptera	20	13%
120	Empididae	Empididae / Diptera	20	13%
121	Serratella	Ephemerellidae / Ephemeroptera	20	13%
122	Protoptila	Glossomatidae / Trichoptera	20	13%

Obs	Taxa	Family / order	Count	Percent
123	Psychomyia	Psychomyiidae / Trichoptera	20	13%
124	Aeshnidae	Aeshnidae / Odonata	19	12%
125	Xylotopus	Chironomidae / Diptera	19	12%
126	Ephemera	Ephemeridae / Ephemeroptera	19	12%
127	Goera	Goeridae / Trichoptera	18	11%
128	Labrundinia	Chironomidae / Diptera	17	11%
129	Nilotanypus	Chironomidae / Diptera	17	11%
130	Hydrobiidae	Hydrobiidae / Littorinimorpha	17	11%
131	Planorbidae	Planorbidae / Hygrophila	17	11%
132	Belostoma	Belostomatidae / Hemiptera	16	10%
133	Paracapnia	Capniidae / Plecoptera	16	10%
134	Paramerina	Chironomidae / Diptera	16	10%
135	Corduliidae	Corduliidae / Odonata	16	10%
136	Dixella	Dixidae / Diptera	16	10%
137	Stenacron	Heptageniidae / Ephemeroptera	16	10%
138	Lymnaeidae	Lymnaeidae / Hygrophila	16	10%
139	Taeniopteryx	Taeniopterygidae / Plecoptera	16	10%

Appendix 7-V. List of macroinvertebrate taxa by potentially flow sensitive traits.

Obs	Taxon	n	climb	cling	burrow	swim	depo	eros	nodrift	Female-disp	desicc	Uni-voltine	Semi-voltine	Bi-voltine	cold	Cold cool	warm
1	Polypedilum	146	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
2	Optioservus	138	0	1	0	0	0	1	0	1	1	0	1	0	0	0	0
3	Tvetenia	138	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
4	Lepidostoma	132	1	0	0	0	0	0	1	0	0	1	0	0	0	1	0
5	Ceratopsyche	128	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0
6	Rheotanytarsus	126	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0
7	Simulium	126	0	1	0	0	0	1	0	0	0	0	0	1	0	0	0
8	Cricotopus	115	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0
9	Microtendipes	104	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0
10	Cheumatopsyche	103	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0
11	Chimarra	98	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0
12	Eukiefferiella	98	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
13	Tanytarsus	97	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0
14	Parametriocnemus	95	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
15	Micropsectra	93	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
16	Gomphidae	89	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
17	Paraleptophlebia	89	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0
18	Baetis flavistriga	86	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
19	Hemerodromia	83	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
20	Acentrella turbida	75	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
21	Leucrocuta	75	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0
22	Ferrissia	74	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
23	Thienemanniella	71	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
24	Orthocladius	70	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
25	Atherix	69	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
26	Hydroptila	69	0	1	0	0	0	0	0	1	0	1	0	0	0	0	0
27	Nigronia	68	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0
28	Ephemerella	66	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0
29	Eurylophella	66	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0
30	Heptageniidae	65	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
31	Ceratopsyche slossonae	64	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
32	Corynoneura	64	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
33	Baetis	63	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0

Obs	Taxon	n	climb	cling	burrow	swim	depo	eros	nodrift	Female-disp	desicc	Uni-voltine	Semi-voltine	Bi-voltine	cold	Cold cool	warm
34	Stenelmis	63	0	1	0	0	0	0	0	1	1	1	0	0	0	0	0
35	Epeorus	62	0	1	0	0	0	0	1	0	0	1	0	0	0	1	0
36	Glossosoma	62	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0
37	Orthocladiinae	62	0	0	1	0	0	0	0	1	0	1	0	0	0	1	0
38	Pteronarcys	59	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0
39	Tanypodinae	57	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
40	Acroneuria	56	0	1	0	0	0	1	1	1	0	1	0	0	0	0	0
41	Oecetis	51	0	1	0	0	0	0	1	1	0	1	0	0	0	0	0
42	Ophiogomphus	51	0	0	1	0	1	0	1	0	0	0	1	0	0	0	0
43	Antocha	50	0	1	0	0	0	0	1	0	1	1	0	0	0	0	0
44	Baetidae	49	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
45	Rheocricotopus	49	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
46	Boyeria	48	1	0	0	0	0	0	1	1	0	0	1	0	0	0	0
47	Stenochironomus	48	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
48	Glossosoma intermedium	47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
49	Stenonema	47	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
50	Tipula	47	0	0	1	0	0	0	1	0	1	1	0	0	0	0	0
51	Baetis tricaudatus	46	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
52	Dubiraphia	45	0	1	0	0	0	0	0	1	1	1	0	0	0	0	0
53	Nanocladius	45	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
54	Glossosoma nigrior	44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
55	Acerpenna	42	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
56	Gyraulus	41	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
57	Polycentropus	41	0	1	0	0	0	1	1	1	0	1	0	0	0	0	0
58	Leuctridae	39	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
59	Oxyethira	39	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0
60	Brillia	38	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
61	Dicrotendipes	38	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
62	Calopteryx	37	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0
63	Ceraclea	37	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0
64	Mystacides	37	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
65	Perlodidae	34	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
66	Caenis	33	0	0	0	0	1	0	1	0	0	0	0	1	0	0	1
67	Helicopsyche borealis	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1

Obs	Taxon	n	climb	cling	burrow	swim	depo	eros	nodrift	Female-disp	desicc	Uni-voltine	Semi-voltine	Bi-voltine	cold	Cold cool	warm
68	Hydropsyche	33	0	1	0	0	0	1	0	1	0	1	0	0	0	0	0
69	Stempellina	33	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
70	Micrasema rusticum	32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
71	Paragnetina	32	0	1	0	0	0	1	1	1	1	0	1	0	0	0	0
72	Acentrella	31	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
73	Cordulegaster	30	0	0	1	0	1	0	1	1	0	1	0	0	0	0	0
74	Dicranota	29	0	0	1	0	0	0	1	0	1	1	0	0	0	0	0
75	Hyalella	29	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
76	Dolophilodes	28	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0
77	Rhyacophila	28	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0
78	Bezzia	27	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
79	Orconectes	27	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80	Procloeon	27	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
81	Hydropsyche betteni	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
82	Isonychia	26	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0
83	Tricorythodes	26	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0
84	Phaenopsectra	25	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
85	Sialis	25	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0
86	Capniidae	24	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0
87	Helisoma	24	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	Neureclipsis	24	0	1	0	0	0	1	1	1	0	0	0	1	0	0	0
89	Cardiocladius	22	0	0	1	0	0	1	0	0	0	0	0	1	0	0	0
90	Conchapelopia	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
91	Hyalella azteca	22	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
92	Rhithrogena	22	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0
93	Aeshna	21	1	0	0	0	0	0	1	1	0	0	1	0	0	0	0
94	Baetis brunneicolor	21	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
95	Hexatoma	21	0	0	1	0	0	0	1	0	1	1	0	0	0	0	0
96	Roederiodes	21	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
97	Empididae	20	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
98	Protoptila	20	0	1	0	0	0	1	1	0	0	1	0	0	0	1	0
99	Somatochlora	20	0	0	0	0	1	0	1	1	0	0	1	0	0	0	0
100	Aeshnidae	19	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
101	Calopteryx aequabilis	19	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Obs	Taxon	n	climb	cling	burrow	swim	depo	eros	nodrift	Female-disp	desicc	Uni-voltine	Semi-voltine	Bi-voltine	cold	Cold cool	warm
102	Ephemera	19	0	0	1	0	1	0	1	0	0	0	1	0	0	0	0
103	Goera	18	0	1	0	0	0	1	1	0	0	1	0	0	0	1	0
104	Micrasema	18	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0
105	Epeorus vitreus	17	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
106	Hydrobiidae	17	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
107	Nilotanypus	17	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
108	Planorbidae	17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
109	Brachycentrus	16	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0
110	Corduliidae	16	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
111	Dixella	16	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
112	Paracapnia	16	0	0	0	0	0	0	1	0	1	1	0	0	0	1	0
113	Paramerina	16	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
114	Stenacron	16	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0
115	Taeniopteryx	16	0	0	0	0	0	0	1	0	1	1	0	0	0	0	0
116	Isoperla	15	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0
117	Potthastia	15	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
118	Ptilostomis	15	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
119	Tribelos	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
120	Cladotanytarsus	14	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
121	Ephydridae	14	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
122	Pycnopsyche	14	0	0	0	0	0	0	1	0	0	1	0	0	0	1	0
123	Elmidae	13	0	1	0	0	0	0	0	0	1	0	1	0	0	0	0
124	Erpobdella	13	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0
125	Hydraena	13	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
126	Plauditus	13	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
127	Belostoma	12	1	0	0	0	1	0	1	1	1	1	0	0	0	0	1
128	Paratendipes	12	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
129	Amphinemura	11	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
130	Gomphus	11	0	0	1	0	1	0	1	0	0	0	1	0	0	0	0
131	Leuctra	11	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
132	Macronychus glabratus	11	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
133	Nephelopsis obscura	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
134	Anacaena	10	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
135	Ceratopogonidae	10	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0

Obs	Taxon	n	climb	cling	burrow	swim	depo	eros	nodrift	Female-disp	desicc	Uni-voltine	Semi-voltine	Bi-voltine	cold	Cold cool	warm
136	Coenagrionidae	10	1	0	0	0	0	0	1	0	0	1	0	0	0	0	0
137	Gyrinus	10	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0
138	Stictochironomus	10	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
139	Chironomidae	9	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0
140	Diphetor hageni	9	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
141	Heleniella	9	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
142	Helobdella stagnalis	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
143	Mayatrichia ayama	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
144	Neoplasta	9	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
145	Ophiogomphus carolus	9	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
146	Phylocentropus	9	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0
147	Triaenodes	9	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
148	Zavrelimyia	9	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
149	Amnicola	8	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
150	Aquarius	8	0	0	0	0	1	0	1	0	1	0	0	1	0	0	0
151	Brachycentrus americanus	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
152	Diplectrona modesta	8	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
153	Haliplus	8	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
154	Helicopsyche	8	0	1	0	0	0	1	1	1	1	1	0	0	0	0	0
155	Hetaerina	8	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0
156	Hydatophylax	8	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0
157	Paraponyx	8	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
158	Probezzia	8	0	0	1	0	0	0	1	0	0	0	0	1	0	0	0
159	Serratella	8	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0
160	Aeshna umbrosa	7	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
161	Agabus	7	0	0	0	1	0	0	1	1	0	0	1	0	0	0	0
162	Caecidotea	7	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
163	Cernotina	7	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
164	Chironomus	7	0	0	1	0	0	0	0	1	0	1	0	0	0	0	0
165	Dytiscidae	7	0	0	0	1	0	0	1	1	0	0	1	0	0	0	0
166	Heptagenia	7	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0
167	Heterotrissocladius	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
168	Isogenoides	7	0	1	0	0	0	0	1	1	0	1	0	0	0	0	0
169	Agnetina	6	0	1	0	0	0	1	1	1	0	0	1	0	0	0	0

Obs	Taxon	n	climb	cling	burrow	swim	depo	eros	nodrift	Female-disp	desicc	Uni-voltine	Semi-voltine	Bi-voltine	cold	Cold cool	warm
170	Bezzia/Palpomyia	6	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0
171	Cordulegaster maculata	6	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
172	Enallagma	6	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0
173	Nectopsyche	6	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0
174	Ophiogomphus rupinsulensis	6	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
175	Sigara	6	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0
176	Thienemannimyia	6	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
177	Tipulidae	6	0	0	1	0	0	0	1	0	1	1	0	0	0	0	0
178	Apatania	5	0	1	0	0	0	1	1	0	0	1	0	0	0	1	0
179	Brachycentridae	5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
180	Chloroperlidae	5	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0
181	Cladopelma	5	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
182	Corixidae	5	0	0	0	1	1	0	1	1	1	0	0	1	0	0	0
183	Hexagenia	5	0	0	1	0	1	0	1	0	0	0	1	0	0	0	0
184	Lauterborniella	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
185	Liodessus	5	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
186	Neophylax	5	0	1	0	0	0	1	1	0	0	1	0	0	0	0	0
187	Neurocordulia	5	1	0	0	0	1	0	1	1	0	0	1	0	0	0	0
188	Phryganea	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
189	Pilaria	5	0	0	1	0	0	0	1	0	1	1	0	0	0	0	0
190	Psychomyia	5	0	1	0	0	0	1	1	1	0	1	0	0	0	0	0
191	Rhagovelia	5	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0
192	Tropisternus	5	1	0	0	0	1	0	0	0	0	0	0	1	0	0	0
193	Xenochironomus xenolabis	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
194	Alloperla	4	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0
195	Anopheles	4	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
196	Belostoma flumineum	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
197	Brachycentrus numerosus	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
198	Constempellina	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
199	Diamesa	4	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
200	Diplectrona	4	0	1	0	0	0	1	1	0	0	1	0	0	0	1	0

**For taxa present at fewer sites (not analyzed except as metrics), consult the data archive.*

*** Also see database for classification of taxa and group/taxa membership by family and higher taxonomic levels*

Variable	**Classification based on EPA Traits database value**
climber	CB = dwell on live aquatic plants or plant debris
clinger	CN = maintain a relatively fixed position on firm substrates in current
burrow	BU = dig down and reside in the soft, fine sediment
swimmer	SW=adapted for moving through water
depo	Rheophily_abbrev = depo (primarily depositional habitat)
eros	Rheophily_abbrev = eros (primarily erosional habitat)
nodrift	Drift_abbrev = rare (rarely present in drift)
femaledisp	female dispersal ability = high
desicc	Ability to survive desiccation = present
univoltine	voltinism = univoltine
semivoltine	voltinism = semivoltine
bivoltine	voltinism = bi_multivoltine
cold	thermal preference = cold stenothermal (< 5C)
coldcool	thermal preference = cold-cool eurythermal (0-15 C)
warm	thermal preference = warm (15-30 C)