THE VALUE OF HABITAT DATA FOR CONSERVING STREAMS WITH CHANGING CLIMATE: PROMOTING GREATER USE FOR MORE EFFECTIVE MANAGEMENT

By

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ABSTRACT

THE VALUE OF HABITAT DATA FOR CONSERVING STREAMS WITH CHANGING CLIMATE: PROMOTING GREATER USE FOR MORE EFFECTIVE MANAGEMENT

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North America's rivers and streams support a diversity of fish species that provide significant ecological, socioeconomic, cultural, and spiritual benefits, and the quality and quantity of habitat in streams directly supports fish diversity. Because rivers are products of the landscapes they drain, features of the landscape like land use, geology, and climate control habitat. Based on these relationships, it stands that anticipated changes in climate will lead to changes in stream fishes through changes in habitat. While natural resource management agencies collect habitat data to help conserve streams into the future, stream habitat data are not always used as intended, in part because some managers may have an incomplete understanding of interactions between rivers and the landscapes they drain. To fully address the impacts of climate change on stream fishes, managers must better understand how climate affects stream habitat and incorporate these concepts into management decision-making processes. This thesis addresses that need. In Chapter 1, we identify ways to increase use of stream habitat data by natural resource management agencies to better conserve fishes from current and future stressors. In Chapter 2, we investigate influences of multiple landscape factors on physical stream habitat, including climate factors. Collectively, outcomes of this research offer managers information and strategies for using stream habitat data to conserve stream habitats and the fishes they support with changing climate.

To my partner and husband Max Betances, my parents Victoria and John Thiede, my sisters Stephanie and Nicole Thiede, and to everyone who supported me on this journey.

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PREFACE

The research chapters in this thesis have been prepared and formatted for publication. Therefore, there is some repetition in concept, study site descriptions, and methods among chapters.

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OVERVIEW

North America's rivers and streams support diverse fish species that provide significant ecological, socioeconomic, cultural, and spiritual benefits to the public (Jelks et al. 2008). However, an assessment conducted in 2008 found that approximately 40% of all North American freshwater fish species may be imperiled, with the number increasing annually (Jelks et al. 2008). Currently, degradation of habitats as a result of human land uses and other activities is the greatest contributor to the imperilment of stream fishes (Allan et al. 2005), and changes in climate are expected to exacerbate conditions by further changing habitats into the future (Maddock 1999; Allan et al. 2005; Wuebbles et al. 2019). The quality and quantity of stream habitat features structure and constrain fish assemblages, and changes to stream habitat through changes in climate will impact the distribution and composition of these assemblages.

Alterations to stream habitat via changes in climate have already been observed, and these changes vary by region. Changes in timing and intensity of precipitation patterns have caused stream discharges to decrease in some areas of the US, while other streams have become more variable due to extreme high flow events (Cisneros et al. 2014). Compounding effects on stream flows, increased intensity and duration of droughts in western regions of the US have reduced some streams' baseflows, as reductions in precipitation have reduced groundwater recharge (Afzal and Ragab 2020). In the Great Lakes region, mean annual air temperature is warming at a greater rate than in the rest of the continental US (Wuebbles et al. 2019). As air temperatures increase, stream thermal regimes are expected to shift in response, and some types of thermal habitats may increase in prevalence while others may decline (Comte et al. 2013). Additionally, the timing, duration, and magnitude of extreme storm events in the Great Lakes region have increased significantly due to altered precipitation patterns (Cherkaur and Sinha 2010; IPCC 2018; Wuebbles et al. 2019).

Natural resource management agencies are tasked with conserving fishes and their habitats now and into the future. To accomplish this, some state and federal natural resource management agencies monitor and collect stream habitat data, and the use of such data is often tailored to the agency's specific management needs. However, stream habitat data are sometimes not used in management decision-making (Sass et al. 2017). This can result from the fact that managers may be unsure of how to use the data (Schindler 2014; Sass et al. 2017). Additionally, many managers have an incomplete understanding of interactions between rivers and the landscapes they drain (Fausch et al. 2002). To fully address the impacts of climate change to fishes, managers must better understand stream habitats' influences on fishes and incorporate these concepts into management decision-making processes. Considering this need, the goal of this thesis is to provide natural resource managers with novel information related to using stream habitat data for conserving streams under changing climate, and we attempt to address our goal with research separated into two chapters. In Chapter 1 we address barriers to using stream habitat data in natural resource management decision-making processes and provide managers with recommendations to increase its usage. Next, Chapter 2 investigates influences of multiple landscape factors on physical stream habitat, including factors influenced by climate, and attempts to address knowledge gaps in using a landscape approach in management decision-making. Collectively, outcomes of this research will provide managers with information and strategies for using stream habitat data to conserve stream habitats and the fishes they support into the future, under changing climate.

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CHAPTER 1:
INCREASING THE USE OF STREAM HABITAT DATA FOR MANAGING FISHES: IMPROVING EFFORTS TO CONSERVE STREAMS INTO THE FUTURE

ABSTRACT

Habitat degradation is one of the most pervasive stressors threatening streams across the globe, and changes in climate are expected to further affect stream habitats and the fishes they support. Because of this, understanding the influence of stream habitat on fishes and using this understanding to protect and conserve important stream habitat factors is critical to effectively managing and conserving freshwater fishes. Stream habitat data, however, are not regularly used in management decision-making, and the goal of our study was to identify reasons why this occurs along with strategies to increase use of stream habitat data by natural resource management agencies. We focused our study on the Michigan Department of Natural Resources (MDNR) Fisheries Division, and we interviewed managers and biologists on their use of stream habitat data collected through the Status and Trends Program (STP). Our interview questions focused on participants' perceptions of STP stream habitat data as well as barriers to use in management decision-making. Our results indicated that one of the most common barriers limiting use of data was related to participants' uncertainty about how to incorporate data into management decision-making. We also identified additional barriers related to difficulties in accessing data collected through the STP. Building on our findings, we describe specific strategies for increasing the use of stream habitat data, including providing specific training on how fish are influenced by their physical environment. Outcomes of this study can be used to help fisheries managers apply stream habitat data in management decision-making processes and ultimately contribute to efforts to conserve streams and the fishes they support into the future.

INTRODUCTION

The greatest biodiversity of freshwater fishes occurs on the North American continent (Jelks et al. 2008), and unique assemblages of stream species can be found throughout North America including endemic percid species in the southeastern US, highly migratory salmonid species throughout the west coasts of the US and Canada, and coldwater species in Midwestern rivers and streams. While these fishes provide significant ecological, socioeconomic, cultural, and spiritual benefits, many are highly threatened (Jelks et al. 2008; Calantone et al. 2019). An assessment conducted in 2008 found that approximately 40% of all North American freshwater fish species may be imperiled, with the number increasing annually (Jelks et al. 2008). Multiple stressors such as overexploitation, introduction of invasive species, and spread of disease have contributed to the current imperilment of freshwater fishes, but one of the most pervasive stressors is degradation of aquatic habitats as a result of human land use and other anthropogenic activities (Allan et al. 2005). In fact, 92% of all imperiled freshwater fishes in the US are directly threatened by habitat degradation (Jelks et al. 2008), and climate change is only expected to compound effects of current stressors on freshwater fish habitats into the future (Allan et al. 2005; Wuebbles et al. 2019). To effectively evaluate how these stressors will impact streams and ultimately the fishes they support, managers must account for the role of habitat, including ways to conserve and protect those habitat characteristics most important to stream fishes.

Stream habitat characteristics are critical to the maintenance and survival of fish species by providing fish with areas to spawn, avoid predation, and forage. Stream habitat factors are known to be influenced by natural and anthropogenic landscape-scale factors, and these factors directly affect the type, distribution, and quality of habitats available to fishes in streams (Poff 1997; Allan 2004). Natural landscape factors include geology, topography, natural land covers, and climate, while anthropogenic landscape-scale factors include multiple human land uses and climate change, and these landscape-scale features affect stream habitat characteristics such as hydrology, water chemistry, connectivity, and physical structure (Allan, 2005, Allan and Castillo 2007). Understanding stream habitat's effects on fishes, as well as how to protect stream habitat, is critical to effectively manage and conserve freshwater fishes into the future.

Currently, some state and federal natural resource management agencies monitor and collect stream habitat data, and the use of such data is often tailored to the agency's specific management needs. For example, the US Fish and Wildlife Service uses stream habitat data to identify critical habitat for threatened and endangered species (USFWS 2017a) and to prioritize habitat restoration projects (USFWS 2017b). The Washington Department of Fish and Wildlife uses stream habitat data to address management issues such as predicting the best areas to stock salmonids (WADFWS 2017). Additionally, the US Forest Service collects stream habitat data for their various monitoring programs and to assess the effectiveness of restoration projects (USDA 2019). For these and other agencies, stream habitat data can be critical to successful stream management projects.

In spite of the examples provided above, stream habitat data are sometimes not used in management decision-making (Sass et al. 2017). This can result from the fact that managers may be unsure of how to use the data (Schindler 2014; Sass et al. 2017). Traditionally, fisheries managers have focused substantial effort on responsive population management, including stocking and setting harvest regulations, with comparatively less effort focused on stream habitat conservation (Sass et al. 2017), and this focus on responsive population management efforts may be due in part to fisheries educational curricula and training (Oglesby and Krueger 1989). Because of this, managers may have difficulty interpreting stream habitat data and understanding how to apply the data in management decision-making processes (Sass et al. 2017).

Consequently, limitations to data interpretability often result in omission of relevant variables from analyses used to support decisions (Bonar et al. 2009). Such omissions can also make it more difficult for managers to fully understand the mechanisms by which landscape factors can affect fishes. In addition to the difficulties associated with interpreting stream habitat data, many managers have an incomplete understanding of interactions between rivers and the landscapes they drain (Fausch et al. 2002). Because of this, managers may focus their efforts at smaller spatial and shorter temporal scales than at the larger spatial and longer temporal scales necessary to address management issues, such as climate change (Fausch et al. 2002). Improving upon managers' understanding of stream habitat data and how to use it in management decision-making would allow managers to better prioritize where to implement conservation efforts and mitigation strategies to buffer against future changes.

The goal of this study was to identify ways to increase the use of stream habitat data by natural resource management agencies to better conserve freshwater fishes from current and future stressors. In support of this goal, we interviewed Michigan Department of Natural Resources (MDNR) managers and biologists regarding their use of stream habitat data collected through the Status and Trends Program (STP) in management decision-making, and we used response data from these interviews to address three objectives. First, we characterized the managers' and biologists' perceptions of the STP program, including the degree to which they currently use STP data in management decision-making. Next, we identified barriers to using STP stream habitat data in decision-making. Finally, based on results of our first two objectives, we identified strategies to increase the use of stream habitat data collected both by MDNR and by other natural resource management agency programs. Outcomes of this study can be used to help fisheries managers apply stream habitat data in decision-making processes and better conserve freshwater streams and the fishes they support into the future.

METHODS

Study agency

We focus our study on the Michigan Department of Natural Resources (MDNR). The mission of the MDNR is to protect and enhance Michigan's natural resources for use by society now and into the future (MDNR 2020a), and meeting this mission requires intensive knowledge of the current state of Michigan's natural resources. The MDNR Fisheries Division focuses its management and conservation efforts on fishes and their habitats throughout the state. MDNR Fisheries Division is subdivided into eight unique management units (i.e., Northern Lake Huron, Southern Lake Huron, Lake Erie, Northern Lake Michigan, Central Lake Michigan, Southern Lake Michigan, Western Lake Superior, and Eastern Lake Superior) and each unit is responsible for managing the watersheds within their unit area, including inland lakes, rivers, and streams (MDNR 2020b). In 2002, to address concerns regarding variation in sampling protocols and gear types used across the different management units, MDNR formed the Resource Inventory Team (RIT; MDNR 2020c). The RIT was tasked with standardizing sampling gear, determining statistical methods for site selection, and expanding traditional game fish surveys to include collection of data on habitat, water quality, and non-game fish (MDNR 2020c).

With these goals in mind, the RIT created the Michigan Status and Trends Program (STP), which uses standardized sampling protocols to collect data, identify reference points and benchmarks for management needs, and assess the status of and changes to stream communities across the state of Michigan (MDNR 2020c; Wills et al. 2015). The STP measures habitat factors identified as influencing fishes and that are indicators of whole watershed condition (e.g., channel width and depth, fish cover, substrate type, etc.; Wills et al. 2015), and these factors are measured within the stream channel as well as within the riparian zone of streams. Two types of sites are sampled through the STP. First, long-term fixed sites are sampled each year in the same location to provide managers with insights into changes over time. Second, random sites throughout Michigan are sampled to establish a representative, broad picture of Michigan's statewide stream habitat conditions. Collecting data is time intensive, yet according to managers of the STP, the full potential of such data for improving conservation efforts has not been fully realized by MDNR. For this reason, the evaluation of MDNR's STP provides an excellent case study for understanding barriers to using and incorporating stream habitat data into management decision-making.

Study region

Michigan has more than 36,000 river miles throughout the Upper (UP) and Lower (LP) Peninsulas, including 86 major watersheds. Due to its glacial history, Michigan has diverse types of surficial lithology that form landscapes with wide-ranging hydraulic conductivities, leading to varied stream habitats present throughout the rivers in the state. In the UP, flashier flows occur in rivers draining landscapes comprised of bedrock, creating naturally hydrologically variable conditions (Brooks et al. 2012). In the Northern LP (NLP), where coarse-textured glacial moraines are common, streams have less variability in discharge due to high permeability of landscapes and larger inputs of groundwater into streams versus surface runoff (Strayer 1983). Michigan also has a variety of forest types, with predominantly boreal forest found in the UP and temperate forest throughout the NLP and Southern Lower Peninsula (SLP). Timber harvest occurs throughout northern portions of the state, along with mining and agriculture, which are less common. In contrast, agriculture is more common in southern portions of the state, and urban areas are also concentrated in southern Michigan.

The diversity of freshwater habitats allows Michigan to support a variety of fish species that are ecologically, economically, culturally, and spiritually important (Herb et al. 2014). White Sucker (*Catostomus commersonii*), for example, is an ecologically important, migratory fish species found throughout the state that provides energetic inputs and nutrients to aquatic and terrestrial ecosystems (Childress et al. 2014). In addition, anglers from across the US travel to Michigan to target salmonids, Walleye (*Sander vitreus*), bass species (*Micropterus spp.*), Northern Pike (*Esox lucius*), Muskellunge (*Esox masquinongy*), and panfish species (*Lepomis spp.*), and angling expenditures contribute more than 2 billion USD to Michigan's economy (Calantone et al. 2019). Furthermore, species including Lake Whitefish (*Coregonus clupeaformis*) and Lake Sturgeon also have significant cultural and spiritual value for tribal communities (Gagnon et al. 2013).

Survey

We followed five steps in conducting this qualitative study (Figure B.1.1) in which we interviewed multiple personnel from MDNR Fisheries Division. Each step is described in detail below.

Interview design

Several discussions with MDNR managers familiar with the STP, including members of the RIT, aided in shaping the interview and its questions. Through these discussions, interviews were designed to prompt managers to discuss four themes: (1) perceptions of the STP, (2) barriers to using STP stream habitat data, (3) approaches for increasing the use of STP stream habitat data, and (4) management decision-making. Participants were also given a chance at the end of the interview to discuss any important topics not previously addressed during the interview. See Appendix C.1 for survey questions and consent form.

Participant selection

MDNR Fisheries Division personnel were contacted via their internal list serve and invited to sign-up to participate in the study. Additional participants were identified using chain-referral sampling (i.e., interviewed participants suggested other MDNR personnel who might be interested in participating; Biernacki 1981). Participants were selected from all eight management units, and agency personnel included both men and women, new and tenured staff, and various types of personnel including biologists, researchers, technicians, managers, and supervisory staff to ensure that a diversity of perspectives were represented (following Yin 2016). Sample size (n=19) was determined by saturation of participant perspectives, which is defined as the point at which no new subjects or concepts emerged compared to the marginal cost of continuing to interview new participants (Whittemore et al. 2001).

Survey delivery

Interviews were conducted between December 2018 and April 2019, and generally, interviews lasted 45 to 60 minutes. Some interviews were conducted in-person (n=6) while others were conducted using web conferencing (n=13). Interviews were recorded with a handheld recording device or via teleconferencing software (i.e., Zoom) and stored on a password protected computer. Participation in the interviews was anonymous and voluntary. Participants additionally gave their written consent before they took part in the research study. An exempt status was granted by Michigan State University's Internal Review Board (IRB; #STUDY00001652) for the interview and consent form that were designed for this study prior to implementation.

Detailed notes were taken during the interviews. The notes were used to document observations and as a form of supplemental data collection (Yin 2016). Additionally, participants were given all questions at least one week ahead of the interview so that they had the opportunity to reflect on the questions prior to the interview. Some participants made detailed notes ahead of time which they willingly shared with the researchers to use in addition to their interview.

Interview transcription and thematic data analysis

Interviews were transcribed from the recorded audio files and deidentified. Transcribed interviews were uploaded to NVivo 12, a program used for qualitative thematic analysis. All interviews were then coded for each research theme (Table A.1.1. Four themes that guided the study and five research questions coded using inductive data-driven thematic analysis in NVivo12.) using inductive data-driven thematic analysis (Braun and Clarke 2006; Yin 2016). Thematic analysis is a commonly applied qualitative research method to identify, analyze, and report patterns (i.e., themes) within the data (Braun and Clarke 2006). Thematic analysis is an ideal method to analyze interview data because it is not theory-bound and therefore a flexible research mechanism that has the potential to provide rich, detailed, and complex accounts of the data (Braun and Clarke 2006; Yin 2016).

The process of thematic analysis requires closely reading all interview data to create "codes" that may help to answer research questions or identify patterns in the data. Codes are defined as labels that assign units of meaning to prevalent, descriptive information compiled from the data. Assigning codes to the interviews allows for data reduction and simplification but also allows the researcher to transform the data into meaningful units and to make connections between concepts (DeCuir-Gunby et al. 2011).

Interview data were first open coded as an exploratory methodology and mechanism for delineating the raw transcribed interview data (DeCuir-Gunby et al. 2011). Through this process of open coding the interview data using the four themes as a guide, five research questions were developed (Table A.1.1): What are the current perceptions and opinions of the Status and Trends Program (Theme 1); Why are MDNR personnel not using the Status and Trends Program stream habitat data (Theme 2); What could be done to help stream habitat data be used more effectively and often (Theme 3); What programs or projects are top priority in your management unit (Theme 4) and; What management scenarios and questions can be addressed using the Status and Trends Program stream habitat data (Theme 4)?

Next, open coding was applied again using the questions as a guide to create parent and daughter codes for each question. These parent and daughter codes (i.e., primary code and subcodes, respectively) can reflect common or significant responses given by the interview participants. Data were given to collaborators to determine intercoder reliability, and adjustments to the coding structure and scope were corrected based on feedback from collaborators (Yin 2016), then data were re-coded by the primary researcher to better incorporate the collaborators' input. Finally, axial coding was employed to identify connections or patterns that may exist between or within codes (DeCuir-Gunby et al. 2011; SAGE 2017). This qualitative technique is the process of inductively locating linkages between data (SAGE 2017) or in other words, identifying why two or more codes may or may not be occurring together under a particular research question. Diagramming was used to aid in the axial coding process to better examine in what context two codes might be discussed in relation to one another, to determine if there were any consequences from interactions between adjacent codes, and to understand the conditions in which two or more codes might occur (Tie et al. 2019).

Analyzing results

After coding was complete, themes were processed, described, and written out in narrative format to answer each question (Ryan and Bernard 2003). A codebook was created that provides code names, descriptions, and examples of a quote that would be categorized as a certain code (Table A.1.2; Table A.1.3; Table A.1.4; Table A.1.5; Table A.1.6). Approximately one third of participants provided notes, and these served as supplementary material during analysis (Yin 2016). Additionally, throughout the duration of this study, the researcher implementing the interviews attended many internal and public meetings related to the STP. The use of meeting notes, agendas, and participant-written notes in this analysis helped triangulate and validate the themes that emerged from the coded, transcribed interview data (Yin 2016).

RESULTS

Overview

The following results are derived from 19 open-ended, semi-structured interviews with personnel of MDNR Fisheries Division conducted between December 2018 and April 2019 as well as supplementary notes from those interviews. Results are organized by research questions.

What are the current perceptions and opinions of the Status and Trends Program?

Positive perceptions and opinions about the STP

Overall, most survey participants had positive opinions and perceptions about the STP and recognized the value in the program's design (12/19; 63%; Figure B.1.2). When describing aspects that they perceived positively about the program, participants commonly identified three benefits. First, several participants found the STP to be useful for providing baseline data and making comparisons among waterbodies (9/19; 47%; Figure B.1.2). Second, some participants thought that the STP was useful for examining trends through time (5/19; 26%; Figure B.1.2). As one participant stated, “We can basically continue to take the blood pressure [of a stream or stream network] over a very long period of time and make some changes or recommendations that impact decades from now,” (INT10). Finally, some participants stated that the STP is effective because it is collecting quality data that are useful when describing fish communities and habitat condition of streams in their work (5/19; 26%; Figure B.1.2).

Negative perceptions and opinions about the STP

In contrast, 42% (8/19; Figure B.1.2) of survey participants had negative perceptions and opinions regarding the STP. When describing aspects of the STP that participants perceived negatively, three limitations emerged. The first was that the STP does not yet have enough relevant information for management decision-making; that is, many streams that managers are interested in have not yet been sampled (5/19; 26%; Figure B.1.2). One participant stated, “People [i.e., biologists and technicians] come [to me] and say: ‘Why am I working on this little dummy stream that doesn’t have any fish in it?’ or ‘It’s all warm water,’” (INT8). However, some perceived this lack of data to be a temporary issue due to the recent implementation of the program and generally recognized that the data will be become more robust as time passes and more random and fixed sites are sampled. One participant stated, “I look at this as kind of a time-sensitive thing. In the grand scheme of things, the STP hasn’t been around for very long. There’s a lot of utility in this [program], [but] I don’t think a lot of managers or biologists have really embraced it, yet. They’re probably not going to see as much benefit as those biologists that follow in 20, 30, 40, 50 years when we [still] have this [program],” (INT9). Another participant stated, “The benefit of the STP, I think, is once you get to when you’re thirty years in, that’s when you just begin to have the dataset that allows you to really make some changes and observe the things that the program is meant to observe,” (INT10).

The second limitation was that data were difficult to summarize and compare between streams in their current format in the Fish Collection System (FCS) database (4/19; 21 Figure B.1.2). Because of this, participants felt that it was difficult to incorporate stream habitat data into their analyses. One participant mentioned, "The [FCS] is set up for biologists to load the data, to complete a report after an assessment is done, but it's not set up to do any kind of queries, especially if biologists want to compare, say, the average growth of a Brown Trout in a stream that they just surveyed to the streams in the adjacent county or region. The [FCS] isn't really set up to allow them to do those kinds of comparisons," (INT18). Another participant specified: "One of the biggest barriers is our computer system, our Fish Collection System. It makes it a little difficult to output summary data in a usable format. So, if you want to make big comparisons, you're kind of reliant on queries, [and] usually you have to go to one of the biologists that's in charge of the system to give you the data you need. Once you can get that data, it's good, but it's not readily accessible in a format that you can just output and play with which is the way I like to do it," (INT12). Other participants stated that they wanted greater ability to examine data across their unit, region, and state to make more "big picture decisions," rather than focusing management actions at an individual site level (INT1). To increase the use of STP data, another participant specified, "The next step would be to make the system such that managers could pull information freely, as they wish, from the Fish Collection System," (INT14).

Finally, the third limitation identified by participants were resource limitations, such as inadequate funding sources and insufficient number of personnel to complete the required STP surveys annually (3/19; 16%; Figure B.1.2). While MDNR is required to devote 40% of their sampling effort to STP surveys (Wills et al. 2015), many participants felt that MDNR does not have enough individual staff to accomplish the STP surveys along with their other sampling responsibilities. Due to budget cuts, MDNR has been understaffed in recent years, and because there are fewer staff to collect data, the proportion of time taken to survey sites has increased, especially for larger streams requiring extra effort to sample through long station lengths. Consequently, some management units could only sample a subset of assigned sites each field season.

Why are MDNR personnel not using the Status and Trends Program stream habitat data?

Several constraints for using the STP stream habitat data by MDNR personnel were identified. These can be subdivided into constraints related to data as well as other miscellaneous constraints. The following findings emerged from these two categories.

Data constraints

Participants identified four data constraints to using STP stream habitat in their management decision making processes. First, many participants felt that the STP lacked the data that were needed to make meaningful decisions (13/19; 68%; Figure B.1.3). The second constraint identified was the ability to access and query the STP data in the FCS database (12/19; 63%; Figure B.1.3). These constraints are described in greater detail above in results section: Negative perceptions and opinions about the STP.

The third data constraint identified was the interpretability of the STP habitat data (8/19; 42%; Figure B.1.3). Largely, MDNR personnel identified two reasons that data were difficult to interpret: the format of the data and the level of measure. For some participants, the format of the database made it difficult for them to create summaries and analyze the data. One participant expressed frustration with how data are summarized from the FCS database and went on to state, "The parameters measured are useful, but they need to be entered in a way that summarizes the reach better. It gives you a percent at the end, but that's just for the transects not the for the whole reach. That is limiting in its use," (INT16). Other participants mentioned that the spatial extent over which data were collected was difficult to interpret. One participant stated, "It seems like a lot of really good data, but it's not being used. [Prior to] the STP, what we'd do is depending on the width of the stream, we'll [sample] a given length of the stream, but it [i.e., the data] was quantitative. So I would write up the analysis looking at the fish community that would rely on that type of information but now that we are [collecting] qualitative data measurements, it's harder to translate into how that affects the fish community. As a biologist, to sit down and write up [a report on] an individual stream, I don't think there's value in that," (INT3).

The final data constraint identified was that participants felt that the STP data were outdated (5/19; 26%; Figure B.1.3). One participant said, "I think another barrier, which again relates to FCS and other web tools, is the time span between updates with the data. Waiting every six years for statewide summaries is not good. Most of our online tools are not updated in real time," (INT15). Another participant mentioned, "I like to use those summary spreadsheets that are on the intranet that you can also search and kind of adapt to the particular question that you have. And those haven't been updated since like 2008 or something like that, so that's the biggest impediment I see. Those work great, they just haven't been updated in a long time. So, if those were updated, I think we would use them even more," (INT11). However, some participants added the caveat that as new tools are developed and technology advances, the data have become more frequently updated, "The summary statistics in those programs, it's a little old, so it'd be nice to have more current versions. And the new viewers do a good job at keeping that data pretty up to date," (INT12).

Miscellaneous constraints

Four miscellaneous constraints were identified as limiting the use of the STP stream habitat data by MDNR personnel. The first was that some participants did not perceive the STP stream habitat data to be useful for making management decisions (13/19; 68%; Figure B.1.3). One participant holding this opinion stated, "One difficulty is that the STP sampling only speaks to a specific site on what can be miles of stream or river. Historically, I would try to conduct multiple surveys at different locations and provide an analysis of the entire stream. The STP now tends to force us into conducting more random surveys across multiple streams. The STP is great in getting us to new areas, but it really doesn't lend itself to characterizing the stream as a whole. And when you are only looking at one specific site on a stream, how much can you say?" (INT15). Another participant mentioned that they did not see the relevance in using variables such as riparian and bank condition, stating that they held little importance for aiding in management decision-making, "I don't use anything from the transect data. I'm looking at the riparian and bank condition data. So, for example, this stream here had 10% tag alder type for these thousand feet, or it has 20% large coniferous for these thousand feet, and so on. I don't use any of that; I don't use it because I don't see the relevance," (INT6).

The second additional constraint identified was time (11/19; 58%; Figure B.1.3). Many participants felt their management units had too many sampling responsibilities for the number of staff employed per office. One participant expressed, "I think by far the biggest [constraints] are the lack of data and the lack of staff, time, and money to collect the data and analyze it, if we are able to collect it [at all]. We have about 1,100 lakes in our unit and thousands of miles of streams. And we have five or six of us [employees] full-time; so, that is a really long rotation to get to all our lakes and streams. I think that is our biggest thing is we just don't have the people or the money to get the data that we need. That is going to be a tough one to solve, but that's just the reality of the situation," (INT11).

The third constraint identified was that MDNR personnel felt unsure of how to incorporate the STP stream habitat data into their work and decision-making (9/19; 47%; Figure B.1.3). One participant stated, "I think we need to teach our biologists how to use it [i.e., the stream habitat data]. What does it mean? I don't think it's clear. They take the data, they throw it in the system, but they really don't get a lot of expertise to tell them how to use it," (INT19). Another participant mentioned that they were unsure how to extrapolate the STP stream habitat data beyond the sampled reach. The participant stated, "Trying to figure out better ways to incorporate it into our write-ups and how, outside of just putting our surveys into perspective, how can we use it? I've struggled to find ways to utilize this outside of things like, how can we make management recommendations for the whole management unit using some of this information not just on that single waterbody?" (INT4). Other participants echoed these sentiments, and one stated, "I don't know that we really know what variable is relevant. Some of the difficulties I see is the biologists' comfort level with working with data. And while I certainly believe all biologists in Michigan are capable of understanding data, I just feel like there needs to be like kind of a refresher about why they're collecting some of the data they are," (INT10).

The final additional constraint identified was a participant's tenure in MDNR (5/19; 26%; Figure B.1.3). Tenure in MDNR was self-identified by participants based upon the length of time the participant had worked for the agency. Both recently employed (3/5) and long-term (2/5) personnel participants named the length of their employment as a barrier to using the STP stream habitat data. For example, one recently employed participant stated, "I'm relatively new so I'm still getting used to a lot of things. I appreciate the STP, and I think it's collecting good data, and

I wish I made more use of it, and I think when I have more experience that I will use it more," (INT1). Another recently employed participant said, "I've been with the [Fisheries] Division for [a few] years and I have not spent a huge amount of time on stream data, specifically. I have spent a lot of time with lake data, and that's simply because of my being new to the position. But, within this next year or over the next two years, I'll be spending a pretty significant amount of time using Stream Status and Trends data, specifically," (INT10). In contrast, tenured personnel sometimes felt the increasing use of database and analytic software technology were sometimes a barrier. One long-tenured participant stated, "I'm not used to going to databases for information. So, as I learn to look for this stuff and how to work with it, I use it more and more. The [newer] guys, they are used to using viewers and imaging and computers. So, there is a little disconnect with me with technology," (INT17).

What could be done to help the Status and Trends Program stream habitat data be used more effectively and often?

Five strategies were identified that would help MDNR personnel use the STP stream habitat data more effectively and more often. First, several participants expressed wanting more tools to help them better access and analyze data (11/19; 58%; Figure B.1.4). These participants recognized that there are some MDNR tools already in place, such as the Stream Evaluator tool (https://www.mcgi.state.mi.us/smdt/) and the Stream Fish Population Trend Viewer (https://www.mcgi.state.mi.us/fishpop/). Many of these participants expressed that the Stream Evaluator tool helped them to use the random site data more frequently and expressed interest in development of additional tools that could help them further incorporate the STP data. One participant stated, "Part of the problem is we don't have a good database that makes it easy to work with all the time. I know we've got the stream habitat viewers and those are very helpful, and I use those, and as we go, I use them more," (INT17). Others mentioned that it would be beneficial to build a comparison tool, like the Stream Evaluator, but using fixed site data as well (4/19; 21%; Figure B.1.4). Another participant stated, "It would be nice to have a way to compare cold water streams across the different strata of Status and Trends. [To] compare the habitat variables, what is the riparian zone, the substrate, the large woody debris index; how does that influence the fish?" (INT2).

The second strategy identified was the creation of formatted templates for both analysis and report writing (8/19; 42%; Figure B.1.4). In regard to using the STP data to write up reports, one participant detailed, "There's an outline report form that we have whether we're writing a Status and Trends survey report or we're writing a discretionary survey report or we're writing a status of the fishery report. But there is currently no preapproved or department-developed outline that we follow to actually present the information," (INT 10). This same participant also mentioned that providing context for how to use these variables could increase data use, "To my knowledge, I don't think there's a description of each of the variables and just how they might be a good indicator of ecosystem health. If there's a brief description of how a variable, like substrate, can benefit [ecosystem health] I think it might saturate a little bit better with some of the biologists trying to use the Status and Trends data to make management decisions," (INT10).

Regarding the data itself, many participants expressed that developing standardized tables that could be used to compare streams at multiple spatial scales (i.e., unit, region, or statewide) would help them to use data more frequently (4/19; 21%; Figure B.1.4). Participants additionally wanted more summary data, in more frequent intervals, such as annual summaries and fixed site summaries (3/19; 16%; Figure B.1.4). One participant mentioned, "It could be useful to provide [more frequent] summaries in a report card format, with the option [for biologists] to dig deeper into the data itself if interested," (INT18).

The third strategy identified was to provide biologists with examples of how to use stream habitat data so they could incorporate the STP habitat data more frequently into their work (7/19; 37%; Figure B.1.4). One participant stated, "The Status and Trends data needs some kind of context to interpret it. The Status and Trends data is a lot more qualitative, and when I was sitting in the biologist chair, I did not feel that I had the context to be able to best use that data. Here is a cross section of the stream, here is your thalweg depth, but it was just hard to make the connection of how that affected the fish community," (INT3). Other participants echoed the need for examples to link how fishes are affected by stream habitat. One participant mentioned that they greatly appreciated the creation of a "fact sheet" for Smallmouth Bass (*Micropterus dolomieu*) by an MDNR biologist familiar with the STP data (INT17). This fact sheet detailed the most important habitat variables for this species, and the participant felt this fact sheet provided better context for how to incorporate stream habitat data into Smallmouth Bass management decision-making (INT17). They hoped to see fact sheets created for other species such as Walleye, Northern Pike, and Muskellunge (INT17). Furthermore, participants expressed a desire for concrete examples of how to use stream habitat data in management decision-making. This finding is especially important as it relates back to previous findings, that many participants have positive opinions about the value of the STP stream habitat data but mentioned that they felt unsure about how to use it (9/19; 47%; Figure B.1.4).

The fourth strategy identified to increase the use of STP stream habitat data is to improve the FCS database (6/19; 32%; Figure B.1.4). Participants stated that to increase data use, the accessibility of the database should be improved upon, which would allow biologists to more easily query data. Additionally, participants wanted more summary programs and greater ability to compare sampling sites. Interestingly, 12 participants (Figure B.1.3) initially identified the FCS database as a barrier to using STP data, but only half as many (6, Figure B.1.4) cited improvements of the database to increase data use. One participant pointed out, “The data in the Fish Collection System aren’t necessarily boiled down and summarized in the easiest to interpret way. Whereas the Stream Evaluator, we have that kind of boiled down into some good summaries for managers. So just having unlimited access to the Fish Collection System may not solve everyone’s problems either,” (INT17).

Finally, participants expressed that having more training and continued education regarding how to use both the tools and stream habitat data would ultimately increase their use of STP habitat data in their work (6/19; 32%; Figure B.1.4). Several participants mentioned that while tools such as the Stream Evaluator are helpful for comparing streams, biologists have received little instruction about how to use these tools and would benefit from having examples of how to use the tools for management decision-making. Other participants mentioned that many biologists have had little formal training in hydrology, geomorphology, and to a lesser extent, stream rehabilitation techniques. Supporting the continued education of MDNR biologists regarding subjects such as stream ecology and hydrology would help biologists to better use the STP stream habitat data as it would give biologists a clearer understanding of how fish are affected by their habitats.

In addition to the five strategies identified by participants to improve the use of the STP stream habitat data, it should be noted that one participant did state that there were no improvements that would increase their use of the data, simply stating, “I just need the basics of the fisheries data,” (INT6).

What programs or projects are top priority in your management unit?

Several priorities within MDNR Fisheries Division were identified. Priorities were then subdivided into agency priorities, program priorities, and other priorities. Participants expressed management unit priorities for both streams and lakes. The following details findings from these three categories.

Agency priorities

Seven agency priorities were identified by interview participants, defined as mandates from the state and/or the public trust doctrine. The first was fisheries (19/19; 100%; Figure B.1.5) which follows because the interview was conducted with MDNR Fisheries Division. Primarily, participants identified priority fisheries within their respective management units (Figure B.1.6), and these participants' management units specifically focused on the management of salmonids (7/19; 37%), Walleye (7/19; 37%), Lake Sturgeon (2/19; 11%), Cisco (*Coregonus artedi*; 2/19; 10%), and Northern Pike (1/19; 5%). The second agency priority identified included restoration and habitat improvement projects for both lakes and streams (16/19; 84%; Figure B.1.5). The 16 participants who identified restoration and habitat improvement projects as top agency priorities additionally identified five specific types of habitat restoration and improvement projects (Figure B.1.7). They included improving connectivity (6/16; 37%), general habitat improvement projects (5/16; 31%), managing woody debris (2/16; 13%), erosion control and prevention (2/16; 13%), and restoring channel morphology (1/16; 6%). The third agency priority identified was stocking programs (8/19; 42%; Figure B.1.5). Next was improving angling opportunities for the public (5/19; 26%; Figure B.1.5), and this includes allocating resources to multiple user groups, prioritizing projects that improve fishing, and creating materials for the public who want to know what species reside in specific water bodies.

The Areas of Concern were the fifth agency priority identified (2/19; 11%; Figure B.1.5). Areas of Concern are geographic areas designated by the U.S.-Canada Great Lakes Water Quality Agreement where significant impairment of beneficial uses has occurred as a result of anthropogenic activities (MDNR 2018). The sixth agency priority identified included fisheries regulation evaluations (2/19; 11%; Figure B.1.5). Finally, the seventh agency priority identified was an overarching priority of conserving and protecting Michigan's aquatic resources (1/19; 5%; Figure B.1.5).

Program priorities

Program priorities are defined as also being priorities of the state but are managed and addressed via specific MDNR programs. Five MDNR program priorities were identified by survey participants. The first top program priority identified by survey participants was the Status and Trends Program. One participant stated, "Our top priority should be really knowing what is going on in our waters. And the only way you can do that is having some sort of systematic look at what's going, and you need to know the trends. The only way we as a Division have credibility and that the public has some respect and belief in our [Division] is to have our pulse on what's going on in our waters, which the Status and Trends Program does," (INT9). The review of [Michigan's] Department of Environmental Quality permits was the second program priority identified (3/19; 16%; Figure B.1.5) such as construction and maintenance of seawall infrastructure; aquatic nuisance plant control; evaluating potential deleterious effects from mining, forestry, and other industrial enterprises in a watershed; constructing and replacing culverts and stream crossings; and dam infrastructure management [note: this agency is now referred to as the Michigan Department of Environment, Great Lakes, and Energy]. The third priority identified was the Resource Inventory Program (2/19; 11%;

Figure B.1.5). Next, performing grant reviews (1/19; 5%; Figure B.1.5) such as for granting funds for managing species of concern, like Lake Sturgeon conservation, were the fourth priority identified. Finally, the fifth priority identified was addressing the goals and objectives of the Wildlife Action Plan (1/19; 5%; Figure B.5).

Additional priorities

Five additional priorities were identified by survey participants that are not specific to any single MDNR program or state mandate. The first was lake management (9/19; 47%; Figure B.1.5) which includes actions such as installing woody structures, restoring natural shorelines, stocking, and collecting limnological data. The next priority identified was stream management (4/19; 21%; Figure B.1.5) and included similar management actions such as restoring stream channels, managing sediment regimes, collecting stream habitat and biologic data, and to a lesser degree, stocking. Outreach and education (3/19; 16%; Figure B.1.5) was the third additional priority identified, and survey participants mentioned that fishing tournaments and outdoor club events were great opportunities to "go out and answer questions to the public," (INT3). Subsequently, reactive management (i.e., responding to crises) was the fourth additional priority identified (3/19; 16%; Figure B.1.5). One participant described it as much like fighting fires, "If something starts dying [i.e., burning] then we pay attention to it," (INT19). Finally, the fifth additional priority identified was conducting fisheries research (2/19; 11%; Figure B.1.5), and research topics included invasive species, how fish communities change with climate, watershed effects on fish communities, and habitat mapping in the Great Lakes (INT14; INT19).

What management scenarios and questions can be addressed using the Status and Trends Program stream habitat data?

Ten management scenarios that could be addressed using STP stream habitat data were identified. The first management scenario identified was using STP stream habitat data to communicate with the public and stakeholders (19/19; 100%; Figure B.1.8). One participant mentioned, “I use a lot of the information from the STP as a reference when speaking with the public to support what we’re doing and why. Like, I can discuss what variables could be important to whatever fish species the public is interested in,” (INT17).

The second management scenario identified was stream restoration (18/19; 95%; Figure B.1.8). Several participants offered a variety of uses for STP stream habitat data for stream restoration such as determining locations for additions of large woody debris, identifying what streams would benefit most from riparian buffer rehabilitation, identifying streams in need of channel restoration, and addressing erosion or deposition concerns in channels. Other participants mentioned that the STP is particularly useful for evaluating stream systems and determining which could benefit most from intensive or larger scale restoration, specifically efforts at a scale greater than a stream site.

The following three management scenarios had equal numbers of responses (15/19; 79%; Figure B.1.8). One management scenario identified was using STP data for conservation and protection of species and their habitats (15/19; 79%; Figure B.1.8). One participant stated: “[Another] thing might be correlating some stream habitat variables to the distribution of rare species; federal, state, threatened and endangered species that live in streams. It would be nice if we could kind of predict where those are. [It] would be good to know if a stream might be potential habitat for a rare species,” (INT11). The next management scenario identified was using STP data to address dam removals and fish passage (15/19; 79%; Figure B.1.8). Several participants mentioned that the STP data are useful for selecting and prioritizing the removal of dams. Additionally, participants stated that referencing fixed sites where dams have been previously removed can aid managers in anticipating how similar streams may respond. The STP data are additionally used when reviewing large projects for FERC licenses. Several participants also stated that the STP data were useful for evaluating the benefits and deleterious effects of barriers to fish passage, including invasive species like Sea Lamprey (*Petromyzon marinus*). Finally, the other management scenario identified was the prioritization of projects (15/19; 79%; Figure B.1.8). One participant stated, “The Status and Trends Program really kind of steers me in the direction of which waterbodies I’m going to sample next,” (INT10). Participants were extremely conscious of budget limitations and reductions, and as such, many participants mentioned that the STP data were useful for determining which improvement and conservation projects would have the greatest return on investments for populations responses.

The sixth management scenario identified was using STP data to aid in stocking Michigan’s fisheries (14/19; 74%; Figure B.1.8). Several participants mention STP data are useful for identifying areas with optimal habitat for stocking as well as areas where habitat can be limiting for fishes. The STP data were additionally useful in reviewing private stocking permits. The STP data were also identified as beneficial in identifying areas where stocking certain species should be discontinued due to changes in the system. For example, one participant mentioned after many attempts to reestablish a trout fishery in a UP stream, the stream’s habitat was evaluated, and results indicated that channel degradation and the stream’s transition from cool water to warm water did not make the stream conducive to holding trout year-round, and thus the stocking program was discontinued (INT10). Evaluations such as these allow managers to get better return on investments for stocked fishes.

The following management scenarios had equal number of responses (12/19; 63%; Figure B.1.8). One management scenario identified is using STP data to inform knowledge gaps (12/19; 63%; Figure B.1.8). One participant suggested examining correlations between stream habitat variables and the distribution of rare, as well as threatened and endangered, lotic species (INT11). Another participant mentioned, “I think if you see a difference in fish populations, and you can’t look at the habitat, then you really don’t know why there’s a difference, and so I think that’s where the value [in the STP] comes in, in particular. Does a stream have the potential to even maintain the population you’re trying to achieve there or not? [The answer is] habitat based almost all [of] the time,” (INT12).

The next management scenario identified is using STP data to monitor stream systems, as well as trends, through time (12/19; 63%; Figure B.1.8). One participant stated, “Documenting change or documenting no change: I think that’s very important. By 2065, there’s going to be a lot of tributaries in the western Upper Peninsula that aren’t going to be able to house Brook Trout anymore. So, having that habitat information collected from the Status and Trends Program over that period of 60 years is going to be pretty valuable,” (INT10). Another participant specified, “I could see there being changes in stream habitat based on global warming; you’ll get more runoff and faster, flashier flows, and longer periods of low flows. You’re going to see some shifts in stream stability, and it’d be really nice to be able to measure that using a long-term habitat database,” (INT12).

The ninth management scenario identified was using STP data to help managers make recommendations and in management decision-making processes (8/19; 42%; Figure B.1.8). Participants listed a variety of ways that the STP data could be used to make management recommendations and decisions such as fisheries regulation evaluations, reviewing aquatic habitat grants, and assessing culvert replacement and removals. Participants also mentioned the data could be and have been used in other management decisions and actions previously mentioned such as making stocking decisions, evaluating dam removals, determining priority streams for restoration projects, and conserving and protecting aquatic species and their habitats.

Finally, the tenth management scenario identified was using STP data to aid in the management of aquatic invasive species (7/19; 37%; Figure B.1.8). Participants mentioned that the STP data could be useful for identifying areas highly vulnerable to the spread of invasives and for monitoring these areas most frequently. Additionally, participants mentioned that the STP data could be used to monitor the effects and impacts of aquatic invasions on streams through time.

DISCUSSION

The goal of this study was to identify ways to increase the use of stream habitat data by natural resource management agencies to better conserve freshwater fishes from current and future stressors. We addressed this by interviewing MDNR managers and biologists about their perceptions of and barriers to using stream habitat data in management decision-making. Our results detailed their perceptions of the STP program, identified barriers to using STP stream habitat data, and identified strategies to increase the use of STP stream habitat data in management decision-making processes. Findings from this study can help MDNR revise the STP and create additional tools that can help managers better conserve fishes and their habitats into the future. These results also have broader implications for natural resource management, as our findings indicate that managers want more tools and continued education and trainings to facilitate their use of stream habitat data. Based on the responses of survey participants, our findings also illustrate the value of standardized stream habitat data collection for natural resource management agencies performing fisheries management and conservation work. This study provides practical solutions to address barriers to using stream habitat data in day-to-day fisheries management decision-making and conservation.

Perceptions of the STP and standardized sampling protocols

Currently, the STP is well-regarded overall by MDNR managers and biologists. Most survey participants acknowledged the long-term management value of the STP and indicated that the program's value would increase over time as more data were collected. This overall positive perception of the STP is likely the result of the collaborative efforts between MDNR fishery biologists, administrative and supervisory staff, collaborators from other natural resource management agencies, and university faculty in the creation of the STP (Hayes et al. 2003). Initially, in attempting to standardize sampling efforts, some MDNR personnel expressed concern over the new protocols, citing worries that they would lose their ability to make autonomous decisions as mangers (*conversations with multiple experts*). However, allowing for feedback and collaboration between biologists and administrative staff led to greater acceptance of the program over time (Hayes et al. 2003; Flinchbaugh et al. 2020). Survey participants indicated that they did perceive the STP data to be useful for management decision-making, but largely the data used by managers were biological data and not related to stream habitat (*conversations with survey participants*). In limited cases when stream habitat data were used by managers, data were most frequently used to communicate with the public or to prioritize fisheries management actions and projects (*conversations with survey participants*).

Historically, natural resource managers in the US have been resistant to standardizing sampling protocols (Bonar et al. 2009). Managers suggest that implementation is costly, that standardization reduces biologists' innovation, and that natural variation across regions invalidates standardized techniques (Bonar and Hubert 2002). Typically, an agency's supervisory staff are primarily responsible for creating new standardized sampling protocols. In contrast, field biologists directly affect how these protocols are (or are not) implemented in management practices. Because of this, it is crucial that supervisory staff collaborate with field biologists and incorporate field biologist's expertise when creating standardized sampling methods to best ensure that protocols are accepted by those implementing them (Bonar and Hubert 2002; Flinchbaugh et al. 2020).

Barriers to using stream habitat data

Broadly, two barriers to using the STP stream habitat data were identified through this study. The first was that stream habitat data are difficult to access, and this was supported by multiple criticisms of the database by survey participants. For example, managers explained that data are not stored in a format that are easy to interpret and use in analyses to support decision-making. Also, many managers stated that because these data are poorly formatted, they do not have the time to re-format the data for use in analyses. Because of these barriers to accessing data in an interpretable format, managers stated that it was difficult to incorporate stream habitat data into their management decision-making processes.

The second barrier identified was managers' uncertainty about how to incorporate data into decision-making processes. Overall, natural resource management agencies have traditionally focused efforts on various forms of responsive population management (e.g., stocking and setting harvest regulations), rather than on habitat conservation, and limited research has been dedicated to the applied management implications of stream habitat changes (Sass et al. 2017). In the past, fisheries educational curricula have focused primarily on fish biology and fisheries management and less on courses that depict ways in which the physical environment affects fishes and their habitats, including courses like stream ecology, hydrology, or landscape ecology (Oglesby and Krueger 1989). Because of this, many managers have an incomplete understanding of interactions between the riverscape and landscape (Fausch et al. 2002), and this is a barrier to using these data in management decision-making processes. Because of these described barriers, MDNR managers and biologists have not consistently used stream habitat data in their management decision-making processes. Strategies for overcoming these barriers are described in the following section.

Strategies for increasing use of stream habitat data

One strategy identified to increase the use of stream habitat data by managers is to provide them with more tools and improved data formatting to remedy barriers to accessing data. In support of these needs, MDNR participants were interested in implementing more practical, less expensive solutions to improve STP data use, such as developing web tools to improve analysis and creating formatted templates to streamline report writing. Participants also wanted training to use these tools to alleviate issues with data interpretability in its current format. Web tools such as the Michigan Stream Evaluator (MSE) tool by MDNR Fisheries Division (Zorn et al. 2017) have been well received by MDNR managers (*conversations with STP experts*). The MSE allows users to access summarized benchmark values, including mean values and ranges in conditions, for parameters collected from random site survey protocols and allows users to compare local site data with sites across the state (Zorn et al. 2017). Additionally, MDNR participants recognized that likely budgetary constraints for natural resource management agencies (*conversations with survey participants*) would limit more expensive solutions such as improvements to the FCS database. This was reflected in our results, as most MDNR participants indicated that limited access to STP data in the FCS was a barrier to data use, but when asked what could be done to overcome this barrier, only half mentioned improving the FCS database as a solution.

The development of web tools can integrate analysis and visualization capabilities that allow users to assess how streams compare to others or identify changes in a stream through time (Lynch et al. 2012; Bonar et al. 2015; Moody et al. 2017). However, creation of such web tools requires standardized sampling methods in order to have meaningful comparisons between surveys (Kemp and Meaden 2002; Bonar et al. 2015), further highlighting the importance of standardizing sampling methods within and across natural resource management agencies (Bonar et al. 2009). Developing more web tools for biologists can ease the burdens of accessing, cleaning, and analyzing data by providing data in a format that is streamlined, easily interpretable, and standardized. Web tools could also help managers who stated that time constraints associated with re-formatting data were a barrier to data use, as the creation of web tools can allow for easier data interpretability than printed summaries (Bonar et al. 2015). Web tools should be designed to compare streams at multiple spatial scales (i.e., local, regional, or statewide) because of the multiple spatial scales at which management actions can occur. Recently, web tools have increased in popularity with natural resource management agencies as they allow managers to better visualize a broad array of data in the form of models, metadata, and images, and ultimately, facilitate the integration of these data into decision-making processes (Korschgen and Knutson 2005, Peterson et al. 2013).

The second strategy identified to increase the use of stream habitat data is to provide managers with continued education and trainings on the broad fundamentals of how the physical environment (e.g., stream habitat, watershed hydrology, climate, land cover, etc.) affect fishes and their habitats. This includes effects of habitats on fish as well as how landscape factors affect fish through effects on habitat. Many survey participants mentioned that they would feel more confident and inclined to use the stream habitat data if they were provided with additional education regarding how to use stream habitat variables for fisheries management. Providing further training and education to managers and biologists on topics such as hydrology and landscape ecology or even stream restoration courses would aid in incorporating stream habitat data into management decision-making (Keeney 1982; Ascough II et al. 2008). Effective continued education is critical to continuing innovative problem solving and decision making by fisheries managers (Hardré 2001).

Professional societies whose missions include preparing and promoting the development of fisheries professionals, such as the American Fisheries Society (AFS), could help address this need by providing continuing education on topics such as stream restoration. Continued education and trainings through professional societies could provide a richer understanding of how habitat data can be used in management decision-making processes (Flinchbaugh et al. 2020). AFS has a unique opportunity to address these gaps in education by restructuring and revisioning course curricula for programs such as the AFS Professional Certification, as well as additional avenues such as creating specific trainings and workshops for specific subject matter such as stream ecology and hydrology (Kaemingk et al. 2016). In addition to continued education, managers should be provided with contextual materials about stream habitat data and management decision-making that is relevant to their management region. These contextual materials could include annotated bibliographies highlighting other studies that have used stream habitat data to support or make management decisions. To provide managers with additional contextual materials, all variables found in a natural resource management agency's database and tools should be described and incorporated as metadata. This will provide biologists and managers with a greater understanding of what each variable measures.

Using stream habitat data in management decision-making

Many of the MDNR management priorities identified by survey participants can be addressed using stream habitat data. Several of these priorities identified by survey participants are related to traditional responsive population management practices such as stocking, improving angling opportunities, managing fishery regulations, and monitoring fisheries through time. As such, stream habitat data are not only valuable to habitat restoration and conservation management but also for traditional responsive population management. For example, stream habitat data have been used to explain spatial patterns of fish densities and distributions (Creque et al. 2005), address management objectives for sportfish species like Brown Trout (*Salmo trutta*; MacDonald et al. 2011), Brook Trout (*Salvelinus fontinalis*; Nuhfer et al. 2015), and Steelhead (*Oncorhynchus mykiss*; Grantham et al. 2012), evaluate rivers for the reintroduction of native species like the Arctic Grayling (*Thymallus arcticus*; Danhoff et al. 2017), and monitor fish populations for changes post-restoration (Tyler and Rutherford 2007).

Additionally, most participants expressed a growing need to prioritize their projects. Due to multiple factors, budgetary limitations are expected to increase into the foreseeable future and natural resource management agencies have an increasing need for prioritizing projects and programs with the most cost-effective outcomes. Using stream habitat data could help managers to efficiently prioritize streams that would benefit most from restoration, stocking, or other management efforts (Rios-Touma et al. 2014; Moody et al. 2017). For example, stream habitat data can be used for prioritizing dam removal and fish passage projects (Roni et al. 2001; O’Hanley et al. 2013; Hoenke et al. 2014; Moody et al. 2017). Additionally, these data can be used to understand conditions within reference streams which would allow managers to compare how similar streams have responded to dam removal or implementation of fish passage in the past (Bushaw-Newton et al. 2002; Dodd et al. 2003; Doyle et al. 2005; Briggs and Galarowicz 2013). This could help managers potentially predict how stream habitats and fish populations may respond to these interventions.

Furthermore, survey results indicated that stream habitat data were useful for communicating with the public and stakeholder groups. For example, survey participants have used stream habitat data to communicate with anglers about why a fishery had changed, to explain why a certain species was not a viable stocking option due to habitat limitations, and to aid local conservation groups in stream habitat restoration projects. Effective communication with the public and stakeholders is important to upholding the public trust (Sax 1969) and will lead to more effective collaborative partnerships between agencies and user groups (Bryson 2004). For this reason, stream habitat data are not only important to managing habitats and the fishes they support, but also with creating positive relationships and open communication with the public.

CONCLUSION

By interviewing MDNR managers and biologists throughout the state, we have identified barriers to using stream habitat data in management decision-making and strategies for increasing the use of stream habitat data within natural resource management agencies. Additionally, the broad implications of this study illustrate the extensive value of standardized stream habitat data collection for natural resource management agencies performing fisheries management and conservation work. Outcomes of this research include novel, practical solutions to increase the use of stream habitat data by mangers in management decision-making processes to better conserve streams and the fishes they support into the future.

APPENDICES

APPENDIX A

TABLES

Table A.1.1. Four themes that guided the study and five research questions coded using inductive data-driven thematic analysis in NVivo12.

Theme	Research question
Perceptions of the Status and Trends Program	What are the current perceptions and opinions of the Status and Trends Program?
Barriers to data use	Why are MDNR personnel not using the Status and Trends Program stream habitat data?
Utility of data	What could be done to help stream habitat data be used more effectively and often?
Management decision-making:	a. What programs or projects are top priority in your management unit?
	b. What management scenarios and questions can be addressed using the Status and Trends Program stream habitat data?

Table A.1.2. A codebook was developed from interview analysis for the theme perceptions of the Status and Trends Program. It includes a list of parent codes, describes the definition of the parent code, and includes an example of participant responses related to each parent code.

Theme	Definition	Parent Code	Examples
Perceptions of STP: What are the current perceptions and opinions of the Status and Trends Program?			
	Participants gave positive responses or feedback about the STP Program	Positive	"I appreciate the Status and Trends Programs and I think it's collecting good data."
	Participants gave negative responses or feedback about the STP Program	Negative	"The whole Status and Trends Program was an ill-conceived idea."

Table A.1.3. A codebook was developed from interview analysis for the theme barriers to data use. It includes a list of parent codes (i.e., categories) and daughter codes (i.e., subcategories), describes the definition of the codes, and includes an example of participant responses related to each code.

Theme	Definition	Parent code	Daughter code	Examples
Barriers to use: Why are MDNR personnel not using the STP stream habitat data?				
	Ability to access or query the database in FCS is a barrier to using stream habitat data	Access and queryability		"I guess one of the biggest barriers is our computer system, our Fish Collection System, it makes it a little difficult to output summary data in a usable format so if you want to make big comparisons you're kind of reliant on queries, usually you have to go to one of the biologists that's in charge of the system to give you the data you need."
	Ability to interpret stream habitat data is a barrier to using it in MDNR management decision-making	Data interpretability		"But the data in the Fish Collection System aren't necessarily boiled down and summarized in the easiest to interpret way."
	The suggestion that there is not enough data to draw meaningful conclusions; or that data were not available when implementing management action(s)	Lack of data		"It's pretty rare for us to actually have Status and Trends data on a particular stream [that require management actions]...So if it's available we'll look at the Status and Trends data, but I wouldn't say it happens very often where I have data for that particular stream to analyze."

Table A.1.3. (cont’d)

Theme	Definition	Parent code	Daughter code	Examples
Barriers to use: Why are MDNR personnel not using the STP stream habitat data?	Much of the data are not updated in real-time, preventing personnel from using the data	Outdated information		"A lot of [stream surveys] were done in the 90s, some were done in the 2000s, we’re still limping through getting a few more done. The data’s outdated, frankly it wasn’t done with the best of analyses."
	Participants indicated that they did not think stream habitat data were useful or relevant to their programs, projects, and or work	Perception that data are not useful or relevant		"When you are only looking at one specific site on a stream, how much can you say?"
	Participants felt they did not have enough time to additionally incorporate stream habitat data into their work	Time constraints		"Because they’re so busy barely keeping up with their workloads that they’re more looking at being expedient instead of being good. And that’s an unfortunate position that we are in, probably. It’s not in any way a degradation of their abilities, I think part of it’s just plain time. They don’t have the time to play with the datasets to understand what they mean."
	Participants were not sure how to incorporate stream habitat data into management decision-making	Unsure how to incorporate data		"I don’t know that we really know what variable is relevant."

Table A.1.3. (cont'd)

Theme	Definition	Parent code	Daughter code	Examples
Barriers to use: Why are MDNR personnel not using the STP stream habitat data?	Tenure in MDNR is self-identified. Some MDNR personnel expressed that the length of time they have been working for MDNR is directly related to their use (or lack of use) of stream habitat data	Tenure in MDNR		
	Participant self-identified as working for MDNR for an extended period of time		Long-time personnel	"One of the problems is I'm in…I'm older, I'm 55 years old and I'm not used to going to databases for information. So, as I learn to look for this stuff and how to work with it I use it more and more. The younger guys, they're used to using viewers and imaging and computers. So there's a little disconnect with me with technology."
	Participant self-identified as being recently or newly employed at MDNR		Recently employed	"Yeah so I'll preface that by saying that I'm relatively new so I'm still getting used to a lot of things and I appreciate the Status and Trends Program and I think its collecting good data and I wish I made more use of it, and I think if I got more involved that I will use more of it."

Table A.1.4. A codebook was developed from interview analysis for the theme improving utility of data. It includes a list of parent codes, describes the definition of the parent code, and includes an example of participant responses related to each parent code.

Theme	Definition	Parent Code	Examples
Improving utility: What could be done to help stream habitat data be used more effectively and often?			
	Participants indicated improving the FCS database would increase their use of stream habitat data	Formatting and templates for analysis	"If there was a way to have canned summary programs or query data, or if you wanted to get information from more than a couple of surveys."
	Participants indicated having more examples of how stream habitat data have been used in other studies would help them apply the data to their own work	Improve database	"The next step would be to make the [FCS] such that managers could pull information freely as they wish. But the data in the Fish Collection System aren't necessarily boiled down and summarized in the easiest way to interpret."
	Participants indicated having formatted templates for analysis and writing would increase their use of stream habitat data	Providing examples of use	"I think field biologists are looking to researchers to help explain to them how [habitat data] could be used. To provide them concrete examples. We're very focused on our one stream and we don't often look at the big picture."

Table A.1.4. (cont'd)

Theme	Definition	Parent Code	Examples
Improving utility: What could be done to help stream habitat data be used more effectively and often?	Participants indicated having access to more tools would increase their use of stream habitat data	Tools	"[It would be easier] if everything I did could be condensed into one or two applications [i.e., tools], if it wasn't spread over three different applications instead of jumping around and having to compare."
	Participants indicated having more training and education about how to use stream habitat data would increase their use of the data	Training and education	"I think clear training on how to query the information more effectively is probably the first starting place."
	Nothing could be done to increase the use of stream habitat data	Nothing	"Nothing, I just need the basics of the fisheries data."

Table A.1.5. A codebook was developed from interview analysis for the theme management decision-making, research question (a). It includes a list of parent codes (i.e., categories) and daughter codes (i.e., subcategories), describes the definition of the codes, and includes an example of participant responses related to each code.

Theme	Definition	Parent Code	Daughter Code	Examples
Management decision-making: What programs or projects are top priority in participant's management unit?	Participants self-identified priorities specific to their management unit			
		Areas of Concern		"When I think of projects in our Area of Concern, I think of how a number of our watersheds are identified as Areas of Concern."
		Conservation and protection		"We got a lot of waters down here, but we don't do a lot of active habitat work, like creating habitat, so our philosophy is the more we conserve it the better."
		DEQ permit reviews		"We do a lot of reviews so DEQ whether it be seawalls, aquatic nuisance plant control."
		Fish health		"On the fish health side, which has implications on habitat, is pathogen ecology and its interaction with its hosts."

Table A.1.5. (cont'd)

Theme	Definition	Parent Code	Daughter Code	Examples
Management decision-making: What programs or projects are top priority in participant's management unit?		Fisheries		
			Cisco	"We have several cisco lakes [and we are] assessing those, that's a pretty big priority for us."
			Northern Pike	"I focus a lot on our Northern Pike waters and populations."
			Panfish	"General areas are lake management, and then within lake management we have panfish management."
			Salmonids	"Again, we have some of the best trout, salmon, and steelhead streams in the state and so obviously those are very high priority."
			Sturgeon	"Lake Sturgeon gets a lot of money put towards it because it's a species of special conservation need and it's also a listed species in our state and besides that it's charismatic megafauna, everybody loves sturgeon."
			Walleye	"I'm going to say the majority of our time is spent on walleye management."
		Grant review		"There's external grants that wander in, like there's individual species like Lake Sturgeon gets a lot of money put towards it."

Table A.1.5. (cont'd)

Theme	Definition	Parent Code	Daughter Code	Examples
Management decision-making: What programs or projects are top priority in participant's management unit?		Improving angling opportunities		"We try to prioritize things that will help make fishing better."
		Lake management		"We've made Status and Trends Program a priority in our management unit as well, and the collecting of limnological data is a big priority."
		Outreach and engagement		"We had a couple guys at the ultimate fishing show, so that's an opportunity to go out and answer questions to the public. We've got a lot of clubs down here, so we do the circuit and make a lot of presentations to them. Lots of opportunity for information and education, that continues to be important."
		Responding to crises		"[Your priority] depends who you're dealing with at that moment."
		Regulations		"Okay, so these are just what are our top priorities, period? Ok for us: dam removals are huge, stocking evaluations, regulation evaluations."

Table A.1.5. (cont'd)

Theme	Definition	Parent Code	Daughter Code	Examples
Management decision-making: What programs or projects are top priority in participant's management unit?		Research		"We do a little bit of work on temperature too. Statewide. And we do some pointed analyses, targeted analysis like for example on sand traps. We just got done publishing a paper, on frankly the ineffectiveness of sediment traps. They don't work."
		Resource Inventory Program		"So top priority projects, our Resource Inventory Program is probably one of the biggest that is high priority."
		Restoration or habitat improvement projects		
			Connectivity	"In terms of habitat, I'd say dam removals are probably number one. We've got a large one going on in Niles, or about to start in Niles, here on the Dowagiac River that we spent years on. So dam removals would be huge."

Table A.1.5. (cont’d)

Theme	Definition	Parent Code	Daughter Code	Examples
Management decision-making: What programs or projects are top priority in participant’s management unit?		Restoration or habitat improvement projects	Erosion	When asked what priorities their Management Unit had, one participant stated: "We’re doing some erosion control and habitat."
			General	"Restoration programs, stream restoration programs are a big priority."
			Morphology	"The other thing that we do is a lot of times for smaller streams we know that depth is important and a lot of our streams are overly wide and shallow because they’re so sandy and so a lot of times a goal, one of the primary goals of a stream habitat project will be to narrow and deepen a stream and just provide habitat that way."
			Woody debris	"We spend a lot of time working on stream habitat projects and we try to improve carrying capacity for the fish that anglers prefer. So, we spend a lot of time strategically placing wood in streams."

Table A.1.5. (cont'd)

Theme	Definition	Parent Code	Daughter Code	Examples
Management decision-making: What programs or projects are top priority in participant's management unit?		Status and Trends Program		"We've made Status and Trends Program a priority in our management unit."
		Stocking		"Most of our salmonids are intensively cultured in a hatchery where they raise and thrive and then they turn them back to the field for actual production. That's an important component to what we do."
		Stream management		"We have lakes that we do discretionary surveys, and streams of course, that we do focused management on."
		The Wildlife Plan		When asked what priorities their Management Unit had, one participant stated: "The Wildlife Plan."

Table A.1.6. A codebook was developed from interview analysis for the theme management decision-making, research question (b). It includes a list of parent codes (i.e., categories) and daughter codes (i.e., subcategories), describes the definition of the codes, and includes an example of participant responses related to each code.

Theme	Definition	Parent Code	Examples
Management decision-making: What management scenarios and questions can be addressed using the STP stream habitat data?	Responses could be suggestions of how MDNR would like to use STP data or responses could relate to ways MDNR have already used STP stream habitat data		
		Communicating with the public and stakeholders	"But I think being able to use STP data in a more meaningful way would allow both field and research biologists a way to better communicate to our watershed groups and public."
		Conservation and protection	"There's always a question of how's climate change going to affect fish, or are populations up or down, are we having a disaster on the north branch of the Au Sable with trout, if that's because of PFAS or something else or is this just normal variability. So, we use the data to try to tease those types of things out. Should we add wood to the stream, should we add a sand trap, is the sand trap working?"
		Dam removal and fish passage	"I have relied upon some STP sampling when evaluating fish passage at dams and rock ramps."

Table A.1.6. (cont'd)

Theme	Definition	Parent Code	Examples
Management decision-making: What management scenarios and questions can be addressed using the STP stream habitat data?		Inform knowledge gaps	"[Does] this stream does lack woody debris but maybe it's because that stream has high power flows on a two- or three-year cycle and a lot of that wood gets flushed out. We don't have the data, the knowledge, to answer that, but I think with some work we could maybe start to fit those pieces of the puzzle together."
		Invasive species	"The Status and Trends habitat ties into some habitat suitability indices that exist for different species, so that would probably help us if we're looking at combat[ting] introductions of aquatic invasive species."
		Monitoring	"[It] makes a lot of sense to look at habitat changes through time. Especially if we're expecting any kind of changes."
		Prioritization of projects	"I think ultimately it [i.e., STP] could be used for prioritization of habitat improvement projects."

Table A.1.6. (cont'd)

Theme	Definition	Parent Code	Examples
Management decision-making: What management scenarios and questions can be addressed using the STP stream habitat data?		Recommendations and decision-making	"You could really put your survey results for a particular site into comparable variables that you could go look – you could go make more informed management decisions based on, rather than just trying to evaluate your site you could really look at it on a statewide perspective regional perspective or even filter it by lake or stream type a little bit more easy."
		Restoration	"I know our field biologists would definitely benefit from it. They would benefit from it not only just writing up reports but also in evaluating habitat projects and things like that that are coming."
		Stocking	"We review private stocking permits, for example, when a private entity has enough money and they would like to stock a public waterbody, they're certainly welcome to do so provided they have fish health certification forms and provided there's not going to be some adverse impact. Nobody should be stocking bull trout for example in a public waterbody, so a fisheries biologist would review that and provide some management recommendations or denial of approval."

APPENDIX B

FIGURES

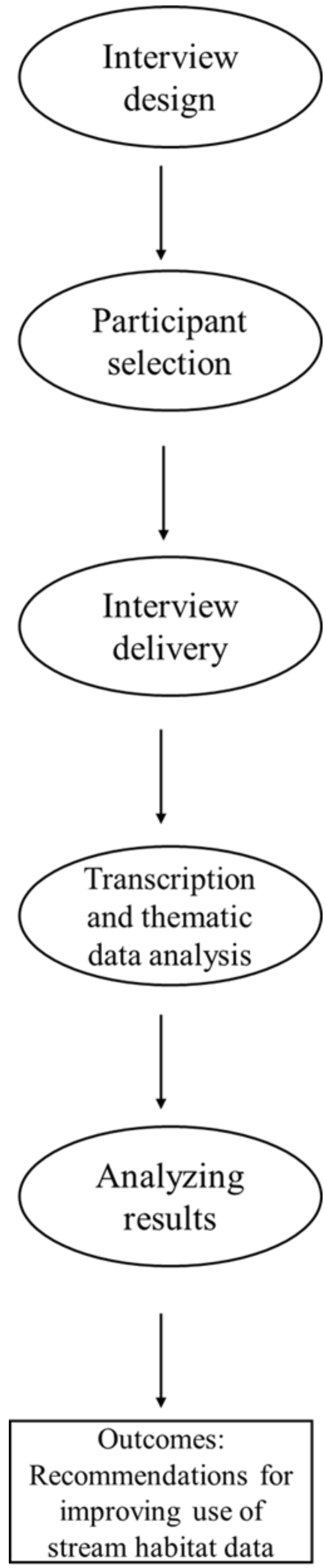

Figure B.1.1. Five steps taken to conduct this qualitative interview study.

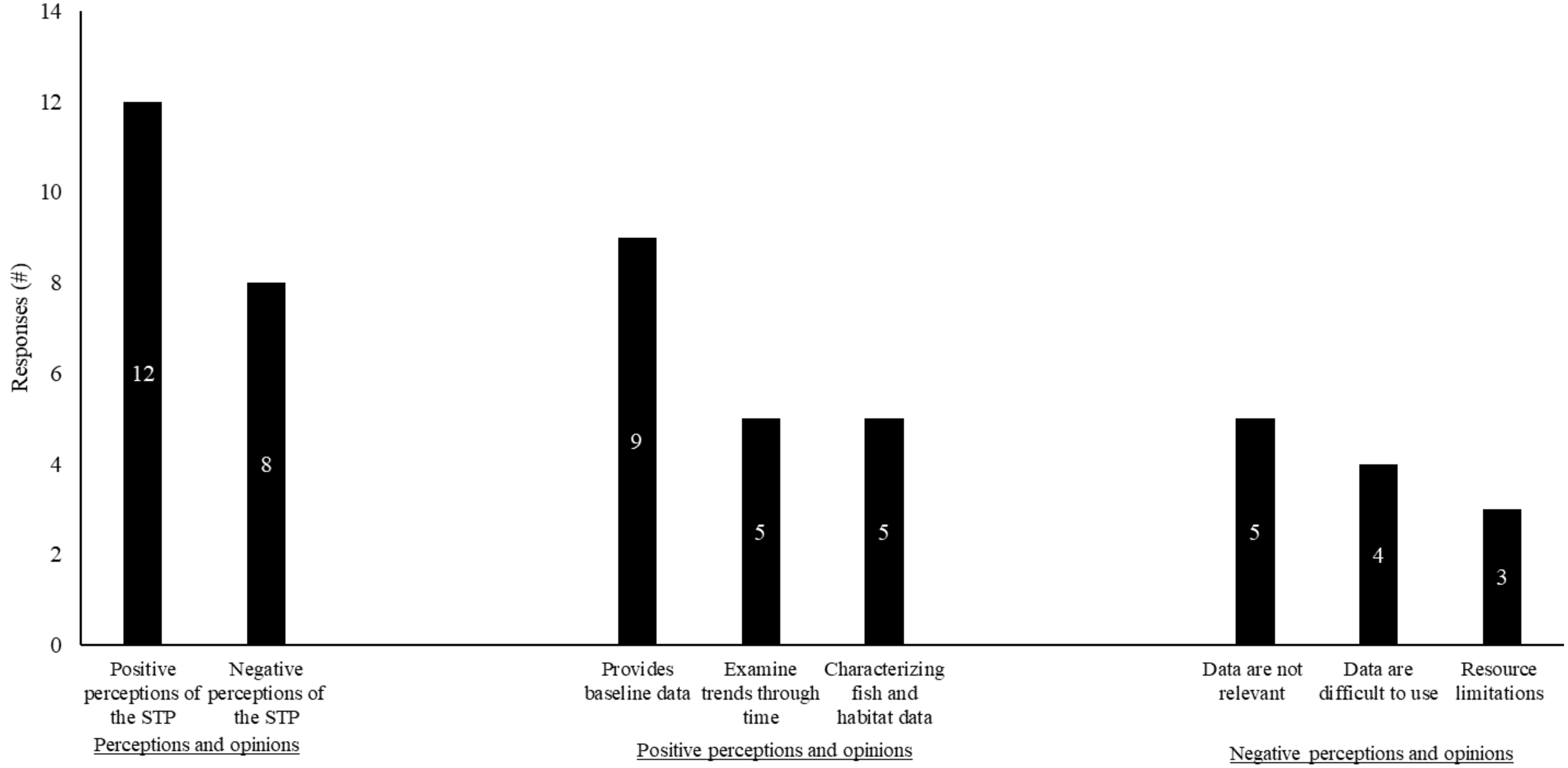

Figure B.1.2. Responses by survey participants in relation to the first theme question: What are the current perceptions and opinions of the STP?

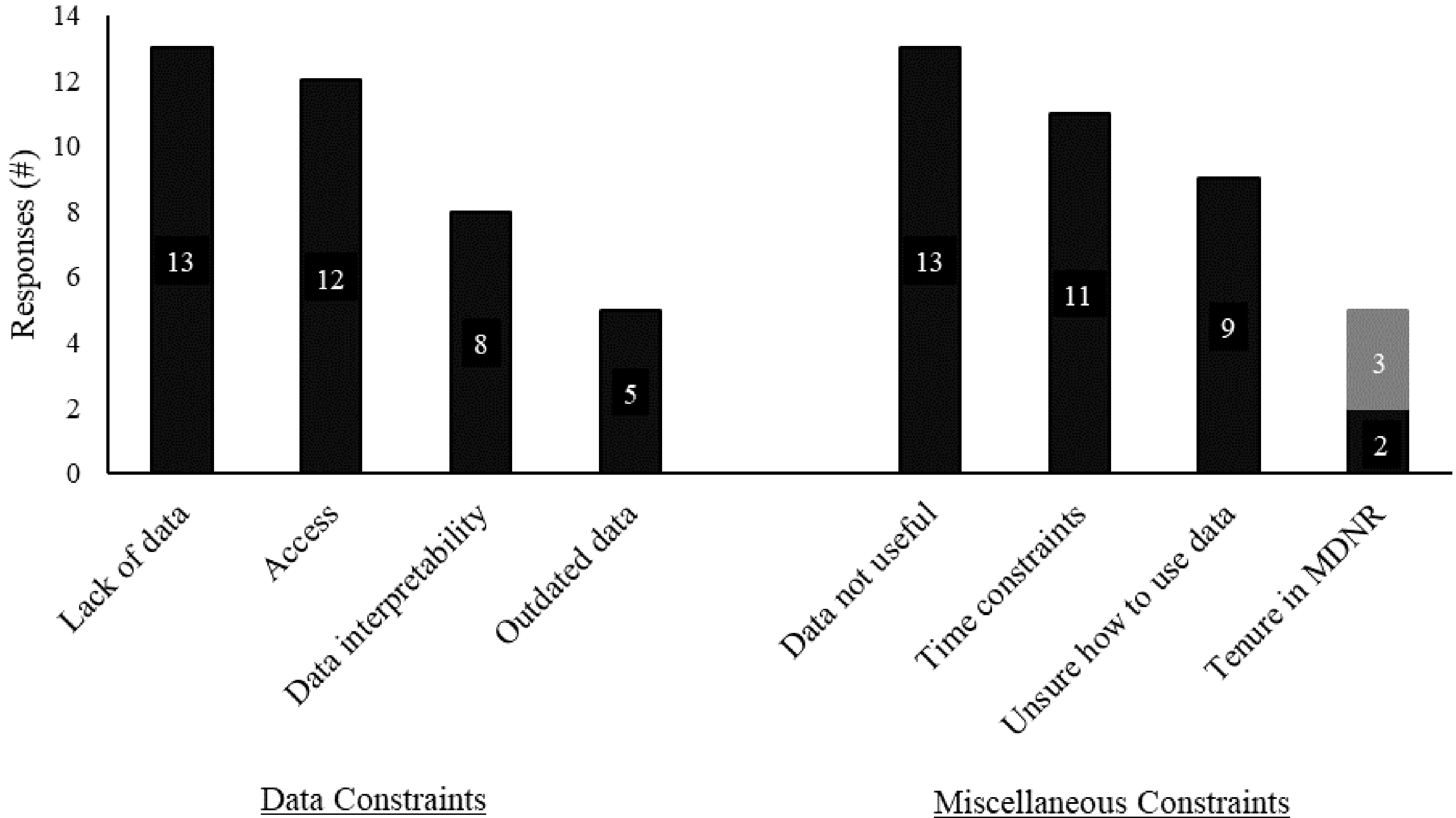

Figure B.1.3. Responses by survey participants in relation to the second theme (i.e., barriers to data use) and corresponding research question: Why are MDNR personnel not using STP stream habitat data? Survey responses were grouped into two categories: data constraints and miscellaneous constraints. In the miscellaneous constraints, black represents long-term MDNR employees and gray represents recently employed MDNR biologists.

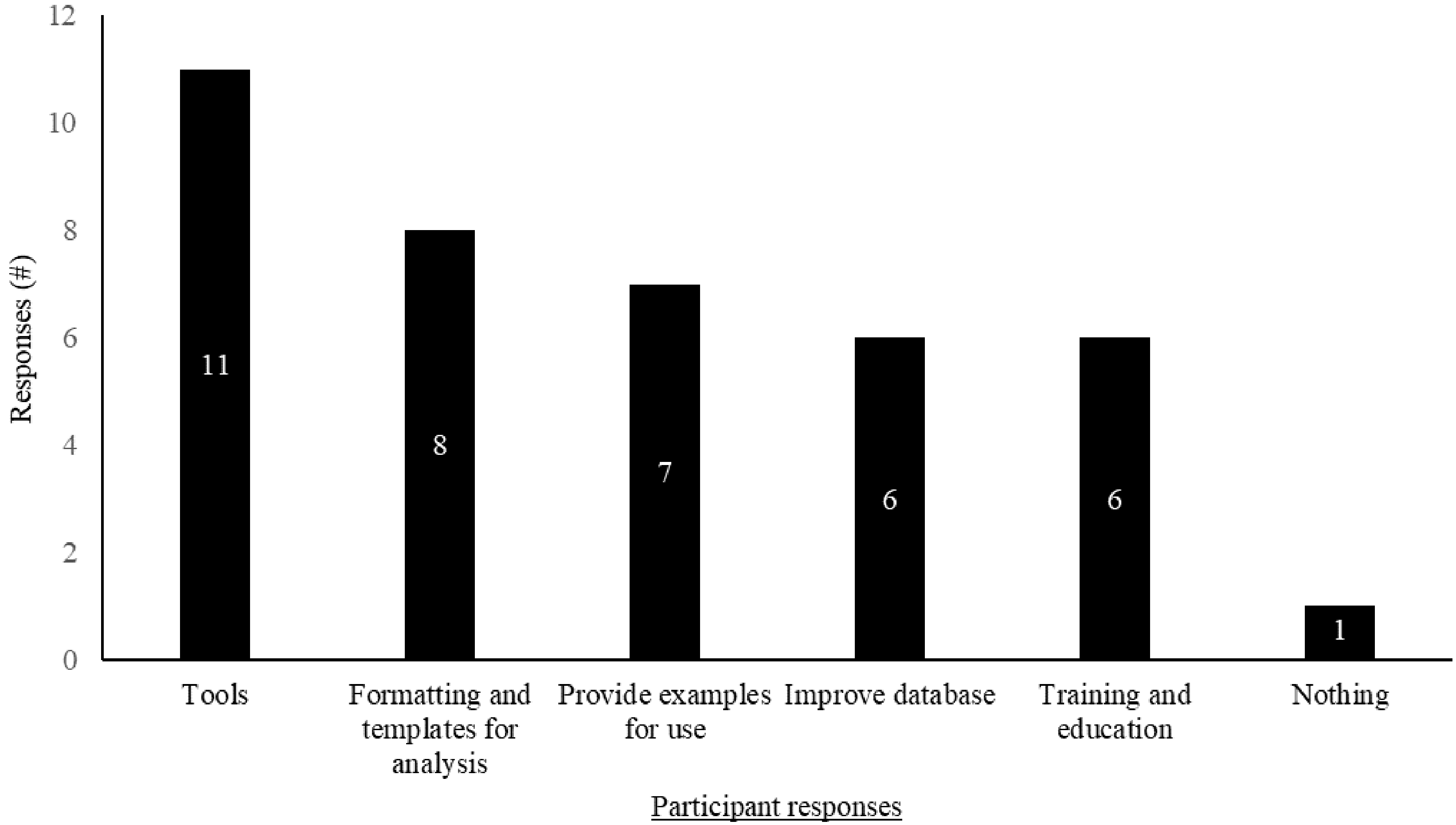

Figure B.1.4. Responses by survey participants in relation to the third theme (i.e., utility of data) and corresponding research question: What could be done to help STP stream habitat data be used more effectively and often?

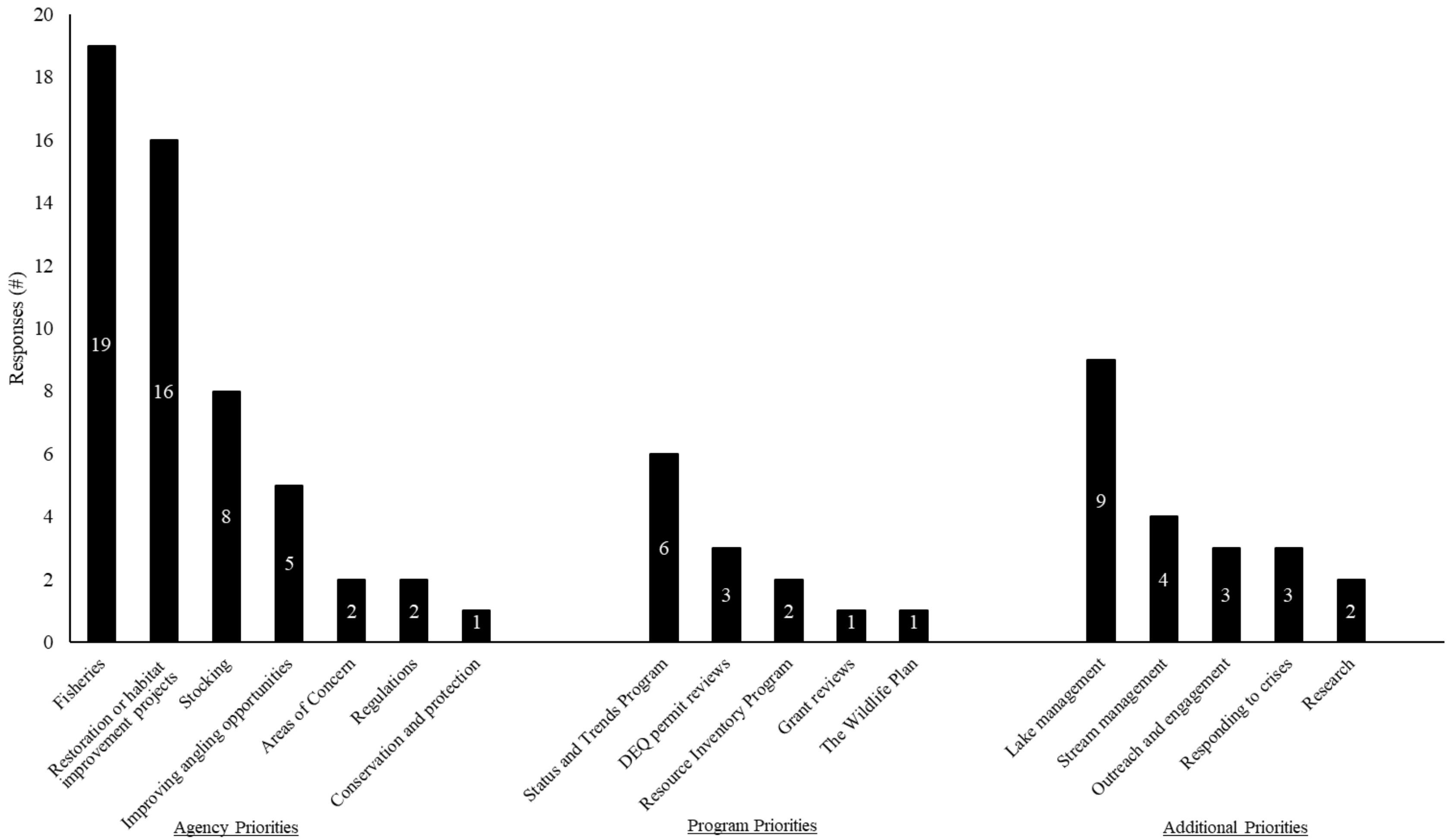

Figure B.1.5. Responses by survey participants in relation to the fourth theme (i.e., management decision-making) and corresponding research question: What programs or projects are top priority in your management unit? Survey responses were grouped into three categories: agency priorities, program priorities, and additional priorities.

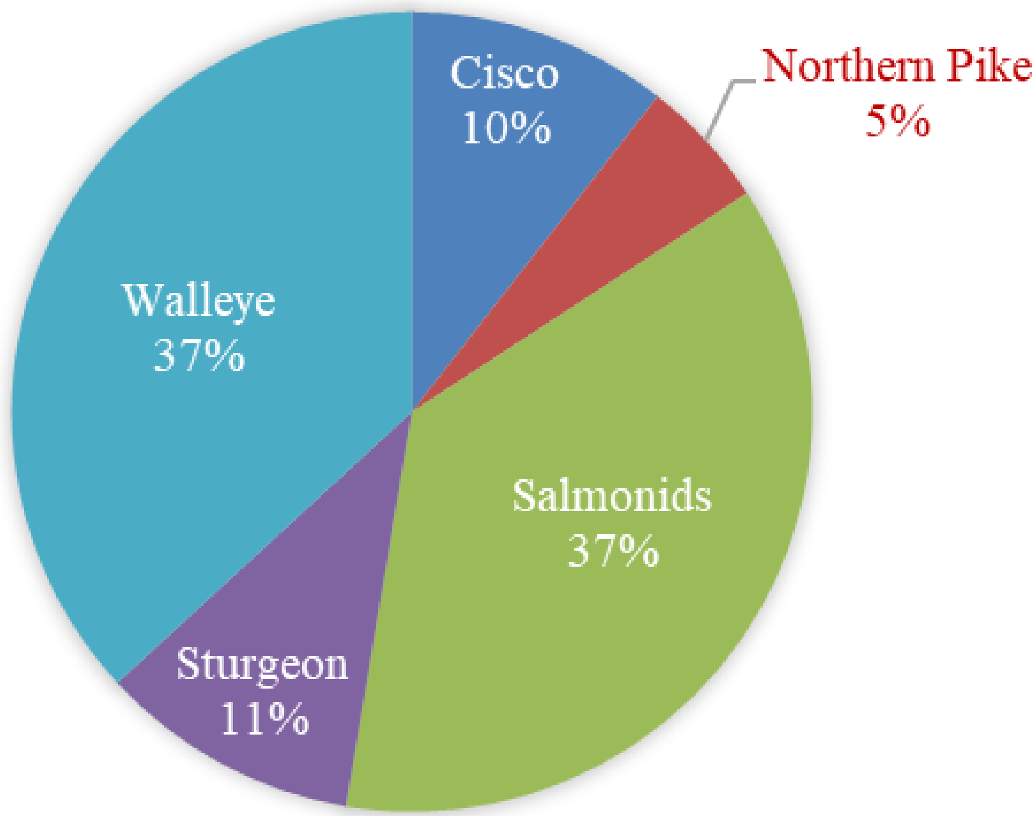

Figure B.1.6. Responses by survey participants who identified the top priority fisheries within their management units.

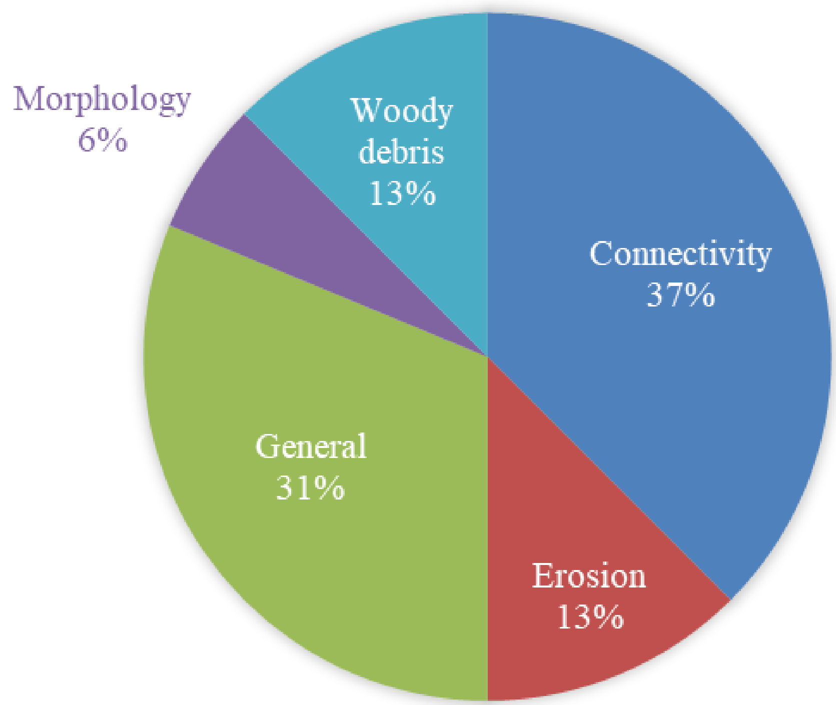

Figure B.1.7. Responses by survey participants who identified priority restoration and habitat improvement projects within their management units.

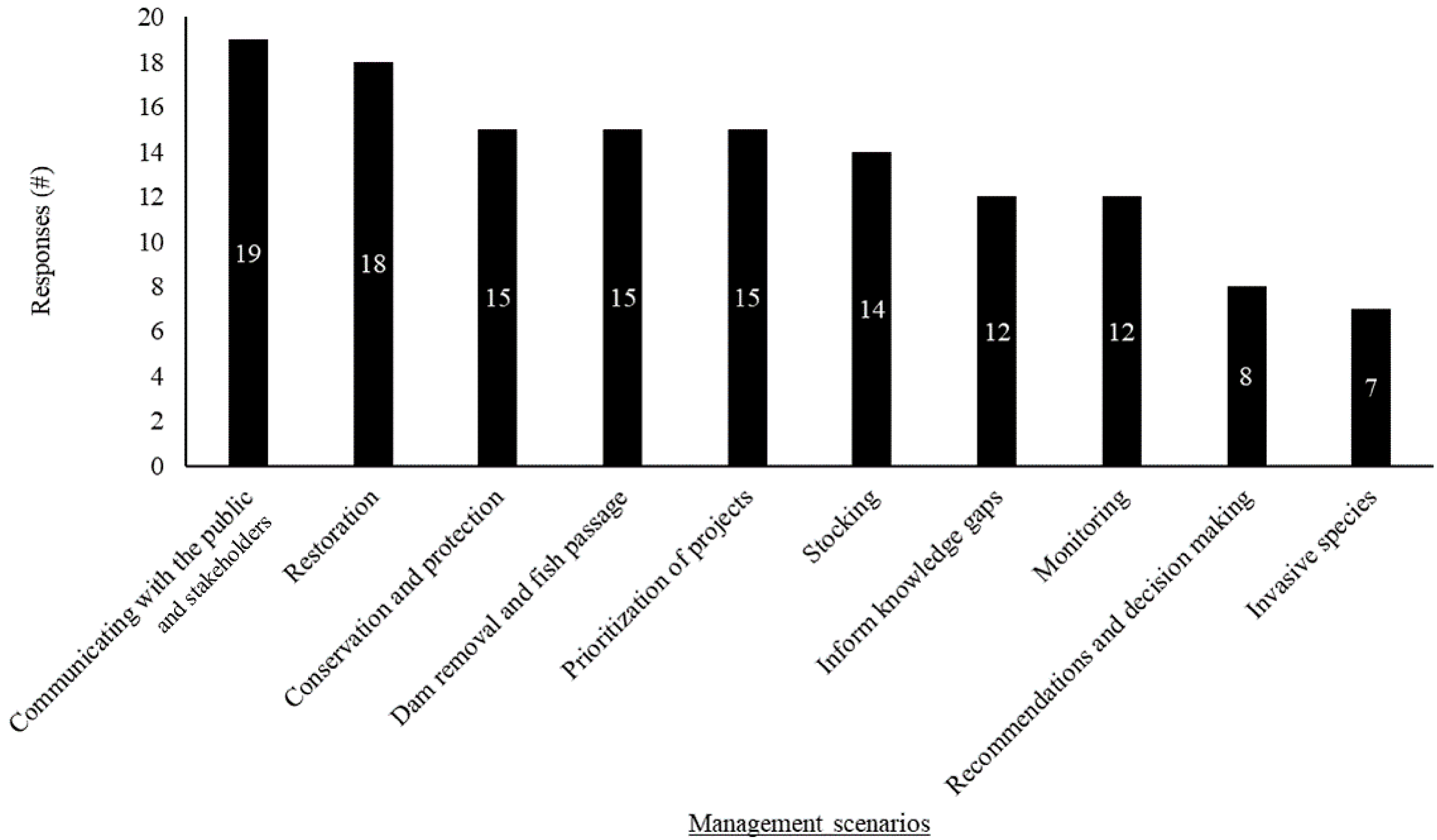

Figure B.1.8. Responses by survey participants in relation to the fourth theme (i.e., management decision-making) and corresponding research question: What management scenarios and questions can be addressed using STP stream habitat data?

APPENDIX C

SUPPLEMENTARY MATERIALS

Interview consent form

Research Participant Information and Consent Form

1. EXPLANATION OF THE RESEARCH and WHAT YOU WILL DO:

You are being asked to participate in a research project to assess the utility of data collected by the Michigan Department of Natural Resources (MDNR), specifically data collected by Fish Division's Status and Trends Program. This is an exploratory study to gather information on the current barriers to using stream habitat data. You have been selected as a participant based on your involvement with the MDNR. As part of this interview you will be asked to answer a series of questions to the best of your ability over the course of about 1 hour. Any data collected from you, pertaining to this study, will be de-identified prior to being published/disseminated; your name will never be published or part of dissemination nor will it be possible to link any of the individual question responses to you personally.

2. YOUR RIGHTS TO PARTICIPATE, SAY NO, OR WITHDRAW:

- Participation in this research project is completely voluntary.
- You may withdraw from this project at any time by notifying the researcher (listed below)
- "Withdrawing" from the study simply means that the data collected from you from the interview will not be used when publishing/disseminating this research.

3. COSTS COMPENSATION AND CONFLICT OF INTEREST FOR THE STUDY:

- There are no costs to participants in this study.
- There is no compensation offered to participants in this study.
- There are no conflicts of interest that the researchers are aware of.

4. CONTACT INFORMATION FOR QUESTIONS AND CONCERNS:

- If you have concerns or questions about this study please contact the researcher: Samantha (Sam) Betances, 318 Manly Miles Building 1405 S. Harrison Rd., East Lansing 48823. Tel. 812-870-7609. Email: thiedesa@msu.edu

If you have questions or concerns about your role and rights as a research participant, would like to obtain information or offer input, or would like to register a complaint about this study, you may contact, anonymously if you wish, the Michigan State University's Human Research Protection Program at 517-355-2180, Fax 517-432-4503, or e-mail irb@msu.edu or regular mail at 4000 Collins Road, Ste. 136, Lansing, MI 48910.

5. DOCUMENTATION OF INFORMED CONSENT.

- By signing below you indicate that you have read this form and understand its contents.

____________________________________ _______________________

Signature Date

Interview questionnaire

Improving opportunities to conserve streams and the fishes they support: Demonstrating the value of stream habitat data

Sam Betances, Graduate Assistant, Michigan State University, thiedesa@msu.edu

Hello, my name is Sam Betances and I am one of this year's Fenske Fellows. I'm working with Jan-Michael Hessenauer and Todd Wills on a project that will help in efforts to better use MDNR's Status and Trend Program's stream habitat data. As part of this project, we are talking with MDNR managers and biologists from each management unit across Michigan. For clarity, I have provided a definition of stream habitat below.

I would first like to thank you for taking the time to sit down and talk with me. If you need me to repeat any questions or clarify anything, please ask. This interview should take approximately one hour to complete. To start off, I'd like to get to know more about you. Tell me a little about yourself. What is your role in the MDNR and what responsibilities does that come with?

Interviewee Information

What is your professional background? Specifically, what would you consider to be your area of expertise and/or professional training?

Habitat Data – General

The next 3 questions are going to be specific questions regarding stream habitat data. Provided below is a definition of stream habitat that will serve as a reference for this interview.

- **Stream habitat** – Stream habitat includes physical and biological components that comprise aquatic ecosystems and constrain species composition. Stream habitat includes features such as substrate, woody debris, riparian and instream vegetation, undercut banks, and other structures. It can also include factors such as the flow regime, channel morphology, and water temperature. Aquatic species depend on quality habitat for foraging, reproducing, and cover.

1. What types of stream habitat variables are most important or relevant to your responsibilities in MDNR?
2. What are some of the main factors that affect the stream habitat variables that are important or relevant for your responsibilities?
3. Do you expect that any of the affecting factors or habitat variables will change in the future? If so, how and why?

Utility of the SnT and SSTP stream habitat data and the database

The following 6 questions are related to MDNR's Status and Trends Program, or SnT as it is often referred to. SnT encompasses all inland waters in Michigan including lakes and streams. SnT aims to expand on traditional gamefish surveys by including surveys for nongame fish, water quality, and habitat assessments. These questions are related to how data are currently utilized and how the data are stored. Some questions will be specific to the Streams Status and Trends Program (SSTP), a subset of the SnT Program that specifically monitors streams in Michigan.

1. Do you use any data from the SnT Program? If so, what data do you use and for what is it used?

Note: Data could be physical or biological. Uses could be: scientific analysis, projects, management decisions? What data do you use the most? Is it mostly lakes, a mix of lake and stream, mostly stream data?

2. Do you know what habitat variables are available through the Fish Collection System (FCS) and SnT?
3. What are current barriers or difficulties with using and incorporating stream habitat data into analyses or management decisions?
4. What could be done to help you use habitat data more effectively and/or more often?
5. If data accessibility could be improved, who would benefit most from its use, in your opinion?

6. Every 6 years, SnT releases a report that describes the state of Michigan streams, including characteristics of their habitats. What summaries did you find most useful in the first SnT report?
    a. Are there summaries that you wish to see in future SnT summary reports?

Management-decision making in MDNR

The next 13 questions will broadly cover management decision making in the MDNR. Questions will be related to how decisions are made in MDNR and what influences and structures decision making.

1. What programs/projects are top priority to your management unit?
2. What types of decisions do you make in your position?
3. What questions are managers currently asking in Michigan?
    a. What questions would managers want to address in the (near) future?
4. What are some of the biggest challenges in MDNR decision-making?
5. Do you participate in any committees that grant money?
    a. If so, what committee(s)?
    b. How do you currently make decisions regarding who gets the grant(s)?
        i. Do you use other sources of data (internal and external data sources)?
6. Do you currently utilize SnT data when making decisions? How so?
7. Have you ever used SnT stream habitat data directly for making management decisions?
8. What could be done to make it easier to use habitat data in analyses and/or decision making?
9. If data accessibility could be improved, what additional management scenarios would you use/like to use habitat data for?
10. Do you have any future analyses that you want to be conducted using habitat data?

a. What analyses would you specifically use fixed site data for?

b. What analyses would you specifically use random site data for?

11. Do you find it useful to compare streams, based on their habitat, within your management unit? Why or why not?

12. Where are areas/topics you'd like to see more science-based management?

13. Is there anything that we didn't cover that you would like to address?

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LITERATURE CITED

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CHAPTER 2:
UNDERSTANDING INFLUENCES OF LANDSCAPE FACTORS ON STREAM HABITAT: INFORMATION TO CONSERVE MICHGAN'S STREAMS WITH CHANGING CLIMATE

ABSTRACT

Globally, degradation of stream habitats as a result of human land use and other activities is the greatest contributor to the current imperilment of many stream fishes, and changes in climate are expected to compound this problem by further changing habitats into the future. Because of this, understanding how stream habitat factors might change with climate would allow managers to better target their conservation efforts. This study investigates associations between multiple stream habitat factors and various landscape factors including natural and anthropogenic landscape variables along with variables that we theorized could be sensitive to changes in climate. Climate-sensitive measures included annual and seasonal precipitation and the amount of groundwater delivered to streams. These factors are known to be important to streams in our study region, the state of Michigan, which contains many diverse stream habitat types. We addressed our goal by first selecting 14 stream habitat variables that characterized different aspects of habitat and then investigating patterns in habitat using PCA. We identified 6 axes that explained a majority of variation in habitat across our study sites, and these included measures of channel condition and fish cover, channel size, riffles and coarse substrate, forest cover in the riparian area, pools and tag alder riparian cover, and stream embeddedness. We next predicted each of the 14 stream habitat variables from landscape factors. We saw influences from natural landscape factors including reach slope and network catchment area as well as anthropogenic land uses like urbanized areas and agriculture in catchments. We also saw multiple effects of climate-sensitive landscape variables. For example, measures of channel morphology, large woody debris, riparian cover, and bank condition were all influenced by at least one of the climate-sensitive landscape factors. These results suggest which habitat features are likely to change with changes in climate and can be used by managers to better conserve stream habitat and the fishes they support into the future.

INTRODUCTION

North America's rivers and streams support diverse fish species that provide significant ecological, socioeconomic, cultural, and spiritual benefits (Jelks et al. 2008). However, an assessment conducted in 2008 found that approximately 40% of all North American freshwater fish species may be imperiled, with the number increasing annually (Jelks et al. 2008). While degradation of habitats as a result of human land uses and other activities is the greatest contributor to the current imperilment of stream fishes (Allan et al. 2005), changes in climate are expected to exacerbate conditions by further changing habitats into the future (Maddock 1999; Allan et al. 2005; Wuebbles et al. 2019). For example, as air temperatures increase, stream thermal regimes are expected to shift in response, and depending on regional effects of changing climate, some types of thermal habitats may become more common while others may decline (Comte et al. 2013). Also, changes in timing and intensity of precipitation patterns have already reduced stream flows in some areas of the US, while stream flows in other regions have become more variable due to extreme high precipitation events (Cisneros et al. 2014). Compounding effects on stream flows, increased intensity and duration of droughts can reduce stream baseflow, as reductions in precipitation will reduce groundwater recharge (Afzal and Ragab 2020). Ultimately, such climate-induced changes to stream habitats will exacerbate conditions for currently imperiled stream fishes, reducing their likelihood of persistence into the future.

Stream habitat is defined as the physical and chemical features that comprise an environment, directly constraining a stream's biotic assemblages and distributions of organisms (Jowett 1997, Maddock 1999). Stream habitat can include many broad categories of factors such as the stream flow regime; biotic interactions; and connectivity within river networks, with floodplains, and with the hyporheic zone (Ciruna and Braun 2004). Stream habitat can also include various structural features within and in close proximity to the stream channel such as channel morphology, riparian cover, substrate, fish cover, and woody debris (Ciruna and Braun 2004). These physical stream habitat features are known to be important to stream fishes and affect the types and distributions of species found in a given location. For example, channel morphology controls movement of water within the channel, influencing water velocity and shear forces as well as a stream's capacity to access its floodplain or riparian zone (Frissell et al. 1986; Infante et al. 2006), and stream hydraulics can exclude some fish species or small individuals from habitats (Gorman and Karr 1978; Aaland 1993). Furthermore, riparian cover plays a role in regulating stream temperature and can provide thermal refuges for fish where riparian vegetation creates patches of shade (Gorman and Karr 1978). Substrate is also important as it provides habitat necessary for fishes to reproduce, forage, and find refuge (Kratt and Smith 1977; Bisson et al. 1982). Woody debris can also influence channel hydraulics, modifying water velocity and creating habitat features such a plunge pools, which can provide areas for fish to forage (Bisson et al. 1982) and that serve as refuge habitats (Bisson et al. 1982; Schlosser 1991; Rosenfeld and Huato 2003).

Just as the composition and distribution of fish assemblages are shaped by their habitats, stream habitat characteristics are shaped by landscape-scale features and processes (Allan and Castillo 2007). These interrelationships constitute a framework for understanding influences in stream environments, also known as the landscape approach, which emphasizes that rivers are hierarchically influenced by characteristics of their catchments (Frissell et al. 1986; Allan 2004). A catchment refers to the extent of a topographically delineated unit of land throughout which hydrologic processes occur and which are drained by a stream network (Brooks et al. 2012). Hydrologic processes operating throughout catchments are influenced by timing, duration, frequency, and intensity of precipitation events (e.g., rainfall, snowfall) and also by natural and anthropogenic landscape factors. These landscape factors can operate over different spatial extents within network catchments, including entire catchments or small areas such as stream buffers (Wang et al. 2011). Anthropogenic landscape factors include human uses of the landscape such as urbanization or agriculture, and natural landscape factors include geology, topography, and land cover. Some landscape factors, such as average annual precipitation and stream baseflow index, are expected to be sensitive to changes in climate; and future climate, as modified by human activities, may be considered an anthropogenically-influenced landscape factor. Collectively, these landscape factors directly affect the types, distribution, and quality of habitats in streams (Poff 1997; Allan 2004).

The landscape approach can be applied to better understand complex relationships between landscape factors and stream habitat. Early studies were conducted at small spatial scales (e.g., single river reaches or a set of reaches within a single river basin; Richards and Host 1994; Jeffers 1998), and less consideration was given to understanding influences over larger spatial areas (e.g., a region or state), which is often the spatial extent over which managers may need to compare conditions in order to prioritize management actions. However, our understanding of aquatic ecosystems has evolved, and rivers are now understood as complex systems that require consideration of the landscape-scale processes and features of the catchments they drain in order to best conserve stream conditions (Wiens 2002; Allan 2004). In acknowledgement of this updated understanding and the role of anthropogenic landscape factors in degrading stream habitat conditions, efforts have occurred to assess stream habitats over very large regions including the conterminous United States using landscape factors (e.g., Esselman et al. 2013, Crawford et al. 2016), with outcomes suggesting that more types and intensities of anthropogenic landscape factors will lead to degraded stream habitat conditions. However, few studies have attempted to specifically predict stream habitat factors from landscape factors, and those that do rarely attempt to model habitat over large regions such as entire states or multi-state regions (but see Brenden et al. 2007 and Wang et al. 2013). Furthermore, only a few studies have specifically modeled how stream habitats might change under changing climate, and they are typically focused on modeling stream flow (e.g., Mantua et al. 2010; Doulatyari et al. 2015) or temperature (e.g., Steen et al. 2010; Snyder et al. 2015). Comparatively, much less is known about how physical habitat factors like channel morphology, substrate, riparian cover, and woody debris will change with changes in climate. This is a limitation because these variables can sometimes be more easily manipulated by management actions than other factors. Due to the importance of stream habitats and the species they support, conservation of freshwater habitats is a high priority for natural resource management agencies (Lynch et al. 2016; Calantone et al. 2019), and understanding how stream habitat factors might change with climate may allow managers to better target their conservation efforts.

The goal of this study is to investigate influences of multiple landscape factors operating through stream catchments on physical stream habitat variables. Our study occurs in the state of Michigan, an ideal study region for investigating effects of landscape factors on stream habitats because of the many diverse types of streams it contains. In support of this goal, we address three objectives. First, from a large set of habitat variables, we select a subset that describe the wide range of physical stream habitat conditions across Michigan, including specific measures of channel morphology, fish cover, substrate, large woody debris, and riparian area and bank condition. Second, we characterize patterns in habitat that occur across the state to identify prominent differences in habitat and to produce component scores that can be used in predictive modeling. Finally, we predict each of the habitat factors, as well as the component scores that we generate, from multiple landscape factors. Landscape factors include multiple measures of anthropogenic land uses as well as various natural factors, and additionally includes factors which may be affected by changing climate, such as measures of precipitation. Results of this study will document influences of landscape factors on stream habitat, including those that may be vulnerable to changes in climate, and we will use results to make recommendations to aid managers in conserving streams and the important species they support into the future.

METHODS

Study region

Michigan has more than 36,000 miles of streams that support a variety of cold, cool, and warm water fisheries, and these diverse habitats result from the state's variable landscape features. Due to the state's geologic history, the composition of Michigan's landscape includes areas of exposed bedrock, glacial moraines, glacial outwash plains, lacustrine clays and silts, and peats and muck (Farrand and Bell 1982). These varied features in geology and other landscape factors result in a diversity of stream habitats that also occur throughout the state. In the Upper Peninsula (UP), flashier flows occur in rivers draining landscapes comprised of bedrock, creating hydrologically variable conditions. In areas of the Southern Lower Peninsula (SLP), including in the south central and southeastern portions of the state, lacustrine soils create wetlands and also warm water habitats in streams because more flow is delivered to these systems via surface runoff than groundwater. Furthermore, in the Northern Lower Peninsula (NLP), where coarse-textured glacial moraines are common, streams have comparatively less variability in discharge than streams in other parts of the state due to high permeability of landscapes and high inputs of groundwater versus surface runoff to streams (Strayer 1983). Land cover, which can affect infiltration within catchments as well as sediment delivery and woody debris inputs to streams, also varies across the state. The NLP and UP contain boreal forests composed of spruce, pine, and aspen trees, and the SLP contains temperate deciduous forests composed of oaks, maples, and beech trees (Danz et al. 2007). Land use also differs throughout Michigan. The SLP includes many urban and agricultural areas, which are less common in the NLP and UP. Additionally, timber harvest can be a common activity in forested areas of the state (Danz et al. 2007; MDNR 2020a). Anthropogenic land uses such as these can increase inputs of sediments and runoff to streams and can negatively affect the quality of stream habitats (Wang et al. 2013). Climate conditions such as air temperature and precipitation also vary across the state. Average annual air temperatures are typically colder in the UP and NLP and warmer in the SLP (Andresen et al. 2012). Annual precipitation is highest in the southwest corner of the SLP, while the least precipitation annually occurs in the northeast portion of the NLP (Andresen et al. 2012). Across the UP, average annual precipitation varies little. Patterns in annual July precipitation broadly follow trends in average annual precipitation, except in the eastern UP, which is on average drier in the summer months than the western portion of the UP (Andresen et al. 2012).

Spatial framework and landscape data

We selected landscape predictors *a priori* that were factors previously documented to influence stream habitat (e.g., Esselman et al. 2011, Daniel et al. 2015, Crawford et al. 2016). Our overall analytical approach assumed a space for time substitution as we selected locations having a range of different landscape factors. We selected 11 different landscape variables in three categories (i.e., 6 natural, 2 anthropogenic, and 3 climate sensitive landscape variables); trends in these landscape variables are described in the results section. Average, maximum, and minimum values of all variables are reported in Table A.2.2. Pearson's correlations were performed on all landscape variables to ensure minimal redundancy (Table C.2.1). If highly correlated variables were identified (Pearson's r >0.6), one was retained based on ecological interpretability.

The 1:100,000 National Hydrography Dataset Plus Version 2 (NHDPlusV2) was used to characterize streams assessed in this study (NHDPlus 2008). The basic unit of our spatial framework is the stream reach, defined as stream segments extending from stream headwaters to stream confluences, stream confluences to stream confluences, or stream confluences to terminal outlets (e.g., the Great Lakes, Wang et al. 2011). All stream reaches have defined local catchments (i.e., land areas that drain directly to reaches) as well as local buffers (i.e., 90 m area of land on either side of stream reaches). Additionally, information can be summarized within the network catchment or network buffer (i.e., cumulative land area draining into a given local catchment or local buffer, respectively; Tsang et al. 2014). Sites where habitat data were collected were linked to individual stream reaches in the NHDPlusV2 (Table A.2.1).

Landscape variables used in these analyses were obtained or developed from a variety of data sources and summarized within different spatial extents (Table A.2.2). Six natural landscape and land cover factors known to influence stream habitat factors were selected. Land use/land cover data are from the National Land Cover Dataset (NLCD) 2006 (https://www.mrlc.gov). In the network buffers, percent deciduous forest, evergreen forest, and mixed forest were summarized to create a combined forest variable. Also, percent woody wetlands and emergent herbaceous wetlands were summarized in the network buffer to create a combined wetlands variable. Surficial geology data (Farrand and Bell 1982, https://ngmdb.usgs.gov/Prodesc/proddesc_71889.htm) were summarized in network catchments to create combined variables for coarse and fine geology, which we theorized would capture broad differences in infiltration rates in catchments of study sites. Combined coarse geology includes the sum of all geologic types with hydraulic conductivity greater than 5.0 m/day including ice contact, coarse end-moraines, coarse outwash, dune sand, lacustrine deposits, and alluvium. Combined fine geology includes the sum of all geologic types with a hydraulic conductivity less than 0.005 m/day including exposed bedrock, fine end-moraine, lacustrine clay and silt, fine glacial till, and water. Maximum elevation and mean slope in the reach (m/m) were obtained from National Elevation Dataset (NED) 2005 (http://nationalmap.gov/elevation.html) and the NHDPlusV2. Additionally, using data obtained from the NHDPlusV2, network catchment area was calculated by aggregating the area of all local catchments occurring above a given reach (Tsang et al. 2014).

Additionally, two anthropogenic landscape factors known to contribute to stream habitat degradation were selected. Percent developed open space and percent developed low, medium, and high intensity land cover were summarized at the network catchment scale to create a combined percent urban cover variable. Percent pasture/hay and percent cultivated crops were also summarized at the network catchment scale to create a combined agricultural cover variable.

Finally, we selected three landscape variables assumed to be sensitive to changes in climate and that should have important effects on physical stream habitat. Climate data were summarized for the climatological period from 1995 to 2015 by the PRISM Climate Group for air temperature and precipitation variables (PRISM 2013). Average annual precipitation and average annual July precipitation were summarized within network catchments (PRISM 2013). The baseflow index, developed by the United States Geological Survey (USGS), is defined for each stream reach as the ratio of baseflow (defined as the component of streamflow that can be attributed to groundwater) to total flow *100 (http://water.usgs.gov/GIS/metadata/usgswrd/XML/bfi48grd.xml). Baseflow was included because increased duration and intensity of drought events with changes in climate are expected to reduce groundwater recharge, which can result in reductions to streams' baseflows (Afzal and Ragab 2020).

Stream habitat data collection

Data for this study were collected between July and September from 2002 to 2017 by the Michigan Department of Natural Resources (MDNR) Fisheries Division Status and Trends Program (STP). For this study, we used data from 205 study reaches occurring throughout the state (Figure B.2.1). Methods used to collect data follow the STP protocol (Wills et al. 2006) and are described below.

Stream habitat data were collected from within stream channels and riparian zones of streams. Data collected from within the stream channel included measures of channel morphology (Table A.2.3), fish cover (Table A.2.4), substrate (Table A.2.5), and large woody debris (Table A.2.6); data collected from the riparian zone included estimates of riparian cover and bank condition (Table A.2.7). At each sample site, a length of stream was sampled that varied with stream catchment area (Wills et al. 2006). Each sampled reach was divided into 13 transects across the sampled reach length. Some stream habitat factors were assessed within transects, while others were assessed through the entire reach.

Channel morphology

At each transect, wetted and bankfull width measurements were taken (Wills et al. 2006). For analysis, we used the average of the bankfull and wetted widths as well as the maximum and minimum values of bankfull width at each site. Presence of islands in the channel at each transect were recorded and included in the determination of bankfull width but not wetted width (Wills et al. 2006). Presence of islands in the reach were also summarized by percentage of points per reach for analysis. Bank undercuts were noted on the left and right banks at each transect and summarized by percentage of points per reach for analysis (Wills et al. 2006). Five stream depth measurements were recorded to the nearest tenth of a foot across each transect (Wills et al. 2006), with the space between sampling points occurring at 1/5, 2/5, 3/5, and 4/5 across the transect and at the thalweg, and average stream depth through the channel was calculated for analysis. The dominant mesohabitat was also visually estimated at each transect and summarized by percentage of points per transect for analysis (e.g., run, riffle, or pool; Wills et al. 2006).

Fish cover

Fish cover was also visually assessed at the same five points across each transect where depth measurements were taken (1/5, 2/5, 3/5, and 4/5 across the channel and at the thalweg) and were summarized by percentage of points per transect for analysis (Wills et al. 2006). Fish cover includes the percentage of small wood (<6 inches in diameter and <6 feet in length) occurring in a 1-inch diameter circle at each sample point as well as the percentage of rooted plans in a 1-inch diameter circle at the sample point (Wills et al. 2006). Percentage of woody cover and rooted plant cover were determined based on the number of times they occurred at transect points through the reach, and these measures were also summed to create a single combined fish cover variable for analysis.

Substrate

Dominant substrate was visually estimated within a 1-foot diameter circle at five points across each transect (space between sampling points occurring at 1/5, 2/5, 3/5, and 4/5 across the channel and at the thalweg; Wills et al. 2006). Substrate types documented included clay, detritus and silt, sand, gravel, small cobble, large cobble, boulder, wood, bedrock, and island. Gravel, small cobble, large cobble, and boulder were summarized into a coarse substrate variable, and sand and detritus and silt were summarized into a fine substrate variable for analysis. Where gravel substrate was present, embeddedness of gravel by fine sediments was visually assessed, with low gravel embeddedness defined as <50% of vertical profile of gravel buried in fines and high gravel embeddedness as >50% of vertical profile of gravel buried in fines (Wills et al. 2006).

Large woody debris

Large woody debris (LWD) data were collected from the entire length of the reach (Wills et al. 2006). Individual logs at least 6 feet long and in contact with at least 6 inches of water were considered LWD. LWD is classified by diameter at breast height (dbh) and include dbh classes 6 to 12 in, 12 to 18 in, 18 to 24 in, and >24 in. For analysis, log counts less than 18 dbh were combined to create a small logs variable, and log counts in the greater than 18 dbh were combined to create a large logs variable. Additionally, for analysis, all dbh classes of logs were summarized to create a total LWD variable.

Riparian cover and bank condition

Dominant riparian vegetative cover was recorded on the left and right banks as cover comprising more than 50% of an area extending from bankfull to 30 ft perpendicular to the transect and in a region 30 ft upstream and downstream from that point (Wills et al. 2006). Cover categories included pasture, row crop agriculture, small or large coniferous tress, small or large deciduous trees, grassland and forbs, tag alder types, yard/lawn, and other. For analysis, pasture, row crop agriculture, and yard/lawn were summarized into a combined anthropogenic variable. Additionally, small coniferous trees, large coniferous tress, small deciduous trees, and large deciduous trees were summarized to create a combined forest variable. Bank condition was measured on a scale of 1 to 4 on the left and right banks and was visually assessed by observing the percentage of bare soil exposed on the streambanks (Wills et al. 2006). Good stability is indicated by a 1 (<25% bare), 2 is fair stability (25-50 % bare), 3 is poor stability (50-75 % bare), and 4 is very poor stability (>75 % bare). Each measure of bank stability was summarized by percentage of points per reach for analysis.

Patterns in habitat

To evaluate patterns in habitat across the state and select a subset for further analysis, we first calculated summary statistics (e.g., average, maximum, and minimum values) for all habitat variables; variables that did not range substantially across sites were eliminated from analysis. Next, variables' P-P plots were inspected for linearity. Non-linear variables were transformed using natural log plus one (ln(x+1)) for continuous variables, square root for counts, and arcsine square root for proportions. Pearson's correlations were performed on groups of stream habitat variables separately, and when highly correlated variables were identified (Pearson's r >0.6), one was retained based on ecological interpretability.

Next, we used principal component analysis (PCA) on the selected stream habitat variables to identify major dimensions in habitat across Michigan. Components with eigenvalues of 1.00 or greater were considered for interpretation. A varimax rotation was applied to the principal components (PCs) to improve interpretation. Components with loadings greater than the absolute value of 0.55 were considered the strongest descriptors of the individual components.

Predicting habitat variables from landscape factors

Forward entry stepwise multiple linear regression was performed to predict selected stream habitat variables and scores generated from PCA and landscape factors. The significance of the F statistic ($p = 0.05$) was used as the model entry criterion, and the F statistic ($p = 0.10$) was used as the model removal criterion. The proportion of variance explained was reported as the adjusted R^2, and models with an adjusted $R^2 < 0.10$ were not considered to be suitable predictors of stream habitat variables. Additionally, only models containing significant independent variables ($p < 0.05$) were considered to avoid overfitting. If multiple models for a single variable met these criteria, we selected the model with the lowest Akaike Information Criterion (AIC) as the best model from the group.

RESULTS

Summaries of landscape predictors

Patterns in the eleven landscape predictors selected varied across the study sites (Table A.2.2). On average, network catchment area was 314.64 km^2 but varied widely across sites, with the smallest sampled network catchment measuring 2.46 km^2 and the largest measuring 6,447.89 km^2. The average maximum elevation in local catchments at sites was 261.96 m. Slope varied three orders of magnitude across sites and ranged from 0.000010 m/m to a high of 0.023044 m/m and was on average 0.002973 m/m. On average, coarse geology was more common across the sites than fine geology (66.74% vs. 10.70%, respectively). Additionally, wetland land cover in network buffers of sites was observed more frequently on average (36.25%) than forested land cover in network buffers of study sites (26.85%). Further, agricultural land cover in network catchments was more common than urban land cover (average of 25.46% vs. 8.09%, respectively). Across the sites, precipitation varied annually from 760.32 mm to 1070.98 mm and averaged 894.12 mm (Table A.2.2). Additionally, average annual July precipitation was 85.64 mm and ranged between 65.73 mm and 116.33 mm. The average baseflow index, again, the contribution of streamflow from groundwater, was 63.70% and ranged between 32.48% to 88.00%.

Habitat variable selection

We began with 53 stream habitat variables (i.e., 14 channel morphology, 3 fish cover; 12 substrate, 7 LWD, and 17 riparian cover variables). Average, maximum, and minimum values of all variables in groupings above are reported in Table A.2.3, Table A.2.4, Table A.2.5, Table A.2.6, and Table A.2.7, respectively. Pearson's correlations were performed on groupings of stream habitat variables separately (Table C.2.2, Table C.2.3, Table C.2.4, Table C.2.5, and Table C.2.6, respectively), and when highly correlated variables were identified (Pearson's r >0.6), one was retained based on ecological interpretability. This left us with14 different habitat variables within 5 habitat categories (i.e., 5 channel morphology, 3 substrate, 1 fish cover. 1 LWD, and 4 riparian cover and bank condition variables).

Patterns in habitat

Patterns in the 14 habitat variables varied across the state (Table A.2.8). In terms of channel morphology, average bankfull width for study sites was 38.72 ft and ranged from 5.23 to 300.71 ft, and average stream depth for sites was 1.28 ft and ranged between 0.16 ft and 5.11 ft. On average, reaches across the sites had 32.17% of points in transects containing undercut banks, suggesting that undercut banks are a fairly common habitat feature. Additionally, riffle habitats were more common on average across sites (average of 14.90% of transects for all sites) than pool habitats (average of 6.44% of transects for all sites). Combined forest cover was the most common riparian cover type observed across the sites (average of 55.68% of points in transects) followed by grassland and forbs (average of 25.01% of points in transects), and tag alder (average of 22.56% of points in transects for sites). Most reaches surveyed had banks in good condition (66.16% of points in transects). Combined coarse substrate was the most frequently observed substrate type throughout the sites (50.14% of points in transects). Low gravel embeddedness (<50% of the gravel profile embedded) was more frequently observed (51.59% of points in transects) than high gravel embeddedness (>50% of the gravel profile embedded; 44.96% of points in transects). Additionally, fish cover (assessed by the combination of woody cover and rooted plant cover) was only present on average in 13.00% of points in transects. Finally, total LWD varied widely across the sites from as many as 3,540.00 logs to an absence of logs (0.00) in a reach; on average each site contained approximately 390.12 logs per sampled reach.

After variable reduction was complete, 14 stream habitat variables were investigated with principal component analysis, and six principal components (PCs) were retained based on eigenvalues greater than 1.00 (Table A.2.9) Additionally, the six PCs explained 74.97% of the variation in habitat data and resulted in each of the 14 variables loading to single component. PC1 explained the most variation (18.01%) and was weighted positively by undercut banks, combined fish cover, and banks in good condition; because of this we referred to this axis as channel condition and fish cover (Figure B.2.2). The second axis explained 14.83% of variation and it represented measures of channel size. Average bankfull width, average stream depth, and total LWD were weighted positively on this component (Figure B.2.3). PC3 explained 13.69% of the variation and was positively weighted by riffle habitat type and combined coarse substrate (Figure B.2.4). For this reason, we referred to the third axis as riffles and coarse substrate. The fourth axis (10.30% of variation) represented a gradient of forest cover in the riparian area. The riparian forest cover variable was positively weighted on this axis, while the grassland and forbs cover variable was negatively weighted on this axis (Figure B.2.5). PC5 explained 10.15% of variation and represented pool habitat type and tag alder riparian cover (both variables were positively weighted on the axis, Figure B.2.6). Finally, the sixth axis (capturing 7.99% of the variation) represented a range in gravel embeddedness and for this reason was referred to as stream embeddedness (Figure B.2.7). High gravel embeddedness was positively weighted and low gravel embeddedness was negatively weighted on the axis.

Predicting habitat variables from landscape factors

Stream habitat individual variable results

Ten of the fourteen stream habitat variables were suitably predicted (adjusted R^2>0.10) using forward entry stepwise multiple linear regression: average bankfull width, average stream depth, undercuts, pool habitat, riffle habitat, combined coarse substrate, total LWD, combined forest cover, tag alder cover, and banks in good condition (Table A.2.10). Combined fish cover, low gravel embeddedness, high gravel embeddedness, and grassland and forbs riparian cover were not suitably predicted (adjusted $R^2 < 0.10$) by landscape factors. The most common predictors of stream habitat were reach slope and agricultural land cover in the network catchment (each were significant predictors in 7 models), followed by network catchment area and maximum elevation (significant predictors in 5 models) and average annual precipitation and baseflow index (significant predictors in 4 models; Table A.2.10). The least common predictors were only significant in one model each and included coarse lithology, average annual July precipitation, and forested land and wetland cover in the network buffer.

As expected, natural landscape factors were strong predictors of stream habitat variables. Slope was the most common predictor in this grouping and was positively associated with forest riparian cover ($\beta = 0.40$), coarse substrate ($\beta = 0.30$), riffle habitats ($\beta = 0.17$), undercuts ($\beta = 0.16$), and pool habitat ($\beta = 0.16$). It was negatively associated with average stream depth (β = -

0.34) and tag alder cover (β = -0.29). Network catchment area and maximum elevation were the second most common predictors of stream habitat. Network catchment area was positively associated with average bankfull width (β = 0.92), average stream depth (β = 0.56), coarse substrate (β = 0.37), total LWD (β = 0.35), and forested riparian cover (β = 0.31). Maximum elevation was positively associated with coarse substrate (β =0.33), riffle habitat (β =0.24), pool habitat (β = 0.19), and tag alder riparian cover (β =0.18) and negatively associated with total LWD (β = -0.22). Natural land cover predictors (e.g., forested land cover in the network buffer and wetland cover in the network buffer) were not common predictors of stream habitat variables. Additionally, wetland cover in the network buffer was positively associated with undercuts (β = 0.12), which did not match our expectations.

Of the anthropogenic landscape factors, agricultural land cover in the network catchment was the most influential predictor of stream habitat variables. It was negatively associated with tag alder riparian cover (β = -0.45), total LWD (β = -0.36), banks in good condition (β = -0.29), pool habitat (β = -0.24), average bankfull width (β = -0.20), and average stream depth (β = -0.20). However, this predictor was also positively associated with combined coarse substrate (β = 0.33), and this finding did not match expectations. Urban land use in the network catchment had less influence in predicting stream habitat variables, but results reflected known influences of urban land use on streams. Tag alder riparian cover (β = -0.24), banks in good condition (β = -0.24), and riffle habitat (β = -0.15) were the only variables predicted by urban land use in the network catchment, and each had a negative association with this landscape predictor.

Baseflow index and average annual precipitation, two of the three climate sensitive landscape factors, significantly predicted the same number of stream habitat variables. Baseflow index was positively associated with undercuts (β = 0.56), total LWD (β = 0.37), and banks in good condition (β = 0.31), and negatively associated with average bankfull width (β = -0.09). These results reflect known influences of baseflow stability on streams, except for the variable undercuts, which matched our expectations. Average annual precipitation was positively associated with forested riparian cover (β = 0.21), riffle habitats (β = 0.15), average bankfull width (β = 0.14), and average stream depth (β = 0.11). Average annual July precipitation was not a common predictor of stream habitat.

Stream habitat component score results

Results of the component regressions were similar to the predicted individual variables. Five of the six components were suitably predicted (adjusted $R^2 > 0.10$) using forward entry stepwise multiple linear regression except for gravel embeddedness (PC6, Table A.2.11). The most common predictors of stream habitat component scores generally matched those of the individual variable predictions and included reach slope and agricultural land cover in the network catchment (each were significant predictors in 4 models) followed by network catchment area and maximum elevation (significant predictors in 3 models) and baseflow index and average annual precipitation (significant predictors in 2 models; Table A.2.11). The least common predictors were only significant in one model each and included: coarse lithology, urban land cover in the network catchment, and average annual July precipitation. Unlike the individual variable predictions, two landscape factors, forested land cover and wetland cover in the network buffers, were not included as predictors for any of the components.

DISCUSSION

The goal of this study was to investigate influences of multiple landscape factors, including factors that may be sensitive to changes in climate, on multiple measures of physical stream habitat collected from 205 sites located across the state of Michigan. We addressed this goal by selecting a subset of 14 stream habitat variables from a larger set and then investigating patterns in variables across sites. We also used PCA to create groupings of variables, which suggested that six broad gradients in habitat occur across the state including ranges in channel condition and fish cover, channel size, riffles and coarse substrate, forest cover in the riparian area, pools and tag alder riparian cover, and stream embeddedness. We next predicted individual habitat variables and PCA component scores from natural landscape and anthropogenic factors known to influence stream habitat along with three additional factors that we theorized would be sensitive to changes in climate including average annual and July precipitation and an estimate of groundwater delivery to streams. For natural factors, our findings generally matched expectations based on foundational literature on landscape influences on stream habitat (Ciruna and Braun 2004; Brooks et al. 2012). For anthropogenic factors, our findings matched those of previous studies (Brenden et al. 2007; Wang et al. 2013), but we also showed that agricultural land use was one of the most common predictors of habitat variables that we tested. One key difference in our study from previous works, however, is that we specifically considered landscape factors that may be sensitive to changes in climate. Our results show that baseflow index and average annual precipitation, two climate sensitive landscape factors, are particularly influential predictors of several features of stream habitat such as channel morphology, LWD, riparian cover, and bank condition. These results can be used by managers to consider how Michigan’s stream habitat features will change with climate to effectively conserve stream habitat and the important species they support into the future.

Influences of natural landscape factors on stream habitat

Natural landscape factors including stream reach slope, network catchment area, catchment elevation, and the amount of coarse geology and natural land cover in network catchments are important controls on stream habitat features (Frissell et al. 1986; Ciruna and Braun 2004). For all suitable models (adjusted $R^2 > 0.10$), at least one natural landscape factor was included as a significant predictor of stream habitat, and many of our results matched expectations from the literature regarding influences of natural landscape factors on stream habitat (Bisson et al. 1987; Allan 2004; Ciruna and Braun 2004; Brooks et al. 2012). Reach slope was the most influential of all the natural landscape predictors for both individual habitat variables and the habitat component scores. Reach slope influences water velocity which determines stream power (i.e., the rate at which a stream can do work to transport bed load particles; Brooks et al. 2012). As reach slope increases, so too does stream power, which can affect stream habitat features like channel morphology, substrate, and riparian cover (Brooks et al. 2012), and these outcomes were reflected in our model results. For example, slope was positively associated with coarse substrate; greater slope should allow more materials to be moved through river reaches, directly affecting particle size of reach substrate (Strayer 1983). Further, slope was positively related to undercuts as well as pool and riffle habitats. This could result from streams with higher slopes having greater channel shaping power and therefore greater diversity of habitat conditions (Frissell et al. 1986; Allan 2004; Brooks et al. 2012). Similarly, a study in Oregon found slope to be an important predictor of mesohabitats as well as undercut banks (Anlauf et al. 2011). Finally, tag alder, a riparian cover type associated with wetlands in riparian zones, was less likely to occur with increasing reach slope. Wetlands can be common in low gradient areas of landscapes (Ciruna and Braun 2004), and locations with more wetlands may also be associated with streams with smaller reach slopes.

Network catchment area was also an important predictor of stream habitat. Network catchment area represents the total drainage area of a watershed, with larger watersheds draining greater volumes of water from landscapes (Brooks et al. 2012). Network catchment area is known to be associated with channel morphology as increases in the volume of water accumulating from throughout larger areas of the landscape generally result in larger channel dimensions (Brooks et al. 2012). Our models predicted a strong, positive association between network catchment area and average bankfull width and average stream depth, findings that were similar to previous studies (Brenden 2007; Wang et al. 2013). Total LWD was also associated with network catchment area, which could be the result of more wood moving into lower portions of the stream network from upper portions of the watershed (Strayer et al. 1983; Bisson et al. 1987). Additionally, more total LWD with increasing catchment area may also result from the positive association between larger network catchment areas and greater combined forest cover in the riparian zone across our study sites.

Another important predictor of stream habitat was maximum elevation in stream catchments, which represents the highest point that occurs in a catchment. Differences in elevation between any two locations in a catchment can influence the rate at which water moves across the landscape as well as the rate of delivery to stream channels (Flint 1974; Brooks et al. 2012). The frequency of pool and riffle habitats were both positively associated with maximum elevation. Water can move more swiftly to the channel with greater changes in landscape gradient and is associated with increases in stream habitat complexity (Ciruna and Braun 2004) Additionally, total LWD was negatively associated with elevation. Quicker delivery of water to the channel may have more power to move wood into lower portions of the watershed (Bisson et al. 1987; Brooks et al. 2012), resulting in LWD being less common in some headwater reaches at higher elevations in the watershed versus lower reaches near the mouth, which could be a potential driver for this association. Finally, coarse lithology was not a common predictor of most stream habitat factors; it was only negatively associated with pool habitat. This may reflect an association between geology and mesohabitat, with flashier flows stemming from more fine geology associated with more complex habitats.

Wetland and forest in network buffers, two natural land cover variables we considered, were not influential predictors of stream habitat features. One exception, however, was a positive association between buffer wetland cover with undercut banks. Wetland land cover may moderate stream flows by trapping surface runoff before it enters stream channels and because of this, can be associated with more stable stream flows (Ciruna and Braun 2004; Brooks et al. 2012). Our results follow those of Anlauf et al. (2011) who also showed that undercuts were associated with more stable baseflows. A second exception was our finding that forest cover in the network buffer was negatively associated with banks in good condition. Forest cover in buffers can result in shaded patches on banks that prevent continuous vegetative growth, leaving portions of the banks bare and more vulnerable to erosion. This is in contrast to streams that may have more continuous vegetative cover on banks, such as grass and forb cover, that may prevent erosion more effectively than tree cover alone (Allan 2004). This finding is partially reflected by the results of our PCA; vegetation in the buffers of our study sites spanned a gradient from forest to grassland riparian cover.

Influences of anthropogenic landscape factors on stream habitat

All suitable models (adjusted $R^2 > 0.10$) had at least one anthropogenic landscape factor included as a significant predictor of stream habitat, except for undercuts and combined forest riparian cover. Anthropogenic landscape factors, including agricultural or urban land use, have been shown to have multiple negative impacts on stream habitat features (Wang et al. 2003; Allan 2004; Wang et al. 2006; Wang et al. 2008), and this was reflected in our findings.

Agricultural land use was tied with reach slope as the most frequent predictors of suitable habitat models; each were included as important predictors in 7 different stream habitat models. Agricultural land use has documented negative effects on channel dimensions including incised channels and homogenization of overall habitat types (Wang et al. 2006), and this was supported by our results that showed that average stream depth and the amount of pool habitat were negatively associated with agricultural land cover. Additionally, agricultural land use was negatively associated with total LWD, tag alder riparian cover, and banks in good condition, and this reflects factors associated with agricultural land use including removal of riparian cover (Wang et al. 2003), erosion of stream banks due to flashier flow regimes (Infante et al. 2006), and absence of LWD in the channel (Roth et al. 1996). Unexpectedly, average bankfull width was negatively associated with agricultural land use; this is counter to what we would expect, as increasing agricultural land use is associated with flashier flow regimes which can erode stream banks and widen channels (Roth et al. 1996; Infante et al. 2006). However, this finding may reflect the way in which this landscape factor was characterized (i.e., in terms of a percentage vs. an absolute amount). For example, smaller catchments can be more likely to include larger percentages of anthropogenic land use compared to larger catchments (even though total areas could be greater in larger catchments). Therefore, higher percentages of agricultural land use are more likely to occur in small versus larger catchments (Crawford et al. 2016), which could partially explain the association between increasing agricultural land use with narrowing bankfull widths. Interestingly, combined coarse substrate was positively associated with agricultural land use, counter to previous findings that document increased sediment deposition with increasing agricultural land use (Wang et al. 2008). This association could again reflect differences in catchment sizes, as the proportion of fine sediments comprising stream beds increases with increasing catchment area (Brooks et al. 2012). Therefore, smaller catchments could be more likely to have larger proportions of agricultural land use as well as coarse sediment.

Urban land use was also an influential predictor of stream habitat, though less so than agricultural land use based on the total number of stream habitat variables suitably predicted by each landscape factor. Urban land use was negatively associated with tag alder riparian cover and banks in good condition. Increases to urban land use can alter delivery of water to the stream channel and produce flashier flow regimes that can erode stream banks and scour riparian areas (Wang et al. 2003; Allan 2004). Additionally, riffle habitats were negatively associated with urban land use in network catchments. Increased urban land use is associated with the homogenization of habitat types (Wang et al. 2006) which was reflected in our model results. Generally, anthropogenic landscape variables were shown to be highly influential predictors of stream habitat features. On average, percentage of agricultural land use was greater in sampled network catchments than percentage of urban land use which could explain, in part, why agricultural land use had greater influence on stream habitat features compared to urban land use.

Influences of climate-sensitive landscape factors on stream habitat

Currently, little consideration has been given to understanding how physical stream habitat features will be affected by changes to landscape factors, including baseflows and precipitation, under changing climate. All suitable models (adjusted $R^2 > 0.10$) had at least one climate sensitive landscape factor included as a significant predictor of stream habitat, except for pool habitat, combined coarse substrate, and tag alder riparian cover. Our results showed that average annual precipitation was positively associated with bankfull width and stream depth; these match fundamentals of hydrology, as increases in precipitation are associated with greater channel shaping flows and widening and deepening stream dimensions (Ciruna and Braun 2004; Brooks et al 2012). Additionally, average annual precipitation was positively associated with riffle habitat; this follows as annual precipitation patterns directly influence the distribution and availability of habitat types (Poff and Ward 1990).

The most influential of our three climate sensitive landscape predictors was baseflow index which represents the percentage of groundwater versus surface runoff input within a stream's network catchment. Streams with a larger baseflow index have higher inputs of groundwater and generally have more stable flow regimes (Brooks et al. 2012). Decreases in baseflow index via changes to precipitation patterns under changing climate will lead to less stable flow regimes and greater potential for changes in stream habitat, such as channel morphology and bank condition (Cisneros et al. 2014; Afzal and Ragab 2020). Baseflow index was also positively associated with banks in good condition. This follows, as streams with more stable flow regimes are more resilient to disturbance events such as large pulses of water that can degrade stream banks (Holling 1973; Poff et al. 1997; Brooks et al. 2012), and these disturbance events are likely to increase with changes in climate (Wuebbles et al. 2019). Further, baseflow index was positively associated with undercut banks. Our results follow those of Anlauf et al. (2011), whose results also found that undercuts were associated with more stable baseflows. Stable baseflow might provide the continuous power necessary to carve out undercuts in banks, without fully eroding channels. Moreover, the persistence of stream habitat features is dependent on the frequency of disturbances experienced; therefore, streams with more stable flow regimes generally have greater habitat heterogeneity (Poff and Ward 1990; Poff et al. 1997; Frissell et al. 1986). More stable flow regimes are additionally associated with narrower bankfull widths, as channel shaping flow events are less common (Brooks et al. 2012); this was demonstrated in our results as baseflow index was negatively associated with bankfull width. Finally, baseflow index was positively associated with total LWD. This association is likely correlative, as streams with more stable flow regimes are more likely to occur in forested landscapes, which generally provide greater inputs of LWD (Holling 1973; Poff et al. 1997; Brooks et al. 2012).

The third climate-sensitive variable that we considered, average annual July precipitation was not a common predictor of stream habitat and was only negatively associated with combined forest riparian cover. Average annual July precipitation is representative of low flows and is generally the month that receives the least amount of precipitation in the state of Michigan (Andresen et al. 2012). As the most influential climate sensitive landscape factors (i.e., baseflow index and average annual precipitation) have greater influence over hydrologic processes than low flows in a given year, it stands to reason that average annual July precipitation would have the least influence of the three factors on stream habitat features.

Comparison of component scores versus individual habitat variable regressions

In general, findings to predict component scores from landscape factors matched findings predicting the individual habitat variables from landscape factors. Natural landscape variables were, again, the most common predictors of habitat features summarized by component scores. We found that agricultural land use was tied with reach slope as the most frequent predictor of component scores (just as we did with individual habitat variables); both agricultural land use and slope were included as important predictors in 4 different models. Also, climate sensitive landscape factors were similarly influential predictors of component scores. Investigations that characterize influences of landscape factors on stream habitat suggest the mechanisms by which landscape factors will affect stream fishes; limited studies have attempted to predict these potential changes. In a study by Infante and Allan (2010), several stream habitat features were similarity predicted using natural and anthropogenic landscape factors. For example, both this study and Infante and Allan (2010) found that the channel size components (specifically bankfull width and stream depth) were both positively associated with network catchment area and negatively associated with reach slope. Additionally, habitat complexity (e.g., riffle and pool habitats) in both studies was strongly associated with network catchment area and reach slope. Results of our study highlight the importance of both natural and anthropogenic landscape factors and their controls on formation and degradation of stream habitat features.

Some component score predictions differed from the results of the individual variable model predictions. For example, elevation was a suitable predictor of Axis 1, channel condition and fish cover, but was not included as a predictor in models for individual habitat variables. Additionally, network catchment area, reach slope, and average annual precipitation were included as suitable predictors of the second axis, channel size, but baseflow index was not. Finally, average annual July precipitation was a suitable predictor of the fifth component, pools and tag alders, which did match our expectations. However, average annual July precipitation was not a predictor for these respective habitat variables in the individual habitat variable models.

The value of monitoring and assessing stream habitat under changing climate

Natural resource management agencies monitor and collect stream habitat data to identify causes of disturbances to stream fishes and ultimately to mitigate negative anthropogenic effects. While these data are readily collected by natural resource agencies, these data are under-used in management decision-making processes (Sass et al. 2017). Omission of stream habitat data limits the overall understanding of how and why fish communities may respond to disturbances, and it may limit the identification of suitable management actions to support fish and fisheries (Bonar et al. 2009). Additionally, budgetary limitations within natural resources agencies are expected to increase into the foreseeable future, resulting in the growing need for these agencies to prioritize projects and programs with the most cost-effective outcomes.

Stream habitat factors such as woody debris, fish cover, substrate, bank condition, and riparian cover are known to be important to fishes, yet they are rarely incorporated into management decision-making (Sass et al. 2017). Using stream habitat data to predict potential impacts of changing climate on fishes will enable natural resource managers to anticipate which habitat variables may change and how those changes might then impact fishes. Additionally, using stream habitat data could help managers to identify streams that may be most impacted by changing climate and efficiently prioritize streams that would benefit most from restoration, conservation, or other management efforts (Rios-Touma et al. 2014; Moody et al. 2017).

Biases in data

Some of our results could potentially reflect sampling biases within MDNR's STP protocols and site selection methodology. First, the STP only collects data from streams likely to support a fishery (Wills et al. 2006), and because of this, site selection likely excludes many headwaters as well as intermittent and ephemeral streams, in spite of their known importance to fish habitats. While these streams may not support fisheries year-round, they are critical for providing refuge habitats, maintaining aquatic and riparian biodiversity, and offering a variety of ecosystem services (Colvin et al. 2019). Understanding how these streams are affected by landscape factors can be consider in conjunction with streams further down in the network to better understand how controls on stream habitat affect fishes. Second, the STP only collects data from wadeable streams (Wills et al. 2006). This excluded larger, deeper reaches that are certainly important habitat for maintaining fisheries and are also products of the landscapes they drain (Wilhelm et al. 2005).

Future studies

Additional studies focused on the prediction of how stream habitat will change under different projected climate change scenarios will be particularly useful for the conservation and management of streams into the future. Specifically, understanding how stream habitat variables, including measures of channel shape, large woody debris, riparian cover, and bank condition, will change as precipitation patterns and baseflow index change under different projected climate change scenarios would aid managers in identifying what streams and stream habitat features should be prioritized to mitigate negative impacts into the future. Further, some studies have associated stream habitat features that are important to specific fish taxa, such as substrate's importance for salmonid spawning (Dean et al. 2020). However, many of these species for which we have a good understanding of their relationship to habitat are typically species that are of socioeconomic importance or are threatened and/or endangered. Little is known about species not of traditional management interest, including habitat requirements of these fishes. Additional studies could focus on identifying features of stream habitat important to these various species, allowing for a richer understanding of the habitat requirements for entire stream fish communities. This would allow managers to better predict changes to species distributions across the state as habitat availability and quality changes with climate.

CONCLUSION

The state of Michigan is home to a diversity of stream habitat types that are important for many ecologically, socioeconomically, culturally, and spiritually important fishes that must be conserved into the future. This study suggests that natural, anthropogenic, and climate sensitive landscape factors largely influence several physical stream habitat variables across the state of Michigan, and these factors must be considered further, especially considering future impacts via changing climate. Many stream habitat variables are influenced by landscape factors that are driven by hydrologic processes, and mitigating impacts to habitat under changing climate must be addressed at multiple spatial scales (i.e., reach, local catchment, network catchment, etc.). Outcomes of this research offer insights to natural resource managers on what stream habitat features might change with changes in climate. Ultimately, understanding how stream habitat features will change with climate will allow natural resource managers to more effectively conserve streams and the fishes they support into the future.

APPENDICES

APPENDIX A

TABLES

Table A.2.1. List of selected STP stream habitat surveys including the stream's name and associated reach code.

Reach code	Region	Stream name
12120316	NLP	Anderson Creek
12942134	NLP	Au Gres River
12953314	NLP	Au Sable River
12121572	NLP	Bear Creek
8991194	NLP	Big South Branch Pere Marquette River
12134742	NLP	Bigelow Creek
13057812	NLP	Boardman River
12498830	NLP	Canada Creek
12134374	NLP	Cold Creek
12961811	NLP	Cole Creek
12944854	NLP	Dedrich Creek
13055842	NLP	Deer Creek
12942170	NLP	East Branch Au Gres River
12953286	NLP	East Branch Au Sable River
12501809	NLP	East Branch Maple River
12954914	NLP	East Creek
12120244	NLP	Fife Lake Outlet
12944334	NLP	Gamble Creek
12942022	NLP	Guiley Creek
12203110	NLP	Haynes Creek
12132378	NLP	Hersey River
12944336	NLP	Houghton Creek
12960419	NLP	King Creek
12133108	NLP	Lincoln Creek
12135384	NLP	Little Cedar Creek
12120880	NLP	Little Manistee River
12503375	NLP	Little Pigeon River
8990078	NLP	Little South Branch Pere Marquette River
12962277	NLP	Little Wolf Creek
12116576	NLP	Manistee River
12501827	NLP	Maple River
8990202	NLP	Martin Creek
12953268	NLP	North Branch Au Sable River
904060095	NLP	North Branch Manistee River
12202316	NLP	Ocqueoc River
8990046	NLP	Pere Marquette River

Table A.2.1. (cont'd)

Reach code	Region	Stream name
8992044	NLP	Pere Marquette River
12120714	NLP	Peterson Creek
12503351	NLP	Pigeon River
12503419	NLP	Pigeon River
12120870	NLP	Pine River
12227889	NLP	Platte River
13058032	NLP	Rapid River
12944462	NLP	Rifle Creek
12942744	NLP	Rifle River
12945058	NLP	Rifle River
12942922	NLP	Silver Creek
12121130	NLP	Smail Creek
12952968	NLP	South Branch Au Sable River
13055412	NLP	South Branch Spring Brook
8990450	NLP	South Branch White River
12502977	NLP	Sturgeon River
12963107	NLP	Thunder Bay River
12953210	NLP	Turtle Creek
12962229	NLP	Turtle Creek
12954072	NLP	Van Etten River
12941978	NLP	Vaughn Creek
12502939	NLP	West Branch Minnehaha Creek
13055458	NLP	Warner Creek
12501619	NLP	West Branch Maple River
12502979	NLP	West Branch Sturgeon River
12961701	NLP	Wolf Creek
12953264	NLP	Wright Creek
12926817	SLP	Bad Axe Creek
13028343	SLP	Bad River
15661466	SLP	Bean Creek
3467359	SLP	Bear Creek
9004125	SLP	Bear Creek
13028271	SLP	Beaver Creek
12260594	SLP	Blosser Drain
13031179	SLP	Bogue Creek
12255524	SLP	Burnett Creek
13007340	SLP	Cass River

Table A.2.1. (cont'd)

Reach code	Region	Stream name
13009440	SLP	Cass River
13039110	SLP	Cedar Creek
13045775	SLP	Cedar River
13046091	SLP	Cedar River
13038840	SLP	Chippewa River
13038904	SLP	Chippewa River
13039000	SLP	Chippewa River
12144808	SLP	Coldwater River
12260238	SLP	Coldwater River
13016527	SLP	Farmers Creek
12258056	SLP	Fisher Creek
13015191	SLP	Flint River
13015991	SLP	Flint River
13015373	SLP	Forest Drain
12246200	SLP	Grand River
13015477	SLP	Hemmingway and Whipple Drain
13032057	SLP	Hovey-Pratt Drain
13019613	SLP	Howland Drain
13173721	SLP	Huron River
13175973	SLP	Huron River
3470403	SLP	Indian Creek
13027059	SLP	Jo Drain
15677273	SLP	Joe Drain
13030899	SLP	Jones Creek
3473399	SLP	Kalamazoo River
12937922	SLP	Kawkawlin River
13019563	SLP	Kintz Creek
12241372	SLP	Looking Glass River
13046039	SLP	Mansfield Creek
13045511	SLP	Mid Br Tittabawassee River
10849642	SLP	Middle River Rouge
10849648	SLP	Middle River Rouge
12257022	SLP	Mill Creek
13177149	SLP	Mill Creek
13015549	SLP	Misteguay Creek
13007330	SLP	Mud Creek
13040090	SLP	North Branch Chippewa River - Mecosta Co.
13230380	SLP	Nile Drain
13028347	SLP	North Branch Bad River

Table A.2.1. (cont'd)

Reach code	Region	Stream names
13007440	SLP	North Branch Cass River
13038812	SLP	North Branch Chippewa River
13046755	SLP	North Branch Tobacco River
13007474	SLP	North Branch White Creek
13031455	SLP	North Ore Creek
13040936	SLP	Pine River
13015921	SLP	Plum Creek
12264790	SLP	Pokagon Creek
12260358	SLP	Prairie River
13226732	SLP	River Raisin
13229656	SLP	River Raisin
9003889	SLP	Rogue River
13226892	SLP	Saline River
13039272	SLP	Salt Creek
13039138	SLP	Salt Creek (Little Salt River)
13047469	SLP	Salt River
3472389	SLP	Schnable Brook
13008736	SLP	Scott Drain
13028827	SLP	Shiawassee River
13031021	SLP	Shiawassee River
13031047	SLP	Shiawassee River
13032075	SLP	Shiawassee River
3467305	SLP	Silver Creek
13028453	SLP	South Branch Bad River
13229074	SLP	South Branch River Raisin
13047529	SLP	South Branch Salt River
13031421	SLP	South Branch Shiawassee River
13047167	SLP	South Branch Tobacco River
13008532	SLP	South Branch White Creek
3472663	SLP	Spring Brook
9007813	SLP	Spring Brook
13040706	SLP	Sugar Creek
12260068	SLP	Swan Creek
13027953	SLP	Swan Creek
13019567	SLP	Swartz Creek
13019825	SLP	Swartz Creek
12242504	SLP	Sycamore Creek
13019901	SLP	Thread Creek

Table A.2.1. (cont'd)

Reach code	Region	Stream name
13048217	SLP	Tittabawassee River
13048945	SLP	Tittabawassee River
13045501	SLP	West Branch Tittabawassee River
13045751	SLP	West Branch Cedar River
12917999	SLP	Willow Creek
12927799	SLP	Wiscoggin Drain
12021200	UP	Au Train River
12206528	UP	Bear Creek
11959838	UP	Big West Branch Escanaba River
12206176	UP	Biscuit Creek
12026264	UP	Bismark Creek
6790993	UP	Black River
11959842	UP	Bob's Creek
12025900	UP	Boise Creek
14443816	UP	Brule River
11959836	UP	Bryan Creek
12021738	UP	Chocolay River
11951427	UP	Cisco Branch Ontonagon River
11930334	UP	Clear Creek
12214737	UP	Davenport Creek
11959562	UP	East Branch Escanaba River
12220284	UP	East Branch Fox River
12211124	UP	East Branch Munuscong River
11948631	UP	East Branch Ontonagon River
6838205	UP	East Branch Sturgeon River
11937723	UP	Elm River
12021688	UP	Foster Creek
11937883	UP	Gratiot River
11959888	UP	Hunters Brook - Marquette Co.
14443726	UP	Iron River
12021120	UP	Joel Creek
12188393	UP	Little Beaver Creek
12221810	UP	Little Indian River
11951431	UP	Marshall Creek
904020415	UP	Menge Creek
11951613	UP	Middle Branch Ontonagon River
12021288	UP	Mosquito River
12025632	UP	Mulligan Creek

Table A.2.1. (cont'd)

Reach code	Region	Stream name
12183703	UP	Naomikong Creek
12021302	UP	North Branch Valley Spur
12027134	UP	Ravine River
11931042	UP	Rock River
12021146	UP	Rock River
11958234	UP	Second River
12021166	UP	Silver Creek
904030494	UP	South Branch Paint River
11962022	UP	Squaw Creek
11930068	UP	Sturgeon River
12027630	UP	Taylor Creek
11946997	UP	Trout Creek
12017658	UP	Two Hearted River
11951497	UP	Two Mile Creek
12210984	UP	Unnamed tributary to Taylor Creek
11930116	UP	West Branch Sturgeon River
11930214	UP	West Branch Sturgeon River

Table A.2.2. Mean, maximum (max), and minimum (min) values for measures of landscape variables used in analyses. The scale at which each variable is observed is indicated by (lc) for local catchment, (r) for reach, (nb) for network buffer, and (nc) for network catchment.

Factor grouping	Variable name (unit; scale)	Variable code	Mean	Max.	Min.
Natural factors					
	Network catchment area (km^2; nc)	N_areasqkm	314.64	6447.89	2.46
	Max. elevation (m; lc)	L_maxelev	261.96	513.07	178.61
	Flowline slope (m/m; r)	L_fl_slope	0.002973	0.023044	0.000010
	Combined percent coarse lithology (%; nc)	N_coarse_lith	66.74	100.00	0.00
	Combined percent fine lithology (%; nc)	N_fine_lith	10.70	97.02	0.00
Natural land cover factors					
	Combined percent forest (%; nb)	NB_nlcd_Forest	26.85	91.28	0.88
	Combined percent wetlands (%; nb)	NB_nlcd_Wetlands	36.25	90.26	0.00
Anthropogenic factors					
	Combined percent urban (%; nc)	N_nlcd_Urban	8.09	63.46	0.13
	Combined percent ag (%; nc)	N_nlcd_Ag	25.46	90.30	0.00
Climate sensitive factors					
	Baseflow index (%; nc)	N_bfi	63.70	88.00	32.48
	Average annual precipitation (mm; nc)	N_precip	894.12	1070.98	760.32
	Average annual July precipitation (mm; nc)	N_j_precip	85.64	116.33	65.73
	Average annual air temperature (°C; lc)	L_temp	7.60	10.49	4.01
	Average annual July air temperature (°C; lc)	L_j_temp	21.35	24.04	18.69

Table A.2.3. Mean, maximum (max), and minimum (min) values for measures of channel morphology. Variables selected for additional analysis are denoted by a (*).

Variable (unit)	Mean	Max.	Min.
Average wetted width (ft)	35.44	197.85	1.14
Average bankfull width (ft)*	38.72	300.71	5.23
Minimum bankfull width (ft)	28.14	250.00	3.00
Maximum bankfull width (ft)	54.27	541.00	6.40
Average stream depth (ft)*	1.28	5.11	0.16
Percent islands (% of points in transect)	0.80	15.53	0.00
Percent undercuts (% of points in transects)*	32.17	100.00	0.00
Pool habitat (% of transects)*	6.44	70.98	0.00
Riffle habitat (% of transects)*	14.90	100.00	0.00
Run habitat (% of transects)	84.27	100.00	0.00

Table A.2.4. Mean, maximum (max), and minimum (min) values for measures of fish cover. Variables selected for additional analysis are denoted by a (*).

Variable name (unit)	Mean	Max.	Min.
Woody cover (% of points in transect)	8.41	50.00	0.00
Rooted plant cover (% of points in transect)	7.58	82.00	0.00
Combined fish cover (% of points in transect)*	15.99	98.47	0.00

Table A.2.5. Mean, maximum (max), and minimum (min) values for measures of substrate. Variables selected for analysis are denoted by a (*).

Variable name (unit)	Mean	Max.	Min.
Gravel (% of points in transect)	27.75	85.00	0.00
Boulder (% of points in transect)	2.95	33.85	0.00
Small cobble (% of points in transect)	12.17	67.69	0.00
Large cobble (% of points in transect)	7.27	69.23	0.00
Combined coarse substrate (% of points in transect)*	50.14	100.00	0.00
Detritus and silt (% of points in transect)	8.19	93.85	0.00
Sand (% of points in transect)	40.73	100.00	0.00
Combined fine substrate (% of points in transect)	48.92	100.00	0.00
Clay (% of points in transect)	3.20	100.00	0.00
Wood (% of points in transect)	0.59	10.95	0.00
Low gravel embeddedness (% of points in transect)	51.59	100.00	0.00
High gravel embeddedness (% of points in transect)	44.96	100.00	0.00

Table A.2.6. Mean, maximum (max), and minimum (min) values for measures of large woody debris. Variables selected for additional analysis are denoted by a (*).

Variable name (unit)	Mean	Max.	Min.
LWD 6”-12” dbh (count)*	275.21	3060.00	0.00
LWD 12”-18” dbh (count)	103.43	1188.00	0.00
LWD 18”-24” dbh (count)	13.79	240.00	0.00
LWD >24” dbh (count)	5.03	150.00	0.00
Total LWD (count)	390.12	3564.00	0.00
Combined LWD small dbh (count)	378.64	3540.00	0.00
Combined LWD large dbh (count)	18.82	306.00	0.00

Table A.2.7. Mean, maximum (max), and minimum (min) values for measures of riparian cover and bank condition. Variables selected for analysis are denoted by a (*).

Variable name (unit)	Mean	Max.	Min.
Pasture (% of points in transects)	0.96	50.00	0.00
Row crop agricultural (% of points in transects)	1.11	100.00	0.00
Yard (% of points in transects)	4.85	87.50	0.00
Combined anthropogenic (% of points in transect)	6.92	100.00	0.00
Large coniferous trees (% of points in transects)	13.91	100.00	0.00
Large deciduous trees (% of points in transects)	19.29	100.00	0.00
Small coniferous trees (% of points in transects)	4.74	70.83	0.00
Small deciduous trees (% of points in transects)	17.74	100.00	0.00
Combined forested (% of points in transects)*	55.68	100.00	0.00
Grassland and forbs (% of points in transects)*	25.01	100.00	0.00
Tag alder (% of points in transects)*	22.56	100.00	0.00
Other (% of points in transects)	0.08	8.33	0.00
Banks in good condition (% of points in transects)*	66.16	100.00	0.00
Banks in fair condition (% of points in transects)	23.50	100.00	0.00
Banks in poor condition (% of points in transects)	12.88	100.00	0.00
Banks in very poor condition (% of points in transects)	3.78	73.08	0.00

Table A.2.8. Mean, maximum (max), and minimum (min) values for measures of the fourteen habitat variables selected from the STP stream habitat surveys. Variables selected for additional analysis are denoted by a (*).

Variable (unit)	Mean	Max.	Min.
Average bankfull width (ft)	38.72	300.71	5.23
Average stream depth (ft)	1.28	5.11	0.16
Percent undercuts (% of points in transect)	32.17	100.00	0.00
Pool habitat (% of transects)	6.44	70.98	0.00
Riffle habitat (% of transects)	14.90	100.00	0.00
Combined forest (% of points in transect)	55.68	100.00	0.00
Grassland and forbs (% of points in transect)	25.01	100.00	0.00
Tag alder (% of points in transect)	22.56	100.00	0.00
Banks in good condition (% of points in transect)	66.16	100.00	0.00
Combined fish cover (% of points in transect)	15.99	98.47	0.00
Combined coarse substrate (% of points in transect)	50.14	100.00	0.00
Low gravel embeddedness (% of points in transect)	51.59	100.00	0.00
High gravel embeddedness (% of points in transect)	44.96	100.00	0.00
Total LWD (count)	390.12	3564.00	0.00

Table A.2.9. Principal components analysis of 14 selected stream habitat variables. Components explained 74.97% of variance in habitat. Components with loadings greater than (+/-)0.55 are shown in bold.

	Channel condition and fish cover (1)	Channel size (2)	Riffles and coarse substrate (3)	Forest vs. grassland riparian cover (4)	Pools and tag alder riparian cover (5)	Stream embeddedness (6)
Average bankfull width	-0.062	**0.896**	0.195	0.063	-0.112	-0.051
Average stream depth	-0.009	**0.898**	-0.196	-0.113	0.051	0.034
Undercuts	**0.749**	-0.071	0.139	0.251	0.087	0.006
Pool habitat	-0.064	-0.092	0.083	0.124	**0.779**	0.074
Riffle habitat	0.070	-0.164	**0.767**	0.165	0.195	-0.105
Combined fish cover	**0.686**	0.067	-0.11	-0.036	-0.058	0.154
Combined coarse substrate	0.008	0.092	**0.901**	-0.005	-0.076	0.09
Total LWD	0.538	**0.563**	-0.113	0.277	0.033	-0.053
Combined forest	0.059	0.044	0.256	**0.816**	-0.393	0.013
Grassland and forbs	-0.042	0.001	0.029	**-0.861**	-0.228	0.011
Tag alder	0.372	0.087	0.004	-0.169	**0.753**	-0.008
Banks in good condition	**0.728**	-0.053	0.16	-0.128	0.194	-0.184
Low gravel embeddedness	0.137	0.09	0.339	-0.032	-0.053	**-0.806**
High gravel embeddedness	0.153	0.049	0.344	-0.039	0.036	**0.837**
Eigenvalues	2.52	2.08	1.92	1.44	1.42	1.12
Variance explained (%)	18.01	14.83	13.69	10.30	10.15	7.99

Table A.2.10. Results of forward stepwise multilinear regressions on the selected 14 stream habitat variables. Italicized variables were not suitably predicted by landscape factors (adjusted $R^2 < 0.10$) for a given response variable. Count of suitable model predictors represents the count of the number of suitable habitat models to which an individual landscape variable contributed.

				Standardized beta										
				Natural factors				Natural land cover		Anthropogenic		Climate sensitive		
Category	Habitat variable	Adj R^2	Model sig.	N_area sqkm	L_max elev	L_fl_ slope	N_coarse _lith	NB_ Forest	NB_ Wetlands	N_ Urban	N_Ag	N_bfi	N_ precip	N_j_ precip
Channel morphology														
	Avg. bankfull width	0.79	0.0000	0.92							-0.20	-0.09	0.14	
	Avg. stream depth	0.53	0.0000	0.56		-0.34					-0.20		0.11	
	Undercuts	0.43	0.0000			0.16			0.12			0.56		
	Pool habitat	0.20	0.0000		0.19	0.16	-0.28				-0.24			
	Riffle habitat	0.17	0.0000		0.24	0.17				-0.15			0.15	
Fish cover														
	Combined fish cover	*0.05*	*0.0010*									*0.24*		
Substrate														
	Combined coarse substrate	0.18	0.0000	0.37	0.33	0.30					0.33			
	Low gravel embeddedness	*0.02*	*0.0140*						*0.17*					
	High gravel embeddedness	*0.04*	*0.0020*										*0.21*	
LWD														
	Total LWD	0.41	0.0000	0.35	-0.22						-0.36	0.37		
Riparian cover and bank condition														
	Combined forest cover	0.19	0.0000	0.31		0.40							0.21	-0.17
	Tag alder cover	0.34	0.0000		0.18	-0.29				-0.21	-0.45			
	Banks in good	0.32	0.0000					-0.16		-0.24	-0.29	0.31		
	Grassland and forbs	*0.09*	*0.0000*								*0.32*		*-0.15*	
Count of suitable model predictors (adjusted $R^2 > 0.10$)				5.0	5.0	7.0	1.0	1.0	1.0	3.0	7.0	4.0	4.0	1.0

Table A.2.11. Results of forward stepwise multilinear regressions on the selected stream habitat component scores. Italicized variables were not suitably predicted by landscape factors (adjusted $R^2 < 0.10$).

			Standardized beta										
			Natural factors				Natural land cover		Anthropogenic factors		Climate sensitive factors		
PC	Adj R^2	Model sig.	N_area sqkm	L_max elev	L_fl_ slope	N_coarse _lith	NB_ Forest	NB_ Wetlands	N_ Urban	N_ Ag	N_ bfi	N_ precip	N_j_ precip
Channel condition and fish cover (PC1)	0.43	0.0000		-0.17						-0.27	0.54		
Channel size (PC2)	0.74	0.0000	0.79		-0.18					-0.22		0.10	
Riffles and coarse substrate (PC3)	0.18	0.0000	0.34	0.32	0.32					0.20		0.14	
Forest vs. grassland riparian cover (PC4)	0.14	0.0000	0.17		0.36						0.20		
Pools and tag alder riparian cover (PC5)	0.33	0.0000		0.20	-0.13	-0.21			-0.24	-0.41			0.13
Stream embeddedness (PC6)	*0.08*	*0.0000*		*0.17*						*0.24*		*0.18*	
Count of suitable model predictors (adjusted $R^2 > 0.10$)			3.0	3.0	4.0	1.0	0.0	0.0	1.0	4.0	2.0	2.0	1.0

APPENDIX B

FIGURES

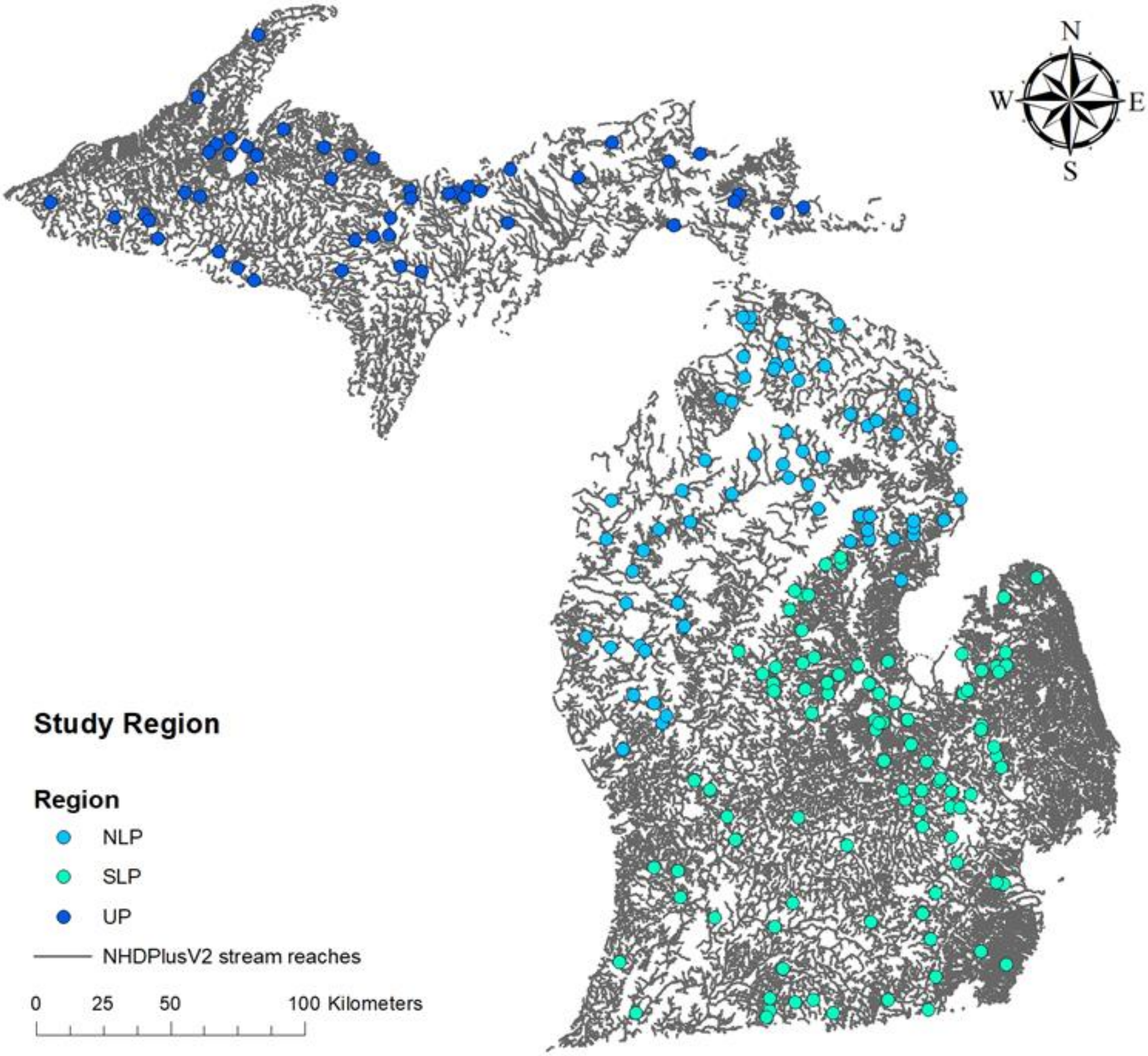

Figure B.2.1. Locations of 205 selected STP study reaches by region used for analysis.

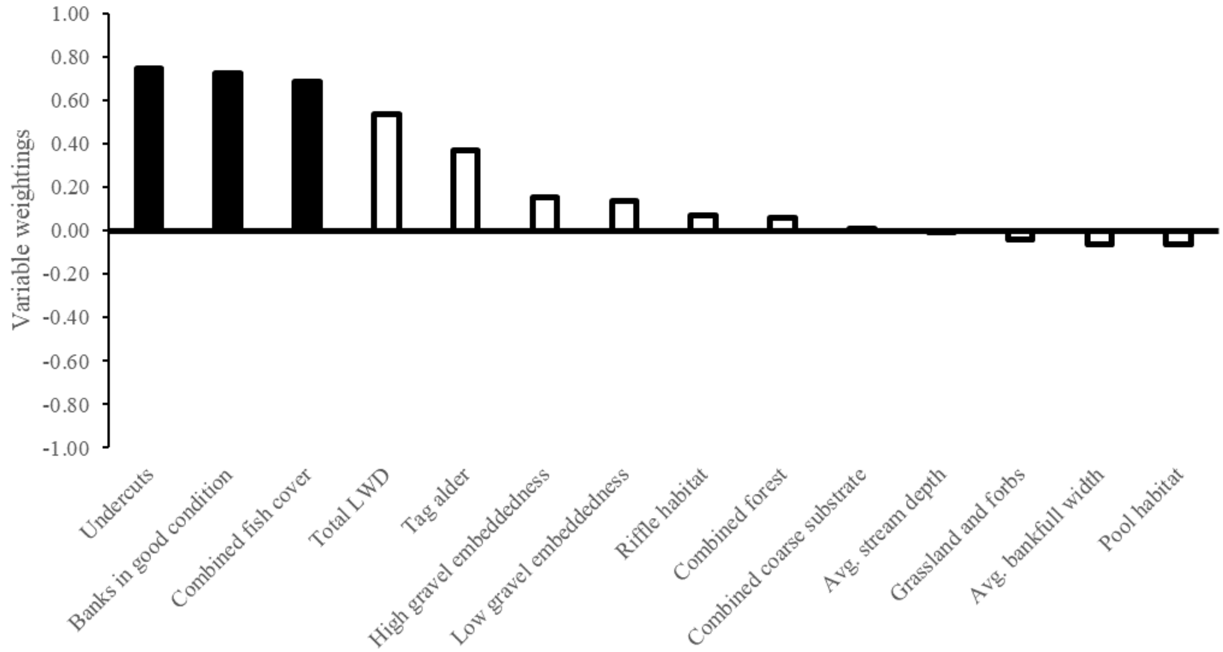

Figure B.2.2. Axis 1 from the PCA, called channel condition and fish cover, explained 18.01% of the variance. The y-axes show the weights on each variable for the individual components. Black bars indicate variables with weights with an absolute value greater than 0.55.

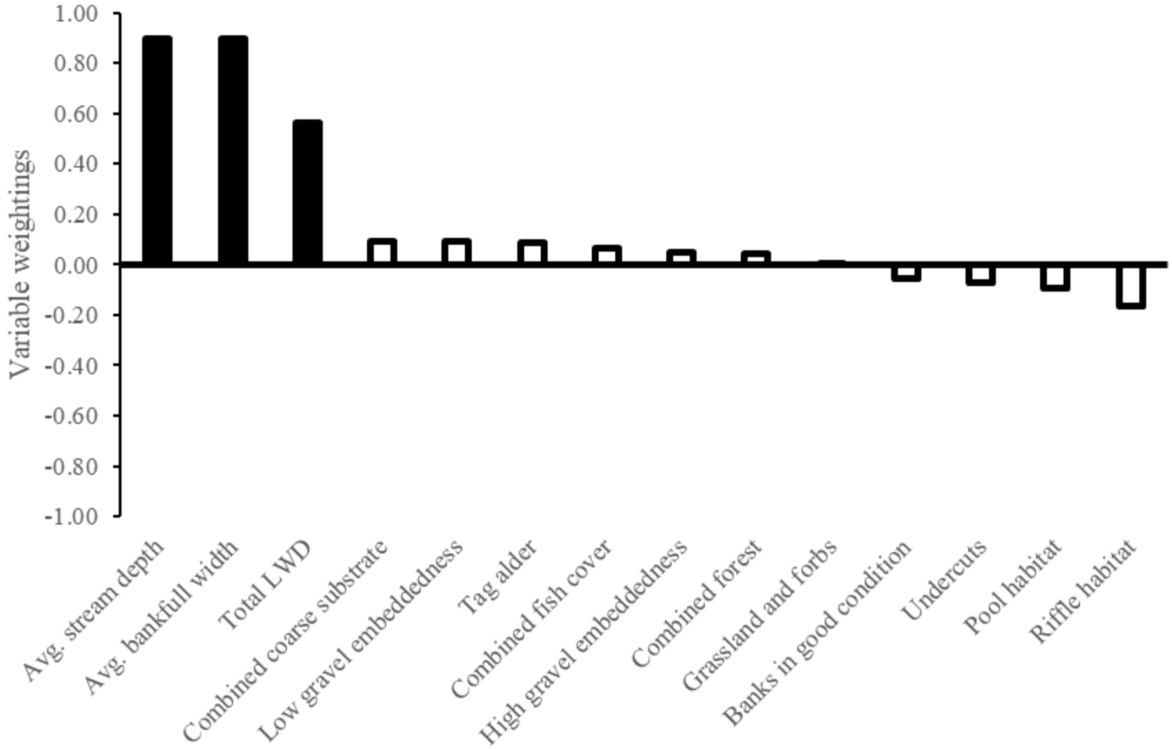

Figure B.2.3. Axis 2 from the PCA, called channel size, explained 14.83% of the variance. The y-axes show the weights on each variable for the individual components. Black bars indicate variables with weights with an absolute value greater than 0.55.

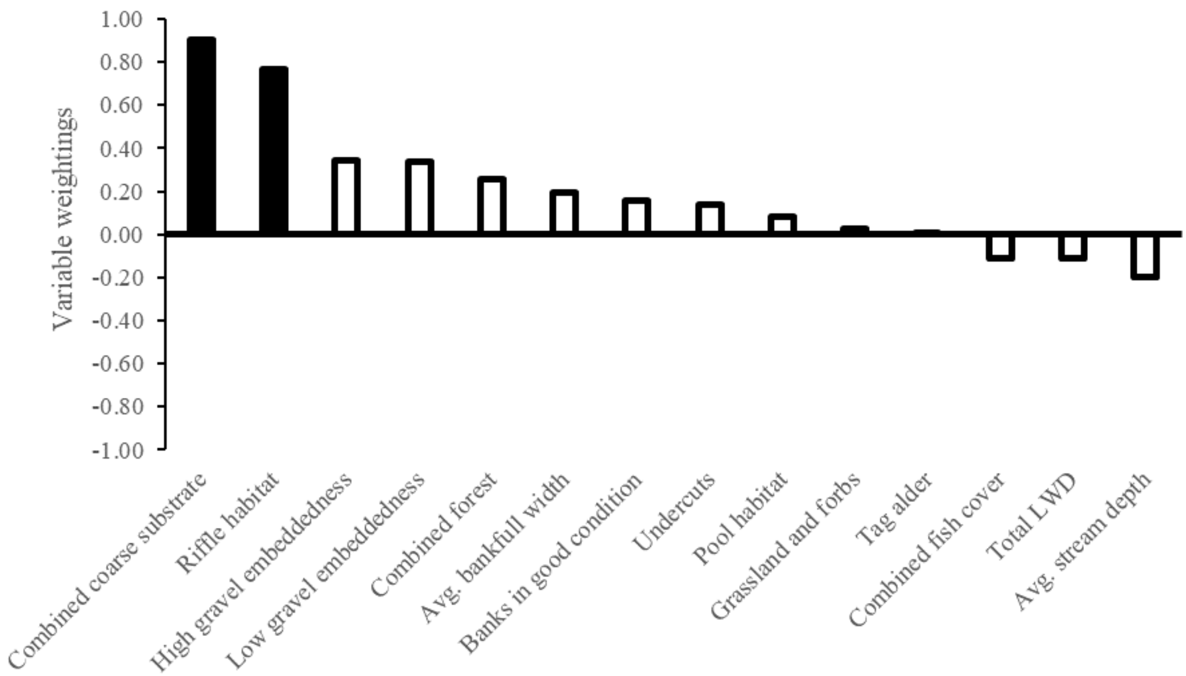

Figure B.2.4. Axis 3 from the PCA, called riffles and coarse substrate, explained 13.69% of the variance. The y-axes show the weights on each variable for the individual components. Black bars indicate variables with weights with an absolute value greater than 0.55.

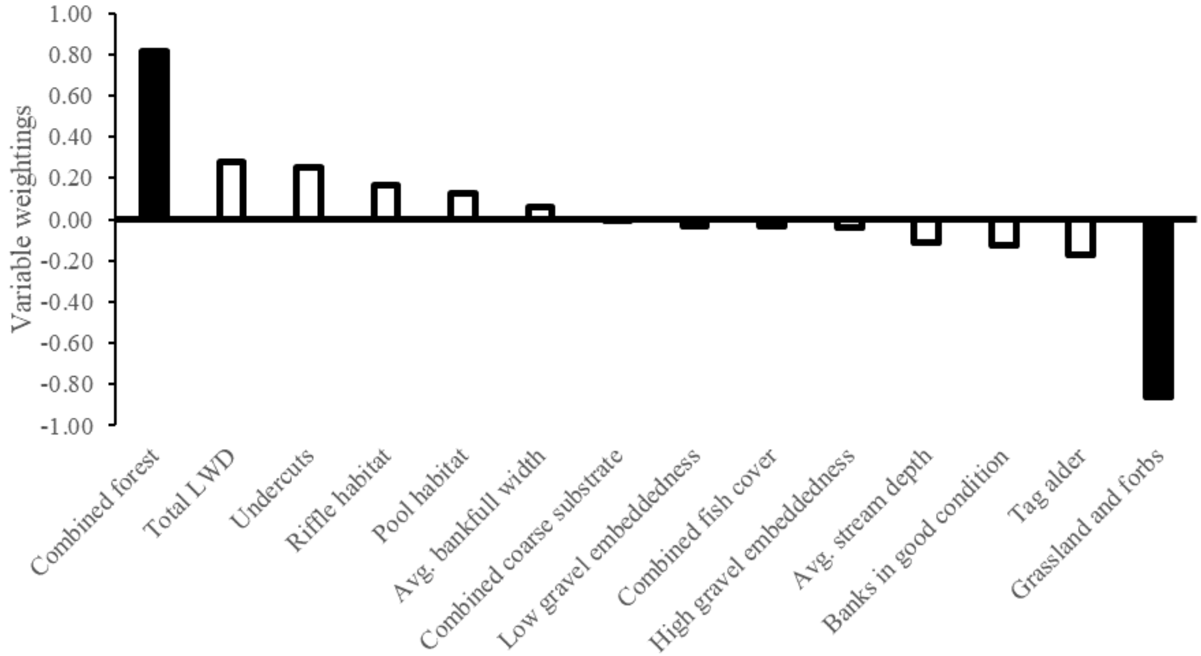

Figure B.2.5. Axis 4 from the PCA, called forest versus grassland riparian cover, explained 10.30% of the variance. The y-axes show the weights on each variable for the individual components. Black bars indicate variables with weights with an absolute value greater than 0.55.

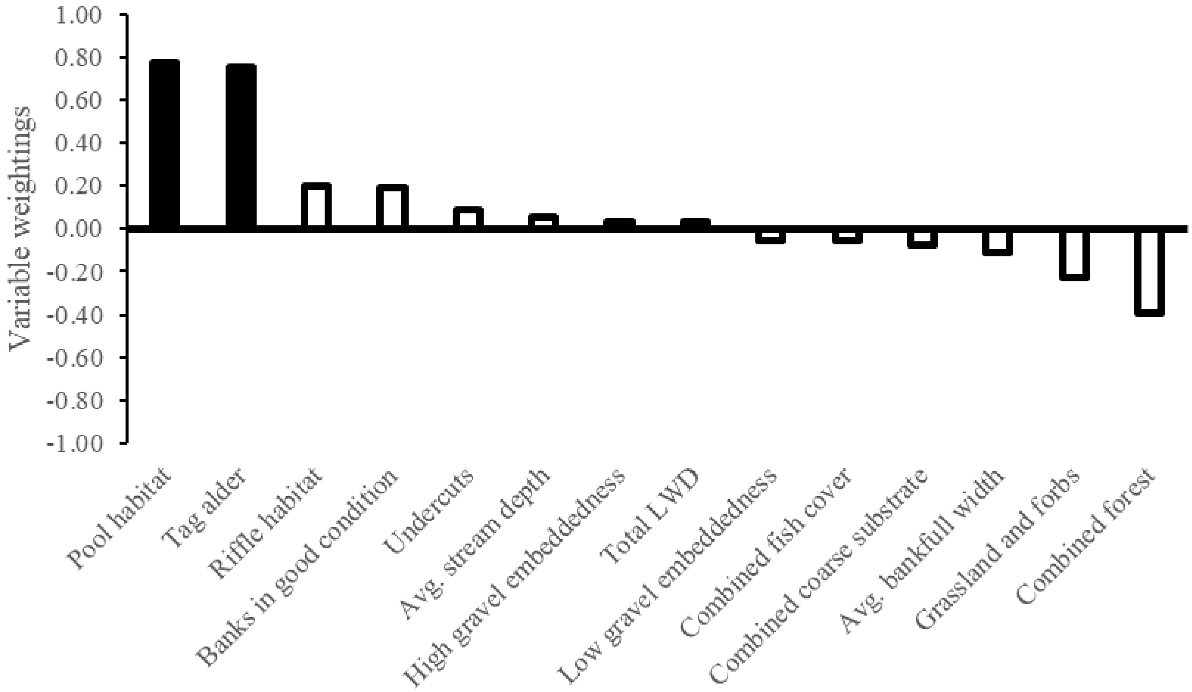

Figure B.2.6. Axis 5 from the PCA, called pools and tag alder riparian cover, explained 10.15% of the variance. The y-axes show the weights on each variable for the individual components. Black bars indicate variables with weights with an absolute value greater than 0.55.

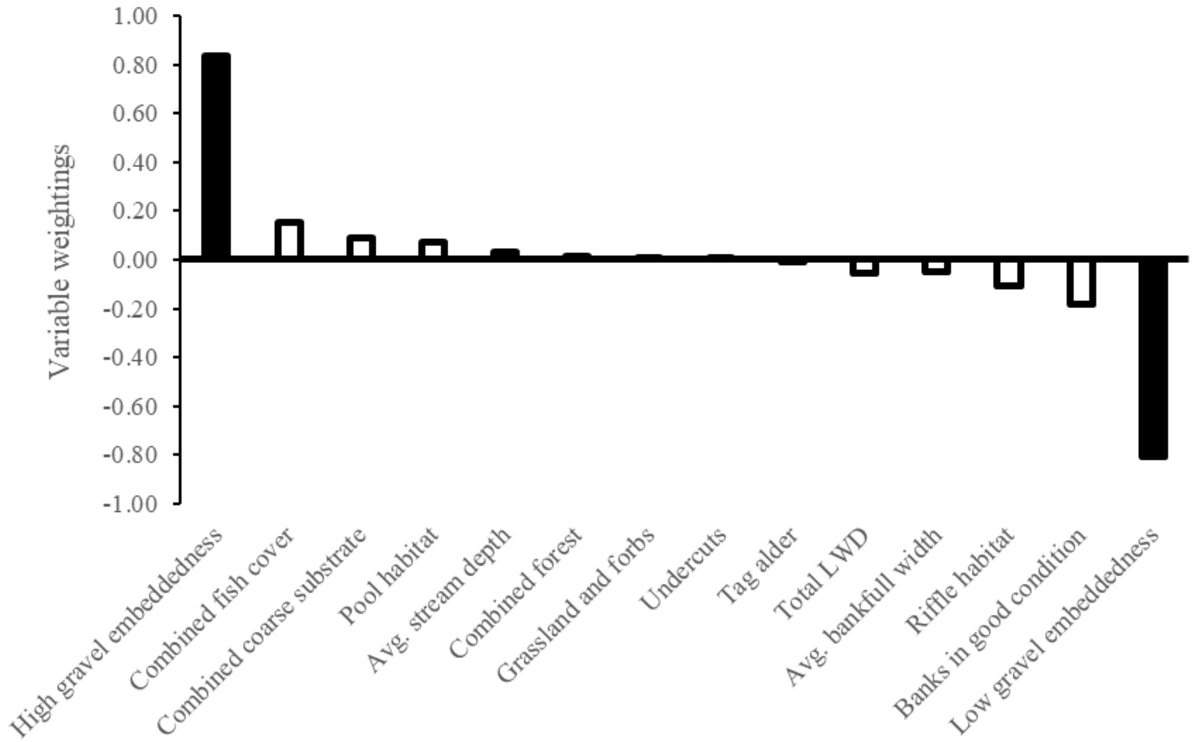

Figure B.2.7. Axis 6 from the PCA, called stream embeddedness, explained 7.99% of the variance. The y-axes show the weights on each variable for the individual components. Black bars indicate variables with weights with an absolute value greater than 0.55.

APPENDIX C

SUPPLEMENTARY MATERIALS

Table C.2.1. Pearson's correlation coefficients for all landscape variables. Bolded correlation coefficients indicate significance (p< 0.05).

Variable	L_max elev	L_fl_ slope	L_ temp	L_j_ temp	NB_ Forest	NB_ Wetlands	N_area sqkm	N_ bfi	N_ Urban	N_ Ag	N_ precip	N_j_ precip	N_ coarse_ lith	N_fine_ lith
L_max elev	1.00													
L_fl_ slope	**0.33**	1.00												
L_temp	**-0.59**	**-0.37**	1.00											
L_j_temp	**-0.51**	**-0.37**	**0.98**	1.00										
NB_ Forest	**0.20**	**0.65**	**-0.43**	**-0.44**	1.00									
NB_ Wetlands	**0.29**	-0.11	**-0.41**	**-0.44**	-0.13	1.00								
N_area sqkm	**-0.27**	**-0.48**	**0.23**	**0.25**	**-0.24**	0.09	1.00							
N_bfi	**0.27**	0.13	**-0.25**	**-0.34**	**0.14**	**0.48**	-0.09	1.00						
N_Urban	**-0.22**	**-0.31**	**0.58**	**0.61**	**-0.35**	**-0.23**	**0.26**	**-0.22**	1.00					
N_Ag	**-0.46**	**-0.38**	**0.79**	**0.82**	**-0.61**	**-0.46**	**0.16**	**-0.48**	**0.33**	1.00				
N_precip	-0.12	0.10	**0.38**	**0.32**	-0.02	-0.11	-0.12	**0.33**	-0.01	**0.25**	1.00			
N_j_ precip	**0.29**	0.09	**-0.19**	-0.07	0.11	**-0.17**	-0.07	**-0.43**	-0.04	0.05	0.00	1.00		
N_coarse _lith	**0.17**	0.07	-0.12	**-0.16**	**0.19**	**0.26**	0.08	**0.57**	**-0.14**	**-0.36**	0.13	**-0.24**	1.00	
N_fine_ lith	**-0.38**	**-0.19**	**0.25**	**0.28**	**-0.18**	**-0.37**	0.09	**-0.48**	**0.17**	**0.39**	**-0.20**	0.07	**-0.45**	1.00

Table C.2.2. Pearson's correlation coefficients for all channel morphology variables. Bolded correlation coefficients indicate significance ($p < 0.05$).

Variable name	Avg. bankfull width	Min. bankfull width	Max. bankfull width	Avg. stream depth	Percent undercuts	Pool habitat	Riffle habitat	Run habitat
Avg. bankfull width	1.00							
Min. bankfull width	**0.85**	1.00						
Max. bankfull width	**0.97**	**0.79**	1.00					
Avg. stream depth	**0.69**	**0.62**	**0.65**	1.00				
Percent undercuts	-0.10	-0.13	-0.06	-0.04	1.00			
Pool habitat	**-0.16**	**-0.20**	-0.10	-0.05	0.08	1.00		
Riffle habitat	0.02	0.00	0.06	**-0.29**	**0.23**	**0.17**	1.00	
Run habitat	**0.16**	**0.21**	0.11	**0.31**	-0.02	**-0.58**	**-0.68**	1.00

Table C.2.3. Pearson's correlation coefficients for all fish cover variables. Bolded correlation coefficients indicate significance ($p < 0.05$).

Variable name	Combined fish cover	Woody cover	Plant cover
Combined fish cover	1.00		
Woody cover	**0.70**	1.00	
Plant cover	**0.86**	**0.28**	1.00

Table C.2.4. Pearson's correlation coefficients for all substrate variables. Bolded correlation coefficients indicate significance ($p < 0.05$).

Variable name	Combined coarse substrate	Combined fine substrate	Low gravel embeddedness	High gravel embeddedness
Combined coarse substrate	1.00			
Combined fine substrate	**-0.75**	1.00		
Low gravel embeddedness	**0.24**	-0.13	1.00	
High gravel embeddedness	**0.34**	-0.08	**-0.39**	1.00

Table C.2.5. Pearson’s correlation coefficients for all large woody debris. Bolded correlation coefficients indicate significance (p< 0.05).

Variable name	LWD 6”-12” dbh	LWD 12”-18” dbh	Combined LWD small dbh	Total LWD
LWD 6”-12” dbh	1.00			
LWD 12”-18” dbh	**0.84**	1.00		
Combined LWD small dbh	**0.99**	**0.91**	1.00	
Total LWD	**0.98**	**0.91**	**0.997**	1.00

Table C.2.6. Pearson's correlation coefficients for all riparian cover and bank condition variables. Bolded correlation coefficients indicate significance ($p < 0.05$).

Variable name	Combined anthropogenic	Combined forested	Grassland and forbs	Tag alder	Banks in good condition	Banks in fair condition	Banks in poor condition	Banks in very poor condition
Combined anthropogenic	1.00							
Combined forested	**-0.19**	1.00						
Grassland and forbs	-0.07	**-0.53**	1.00					
Tag alder	**-0.14**	**-0.41**	-0.13	1.00				
Banks in good condition	0.00	-0.08	-0.04	**0.36**	1.00			
Banks in fair condition	0.04	**0.17**	0.02	-0.11	**-0.61**	1.00		
Banks in poor condition	0.02	0.11	0.09	**-0.22**	**-0.74**	**0.25**	1.00	
Banks in very poor condition	-0.03	0.10	0.00	-0.06	**-0.45**	**0.20**	**0.37**	1.00

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MANAGEMENT IMPLICATIONS AND ADDITIONAL NEEDS

To best conserve fishes under changing climate, natural resource managers must better understand stream habitats' influences on fishes and incorporate these outcomes into management decision-making processes. However, managers must be open to the idea of using concepts, frameworks, and data not traditionally implemented in management decision-making processes, including stream habitat data, which are useful indicators of how habitats and the fisheries they support will change into the future with changes to climate. In this section, we synthesize the main findings of Chapters 1 and 2 of this thesis and present suggestions for how findings can inform management of streams and their habitats under a changing climate along with recommendations for future study needs that would offer key insights into how stream fishes may be affected by habitat that changes with climate.

Chapters 1 and 2: Thesis goals and objectives

In Chapter 1, we identified strategies for increasing the use of stream habitat data by natural resource managers, specifically in decision-making processes. To accomplish this, we conducted semi-structured interviews with 19 MDNR Fisheries Division personnel to evaluate perceptions of and barriers to using stream habitat data by natural resource managers. While participants expressed their overall support for the value of habitat data, they identified several challenges to using data, including difficulties accessing and interpreting data. To overcome these barriers, we provide specific recommendations for managers to use to better incorporate stream habitat data into their management decision-making processes, including incorporating the use of habitat data into decision support tools; providing managers with continued education and trainings on the broad fundamentals of how the physical environment affect fishes and their habitats; and providing managers with additional research examining how individual stream habitats features are influenced by landscape factors. In our second chapter, we investigated influences of multiple landscape factors on physical stream habitat, including factors influenced by climate. This study was conducted in partial response to the interest shown by managers in Chapter 1 for more information regarding how physical stream habitat will change with climate. The state of Michigan has a diversity of landscape factors important in structuring stream habitats, and so our first step was to summarize habitat conditions and patterns across the state to identify those that varied most across the study area. Next, we predicted these stream habitat variables from landscape factors, including factors sensitive to changes in climate. Based on the results of our two chapters, we developed recommendations for natural resource managers to incorporate the use of habitat data more in management decision-making.

Identify stream habitat features important to fishes that are likely to change with climate

Our results showed that some measures of channel morphology, large woody debris, riparian cover, and bank condition are influenced by at least one of our tested landscape factors likely to change with changes in climate (these are termed “climate-sensitive” factors). Because of this, we recommend that managers identify associations between these habitat features and priority fish species of management interest. This could be conducted with existing STP data in addition to the STP data collected into the future by MDNR. Managers could then prioritize the management of these factors in streams known to support these priority fishes, including implementing restoration and mitigation practices. At the reach scale, managers can use information to identify stream reaches for large woody debris inputs and reaches in need of bank restoration or erosion mitigation efforts. Larger scale improvements can also be identified, such as identifying stream networks that require channel morphology restoration or mitigation work. Ultimately, these results can be used by managers to identify streams that that might be most vulnerable to changes in climate and to protect these streams and the fishes they support into the future.

Provide managers with continued education regarding fundamentals of aquatic ecology

To ensure that streams and fishes are conserved into the future, managers must increase their understanding and use of stream habitat data in management decision-making processes. Managers reported feeling uncertainty about how to incorporate data into decision-making processes. Because managers have historically focused on responsive population management practices, participants felt that they had an incomplete understanding of interactions between the riverscape and landscape. For this reason, we recommend professional societies and academic departments provide further training and education to managers and biologists on topics such as stream ecology, hydrology, and landscape ecology, as effective continued education is critical to continuing innovative problem solving and decision-making by managers. Natural resource management agency leadership should be supportive of employees' enrollment in continued education courses and workshops and should foster a culture that emphasizes the importance of using multiple approaches and frameworks to address fisheries management decisions, such as the use of stream habitat data.

Provide managers with additional research

Besides describing uncertainty in their understanding of interactions between landscape factors, stream habitat, and fishes, participants also mentioned that limited examples exist regarding how to use habitat data in decision-making processes. Participants wanted additional research examples of how physical stream habitat features are influenced by landscape factors, including ways in which changing climate may affect habitat. Currently, few studies attempt to predict physical stream habitat features from landscape factors. For this reason, we recommend more studies be conducted to address knowledge gaps regarding how physical habitat is affected by changes in climate, especially within the Great Lakes region. Additional studies, including studies that document regional effects of climate-sensitive landscape factors on habitat, would offer managers a more holistic understanding of expected changes into the future. Specifically, understanding how stream habitat features will change under differing climate change projections could help managers identify and prioritize streams at greatest risk to future degradation. Future studies could additionally examine how stream habitat variables not featured in this study, such as stream temperature, or other influential landscape factors not featured in this study, such as water withdrawals, will change with climate (where data are available).

Provide managers with more decision support tools

Stream habitat data in the MDNR's STP are often difficult to access, and once accessed, require significant re-formatting before data can be used in analyses. Because of this, managers stated that it was difficult to incorporate stream habitat data into their management decision-making processes. To address this limitation, our recommendation is to provide managers with more decision support tools that allow them to compare both fish and stream habitat data statewide and across time where data are available. These tools should additionally incorporate landscape features identified as influential to stream habitat in this study (e.g., natural factors like catchment area, reach slope, maximum elevation, and anthropogenic factors like agricultural and urban land use in the catchment), including landscape factors sensitive to climate (e.g., average annual precipitation and baseflow index). Developing more decision support tools for managers and biologists can ease the burdens of accessing, cleaning, and analyzing data by providing data in a format that is streamlined, easily interpretable, and standardized. Decision support tools should be designed to compare streams at multiple spatial scales (i.e., local, regional, or statewide) because of the multiple spatial scales at which management actions can occur.

CONCLUSION

Michigan has an abundance of stream habitats throughout the state that support a diversity of ecologically and socioeconomically important fishes that must be conserved into the future, especially under changing climate. Responding to the effects of climate change on stream habitat will require a richer understanding of how to incorporate data into decision-making as well as how physical habitat is expected to change into the future. Outcomes of this research offer natural resource managers with strategies to increase the use of habitat data and provide novel information regarding the influences of landscape factors, including climate sensitive factors, on stream habitat, ultimately facilitating better conservation and management of stream habitats and the fishes they support into the future.