TITLE
Fish Habitat Change Caused by Groundwater Withdrawals: Impacts on Water Management in Michigan

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ABSTRACT
A modeling investigation of high-capacity groundwater pumping found that significant impacts to fish habitats in Michigan streams were affected due primarily to changes in stream temperature. These impacts continued to occur even at a modeled pumping distance of 1.6km away from the stream. Downstream impacts to fish community habitat were also demonstrated. Historically, groundwater pumping scenarios were not closely considered, and studies showed minimal impact to fish habitat caused by even large-scale surface water pumping. Due to Michigan's 2008 groundwater conservation law, determination of local-scale impacts from groundwater pumping impacts on fish habitat may become an important consideration in the decision of stakeholders to commence with large-scale groundwater pumping operations.

Key words:
Groundwater, Fish habitat alteration, Freshwater management

INTRODUCTION

Michigan Groundwater-Surface Water-Fish Community Interactions
One might say that the US state of Michigan is blessed with an abundance of water, being surrounded by the Great Lakes, which contains roughly 84% accessible of the United States' freshwater (Groombridge & Jenkins, 1998), and has vast amounts of groundwater that also provide the water source for many of the rivers in the state. Furthermore, it is well demonstrated that groundwater influx can have significant influence on the taxonomic composition and diversity of fish communities in Michigan (Abbas, Liao, Li, & Richard, 2010; Brendan, Wang, & Seelbach, 2008; Seelbach, Wiley, Kotanchik, & Baker, 1997; Zorn, Seelbach, & Wiley, 2002). One shorthand way of indexing the influence that groundwater inputs have on local ecological habitat is encapsulated in the concept of "base-flow water yield"; a measure derived by dividing a stream's stream discharge during the low-flow season (typically July) by its upstream catchment area (Seelbach, Wiley, Kotanchik, & Baker, 1997). Streams with high "base-flow water yield" values have greater groundwater inputs than streams with low base-flow "water yield" values, and in Michigan; and this metric has been shown to be a useful factor in models predicting the fish species that one might expect to find in a particular stretch of a river (Zorn, Seelbach, & Wiley, 2002).

By examining hydrologic characteristics of the sites were they occur, it is possible to group Michigan fish species into different "guilds" of species reflecting their association with habitat conditions created by constituent groundwater inputs (Zorn, Seelbach, & Wiley, 2002). Further state-wide statistical analysis shows that a relationship between water yield and a fish species' abundance is relatively consistent (Zorn, Seelbach, Rutherford, Wills, Cheng, & Wiley, 2008). This relationship provides an ability to predict the expected range of abundance of fish species in a particular stretch of river, based primarily on water yield, stream size, and discounting pollution or other direct stressors.

Recent concern over groundwater withdrawal (Annan, 2006) led, in the case of Michigan, to the creation of legislation whose language explicitly connected permitting of groundwater withdrawals to the conservation of specific surface water fish assemblages (Steinman, Nichols, Seelbach, Allan, & Ruswick, 2011).

Legal Framework for Michigan Groundwater Management

Concern over the removal of water was reignited in 2000, with public discussion of a proposed plan to ship fresh water from Lake Superior to China via tanker (Annan, 2006). Although there was an already existing governance agreement (Anonymous, 1985), there was no formal legal framework within the region to govern water withdrawals from the lakes. This water withdrawal proposal was a major impetus for the development of a formal, legal framework for water conservation throughout the Great Lakes region. However, due to constitutional problems associated with writing and passing any law across the whole region, which includes eight US states and two Canadian provinces, the US states needed to pursue the process of an interstate compact. (A compact has to be passed with the exact same language by each state government as well as the national government, thus providing a single law for the region that will be enforced by the states and not the federal government as would be normal for inter-state matters.) The Great Lakes-St. Lawrence River Basin Water Resources Compact was the final document passed through all eight state governments as well as the US national government, and it was signed into law by President George W. Bush in December of 2008. In order to fulfill conservation goals, each state agreed to derive its own methodology to conserve the waters of their state.

In 2006, the state of Michigan passed a groundwater conservation law that would form its basis for water conservation, as would eventually be necessary under the compact. Michigan's state law required the determination of the level at which any large-scale groundwater pumping would create an adverse resource impact (ARI), defined in the law as including, "Decreasing the flow of a stream by part of the index flow such that the stream's ability to support characteristic fish populations is functionally impaired" (Anonymous, Public Act 33 of 2006). Through this language, Michigan's groundwater conservation law implicitly linked groundwater quantity to surface water ecology. It must be noted that, as part of the process undertaken to create the state's regulatory model, state scientists finalized the definition of "index flow" as being equivalent to average August water yield (Zorn, Seelbach, Rutherford, Wills, Cheng, & Wiley, 2008), however, the means of determining this definition (as well as the means of determining the definition of "characteristic fish populations") will not be discussed here.

In determining the State's regulatory rule, an advisory council was established and instructed to create a management rule for groundwater conservation, using "factually based recommendations" provided by the state agencies and universities (Anonymous, Public Act 34 of 2006). Michigan DNR scientists (along with department of agriculture) were tasked with constructing an assessment tool for which the appointed council could determine what would constitute an ARI.

In pursuing the particular means of determining an ARI, scientists utilized an existing wealth of inland fishery, landscape ecology, and modeling research in order to define the regulatory definition of "characteristic fish populations" as well as to determine the means of measuring how "[decreases in] the … index flow … functionally impair [characteristic fish populations]" for use in an automated assessment tool.

Agency scientists defined characteristic fish populations by statistically linking available fish abundance data with physical characteristics previously shown to be significant determinants of fish presence and abundance: baseflow yield and summer water temperature (themselves correlated) were key among them. The relationships were further enhanced by classifying the rivers of Michigan into eleven "river types" (Table 1). Based on relationships between resultant water yield and temperature conditions caused by water withdrawals and the fishes expected to be found in such resultant conditions, fish response curves were determined for each of the eleven "river types" (Zorn, Seelbach, Rutherford, Wills, Cheng, & Wiley, 2008). From these fish response curves, the advisory council determined the levels of water withdrawal that would trigger an ARI (Steinman, Nichols, Seelbach, Allan, & Ruswick, 2011).

The state model generalized the impacts of pumping across the entire state in order to provide a general regulatory model that would fit within an online GIS system in order to provide an initial filter for water use permit applications: applications to the system would fall into three categories: approved, in need of further review, and rejected. Reviews would entail a site-specific analysis conducted by either the state management agency or the applicant. Due to the relative physical robustness of most of the eleven river types, it was initially anticipated that little review would be necessary, save for one group of river types: "cold-transitional" rivers, which are physically characterized by their relatively fragile temperature-change profiles.

A Site-Specific Analysis of Pumping: Augusta Creek

The state of Michigan's proposed regulatory model was based on a statistical analysis of fishery data from across the entire state, statewide water temperature models, and statewide water yield estimates. While such a statistical analysis can provide a powerful analysis for the entirety of the state, local predictions amounted to averages for specific classes of rivers and could not provide high resolution estimates at a particular site. Furthermore, there were relatively few data from rivers of the "cold-transitional" river category which were expected to be the most controversial in terms of permitting decisions, and the most difficult to predict ecologically, Therefore, the benefits of conducting a site-specific analysis of a "cold-transitional" river seemed clear to the advisory council from the start. It was seen as a way to provide a test of the robustness of the state's otherwise largely statistical regulatory mode. Such a study would also illustrate the way in which a high resolution local investigation might be used to augment the state-wide statistical analysis in the context of a “in need of further review” type permitting decision.

Augusta Creek is a tributary system of the Kalamazoo River, in Southwest Michigan. It’s watershed covers an area of 98.2km^2 (37.9mi^2) and had historically been characterized by the Michigan DNR as a trout stream. Augusta Creek was a well-stocked trout stream, having over 1000 trout stocked during any one particular stocking period, based on stocking data held in the Institute for Fisheries Research. The creek flows roughly southward, passing through the town of Augusta, MI before entering the Kalamazoo River as a 3rd order stream. There is one principal tributary, roughly midway along the course of the creek.

The majority of the watershed has little urban development, and no existing large groundwater abstractions. However, the creek is recognized by biologists at the near-by Michigan State University Kellogg Biological Center as a “marginal” trout stream – descriptively similar to a cold-transitional stream (see “Legislation Methods” in the Methods, below) – being able to support trout, but not providing optimal conditions for spawning and continued growth (personal communication with regional experts). With this understanding, Augusta Creek was chosen as a candidate for analyzing the potential thermal impacts arising from groundwater pumping, and how these thermal impacts translate to changes in trout habitat availability. Its physical characteristics make it a "cold transitional" river type under the state's classification new water withdrawal permitting system.

METHODS

Understanding that there was a potential causal relationship between large-scale groundwater pumping and commensurate alterations in fish habitat, a weighted usable area approach (WUA) using the United States Geological Survey’s (USGS) Physical Habitat Simulation System (PHABSIM) (Waddle, 2001), which is routinely used to quantify the impact of flow variation on fish habitats (e.g., Johnson, Elliott, & Gustard, 1995), was selected. However, there is no standard methodology for using WUA in assessing the effects of groundwater withdrawals on fish habitat.

Initial Fieldwork

Temperature and Stream discharge

In 2005, temperature sensors were placed throughout the Augusta Creek watershed, upstream of the USGS gaging station (42.35N, 85.35W). The weather conditions throughout July 2005 proved to be warmer and drier than the long-term average: average daily water temperature at the downstream site was 21.6°C, 2.4°C above the modeled expected July mean temperature and average daily stream discharge was 0.628m^3/s, 0.186m^3/s below the modeled median July stream discharge. These factors were potentially good because they would allow for the testing of warm-weather, low-flow conditions on fish habitat.

Fish Diversity

Little historical fish diversity data were available for this site in the DNR's Institute of Fisheries Research’s stream data collection, especially upstream of the Michigan State University forestry station. Biological surveys were therefore conducted via backpack electrofishing during the summer of 2005 at seven sites within the length of Augusta Creek in order to determine what fish were characteristic. These surveys showed a wide variety of fish species (Table 2) inhabiting the various portions of Augusta Creek. At Lepper Road - which would become the downstream site of the final study - these fish species fell into the cold and cool water guilds of fishes (Zorn, Seelbach, & Wiley, 2002) primarily *Cottus bairdi* (mottled sculpin) and *Rhinichthys atratulus* (blacknose dace).

Due to the higher-than-average temperatures and lower-than-average stream discharge levels that characterized the summer of 2005, very few members of the coldwater guild were found (Table 2). Since the average daily maximum water temperature during July 2005 was, at some of the locations within the watershed, slightly higher than the tolerance limits of many cold-water-guild species, it was assumed that these fishes would be present during more characteristic summer temperature and stream discharge levels. Speaking with local residents confirmed the historic presence of *Salvelinus fontinalis* (brook trout) in the cooler, upstream portions of Augusta Creek, even during summer months.

Working within a Sub-basin

Following a regional groundwater modeling assessment (data not shown), an upstream section of Augusta Creek for a small-scale modeling assessment of high-capacity groundwater pumping was chosen within the upper sub-basin of Augusta Creek, with a total upstream catchment area of 49.3km^2 (19.1mi^2), whose groundwater table was not significantly affected by the greater, regional groundwater flow (Figure 1). The area of the chosen sub-basin was large enough to investigate upstream and downstream impacts from groundwater pumping conducted at a private-property scale (i.e., the scale at which management and legal decisions would be made). In addition, the diversity of fishes at Lepper Road (the downstream site) correlate well with the species determined to be "characteristic" within "cold transitional" type streams .

Channel morphology surveys were conducted within the chosen subbasin at or near road crossings in order to maximize accessibility and to overlap with temperature measurement locations. The total length of Augusta Creek within the subbasin is roughly 10 kilometers. The modeled mean July stream discharge estimates ranged from 0.356m^3/s (12.6cfs) at the upstream (Littis Road) site, 0.362m^3/s (12.8cfs) at the midstream (Hickory Road) site, and 0.585m^3/s (21.0cfs) at the downstream (Lepper Road) site. The estimated long-term base flow inputs from groundwater ranged from 0.048m^3/s (1.7cfs) upstream, 0.122m^3/s (4.3cfs) midstream, to 0.249m^3/s (8.8cfs) downstream, based on groundwater modeling (Abbas, Liao, Li, & Richard, 2010).

In order to construct a PHABSIM-based WUA model, site analyses and physical surveys of the stream cross-sections were conducted at each site. PHABSIM requires cross section morphology, slope, water surface level, and estimated stream discharge at each cross section, as well as some indication of between-cross section sinuosity. These were collected at various times throughout the study period in order to capture changes in the hydraulics of each site at different stream discharge rates.

Constructing the PHABSIM-based WUA

A PHABSIM-type model typically uses the parameters of velocity, water depth, and substrate in its end-calculation of the habitat index called "weighted useable area" (WUA), which is meant to reflect a combination of physical microhabitat quantity and quality (Waddle, 2001). Each parameter inputted into PHABSIM is individually standardized for each fish species along a habitat suitability index (HSI) scale of 0 to 1, based on each species' lifestage's reaction to changes in each parameter while attempting to keep all other parameters at optimum.

The use of HSIs in creating WUA outputs is possible due to a ready source of biological fish data available on various species, many of which were found in the biological survey of Augusta Creek. However, the scope of species of fishes with published HSIs in coldwater guild species found in Augusta Creek is limited to that of brook trout (Raleigh, 1982) and brown trout (Raleigh, Zuckerman, & Nelson, 1986), and does not include any species of sculpin. Therefore, although mottled sculpin were found during the survey, they are not modeled here. Cool water guild species are characterized using the HSIs for blacknose dace (Trial, Stanley, Batcheller, Gebhart, & Maughan, 1983), white suckers (Twomey & Nelson, 1984), and creek chubs (McMahon, 1982).

Modeling the Effects of Temperature

Since the impact of temperature changes to the available habitat of fishes were to be estimated in the model scenarios, the inclusion of this factor within the WUA estimate was critical. Based on the published HSI values for each of the species (see above), changes in suitability were calculated, utilizing the measured water temperatures. These were integrated with the PHABSIM output as a *post hoc* step, producing temperature-inclusive WUA relationships (Figure 2).

$$WUA_i = (v_i \times d_i \times S_i \times T_i)A_i$$

v_i, d_i, S_i all range from 0 to 1.

Where: WUA_i = Weighted useable area at cross-sectional segment i
v_i = Species-lifestage HSI value for velocity at cross-sectional segment i
d_i = Species-lifestage HSI value for depth at cross-sectional segment i
S_i = Species-lifestage HSI value for substrate type at cross-sectional segment i
A_i = Area of cross-sectional segment i
T_i = Species-lifestage HSI value for temperature at cross-sectional segment i

Although it is possible to examine the changes in habitat HSI and WUA using daily temperature data, generalized curves relating habitat suitability to discharge are routinely used in water flow and withdrawal permitting negotiations. Such generalized relationships with discharge can be more useful, because they remove the complications that day-to-day fluctuations can bring to a negotiation, and instead focus more on overall trends. However, recognizing that the range of temperature is likely to have a greater effect that merely a mean temperature, it was decided that upper and lower expected temperatures ought to be used, instead of the mean.

In order to create generalized flow-dendent WUA curve fort each site, generalized Additive Models (GAMs) were created for all pumping scenarios at each site using S-PLUS (S-PLUS, 2007). These models displayed a generally logarithmic relationship between stream discharge and stream temperature (data not shown). In addition, this relationship had a very low standard error at lower discharge values, due to an abundance of data points. The high-discharge region of the curves consistently a showed greater variation in the stream discharge/temperature relationship, due primarily to the relative paucity of high flow data. However, the general trend in this region appeared to be tending toward a low correlation (i.e., relatively linear with very low slope) between stream discharge and temperature.

Based on the GAMs, each stream discharge/temperature relationship was split into two sections based on discharge. Using a regression analysis on the data from each stream site, "transition zones" between the primary and secondary stages were delineated for the three sites (data not shown). Following this, Generalized Linear Models (GLMs) were constructed to produce linear equations that would model the predicted upper and lower temperature bounds (at 1 standard deviation from the mean) of the three sites.

Using these predicted upper and lower bounds, it was possible to create a generalized "envelope" response of habitat availability due to the variability of measured water temperatures at different stream discharges. In this way, it was possible to create site-specific WUA relationships that generalized a range of possible summer water temperatures (Figure 3).

Investigating the Pumping Scenarios

In order to determine the effects of groundwater pumping, changes to groundwater inputs caused by three different groundwater pumping scenarios undertaken near the midstream site were modeled. These pumping scenarios consisted of the inclusion of a high-capacity well located (A) 0km (0mi) from the stream, and (B) 1.6km (1mi) away from the stream. Based on the groundwater modeling, it was possible to determine the difference in the amount of groundwater entering the stream at each of the sites.

In these groundwater pumping scenarios, water temperature was predicted by adjusting each flow-dependent temperature curve (as described above) for thermal energy loss based on simple energy balance assumptions. The general effect was to increase the temperature response curves by an amount proportional to the pumped withdrawal rate based on the following equation:

$$K'_F = \frac{M_O K_O + M'_G K_G + \frac{E_S}{4184}}{M_O + M'_G}$$

where: E_S is total energy entering the system (Joules),
K_O is the temperature of the water (Kelvin) entering the system,
K_G is the energy of the groundwater entering the system (Joules),
K'_F is the temperature (Kelvin) of the water leaving the system,
M_O is mass (kg) of the water entering the system, and
M'_G is changed groundwater mass (kg) under each scenario.

Legislation Analysis

According to Michigan's groundwater conservation legislation, cold-transitional streams are defined as watercourses with less than 207km^2 (80mi^2) upstream catchment area and with a July mean water temperature range of 17.5C-19.5C (63.5F-67F) (Zorn, Seelbach, Rutherford, Wills, Cheng, & Wiley, 2008). The model study area falls within these classification requirements (49.3km^2 (19.1mi^2) upstream catchment area, 19.2C (66.6F) July mean temperature). Therefore, meeting the criteria of a cold-transitional stream, the state model assumes that no more than 4% of the water can be withdrawn before triggering an ARI (Hamilton & Seelbach, 2010). In addition, being of the cold-transitional stream type, no pumping will be authorized without prior agency analysis, either.

If the modeled pumping scenarios indicate a change in either the total flow yield equal to or greater than 4% or a significant change in the habitats of characteristic fishes of this stretch of Augusta Creek, it is reasonable to assume that a high-capacity pumping permit will not be issued.

FINDINGS

Streamflow Impacts Due to Pumping

Groundwater pumping diminished stream baseflow discharge at the midstream and downstream sites under both pumping scenarios (Table 3). (Note: The values for discharge are reported instead of yield. There are no differences in changes caused by pumping, since upstream catchment area remains constant for each site, regardless of pumping scenario.) At the midstream site saw the greatest overall changes, with percent changes in baseflow discharge of -7.18%, and -2.21% under Scenario A and Scenario B, respectively.

Decreases in stream baseflow discharge were also seen at the downstream site. Under Scenario A, there was a -5.30% decline. Under Scenario B, however, there was minimal change from the baseline scenario (-0.17%).

While decreases in stream baseflow discharge at the upstream site under Scenario A was minimal (-0.02%), Scenario B showed declines similar to what was seen at the midstream site under the same scenario (-2.55%).

Fish Habitat Impacts Due to Pumping

Examining the impacts to available habitat for the different fishes at the midstream site and downstream site under Scenario A (Figure 4, Figure 6) one observes that brook trout and brown trout WUAs are severely impacted by the pumping at the midstream site. The upper and lower bounds of the temperature-modeled WUAs were greatly lowered for both of these species. At the downstream site, although the upper and lower bounds of the temperature-modeled WUAs showed little change, the distribution based on the measured temperatures were much lower than in the baseline condition. However, in both sites, the WUAs of blacknose dace, creek chub, and white sucker were not greatly changed.

Under pumping Scenario B, the WUAs for brown trout and book trout, at the midstream site (Figure 5) showed declines although these impacts were not as severe as with the other pumping scenarios. Similarly, at the downstream site (Figure 7), the impacts from pumping were not severe enough to show any major difference from the baseline conditions. Similar to the other pumping scenario, blacknose dace, creek chub, and white sucker were not greatly changed under Scenario B at neither site.

Legal Analysis of the Pumping

Under the regulatory definition that a 4% pumping diminishment would be the cause for an adverse resource impact (ARI), the modeling has shown that pumping under Scenario A would prove -- upon the regulatory requirement of closer inspection for any large-scale pumping project in cold-transitional stream types -- to be an ARI under the water yield diminishment standard alone. Pumping under Scenario B would not immediately trigger an ARI based on water yield diminishment. In these cases, it should be important to examine the impacts to expected fish habitat, in addition to the water withdrawal impacts.

Examining the impact of the pumping scenarios on the habitat of those fish found in the sampling did show a large difference between the baseline condition and Scenario A at the midstream site and a smaller difference at the downstream site, corroborating the justification to deny pumping based on the diminishment of water. However, pumping under Scenario B did not show a major decline in fish habitat at the midpoint site nor at the downstream site compared to the respective baseline conditions, even for brown trout and brook trout, the species that are the most vulnerable to temperature increases caused by water withdrawals.

DISCUSSION

The results demonstrate that high-capacity water withdrawal operations are likely to have measurable impacts to steam environments both locally and several miles upstream and downstream of its location. These impacts occur at a scale that can be large enough to radically alter the habitats of fish species. Furthermore, moving the pumping operation 1.6km (1mi) away from the river still provided a signature impact to the stream, although greatly diminished compared to pumping at the stream. However, upstream and downstream effects were still able to be modeled.

One of the recognized problems of the state's groundwater model is that it may not adequately model the conditions at small scales (Zorn, Seelbach, Rutherford, Wills, Cheng, & Wiley, 2008). This could prove to be problematic for some determinations based on the automated decision tool, especially in systems that are less robust, such as cold-transitional stream systems. Fortunately, the state groundwater regulation requires that -- regardless of the size of withdrawals -- any pumping taking place in cold-transitional-type rivers and streams must undergo expert review (Hamilton & Seelbach, 2010). The case study of Augusta Creek provides an example of an examination of determining local-level groundwater conditions as well as determining the impacts of high-capacity pumping at three different distances away from the creek in an area that would fall under the designation of a cold-transitional stream.

Based both on the groundwater abstraction results together with the habitat change results, it is possible to recognize that a groundwater pumping permit would not be issued for Scenario A. This was corroborated by the expected changes in habitat that would happen to fish species under this scenario. However, an examination of only the change in water yield under Scenario B was not enough to determine whether an ARI would take place. After examining the expected changes to habitat under Scenario B, it was could be argued that no major changes to habitat would occur to the modeled species.

CONCLUSION

This work provides an example of the conducting site-specific modeling required by Michigan state law. However, there are a few caveats that need to be addressed. The first is that a WUA does not directly correlate with the statistical measurement of fish abundance that was used by the state in determining "characteristic fish" (Zorn, Seelbach, Rutherford, Wills, Cheng, & Wiley, 2008). However, by collecting site-specific information, one was able to determine the community of fishes that were expected to be found in the modeled region. This addresses the problem in a different manner by examining the effects of the pumping on the sampled fish species, one is producing a determination of changes to the habitat of those species that are known to occur in the area, as opposed to the change in relative abundance of fish species that are statistically determined to occur in an area based on state-wide metrics.

Another possible concern with this method is that it may produce a conservative estimate of temperature change. In dewatering experiments in groundwater systems, there is evidence of cumulative temperature change downstream of a water withdrawal (Nuhfer & Baker, 2004). However, in the methodology used above, each of the site's temperatures were derived as a energy-balance relationship based on measured temperature and the change in groundwater at the site due to pumping. There was no site-to-site interactions, which are within a potential range of influence that was used in the state's regulatory model (Zorn, Seelbach, Rutherford, Wills, Cheng, & Wiley, 2008). Furthermore, it must be made clear that the water discharge/temperature relationship seen in this example can be generalized to other stream settings, even those of similar size elsewhere in Michigan. Furthermore, one must not make the assumption that the water discharge/temperature relationship will continue along the same trajectory at greater levels of dewatering (i.e., below the measured and modeled limits).

Finally, neither the state's model nor the model used above assume that changes to the fundamental parameters of the model -- save from groundwater pumping -- will occur. These changes, from climatic warming to altered precipitation timing and intensity will have direct implications on parameters such as groundwater temperature and low-flow yield. Land-cover change could have impacts on the effective catchment area, especially if intra-basin water diversions occur (such as with storm sewer or waste water treatment facility discharges). However, these changes fall outside the scope of the Michigan water conservation legislation, and are therefore not considered. Recognizing that near and distant future changes to the environment will affect the fundamentals of any regulatory model ought to be an important part of regulatory analysis, especially if one wishes to examine the long-term effects of environmental laws.

TABLES

Table 1. Stream classification based on upstream drainage area and mean July water temperature. There exist no Cold large rivers in Michigan, and are therefore not included among the river classifications.

`		Drainage area		
		<80^2	80mi^2-300mi^2	>300mi^2
Mean July water temp	<63.5°F	Cold stream	Cold small river	—
	63.5°F–67.1°F	Cold-transitional stream	Cold-transitional small river	Cold-transitional large river
	67.1°F–69.8°F	Cool stream	Cool small river	Cool large river
	>69.8°F	Warm stream	Warm small river	Warm large river

Table 2 Abundance list of species caught during electrofishing at temperature collection sites throughout the upper portions of the Augusta Creek watershed. Stream class designations based on catchment basing area and fish communities. At Lepper Rd ("downstream site" in the sub-basin), stream class designation additionally based on modeled July water temperature.

Site	Stream Class at Site	Fish Caught	Number	HSI Availability
Osborne Rd	Warm stream	Bluegill	1	Yes
		Creek Chub	5	Yes
		Largemouth Bass	8	Yes
		Grass Pickerel	1	Yes
Cobb Rd	Cool stream	Creek Chub	1	Yes
		Johnny Darter	3	No
		Largemouth Bass	1	Yes
		White Sucker	1	Yes
Lepper Rd	Cold-transitional stream	Blacknose Dace	61	Yes
		Creek Chub	12	Yes
		Johnny Darter	4	No
		Mottled Sculpin	4	No
		Northern Hogsucker	4	No
		Rainbow Darter	13	No
		White Sucker	3	Yes
Luce Rd	Cold stream	Brook Trout	5	Yes
B Av (tributary)	Warm stream	Creek Chub	1	Yes
		Green Sunfish	1	Yes
45th St (tributary)	Warm stream	Largemouth Bass	16	Yes

Table 3. Baseline discharge conditions at the upstream, midstream and downstream sites in addition to the two groundwater pumping scenarios: Scenario A (0 mi away from the creek) and Scenario B (1 mi away from the creek).

	Upstream Site		**Midstream site**		**Downstream Site**	
Scenario	**Discharge (cms)**	**% change**	**Discharge (cms)**	**% change**	**Discharge (cms)**	**% change**
Baseline	0.356		0.362		0.585	
Scenario A	0.355	-0.02%	0.336	-7.18%	0.554	-5.30%
Scenario B	0.346	-2.55%	0.354	-2.21%	0.584	-0.17%

FIGURES

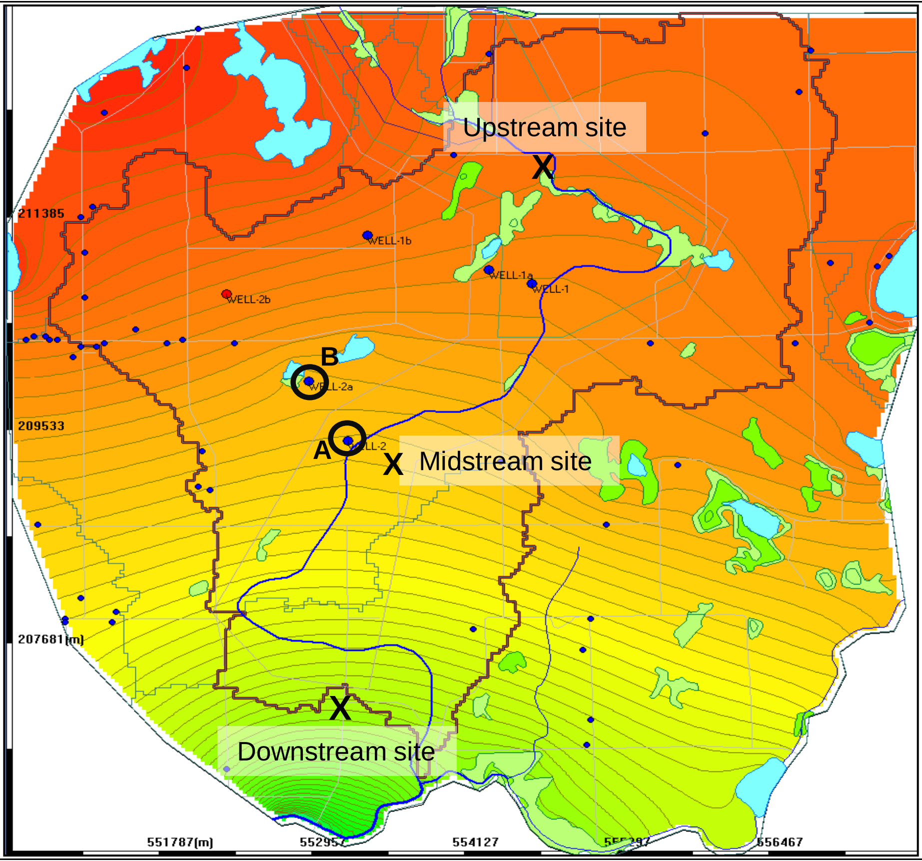

Figure 1. Location stream sites (upstream, midstream, and downstream) and modeled stream pumping (Scenario A at 0km and Scenario B at 1.6km) within the modeled sub-basin.

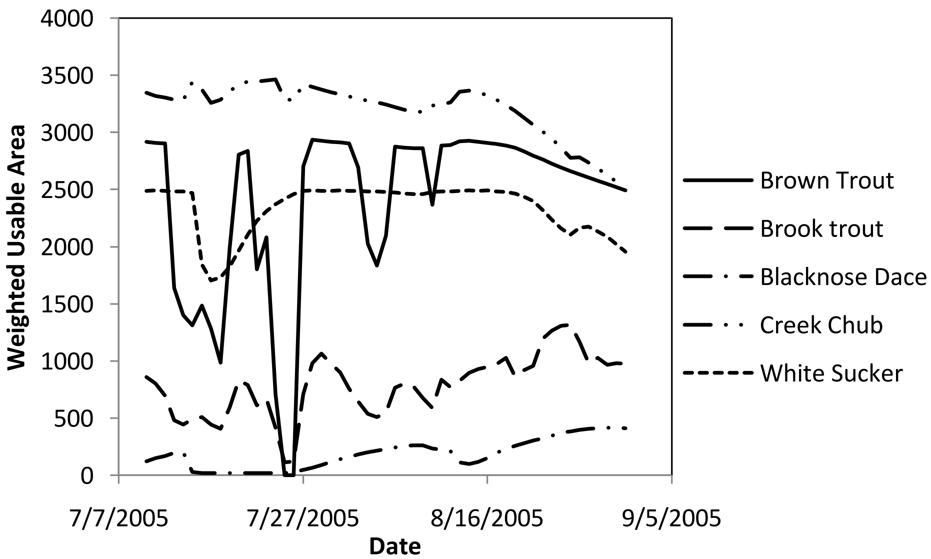

Figure 2. Example of weighted usable area curves, produced for the midstream site under baseline conditions using PHABSIM, comparing weighted usable area by date for species encountered in the area with available habitat suitability indices (HSIs).

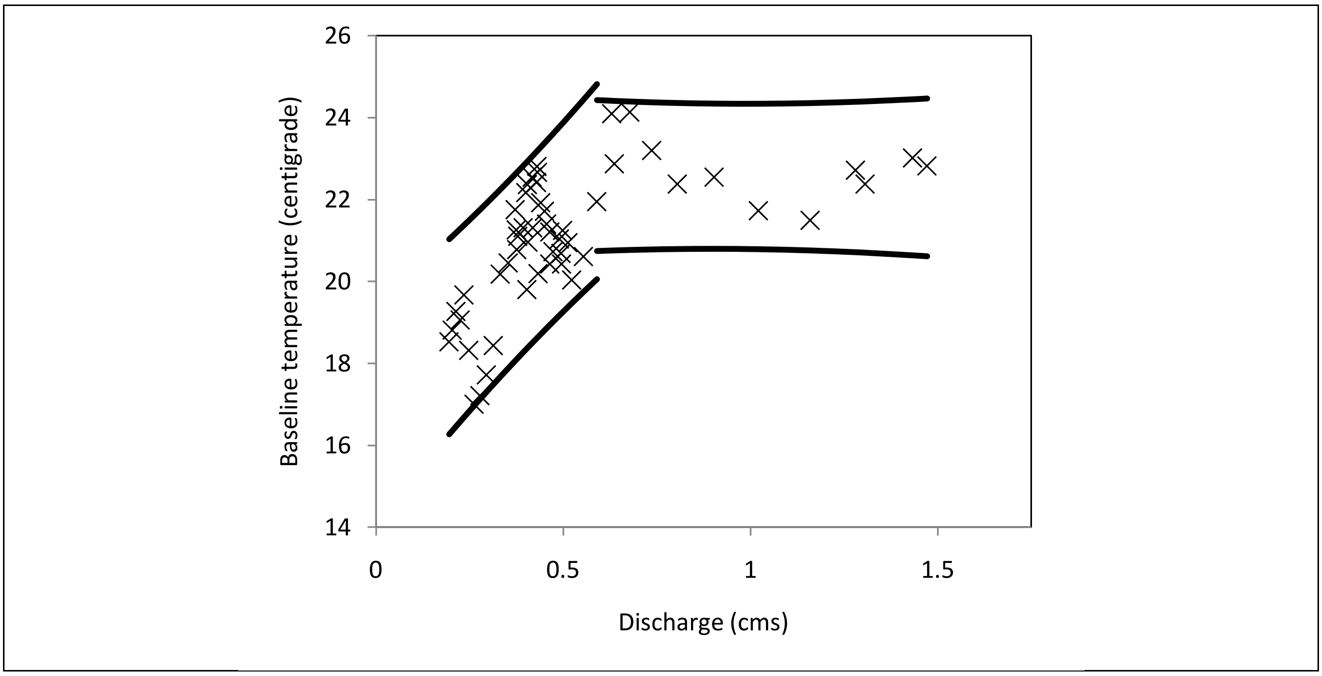

Figure 3. Example of the predicted temperature profile, produced for the midstream site for baseline conditions. Solid lines represent ±1 SD from the Generalized Linear Model of the temperature for the initial (ascending) and secondary sections of the relationship.

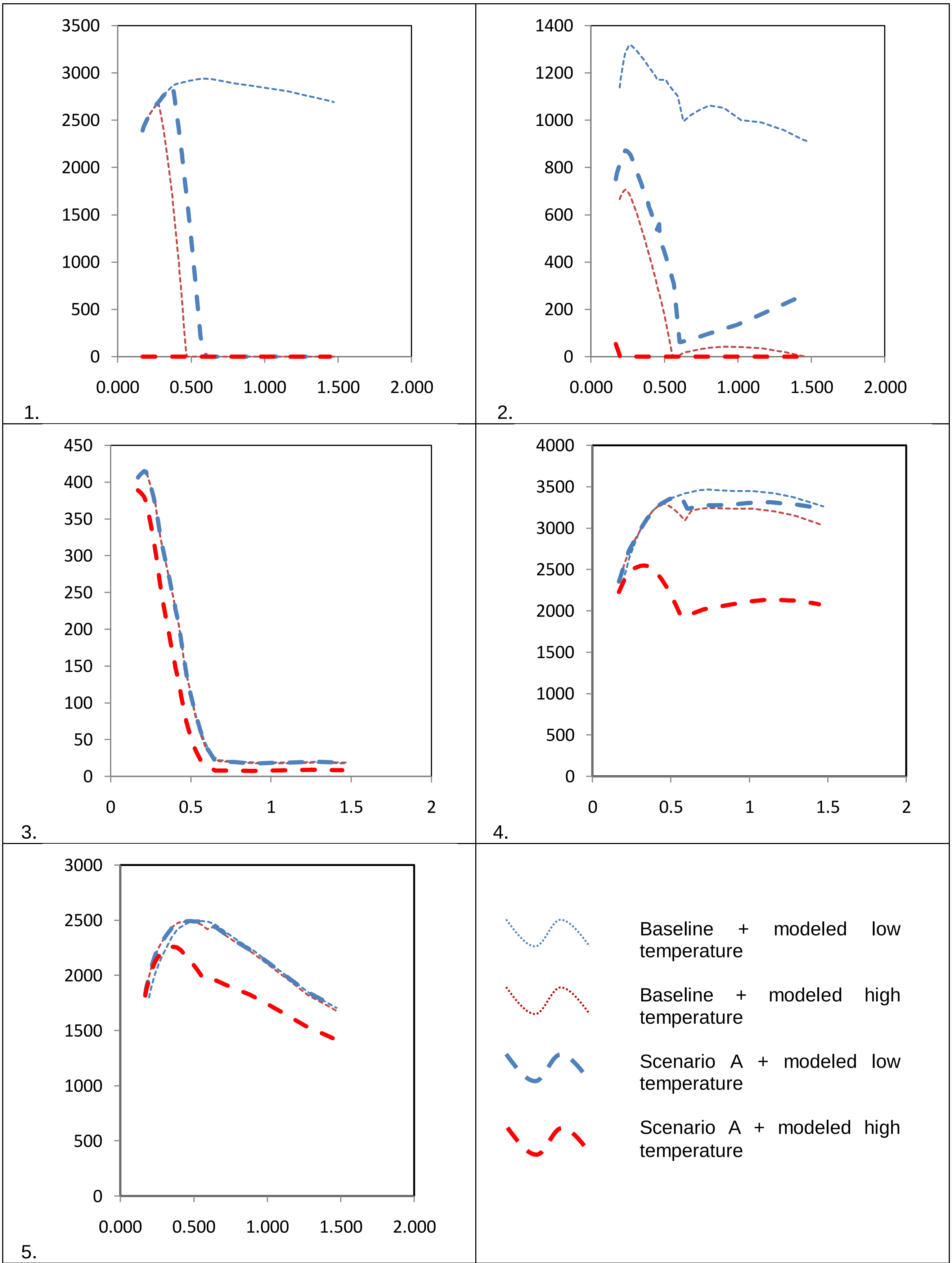

Figure 4. Stream water discharge (cms) by weighted useable area (m^2) showing the upper and lower bounded temperature-inclusive WUA curves for the midstream site under the Scenario A pumping conditions for 1) brown trout, 2) brook trout, 3) blacknose dace, 4) creek chub, and 5) white sucker.

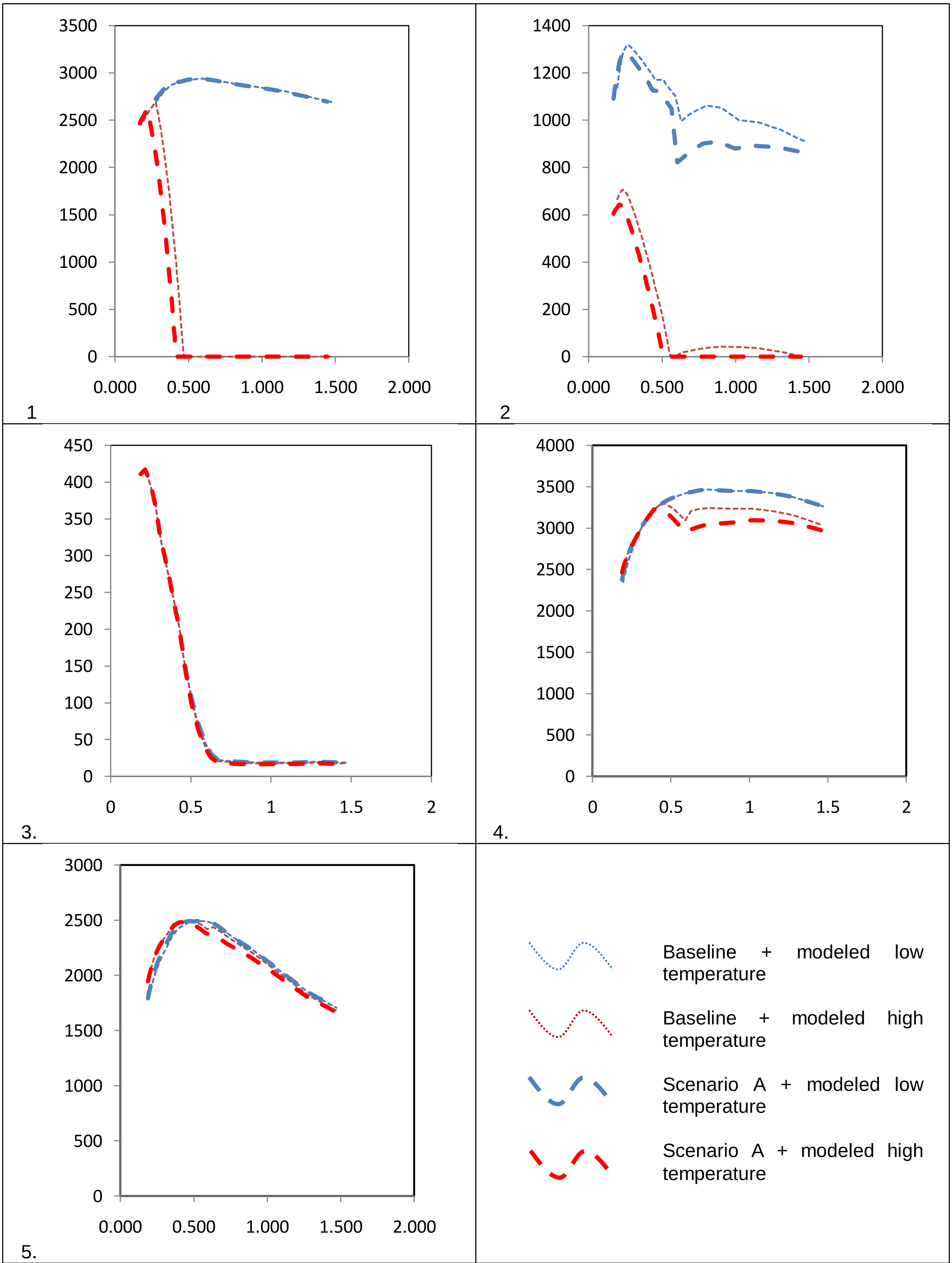

Figure 5. Stream water discharge (cms) by weighted useable area (m^2) showing the upper and lower bounds of temperature-inclusive WUA curves for the midstream site under the Scenario B pumping conditions for 1) brown trout, 2) brook trout, 3) blacknose dace, 4) creek chub, and 5) white sucker.

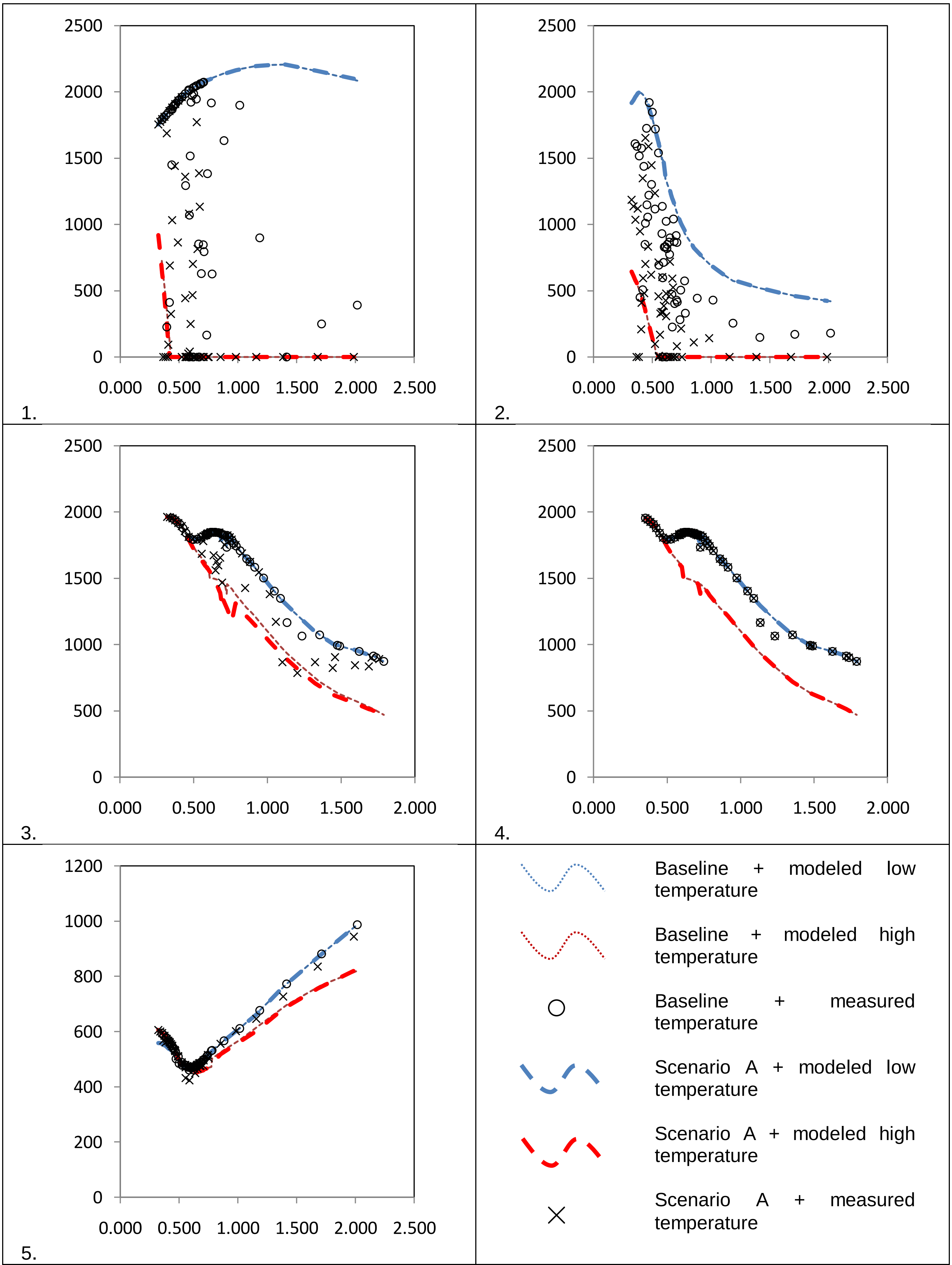

Figure 6. Stream water discharge (cms) by weighted useable area (m^2) showing the upper and lower bounds of temperature-inclusive WUA curves for the downstream site under the Scenario A pumping conditions for 1) brown trout, 2) brook trout, 3) blacknose dace, 4) creek chub, and 5) white sucker.

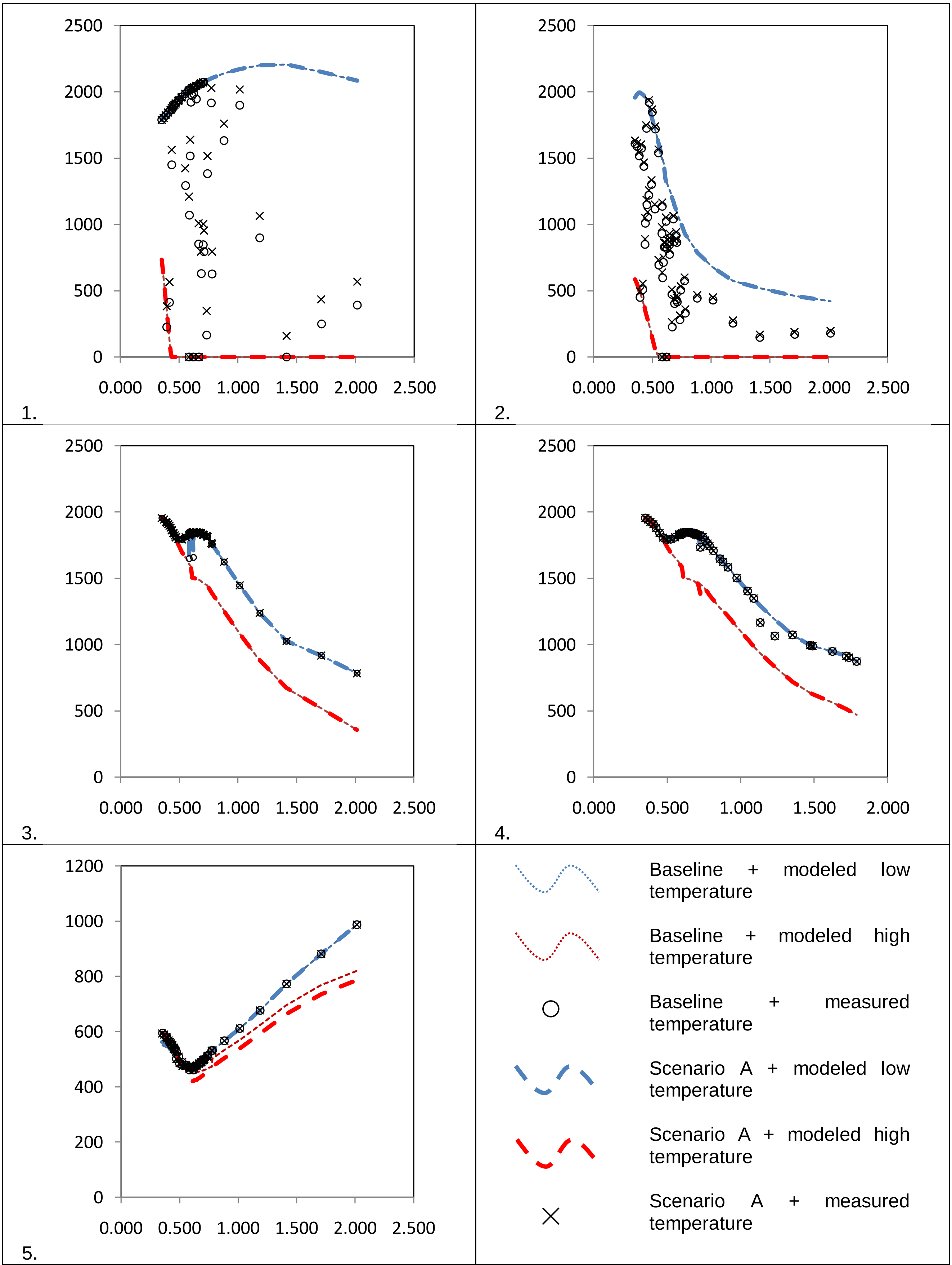

Figure 7. Stream water discharge (cms) by weighted useable area (m^2) showing the upper and lower bounds of temperature-inclusive WUA curves for the downstream site under the Scenario B pumping conditions for 1) brown trout, 2) brook trout, 3) blacknose dace, 4) creek chub, and 5) white sucker.

BIBLIOGRAPHY

Abbas, H., Liao, H., Li, S.-G., & Richard, M. (2010). Application of a GIS-enabled Modeling System to Protect Michigan's Groundwater and Groundwater Dependent Ecosystems. *AWRA 2010 Spring Specialty Conference.* Orlando.

Annan, P. (2006). *The Great Lakes Water Wars.* Washington, DC: Island Press.

Anonymous. (2006, February 22). *Public Act 33 of 2006.* Retrieved May 2011, from Michigan Legislature: http://www.legislature.mi.gov/documents/2005-2006/publicact/pdf/2006-PA-0033.pdf

Anonymous. (2006, February 22). *Public Act 34 of 2006.* Retrieved May 2011, from Michigan Legislature: http://www.legislature.mi.gov/documents/2005-2006/publicact/pdf/2006-PA-0034.pdf

Anonymous. (1985). *The Great Lakes Charter: Principles for the Management of Great Lakes Water Resoruces.* Retrieved May 2011, from Council of Great Lakes Governors, Chicago: http://www.cglg.org/projects/water/docs/greatlakescharter.pdf

Brendan, T. O., Wang, L., & Seelbach, P. W. (2008). A River Valley Segment Classification of Michigan Streams Based on Fish and Physical Attributes. *Transactions of the American Fisheries Society , 137*, 1621-1636.

Groombridge, B., & Jenkins, M. (1998). *Freshwater Biodiversity: a preliminary global assessment.* Retrieved May 2011, from http://quin.unep-wcmc.org/resources/publications/freshwater/index.html

Hamilton, D. A., & Seelbach, P. W. (2010). *Determining Environnmental Limits to Streamflow Depletion Across Michigan.* Lexington: The Council of State Governments.

Johnson, I. W., Elliott, C. R., & Gustard, A. (1995). Modelling the effect of groundwater abstraction on salmonid habitat availability in the river Allen, Dorset, England. *River Research and Applications , 10* (2-4), 229-238.

McMahon, T. E. (1982). *Habitat Suitability Index Models: Creek Chub.* FWS/OBS-82/10.4, Fish and Wildlife Service, US Department of the Interior.

Nuhfer, A. J., & Baker, E. A. (2004). *A Long-term Field Test of Habitat Change Predicted by PHABSIM in Relation to Brook Trout Population Dynamics During Controlled Flow Reduction Experiments.* Fisheries Division, Deparment of Natural Resources. Ann Arbor: State of Michigan.

Raleigh, R. F. (1982). *Habitat Suitability Index Models: Brook Trout.* FWS/OBS-82/10.24, Fish and Wildlife Service, US Department of Interior.

Raleigh, R. F., Zuckerman, L. D., & Nelson, P. C. (1986). *Habitat Suitability Index Models and Instream Flow Suitability Curves: Brown Trout, Revised.* FWS/OBS-82/10.71, Fish and Wildlife Service, US Department of Interior.

Seelbach, P. W., Wiley, M. J., Kotanchik, J. C., & Baker, M. E. (1997). *A Landscape-Based Ecological Classification System for River Valley Segments in Lower Michigan (MI-VSEC Version 1.0).* Fisheries Division, Department of Natural Resources. Ann Arbor: State of Michigan.

S-PLUS. (2007). version 8. Seattle, Washington: Insightful Corporation.

Steinman, A. D., Nichols, J. R., Seelbach, P. W., Allan, J. D., & Ruswick, F. (2011). Science as a Fundamental Framework for Shaping Policy Discussions Regarding the Use of Groundwater in the State of Michigan: A Case Study. *Water Policy , 13*, 69-86.

Trial, J. G., Stanley, J. G., Batcheller, M., Gebhart, G., & Maughan, O. E. (1983). *Habitat Suitability Information: Blacknose Dace.* FWS/OBS-82/10.41, Fish and Wildlife Service, US Department of Interior.

Twomey, K. A., & Nelson, P. C. (1984). *Habitat Suitability Index Models and Instream Flow Suitability Curves: White Sucker.* FWS/OBS-82/10.64, Fish and Wildlife Service, US Department of Interior.

Waddle, T. (2001). *PHABSIM for Windows.* US Geological Survey.
Zorn, T. G., Seelbach, P. W., & Wiley, M. J. (2002). Distributions of Stream Fishes and their Relationship to Stream Size and Hydrology in Michigan's Lower Peninsula. *Transactions of the American Fisheries Society , 131* (1), 70-85.
Zorn, T. G., Seelbach, P. W., Rutherford, E. S., Wills, T. C., Cheng, S.-T., & Wiley, M. J. (2008). *A Regional-scale Habitat Suitability Model to Assess the Effects of Flow Reduction on Fish Assemblages in Michigan Streams.* Fisheries Division, Department of Natural Resources. Ann Arbor: State of Michigan.