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ARTICLE

Abiotic Habitat Assessment for Arctic Grayling in a Portion of the Big Manistee River, Michigan

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Abstract

Arctic Grayling *Thymallus arcticus* were once the dominant salmonid in the Big Manistee River, Michigan, but were extirpated from the watershed around 1900 and from the state of Michigan by 1936, likely due to overfishing, biotic interactions with introduced fish species, and habitat loss occurring largely around the turn of the 20th century. An interest in reestablishing native species by the Little River Band of Ottawa Indians led to an assessment of environmental conditions in a portion of the watershed encompassing 21 km of the Big Manistee River to determine whether suitable Arctic Grayling habitat remains. During summer in 2011–2013, abiotic habitat metrics, including water characteristics, substrate composition, channel profile, channel geomorphic unit, and stream velocity, were assessed across eight tributaries within the watershed. To assess whether abiotic conditions in these tributaries might support Arctic Grayling, the environmental conditions were compared to literature values from rivers where current or historical Arctic Grayling populations have been reported. This comparison, in conjunction with an assessment using a habitat suitability index for Arctic Grayling, indicated that important abiotic conditions were within ranges consistent with those associated with current and past populations of Arctic Grayling in North America. The results of this study will guide potential future reintroductions and indicate that suitable Arctic Grayling habitat does exist in portions of the Big Manistee River watershed, an assessment that will be further refined when coupled with biotic features of the environment.

The Arctic Grayling *Thymallus arcticus* was the dominant salmonid in most of Michigan's Lower Peninsula following the last glaciation event (Leonard 1949); Arctic Grayling and Brook Trout *Salvelinus fontinalis* were the only native salmonids in the state with fully fluvial populations. However, throughout their broader distributions, both species are known to display both fluvial and adfluvial migratory life histories (Scott and Crossman 1973). Throughout the second half of the 19th century, Arctic Grayling numbers likely declined as a result of habitat loss due to landscape changes (e.g., logging), overfishing, and interactions with introduced fish species (Creaser and Creaser 1935; Leonard 1949; Fukano et al. 1964) such that most of the Arctic Grayling in the Lower Peninsula disappeared by 1900 and the remaining Michigan population (Otter River in the Upper Peninsula) was extirpated by 1936 (McAllister and Harington 1969). Attempts to reestablish Arctic Grayling in Michigan occurred in the 20th century, although there have been no reported indications of sustained success (Nuhfer 1992). In the most recent attempt (1987–1991), the Michigan Department of Natural Resources

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(MDNR) stocked Arctic Grayling into seven rivers and streams in the Upper and Lower peninsulas; these isolated rivers were purported to support salmonids and had few other fish species as potential competitors or predators (Nuhfer 1992). Despite these efforts, Nuhfer (1992) reported that water temperature, competition with other salmonids, and mixed fluvial and adfluvial migratory strategies of the source populations were likely the primary reasons for the disappearance of fluvially stocked Arctic Grayling. However, some mortality was attributed to a bacterial infection (furunculosis) and parasitism by Chestnut Lampreys *Ichthyomyzon castaneus*. Although populations of Arctic Grayling have been absent from Michigan waters for nearly a century, they remain a part of Aníšhinaábek ancestral heritage. The Little River Band of Ottawa Indians (LRBOI) and the MDNR both maintain a continued interest in native species restoration and have partnered to revive efforts to reestablish this culturally important fish to local waters.

As with many rivers in North America, the Big Manistee River in Michigan has undergone considerable physical and biological alterations over the past century. In addition to extensive past logging in the region, two hydroelectric dams that act as barriers to migration have impounded the Big Manistee River. Native species such as the Arctic Grayling have been replaced by intentionally introduced salmonids (Brown Trout *Salmo trutta*, Rainbow Trout *Oncorhynchus mykiss*, Coho Salmon *O. kisutch*, and Chinook Salmon *O. tshawytscha*) and by Brook Trout, which have exhibited both natural and assisted range expansions.

Globally, Arctic Grayling are distributed throughout the freshwater drainages of northern Siberia (Eurasia), Alaska, and northwestern Canada (USFWS 2010). Glacial relict populations exist further south in the upper Missouri River drainage, albeit occupying a small portion of their historic range (Byorth and Magee 1996; Magee 2002). The Arctic Grayling is considered a coldwater species, with an optimal water temperature below 16°C (see Hubert et al. 1985) and lethal temperatures above 25°C (Lohr et al. 1996). Sensitivity to and lethality of water temperature appear to be dependent on factors such as geographic location of populations, acclimation, and local adaptation (Nelson 1954; LaPerriere and Carlson 1973; Lohr et al. 1996).

Fluvial and adfluvial Arctic Grayling spawn in rivers during spring when water temperatures are typically between 2°C and 10°C (see Hubert et al. 1985). Spawning habitat is characterized by substrates with abundant interstitial spaces along the margins between riffles and pools (Nelson 1954; Bishop 1971), although successful spawning has been observed in reaches with finer substrates (Vincent 1962). Arctic Grayling migrate after spawning and typically occupy deep pools throughout the summer, where they feed on drifting invertebrates along the margins between pools and riffles (Krueger 1981; Hughes 1992). During the fall, fluvial populations of Arctic Grayling have been noted to migrate to rivers with areas that do not freeze (Krueger 1981; Byorth 1991; West et al. 1992), where they remain throughout the winter months. Although regionally variable and ultimately dictated by the distance between summer and winter habitats, this spring and fall migration has been known to take place over long distances for some populations (Nelson 1954; Lamothe and Magee 2004a).

Guided by information on Arctic Grayling life history and observed habitat characteristics of other extant North American populations (Table 1), we surveyed aspects of the current habitat conditions in Big Manistee River tributaries as well as some regions of the main stem from 2011 to 2013 to assess their suitability for the reestablishment of Arctic Grayling. In addition, we used the habitat suitability index (HSI) model developed by Hubert et al. (1985) for fluvial Arctic Grayling to further evaluate our data. Habitat suitability index models were developed for numerous species in the 1970s and 1980s by the U.S. Fish and Wildlife Service to evaluate observed habitat conditions relative to what are believed to be optimal conditions based on best available information. Likely due to the species' limited distribution, the HSI model for Arctic Grayling has not been widely tested.

Successful reintroduction and establishment of Arctic Grayling in the Big Manistee River will depend on availability of suitable abiotic habitat as well as the biotic aspects of the environment (e.g., competition and predation). The work presented here focuses on abiotic aspects of potential Arctic Grayling needs, whereas information on biotic interactions will be handled in a separate publication.

STUDY AREA

The Big Manistee River originates in the north-central Lower Peninsula of Michigan and flows 373 km before emptying into Lake Michigan (Figure 1). With a drainage area of over 5,000 km^2, the Manistee River watershed is one of the largest in the state of Michigan (Rozich 1998), and much like the neighboring Au Sable River, it is known to have a stable flow throughout the year due to groundwater inputs, which account for over 90% of base flow in some areas (Holtschlag and Nicholas 1998). We assessed the abiotic conditions in a portion of the watershed encompassing a 21-km length of the Big Manistee River (eastern Manistee County) between Hodenpyl Dam and the upstream limits of Tippy Dam Pond (Figure 1). Eight tributary streams and the main stem of the Big Manistee River (hereafter, "main stem") between these two dams were selected due to multiple factors indicating that these waters had a high potential to support coldwater fish populations. Records indicate that this region of the Big Manistee River watershed supports salmonid populations, has low levels of upland development, has extensive federal ownership, and limits the upriver migration of potential competitors and predators of Arctic Grayling (Rozich 1998; LRBOI,

TABLE 1. Range in observed abiotic characteristics of Arctic Grayling habitat. Data are based on a literature review and represent values observed in systems that were reported to support Arctic Grayling.

Habitat metric	Reported literature values	References[a]
	Adult habitat metrics	
Temperature (°C)	2.7–22.0	2, 3, 4, 8, 9, 14, 18
Dissolved oxygen (mg/L)	1.3–12.6	4, 6, 8, 9, 10, 15, 17
pH	5.9–8.5	1, 7, 9, 15, 17
Water velocity (m/s)	0.1–0.9	3, 6, 9, 12, 13,14, 18
Channel width (m)	3.0–60.0	1, 2, 9, 14, 17, 20
Water depth (m)	0.3–2.8	2, 3, 9, 15, 17, 20
Longitudinal gradient (%)	0.08–2.0	3, 7, 9, 12, 14, 16, 18
Pool : riffle ratio	0.3–1.5	9
Substrate composition	Coarse sand–large pebble	3, 6, 9, 13
Fine substrate (%)	<10–30	1, 8, 9, 11, 13
Median substrate size (mm)	4.0–89.0	19
Spawning substrates	Coarse sand–large pebble	1, 6, 11
Spawning velocity (m/s)	0.1–1.46	6, 8, 11, 13
	Age-0/juvenile habitat metrics	
Temperature (°C)	4.5–17.3	13, 19
Water velocity (m/s)	0.04–0.78	6, 12, 16, 17
Water depth (m)	0.1–0.4	12, 17
Substrate	Large gravel–pebble	12

[a] (1) Nelson 1954; (2) Taylor 1954; (3) Vincent 1962; (4) Feldmeth and Eriksen 1978; (5) Elliot 1980; (6) Krueger 1981; (7) Bruce and Starr 1985; (8) Hubert et al. 1985; (9) Liknes and Gould 1987; (10) Kane et al. 1989; (11) Shepard and Oswald 1989; (12) McMichael 1990; (13) Northcote 1993; (14) Byorth and Magee 1998; (15) Barndt and Kaya 2000; (16) Cowie and Blackman 2003; (17) Jones et al. 2003; (18) Blackman 2004; (19) Dion and Hughes 2004; and (20) Lamothe and Peterson 2007.

unpublished data). Previous work has also determined that two rivers (the Little Manistee and Pine rivers) in the watershed have habitat conditions that are suitable for Arctic Grayling (Tingley 2010). In addition, these waters are of great interest to the LRBOI as potential habitat for native species restoration due to their proximity to tribal land.

Sampling sites were chosen in lower, middle, and upper reaches of each tributary (a total of 22 sites among the eight tributaries), representing a range of abiotic conditions in this part of the watershed, and site selections were based on accessibility and proximity to the tributary confluences. Site lengths were set to 40 times the mean wetted channel width (Kaufmann et al. 1999), or a minimum length of 120 m for sites less than 3 m wide, and ranged from 120 to 325 m.

METHODS

Water temperature.—Data from 2009 to 2013 (2009 and 2010 hourly temperature logger data provided by LRBOI) were used to examine July temperatures, which have been determined to represent the warmest months for Michigan streams (Hinz and Wiley 1997). In 2011, water temperature loggers (Onset HOBO v2, accuracy = ±0.21°C from 0°C to 50°C; Onset HOBO U20, accuracy = ±0.37°C at 20°C) were deployed in each of the tributaries and the main stem and recorded the temperature (0.1°C) hourly. Temperature loggers were located near each of the study sites for half of the tributaries; however, for Arquilla, Cedar, Sand, and Slagle creeks, loggers were deployed at only the downstream and/or midstream study sites (Figure 1). Some temperature loggers were lost; therefore, Peterson, Slagle, and Woodpecker creeks were the only tributaries with 5 years of data (Figure 2). In addition to the tributaries, two large pools in the main stem were selected to determine (1) the extent to which water temperature varied between upstream and downstream reaches during summer 2011 and (2) whether the selected pools exhibited a thermal gradient (i.e., cooler temperatures with increasing depth) and thus potential thermal refuge for Arctic Grayling. Tethered temperature loggers (one at the bottom and one in mid-water-column) were deployed at the deepest part of each pool and recorded water temperatures hourly throughout July. Additional hourly temperature logger data for the Big Manistee River main stem were provided by LRBOI for the Red Bridge River Access Site (Figure 1) and were downloaded from U.S. Geological Survey (USGS) gauging station 04124200, located just downstream of Hodenpyl Dam. Temperature data from the Big Manistee

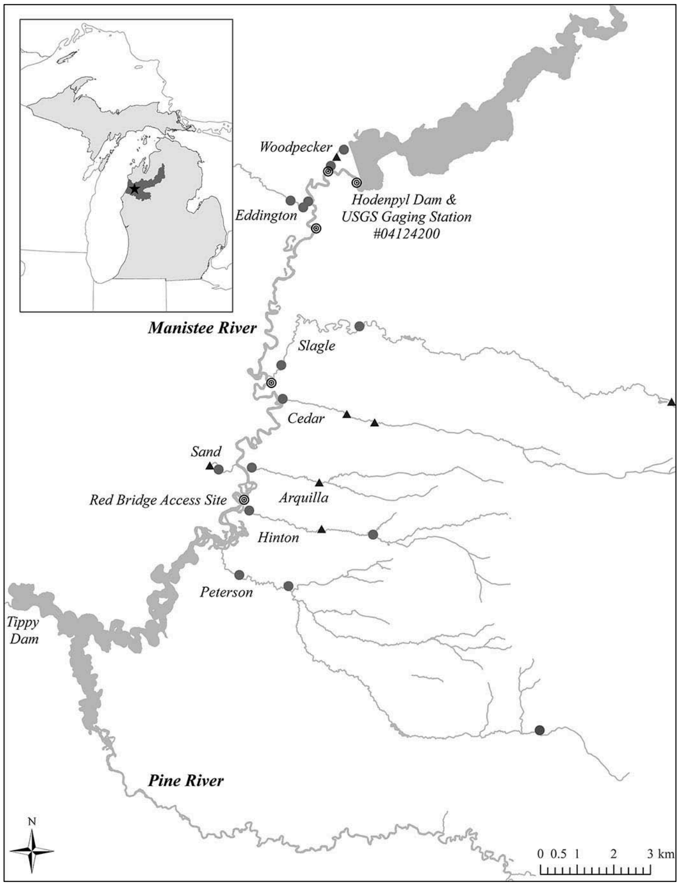

FIGURE 1. Study sites and temperature logger locations in the Manistee River system, Michigan. Solid black triangles represent study reaches without temperature loggers; solid gray circles represent study reaches with temperature loggers. Bullseyes represent locations of temperature loggers and the U.S. Geological Survey (USGS) gauging station in the main stem of the Big Manistee River.

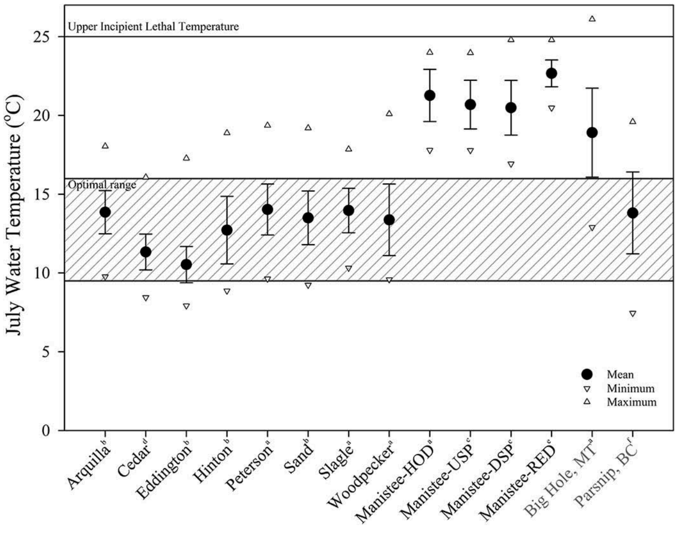

FIGURE 2. Mean (±SD), maximum, and minimum hourly observed July water temperatures for tributaries and the main stem of the Big Manistee River (HOD = Hodenpyl Dam; USP = upstream pool; DSP = downstream pool; RED = Red Bridge Access Site) and for western North American rivers with existing populations of Arctic Grayling (range in data: a = 2009–2013; b = 2010–2013; c = 2011; d = 2011–2013; e = 2012; f = 2012–2013). The upper line represents the upper incipient lethal temperature (Lohr et al. 1996) of 25°C. The shaded area represents the range reported as optimal for Arctic Grayling growth (9.5–16°C; Hubert et al. 1985).

River and its tributaries were compared to data reported for river and stream temperatures where Arctic Grayling historically existed and/or currently exist.

To assess conditions where tributaries discharge into the main stem and to identify potential thermal microhabitats (i.e., potential refugia), temperature loggers were deployed upstream and downstream of the confluences of Woodpecker and Slagle creeks in June 2013. Loggers were placed in the main-stem channel along the tributary input bank directly upstream and approximately 33 and 66 m downstream of each confluence. These loggers recorded water temperature at 5-min intervals throughout July and were retrieved during the second week of August 2013.

Longitudinal surface water temperature profiles of the Big Manistee River at its confluence with the six tributaries were measured once in July 2013 to explore the influence of tributary influx on main-stem water surface temperatures. A tethered logger attached to a float recorded temperatures at 1-s intervals as it drifted with the current in the main stem from immediately upstream of the tributary input to a maximum distance of 91 m downstream of the tributary. Float duration ranged from 120 to 657 s (median = 337 s) depending on river current. Slagle Creek was excluded due to limited access during sampling; Peterson Creek was excluded because sufficient flow was not detected at the confluence, likely because the creek flows into the main stem via a backwater area of Tippy Dam Pond.

Substrate.—Streambed substrate composition was quantified by using a modified Wolman pebble count to characterize substrate size and structure in 2011 and 2012 (Wolman 1954) and by using the bulk shovel method to characterize percent fine substrates in 2012 (Hames et al. 1996). For the pebble counts, each site was divided into 100 equally spaced longitudinal transects (every 1–3 m depending on total site length), and a point along each transect was randomly generated based on a percentage of the total wetted width (i.e., percentages in 10% increments starting from the left bank). At each of these points, a substrate particle was arbitrarily drawn from the channel and measured along its intermediate axis. For each particle location, we recorded the water depth and channel geomorphic unit (CGU) mesohabitat type, including pools (topographic low points with deep, slow-flowing water), riffles (topographic high points with shallow, fast-flowing, turbulent water), and runs (nonturbulent, fast-flowing water;

Hawkins et al. 1993), where each substrate particle was collected. Substrate size distributions and the median particle diameter (D_{50}) were calculated for each tributary. The percentages of substrate particles that were gravel or pebbles (>2–256 mm) or smaller than 2 mm (i.e., sands, silts, or clays) were also calculated.

The shovel-based method (Hames et al. 1996) was used to approximate the percentage of fine particles (0.25–2.0 mm) in a bulk substrate sample collected with a number-2 round-point shovel. Samples were collected at the downstream, middle, and upstream locations within riffles and runs unless longitudinal CGU lengths were less than 5 m, in which case samples were collected in the middle of the CGU. A portable stilling well (see Hames et al. 1996) was placed at the upstream side of each sample location to divert stream current and minimize loss of particles from the sample. Volume of each bulk sample was measured by water displacement after being placed into a measuring bucket containing a known volume of water (3.0 L). After the volume of the total bulk sample was determined, the sample was rinsed through a series of 2-mm and 0.25-mm stacked sieves to separate the coarse (<2 mm) from the fine (0.25–2.0 mm) substrate. The volume of the fine material was then measured by displacement, and the percent fine substrate was calculated as the ratio of the volume of fine materials relative to the total initial bulk volume.

Water characteristics.—Dissolved oxygen (DO) concentration, pH, temperature, and turbidity were collected at the upper, middle, and lower regions of each study site in June, July, and August of 2011 and 2012 (2011–2013 for Hinton and Woodpecker creeks; Hydrolab DS5 Multiparameter Sonde, Hach Hydromet; accuracy = ±0.1–0.2 mg/L for DO, ±0.2 units for pH, ±0.1°C for temperature, and ±1% NTU for turbidity). For each measurement, the Hydrolab Sonde was placed in the channel and allowed to equilibrate prior to recording measurements. Water characteristics were measured prior to any other sampling (e.g., pebble counts) and began at the downstream end of each site to minimize the effects of walking in the channel. Additionally, DO data for the main stem were acquired from USGS gauging station 04124200 for the Big Manistee River at Hodenpyl Dam.

Velocity.—Stream velocities (m/s) were estimated in early summer (May–June), midsummer (June–July), and late summer (July–August) at each study site during base flow conditions. Calculated velocities were averages from three perpendicular transects (upstream, midstream, and downstream) at each site. Along the three transects, water depth and velocity at 60% of total depth were measured at 10 equally spaced points (Rantz 1982) by using a Marsh–McBirney Flo-Mate (Hach; accuracy = ±2%). Mean velocity for each site on a given sampling date was estimated as the mean of the upstream, midstream, and downstream measurements. Discharge was also estimated at these transects following methods similar to those outlined by Gallagher and Stevenson (1999). In addition, during May and June 2012, velocity data with a higher spatial resolution were collected at each of the sites. Water depth and velocity at the bottom (100%) and at 60% of total depth were measured at four equally spaced points (i.e., 20, 40, 60, and 80% across wetted width from the left bank) along longitudinal transects spaced approximately 2 m apart. The number of transects for each site depended on total site length and ranged from 56 to 146 transects.

Channel morphology.—To quantify habitat within the tributaries and compare with conditions for Arctic Grayling habitat reported in the literature, a longitudinal profile map of physical measurements within CGUs was developed for each site using field measurements analyzed in ArcMap version 10.1 (ESRI) and CGU classifications based on Hawkins et al. (1993). In 2011, the longitudinal length of each CGU was measured to the nearest 0.1 m with a hip chain (Forestry Suppliers, Inc.; accuracy = ±0.2%) while walking upstream following the midpoint of the channel. A similar method was employed in 2012 using a handheld GPS unit to mark a waypoint at the transition of each classified CGU. Additionally, in 2012, surface area (m^2) and mean water depth (m) were estimated for each of the study sites. Wetted width and depth were measured at six equally spaced points (i.e., 0, 20, 40, 60, 80, and 100% of wetted width) along transects spaced every 2 m beginning at the downstream end of each study site. Wetted width measurements from each transect were combined in ArcMap version 10.1 to create polygons of river surface area. The CGU classifications based on the longitudinal GPS survey were then applied to each polygon, yielding an approximate surface area (m^2) for each pool, riffle, and run. The resulting values were used to estimate the total percentage of each CGU type based on surface area (i.e., 100 × [total surface area of each CGU]/[total surface area of the reach]).

Arctic Grayling habitat conditions.—An extensive literature review was conducted to establish a range of abiotic conditions associated with extinct and extant populations of Arctic Grayling in North America (Table 1). Current abiotic conditions in Big Manistee River tributaries were then compared to these data to determine whether the tributaries might provide suitable habitat for reintroduced Arctic Grayling. Most of the data from the literature review came from extant populations in Alaska, Montana, and Canada, although some information describing conditions that may have existed in Michigan prior to the Arctic Grayling's extirpation was available (Vincent 1962). Literature values used to develop Table 1 represent a broad range of what has been reported for locations where Arctic Grayling currently exist and may not necessarily be the "optimal" conditions.

Habitat suitability index.—Comparing the current habitat conditions in the Big Manistee River watershed to systems where Arctic Grayling are known to exist is an important first step in determining which tributaries have the greatest potential as Arctic Grayling habitat. However, it does raise the question of exactly how "suitable" a particular stream might be or what factors may be limiting. To address this question, the HSI model developed by Hubert et al. (1985) was applied to each of the tributary reaches. The HSI evaluates the suitability of habitat based on 10 variables (V1–V10) divided into two categories. Variables 1–6 represent the suitability of habitat conditions for spawning and juvenile Arctic Grayling (category A1), whereas V7–V10 represent the suitability of habitat conditions for adults (category A2). Each of the variables is assigned a score from 0 to 1 based on curves developed to estimate how suitable they are for Arctic Grayling. For each category (A1 and A2), the lowest score is assigned as the overall score. For example, if V7, V8, and V9 for the adult stage (A2) all score between 0.5 and 1.0 but V10 scores a 0.1, then the score for category A2 is 0.1. The overall HSI score is similar in that it is the lowest value observed for categories A1 and A2. One benefit of allocating the variables to categories for adult and juvenile stages is the ability to determine (1) the life stage to which a particular site is best suited; and (2) which abiotic factor is most likely to be limiting.

RESULTS

Water Temperature

Across all years and tributaries in this study, mean (±SD) July water temperature ranged from 10.5 ± 1.2°C (Eddington Creek) to 14.0 ± 1.6°C (Peterson Creek) and was within the overall range reported in the literature (see Table 1) and the temperature range proposed as optimal for Arctic Grayling growth (Figure 2; Hubert et al. 1985). Across all years, the maximum hourly temperature recorded in July ranged from 16.1°C in Cedar Creek to 20.1°C in Woodpecker Creek. The main-stem Big Manistee River upstream at Hodenpyl Dam (based on data from the USGS gauging station) averaged 21.3 ± 1.7°C (range = 17.8–24.0°C) from 2009 to 2013, while the downstream Red Bridge Access Site averaged 22.7 ± 0.9°C in 2012. The upstream and downstream main-stem pool locations differed by less than 0.2°C during July 2011. A slight thermal difference was observed between bottom and mid-water-column temperature logger locations of the upstream (difference = 0.5°C) and downstream (difference = 1.1°C) main-stem pool (LRBOI, unpublished data), indicating that the water column at these locations was mostly mixed and that influence by groundwater may not have been strong enough to detect. From main-stem temperature loggers, the maximum observed July surface temperature was 24.8°C, and the July average was 21.1 ± 1.7°C.

Data from temperature loggers deployed above and below the confluence of Slagle Creek in July 2013 indicated that the tributary created a plume of cool water downstream of the confluence (Figure 3). The main-stem mean (±SD) temperature above Slagle Creek was 8.0 ± 1.2°C warmer than the main-stem temperature 33 m downstream of the confluence and was 1.0 ± 0.2°C warmer than the temperature 66 m downstream of the confluence (Figure 3). Big Manistee River water temperature 33 m downstream of Slagle Creek appeared to closely track the daily mean temperatures observed in Slagle Creek over the same timeframe (Figure 3). Differences in water temperature upstream and downstream of Woodpecker Creek were small, with a maximum difference of 0.3°C except for an apparent anomaly in the data between July 8 and 13 from the location 33 m downstream of the Woodpecker Creek confluence, where the temperature logger may have become exposed to the air (Figure 3).

Drifting a tethered temperature logger down the main stem past tributary confluences also revealed reductions in surface water temperatures at the mouths of Eddington, Hinton, Arquilla, and Woodpecker creeks and less-pronounced temperature reductions at Sand and Cedar creeks (Figure 4). The maximum temperature differentials across confluences were measured at Woodpecker Creek (7.1°C) and Eddington Creek (6.8°C), and the minimum temperature differential was measured at Sand Creek (0.6°C). Distance traveled by the temperature logger also varied between tributaries and ranged from less than 5 m to 91 m depending on local water velocity (Figure 4).

Substrate

All of the tributaries surveyed in 2011 and 2012 had dominant substrates that fell within the ranges reported for Arctic Grayling (see Table 1). In addition, all tributaries except Sand Creek had substrates with over 20% pebble/gravel-sized particles (>2–256 mm), which have been reported as important for Arctic Grayling spawning habitat (Hubert et al. 1985). Percent coarse substrate (i.e., gravel/pebble) ranged from less than 10% in Sand Creek to over 60% in Arquilla Creek (Table 2). The D_{50} ranged from sand (2 mm) in Sand and Peterson creeks to pebbles (4–64 mm) in Arquilla Creek (Table 2).

Across all tributaries in 2012, percent fines (0.25–2.0 mm) in a bulk shovel sample was greater in runs than in riffle habitat (one-way ANOVA: $F_{7,\ 8} = 6.87$, $P < 0.01$). Mean (±SD) percent fines in riffles ranged from 29.4 ± 10.1% in Arquilla Creek to 48.4 ± 7.3% in Eddington Creek (Table 2). Mean percent fines in all tributary riffles were below the percentage suggested as the upper suboptimal level of ≥50% for Arctic Grayling spawning habitat, as reported by Hubert et al. (1985).

Water Characteristics

In 2011 and 2012 (2011–2013 for Hinton and Woodpecker creeks), our measurements of pH, turbidity, and DO in tributaries did not differ greatly throughout this portion of the watershed (Table 2). All Big Manistee River study tributaries

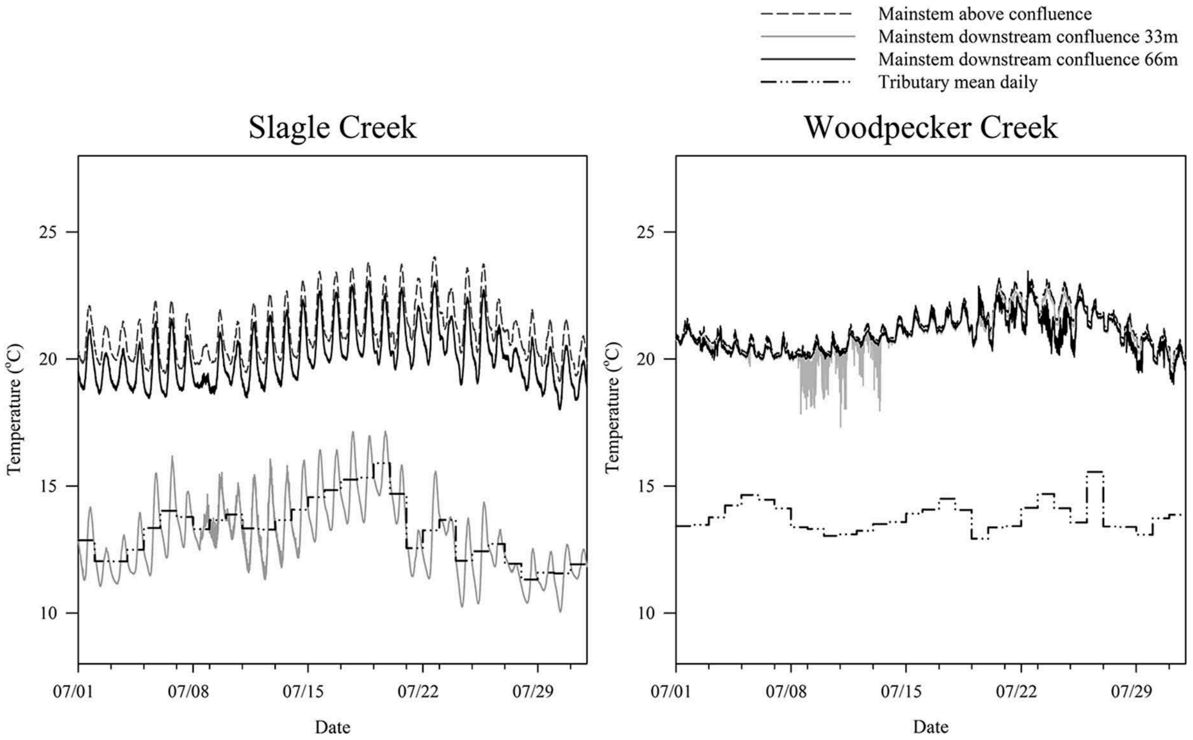

FIGURE 3. Differences in July 2013 surface water temperature in the Big Manistee River, Michigan, above and below the confluences with Slagle and Woodpecker creeks. Temperature data were collected in 5-min intervals with loggers positioned directly upstream, 33 m downstream, and 66 m downstream of each confluence. Mean daily temperatures for Slagle and Woodpecker creeks are included to show the relationship between tributary and main-stem temperatures.

were within the range of pH values (5.9–8.5) where Arctic Grayling have been observed by other investigators (see Table 1). Turbidity (mean ± SD) in this part of the watershed was below the reported maximum turbidity (30.8 NTU) for reference stream conditions in this sub-ecoregion (USEPA 2001) and ranged from 1.4 ± 1.3 NTU in Slagle Creek to 4.0 ± 4.2 NTU in Peterson Creek. Dissolved oxygen levels were similar across all tributaries, ranging from 8.8 ± 1.6 mg/L (mean ± SD) in Sand Creek to 10.4 ± 0.6 mg/L in Eddington Creek, while main-stem DO at the USGS gauging station at Hodenpyl Dam was 8.4 ± 0.8 mg/L (Table 2). Arctic Grayling have been observed in water with DO ranging from 1.3 to 12.6 mg/L (see Table 1), and all Big Manistee River tributary samples were within the observed ranges for sites occupied by Arctic Grayling in Alaska, Canada, and Montana.

Velocity

Velocity measurements were relatively stable among the sampling periods in early summer (May 29–June 27), midsummer (July 16–August 1), and late summer (August 6–14) of 2012 (as well as higher-spatial-resolution data from early summer 2012) but varied among tributaries, with the highest velocities measured in Slagle Creek (Table 3). Mean tributary velocities were near or within the range of observed mean velocities reported for Arctic Grayling juveniles (0.04–0.21 m/s; Hubert et al. 1985; Blackman 2004) and adults (0.34–0.52 m/s; Nelson 1954; Blackman 2004), with the exception of Sand Creek (adults; <0.34 m/s).

Channel Morphology

Individual depth measurements indicated that all tributaries had locations where depth was within the mean ± SD for Arctic Grayling habitat in Montana (Figure 5), and locations in each tributary fell within the range of what has been observed for rivers supporting Arctic Grayling (Table 1). Maximum measured water depth ranged from 0.3 m in Sand Creek to 0.9 m in Arquilla, Peterson, and Slagle creeks.

For all tributaries in 2011, the pool areal percentage was 42.9 ± 16.3% (mean ± SD), while riffles accounted for 38.9 ± 16.4% of tributary area, and runs (including glides) accounted for 19.6 ± 6.8% of tributary area. The CGU estimates based on longitudinal GPS mapping for 2012 revealed that between 16% and 39% of the area at tributary study sites comprised pool habitat (27.3 ± 7.1%), while riffles made up less of the area (16.8 ± 11.5%; Figure 6). Differences between 2011 and 2012 CGUs may have been real or may have been attributable to differences in (1) the level of experience of the people performing the classification or (2) measurement techniques (i.e., a hip-chain was used in 2011, whereas a GPS unit was used in 2012). Accordingly, we believe that 2012 data provide

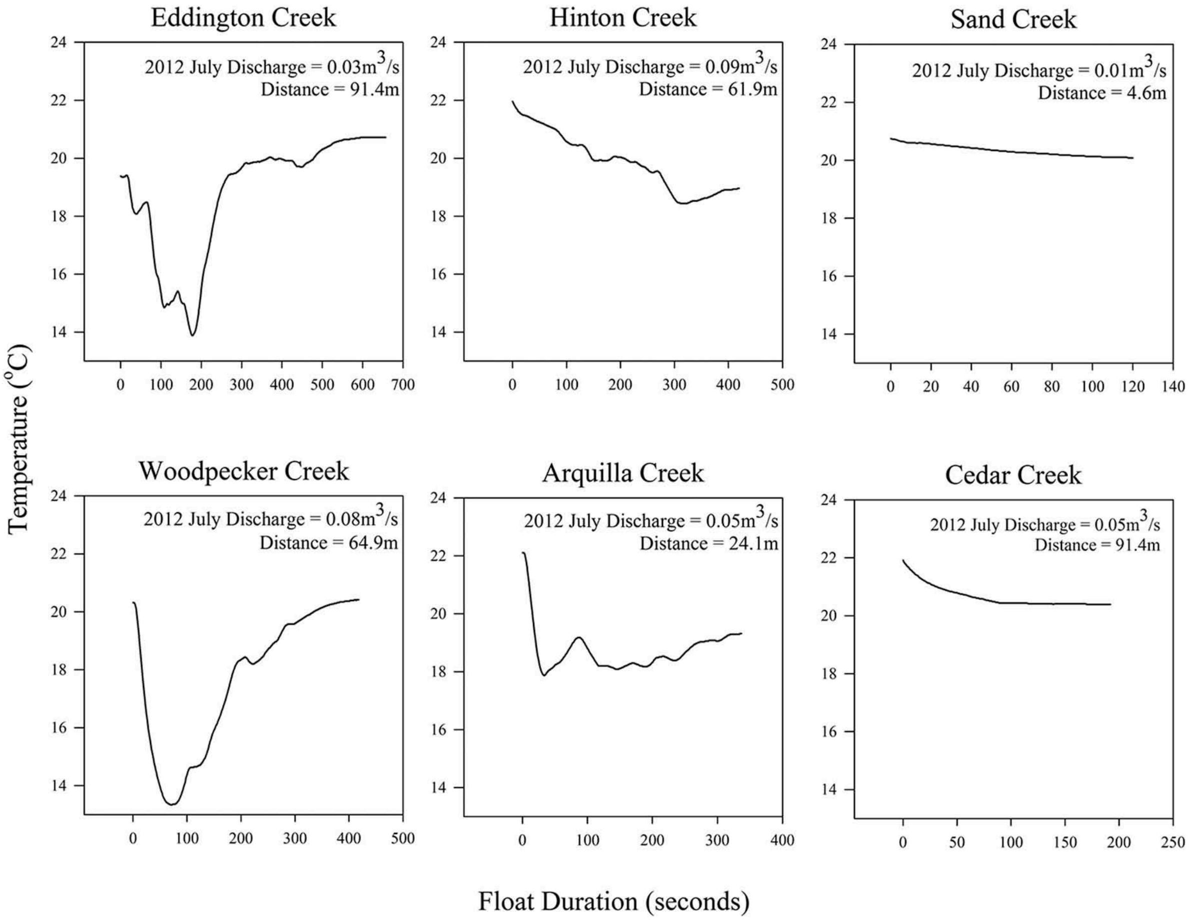

FIGURE 4. Longitudinal surface temperature of the Big Manistee River, Michigan, across tributary confluences. In July 2013, a temperature logger was released upstream of each tributary confluence and was allowed to drift downstream past the confluence to a maximum distance of 91 m. The temperature logger was drifted once past each tributary. July 2012 base flow discharge data are included to characterize the size of each tributary.

a more accurate representation for the classification of CGUs. Sand and Eddington creeks had the lowest percentage riffles at 0% and 5%, respectively, while Peterson Creek had the highest at 36% (Table 2). Runs were the dominant CGU and ranged from 36.2% to 72.7% (55.8 ± 12.7%; Figure 6). In 2011, Sand Creek was the only tributary with an areal pool : riffle ratio that was outside of the range previously observed in rivers that contain Arctic Grayling. Areal pool : riffle ratios changed for 2012 such that only Cedar, Peterson, and Slagle creeks were within the reported literature values of 0.3–1.5 (Liknes and Gould 1987). Eddington, Hinton, and Woodpecker creeks had ratios above 1.5, while Sand Creek did not contain detectable riffle habitat at the time of sampling (Table 2).

Abiotic Habitat Suitability in Tributaries

Seven of the eight study tributaries appeared to have suitable Arctic Grayling habitat conditions based on comparisons with 17 habitat metrics reported in the literature for this species (Table 4). At the tributary scale, Sand Creek met the least number of habitat metrics (*n* = 8), while the remaining tributaries were all within the literature ranges for 14–16 of the metrics (Table 4).

Applying the same comparisons at the reach scale offered specific locations within Big Manistee River tributaries for consideration as suitable for Arctic Grayling reintroduction depending on life stage. Seventeen metrics were considered for the various Arctic Grayling life stages; however, since temperature loggers were not located in each of the reaches, some reaches (*n* = 7) were scored based on 15 metrics. It should be noted that temperature data collected with the Hydrolab Sonde during biotic sampling indicated that those seven sites did not exceed the temperature range reported for age-0/juvenile or adult Arctic Grayling (our unpublished data). Of the 22 reaches evaluated, 15 reaches met over 75% of the abiotic habitat metrics considered, while 12 reaches met over 80% (Table 5). Lower and middle reaches of Peterson Creek met 94% of the habitat metrics.

At the reach scale, Sand Creek met the fewest metrics at the middle (*n* = 7 metrics) and upper (*n* = 6 metrics) reaches.

TABLE 2. Summary of abiotic conditions in tributaries of the Big Manistee River, Michigan. All values are means (SDs in parentheses) unless otherwise noted (D_{50} = median particle size).

	Stream								
Variable	Arquilla	Cedar	Eddington	Hinton	Peterson	Sand	Slagle	Woodpecker	Manistee
Wetted width (m)	4.3	2.2	2.2	3.5	4.2	1.8	7.5	3.6	
	(1.6)	(0.8)	(0.6)	(1.3)	(1.4)	(0.6)	(2.3)	(1.2)	
Depth (m)	0.16	0.13	0.11	0.19	0.22	0.11	0.26	0.14	
	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.1)	(0.2)	(0.1)	
Mean July temperature (°C)	13.9	11.3	10.5	12.7	14.0	13.5	14.0	13.4	21.1
	(1.4)	(1.1)	(1.2)	(2.0)	(1.6)	(1.7)	(1.4)	(2.3)	(1.7)[a]
Maximum July temperature (°C)	18.1	16.1	17.3	18.9	19.4	19.2	17.9	20.1	24.8[a]
Turbidity (NTU)	2.5	3.5	1.8	3.4	4.0	2.6	1.4	1.6	
	(2.8)	(4.6)	(2.8)	(4.3)	(4.2)	(2.7)	(1.3)	(1.2)	
pH	8.1	8.2	7.9	8.0	8.2	8.0	8.1	7.9	
	(0.5)	(0.3)	(0.2)	(0.4)	(0.4)	(0.3)	(0.5)	(0.3)	
Dissolved oxygen (mg/L)	9.9	9.8	10.4	9.9	9.7	8.8	9.1	9.2	8.3
	(1.1)	(1.3)	(0.6)	(0.9)	(1.0)	(1.6)	(1.6)	(1.0)	(0.8)[b]
2012 percent fines in riffles	29.4	47.9	48.4	44.7	42.4	35.0	40.7	34.6	
	(10.1)	(18.0)	(7.3)	(11.4)	(4.8)	(NA)	(10.4)	(3.7)	
2011/2012 percent gravel and pebble	63.1/68.0	53.8/53.4	58.3/67.0	54.1/63.9	37.4/39.6	4.4/7.1	55.2/56.9	60.5/60.4	
2011/2012 percent sand, silt, and clay	36.9/31.0	46.2/45.8	41.7/33.0	45.6/34.5	62.6/56.8	95.6/92.9	43.0/37.5	39.5/38.1	
2011/2012 D_{50} (mm)	22.0/19.5	11.0/6.0	14.3/13.0	10.8/15.0	2.0/2.0	2.0/2.0	12.0/16.0	14.5/11.0	
2011/2012 areal pool (%)	37/39	38/16	33/22	47/23	32/33	81/29	32/26	45/30	
2011/2012 areal riffle (%)	42/11	49/29	57/5	35/13	42/36	2/0	48/29	36/16	
2011/2012 areal pool : riffle ratio	0.9/3.4	0.8/0.6	0.6/4.0	1.4/1.8	0.7/1.1	35.1/NA	0.7/0.9	1.2/1.9	
Maximum pool depth (m)	0.9	0.48	0.6	0.7	0.92	0.49	0.96	0.58	
Winter 2010–2011 minimum temperature (°C)	0.5		0	–0.1	–0.1	0		0.5	0.4[c]

[a] Combined main-stem Manistee River data from 2009 to 2013.

[b] Data for May–August 2009–2013 from U.S. Geological Survey (USGS) gauging station 04124200 near Hodenpyl Dam.

[c] Winter 2010–2011 minimum temperature at the USGS gauging station.

TABLE 3. Mean velocity (m/s; SD in parentheses) in tributaries of the Big Manistee River, Michigan. Data represent averages across sites based on measurements taken in early summer (May 29–June 27), midsummer (July 16–August 1), and late summer (August 6–14); and high-spatial-resolution data collected in early summer (May 29–June 26) of 2012.

Tributary	Early summer	Midsummer	Late summer	High spatial resolution (early summer)
Arquilla	0.23 (0.08)	0.19 (0.04)	0.24 (0.05)	0.20 (<0.01)
Cedar	0.27 (0.19)	0.20 (0.12)	0.23 (0.13)	0.22 (<0.01)
Eddington	0.21 (0.06)	0.18 (<0.01)	0.23 (0.02)	0.20 (<0.01)
Hinton	0.26 (0.05)	0.20 (0.12)	0.24 (0.05)	0.21 (<0.01)
Peterson	0.23 (0.01)	0.15 (0.04)	0.23 (0.04)	0.31 (<0.01)
Sand	0.08 (<0.01)	0.07 (0.02)	0.08 (0.01)	0.07 (<0.01)
Slagle	0.34 (0.12)	0.38 (0.12)	0.37 (0.13)	0.39 (<0.01)
Woodpecker	0.23 (0.07)	0.19 (0.07)	0.25 (0.08)	0.25 (<0.01)

Although Cedar Creek scored highly at the tributary scale, most of that suitable habitat was observed at the lower site, as the middle and upper reaches met among the lowest number of suitable habitat criteria (Table 5).

Habitat Suitability Index

At the reach scale, variables that addressed water temperature (V1 and V7) scored 0.78–1.00 (Table 6). All reaches scored 1.00 for the DO variables (V2 and V8). Percent coarse substrate (V3) scored 0.11–1.00, and percent fine substrate (V4) scored 0.00–0.82. Water velocity variables (V5 and V6) ranged from 0 to 1.00 and from 0.44 to 1.00, respectively. The variable that represented annual access to spawning streams (V9) scored 1.00 for all reaches, and the variable describing availability of overwintering habitat (V10) was not assessed due to a lack of data (Table 6).

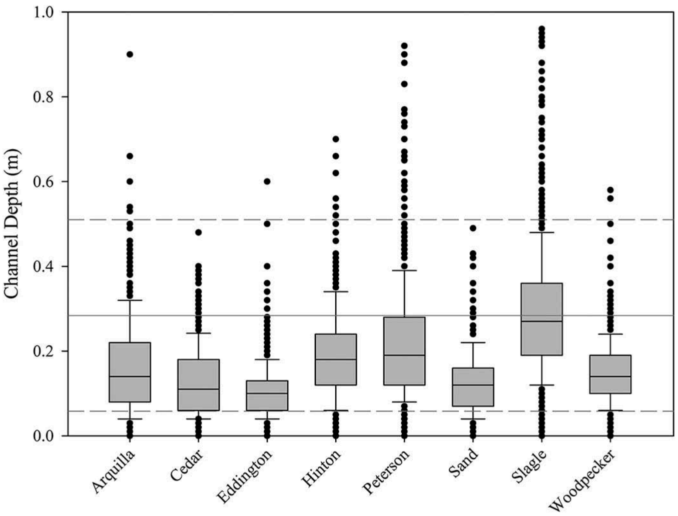

FIGURE 5. Box plot of measured channel depths in tributaries of the Big Manistee River, Michigan. Data are from 2012 site transects. The line within each box represents the median, the ends of the box represent the 25th and 75th percentiles, the ends of whiskers represent the 10th and 90th percentiles, and the black dots denote outliers. Horizontal lines represent the mean (solid line) and SD (dashed line) of depths for Big Hole River, Montana, sites that support Arctic Grayling (Liknes and Gould 1987).

DISCUSSION

In this study, we examined the suitability of eight tributaries in the Big Manistee River system based on whether abiotic conditions in this part of the watershed were within previously reported ranges for past and extant Arctic Grayling populations (Table 1). Environmental attributes were not ranked; therefore, no weighting was assigned to a given category, although it should be noted that certain conditions are potentially more important than others (e.g., stream temperature versus areal pool : riffle ratio). To complement this analysis, we applied the HSI model developed by Hubert et al. (1985) to the data as an alternative assessment that highlighted what habitat factors

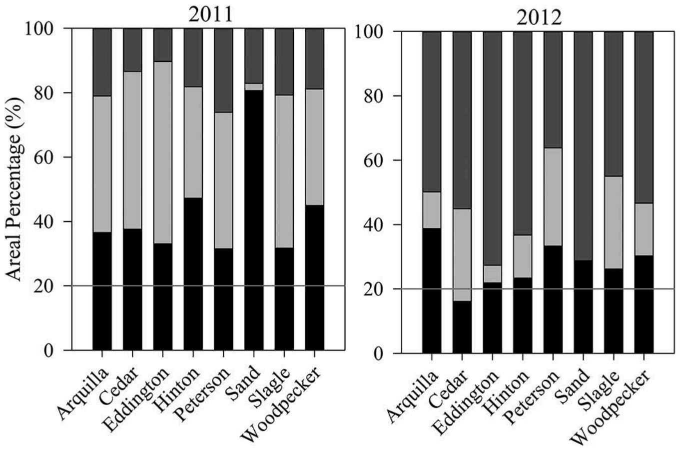

FIGURE 6. Areal percent channel geomorphic unit (CGU) composition in tributaries of the Big Manistee River, Michigan (black = percent pool; light gray = percent riffle; dark gray = percent run). Data are from 2011 and 2012 CGU measurements. The horizontal line represents the observed percentage of pools in Arctic Grayling habitat (Lamothe and Magee 2004a).

TABLE 4. Abiotic habitat scores for tributaries of the Big Manistee River, Michigan. Each black dot represents that the measured values for the tributary (2009–2013 data) fell within the range considered typical for Arctic Grayling habitat. No weighting was assigned to habitat metrics.

	Tributary							
Variable	Arquilla	Cedar	Eddington	Hinton	Peterson	Sand	Slagle	Woodpecker
Adult habitat								
Water temperature	•	•	•	•	•	•	•	•
Dissolved oxygen	•	•	•	•	•	•	•	•
pH	•	•	•	•	•	•	•	•
Water velocity	•	•	•	•	•		•	•
Channel width	•			•	•		•	•
Channel depth	•	•	•	•	•	•	•	•
Gradient		•	•		•	•	•	•
Pool : riffle ratio		•			•		•	
Primary substrates	•	•	•	•	•		•	•
Percent fines								
Median substrate	•	•	•	•			•	•
Spawning substrate	•	•	•	•	•		•	•
Spawning velocity	•	•	•	•	•		•	•
Age-0/juvenile habitat								
Water temperature	•	•	•	•	•	•	•	•
Water velocity	•	•	•	•	•	•	•	•
Channel depth	•	•	•	•	•	•	•	•
Primary substrates	•	•	•	•			•	•
Final tally	14/17	15/17	14/17	14/17	14/17	8/17	16/17	15/17

may be limiting to Arctic Grayling success, and we determined that at least four tributaries have abiotic conditions that may be suitable for Arctic Grayling.

Although previous attempts at reintroducing Arctic Grayling to the Big Manistee River and other rivers in Michigan have been unsuccessful (see Nuhfer 1992), future efforts are warranted, as new information on potentially suitable rivers (e.g., Tingley 2010) and methods for reintroduction are explored (e.g., remote site incubators; Lamothe and Magee 2004b). Furthermore, since only two of the seven Michigan rivers selected for the reintroduction attempt in the 1980s were reported to have previously supported Arctic Grayling (Vincent 1962), it is unknown whether the suite of rivers chosen would have been suitable, even under preextirpation conditions.

Our findings support the work of Tingley (2010), which aimed to determine Arctic Grayling habitat suitability in Michigan based on analysis at a larger spatial scale. Tingley (2010) determined that parts of the Manistee River watershed were suitable as potential Arctic Grayling habitat. Of those areas, the Pine River is closest to and accessible by our study region via Tippy Dam Pond (Figure 1). However, Arctic Grayling movement into the Pine River may be somewhat limited by Tippy Dam Pond due to potential predation by Walleyes *Sander vitreus* as well as summer water temperatures reaching 25°C (NWQMC 2016).

Although nearly all tributaries exhibited a majority (14–16) of favorable abiotic conditions for Arctic Grayling, with Cedar, Slagle, and Woodpecker creeks meeting the greatest number of habitat metrics (Table 4), some of the tributaries were probably not appropriate for all life stages of Arctic Grayling. Sand Creek met the fewest conditions and is likely the least suitable as Arctic Grayling habitat. However, determining which tributaries have the most potential for Arctic Grayling habitat raises the question of which reaches, if any, would be the most appropriate sites to consider for reintroduction.

In addition to considering the suitability at the tributary scale, we evaluated how each of the 22 study reaches met the criteria for known Arctic Grayling habitat (Table 5). As a result, the lower study reaches of Eddington, Hinton, Peterson, and Woodpecker creeks and the middle reaches of Peterson and Slagle creeks met the greatest number of habitat metrics (Table 5). For the reaches with the lowest scores, a common theme was that they were small streams (mean width = 2.2 ± 0.5 m; mean depth = 0.1 ± <0.1 m) and were located in the headwaters of their respective tributaries (see Table 5; Figure 1). Of these reaches, upper Slagle Creek was somewhat of an anomaly because it flows through an old fish hatchery and therefore has manmade features that may have influenced the final score.

The lower reaches of Arquilla and Cedar creeks and the upper reach of Slagle Creek were the only reaches to have

TABLE 5. Scores for abiotic metrics (*n* = 17) describing the lower (L), middle (M), and upper (U) reaches of tributaries to the Big Manistee River, Michigan. Each black dot represents that the measured values for the reach (2009–2013 data) fell within the range considered typical for Arctic Grayling habitat. Asterisks indicate reaches without continuous temperature data (§), which were scored out of 15 instead of 17. No weighting was assigned to habitat metrics.

	Arquilla		Cedar			Eddington			Hinton			Peterson			Sand		Slagle			Woodpecker		
Variable	L	U*	L	M*	U*	L	M	U	L	M*	U	L	M	U	M	U*	L	M	U*	L	M*	U
Adult																						
Water temperature	•	§	•	§	§	•	•	•	•	§	•	•	•	•	•	§	•	•	§	•	§	•
Dissolved oxygen	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
pH		•		•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Water velocity	•	•	•	•	•	•	•	•	•	•	•	•	•	•			•	•	•	•	•	•
Channel width	•	•							•			•	•				•	•	•	•	•	
Channel depth	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Channel gradient		•				•	•			•	•	•	•			•			•	•		
Pool : riffle ratio						•			•			•	•					•	•		•	
Primary substrates	•	•	•			•	•	•	•	•	•	•	•				•	•		•	•	
Percent fines	•		•																•			
Median substrates	•	•	•			•	•	•	•	•	•	•	•				•	•		•	•	
Spawning substrates	•	•	•			•	•	•	•	•	•	•	•				•	•		•	•	
Spawning velocity	•	•	•	•	•	•	•	•	•	•	•	•	•	•			•	•	•	•	•	•
Age-0/juvenile																						
Water temperature	•	§	•	§	§	•	•	•	•	§	•	•	•	•	•	§	•	•	§	•	§	•
Water velocity	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Channel depth	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Primary substrates	•	•	•			•	•	•	•	•	•	•	•				•	•		•	•	
Final tally	14/17	13/15	13/17	7/15	7/15	15/17	14/17	13/17	15/17	12/15	14/17	16/17	16/17	8/17	7/17	6/15	14/17	15/17	11/15	15/17	13/15	9/17

percent fine substrate measurements low enough to fall within the reported range for Arctic Grayling. These results were somewhat consistent when we applied the HSI model to our data, which indicated that four tributary reaches had percent fine substrates (V4) believed to be unsuitable (i.e., HSI = 0), while others ranked as having "low" suitability (i.e., HSI < 0.50) for spawning and rearing (Hubert et al. 1985; Table 6). Although the percentage fine substrates was greater than what is believed to be optimal (<10%) for Arctic Grayling, 15 reaches (7 tributaries) had median substrate sizes within the range observed for Arctic Grayling habitat in the Big Hole River, Montana (Lamothe and Peterson 2007). It should be noted that our study characterized overall tributary and reach suitability rather than identifying specific habitat units (i.e., specific riffles or pools) for reestablishment. Therefore, it is likely that spawning and rearing habitat with optimal embeddedness (~10%) does exist within the reaches considered and elsewhere in Big Manistee River tributaries. In addition, although spawning habitat differs across species of salmonids, we documented natural recruitment of Brook Trout and Brown Trout in all tributaries (our unpublished data), which—based on HSI models developed for these species—are believed to have optimal percentages of fine substrates in spawning habitat (i.e., <5%; Raleigh 1982; Raleigh et al. 1986).

The suitability model developed for Arctic Grayling has not been widely tested, and HSI models have been described as "hypotheses of species–habitat relationships rather than statements of proven cause and effect relationships" (Schamberger et al. 1982). However, incorporating models based on real data such as HSIs can be helpful in guiding habitat suitability analysis, especially in this situation, where quantitative data for Arctic Grayling prior to their extirpation was limited. The Arctic Grayling HSI model may have some limitations to its efficacy and transferability. For example, Jones and Tonn (2004) developed resource selection models for young-of-the-year Arctic Grayling and found that in comparison with water depth and velocity, percent fine substrate was relatively unimportant in determining where Arctic Grayling were located. Jones and Tonn (2004) did mention that this result deviated from what others have observed (see Knapp and Preisler 1999) and may have been attributable to the underlying geomorphology of the system, which further highlights the issue of generality of these models. It is possible that the HSI model's simplicity (i.e., lowest variable score = overall model score) does not properly characterize the habitat metrics that will be most limiting for regions other than where the model was developed (Leftwich et al. 1997), and ultimately the limiting factor for a species may be a combination of factors rather than just one (Allen 1929). For some species, issues can arise with the comparability of habitat criteria across systems (Groshens and Orth 1994), whereas for other species, HSI models are not generally applicable as assessment tools (Hubert and Rahel 1989), which again may be due in part to geographic differences (Bowlby and Roff 1986). Given these conditions, it is important to consider multiple studies for information in addition to using an HSI model score as one part of an overall assessment. Furthermore, any efforts at reintroduction should be coupled with long-term monitoring and evaluation so that the methods or sites used can be adjusted to maximize success.

Big Manistee River tributaries may play different roles for different life stages of Arctic Grayling. Slagle Creek, for example, is the largest tributary in terms of mean width, depth, and velocity and may be one of the more suitable streams for adult Arctic Grayling. In contrast, all other tributaries are smaller and would possibly be more suitable for age-0 and juvenile Arctic Grayling due to lower water velocities. Overall, according to the literature values used to quantify Arctic Grayling habitat (Table 1) and the variable scores of the HSI model (Table 6), the lower reaches on Eddington, Hinton, and Peterson creeks and the middle reaches on Peterson and Slagle creeks may be the most suitable tributary reaches in this part of the watershed for all life stages, but other tributaries may provide necessary refugia at certain life stages and be equally valued. When considering metrics that met criteria for different life stages, 14 of 22 reaches satisfied over 75% of criteria for the adult life stage of Arctic Grayling (Table 5); for the HSI model variables, all reaches scored over 0.76. Fifteen of 22 reaches met all abiotic habitat metrics considered for age-0 and juvenile Arctic Grayling, while 19 reaches had scores greater than 0.7 for at least four of the six HSI model variables.

One of the challenges in assessing the potential for reintroduction is considering which habitat components are most critical to survival and/or what factors will be limiting in the system. Many factors have been reported as potentially limiting to Arctic Grayling, including temperature and substrate embeddedness, as has been described for salmonids (Hubert et al. 1985; Suttle et al. 2004). The results of our assessment as well as the HSI model did indicate that percent fine substrate tended to be outside the previously reported ranges (Table 5) and scored the lowest for the HSI model (Table 6). Despite these results, it is possible that fine substrate assessment would not hinder (or at least would not be the limiting factor to) the success of Arctic Grayling in Michigan since rivers in the state may have a higher intrinsic abundance of fine sediment than rivers in the western United States. Accounts of rivers that once supported Arctic Grayling in Michigan indicated that spawning occurred over substrates comprising a mix of sand and gravel (see Vincent 1962). Based on data collected from the middle of the Big Manistee River, water temperature in the tributaries during summer months is within the reported ranges for Arctic Grayling and is unlikely to be a limiting factor in tributaries' suitability as habitat. Mean July water temperatures for all tributaries were below the upper incipient lethal temperature (UILT) of 25°C reported for Arctic Grayling in Montana (Lohr et al. 1996) as well as within the range purported as optimal for Arctic Grayling growth (Hubert

TABLE 6. Habitat suitability index (HSI) scores for the lower (L), middle (M), and upper (U) reaches of tributaries to the Big Manistee River. Variables V1–V6 (category A1) represent habitat conditions for spawning, embryos, and fry of Arctic Grayling, while variables V7–V10 (category A2) represent adult habitat conditions (V1 and V7 = average maximum water temperature; V2 and V8 = average minimum dissolved oxygen in the water; V3 = percent coarse substrate in spawning areas; V4 = percent fine substrates in riffles; V5 = average velocity in spawning areas; V6 = percent low-velocity [<0.15-m/s] areas; V9 and V10 = access to spawning habitat following winter and whether winter habitat is available for adults, respectively). Specific variables for which we have no data are marked with §.

	Arquilla		Cedar			Eddington			Hinton			Peterson			Sand		Slagle			Woodpecker		
Variable	L	U	L	M	U	L	M	U	L	M	U	L	M	U	M	U	L	M	U	L	M	U
V1	1.00	§	1.00	§	§	1.00	1.00	1.00	1.00	§	1.00	1.00	1.00	0.92	1.00	§	1.00	1.00	§	1.00	§	0.78
V2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
V3	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.29	0.11	0.58	1.00	1.00	1.00	1.00	1.00	1.00
V4	0.82	0.26	0.44	§	0.00	0.17	0.04	0.00	0.32	0.16	0.00	0.11	0.28	§	§	0.38	0.00	0.35	0.75	0.46	0.32	§
V5	0.92	0.59	1.00	0.59	0.35	0.76	0.71	0.74	0.96	0.67	0.76	1.00	1.00	0.97	0.10	0.00	1.00	1.00	1.00	1.00	1.00	0.35
V6	1.00	1.00	0.78	1.00	1.00	0.78	0.62	0.80	0.56	1.00	0.91	0.81	0.92	0.71	1.00	1.00	0.45	0.44	0.84	0.78	0.89	1.00
V7	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.78
V8	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
V9	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
V10	§	§	§	§	§	§	§	§	§	§	§	§	§	§	§	§	§	§	§	§	§	§
A1	0.82	0.26	0.44	0.59	0.00	0.17	0.04	0.00	0.32	0.16	0.00	0.11	0.28	0.29	0.10	0.00	0.00	0.35	0.75	0.46	0.32	0.35
A2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.92	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.78
HSI	0.82	0.26	0.44	0.59	0.00	0.17	0.04	0.00	0.32	0.16	0.00	0.11	0.28	0.29	0.10	0.00	0.00	0.35	0.75	0.46	0.32	0.35

et al. 1985). Similarly, the maximum observed hourly water temperatures in this part of the watershed were below the UILT. However, this was not always the case in the main stem, where mean July temperatures reached levels that have been documented to cause avoidance in Arctic Grayling (Wojcik 1955; Schallock 1966). Although main-stem temperatures did not reach lethal levels as defined by Lohr et al. (1996), water temperatures exceeding 18–20°C generate an increased chance of physiological stress to Arctic Grayling (Wojcik 1955; Hubert et al. 1985; Lamothe and Peterson 2007), thus requiring them to seek refuge from these elevated water temperatures. Similarly, climate-change-related implications for coldwater fish have been predicted for other rivers in the Midwestern United States (Lyons et al. 2010). Brook Trout and Rainbow Trout are able to maintain internal body temperatures 2.3°C and 4.0°C cooler (on average), respectively, than river temperatures (>20°C) by finding and using thermal refuge habitat (Baird and Krueger 2003). In this study, we demonstrated that many of the tributaries create coolwater microhabitat as they mix with the main stem, lowering the surface temperature by as much as 8°C in areas around tributary confluences (Figure 3); therefore, these tributaries have potential to provide thermal refuge and may already be playing this important role for resident salmonids during the warmest periods of the year. For example, Slagle Creek reduced main-stem water temperature by as much as 8°C more than 30 m downstream of the confluence, and Eddington and Woodpecker creeks reduced main-stem surface water temperatures from over 20°C to less than 14°C. This ability of coldwater fishes to seek out thermal refuge has been further demonstrated for the Big Hole River system, which reaches water temperatures that exceed the UILT yet support multiple salmonid species, including Arctic Grayling (Lamothe and Peterson 2007).

Although we observed clearly lower water temperature downstream of Slagle Creek, this was not the case for Woodpecker Creek. The three loggers used to compare main-stem temperatures upstream and downstream of Woodpecker Creek were secured close to the bank of the Big Manistee River (Figure 3), while the temperature logger that was floated past the confluence with Woodpecker Creek took a path further out toward the center of the channel as a result of water currents and thus recorded a thermal difference (Figure 4). We believe the floated temperature logger recorded a decrease in temperature as it passed by Woodpecker Creek's confluence with the Big Manistee River because it was able to capture the plume of cold water entering the main stem, which did not follow closely along the bank and therefore did not register with the temperature loggers downstream of Woodpecker Creek.

In the Big Manistee River, Arctic Grayling reportedly spawned during the spring thaw (Vincent 1962). In our study, the majority of habitat data were collected during the summer months, which means that despite the overall positive results indicating that a number of tributaries are potentially suitable as Arctic Grayling habitat, some of the variables we compared with the literature values and scored using the HSI model (e.g., water velocity) may not fully represent conditions when Arctic Grayling would spawn. Although it is important to consider the limits to this analysis, our data are useful for moving forward toward the reintroduction of Arctic Grayling because the Big Manistee River is a relatively stable, groundwater-fed system (Hay-Chmielewski et al. 1995; Rozich 1998).

Winter habitat availability in tributaries was also not evaluated, although continuous temperature data suggested that most of the tributary sites reached freezing temperatures during the winter of 2010–2011 (Table 2). Temperature logger locations were not chosen based on suitability as overwintering habitat (e.g., deep pools) and therefore do not represent thermal conditions in possible overwintering habitat. These data do raise the question of whether these tributaries could act as winter habitat or whether overwintering could be expected to occur in the Big Manistee River or further downstream (i.e., Tippy Dam Pond). Barndt and Kaya (2000) documented overwintering within pools ranging in depth from 0.1 to 0.9 m and with ice cover as thick as 0.6 m in a Montana irrigation canal; therefore, it is conceivable that Arctic Grayling could use some of the larger pools within tributaries such as Slagle Creek (Figure 5) in addition to available winter habitat in the main-stem Big Manistee River. Within most of the Big Manistee River tributaries, several depths (Figure 5) were measured beyond the upper end (>0.5 m) of what Barndt and Kaya (2000) observed for overwintering locations in the canal in Montana; this was particularly true of Peterson and Slagle creeks, although conditions (e.g., ice thickness, DO, temperature, volume of overwintering habitat, and channel depth) at these locations during winter months are presently unknown.

Among the many challenges faced when considering reintroduction of a species that has been extirpated for nearly a century is identifying the habitat conditions that can be used in comparisons; for Arctic Grayling in Michigan, there are few quantitative data describing the conditions that existed when their populations were thriving. Therefore, we were left with having to compare conditions in the Big Manistee River watershed to those elsewhere in the species' range where such data exist. What is known is that the lands surrounding the Big Manistee River have retained fairly low levels of urban development, with roughly 95% of the watershed comprised of forests, agricultural lands, and wetlands with extensive public and tribal ownership (Rozich 1998), making it an ideal system in which to focus initial Arctic Grayling restoration efforts in Michigan.

The implications of this research could be far reaching, and our work has been used as a motivating factor to support efforts to reestablish Arctic Grayling in the Manistee River watershed. Reintroduction as part of a Tribal Native Species Restoration Plan and the MDNR strategic plan could strengthen and preserve native species stewardship and natural ecosystem function (LRBOI 2008) as well as foster the philosophy of conservation among tribal and nontribal members. Additionally, if a fishery could be supported, anglers with a fondness for native species would be catching a fish that is more closely aligned with the natural state of the watershed than the current nonnative salmonids. Efforts aimed at restoring and reintroducing populations in Montana have shown signs of success when using remote site incubators to rear stocked Arctic Grayling (Lamothe and Magee 2004b; Magee et al. 2012). Similarly, in the Pacific Northwest, there has been success at reintroducing spring Chinook Salmon to Lookingglass Creek, part of the Snake River watershed (Boe et al. 2010). Using studies such as the aforementioned work, along with the available body of literature on lessons learned from successful reestablishment, reintroduction, and restoration of native fish species, will help to ensure that the methods used in a potential reintroduction of Arctic Grayling are suitable and offer the greatest likelihood of success.

Based on the abiotic habitat assessment conducted in this study, environmental conditions in select tributaries of the Big Manistee River were within ranges reported from systems where Arctic Grayling are presently established (i.e., Alaska, Montana, and Canada). Ultimately, the reaches chosen for reintroduction would need to be selected such that important abiotic conditions can also be met and the potential for negative biotic interactions can be minimized. When coupled with an evaluation of biotic conditions, this assessment of habitat and environmental conditions will provide a more complete guide to assist managers in determining locations for future Arctic Grayling reintroduction.

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