Assessment of Stocking Advanced Fingerling Brown Trout in a North Carolina Tailrace

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Abstract: Bridgewater Tailrace (BWTR) is a 29-km waterway extending from Lake James to Lake Rhodhiss on the Catawba River in western North Carolina. An 18-km reach of the stream is classified as Special Regulation Trout Waters by the North Carolina Wildlife Resources Commission (NCWRC) and is managed as a put-grow-and-take brown trout (*Salmo trutta*) fishery. Early studies demonstrated recruitment of stocked fingerling (25–75 mm TL) brown trout was highly variable and possibly impacted by elevated discharge water temperatures during late summer months. Recent upgrades to Bridgewater Hydro Station resulted in more consistent minimum flows and dissolved oxygen levels, which may help ameliorate historical recruitment issues. In 2011, the NCWRC initiated a multi-year study to evaluate annual stockings of 10,000 advanced fingerling (200–255 mm TL) brown trout that were stocked during late fall after the threat of elevated discharge water temperatures. Catch rates were variable among years, and several years showed significant differences between spring and fall surveys for CPUE and relative weight (W_r); however, temperatures appeared suitable for year-round survival so other mechanisms must be limiting recruitment. Age and length data suggested that recruitment to age 2 was extremely limited, and older fish were rare. A variety of factors not evaluated during this study may be preventing stocked fish from recruiting to older year classes, including flow alterations, habitat limitations, and excess angler harvest. Stocking advanced fingerlings in the fall appeared to establish a fishery composed primarily of age-1 brown trout. Nonetheless, trophy fish were present in low numbers, W_r was good, and growth rates were fast, suggesting that minor alterations to the current management approach, such as increasing the minimum size limit, may continue to enhance the fishery. Age-structured modeling simulations predicted that an increased minimum-length limit (MLL) of 356 mm to be the best regulation for optimizing structural size indices and yield. Based on this study, the NCWRC adopted a 356-mm MLL and two-fish creel limit per day for the BWTR on 1 August 2018.

Key words: electrofishing, temperature, coded wire tags, relative weight, age and growth

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Tailrace fisheries below dams with hypolimnetic discharges often provide unique coldwater resources in geographic areas that otherwise would be composed of warmwater species. Many resource agencies capitalize on these altered habitats by creating quality and desirable trout fisheries. These tailrace fisheries are often outside the native distribution of salmonids and have much different environmental and ecological conditions than natural trout streams (Cushman 1985). Nonetheless, many tailraces have developed into world-class fisheries growing record-sized trout and are very popular with anglers.

Thermal and flow regimes are the most important variables driving the characteristics of a tailrace fishery. Much research has been conducted evaluating the impacts of these variables on trout growth rates (Elliot et al. 1995, Lobon-Cervia and Rincon 1998, Johnson et al. 2006), persistence (Bettinger and Bettoli 2002), reproductive ecology (Pender and Kwak 2002), movement (Bettinger and Bettoli 2002, Quinn and Kwak 2000, 2003), and other life-history factors that help managers determine the best approach for each fishery. Although hypolemnetic discharges from hydroelectric facilities can create quality trout habitat, the thermal conditions and peaking regimes can have negative impacts on both native fish fauna and reproductive success of non-native trout (Blinn et al. 1995). As a result, resource managers are typically forced to manage these trout fisheries with supplemental stockings, often at high stocking rates, to meet angler demand.

North Carolina has a limited number of tailraces with conditions suitable for trout. The Catawba River below Lake James in Burke and McDowell counties, henceforth called the Bridgewater Tailrace (BWTR), has been recognized by the North Carolina Wildlife Resources Commission (NCWRC) as a potential quality tailrace. The BWTR is a 29-km waterway extending from Lake James to Lake Rhodhiss in the upper Piedmont physiographic region of western North Carolina (Figure 1). The NCWRC has managed the upper 2 km of this tailrace as a put-and-take trout fishery since 1941. An additional 18-km reach from the confluence of Muddy Creek to the City of Morganton's water intake dam has been classified as Special Regulation Trout Waters by the NCWRC and managed as such since 2005 (Figure 1). This section is managed under a seven-fish daily creel limit, with only one fish allowed to be over 356 mm TL. The remaining 9 km downstream of the

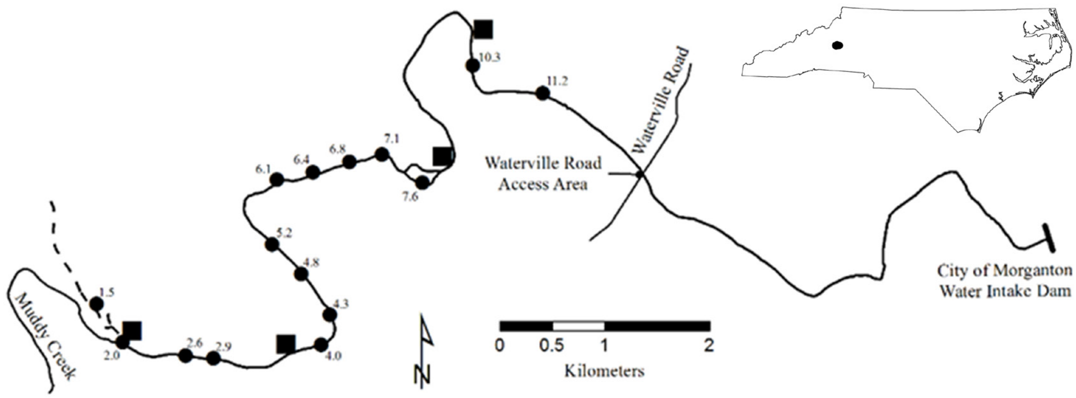

Figure 1. Map of Bridgewater Tailrace, North Carolina. Hatchery Supported Trout Waters (dashed line) and Special Regulation Trout Waters (solid line) are represented. Sample sites (circles) and stocking locations (squares) are shown.

City of Morganton's water intake dam are not managed as trout waters.

The Special Regulation Trout Waters reach was stocked annually each spring from 1996 to 2007 with 25,000–50,000 fingerling brown trout (*Salmo trutta*; 25–75 mm TL) in an effort to establish a quality put-grow-and-take brown trout fishery. Early investigations of BWTR indicated fast brown trout growth rates and that fingerling stocking efforts established a brown trout population (Goudreau 1994, Besler 2003). Besler (2003) also documented high levels of contribution from stocked fish and increases in catch rates through the three-year study, suggesting that stocking efforts were successful in establishing a fishery. However, subsequent surveys and angler reports found that the population declined dramatically between 2005 and 2008 (NCWRC unpublished data), and brown trout were not stocked from 2008 to 2010.

Historically, hypolimnetic discharges from the Bridgewater Hydro Station, owned and operated by Duke Energy, were expected to provide suitable temperatures (<22.9° C; Wehrly and Wang 2007) for a cold water fishery (Besler 2003, Chen et al. 2004); however, long-term temperature data from 1995 to 2005 suggested that late summer discharge temperatures can exceed suitable levels for extended periods, creating a "thermal bottleneck" that may limit trout survival before more suitable temperatures return in the fall (NCWRC unpublished data). In 2012, Duke Energy finalized remediation projects on the Bridgewater, Paddy Creek, and Catawba dams of Lake James to comply with the Federal Energy Regulatory Commission's relicensing agreement. The new license requires an increase in minimum flows from 0.71 m^3 sec^{-1} to 3.5–6.2 m^3 sec^{-1}. Additionally, new turbines and jet valves were installed in the Bridgewater Hydro Station to modulate dissolved oxygen (DO) levels to maintain levels at or above 5 mg L^{-1}. Although the flow changes did not become official until 2016, Duke Energy began implementing minimum flow and DO increases in 2012 when the new hydro station was constructed.

In 2011 NCWRC biologists initiated a multi-year study to evaluate an alternate approach of stocking larger, advanced fingerling brown trout (200–255 mm TL) in the fall (after any potential thermal bottleneck). Surveys were initiated in the spring of 2012 and continued through the fall 2016. The goal of this study was to determine if this alternative management stocking approach, in conjunction with changes to flow and DO dynamics in the BWTR, would enhance the brown trout fishery. Specific objectives of this study were to 1) determine if stocking advanced brown trout fingerlings annually in the fall will result in incremental increases in brown trout abundance as year classes accumulate over time, 2) assess intra-annual differences between spring and fall surveys for catch rates, condition, and contribution of stocked brown trout, 3) determine if water temperatures are within a suitable range for year-round brown trout survival, and 4) evaluate the best harvest regulation to optimize the fishery, with a focus on the production of large trout (≥356 mm TL).

Methods

Tagging and Stocking

Ten thousand brown trout were reared to 200–255 mm TL (advanced fingerlings) and tagged each year from 2011–2015 at the Marion and Table Rock state fish hatcheries, North Carolina. Brown trout fingerlings were netted from raceways, placed into a 10-L container, and anesthetized using Aqui-S 20E (20 mg L^{-1}). Each fish was injected with a 0.1- x 1-mm coded wire tag (CWT) using a Mark IV CWT injector (Northwest Marine Technology, Inc. [NMT], Shaw Island, Washington). The CWT injector needle remained in a fixed position, and 89-mm non-beveled needles were used. All brown trout were checked for coded wire tags using a NMT detection wand immediately after tagging and then returned to raceways and allowed to recover. Different anatomical tag locations were used each year to distinguish between cohorts: left cheek (2011 and 2014), right cheek (2012 and 2015), and snout (2013). Long-term tag retention was evaluated by Rash et al. (2018), who found that tag loss was negligible. Mean size of stocked fish ranged from 208 mm TL (SE = 8.2) to 241 mm TL (SE = 9.4). Brown trout were stocked between the Bridgewater Canoe Launch and Watermill Road Access Area at four strategic point accesses (Figure 1). This reach was chosen due to the availability of high-quality habitat and the logistical constraints associated with sampling and stocking alternate reaches.

Study Site and Field Sampling

The study reach is defined as the area just upstream of the Muddy Creek confluence to Watermill Road Access Area, approximately 12 km (Figure 1). Fifteen fixed sites were determined based on historical site locations (Figure 1; Besler 2003). Electrofishing surveys took place during the day in late spring (before any potential thermal bottleneck) and late fall (after any potential thermal bottleneck but before stocking) in 2012–2016. Electrofishing in 2012 was conducted under maximum-flow conditions (71 m^3 sec^{-1}) using a 5.6-m pontoon raft powered by a 25-hp tiller motor and mounted with a model 5.0 GPP electrofishing unit (Smith-Root, Inc., Vancouver, Washington) operated at 1000 V-DC and 120 pulses per sec. Sampling from 2013–2016 was conducted under minimum-flow conditions (3.5–6.2 m^3 sec^{-1}) using a 4.3-m, oar-framed NRS Expedition raft mounted with a model 5.0 GPP electrofishing unit (Smith-Root, Inc., Vancouver, Washington) operated at 1000 V-DC and 120 pulses per sec.

Electrofishing was conducted in a systematic downstream direction through each riffle complex. The first downstream electrofishing pass was conducted through the thalweg of each riffle, then subsequent passes included boating upstream into the riffle head and floating downstream through the next unsampled riffle section until each riffle was covered effectively. Recorded electrofishing time included upstream boating efforts and was recorded separately for each riffle. All captured trout were placed in a live well. Trout were anesthetized using Aqui-S 20E (20 mg L^{-1}), measured (TL, mm), weighed (g), checked for the presence of a CWT using a hand-held detection wand, and released.

Temperature

Two HOBO Pro v2 temperature loggers (Onset Computer Corporation, Bourne, Massachusetts) were used; one placed 0.5 km below the dam and the other placed approximately 3.5 km below the dam; loggers collected water temperature data hourly each day of the study period. Temperature data were assessed visually to determine if temperatures remained suitable for trout survival throughout the year. A short-term and long-term cutoff was used for temperature assessments based on Wehrly and Wang (2007); specifically, the short-term temperature maximum was 27.6° C for 1 day and the long-term temperature maximum was 22.9° C for 63 days. If temperatures reached and persisted beyond the determined cutoffs, temperatures were considered unsuitable for survival. We did not measure dissolved oxygen levels because the new powerhouse maintained levels at or above 5 mg L^{-1}. Discharge and flow data were not collected in this study.

Catch Rates and Stocking Contribution

Abundance was indexed as CPUE of electrofishing time and expressed as number of fish collected per hour. A one-way ANOVA using a fixed effects model including site as a factor was used to examine differences in CPUE across years for all ages combined and age-1 fish. Tukey's Honestly Significant Difference (HSD) post-hoc analysis was used to identify sample means that were significantly different from each other. Within each year, mean CPUE was compared between spring and fall surveys using a one-sample *t*-test on paired differences. Data from 2012 were excluded since flows and sampling methods were different than 2013–2016. All statistical analyses here and elsewhere were conducted using Rcmdr package, v. 2.4-1 in R, v. 1.1.383 statistical software (The R Foundation for Statistical Computing, Vienna, Austria); and significance for all tests was considered as $P < 0.05$.

The contribution of stocked brown trout to the population was expressed as a percentage by dividing the number of tagged brown trout by the total number of brown trout captured, multiplied by 100. Contributions were compared between spring and fall surveys for each year of the survey using a Fisher's exact test for independence with 2x2 contingency tables.

Size Structure and Condition

Length-frequency histograms were developed for each survey year to describe patterns in size distribution. Proportional size distributions (PSDs) were calculated following Neumann et al. (2012) and Guy et al. (2007), using length categories defined as stock (150 mm TL), quality (230 mm TL), preferred (300 mm TL), memorable (380 mm TL), and trophy (460 mm TL). Data from 2012 were excluded from size structure analyses because flows and sampling methods were different than 2013–2016.

Relative weight (W_r) values were calculated for brown trout greater than 140 mm TL using the standard weight equation in Neumann et al. (2012). A one-way ANOVA using a fixed effects model including site as a factor was used to assess differences in mean W_r across years for all ages combined and age-1 fish. Tukey's HSD post-hoc analysis was used to identify sample means that were significantly different from each other. Within each year, W_r values were compared between spring and fall surveys using a two-sample *t*-test.

Age, Growth, and Mortality.

Ages were determined for marked fish by tag location. Cohorts that were tagged in similar locations but from different years were differentiated by size. Unmarked brown trout were weighed and measured but ages were not determined. Age-frequency histograms were constructed to describe patterns in age. Data from 2012 were excluded from age-frequency determination because flows and sampling methods were different than 2013–2016, and only one stocked year class from this study was present in the fishery. Age data were pooled across years, and growth (mean TL at age) was described using the von Bertalanffy (1938) model. Due to limited older brown trout age classes, the asymptotic length (L_∞) was held constant at 710 mm TL (i.e., the largest brown trout collected during this study). Age frequencies were tabulated from the pooled data set, and the instantaneous total annual mortality rate (Z) was estimated on the descending limb (age ≥1) using the Chapman-Robson catch curve method (Robson and Chapman 1961). Annual survival (S) was calculated as $S = e^{-Z}$, and total annual mortality (A) was calculated as 1 – S (Ricker 1975). The Fisheries Analysis and Modeling Simulator (FAMS) program (version 1.64; Slipke and Maceina 2014) was used to present the instantaneous natural mortality rate (M) estimated from eight equations (Hoenig 1983, Chen and Watanabe 1989, Djabali et al. 1993, Jensen 1996, Lorenzen 1996, Pauly 1980, Cubillos et al. 1999, Quinn and Deriso 1999). The eight M values were then averaged to obtain an overall estimate of M. Conditional natural mortality (*cm*) was computed from overall M as $cm = 1 - e^{-M}$. The instantaneous fishing mortality rate (F) was estimated as $F = Z - M$, and the conditional fishing mortality (*cf*) was then computed from F as $cf = 1 - e^{-F}$.

Harvest Restriction Modeling.

Three harvest restriction effects on the BWTR brown trout population were simulated using FAMS. Population and fishery variables generated in FAMS were derived from the Beverton-Holt equilibrium yield equation (Quinn and Deriso 1999). Three minimum-length limits (MLL) were explored: 1) 233-mm MLL (approximating the current no-MLL regulation; 233 mm = average size of stocked brown trout), 2) a 356-mm MLL, and 3) a 432-mm MLL. The length-weight relationship was derived from brown trout that were sampled in the BWTR from spring 2012 to fall 2016. Additional model input parameters included *cm*, *cf*, and the von Bertalanffy growth model parameters via age and growth as described above. Model simulations were run using the lowest *cm* estimate (0.24), the mean *cm* estimate (0.30), and the highest *cm* estimate (0.44; Sammons 2016). Although the oldest brown trout collected during this study was age 7, the measured TL of this fish (542 mm) was much lower than a 710-mm TL specimen collected during October 2016 that could not be assigned an age. Therefore, the maximum age was set at 8 years for all model simulations, as contemporary sampling was assumed to be unsuccessful at collecting and/or aging the oldest fish present in the population.

The three harvest restriction effects on brown trout yield (kg), number harvested, and number reaching 460 mm (i.e., trophy size) were each initially evaluated using an original population of 10,000 age-1 recruits (i.e., number of stocked brown trout annually) and the yield-per-recruit option in the FAMS model. Metrics response to the three harvest restriction scenarios was simulated over a range of estimated exploitation (u) rates at each *cm*. The range of u was estimated using F values calculated as described above at each level of *cm*. The dynamic pool option in the FAMS model was used because harvest was the primary metric of interest on brown trout population size structure. An initial population size of 10,000 age-1 fish, a *cm* and *cf* of 0.00 during their first year (i.e., mortality rates prior to stocking), and the *cm* at later ages was set to the mean estimated value of 0.30 described above. Proportional size distribution indices of preferred (PSD-P), memorable (PSD-M), and trophy (PSD-T) length-categories calculated in FAMS were used to evaluate harvest restriction effects on brown trout size structure. These same metrics were used to evaluate model accuracy by comparing pooled 2013–2016 BWTR sampling data with the 233-mm MLL scenario (i.e., no size limit). Because brown trout were stocked annually, recruitment was held constant. Rates of *cf* varied accordingly to the von Bertalanffy predicted ages of recruitment to length limit scenarios. Model simulations were run over a 50-year period. The dynamic pool model in FAMS was used to predict yield (kg), number of fish harvested, and number of fish reaching 460 mm under each harvest restriction scenario.

Results

Temperature

Temperatures were recorded for all years of the study and ranged between 0.7° C on 12 February 2012 to 25.6° C on 4 October 2013. Temperatures remained below short and long-term thermal maximums for all years except 2013. In 2013, the highest temperatures of the study were recorded between 3 October and 6 October (range = 22.8°–25.6° C); however, these high temperatures did not persist long enough to be considered unsuitable. Temperatures were highest in late September and early October for each year of the study (Figure 2).

Catch Rate and Stocking Contribution

A total of 733 brown trout were collected during the study, 487 during spring surveys and 246 during fall surveys. Overall mean CPUE in spring (Figure 3) ranged from 29.6 fish h^{-1} (SE = 5.7) to

73.8 fish h^{-1} (SE = 11.4) and was higher in 2014 and 2015 than in 2013 (F = 4.54, df = 3, 40; P = 0.0079). Fall mean CPUE ranged from 23.3 fish h^{-1} (SE = 3.5) to 31.3 fish h^{-1} (SE = 8.9) and appeared to show a slightly increasing trend through time, although mean CPUE was similar among years (F = 0.39, df = 2, 23; P = 0.7590). Mean CPUE was higher during spring surveys than fall surveys in 2014–2016 (t range = -3.34 to -4.83, df = 14, $P \leq 0.0050$), but was similar between seasons in 2013 (t = -0.09, df = 14, P = 0.3824; Figure 3).

Mean CPUE of age-1 brown trout followed a similar pattern to overall CPUE during spring surveys; however, the decreasing trend after 2014 was more evident (Figure 3). Mean CPUE ranged from 20.7 fish h^{-1} (SE = 4.4) to 54.2 fish h^{-1} (SE = 7.0), was highest in 2014, lowest in 2013, and intermediate in the other years (F = 8.06, df = 3, 40; P = 0.0003). Mean CPUE of age-1 fish in the fall ranged from 10.9 fish h^{-1} (SE = 4.4) to 16.5 fish h^{-1} (SE = 4.5) but was similar among years (F = 0.51, df = 3, 42; P = 0.6770). Similar to the trends observed for overall catch, mean CPUE of age-1 fish was higher in the spring than in fall in 2014–2016 (t range -2.92 to -7.10, $P \leq 0.0100$) but was similar between seasons in 2013 (t = -1.37, df = 14, P = 0.1910; Figure 3).

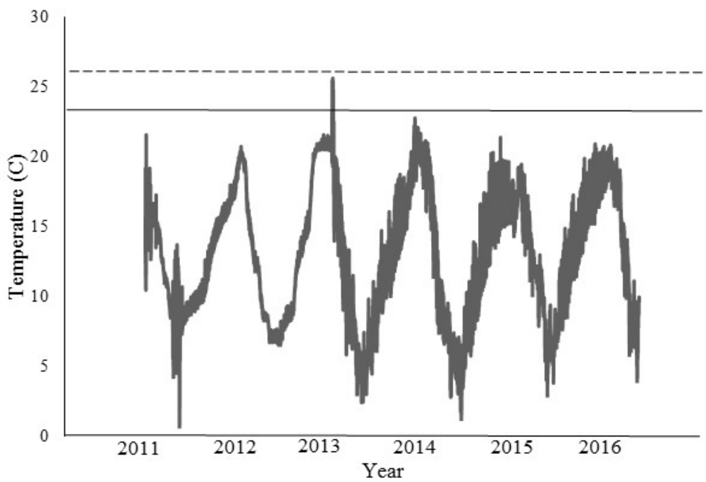

Figure 2. Water temperature data patterns in Bridgewater Tailrace, North Carolina, collected from October 2011 to January 2017. The solid line represents the suggested upper thermal tolerance for brown trout for 63 days (22.9° C), and the dashed line represents the suggested upper thermal tolerance for brown trout for 1 day (27.6° C; based on Wehrly and Wang 2007).

Hatchery contribution remained high during the entire survey; 63.8% to 81.8% of all trout in spring surveys and 56.3% to 80.0% in fall surveys were of hatchery origin (Figure 4). Non-marked fish were considered to be wild fish from natural reproduction, but their numbers were consistently low each year. Fall contribution peaked in 2013 and subsequently declined through the end of the survey, but spring contribution showed no trends. Fischer's exact test for independence indicated the only significant difference between spring and fall surveys was in 2015 when contribution was higher in spring than fall (X^2 = 0.044, df = 1, P = 0.0401).

Size Structure and Condition

Brown trout captured during this survey ranged from 89 mm to 710 mm TL. PSD, PSD-P, and PSD-M values were all higher in fall than spring for each year: PSD values ranged from 79 to 97 during spring surveys and 93 to 98 during fall surveys, PSD-P values ranged from 17 to 62 during spring surveys and 51 to 82 during fall surveys, and PSD-M values ranged from 1 to 12 during spring surveys and 9 to 25 during fall surveys (Figure 5). Trophy-length fish were captured each survey except during springs of 2014 and 2015; however, the numbers of harvested trophy-length fish were consistently extremely low throughout the study, and PSD-T values ranged from 0 to 3 during spring surveys and 2 to 5 during fall

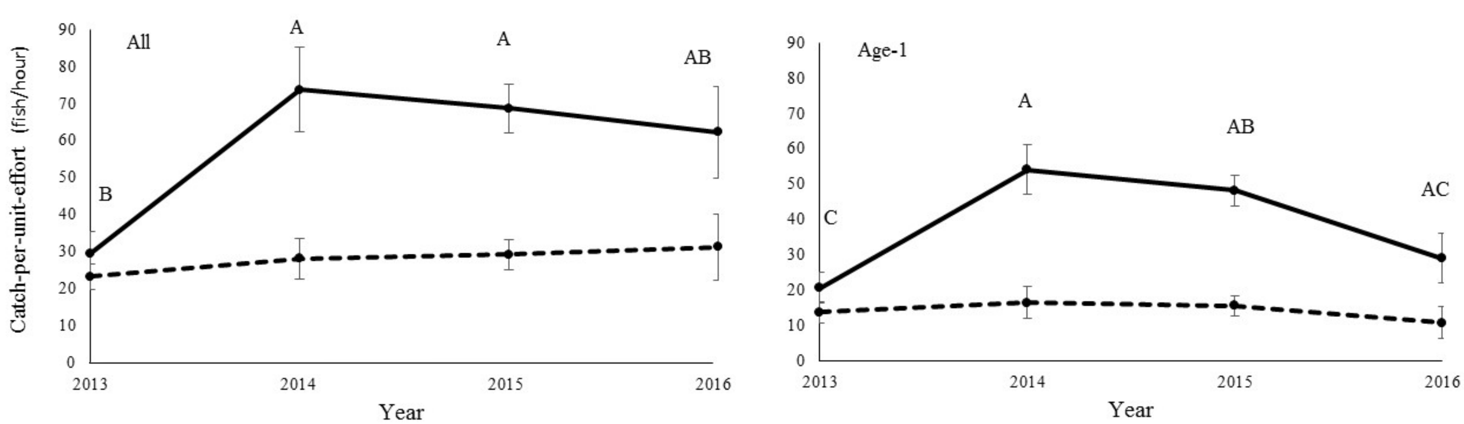

Figure 3. Catch-per-unit-effort for all brown trout and age-1 brown trout collected during the 2013–2016 electrofishing survey on Bridgewater Tailrace, North Carolina. Solid lines represent spring surveys, and dashed lines represent fall surveys. Means with different letters indicate significant differences from Tukey's HSD post hoc analysis among years. Error bars represent standard error.

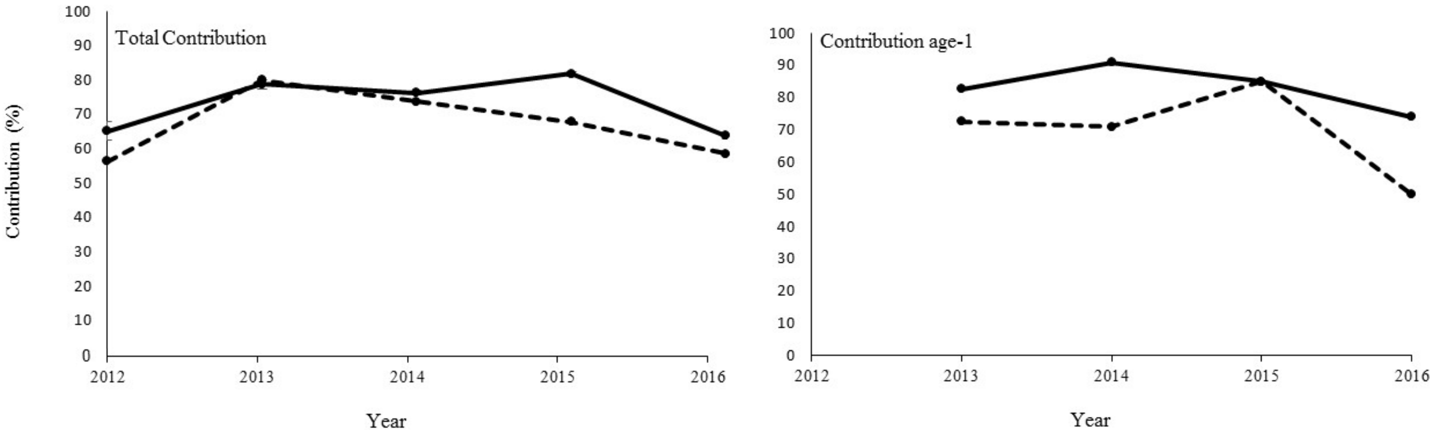

Figure 4. Percent contribution of stocked brown trout collected during the 2012–2016 Bridgewater Tailrace, North Carolina, electrofishing surveys for all ages compared to the entire sample and for age-1 fish compared to all tagged fish. The solid lines represent spring surveys. The dashed lines represent fall surveys.

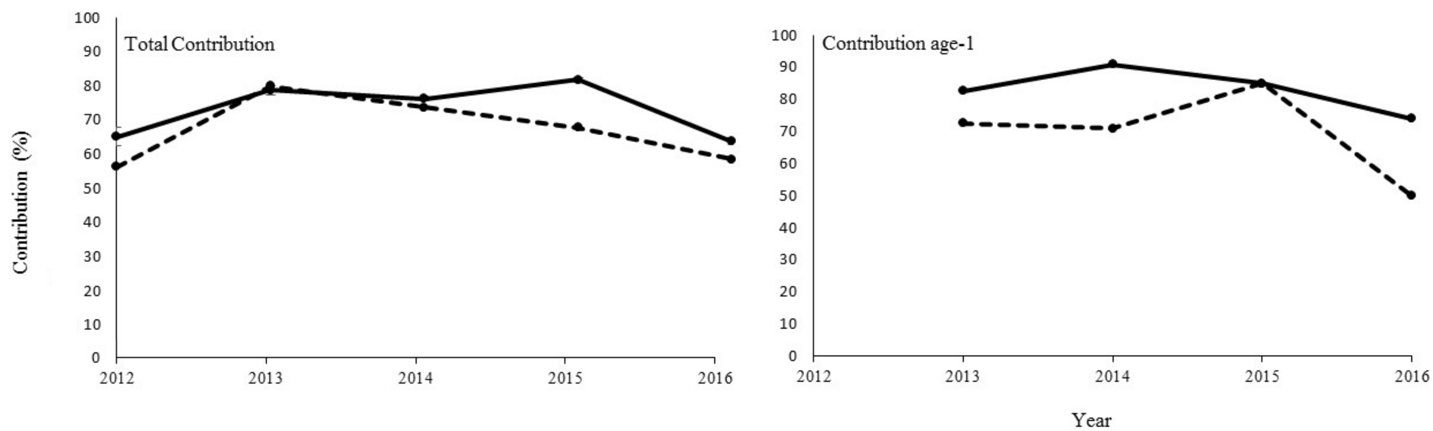

Figure 5. Proportional size distributions of quality (PSD = 230 mm TL), preferred (PSD-P = 300 mm TL), memorable (PSD-M = 380 mm TL), and trophy (PSD-T = 460 mm TL) length brown trout collected during spring (solid lines) and fall (dashed lines) survey periods (2013–2016) on Bridgewater Tailrace, North Carolina.

surveys (Figure 5). Length frequencies suggested smaller fish were captured more frequently during spring surveys than fall surveys (Figure 6).

Overall mean W_r values ranged from 88 to 96 in spring surveys and 86 to 95 in fall surveys (Table 1). Spring mean W_r was highest in 2012 and 2016 and lowest in 2015 (F = 13.1, df = 4, 482; P < 0.001). Fall mean W_r was highest in 2012 and lowest in 2014 (F = 4.42, df = 4, 241; P < 0.05). Overall mean W_r was higher in the spring than in the fall for 2014 and 2016 (t range 3.50 to 4.68, P < 0.001) but the reverse was true in 2015 (t = -2.52, df = 113, P = 0.0130). Mean W_r was similar between seasons in 2012 and 2013 (t range 0.09 to 1.47, $P \geq 0.1400$; Table 1).

Mean age-1 W_r values ranged from 87 to 92 in spring surveys and 83 (SE = 1.6) to 90 (SE = 1.1) in fall surveys (Table 1). Unlike overall W_r, mean W_r of age-1 fish was similar across years in spring (F = 2.13, df = 4, 308; P = 0.0773) and fall (F = 2.10, df = 4, 121; P = 0.0844). Likewise, mean W_r of age-1 fish was similar between spring and fall in 2012, 2013, 2015, and 2016 (t range -1.46 to 1.84, $P \geq 0.0710$) but was higher in spring than fall in 2014 (t = 4.92, df = 48, P < 0.001; Table 1).

Age, Growth, and Mortality

Ages were estimated for 596 tagged brown trout over the course of this study. Age-frequency histograms demonstrate a fishery dominated by age-1 fish with few fish recruiting to older year classes (Figure 7). Growth was rapid: fish attained 356 mm TL and 432

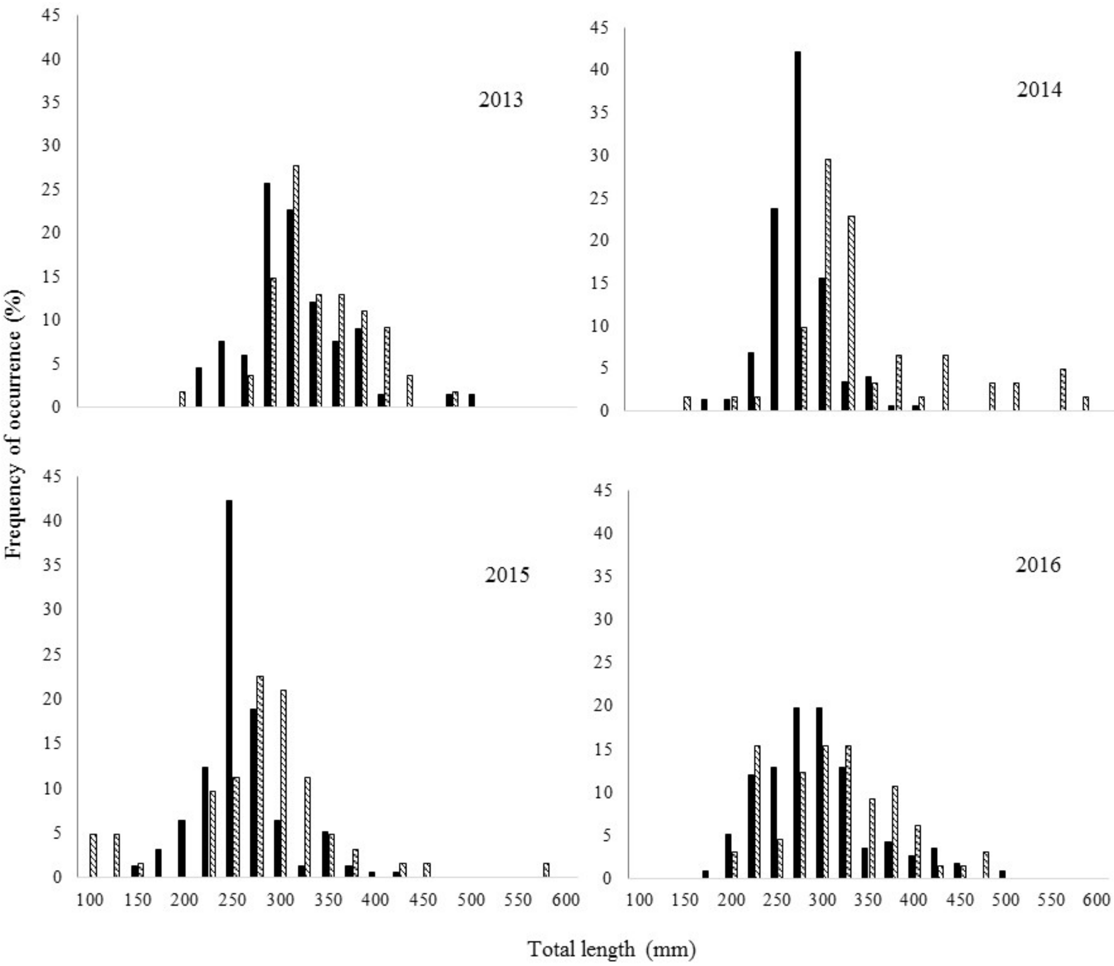

Figure 6. Length-frequency distributions for all brown trout collected during the 2013–2016 electrofishing surveys on Bridgewater Tailrace, North Carolina. Dark bars represent spring surveys, and dashed bars represent fall surveys. Fish are grouped by 25-mm size classes.

mm TL in 1.7 years and 2.9 years, respectively. Catch-curve analyses estimated *Z* at -0.600 thus conferring S and A values of 0.55 and 0.45, respectively (Table 2). The eight equations in the FAMS model estimated M to range from 0.27 to 0.58 (mean = 0.35); using the lowest, mean, and highest estimates of *M* along with the estimate of A from the catch curve conferred estimated *F* of 0.33, 0.25, and 0.02, respectively (Table 2).

Harvest Restriction Modeling

Modeling simulation parameters are presented in Table 2, and the *cm* and *cf* values used in the dynamic pool model are provided in Table 3. Given that F values estimated at the highest levels of *M* were unrealistically low, models were only run at the minimum and mean levels of *M* estimated by the FAMS model. The dynamic pool model size-structure predictions for the current approximated 233-mm MLL were similar to the size structure computed for electrofishing data (Table 4); thus, the model was relatively accurate

Table 1. Mean relative weights (standard errors) for all brown trout and age-1 brown trout collected during spring and fall survey periods (2012–2016) on Bridgewater Tailrace, North Carolina. Means with different letters within columns indicate significant differences from Tukey's HSD post-hoc analysis among years.

		Relative weight values	
Age class	Year	Spring	Fall
All	2012	94.9 (2.6)^{AC}	94.6 (1.9)^{A}
	2013	90.4 (1.3)^{AB}	87.5 (1.4)^{AB}
	2014	91 (0.7)^{AB}	85.5 (1.4)^{B}
	2015	88 (0.7)^{B}	91.0 (1.0)^{AB}
	2016	96.3 (0.9)^{AC}	89.5 (1.1)^{AB}
Age-1	2012	90 (1.8)	92 (2.1)
	2013	91 (3.1)	84 (1.9)
	2014	91 (0.7)	83 (1.6)
	2015	87 (1.0)	90 (1.1)
	2016	92 (1.1)	89 (5.6)

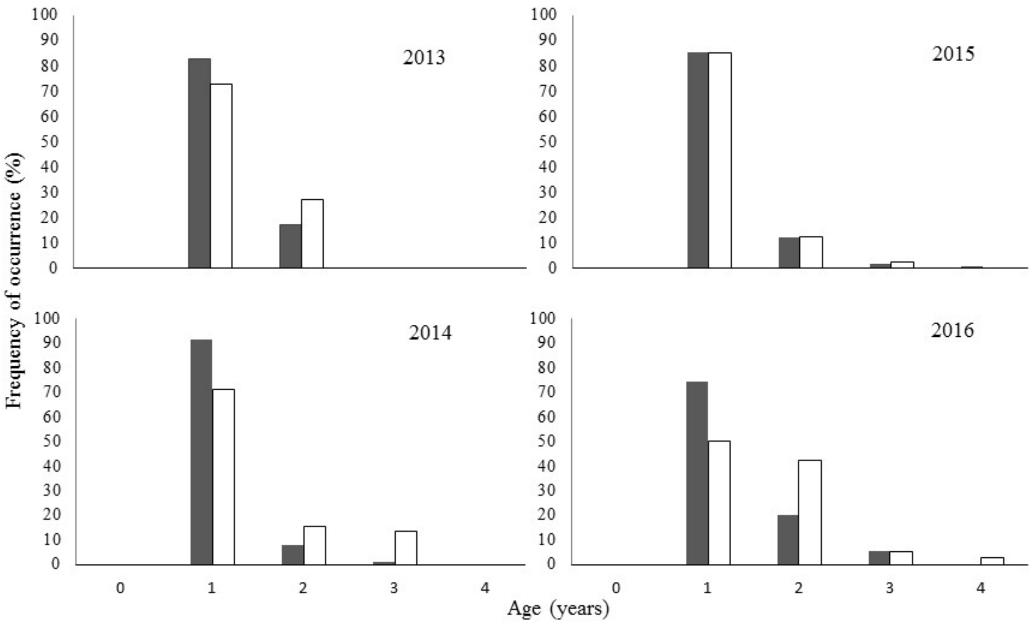

Figure 7. Age-frequency distributions of tagged brown trout collected during the 2013–2016 electrofishing surveys on Bridgewater Tailrace, North Carolina. Dark bars represent spring surveys, and dashed bars represent fall surveys.

at modeling this population. The yield-per-recruit model results in FAMS predicted that yield was maximized under the current MLL scenario when *cm* was 0.24, but growth overfishing occurred when *u* exceeded 0.30 (Figure 8). When *cm* was 0.30, yield was similar among all MLL scenarios when *u* was below 0.10; increases in *u* above this level displayed small decreases in yield with the 432-mm MLL compared to the 233-mm MLL. Once *u* increased above 0.20, yield was maximized with the 356-mm MLL, and at *u* above 0.30, yield under the 233-mm MLL leveled off (Figure 8). At a *cm* of 0.24, the number of fish reaching 460 mm with no MLL would range from approximately 17% at a *u* of 0.15 to 8% at a *u* of 0.30. These numbers were predicted to increase approximately 50% and 90% at a *u* of 0.15 under a 356-mm and 432-mm MLL, respectively (Figure 8). If *u* was as high as 0.30, the number of fish reaching that length would increase 2- to 4-fold. At a *cm* of 0.30, the number of fish reaching 460 mm would be correspondingly lower at all *u* levels, but the effects of each MLL would be similar to what was predicted at a *cm* of 0.24. Both MLL scenarios sharply decreased the number of fish anglers harvested compared to the current 233-mm MLL, especially when *u* was higher than 0.25, regardless of *cm* level. However, the tradeoff of larger, but fewer fish harvested was predicted to cause either little change in yield (at lower *u* levels) or increases in yield (at higher *u* level) for both MLL scenarios relative to the no-MLL scenario.

Compared to the current MLL, increased size structure indices were predicted under the 356-mm MLL, which corresponded to a predicted increase in the number of fish reaching 460 mm

Table 2. Parameters used for modeling simulations in the Fisheries Analysis and Modeling Simulator (FAMS) program (Slipke and Maceina 2014). Growth, length-weight, and catch-curve parameters were calculated across pooled samples of brown trout collected in the Bridgewater Tailrace, North Carolina, during 2012–2016. Conditional natural mortality (*cm*) rates were estimated from equations provided in FAMS. The instantaneous fishing mortality (*F*) rates were calculated from catch-curve results using FAMS-generated estimates of instantaneous natural mortality (*M*).

Category	Parameter and literature source	Estimate(s)
Growth	L_∞, fixed	710 mm
	K	0.184
	t_0	−1.884
Length-weight	*a*	−5.089
	b	3.032
Catch-curve analysis	A	0.45
	Z	−0.600
	S	0.55
cm	Chen and Watanabe (1989)	0.25
	Cubillos (1999)	0.25
	Djabali (1993)	0.24
	Hoenig (1983)	0.41
	Jensen (1996)	0.24
	Lorenzen (1996)	0.25
	Pauly (1980)	0.28
	Quinn and Deriso (1999)	0.44
	Mean *cm*	0.30
F	Lowest *M*	0.33
	Mean *M*	0.25
	Highest *M*	0.02

Table 3. Conditional natural mortality (*cm*) and conditional fishing mortality (*cf*) rates used in the dynamic pool model within Fisheries Analysis and Modeling Simulator program (Slipke and Maceina 2014) to evaluate brown trout size structure responses to three harvest restriction scenarios (MLL = minimum length limit). The *cf* values were determined by using catch-curve analyses.

Harvest restriction	Age range (years)	*cm*	*cf*
233-mm MLL	0–1	0.00	0.00
	1–3	0.30	0.22
	3–8	0.30	0.17
356-mm MLL	0–2	0.00	0.00
	2–8	0.30	0.17
432-mm MLL	0–3	0.00	0.00
	3–8	0.30	0.17

Table 4. Proportional size distribution indices for preferred (PSD-P), memorable (PSD-M), and trophy (PSD-T) length-categories with 95% confidence intervals (CI) for pooled electrofishing (EF) samples of brown trout collected from Bridgewater Tailrace, North Carolina, from 2012–2016. Dynamic pool option modeling results within the Fisheries Analysis and Modeling Simulator program (Slipke and Maceina 2014) are displayed for three harvest restriction scenarios: the approximated current 233-mm minimum length limit (MLL), a 356-mm MLL, and a 432-mm MLL. Models were run using conditional fishing and conditional natural mortality rates given in Table 3 with 10,000 (number of annual stocked brown trout) initial recruits.

Variable	EF data (CI)	233-mm MLL	356-mm MLL	432-mm MML
Number harvested		3865	3355	3044
Yield (kg)		2406	3134	3800
Number at 460 mm		1942	3786	6778
PSD-P	43 (40–47)	44	53	57
PSD-M	11 (9–13)	18	29	36
PSD-T	3 (2–5)	5	9	14

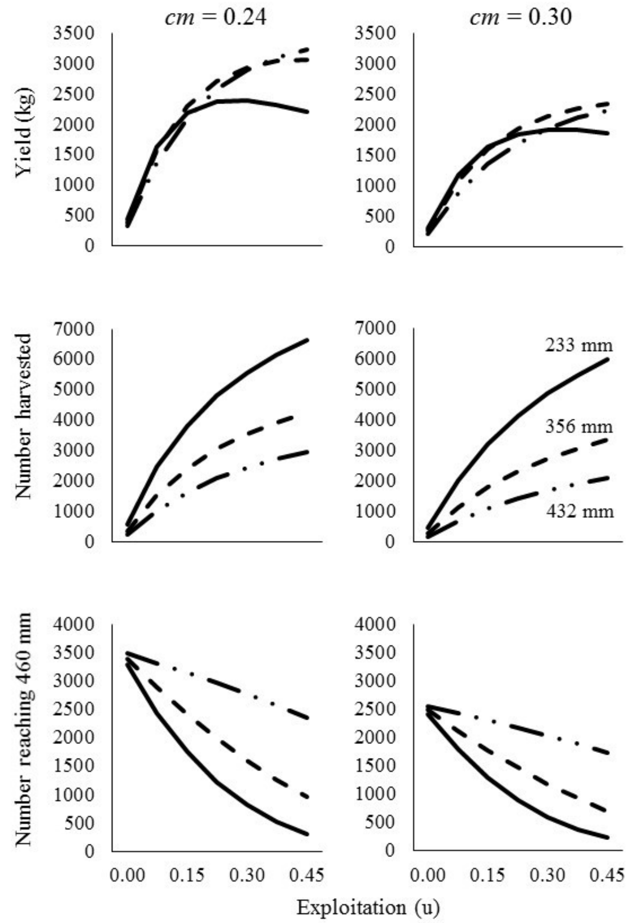

Figure 8. Yield-per-recruit modeling results within the Fisheries Analysis and Modeling Simulator program (Slipke and Maceina 2014) predicting brown trout yield, number harvested, and number reaching trophy-length (460 mm) at three levels of conditional natural mortality (*cm*) as a function of three minimum size limits (the approximated current 233-mm minimum length limit [MLL], a 356-mm MLL, and a 432-mm MLL) over a range of exploitation rates (*u*).

by 95% (Table 4). Implementation of the 432-mm MLL decreased the amount of harvested fish by 21%; however, yield was predicted to increase by 58% compared to the current MLL (Table 4). The 432-mm MLL was also predicted to increase the number of fish reaching 460 mm by 249% relative to the current MLL. Both 356-mm MLL and 432-mm MLL were predicted to result in higher size-structure indices due to redistribution of harvest, as PSD-P, PSD-M, and PSD-T values increased by 20%-30%, 61%-100%, and 80%-180%, respectively, compared to the current MLL (Table 4).

Discussion

Stocking advanced brown trout fingerlings in the fall was successful at creating and maintaining a fishery in BWTR; however, most of the population was composed of age-1 fish, with few recruiting to older year classes. An instantaneous fishery was created by using advanced fingerlings, and these fish persisted well until the following spring fishing season. A large decline in age-1 fish over summer, conjointly with few age-1 fish surviving to older year classes, resulted in a fishery dominated by young, small fish. Nevertheless, the fishery remains a popular destination for anglers and offers a unique experience in that area of North Carolina due to the floatable tailrace experience and the persistent, albeit low-density, population of trophy-sized fish. This study allowed NCWRC biologists to advance management approaches by evaluating whether this new stocking regime can enhance the BWTR and other similar fisheries.

Previous research suggested that elevated temperatures were responsible for declines in the BWTR brown trout population. Many studies have evaluated both the optimal temperature for growth and the thermal tolerance for lotic salmonids. Water temperature is a critical variable for survival and growth, and at times can be the dominant limiting factor in fisheries below dams (Johnson et al. 2006). Researchers have determined optimal growth temperatures for brown trout is between 12° and 19° C (Krause et al. 2005, Wehrly and Wang 2007). Most studies evaluating the thermal tolerance of salmonids are based on relatively short time periods (up to seven days; see Eaton et al. 1995). The long-term impacts on salmonids of elevated temperatures above optimal growth levels but below known short-term thermal tolerances are often not evaluated. Selong et al. (2001) suggested that studies describing sublethal temperatures during acute tests may not fully evaluate the effects of delayed mortality during long exposure. In response to this knowledge gap, Wehrly and Wang (2007) described upper thermal tolerance limits of brook trout (*Salvelinus fontinalis*) and brown trout for both short- and long-term exposure in natural conditions and determined these two species could tolerate max temperatures of 27.6° C for one day, 25.4° C for seven days, 24.2° C for 21 days, and 22.9° C for 63 days. Although water temperatures in the BWTR were high at times during certain years during this study, those temperatures did not reach or persist at detrimental levels for brown trout. Relative weight values during this study were generally moderate to high, regardless of when the sample occurred or what age class was being evaluated, suggesting that thermal stress was low and food supply was adequate (Blackwell et al. 2000, Hartman and Margraf 2006). Many other abiotic and biotic factors that were not assessed during this study could be responsible for the observed declines, however, including flow alterations, habitat limitations, and exploitation.

Altered flow regimes below dams usually result in rapid changes in flow and stage, which can negatively impact fishes in a variety of ways (Freeman et al. 2001). One of the most frequently employed methods of reducing flow fluctuation impacts from hydroelectric dams is the establishment of minimum flows (Weisberg and Burton 1993), and minimum flows in BWTR were increased and stabilized in 2012. Several studies have demonstrated that even when the frequency of flow fluctuations go unchanged, that increases in minimum flows can positively influence the feeding and growth of fish (Weisberg et al 1990, Wolff et al. 1990, Weisburg and Burton 1993). Other studies have suggested that reducing the frequency or magnitude of flow fluctuations is the best way to benefit downstream biota (Gislason 1985, Gaschignard and Berly 1987). Many of the historical issues in BWTR were hoped to be ameliorated with the increased minimum flows; however, summer impacts are persist.

Suspended sediments leading to habitat limitations can also negatively impact trout populations. Muddy Creek, a large third order stream and the main tributary in the study reach, was a known source of high sediment loads. Newcombe and MacDonald (1991) investigated parameters that regulated brown trout populations in Spruce Creek, Pennsylvania, and demonstrated that sediment concentrations exceeding 2000 mg L^{-1} for more than 10 h resulted in mortality of age-0 fish. A study evaluating sediment issues in Muddy Creek suggested that during large storm events sediment concentrations reached as high as 16,000 mg L^{-1} (Chen et al. 2004). Although Muddy Creek sediment inputs into the tailrace disperse rapidly due to dilution, it is nonetheless a major sediment input and may have negative impacts on brown trout.

An important unknown variable in the BWTR is the level of angler harvest; however, modeling simulation results confirm that given the estimated range of *u* used in predictions, the current BWTR harvest regulation is not sufficiently protecting the size structure of the brown trout population. True maximum age in the BWTR brown trout population was unknown (i.e., ages in models were estimated from tagged fish during this study); consequently, two FAMS-generated estimates of *cm* (Hoenig 1983, Quinn and Deriso 1999; Table 2) were likely biased, resulting in an overestimated level of *M* (Maceina and Sammons 2016). Over estimation of *M*, even in moderately exploited fisheries, can lead to management strategies that reduce the number of large, catchable-sized fish typically desired by anglers. Given that *M* values estimated in this study conferred unrealistic values of *u*, we elected to model only using the minimum and mean values of *M* estimated by the FAMS program. However, at these *cm* levels, model predictions showed evidence of growth overfishing and yield asymptoting at higher (≥30%) levels of *u*, which suggested that angler harvest could greatly influence the BWTR brown trout population managed under the no-MLL regulation. Exploitation was the most important factor in model predictions limiting the trophy potential of the BWTR fishery. Because management of a quality fishery was the desired goal, the model predicted that measures to reduce exploitation of smaller fish would be needed to achieve this goal, as the no-MLL regulation was likely too liberal under estimated levels of *u*. Advanced fingerlings are stocked at sizes susceptible to harvest, and based on observed and estimated growth rates, brown trout in the BWTR reached 356 mm TL in approximately 1.7 years after being stocked, whereupon only one fish could be harvested per day. Newly-stocked fish often are extremely vulnerable to angling and harvest rates may be high (Heimer et al. 1985, Clemon and Pardue 1986, Bettoli et al. 1999). Our electrofishing results confirmed that relatively few fish reached the protected length of 356 mm TL.

The critical length or age of a population managed under inadequate length limits may be unable to support a quality fishery unless exploitation is low (Ricker 1975, Slipke and Maceina 2014).

Dynamic pool model results indicated the critical length (or age) of the brown trout population in the BWTR was much higher than the no-MLL restriction. Therefore, a change in harvest restrictions from the current regulation was warranted due to the management goal of producing a quality fishery in the BWTR. Higher MLLs always result in a reduction of the number of fish available for angler harvest (Isermann et al. 2002, Sammons and Maceina 2008); however, anglers often support the use of increased MLLs to meet management goals (Newman and Hoff 2000, Paukert et al. 2002). Of the two increased MLLs examined, modeling simulations predicted the 356-mm MLL would provide adequate benefits to the BWTR brown trout size structure without severely reducing the number of fish anglers could harvest: our simulations showed 36%–61% fewer brown trout would be harvested under a 356-mm MLL compared with the no-MLL regulation, but fish would be 20%–80% larger, resulting in small reductions in overall yield from the fishery.

Overall, stocking advanced fingerling brown trout in the fall appears to be creating and maintaining a fishery in the BWTR; however, the numbers of large (≥356 mm TL) and older (≥2 years) fish are low. There is most likely a combination of abiotic and biotic factors preventing robust recruitment of young fish to older year classes. Trophy fish were still present in low numbers and growth rates were fast, suggesting that minor alterations to the current management approach such as increasing the minimum size limit may continue to enhance the fishery. Thus, the NCWRC adopted a 356-mm MLL and two-fish creel limit per day for the BWTR on 1 August 2018, based on the findings from this study.

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Literature Cited

Besler, D. A. 2003. Performance of stocked fingerling brown trout in the Bridgewater Tailrace, 2000–2002. North Carolina Wildlife Resources Commission, Raleigh.

Bettinger, J. M. and P. W. Bettoli. 2002. Fate, dispersal, and persistence of recently stocked and resident rainbow trout in a Tennessee tailwater. 2002. North American Journal of Fisheries Management 22:425–432.

Bettoli, P. W., S. J. Owens, and M. Nemeth. 1999. Habitat, reproduction, survival, and growth in the South Fork of the Holston River. Final Report to Tennessee Wildlife Resources Agency, Fisheries Report 99–3, Nashville.

Blackwell, B. G., M. L. Brown, and D. W. Willis. 2000. Relative weight (W_r) status and current use in fisheries assessment and management. Reviews in Fisheries Science 8(1):1–44.

Blinn, D. W., J. P. Shannon, L. E. Stevens, and J. P. Carder. 1995. Consequences of fluctuating discharge for lotic communities. Journal of North American Benthological Society 14:223–248.

Chen, C. W., L. Weintraub, L. Olmsted, and R. A. Goldstein. 2004. Decision framework for sediment control in muddy creek watershed. Journal of the American Water Resources Association 1553–1562.

Chen, S. and S. Watanabe. 1989. Age dependence of natural mortality coefficient in fish population dynamics. Nippen Suisan Gakkaishi 55:205–208.

Clemon, W. F. and G. B. Pardue. 1986. Harvest, survival, growth, and movement of five strains of hatchery-reared rainbow trout in Virginia streams. North American Journal of Fisheries Management 6:569–579.

Cubillos, L. A., R. Alarcon, and A. Brante. 1999. Empirical estimates of natural mortality for the Chilean hake (*Merluccius goyi*). Fisheries Research 42:147–153.

Cushman, R. M. 1985. Review of ecological effects of rapidly varying flows downstream from hydroelectric facilities. North American Journal of Fisheries Management 5:330–339.

Djabali, F., A. Mehailia, M. Koudil, and B. Brahmi. 1993. Empirical equations for the estimation of natural mortality in Mediterranean teleosts. Naga, the ICLARM Quarterly 16:35–37.

Eaton, J. G., J. H. McCormick, B. E. Goodno, D. G. O'Brien, H. G. Stefany, M. Hondzo, and R. M. Scheller. 1995. A field information-based system for estimating fish temperature tolerances. Fisheries 20(4):10–18.

Elliot, J. M., M.A. Hurley, and R. J. Fryer. 1995. A new, improved growth model for brown trout *Salmo trutta*. Functional Ecology 9:290–298.

Freeman, M. C., Z. H. Bowen, K. D. Bovee, and E. R. Irwin. 2001. Flow and habitat effects on juvenile fish abundance in natural and altered flow regimes. Ecological Applications, 11, 179–190.

Gaschignard, O. and A. Berly. 1987. Impact of large discharge fluctuations on the macroinvertebrate populations downstream of a dam. Pages 145–157 *in* J.F. Craig and J.B. Kemper, editors. Regulated Streams, Advances in Ecology. Plenum Press, New York, New York.

Gislason, J. C. 1985. Aquatic insect abundance in a regulated stream under fluctuating and stable diel flow patterns. North American Journal of Fisheries Management 5:39–46.

Goudreau, C. J. 1994. Bridgewater tailrace survey—1993. North Carolina Wildlife Resources Commission, Raleigh.

Guy, C. S., R. M. Neumann, D. W. Willis, and R. O. Anderson. 2007. Proportional size distribution (PSD): A further refinement of population size structure index terminology. Fisheries 32:348.

Hartman, K. J. and F. J. Margraf. 2006. Relationships among indices, feeding, and growth of walleye in Lake Erie. Fisheries Management and Ecology13:121–130.

Heimer, J. T., W. M. Frazier, and J. S. Griffith. 1985. Post-stocking performance of catchable-size hatchery rainbow trout with and without pectoral fins. North American Journal of Fisheries Management 5:21–25.

Hoenig, J. M. 1983. Empirical use of longevity data to estimate mortality rates. U.S. National Marine Fisheries Service Fishery Bulletin 82:898–903.

Isermann, D. A., S. M. Sammons, P. W. Bettoli, and T. N. Churchill. 2002. Predictive evaluations of size restrictions as management strategies for Tennessee reservoir crappie fisheries. North American Journal of Fisheries Management 22:649–657.

Jensen, A. L. 1996. Beverton and Holt life history invariants result in optimal trade-off of reproduction and survival. Canadian Journal of Fisheries and Aquatic Sciences 53:820–822.

Johnson, R. L., S. C. Blumenshine, and S. M. Coghlan. 2006. A bioenergetics analysis of factors limiting brown trout growth in an Ozark tailwater river. Environmental Biology of Fish 77:121–132.

Krause, C. W., T. J. Newcomb, and D. J. Orth. 2005. Thermal habitat assessment of alternative flow scenarios in a tailwater fishery. River Research and Applications 21:581–593.

Lorenzen, K. 1996. The relationship between body weight and natural mortality in juvenile and adult fish: a comparison of natural ecosystems and aquaculture. Journal of Fish Biology 49:627–647.

Lobon-Cervia, J. and P. A. Rincon. 1998. Field assessment of the influence of temperature on growth rate in a brown trout population. Transactions off the American Fisheries Society 127:718–728.

Maceina, M. J. and S. M. Sammons. 2016. Assessing the accuracy of published natural mortality estimators using rates determined from five unexploited freshwater fish populations. North American Journal of Fisheries Management 36:433–446.

Neumann R. M., C. S. Guy, and D. W. Willis. 2012. Length, weight, and associated indices. Pages 637–676 *in* A. V. Zale, D. L. Parrish, and T. M. Sutton, editors. Fisheries Techniques, 3rd edition. American Fisheries Society, Bethesda, Maryland.

Newcombe, C. P. and D. D. McDonald. 1991. Effects of suspended sediment on aquatic ecosystems. North American Journal of Fisheries Management 11:72–82.

Newman, S. P. and M. H. Hoff. 2000. Evaluation of a 16-inch minimum length limit for smallmouth bass in Pallete Lake, Wisconsin. North American Journal of Fisheries Management 20:90–99.

Paukert, C. P., D. W. Willis, and D. W. Gablehouse, Jr. 2002. Effect and acceptance of bluegill length limits in Nebraska natural lakes. North American Journal of Fisheries Management 22:1306–1313.

Pauly, D. 1980. On the interrelationships between natural mortality, growth parameters, and mean environmental temperature in 175 fish stocks. ICES Journal of Marine Science 39:175–192.

Pender, D. R. and T.J. Kwak. 2002. Factors influencing brown trout reproductive success in Ozark tailwater rivers. Transactions of the American Fisheries Society 131:698–717.

Quinn, J. W. and T. J. Kwak. 2000. Use of rehabilitated habitat by brown trout and rainbow trout in an Ozark tailwater river. North American Journal of Fisheries Management 20:737–751.

_____ and _____. 2003. Fish assemblage changes in an Ozark river after impoundment: a long-term perspective. Transaction of the American Fisheries Society. 132:110–119.

Quinn, T. J. and R. B. Deriso. 1999. Quantitative Fish Dynamics. Oxford University Press, New York.

Rash, J. M., D. W. Goodfred, and E. M. Jones, Jr. 2018. Evaluation of coded wire tag retention in brown trout (*Salmo trutta*) fingerlings tagged at three anatomical locations. Journal of Freshwater Ecology 33:1, 513–519.

Ricker, W. E. 1975. Computation and interpretation of biological statistics of fish populations. Bulletin of the Fisheries Research Board of Canada 191:382

Robson, D. S. and D. G. Chapman. 1961. Catch curves and mortality rates. Transactions of the American Fisheries Society 90:181–189.

Sammons, S. M. 2016. Catch and exploitation of shoal bass in the Flint River, Georgia, USA: implications for harvest restrictions. North American Journal of Fisheries Management 36:606–620.

_____ and M. J. Maceina. 2008. Evaluating the potential effectiveness of harvest restrictions on riverine sunfish populations in Georgia, USA. Fisheries Management and Ecology 15:167–178.

Selong, J. H., T. E. McMahon, A. V. Zale, and F. T. Barrows. 2001. Effect of temperature on the growth and survival of bull trout, with application of an improved method of determining thermal tolerance in fishes. Transactions of the American Fisheries Society 130:1026–1037.

Slipke, J. W. and M. J. Maceina. 2014. Fishery Analysis and Modeling Simulator (FAMS). Version 1.64. American Fisheries Society, Bethesda, Maryland.

von Bertalanffy, L. 1938. A quantitative theory of organic growth. Human Biology 10:181–213.

Wehrly, K. E. and L. Wang. 2007. Field-based estimates of thermal tolerance limits for trout: incorporating exposure time and temperature fluctuation. Transactions of the American Fisheries Society 136:365–374.

Weisberg, S. B. and W. H. Burton. 1993. Enhancement of fish feeding and growth after an increase in minimum flow below the Conowingo Dam. North American Journal of Fisheries Management 13:103–109.

_____, A. J. Janicki, J. Gerritsen, and H. A. Wilson. 1990. Enhancement of benthic macroinvertebrates by minimum flow from a hydroelectric dam. Regulated Revers: Research and Management 5:265–277.

Wolff, S. W., T. A. Wesche, D. D. Harris, and W. A. Hubert. 1990. Brown trout populations and habitat changes associated with increased minimum low flows in Douglas Creek, Wyoming. Biological Report 90(11), U.S. Fish and Wildlife Service, Washington D.C.