Notes

Standard Weight Equation for Brook Trout in Southern Appalachian Mountains Streams

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Abstract

Brook Trout *Salvelinus fontinalis* in southern Appalachian Mountains streams of the United States occur at the southernmost portion of their native range, and occupy small, isolated, and low-productivity headwater streams. The existing standard weight (W_s) equation is applicable only to Brook Trout $>$ 120 mm total length (TL), but many individuals in the region are smaller than this minimum size threshold due to their habitat characteristics. Here, we developed a new W_s equation for Brook Trout in southern Appalachian Mountains streams using length–weight data on 72,502 individuals. The weighted quadratic empirical-percentile method minimized length-related bias in relative weight compared to the regression-line-percentile and weighted linear empirical-percentile methods. The proposed W_s equation was: $\log_{10}W = -3.364 + 1.378 \times \log_{10}L + 0.397 \times (\log_{10}L)^2$, where W was weight (g) and L was TL (mm). The new equation characterized body condition of Brook Trout in southern Appalachian Mountains streams more accurately than the existing equation.

Keywords: *Salvelinus fontinalis*; fisheries management; relative weight index; body condition; length-weight indices

Received: April 2020; Accepted: October 2020; Published Online Early: October 2020; Published: June 2021

Citation: Harris AC, Hanks RD, Rash JM, Goodfred DW, Kanno Y. 2021. Standard weight equation for Brook Trout in southern Appalachian Mountains streams. *Journal of Fish and Wildlife Management* 12(1):183–189; e1944-687X. https://doi.org/10.3996/JFWM-20-026

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Introduction

Weight–length relationships are a key index in fisheries management as they provide a rapid, noninvasive means of evaluating the physiological condition of fish (Neumann et al. 2012). Of several methods to assess fish condition, managers often rely on relative weight (W_r), where an individual fish's weight is compared to that of a fish with the same length based on a standard weight (W_s) equation developed for that species (Blackwell et al. 2000). Researchers have developed standard weight equations for a number of North American freshwater fishes (Murphy et al. 1990),

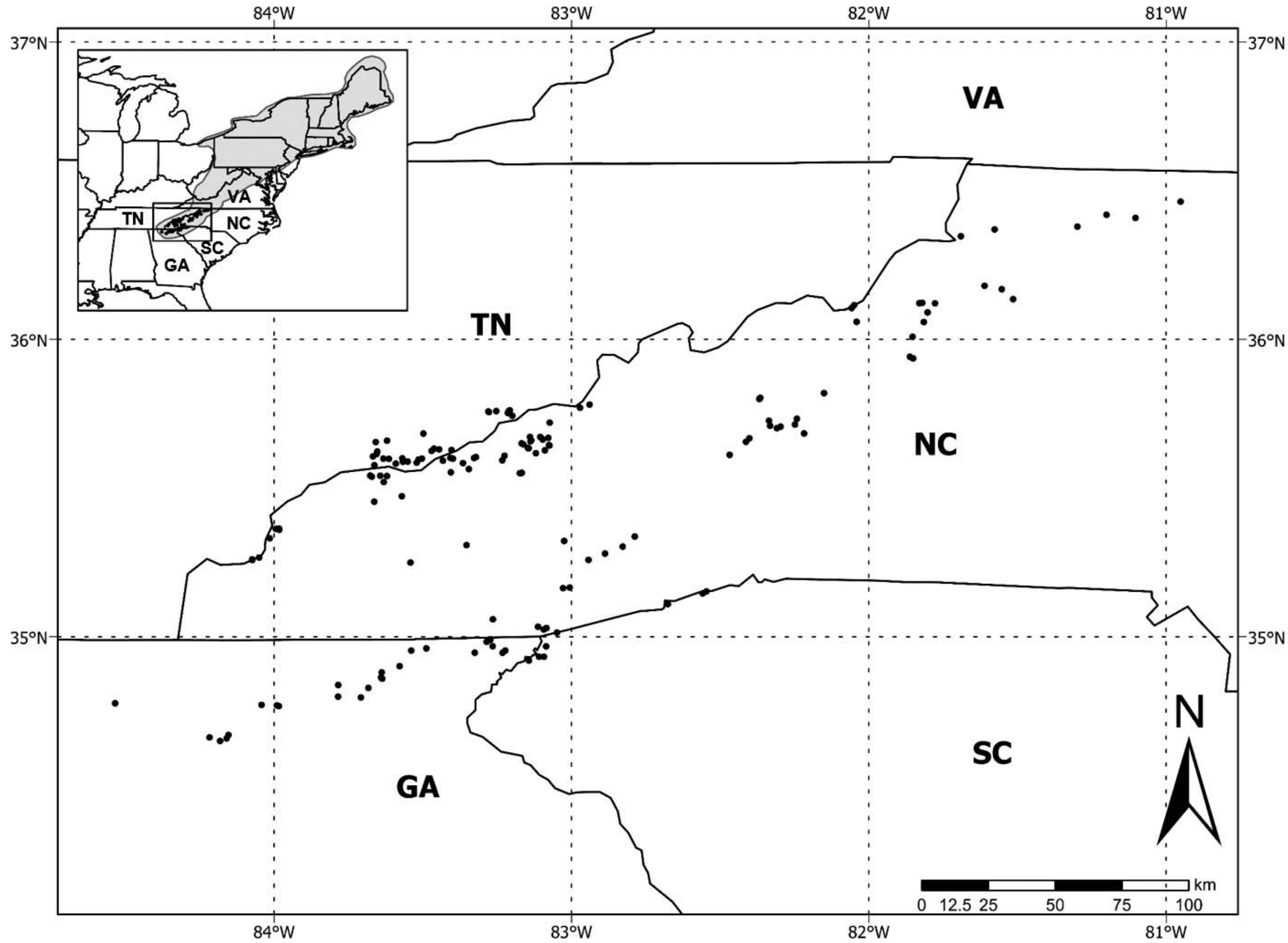

Figure 1. Locations of 153 populations from which we developed the standard weight (W_s) equation for Brook Trout *Salvelinus fontinalis* in southern Appalachian Mountains streams using data from 1980 to 2019. States shown are Georgia (GA), North Carolina (NC), South Carolina (SC), Tennessee (TN), and Virginia (VA). The shaded region of the inset map indicates the native range of Brook Trout in the eastern United States.

with different equations for a single species by sex (Brown and Murphy 1993; Neumann and Willis 1994), habitat type (Milewski and Brown 1994; Simpkins and Hubert 1996), and body size (Flammang et al. 1999). Given their ability to exploit a variety of lotic and lentic habitat types, this practice is common for fishes in family Salmonidae, including Brown Trout *Salmo trutta* (Milewski and Brown 1994; Hyatt and Hubert 2001a), Rainbow Trout *Oncorhynchus mykiss* (Simpkins and Hubert 1996), and Cutthroat Trout *Oncorhynchus clarkii* (Kruse and Hubert 1997).

Brook Trout *Salvelinus fontinalis* in southern Appalachian Mountains streams occur at the southernmost limit of their native range in eastern North America (Figure 1) and are a Species of Greatest Conservation Need in North Carolina, South Carolina, and Tennessee (North Carolina Wildlife Resources Commission 2015; South Carolina Department of Natural Resources 2015; Tennessee Wildlife Resources Agency 2015). These populations have declined greatly due to habitat loss and fragmentation and introductions of nonnative Brown Trout and Rainbow Trout (Moore et al. 1986; Hudy et al. 2008; Kanno et al. 2016a). Small, isolated Brook Trout populations in southern Appalachian Mountains streams show signs of genetic drift including decreased genetic diversity, low effective population size, and increased extinction risk (Pregler et al. 2018; Weathers et al. 2019). Remaining populations occur in low-productivity, high-elevation headwater streams (i.e., suboptimal habitat), where limited food availability and habitat space lead to small adult size (Konopacky and Estes 1986; Ensign et al. 1990; Kulp and Moore 2005; Knoepp et al. 2016). The existing W_s equation for Brook Trout (Hyatt and Hubert 2001b) is applicable to fish 120–620 mm in total length (TL), but those in southern Appalachian Mountains streams attain a much smaller maximum body size ($\leq$ 270 mm TL; see below) with many fish below the 120-mm TL minimum threshold for the existing equation. Importantly, researchers developed the existing W_s equation based on a data set comprised of 113 sites (68 lotic and 45 lentic sites) across 15 U.S. states and two Canadian provinces, with only two lotic sites in the southern Appalachian Mountains region (North Carolina) included in the

Table 1. Geographic distribution, date range, number of populations, and number of individuals used to develop a new standard weight (W_s) equation for southern Brook Trout *Salvelinus fontinalis* in southern Appalachian Mountains streams.

State	Date range	Populations	Individuals
Georgia	2009–2017	24	2,839
North Carolina	1986–2019	92	48,299
South Carolina	2014–2015	9	572
Tennessee	1980–2016	28	20,792
Total	1980–2019	153	72,502

analysis (Hyatt and Hubert 2001b). Fisheries biologists should not apply standard weight equations for individuals outside the target body size range (Flammang et al. 1999), highlighting the need for a separate W_s equation for Brook Trout populations in the southern Appalachian Mountains streams. To achieve an unbiased assessment of body condition of Brook Trout in southern Appalachian Mountains streams, we developed a new W_s equation using length–weight data on 72,502 individuals from 153 populations.

Methods

To develop a W_s equation for Brook Trout in southern Appalachian Mountains streams, we compiled a length (mm) and wet weight (g) data set of self-reproducing Brook Trout (i.e., no stocked fish) collected by backpack electrofishing surveys in wadeable streams (mean stream width $= 5.9$ m; SD $= 3.0$ m) from four states (Georgia, North Carolina, South Carolina, and Tennessee; Figure 1; Data S1, *Supplemental Material*). We measured length as TL for all records. We defined a population as a collection of individuals from the same stream. We filtered sampling dates to range from June through September (mean $=$ July 22) by following the approach of Hyatt and Hubert (2001b) for developing the North American range-wide equation for Brook Trout. Additionally, we removed populations with < 20 individuals (Bonvechio et al. 2010) and individuals with weight > 2 SD from the mean for each 10-mm length category. Finally, we limited the body length range to 80–266 mm TL. We chose the minimum body length following the variance-to-mean ratio method (Murphy et al. 1990), and this threshold approximately removed young-of-the-year fish. Individuals larger than the maximum limit were not common in our small headwater streams (≤ 10 individuals per 10-mm length category). After the screening process, the data set included 72,502 individuals from 153 populations collected between 1980 and 2019 (Table 1). Forty-one percent of the individuals in our data set were below the 120-mm TL minimum size threshold for the existing equation (Hyatt and Hubert 2001b).

We developed and compared three W_s equations using the regression-line-percentile (RLP) method (Murphy et al. 1990) and weighted linear and quadratic empirical-percentile (EmP) methods (Gerow et al. 2005; Bonvechio et al. 2010). The RLP method characterizes weight–length relationships by giving an equal weight to each population, and its derivation included three steps: 1) fit a linear regression between $\log_{10}$ length and $\log_{10}$ weight for each population, 2) identify the 75th percentile predicted weights in each 10-mm length category across populations, and 3) $\log_{10}$ transform the 75th percentile predicted weights and regress them against the $\log_{10}$ transformed midpoint of each 10-mm length category. The EmP method is similar to the RLP method, except that the 75th percentile weights in each 10-mm length category are based on means from measured body weights across populations (Gerow et al. 2005). For the EmP method, we used weighted linear regression (EmP–L) and quadratic regression (EmP–Q), the latter of which is effective in reducing length-related bias by allowing the $\log_{10}$(length)–$\log_{10}$(weight) relationship to be curvilinear (Gerow et al. 2005). We used the number of populations represented in each 10-mm length category as regression weights. Thus, fish of commonly observed body length ranges influenced the function of length–weight relationship. All three methods resulted in similar weight–length functional forms (i.e., an exponential increase in weight with length). We chose one equation by quantifying bias as the 75th percentile of mean measured weights across populations for each 10-mm length category divided by predicted weights, and visually confirming lack of length-related bias in predicted weights. Finally, we predicted and compared weights using the new equation and the existing equation (Hyatt and Hubert 2001b) and characterized percent differences in predicted weights between the two methods for each 10-mm length category. We performed all analyses in R v. 4.0.2 (R Core Team 2020).

Results

Both the RLP and EmP-L approaches resulted in length-related bias, but we did not observe this in the EmP-Q method (Figure 2). The 75th percentile of mean measured weights across populations exceeded predicted weights at the smallest and largest individuals in the RLP and EmP-L methods, and the bias was particularly evident at 230–269 mm TL (3–6%). The EmP-Q method quantified the length–weight relationships most accurately across the body length range considered here (80–266 mm); Equation 1 is our proposed W_s equation for Brook Trout in southern Appalachian Mountains streams:

$$\log_{10}W = -3.364 + 1.378 \times \log_{10}L + 0.397 \times (\log_{10}L)^2 \quad (1)$$

where W is weight (g) and L is TL (mm).

Find equations derived from the RLP and EmP-L methods in Figure S1, *Supplemental Material*. Predicted weights based on the new equation were lower than those predicted by the existing W_s equation across all length categories (Figure 3).

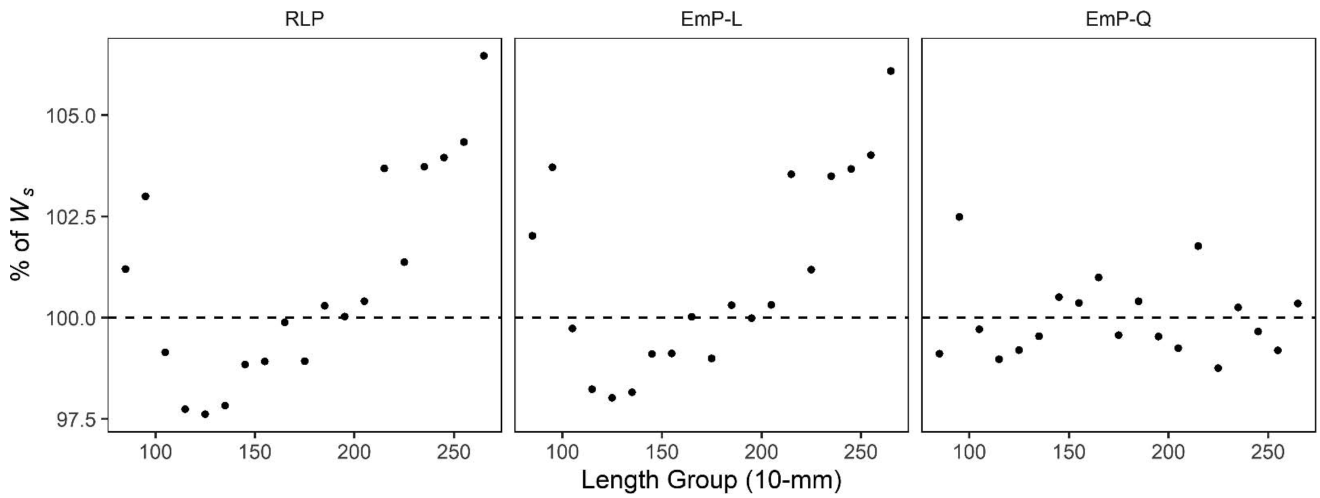

Figure 2. Length-related bias plots of the regression-line-percentile (RLP; left panel), linear empirical-line percentile (EmP-L; middle panel), and quadratic empirical-line percentile (EmP-Q; right panel) standard weight (W_s) equations developed for Brook Trout *Salvelinus fontinalis* in southern Appalachian Mountains streams using data from 1980 to 2019. Length categories are in 10-mm increments (e.g., 105 = 100–109.99 mm TL), and % of W_s represents the 75th percentile of mean measured weights across populations for each 10-mm length category divided by the predicted weights and expressed as a percentage. The dashed line at 100 represents the point at which the predicted and measured weights are equal.

Discussion

The small body length of Brook Trout in southern Appalachian Mountains streams, for which the existing W_s equation for the species (Hyatt and Hubert 2001b) cannot apply, necessitated the development of a separate W_s equation. Our study highlighted additional insights on the importance of this new equation for characterizing and managing these populations at the southern periphery of the native range. Predicted weights based on the new equation were consistently lower than those predicted by Hyatt and Hubert (2001b) across the body length range considered in this study. Lower weights at given body lengths are likely due to the low-productivity, high-elevation headwater streams (i.e., suboptimal habitat) in which Brook Trout currently persist (Konopacky and Estes 1986; Ensign et al. 1990; Kulp and Moore 2005; Knoepp et al. 2016). Historically, Brook Trout occurred in larger streams which are currently predominated by nonnative Brown Trout and Rainbow Trout (Moore et al. 1986; Hudy et al. 2008; Kanno et al. 2016a). The new equation is applicable to fish $\geq$ age 1 from 80 to 266 mm TL in the isolated headwaters of the southern Appalachian region. In addition, the new equation was derived using the EmP-Q method, whereas the existing equation was derived using the RLP method (Hyatt and Hubert 2001b). The EmP-Q method minimized length-related bias in this study and provides a more accurate tool to evaluate body condition of Brook Trout across a range of body lengths. The superior performance of the EmP-Q method is due to its ability to accommodate a curvilinear relationship between body length and weight, which persists even after both variables are $\log_{10}$ transformed (Gerow et al. 2005).

Evaluation of trout condition is critical in the face of emerging and continued threats to southern Appalachian Brook Trout, such as disease (Ruiz et al. 2017a, 2017b) and climate change (Kanno et al. 2016b). Southern Appalachian Mountains Brook Trout not only occupy unique habitat, but are also genetically distinct from the northern populations within the native range (Danzmann et al. 1998; Fausch 2008). Fisheries managers tasked with the conservation of Brook Trout, such as those in southern Appalacian Mountains streams, may put forth management goals and actions based on biased inferences when comparing their resources to those in other portions of the species range using a universal W_s equation. However, the new W_s equation allows managers to make unbiased inferences regarding fish condition among populations within their jurisdictional waters and monitor the same populations over time in response to management actions and environmental change. The new W_s equation provides fisheries managers with a tool to characterize body condition more accurately than the existing equation.

Supplemental Material

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Data S1. Excel spreadsheet containing the compiled Brook Trout *Salvelinus fontinalis* length and weight data from Georgia, North Carolina, South Carolina, and Tennessee. Compiled data include observations from 1980 to 2019. Table includes the following fields: total length in millimeters (Length_mm), weight in grams (Weight_g), and 10-mm length category (Length_Cat).

Found at DOI: https://doi.org/10.3996/JFWM-20-026.S1 (1.02 MB XLSX).

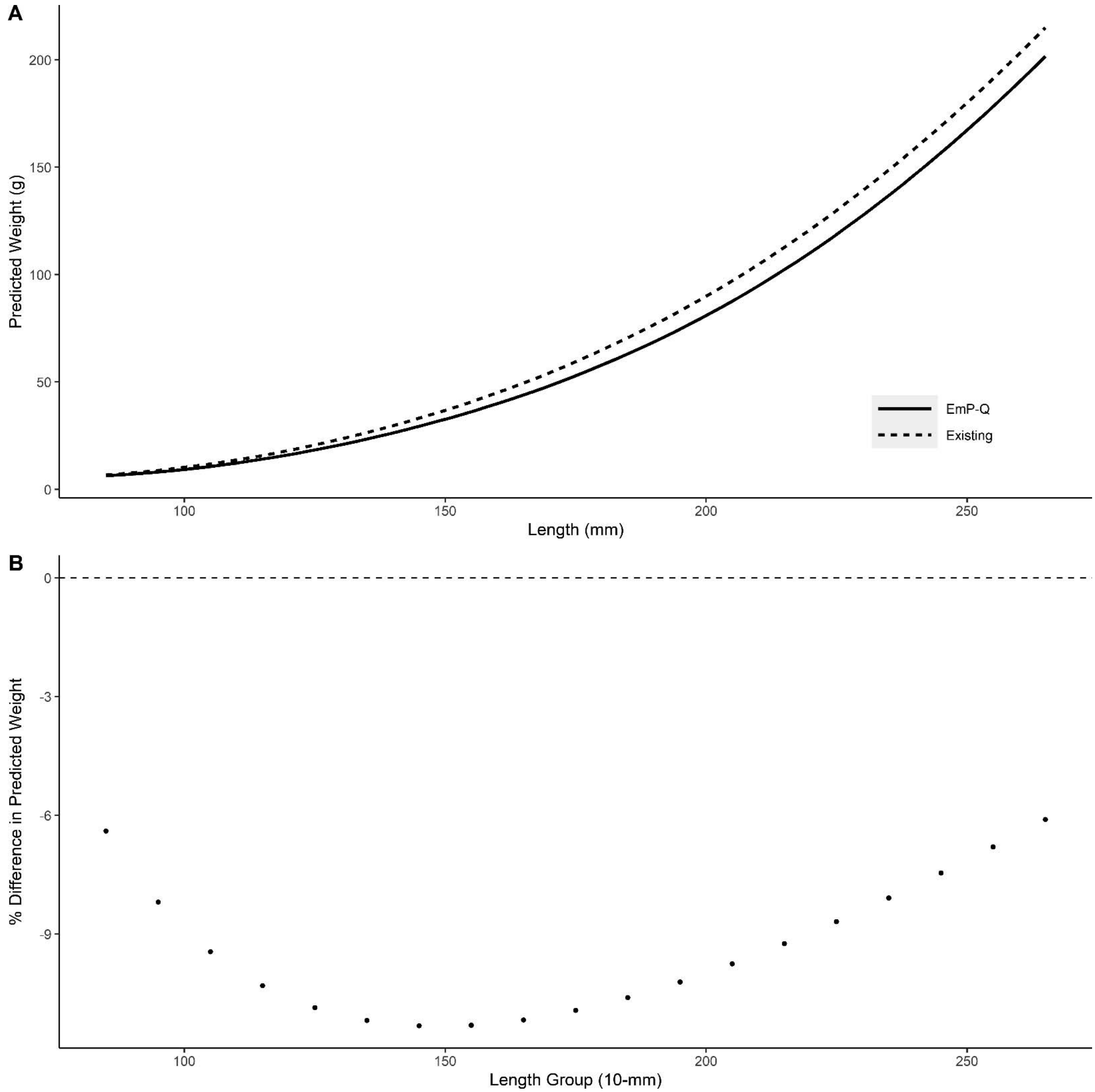

Figure 3. (**A**) Comparison of the existing standard weight (W_s) equation (Hyatt and Hubert 2001b; dashed line: $\log_{10}W = -5.186 + 3.103 \log_{10}L$) and the new W_s equation for Brook Trout *Salvelinus fontinalis* in southern Appalachian Mountains streams (solid line: $\log_{10}W = -3.364 + 1.378 \times \log_{10}L + 0.397 \times [\log_{10}L]^2$). (**B**) Percent difference between predicted weight values of the existing W_s equation and new southern Appalachian W_s equation. Length categories are in 10-mm increments (e.g., 105 = 100–109.99 mm TL).

Figure S1. Comparison of the existing equation (Hyatt and Hubert 2001b; dashed line: $\log_{10}W = -5.186 + 3.103 \log_{10}L$), new regression-line-percentile equation (RLP; dotted line: $\log_{10}W = -5.164 + 3.072 \times \log_{10}L$), new linear empirical-line percentile equation (EmP-L; dot-dashed line: $\log_{10}W = -5.187 + 3.082 \times \log_{10}L$), and new quadratic empirical-line percentile equation (EmP-Q; solid line: $\log_{10}W = -3.364 + 1.378 \times \log_{10}L + 0.397 \times [\log_{10}L])^2$. The new equations were developed for Brook Trout *Salvenius fontinalis* in southern Appalachian Mountains streams using data from 1980 to 2019.

Found at DOI: https://doi.org/10.3996/JFWM-20-026.S2 (98 KB DOCX).

Acknowledgments

This study was financially supported by the North Carolina Wildlife Resources Commission via funds provided by the U.S. Fish and Wildlife Service's Federal Aid in Sport Fish Restoration Program. We thank Matt Kulp (Great Smoky Mountains National Park), Anthony Rabern (Georgia Department of Natural Resources), and Dan Rankin (South Carolina Department of Natural Resources) for their assistance with the access and acquisition of trout data. We thank Jim Habera, Matt Kulp, Anthony Rabern, three anonymous reviewers, and the editors at *Journal of Fish and Wildlife Management* for their constructive reviews of an earlier version of this manuscript.

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