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THERMAL HABITAT ASSESSMENT OF ALTERNATIVE FLOW SCENARIOS IN A TAILWATER FISHERY

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ABSTRACT

Tailwaters below hydropower dams can create desirable coldwater trout fisheries; however, a flow regime ideal for hydropower often presents challenges for management of the fishery. The Smith River tailwater (Henry County, VA) offers a self-sustaining brown trout fishery managed for trophy trout (≥ 406 mm), yet trophy-sized fish are rare. Slow growth and small size are likely caused by any one or a combination of thermal habitat, limited food resources, and/or physical habitat. To evaluate the potential for thermal habitat improvement, temperature changes resulting from alternative flows were assessed with a one-dimensional hydrodynamic model coupled with a water temperature model. Simulated temperatures from each flow scenario were assessed every 2 river kilometres over a 24 kilometre river section below the dam for occurrence of optimal growth temperatures, as well as compliance with Virginia Department of Environmental Quality hourly temperature change and daily maximum temperature standards. The occurrence of optimal growth temperatures increased up to 11.8% over existing conditions by releasing water in the morning, decreasing the duration of release, and not increasing baseflow. Incidences of hourly temperature changes greater than 2°C were reduced from 4% to 0–1.2% by non-peaking releases, increasing baseflow, morning releases, and decreasing the duration of release. Maximum temperature occurrence (>21°C) decreased from 1.3% to 0–0.1% by releasing flows daily to prevent elevated temperatures on non-generation days, increasing baseflow, increasing duration of release, and releasing in the morning rather than evening. Despite conflicting adjustments to best improve all thermal criteria concurrently, a 7-day/week, morning, one hour release regime was determined to improve all criteria throughout the tailwater compared to existing conditions.

KEY WORDS: temperature modelling; thermal habitat; flow regime; tailwater; ADYN & RQUAL; brown trout; growth

INTRODUCTION

Tailwater fisheries in river reaches below dams with hypolimnetic releases often provide unique and highly desirable fishing opportunities for trout in geographic areas that could not otherwise support coldwater fish species. However, while beneficial for supporting coldwater fisheries, the thermal aspects of a hypolimnetic release can be biologically limiting to the aquatic community. Determination of those limiting factors can be a challenge without resources to conduct a comprehensive study of the biological community. Additionally, funding resources may limit large structural alterations to the hydro facility. In some cases, approaching these situations with the best guess at the biological limiting factor allows for incremental improvements to be made with a willing partner agency. Modelling physical aspects of the river, such as temperature, is often a cost-effective way to begin evaluating changes that may prove beneficial to the fishery (Dortch and Martin, 1989). This is especially true if flow regulation is the only approach to achieving changes.

Water temperature is a critical parameter for survival, growth, spawning and embryonic development of fish, and in some cases may present the dominant limiting factor in rivers below dams (Petts, 1984). Temperature influences survival and growth by regulating the speed of muscle contractions and metabolic rates, which dictate swimming, prey capture, and food assimilation ability (Chavin, 1973; Reynolds and Casterlin, 1979; Wardle, 1979; Saltveit, 1990). Temperatures consistently below or above species-specific thresholds cause stress or mortality to fish while

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constant temperatures may limit growth. For example, a diel temperature cycle causes significantly greater growth rates in brown trout than constant temperature conditions (Spigarelli *et al.*, 1982). In tailwaters that rapidly fluctuate releases to generate electricity, the wide range and quickly changing temperatures can reduce fish survival and growth. Peaking flow regimes may cause rapid temperature declines when the cold water flow pulse mixes with downstream water warmed by ambient conditions (Cushman, 1985; Krause, 2002; Orth *et al.*, 2001, 2002). When temperature quickly declines (i.e. cold-shock) the rate of body heat loss is rapid and fish can experience a loss of equilibrium, reduced swimming ability, or mortality (Chavin, 1973; Reynolds and Casterlin, 1979; Ottaway and Forrest, 1983; Saltveit *et al.*, 1995; Smythe and Sawyko, 2000). In tailwaters, many of these restrictive temperature conditions such as constantly cold release temperatures, warm temperatures downstream due to ambient conditions and low flows, and large hourly temperature changes during hydropeaking may occur simultaneously or throughout a 24 h period.

The Smith River Tailwater (SRT) in southwestern Virginia (Henry County) was formed when Philpott Dam was completed by the Army Corps of Engineers (USACE) in 1953 to provide flood control, hydropower, and recreational opportunities (Figure 1). The hydropower operation uses a peaking regime in which flow releases vary widely and rapidly (1.4 to 36.8 $m^3 s^{-1}$ within 30 min) to provide electricity during peak demand periods (USACE, 2001; USGS, 2001). The tailwater offers a stocked rainbow trout fishery and a self-sustaining brown trout fishery. The SRT, managed for trophy trout (i.e. $\geq$406 mm) from 5.3 to 10.0 river kilometres (rkm) below Philpott Dam, produced the historic Virginia state record brown trout caught in 1979 weighing 8.48 kg (Mohn, 2001). Presently, brown trout seldom exceed 406 mm (0.63 kg) (Orth *et al.*, 2001, 2002, 2003). Slow growth and small size are likely caused by any one or a combination of thermal habitat, limited food resources, and/or physical habitat. The fishery provides a unique recreational opportunity logging over 36 000 angler hours in 1995 and generating approximately $500 000 in economic revenue (Hartwig, 1998).

One hypothesis based on four years of temperature data in the SRT is that brown trout growth is limited by lack of optimal growth temperatures, high temperatures at downstream locations, and rapid hourly temperature fluctuations. Near the dam (0.7 rkm) temperature averages 8°C (SD = 3°C) and exhibits very little daily fluctuation. At upstream locations (*c.* 0–5 rkm) daily temperature rarely exceeds 12°C and these cold temperatures would extend further downstream during summer (June, July, August) if not for inflows from a tributary at 5.3 rkm which raises

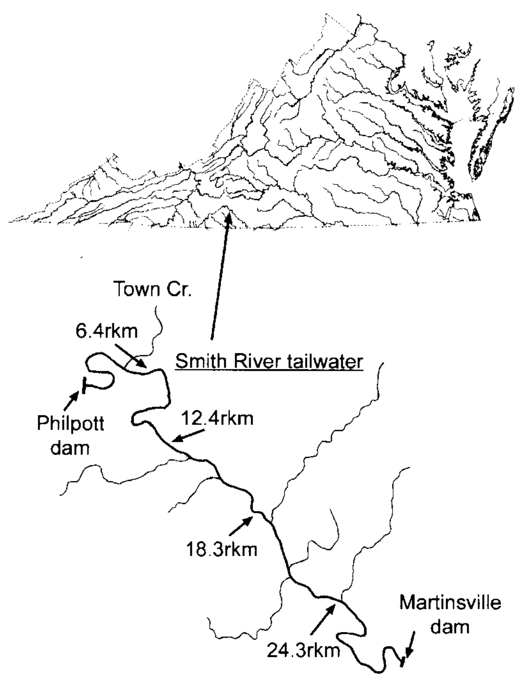

Figure 1. Location of the Smith River Tailwater in southwestern Virginia and selected river kilometre (rkm) locations where temperatures were modelled

temperature an average of 2°C. Occurrences of brown trout optimal growth temperatures (12–19°C; Brown, 1974; Brungs and Jones, 1977; Raleigh *et al.*, 1986; Smith, 1994; Ojanguren *et al.*, 2001) are greatest from May to September and occurrence increases with downstream distance. During non-generation periods (typically weekends) at downstream locations (*c.* 14–24 rkm) water temperatures up to 25°C were recorded which infringes upon the upper critical range (22–26°C; Brungs and Jones, 1977; Elliot, 1981) of brown trout. Additionally, these elevated temperatures exceed the Virginia Department of Environmental Quality's (DEQ) 21°C maximum temperature standard for stockable trout waters (DEQ, 1997). The DEQ's hourly temperature change standard of 2°C was also exceeded by temperature declines up to 7°C within an hour caused by the hydropeaking releases.

The SRT flow schedule directly influences thermal regime, therefore, in the absence of temperature control devices, adjustment to the flow schedule may improve thermal habitat. Adjustments could include changes in flow duration, magnitude, time of day, and days per week. Additional alternatives include increases in baseflow and ramping rather than peaking the release. In the absence of consideration of structural changes to the hydro project, our goal was to assess the thermal regime to determine if benefits to the fishery could be achieved by flow management alone. Specifically, our objectives were to use a dynamic flow and stream temperature model (Hauser and Walters, 1995) to evaluate alternative flow scenarios for: (1) increasing occurrence of optimal growth temperatures (12–19°C), (2) reducing occurrence and magnitude of hourly temperature fluctuations, and (3) reducing occurrence of 21°C temperature exceedance for the improvement of brown trout growth and survival. While temperature may be the dominant limiting factor on this fishery, additional parameters such as physical habitat, food resources, and dissolved oxygen (DO) were reviewed from other studies on the SRT (USFWS, 1986; Newcomb *et al.*, 2001; Orth *et al.*, 2001, 2002, 2003).

METHODS

Data collection and field measurements

Water temperatures were predicted with the TVA River Modeling System developed by the Tennessee Valley Authority (Hauser and Walters, 1995), which links the ADYN hydrodynamic model and the RQUAL water quality model. Hourly temperatures were predicted from July 1999 to February 2001 at 2 rkm intervals from 0.6 to 24.3 rkm below Philpott Dam. We evaluated thermal habitat from May to September 2000 when SRT brown trout mean absolute growth rates are greatest (Orth *et al.*, 2001). To develop the model for the SRT a suite of input parameters were collected. Hourly meteorological and solar radiation parameters were obtained from the nearest observation stations: Roanoke, VA, 74 km away (NCDC, 2001) and Bluefield, WV, 144 km away (CONFRRM, 2001). Discharge data were obtained from three gauging stations along the SRT (USGS, 2001). Lateral inflows were estimated by calculating flow differences between gauging stations. Town Creek, which has a temperature influence on the SRT, was included as an individual lateral inflow in the model. Water temperature was recorded every 30 min with Onset® data loggers at locations near the dam and downstream (0.6, 2.7, 5.1, 5.6, 10.2, 18.3, and 24.3 rkm) for SRT thermal habitat assessment and model calibration, validation, and predictive ability assessment. An hourly recording data logger in Town Creek provided lateral inflow temperature data for this tributary. Cross-sectional streambed profiles at 37 locations were measured using surveying techniques (Figure 2). Stream width, riparian vegetation offset from stream-bank, and vegetation height (Bartholow, 1989) were measured at 102 random locations along each stream bank from 0.5 to 24.0 rkm. Elevation, latitude, longitude, river kilometre locations, and azimuth were measured from a topographic map.

Model calibration and validation

The RQUAL model was calibrated with one year of data and validated with a second year of data. To calibrate the model, input parameters (typically calibration coefficients) were adjusted until the trend of the predicted and measured water temperature closely matched when viewed graphically at multiple longitudinal river locations. Calibration effectiveness was further assessed by calculating predictive ability, which is the difference between the measured and predicted temperature values. Predictive ability of hourly temperature predictions and daily maximum hourly temperature change was assessed as hourly residuals (i.e. the difference between predicted and measured temperature) averaged by month.

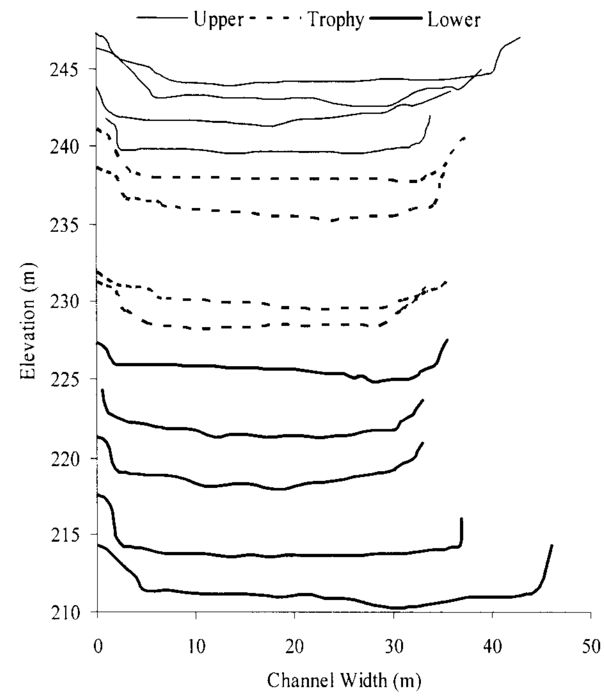

Figure 2. Representative bankfull cross-sections of pools and runs in the upper (0.0–5.3 rkm), trophy (5.3–10.0 rkm), and lower (10.0–24.3 rkm) reaches of the Smith River Tailwater

Model validation was assessed with a one-sided chi-square test for difference ($P \leq 0.05$) between counts of absolute residuals from the calibrated time periods (summer, autumn, winter 1999/2000 predictions) to the validation time periods (summer, autumn, winter 2000/01 predictions). Predictions for the validation periods used the same calibrations as the calibrated seasons and the predictions tested were from the most downstream modelled site (24.3 rkm) where residual error was greatest. Counts of absolute residuals were separated into a 2×2 contingency table based on a predictive ability category of suitable (0–4°C) versus unsuitable (>4°C) for predicting biological differences (Conover, 1971).

Alternative flow scenarios

Fifteen alternative flow scenarios were developed in addition to the existing flow regime from May to September 2000 (Table I). Scenarios differed from existing conditions by altering the number of days per week of generation, baseflow, time of day of generation release, whether releases were peaked or ramped, generation duration, as well as no generation. A run-of-river flow regime was developed using daily inflow into Philpott reservoir computed by the USACE (USACE, 2001). Ramping scenarios increased flow from 1.4 $m^3 s^{-1}$ to 36.8 $m^3 s^{-1}$ over three hours and remained at 36.8 $m^3 s^{-1}$ for one hour. Total quantity of water released over this four hour period (3 h ramping + 1 h at 36.8 $m^3 s^{-1}$) is equal to that of the two hour generation scenarios. Time at which flow reached 36.8 $m^3 s^{-1}$ was 7 am or 5 pm.

Hourly predicted temperatures from May to September 2000 at 13 locations (2 rkm intervals) from 0.6 to 24.3 rkm downstream of Philpott dam were compared between the 15 alternative flow scenarios and existing flow conditions. Scenarios were evaluated for percentage time optimal brown trout growth temperatures (12–19°C) occurred, percentage time daily maximum hourly temperature change (MHTC) exceeded 2°C, magnitude of MHTC, and percentage time 21°C was exceeded. Selection of these temperature criteria was based on the assumption that temperatures outside 12–19°C will restrict food assimilation and metabolic activity, rapid temperature fluctuations will induce stress, and temperatures greater than 21°C will induce stress and/or be lethal.

Table I. Flow scenarios assessed with the ADYN & RQUAL model on the Smith River from 1 May to 30 September 2000

Scenario	Days per week of generation	Base flow ($m^3 s^{-1}$)	Peak flow ($m^3 s^{-1}$)	Release time	Ramping duration (h)	Generation duration (h)
Existing conditions	~7	~1.4	~36.8	~5 pm		~1
5-day 2 h release	5	1.4	36.8	5 pm		2
5-day 5 h release	5	1.4	36.8	5 pm		5
Steady baseflow	0	1.4	1.4			
Increased steady baseflow	0	8.5	8.5			
Run of river	0		Daily inflow to Philpott Reservior			
Evening 1 h release	7	1.4	36.8	5 pm		1
Evening 2 h release	7	1.4	36.8	5 pm		2
Morning 1 h release	7	1.4	36.8	7 am		1
Morning 2 h release	7	1.4	36.8	7 am		2
Evening 1 h release with increased baseflow	7	2.8	36.8	5 pm		1
Evening 2 h release with increased baseflow	7	2.8	36.8	5 pm		2
Morning 1 h release with increased baseflow	7	2.8	36.8	7 am		1
Morning 2 h release with increased baseflow	7	2.8	36.8	7 am		2
Evening ramped release	7	1.4	36.8	5 pm	3	1
Morning ramped release	7	1.4	36.8	7 am	3	1

RESULTS

Model calibration

Hourly predictions closely followed the diel temperature fluctuation for most days and river locations; however, there were occurrences of poor predictive ability (Figure 3). Absolute residuals of hourly predictions averaged from May to September 2000 (average under- and over-prediction residuals in parentheses) were 0.9°C (−0.6, +1.1), 1.4°C (−1.2, +1.3), and 1.6°C (−1.7, +1.0) at 5.1, 18.3 and 24.3 rkm respectively. Mean absolute residuals of MHTC were 2.3°C (−0.6, +2.5), 1.8°C (−0.1, +1.9), and 1.0°C (−0.3, +1.0) at 5.1, 18.3, and 24.3 rkm respectively.

Model validation

Graphically, the trend of the predicted and measured temperature for the independent dataset seasons matched in closeness and similarity to the calibrated seasons. Statistically, the RQUAL model validated (i.e. no statistical difference between residual error counts of the calibration and validation time periods) for all assessed seasons within the suitable predictive ability category (0–4°C) ($P = 0.50$).

Alternative flow scenarios

The alternative flow scenarios resulted in thermal conditions that differed from the existing conditions in three different ways: (1) the scenario caused improvement at all river locations (i.e. from the dam at 0 rkm to 24.3 rkm downriver); (2) the scenario caused no improvement at any river location; or (3) the scenario caused improvement at some locations but not others (Figure 4).

Occurrence of optimal growth temperatures. The morning 1 h release scenario caused the largest mean increase over existing conditions for optimal growth temperatures occurring from 2.2 to 24.3 rkm (+11.8%, Table II). The percentage occurrence of optimal growth temperatures increased to +18.9% when narrowed to the trophy trout section (5.3–10.0 rkm). Only the steady baseflow scenario caused greater occurrence of optimal growth conditions (+27.8%) within the trophy trout section. However, the steady baseflow scenario resulted in a decline (−8.1%) over existing conditions in the SRT lower section (10.0–24.3 rkm). Morning releases (7 am), shorter duration releases (1 h), and scenarios with 1.4 $m^3 s^{-1}$ baseflow, caused greater occurrence of optimal growth temperatures

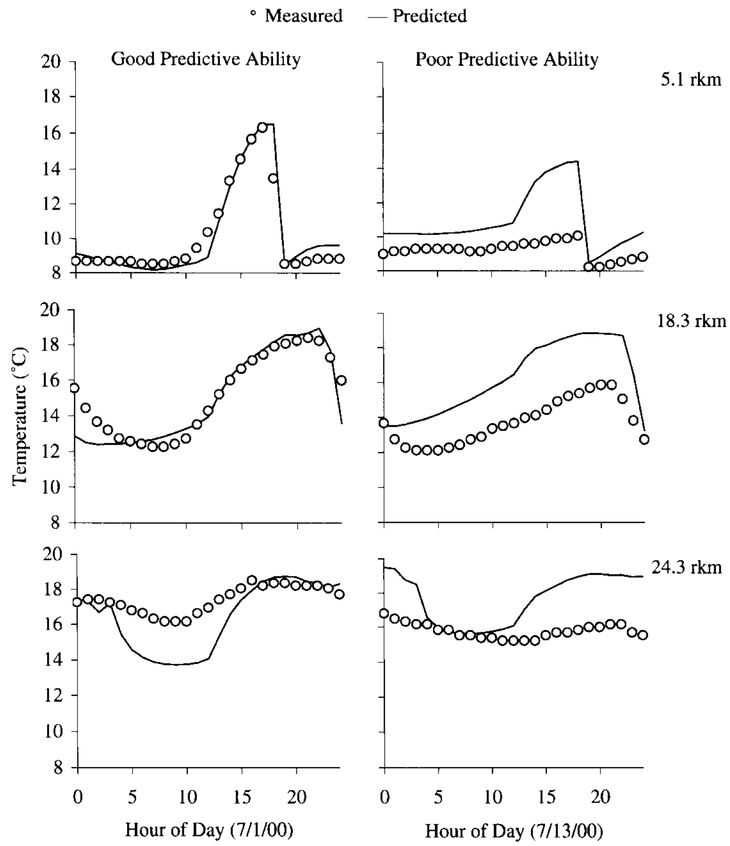

Figure 3. Examples of good (1 July 2000) and poor (13 July 2000) predictive ability over a 24-hour period. Graphs display hourly RQUAL predicted temperatures and data logger measured temperatures at 5.1, 18.3, and 24.3 rkm below Philpott Dam

than evening releases (5 pm), longer duration releases (2 h), and scenarios with increased baseflow (2.8 $m^3 s^{-1}$), respectively.

Morning flow releases allow ambient conditions to warm the water all day following the release, thus water temperatures remain within the optimal growth range for a greater duration of the night. Evening releases, however, halt the day-time warming, temperatures fall below the optimal range, and are unable to warm again until the following day. A shorter duration release (1 h versus 2 h) and no increase to the baseflow allow the river to warm more easily because there is less volume of water in the channel than for other scenarios.

Maximum hourly temperature change (MHTC). Scenarios with no hydropeaking (steady baseflow, increased steady baseflow, and run-of-river) caused the largest reduction in daily MHTC from existing conditions. Additionally, these scenarios prevented MHTC from exceeding 2°C during more than 99% of May to September 2000 at all river locations (0.6–24.3 rkm) (Table II). Of the unsteady release scenarios (i.e. hydropeaking), the morning 1 h release with increased baseflow caused the largest reduction to the average daily MHTC and percentage time MHTC exceeded 2°C (2.8% reduction over existing conditions; for reference 4.2% = 30 days, 2°C is exceeded 1 hour each day) (Table II). Morning releases (7 am), shorter duration releases (1 h), and scenarios with increased baseflow (2.8 $m^3 s^{-1}$), caused less occurrence of MHTC exceeding 2°C than did evening releases (5 pm), longer duration releases (2 h), and scenarios with 1.4 $m^3 s^{-1}$ baseflow, respectively.

Tailwater temperatures are cooler in the morning after nocturnal cooling and thus more similar to the temperature of morning releases, which reduced MHTC when mixed. The smaller quantity of water released over 1 h versus 2 h had reduced ability to change temperature in the channel, and because of attenuation, impacted for a shorter distance downstream. An increased baseflow decreased MHTC by dampening the impact of released water and by maintaining cooler temperatures within the channel. Non-peaking scenarios completely eliminate the pulse of cold

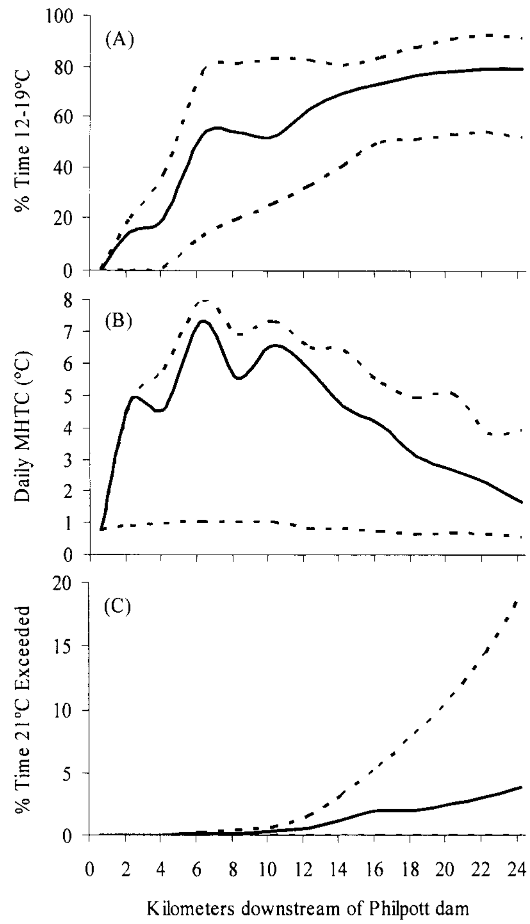

Figure 4. (A) Percentage time (of May to September 2000) that water temperature is within 12 to 19°C (i.e. optimal growth range for brown trout); (B) average daily maximum hourly temperature change (MHTC); and (C) percentage time that 21°C is exceeded under existing conditions (solid line) and the range of simulated conditions (dotted lines)

water travelling rapidly downriver and thus the source of large hourly temperature changes. Ramping flows slightly decreased the magnitude of MHTC by gradually increasing the flow of released water so that released and downstream water mixed more slowly. However, the evening ramped release increased the percentage time 2°C MHTC was exceeded due to an extended mixing period.

Exceedance of 21°C. Temperature predictions exceeded 21°C most often under the steady baseflow and run-of-river scenarios at downstream sites (*c.* 10.0–24.3 rkm) (Table II and Figure 4). Exceedance of 21°C was prevented during more than 99% of May to September 2000 by seven scenarios (increased steady baseflow, morning 2 h release, evening 1 h and 2 h release with increased baseflow, morning 1 h and 2 h release with increased baseflow, and morning ramped release) (Table II). Predicted temperatures rarely exceeded 21°C (<1%) during the months of May and September for all scenarios at all river locations.

The 5-day/week release scenarios caused temperatures to exceed 21°C during weekends when no hydropeaking occurred at sites from 6.4 to 24.3 rkm (Figure 5). Additionally, temperatures remained elevated throughout the weekend where weekend minimum temperatures are similar to weekday maximum temperatures. A 7-day/week release reduces 21°C temperature exceedances and prevents elevated temperatures occurring for prolonged durations (Figure 5). Elevated weekend temperatures from the 5-day/week release scenario increases the diel temperature flux when flows are peaked at the beginning of a week.

Exceedance of 21°C was reduced by 7-day/week, morning, 2 h, and/or increased baseflow release. Seven day/week release prevented the occurrence of elevated temperatures during non-generation weekends. Morning release

Table II. The RQUAL model temperature predictions for existing conditions and alternative scenarios are shown as percentage time 12–19°C temperatures occur, percentage time the maximum hourly temperature change (MHTC) exceeds 2°C, the average daily MHTC (in °C), and the percentage time 21°C is exceeded. Values are averages from 2.2 to 24.3 rkm from 1 May to 30 September 2000 and in parentheses are model predictions averaged within the upper (0.0–5.3 rkm), trophy (5.3–10.0 rkm), and lower (10.0–24.3 rkm) section of the SRT

Scenario	Time 12–19°C (%)	Time MHTC >2°C (%)	Daily MHTC (°C)	Time >21°C (%)
Existing conditions	59.8 (17,53,75)	4.0 (5,5,3)	4.4 (5,6,3)	1.3 (0,0,2)
5-day 2 h release	57.3 (20,58,68)	3.2 (3,3,3)	4.2 (4,6,4)	2.2 (0,0,4)
5-day 5 h release	46.9 (20,50,53)	3.1 (3,3,3)	4.8 (4,6,5)	1.9 (0,0,3)
Steady baseflow	63.9 (29,81,67)	0.0 (0,0,0)	1.0 (1,1,1)	5.3 (0,0,9)
Increased steady baseflow	39.6 (1,19,59)	0.0 (0,0,0)	0.9 (1,1,1)	0.0 (0,0,0)
Run of river	60.0 (21,66,69)	0.0 (0,0,0)	1.0 (1,1,1)	3.8 (0,0,6)
Evening 1 h release	63.1 (16,59,78)	3.6 (4,4,3)	4.0 (5,6,3)	1.6 (0,0,3)
Evening 2 h release	54.3 (16,49,67)	4.4 (4,4,5)	5.4 (5,7,5)	1.0 (0,0,2)
Morning 1 h release	71.6 (28,72,84)	2.2 (0,4,2)	2.5 (2,4,2)	0.4 (0,0,1)
Morning 2 h release	69.9 (27,70,82)	3.3 (0,4,4)	3.7 (2,4,4)	0.1 (0,0,0)
Evening 1 h release with increased baseflow	57.6 (9,38,80)	2.9 (4,4,2)	3.0 (3,5,2)	0.1 (0,0,0)
Evening 2 h release with increased baseflow	48.1 (9,34,65)	3.9 (4,4,4)	4.4 (3,6,4)	0.0 (0,0,0)
Morning 1 h release with increased baseflow	66.1 (14,56,85)	1.2 (0,2,1)	1.6 (1,2,1)	0.0 (0,0,0)
Morning 2 h release with increased baseflow	62.9 (13,55,81)	2.3 (0,2,3)	2.3 (1,2,3)	0.0 (0,0,0)
Evening ramped release	57.6 (10,51,74)	4.5 (3,6,4)	3.9 (3,5,4)	0.9 (0,0,1)
Morning ramped release	68.5 (28,68,80)	3.1 (0,4,4)	3.6 (2,4,4)	0.1 (0,0,0)

cooled temperatures at the beginning of the day, thus reducing the ability of ambient conditions to raise temperatures above 21°C by the end of the day. The larger quantity of water released over 2 h versus 1 h, as well as with an increased baseflow, cooled downstream (*c.* 18.3–24.3 rkm) temperatures thus reducing maximum temperatures.

DISCUSSION

This study provided insight into the complex tradeoffs in tailwater thermal habitat management. We found that the best scenario to improve one temperature criterion was not the best to improve others, therefore managers will be faced with either choosing a scenario that improves all criteria at the least compromise or selecting the regime that will address the most limiting factor without unduly compromising the others. For example, the morning 1 h

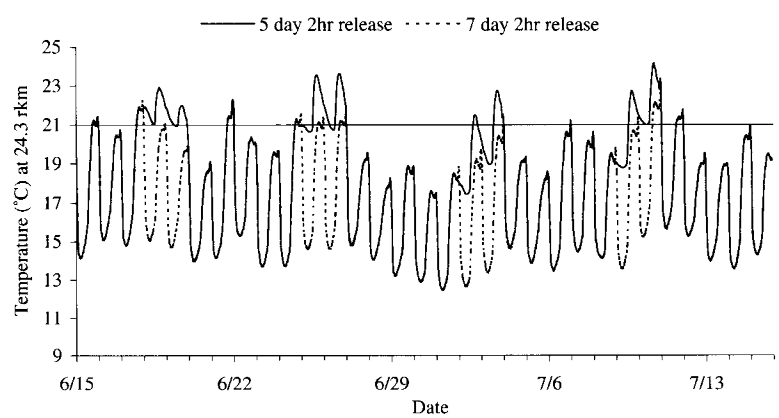

Figure 5. Hourly stream temperature at 24.3 rkm below Philpott dam from 15 June to 15 July 2000 under a 5 versus 7-day/week generation scenario. The horizontal line indicates the Virginia Department of Environmental Quality's 21°C maximum temperature standard for stockable trout waters

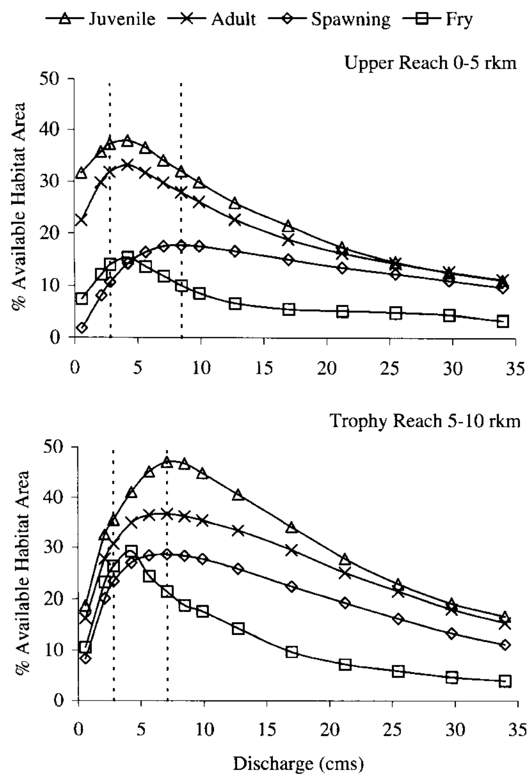

Figure 6. The maximum available habitat from 0 to 10 rkm for brown trout life stages occurs at flows $<17\,m^3\,s^{-1}$ (adapted from USFWS, 1986). The vertical dashed lines indicate a comprehensive optimal flow for all life stages depending on time of year. Optimal flow in the upper reach from January to September is $2.8\,m^3\,s^{-1}$ and from October to December is $8.5\,m^3\,s^{-1}$. Optimal flow in the trophy reach from January to March is $2.8\,m^3\,s^{-1}$ and from April to December is $7.1\,m^3\,s^{-1}$

release scenario offered minimal compromise by providing improvement over the existing conditions throughout the SRT for all assessed criteria. However, within the trophy trout section the steady baseflow scenario improved optimal growth conditions more than the morning 1 h release scenario, but worsened conditions downstream. Therefore, if the desire is to improve the fishery in the trophy trout section because of an increased quality of fishing experience (related to aesthetics), the tradeoff may be appropriate. Through the use of a stream temperature modelling tool, we were able to assess the complexities and trade-offs regarding alternative releases and river temperatures with measures of certainty of anticipated responses. Furthermore, the results from this study provide for the generation of hypotheses to be used in an adaptive management framework with measures of the biological community. Our use of a dynamic model is notable because unlike steady-state temperature models which are commonly used to predict daily temperature under alternative scenarios (Lifton *et al.*, 1985; Wilson *et al.*, 1987; Connor *et al.*, 2003; Horne *et al.*, 2004), similar use of dynamic temperature models is lacking (Deas *et al.*, 1997; Hauser *et al.*, 1998). Modelling temperature in the SRT required a dynamic model due to the rapidly changing flow conditions. The process of appropriate model selection is important because water temperature is often an overriding biological limitation and therefore a likely parameter for modelling by resource agencies that do not always have the resources to conduct comprehensive biological assessments.

Biological significance of alternative flow scenarios

Alternative flow scenarios that improved thermal conditions must also be evaluated from other physical and biological aspects. A small-scale instream flow incremental methodology (IFIM) study assessed availability of physical habitat under different flow regimes in the SRT from 0 to 10 rkm (USFWS, 1986). Findings indicated that habitat for all brown trout life stages is limited by the existing flow regime where baseflow (*c.* $1.4\,m^3\,s^{-1}$)

is too low and generation flow (*c.* 36.8 $m^3 s^{-1}$) is too high for optimal amounts of habitat. Maximum available habitat from 0 to 10 rkm occurs at flows <17 $m^3 s^{-1}$ (Figure 6). Associating IFIM information with temperature modelling reveals that morning release with increased baseflow would improve physical habitat and thermal habitat in the trophy section. However, the increased steady baseflow scenario, which approximates mean annual flow, may improve physical habitat but would reduce the occurrence of optimal growth temperatures.

Flow-induced impairment of brown trout feeding should be assessed prior to implementing an alternative flow aimed toward improving trout growth. Brown trout in the SRT primarily forage on aquatic invertebrates (Orth *et al.*, 2002). Increased water velocities during peak flows improve the availability of food resources by dislodging invertebrates into the water column (e.g. drift) (Lauters *et al.*, 1996; Lagarrigue *et al.*, 2002). Whether brown trout are able to forage with equal effort during peak and base flows in the SRT is unknown. Lagarrigue *et al.* (2002) found evidence that brown trout did not feed during peaking flows, rather consumption was highest after hydropeaking. Brown trout longitudinal movement is also less during peak flows (Lauters (1995) as cited in Lagarrigue *et al.*, 2002) suggesting shorter duration releases would cause less restriction on brown trout forage ability. Thus, hydropeaking may increase the availability of aquatic invertebrate drift, but brown trout feeding is restricted until after peak flows subside (Lagarrigue *et al.*, 2002).

Despite the potential for increased invertebrate drift, the magnitude and duration of hydropeaking may also serve to reduce invertebrate populations. Impaired invertebrate populations occur from their persistent flushing without replenishment from an upstream source (e.g. due to a dam) and from poor substrate diversity due to streambed scouring (Moog, 1993; Lauters *et al.*, 1996). Hydropeaking in the SRT has scoured and reduced substrate diversity in the upstream reaches (<4 km downstream of the dam) to predominantly (80% bottom coverage) large rocks (>64 mm) and bedrock (Orth *et al.*, 2001). The poor substrate diversity, as well as instability in depth, velocity, and temperature are hypothesized reasons for the low invertebrate density and family richness in the upstream reaches of the SRT (Newcomb *et al.*, 2001). Throughout the SRT invertebrate densities are two to five times lower than those in unregulated Virginia rivers of similar size (Newcomb *et al.*, 2001). Unregulated Virginia rivers typically have 800–1000 invertebrates/m^2, whereas the majority of sites in the SRT have less than the poor food grade classification number of 538 organisms/m^2 (Newcomb *et al.*, 2001). Brown trout, which are also piscivorous, must rely heavily on invertebrates in the SRT because reaches where brown trout densities are highest (3–9 rkm) do not overlap with areas of high forage fish densities (13–24 rkm) (Orth *et al.*, 2002; Hunter, 2003).

The DO content in the SRT is optimal (>9 mg l^{-1}; Raleigh *et al.*, 1986) the majority of winter, spring, and summer based on DEQ tailwater data at 5.1 rkm (January–December 1992–2003). However, in the autumn prior to reservoir turn-over, DO can be limiting in the upriver reach (0–5 rkm) primarily during peakflow when concentrations <5 mg l^{-1} are present at the hydropower intake depth (DEQ reservoir DO profiles, April–October 1995–2002). Peakflow DO has been recorded as low as 2 mg l^{-1} at 0.2 rkm during August and September 2003, but rose to 5 mg l^{-1} by 5 rkm (Krause, unpublished data). In this tailwater, DO appears to be limiting for only a short time in the autumn and only in a limited section of the SRT.

Understanding which factors are limiting, as well as the interaction between factors such as water temperature, food resource availability, and physical habitat, will enable managers to determine the potential for flow regime management to improve the fishery. Determining growth-limiting factors and evaluating their effect on growth in the SRT is the focus of a current study using bioenergetics modelling, which links growth to energy intake and losses (Orth *et al.*, 2003).

Control rules

The alternative flow regimes assessed by this study were consistent from one day to the next; however, another potentially challenging option is to alter the flow regime depending on daily conditions. Changing the flow regime from one day to the next could be based on a control rule that if met by conditions one day, would determine the flow regime used later that day or the next day (Schreiner, 1997, 2001). Control rules are typically seasonally specific and must address selected criteria. For example, if a very warm summer day occurs surpassing a set of meteorological conditions (i.e. control rule) known to cause downstream SRT temperatures to exceed 21°C, the flow regime would be changed (e.g. increased baseflow or release duration) to cool downstream temperatures (Schreiner, 2001). The implementation of day to day temperature management via flow alteration requires real-time monitoring of water temperatures, meteorological conditions, and flow. Implementation of control rules may be viewed as disadvantageous by recreationists and anglers if flow schedules are subject to daily changes and thus present a lack of predictability for recreation and fishing.

Conclusion

Our temperature modelling approach demonstrates that thermal conditions in the SRT can be modified to benefit brown trout compared to existing conditions. This study offers a basis toward achieving improved growth via thermal habitat enhancement by providing an understanding of flow effects on temperature. In summary, those effects are: (1) increased occurrence of optimal growth temperatures (12–19°C) by releasing in the morning, for shorter durations, and/or not increasing baseflow; (2) decreased MHTC by releasing in the morning, for shorter durations, increasing baseflow, and/or ramping flow; and (3) decreased 21°C exceedance by releasing every day of the week, in the morning, for longer durations, and/or increasing baseflow. Based on the evaluated scenarios, we found a morning 1 hour release to provide the most benefit; however, selecting a flow regime will require consultation with the USACE to determine what is feasible based on power generation and flood control requirements. A 1 hour release is often too short for sufficient power production and flood control requirements. Thus, other scenarios should be considered which account for the installation of modern generators and/or a variable depth intake. The alternative flow regimes were assessed from a thermal habitat perspective, yet it is unknown how they differ economically. It is recommended that the USACE consider integrating the results of this habitat assessment with hydropower operations via cost–benefit analysis. This may determine if the value of the fishery to the local community would surpass the value of the power created by Philpott Dam. Maximum enhancement of the tailwater fishery will result from a combination of careful selection and adherence to the appropriate flow scenario(s) and adaptive management that provides the greatest benefit for the least compromise.

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