The thermal regimes of brook trout incubation habitats and evidence of changes during forestry operations

R. Allen Curry, David A. Scruton, and Keith D. Clarke

Abstract: The thermal regimes in streambed substrates used by brook trout, *Salvelinus fontinalis* Mitchell, for incubation of embryos were examined in reference and treatment (0- and 20-m riparian buffer strips) streams in a clear-cut harvested, northern temperate forest of western Newfoundland. In these streams, incubation habitats (redds) were primarily composed of downwelling surface waters with variable but minor mixing of upwelling groundwater. The resulting incubation temperatures were cold (<1°C) and surface water temperatures were accurate predictors of redd temperatures. Both treatment streams displayed evidence of warming in the fall and spring of the 2 years beginning the year of initial harvesting. The increase was most pronounced in the stream without a riparian buffer strip. Clear-cut harvesting with and without a riparian buffer strip altered the thermal regime of surface water and the hyporheic zone in this northern temperate forest where, in addition to salmonid incubation, many biological processes take place. The potential for impacts on stream ecosystems is estimated to be high for the managed forests of this region. Future studies should strive to enhance our understanding of the hydrological connections between forests and streams on this landscape to determine the full effects of timber harvesting on the hydrology and biology of a watershed and its streams.

Résumé : Nous avons étudié le régime thermique de lits de cours d'eau utilisés pour l'incubation des embryons par l'omble de fontaine, *Salvelinus fontinalis* Mitchell, dans des ruisseaux témoins et traités (lisières boisées riveraines de 0 et 20 m), dans une forêt tempérée nordique coupée à blanc dans l'Ouest de Terre-Neuve. Dans ces ruisseaux, les habitats d'incubation (frayères) étaient principalement soumis à des courants descendants d'eau de surface influencés à des degrés variables, mais somme toute faibles, par des résurgences de l'eau phréatique. Les températures d'incubation étaient donc froides (<1 °C) et la température à la surface de l'eau permettait de prédire précisément la température des frayères. Pendant 2 ans, incluant l'année de la récolte, les deux ruisseaux traités ont montré des signes de réchauffement à l'automne et au printemps, mais c'est dans le ruisseau sans lisière boisée que le réchauffement a été le plus prononcé. La coupe à blanc, avec ou sans lisières boisées riveraines, modifie le régime thermique de l'eau de surface et de la zone hyporhéique dans cette forêt tempérée nordique au sein de laquelle plusieurs processus biologiques ont lieu en plus de la fraie des salmonidés. L'écosystème des ruisseaux de cette région risque fort d'être affecté par l'aménagement forestier. Il faudrait de nouvelles études pour améliorer notre compréhension des liens hydrologiques entre les forêts et les ruisseaux dans ce type de paysage, de manière à pouvoir déterminer l'ensemble des effets de la récolte ligneuse sur l'hydrologie et la biologie d'un bassin versant et de ses ruisseaux.

[Traduit par la Rédaction]

Introduction

The brook trout, *Salvelinus fontinalis* Mitchell, is a widespread, coldwater species of eastern North American lakes and streams. Its coldwater environments are supported by a variety of landscapes, but it is the eastern forests that provide thermal buffering and groundwater flow that support many populations (e.g., Barton et al. 1985; Curry et al. 1997; Power et al. 1999). Reproduction typically requires burying of fertilized eggs in coarse sand and gravel substrates of lentic and lotic waters during the fall and early winter. Here the embryos develop, hatch as free embryos in midwinter, and emerge as alevins from the substrate in late winter to early summer (Power 1980). There is a period of about 125 days when embryos remain physically protected by the surrounding substrate, but concomitantly are unable to escape the thermal regimes, chemistry, and hydraulics of the interstitial environment.

There is a growing awareness of the dynamic nature of these interstitial environments used by fishes. These habitats are a combination of surface and ground waters with the proportions controlled by surface water hydraulics (Gunn and Keller 1986; White et al. 1987) and the groundwater hydrology of the entire catchment (Curry and Devito 1996;

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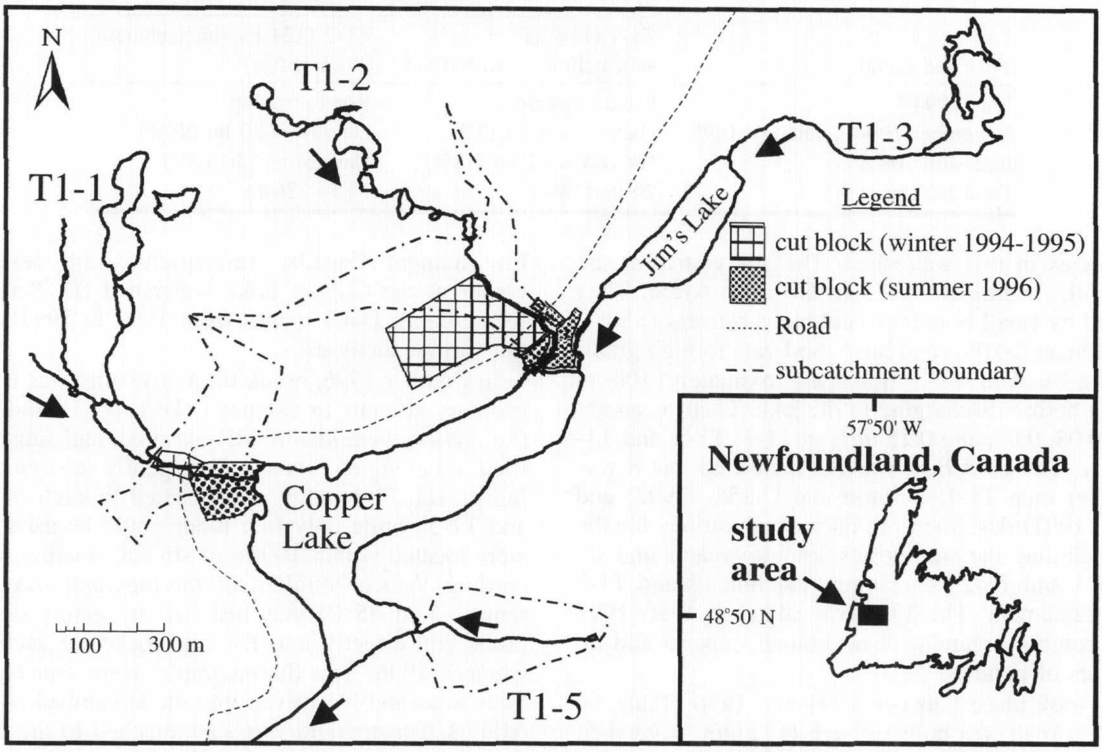
Fig. 1. Location of study streams and timber harvesting areas in the Copper Lake watershed, western Newfoundland. Stream T1-2 received a 20-m riparian buffer strip and T1-1 received no buffer strip. The control streams are T1-3 and T1-5.



Power et al. 1999). Shallow groundwater is typically present if the water body lies in or adjacent to unconsolidated overburden and in an appropriate landscape position (Toth 1963; Silliman et al. 1995). It can be a dominant feature of stream habitats (Curry and Noakes 1995; Brunke and Gonser 1997) and demonstrates the connection between incubation habitats and the adjacent terrestrial environment (see also discussion by Vervier et al. 1992).

The link to the terrestrial environment poses important questions about the potential impacts of human activities that appear removed from incubation habitats. Timber harvesting, particularly clear-cutting operations and consequential reductions in transpiration can raise terrestrial groundwater levels during the period following cutting and before regeneration of the forest begins (Bren 1997; Peck and Williamson 1987). During this post-harvest period, elevated groundwater levels may also result in altered temperatures of shallow groundwater, because this water will be closer to the surface and solar heating and snowpack insulation processes. In addition, the moderating effects of forest cover and its microclimate have been lost (e.g., Jewett et al. 1995). Such changes have the potential to increase groundwater temperatures or thermal variability and, consequently, alter incubation habitats located in substrates receiving the affected groundwater, particularly in areas of distinct groundwater discharge. Smaller lotic systems will be most affected, because shallow groundwater can represent a significant proportion of their total stream discharge (Brunke and Gonser 1997; Power et al. 1999).

There has been speculation about the effects of forestry operations on brook trout incubation habitats (e.g., Curry et al. 1995; Curry and Devito 1996; Ridgway and Blanchfield 1998), but no study has yet to provide quantitative evidence of impacts. In fact, there is very little known about the thermal regimes of incubation habitats and surface water and groundwater interactions that influence these habitats. Our first objective was to describe the thermal regime of brook trout incubation habitats in streams of a forested landscape. The second objective was to search for changes in the thermal regimes in areas of clear-cut, timber harvesting. The study occurred in the western Newfoundland Model Forest where tests of the effects of riparian zone buffer strips on brook trout abundances and habitats had been initiated (Scruton and Clark 1995). This further allowed us to investigate the potential mitigating role of a buffer strip as protection for lotic incubation habitats.

Materials and methods

The Copper Lake watershed is a small headwater system (13.5 km^2) located approximately 17 km southeast of Corner Brook, Nfld., Canada (Fig. 1). The relief is high with altitudes ranging from 350 to 650 m above sea level. Exposed rock barrens dominate the uplands (16% of watershed) with a patchy, shallow overburden (rarely >2 m depth) of moderate- to coarse-textured glacial tills (46%) and bogs (17%) in the lowlands. The northern temperate forest is dominated by *Abies balsamea* (L.) Mill. (balsam fir) with intermixed *Picea mariana* (Mill.) BSP (black spruce). Temperature normals for July are 17.4 and –6.8°C for February at Corner Brook (1933–1990; Environment Canada, unpublished data). The annual total precipitation normal is 1186 mm (1933–1990).

Fluvial habitats in the watershed included in this study consist of four headwater streams, T1-1, T1-2, T1-3, and T1-5 (Fig. 1), that contain resident brook trout populations, the

Table 1. Harvesting and operations schedule in the Copper Lake watershed 1994–1996.

	Stream	
Year and month	T1-1 (114 ha subcatchment, no buffer)	T1-2 (124 ha subcatchment, 20-m buffer)
June 1994	Road crossing	Road crossing
November 1994 – January 1995	Harvest = 8 ha (7%)	Harvest = 30 ha (24%)
June–July 1996	Harvest = 12 ha (11%)	Harvest = 3 ha (2%)
Total harvest	20 ha (18%)	33 ha (26%)

only fish species in this watershed. The study streams are generally small, ranging from 2.5 to 5.0 m in width. They are dominated by small boulder to cobble substrates (>50%) with riffle habitats (>70%) and have moderate to high gradients (2.5–23.8%). The T1-3 flows approximately 100 m through a bog before discharging to the lake. Their mean annual flow is 0.08, 0.08, and 0.15 m^3/s in T1-1, T1-2, and T1-3, respectively. The T1-5 flow was not measured, but it was slightly smaller than T1-1. Scruton and Clarke (1995) and Clarke et al. (1997) described pre-harvest conditions for the watershed, including the similarities among streams and selection of T1-1 and T1-2 as treatment catchments and T1-3 as a control catchment. The T1-5 was added in 1996–1997 as a second control stream with no human impacts and no upstream series of ponds.

Harvesting took place between 1994 and 1996 (Table 1). In June 1994, a road was built through the entire watershed crossing the lower reaches of T1-1 and T1-2 and passing through an upland section of the T1-3 catchment. From November 1994 to January 1995, an area of 8 ha without a buffer strip was clear-cut in T1-1, and an area of 30 ha with a 20-m buffer strip was clear-cut in T1-2 (Fig. 1). Because of the complex pond systems on these streams and their influence on surface water in the stream, the area of groundwater recharge directly connected to the study reaches (subcatchment) was used to represent the percent area of harvest (versus total area). This will increase the apparent proportion of the catchment being harvested, but the area is a more hydrologically realistic connection to the study reaches. The subcatchments of T1-1 and T1-2 were 114 and 124 ha, respectively (Fig. 1). The harvested areas represented 7 and 24% of the subcatchments in T1-1 and T1-2, respectively. No further activities took place in 1995. The final harvest occurred in June and July 1996. An additional 12 ha was cut in T1-1 representing 11% and a total harvest of 18%. In T1-2, three hectares (2%) were harvested for a total harvest of 26% of the subcatchment. No regeneration occurred during the period of this study.

From 1993 to 1995, surface water temperature data were collected in T1-1, T1-2, and T1-3 using Hugrun Seamon underwater temperature recorders (type A, –2 to 38°C range, 0.1°C accuracy). Thermographs were deployed at both the upper and lower part of each stream reach thus allowing an evaluation of water temperature changes over the stream reach. Thermographs were collected, downloaded, and redeployed twice each year of the study (May and October). Thermographs were set to record temperature hourly, and data was averaged on a daily basis. An initial quantification of thermal brook trout habitat was conducted by Scruton et al. (1998). Air temperatures were recorded 18 km to the northwest at the Corner Brook weather station operated by Environment Canada. Temperatures are several degrees cooler at the Copper Lake watershed (D. Scruton, unpublished data). Daily means from 1993 to 1997 were used in the various analyses.

In October 1996, brook trout spawning was mapped in the tributary streams to Copper Lake (Fig. 1). Individual redds (i.e., nests) were identified, measured, and subsequently verified as having embryos by very gently removing and replacing gravel. Five redds were located in each of T1-1, T1-2, and T1-3, while only four redds could be used in T1-5. All were located within 100 m of stream mouths. An hourly recording Vemco Minilog-TR thermograph (accuracy 0.1°C; range –5 to 35°C) was installed by gently depressing the probe end directly into the egg pocket of each redd on 11 October 1996. The thermographs were attached by secure lines to a steel bar driven into the streambed >1 m from the redd. A thermograph was also attached to the bar to record surface water temperatures. Thermographs were recovered on 18 June 1997. Each redd was excavated into a Surber-type sampler (500-μm mesh) to search for dead eggs and live free embryos (sac-fry larvae) and alevins (larvae ready to emerge from the streambed).

Data were separated into discrete seasons to standardize among stream comparisons: fall, 11 October to 30 November; winter, 1 January to 31 March; and spring, 1 May to 18 June. Surface water and redd daily mean temperatures were graphed and compared among streams using a repeated measures analysis of variance (one- and two-way ANOVA, α = 0.01; SAS Institute Inc. 1990; Cody and Smith 1997). Daily and seasonal ranges and thermal units or degree-days (sum of daily averages of hourly temperatures >0°C) for each redd were calculated, graphed, and compared among streams using an ANOVA. For all ANOVAs, assumptions of normality and heterogeneity were tested. No transformations of data were applied. Tukey pairwise comparisons were conducted a posteriori when statistical significance was detected (α = 0.05; SAS Institute Inc. 1990).

The presence of groundwater in redds was determined from differences in thermal regimes between the surface and redd waters (Constantz 1998; Silliman et al. 1995; Sinokrot and Stefan 1993).

There was no information on redd temperatures in other years. Instead, we searched for effects related to forestry operations from 1994 to 1996 by (*i*) an analysis of covariance (ANCOVA) among years for each stream of surface water versus air temperatures for the fall season, and (*ii*) comparing changes in winter and spring parameters relative to the control year (1993–1994) and stream (T1-3). For the fall ANCOVA, it was a comparison of annual stream temperatures with air temperature controlled as the covariate. Such a procedure assumes that the annual relationship between sur-

Table 2. Mean hourly temperatures (°C) in all redds and surface water, mean range in temperature within redds and thermal units (degree-days) among redds during brook trout embryo incubation in four tributary streams of Copper Lake, 1996–1997.

Season and location	T1-1 0-m buffer (n = 5 redds)	T1-2 20-m buffer (n = 5 redds)	T1-3 Control 1 (n = 5 redds)	T1-5 Control 2 (n = 4 redds)
Fall (n = 51 days)				
Redd	3.7*a*, n = 6120	2.6*b*, n = 6120	2.9*c*, n = 6120	2.3*d*, n = 4896
Mean (range) within a redd	7.7*a* (7.3–8.2)	7.1*a* (6.9–7.4)	6.6*b* (6.0–7.3)	6.1*b* (5.5–6.5)
Thermal units	188*a* (174–176)	136*bc* (128–144)	145*b* (127–160)	119*c* (109–135)
Surface	3.1 (–0.8 to 8.1), n = 1224	2.5 (0.0–7.4), n = 1224	2.6 (0.0–7.3), n = 1224	2.1 (–0.1 to 6.4), n = 1224
Winter (n = 89 days)				
Redd	0.4*a*, n = 10 800	0.3*b*, n = 10 800	0.8*c*, n = 10 800	0.5*d*, n = 8640
Mean (range) within a redd	0.7*a* (0.5–1.1)	0.7*a* (0.5–0.8)	1.0*a* (0.7–1.7)	0.6*a* (0.5–0.7)
Thermal units	38*a* (16–70)	29*ab* (20–42)	73*ab* (34–122)	41*a* (21–68)
Surface	0.2 (–0.1 to 0.4), n = 2160	0.3 (–0.1 to 0.5), n = 2160	0.6 (0.0–0.8), n = 2160	0.3 (–0.1 to 0.7), n = 2160
Spring (n = 48 days)				
Redd	3.2*a*, n = 5880	3.2*a*, n = 5880	2.8*b*, n = 5880	1.0*c*, n = 4704
Mean (range) within a redd	13.5*a* (12.4–14.7)	14.0*b* (13.6–14.3)	10.9*c* (10.1–12.0)	5.8*d* (4.5–6.9)
Thermal units	157*a* (152–161)	158*a* (153–163)	135*b* (131–142)	51*c* (49–55)
Surface	3.6 (–0.1 to 24.7), n = 1176	3.2 (0.0–14.2), n = 1176	2.8 (0.0–12.0), n = 1176	1.0 (–0.1 to 6.8), n = 1176
Total				
Thermal units	410*a* (402–474)	336*b* (315–377)	401*ab* (331–489)	240*c* (196–301)

Note: Values are means with ranges given in parentheses. Values with the same letters are not significantly different ($p > 0.05$).

face water and air temperatures remains constant unless the stream experiences some externally driven alteration of its thermal regime, at least over the short time period of this study. The 1993–1994 relationship (no forestry in the watershed) was the control for such an analysis, i.e., there is no confounding problems related to hydrological differences among streams. Differences among years within a stream and season were made using an a posteriori Tukey test. Data gaps (logger failures) were filled by graphing 20 recordings before and after the failures and determining the best power, exponential, or polynomial regression (maximum r^2) for interpolation. Temperatures were $\log_{10}$-transformed daily means. The winter season could not be analyzed in this fashion, because regression slopes were always ≈1 and never parallel. The spring was excluded because of the confounding effect of annual differences in winter snowfall accumulations and its potential effect on the hydrology and, thus, temperature of the streams in spring. To match the fixed dates of 1996–1997 study, the seasons for the interannual analysis were defined as follows: fall, days when temperatures were >1°C from 11 October to 30 November; winter, days when temperatures were <1°C (1 January to 31 March); and spring, days when temperatures were >2°C (1 April to 18 June).

Results

Redd environments, 1996–1997

The physical characteristics of the redds were similar among streams. The ellipse-shaped redds' long axes (parallel to the stream flow) ranged from 25 to 45 cm. Using one-half the length of the axis as a predictor of female fork length (R.A. Curry, unpublished data), brook trout ranged from 13 to 23 cm in length, which concurs with size distributions of mature females in these streams (Clarke et al. 1997; McCarthy 1997). Trout can compete for redd sites, and therefore, thermal characteristics may vary in relation to the size of trout. Redd characteristics were not observed to be correlated with any of the parameters of their thermal regimes, e.g., mean, minimum, maximum, thermal units, or range in temperature during the total or seasonal periods ($|r|$'s < 0.5). Numbers of dead embryos and free embryos was greatest in the treatment streams averaging 6.4 ± 10.5 (mean ± SD) and 2.2 ± 2.8/redd in the no-buffer stream (T1-1) and 20-m buffer stream (T1-2), respectively. The two control streams averaged 0.6 ± 0.9, and 0 ± 0/redd in T1-3 and T1-5, respectively. Alevins appeared to be completely emerged in all streams (i.e., many were observed free swimming along the stream margins), except for two and one live free embryos observed in T1-5 (control) and T1-2 (20-m buffer), respectively.

Temperatures of redd and surface waters followed typical seasonal trends (Table 2). Redd temperatures were always warmer than surface water temperatures until spring, but differences were minimal. Among streams, redd temperatures were found to be significantly different in all seasons (F's > 9308, p's < 0.0001) with the control streams typically cooler in fall and spring and warmer in winter. The control streams displayed the least variation in redd temperatures in fall and spring. In winter, temperature variation in redds was similar among streams. Thermal units (degree-days) were significantly different ($F_{[3,4]} = 16.1$, $p < 0.0001$) among streams in each season similar to the absolute temperatures, although the potential for type II errors were suggested for thermal units (overlap of pairwise significance).

Table 3. The mean, standard deviation, range, and coefficient of variation in seasonal surface water temperatures and cumulative thermal units (degree-days) during the incubation period of brook trout in two treatment (T1-1 and T1-2) and one (T1-3) control streams in the Copper Lake watershed, 1993–1997.

	1993–1994			1994–1995			1995–1996			1996–1997		
Stream parameter	Fall	Winter	Spring	Fall	Winter	Spring	Fall	Winter	Spring	Fall	Winter	Spring
T1-3 (control)												
Mean (°C)	2.3	0.4	3.9	3.3	0.4	7.6	3.4	–0.1	7.6	2.6	0.6	2.8
SD	2.2	0.2	3.6	2.2	0.2	3.3	2.2	0.2	4.0	1.7	0.2	3.2
Range	7.2	0.7	13.2	8.2	0.7	11.4	8.1	1.5	13.4	6.5	0.8	10.3
CV (%)	95.7	50.0	92.3	66.7	50	43.4	64.7	200.0	52.6	65.4	33.3	114.3
Thermal units			359			468			543			353
N	51	90	49	51	90	21	51	90	35	51	90	49
T1-2 (20-m buffer)												
Mean (°C)	1.8	0.3	4.6	3.2	0.2	10.3	3.5	–0.1	11.9	2.5	0.3	3.2
SD	1.8	0.1	4.3	2.6	0.2	3.1	2.6	0.2	2.6	2.1	0.1	3.9
Range	6.7	0.4	16.2	9.3	0.5	15.2	9.3	1.4	9.5	6.7	0.5	12.8
CV (%)	100	33.3	93.5	81.3	100.0	30.1	74.3	200.0	21.8	84.0	33.3	121.9
Thermal units			372			500			543			329
N	51	90	48	51	90	20	51	69	21	51	90	49
T1-1 (0-m buffer)												
Mean (°C)	3.7	0.1	3.5	5.4	0.3	4.8	5.4	0.4	10.8	3.1	0.2	3.3
SD	2.3	0.1	2.9	2.2	0.1	4.0	2.1	0.4	2.5	2.1	0.1	3.9
Range	7.8	0.3	11.7	9.0	0.5	11.7	7.3	2.2	7.5	7.0	0.5	13.0
CV (%)	62.2	100.0	82.9	40.7	33.3	83.3	38.9	100.0	23.1	67.7	50.0	118.2
Thermal units			389			546			798			366
N	51	90	49	51	90	37	51	90	21	51	90	48
Surface												
Mean air temperature (°C)	4.3	–5.3	7.4	5.5	–5.5	7.2	6.0	–3.5	8.3	4.5	–4.6	6.7
Mean precipitation (mm)	4.7	4.6	3.8	3.7	3.5	3.0	4.9	4.3	2.7	2.7	4.6	3.0
Normals												
Mean air temperature (°C)	5.0	–4.4	7.7									
Mean precipitation (mm)	4.0	3.8	2.3									

Note: Seasonal means and normals (1933–1990) of air temperature and precipitation are from Corner Brook, Nfld.

Redds were dominated by surface and not groundwater inputs based on two lines of evidence. Firstly, correlations between surface water and redd temperatures were strong in all streams (*r*'s > 0.95). Partial correlation coefficients when controlling for air temperature were similarly high for all redds in all streams ($r_{\text{surface–redd–air}}$ > 0.89). These results suggest that surface water could explain >79% of the variations in redd temperatures. Secondly, there was no indication of thermal dampening by groundwater during warmer periods and particularly in winter, when redd temperatures (in the substrate) were always <1°C and similar to surface water temperatures. Winter thermal regimes in groundwater-dominated brook trout redds are significantly warmer than surface waters (Curry et al. 1995).

Apparent changes, 1993–1997

The three streams display differences in temperatures prior to the initiation of any treatment, which reflects the differences in catchment physiography and configuration of the lakes in the upper catchments, thus emphasizing the need for interpreting of results in relative terms. The control stream (T1-3) increased in mean temperature by approximately 1°C in fall in 1994–1995 and 1995–1996 and returned to control year temperatures in 1996–1997 (Table 3). This annual trend paralleled the air temperatures. In both treatment streams, temperature increases were approximately 1.5°C in the fall of 1994 and 1995 with differences of <1°C from the control year in 1996. The control stream displayed consistent winter temperatures among years with a notably colder winter in 1995–1996. The 20-m buffer stream (T1-2) had a similar pattern. The no-buffer stream (T1-1) was warmer during the first two winters post-harvesting and similar to the control year in the third winter. In spring, the control stream was about 2.5°C warmer in the first 2 years post-harvesting in the watershed and about 1°C cooler in the third year. Spring temperatures in the first 2 years were distinctly warmer in the 20 m buffer stream, 6–7°C (T1-2), and no-buffer stream, 1–7°C (T1-1). Snowfall accumulations in the region were lowest in this first year at least (Table 3). In the third year post-harvesting, spring temperatures declined and were similar to the control year in both treatment streams.

Trends in thermal units for the incubation period (fall to spring) paralleled stream temperatures. In the first year of harvesting (1994–1995), thermal units were greater than the observed increase in the control stream (19 and 48 in the 20-m and no-buffer streams, respectively). In the second year, thermal unit increases were similar in the control (184) and 20 m buffer (171) streams, but here was a substantial increase in the no-buffer stream (409). All streams had reduced thermal units in the third year in relation to the control year with the treatment streams displaying greater reductions than the control stream (–6, –43, and –23 in the control, 20 m buffer, and no-buffer streams, respectively). Trends in variability (CV and range) in relation to the treatments over time were not apparent.

In the fall, the control stream (T1-3) displayed consistent annual relationships between surface water and air temperatures (Fig. 2; $F_{[1,3]} = 0.7$ and $p = 0.57$). In the 20 m buffer stream (T1-2), no statistical differences were detected in fall ($F_{[1,3]} = 1.0$, $p = 0.40$). Annual differences were apparent in the no-buffer stream ($F_{[1,3]} = 56.8$, $p < 0.0001$; 1994–1995 = 1995–1996 > 1993–1994 = 1996–1997, $p < 0.05$). Treatment streams had similar coefficients of variation for stream temperatures for the all falls combined (both CV's = 2.20). This was greater than the control stream (CV = 1.92). Given the consistency of lower temperature limits in all streams, 1°C, the dispersion about the mean is upward (Fig. 2) and suggests a similar degree of warming in both treatment streams.

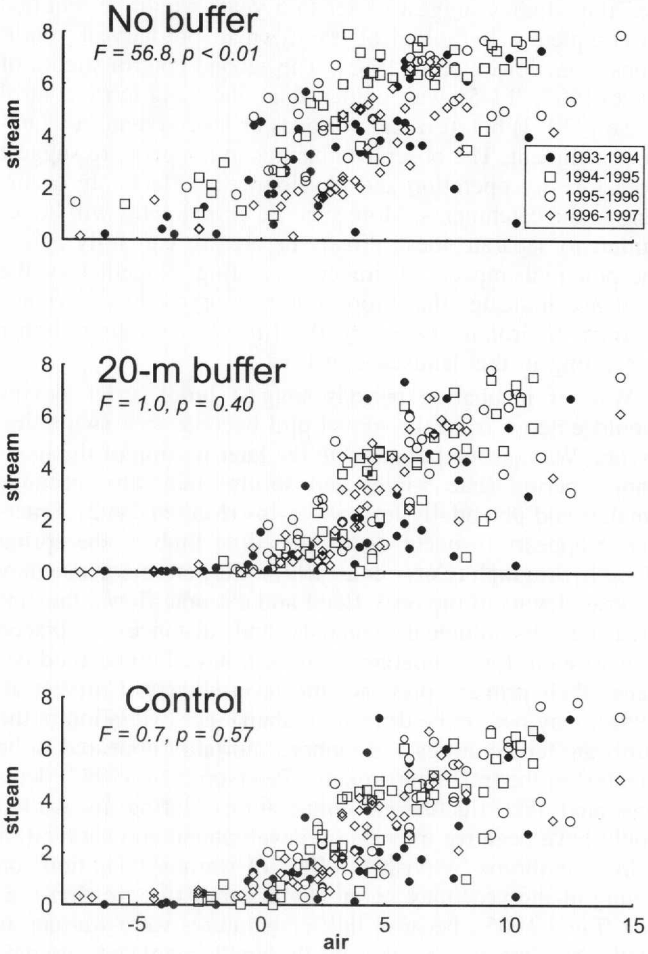
Discussion

We provide the first detailed observations of thermal regimes of the hyporheic zone of stream substrates used as redds or nests of brook trout during fall, winter, and spring. In forested landscapes of western Newfoundland, redds received primarily downwelling surface water with some upwelling groundwater. There were no redds that were dominated by discharging groundwater as has been observed in the forests of the Canadian Shield and glacial outwash plain regions of central Canada (Curry and Noakes 1995; Blanchfield and Ridgway 1997). The western Newfoundland streams are more similar to the highland regions of mixed forests in central Pennsylvania, where no distinct groundwater upwelling was observed in brook trout redds (Curry and Noakes 1995), or streams of Minnesota, where behavioural interactions may override the use of groundwater discharge by brook trout (Essington et al. 1998).

Groundwater can provide a thermal buffer from the near 0°C and colder water temperatures created by ice overriding substrates and incubating embryos in winter (Curry et al. 1995). The coldest temperature in those groundwater-dominated redds was 1–3°C at the forested, Papineau Creek. Temperatures as low as 1.8°C can be tolerated by incubating brook trout in the laboratory (Embody 1934; Balon 1980; Marten 1992). In the redds of the present study where groundwater inputs were minimal, temperatures were <1°C for at least 90 continuous days, yet embryos survived and emerged from the substrate. This is a colder regime than has been previously reported, thus expanding the known thermal tolerance range for incubation of brook trout. Combined with the recognition that groundwater is not always necessary for successful incubation, we can expand the definition of potential brook trout incubation habitats and, thus, expand the total habitat in streams within the temperate forest landscape. Managers of forestry operations in these landscapes will need to be aware that small streams with and without areas of distinct groundwater discharge are potential incubation habitats for brook trout. Such small streams have already been identified as critical juvenile habitat in forested landscapes (Curry et al. 1997).

Many studies have demonstrated that clear-cut timber harvesting can alter surface water temperatures in streams. Increased summer temperatures are commonly reported as well as decreased fall and winter temperatures (Rishel et al. 1982; Lynch et al. 1984; Sweeney 1992). We predicted there would be a warming of the thermal regime as a result of clear-cutting if the incubation habitats were dominated by discharging groundwater. Groundwater was not a distinct element of the redds in the unaltered streams of this study. Instead, redds received some discharging groundwater, but the majority of water originated from the stream surface waters. This result and the consistencies in surface water responses with previous studies validated the use of surface water temperature as surrogates for redd temperature in these western Newfoundland streams during the timber harvesting activities.

Fig. 2. The regressions of stream water on air temperatures for the fall season in the years 1993–1994 to 1996–1997 in three streams of the Copper Lake watershed. Values are daily means.



Despite a lack of distinct, discharging groundwater, temperature was elevated and more variable in redds during harvesting when no riparian buffer strip was present and to a lesser degree when a 20-m buffer strip was present in at least the first 2 years of harvesting. The warmer spring in the first year post-harvesting occurred even though spring air temperatures were the same as the previous year. Snowfall accumulations were lowest in the second and third years and may influence the warmer spring temperatures recorded in the streams of the harvested catchments. By the third year post-initiation of harvesting (1996–1997), temperatures appeared to have returned to pre-harvest regimes, but without additional years of study, it is difficult to determine if the hydrological system has returned to pre-harvest conditions. Existing studies suggest closer to 5 years would be required to complete a hydrological transition to pre-harvest conditions (e.g., Jewett et al. 1995). The second control stream of 1996–1997, T1-5, was colder than the long-term control stream (T1-3) but also had no roads or lake system in its upper catchment. The observed changes in temperature suggest both forestry operation and physiography effects are occurring in the catchments. More specific experiments will be required to separate these effects before we can fully assess the potential impacts of timber harvesting. Nonetheless, the evidence indicates that brook charr embryos do experience warmer environments during the first 2 years after timber harvesting in this landscape at least.

Warmer incubation periods suggest brook trout alevins would emerge from the gravel and become free swimming earlier. Warmer temperatures in the later portion of the incubation period (late winter and spring) may also produce smaller and potentially less fit alevins (Marten 1992). Emergence appears to occur on the receding limb of the spring flood hydrograph (Curry et al. 1991). Earlier emergence may expose alevins to the peak flood and extreme flows, thus increasing physiological demands and distances displaced downstream. Early emergers may also have limited food because their primary prey, aquatic invertebrates (Curry et al. 1993), may not yet be drifting in abundance. Variation in the substrate temperatures and embryo mortality appeared to be greatest in the treatment streams. Peterson et al. (1977) demonstrated that fluctuating temperatures during incubation could have negative impacts on development and survival of salmon embryos. A positive effect of warmer conditions on young-of-the-year may be an extension of the growing season (Latta 1965), because fall temperatures were warmer as well. Our data suggest that all thermally regulated, biological process in the streams will be accelerated and experience increased variability during the fall to spring period. At present, we do not know the ecological consequences of these generally warmer incubation and substrate temperatures in the years immediately following harvesting.

The 20-m riparian buffer strip appeared to partially achieve its objective of protecting the stream's thermal regimes as observed with buffer strips in other studies (e.g., Lynch et al. 1984; Barton et al. 1985). This buffer strip also reduced the magnitude of sedimentation during a major storm event in 1995 (Clarke et al. 1998). We, thus, suspect the 20-m buffer strip on T1-2 has generally been successful in protecting the stream habitats; however, the true significance of the 20-m buffer strip's effect is unknown. The warming of stream water suggests the mechanism of temperature change was related to groundwater flow to the stream and not direct solar inputs, i.e., there was a forested buffer zone to protect the stream from solar radiation. A complication in the interpretation is the relatively small area of harvest within this subcatchment (26%). Other studies indicate that harvesting small areas in relation to the total catchment will not significantly impact stream environments (Martin et al. 1985; Eaglin and Hubert 1993). The concentration of harvesting in this catchment was also hydrologically isolated on one side of the stream (24 of 26%). Water recharge and discharge zones vary within a catchment (Devito et al. 1996) such that the location of the harvesting areas will affect shallow groundwater flow to the stream (Curry and Devito 1996). Additional complications are the upstream ponds that dominate the catchment and, therefore, stream flow and thermal regimes in the study reach, as well as the season of harvest, which controls factors such as soil compaction and evapotranspiration and, therefore, the recharge rates and temperatures or buffering of temperatures of recharging groundwater. We can conclude that this specific 20-m buffer strip and a single, clear-cut harvest block representing 26% of the sub-catchment was a relatively effective management tool, but it is not clear if similar management would be effective or applicable in other streams.

The present study was not designed to experimentally address the potential impacts of timber harvesting on the incubation habitats of brook trout; instead, it provides a first comprehensive examination of this important and often-asked question. The evidence suggests impacts exist, because the results are consistent with the known relationship that clear-cut harvesting will elevate temperatures of surface water in fall and spring. The hyporheic zone was dominated by intruding surface water such that the warmer conditions after harvesting would affect incubating embryos and all thermally regulated systems in the streambed. A 20-m riparian buffer strip may have mitigated the impact to some degree but only if the hydrological and harvesting characteristics are similar to T1-2 in the Copper Lake study. Across the temperate forests of eastern Canada, many smaller streams are not provided any riparian buffer strip during timber harvesting, e.g., Newfoundland streams must appear on 1 : 50 000 topographic maps to receive a buffer strip and New Brunswick streams on free-hold lands must appear on 1 : 10 000 maps. The potential for impacts on small stream ecosystems is high for the managed industrial forests of this region. The cumulative effects within a watershed are unknown. Clearly, we need a better understanding of the hydrological connections between forests and streams in the north temperate landscape and the effects of various forestry activities on the hydrology and biology of a watershed and its streams. The latter can only be accomplished with detailed experiments that manipulate harvest block and buffer strip sizes and their locations in the context of catchment hydrology.

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