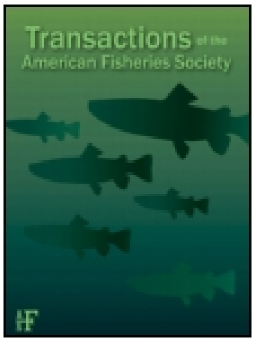

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Potential Loss of Thermal Habitat for Brook Trout, Due to Climatic Warming, in Two Southern Ontario Streams

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Abstract—I calibrated a hydrometeorological model of stream temperature to two southern Ontario streams in the summer to estimate potential reductions, due to climatic warming, of thermal habitat for brook trout *Salvelinus fontinalis*. Summer habitat for brook trout in both streams, determined from electrofishing surveys during 1987 and 1988, was delimited downstream by a thermal barrier of about 24°C. Tagging data for one stream suggested that brook trout moved upstream to summer habitat as water temperatures in downstream areas increased during spring and summer. To estimate upstream movement of the thermal habitat barriers and concomitant reductions in summer habitat for brook trout due to climatic warming, I forced the calibrated stream models with the changes in mean July and August air temperatures (increase, 4.1°C) projected for the region by the climate warming scenario of the Goddard Institute for Space Studies. I also adjusted the temperature of groundwater discharging to the streams by the projected change in mean annual air temperature (increase, 4.8°C). Elevated air and groundwater temperatures increased maximum summer stream temperatures and moved the thermal habitat barriers upstream, which reduced summer thermal habitat for brook trout in the two streams by 42 and 30%.

Steadily increasing seasonal and annual water temperatures in North America in response to global climatic warming (Hengeveld 1990, this issue), will likely affect distributions of fishes in lakes and streams and may shift geographic distributions of some species northward and to higher altitudes (Magnuson et al. 1990, this issue; Meisner 1990; Shuter and Post 1990, this issue). Stenothermic species may experience the greatest effects, which likely will become noticeable first in populations located at the margins of species' hydrologic and geographic distributions.

The distribution of brook trout *Salvelinus fontinalis* in streams is strongly governed by habitat temperature. In Ontario and throughout the species' native range, the thermal habitat (Magnuson et al. 1979) of brook trout is bounded by an upper temperature of about 24°C (Ricker 1934; MacCrimmon and Campbell 1969). See Power (1980) for a review of the thermal autecology of brook trout.

Stream populations of brook trout at low latitudes and altitudes rely heavily on groundwater discharges for base flows and the maintenance of optimum temperatures in their headwater habitats. The importance of groundwater to brook trout has been demonstrated by positive relationships between groundwater discharge and reproductive success (e.g., Webster and Eiriksdottir 1976), biomass (e.g., Bowlby and Roff 1986), and abundance (e.g., Latta 1965). The temperature of groundwater, which can be approximated by adding about 1°C to local mean annual air temperature (Collins 1925), is expected to increase with climatic warming (Meisner et al. 1988).

The purpose of this investigation was to estimate the potential loss of summer thermal habitat of brook trout in two southern Ontario streams in a climate-warming scenario. Specifically, I sought (1) to delimit summer distributions of brook trout in two southern Ontario streams and estimate corresponding downstream thermal habitat barriers, (2) to calibrate a temperature model (Delay and Seaders 1966) to the brook trout zones of the streams, and (3) to assess the potential effect of climatic warming, as implied by the climate warming scenario of the Goddard Institute for Space Studies (Smith 1989), on summer thermal habitat of brook trout in the streams.

Study Area

I studied two headwater streams of the Rouge and Humber rivers of southern Ontario (Figure 1). Both rivers begin as groundwater discharge from a sand and gravel moraine and provide thermal habitats for brook trout in some of the headwater tributaries. Criteria used to select the study streams were that (1) they support self-sustaining populations of brook trout that are allopatric with respect to salmonids, and (2) their downstream, summer habitat boundaries are thermal and develop gradually.

The basin of the Rouge stream is primarily pasture and field except for a small forested section at the extreme headwater end. A large point influx

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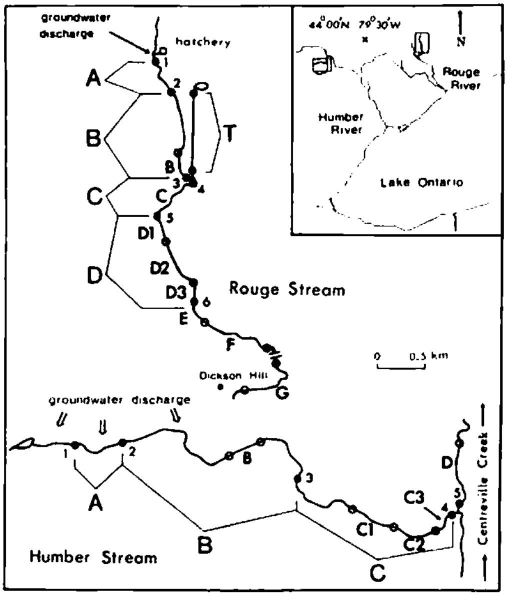

FIGURE 1.—Two brook trout streams in southern Ontario. Stream reaches to which the temperature model of Delay and Seaders (1966) was calibrated are indicated by large upper case letters and are delimited by numbered water temperature stations (solid circles). The tributary of the Rouge stream (T) was included in the calibration. Stream sections electrofished for brook trout are delimited by solid and open circles and indicted by small uppercase alphanumeric characters.

of groundwater occurs near the stream source. This groundwater, which is first used in a hatchery for coho salmon *Oncorhynchus kisutch* and chinook salmon *O. tshawytscha* before it is discharged, forms about 80% of flow in the upper reaches of the stream. The Rouge stream is augmented by a tributary that forms the outfall of a pond, fed by an artesian well, that supports a commercial put-and-take fishery for rainbow trout *O. mykiss*. A small log dam is in place at temperature station 5 (Figure 1) from May 1 to October 31, which prevents upstream movement of fish. About 10% of flow through the small headpond created by the dam is diverted to irrigate a golf course.

A few rainbow trout from the commercial pond escape to the stream each year. I judged the brook trout population in the Rouge stream was allopatric because all rainbow trout captured in the stream during the investigation were of the size-class stocked in the pond (>30 cm). Also, rainbow trout were found only periodically near the mouth of the tributary. This suggested that rainbow trout from the pond either moved downstream out of the study area shortly after entering the stream, or were caught by local fishermen. Occasionally escapee salmon fingerlings were found at the outfall of the hatchery.

The Humber stream is almost completely forested. It has a pond at the headwater but no tributaries. It receives groundwater from seeps and springs along the upper reaches (Figure 1). Brook trout was the only salmonid found in the Humber stream.

Both streams support an association of cyprinids, catostomids, and centrarchids that is dominated by creek chub *Semotilus atromaculatus*, longnose and blacknose daces *Rhinichthys cataractae* and *R. atratulus*, white sucker *Catostomus commersoni*, and pumpkinseed *Lepomis gibbosus*.

Stream Temperature Model

I used the temperature model of Delay and Seaders (1966) in this study. This model simulates water temperature with an equation that balances the energy flux across the air–water interface. The utility of a hydrometeorological model is that it can distinguish the effects of hydrological and meteorological variables on water temperature. With respect to the simulation of climatic warming, this means, for example, that air temperature can be manipulated in the model while solar radiation is held constant.

The model of Delay and Seaders (1966) describes the change in the temperature of a parcel of water as it moves between two points in a stream reach. In practice, the model takes the following form:

$$Tw = \frac{S \cdot A \cdot 0.00287}{\text{discharge}}; \qquad (1)$$

Tw is the change in the temperature (°C) of water as it moves through the reach, S is the change in energy stored in the water mass ($J \cdot cm^{-2} \cdot h^{-1}$), A is surface area (m^2), and discharge is that of the reach (L/s). The equation that balances the flux of energy across the air–water interface and computes the change in energy stored in the water mass is

$$S = Qs(1 - Qr) \pm Ql \pm Qe \pm Qh; \qquad (2)$$

Qs is total direct and diffuse solar radiation received on a horizontal surface at ground level (solar radiation at the surface of the study streams was adjusted to account for shade from overhanging banks and riparian vegetation; see "Model Calibration"); Qr is surface albedo of moving water from Schertzer (1978); Ql is net longwave radiation across the air–water interface; Qe represents energy transfer by evaporation and condensation; and Qh is conduction of sensible heat between air and stream. All terms in equation (2) except surface albedo are expressed here in $J \cdot cm^{-2} \cdot h^{-1}$, and are described in full by Delay and Seaders (1966).

Atmospheric data from meteorological stations of Environment Canada were used, which reduced stream-site data collection to hydrological variables. These stations are located at Buttonville Airport and Woodbridge, less than 30 km from the streams. Other models required that data of some meteorological variables be measured at the stream (e.g., Brown 1969), which was beyond the scope of this study. The time scale of the model is hours, which was appropriate for the length of the study streams and compatible with hourly meteorological data.

I used the climate-warming scenario of the Goddard Institute for Space Studies (GISS; Smith 1989). The scenario provides projected changes in mean monthly and annual air temperatures for North America in an atmosphere with twice the CO_2 now present. The GISS scenario projects increases in mean air temperature for July and August of 4.1°C for the study area. Mean annual air temperature is expected to increase by 4.8°C. I chose this scenario because the magnitude of the projected changes in air temperature for this region is intermediate between those of other scenarios (Smith 1989).

Methods

The streams were divided into sections and reaches (Figure 1). Sections were used in electrofishing surveys for purposes of delimiting summer distributions of brook trout in the streams. Reaches were used in the calibration of the temperature model of Delay and Seaders (1966) to the streams (see "Model Calibration," below).

Summer Distributions

I used stream temperature and presence of geographic features such as road culverts and property lines to define the stream sections. During a survey for brook trout, a single pass through each section was made with a model 12 Smith-Root electrofisher without blocking nets. Brook trout captured in a section were returned to the middle of the section before the next section upstream was fished. My objective was to catch most of the brook trout during the single pass through each section (or subsection; see below). Electrofishing effort per unit length of the sections, which I estimated from shocking time, varied with the number of hiding places for brook trout (pools, overhanging banks, submerged logs). I attempted to fish each section with the same level of effort during successive surveys.

In July and August 1987, subsections of some of the stream sections (Figure 1) were electrofished to determine the presence or absence of brook trout. Subsections of C1, C3, and D of the Humber stream and Centreville Creek were surveyed on July 17 and August 14 and 17, and subsections of B, C, D1, and D3 of the Rouge stream were sampled on July 15 and 23 and August 7. On July 15, I surveyed 0.5 km of the Rouge stream for brook trout (section G), about 2 km downstream from station 6, near Dickson Hill.

During the surveys of the Rouge and Humber streams in 1987, temperatures at stations that delimited the stream reaches (Figure 1) were measured in the early afternoon with a mercury thermometer to estimate maximum temperatures for the day.

In March 1988, I began weekly surveys of the entire sections of both streams. All brook trout captured in section D of Centreville Creek during the weekly surveys of 1988 were marked with an adipose fin clip to allow me to determine if they subsequently moved upstream into the Humber stream. Sections E and F of the Rouge stream were too deep to permit access before July, which prevented a similar movement study. Section G near Dickson Hill was surveyed for brook trout on April 22 and May 12, 1988.

Beginning in April 1988, maximum weekly temperatures were recorded with maximum–minimum thermometers at stations 3, 4, and 5 in the Humber stream and Centreville Creek, and at stations 1, 3, 5, and 6 in the Rouge stream. Temperatures in sections E and F of the Rouge stream were measured with a mercury thermometer when the sections were electrofished.

Thermal Habitat Barriers

The temperature data collected in 1987 and 1988 at stations 6 and 4 in the Rouge and Humber streams, respectively, were used to compute the downstream thermal habitat barriers of the streams, i.e., the upper temperatures avoided by brook trout. The maximum temperatures measured at these stations in July and August 1987, and the weekly maxima recorded in July and August 1988, were averaged and designated as the thermal habitat barriers of the respective streams.

TABLE 1.—Hydrological and structural variables used to calibrate the model of Delay and Seaders (1966) to two brook trout streams in southern Ontario. Discharge was measured at beginning of each stream reach. Reaches are listed from upstream to downstream; T is a tributary (Figure 1).

Reach	Length (m)	Average width ± SD (m)	Area (m^2)	Shade (%)	Discharge (L/s)		
					Jul 24, 1987	Sep 4, 1987	Aug 3, 1988
			Rouge stream				
A	518	2.0±0.3	1,036	95	57.7		51.7
B	1,017	1.4±0.2	1,423	4	57.7		51.7
T	900	1.2±0.6	1,080	1	40.5		30.5
C	540	1.7±0.2	918	5	98.2		82.2
D	967	1.4±0.2	1,353	0	88.4[a]		74.0[a]
			Humber stream				
A	681	2.0±0.3	1,362	95		23.0	
B	2,285	2.3±0.4	5,255	70		41.0	
C	2,160	1.7±0.4	3,672	60		50.0	

[a] Incorporates 10% loss to golf course.

Calibration of Temperature Model

The streams were divided into contiguous reaches (Figure 1). Length and average width of the reaches and amounts of shade from riparian vegetation were determined in 1987. Reach length was measured directly or estimated with a map wheel from 1:10,000 base maps. Average reach width was estimated from transect measurements made at 50-m (Rouge) and 100-m (Humber) intervals (Table 1). At noon on sunny days, I observed that less than 10% of reach A of both streams was exposed to direct sunlight due to the complete canopy of the forest. Therefore, I assigned a shade factor of 95% to reach A of both model streams. To account for portions of reaches B and C of the Humber stream that had been cleared, I estimated from base maps the percentage of these reaches under continuous forest canopy and multiplied that value by the 95% shade factor assigned to reach A. For example, about 75% of reach B of the Humber stream had not been cleared, which meant it was assigned a shade factor of 70%. Percentage shade from overhanging banks in the unforested reaches of the Rouge stream (B–D) was estimated from the transect measurements (Table 1).

I calibrated the temperature model of Delay and Seaders (1966) to the Humber stream with meteorological data for August 17, 1987, and to the Rouge stream with data for July 24, 1987. Hourly data for solar radiation, air temperature, and humidity for these days were obtained from the meteorological stations at Buttonville Airport and Woodbridge. Maximum air temperatures during the calibration days were near 30°C. These data were used to simulate stream temperatures representative of hot summer days, and are in Meisner (1989). The temperature of groundwater discharging to the streams in summer, which was measured at springs and seeps, was 8.5°C.

During the calibration days, temperatures at the stations were either measured continuously with model J Peabody Ryan thermographs, or intermittently with a mercury thermometer. Discharges at the stations were measured by the velocity–area method (Armour and Platts 1983). Discharges in the Humber stream on the calibration day could not be obtained due to technical difficulties with the Gurley current meter. Discharges on September 4 were judged to be similar, and were used for calibration. Discharge and meteorological data for August 3, 1988, were also used in the Rouge model. Maximum air temperature on August 3, 1988, at Buttonville Airport was 34°C.

Because the temperature model assumes that discharge is constant within reaches, I attempted to divide the streams so that discharge did not change within reaches. In the Rouge stream, the only significant change in discharge occurred as a result of the tributary. In the Rouge model, discharge at station 4 (beginning of reach C) equalled the tributary outfall plus discharge at station 3. Temperatures at station 4 were adjusted by a simple dilution ratio.

In the Humber stream, flow through reaches A and B increased steadily due to groundwater discharge, which was determined as the difference between flow at the beginning and end of each reach. In the Humber model, I simulated the effect that groundwater discharge to reach A had on flow and temperature in reach A by attributing all the groundwater to the beginning of the reach, in the same manner as flow and temperature were adjusted at station 4 in the Rouge stream. Flow and temperature in reach B of the Humber stream were adjusted for groundwater discharge in a similar manner.

By dividing the streams into contiguous reaches, I calibrated the model of Delay and Seaders (1966) to the entire brook trout zones of both streams. The only observed temperatures required to run each model stream were those measured at station 1, because simulated water temperatures at the end of the first reach became the initial temperatures of the second reach, and so on to the end of the brook trout zone.

Climatic Warming

To simulate climatic warming, as implied by the GISS scenario, I increased hourly air temperatures in the models for July 24 and August 17, 1987, by 4.1°C. For example, the minimum and maximum air temperatures of 23 and 34°C recorded at Buttonville Airport on July 24 were increased to 27.1 and 38.1°C. The temperature of groundwater discharging to reaches A and B in the Humber model and hourly temperatures of groundwater discharging from the hatchery and commercial trout pond in the Rouge model were increased by 4.8°C (the projected change in local mean annual air temperature).

Results

Brook trout captured in the study streams ranged from 4 to 39 cm in total length. The summer distributions of brook trout in the streams in 1987 and 1988 were continuous; however, catch data for only the lower sections (sections B and downstream) are presented here. Data for upper sections, and length-frequency data for all brook trout, are in Meisner (1989).

Summer Distributions

In July and August 1987, brook trout were present in the Rouge stream above and below the tributary (Table 2). The maximum number of brook trout captured during three surveys were 25 in 100 m of section B, 9 in 350 m of section C, 12 in 100 m of section D1, and 3 in 75 m of section D3. No brook trout were captured in section G near Dickson Hill on July 15. Maximum temperatures measured at stations 3, 5, and 6 in the Rouge stream during the July and August surveys in 1987 were 18, 21, and 25°C (Table 2).

On August 14, 1987, brook trout were captured in section C3 of the Humber stream a few meters upstream of the mouth, but were not captured downstream in 225 m of section D of Centreville Creek (Table 3). Maximum temperatures measured at stations 3, 4, and 5 in the Humber stream and Centreville Creek during the July and August surveys in 1987 were 20, 23, and 24°C (Table 3).

Catch data of 1987 suggested that the summer zones of brook trout ended near section D3 in the Rouge stream, and at the mouth of the Humber stream.

In 1988, brook trout were abundant in Centreville Creek until temperatures at station 5 exceeded 25°C, after which only one brook trout was captured there (Table 3). Marked trout from Centreville Creek began to appear in the Humber stream in April. During a survey on June 21, nine marked brook trout were found 2.7 km upstream in section B. The maximum weekly temperatures recorded at stations 3, 4, and 5 in the Humber stream and Centreville Creek in 1988 were 23, 24, and 28°C (Table 3).

In 1988, the number of brook trout captured in the Rouge stream decreased in successive sections below section C (Table 2). In almost all surveys, more brook trout were captured in section B than in sections D2 and D3. After the dam at station 5 was installed, the number of brook trout captured in sections D1–D3 increased. By mid-June, the numbers of brook trout captured in section C started to decline. Water levels in sections E and F had subsided by late June, which permitted electrofishing, but few brook trout were found. No brook trout were captured in section G near Dickson Hill on April 22 and May 12.

The maximum weekly temperatures recorded at stations 1, 3, 5, and 6 of the Rouge stream in 1988 were 12, 19, 21, and 25°C (Table 2). Maximum temperatures measured in section E with a mercury thermometer, during the July electrofishing surveys, were the same as temperatures measured at station 6. The maximum temperature measured in section F during the July surveys was 26°C.

In 1988, section E of the Rouge stream formed the end of the summer brook trout zone. However, because relatively few brook trout were caught in section E during the July surveys, and maximum temperatures recorded in section E were the same as maximum temperatures at station 6, I assigned station 6 as the end of the brook trout zone. In 1988, the mouth of the Humber stream formed the end of the brook trout zone of that stream.

TABLE 2.—Frequencies of occurrence of brook trout in lower sections of Rouge stream, and maximum temperatures recorded for the month (1987) or the previous week (1988). Blanks indicate that sections or stations were not sampled. The dam at temperature station 5 was installed May 1, 1988.

	Number of fish by stream section and section length (m)									Maximum temperature (°C) by station and stream section		
Date	B 250	C 540	D1 200	D2 642	D3 125	E 275	F 650	G 500	D1–D3 967	3 B	5 C–D1	6 D3
					1987[a]							
Jul 15	20	6			3			0		18	21	25
23	13	8	10									
Aug 7	25	9	12							16		23
					1988							
Mar 28	28	27	26	16	9				51			
Apr 8	37	31	25	10	3				38			
15	35	18	17	9	2				28	13	14	15
22		26	21	11	2			0	34	12	13	14
29			17	9	5				31		13	14
May 5	32		25	10	8				43	13	15	17
12	38	25	44	16	13			0	73	16	18	22
20	53	36	22	24	10				56	17		
26	44	48	26	20	14				60	18	20	21
Jun 9	53	25	35	32	11				78	18	21	22
14	52	29	19	44	13				76	19	21	24
21		27	38	32	9	5			79	19	21	25
29	53	22	42	9	12				63	18	21	24
Jul 6	48	20	45	17	12				74	17	21	22
13	62	20	47	13	12	2	0		72	17	21	24
21	49	13	49	15	12	4	0		76	18	21	25
27	46	17	47	16	15	1	0		78	16	19	22
Aug 3	45	14	42	25	14				81	17	21	25

[a] In 1987, only 40–65% of each section was electrofished.

Thermal Habitat Barriers

The thermal barrier of station 6 of the Rouge stream was 24°C. The thermal barrier of station 4 of the Humber stream was 23°C. This implied that brook trout in the Humber stream were more sensitive to temperature than trout in the Rouge stream. The 23°C barrier occurred at the mouth of the stream, below which maximum temperature at station 5 in Centreville Creek increased abruptly to as high as 28°C (Table 3). In effect, during the warmest period of summer, there was no habitat of temperatures between 23 and 28°C. Because temperatures at station 4 in the Humber stream reached 24°C in 1988, I assigned 24°C as the thermal barrier of that stream.

Simulation of Climatic Warming

Maximum temperatures simulated at stations 3, 5, and 6 of the Rouge stream and at stations 3 and 4 of the Humber stream for July 24 and August 17, 1987, generally agreed with the maximum temperatures observed during these days (Figure 2). The model of Delay and Seaders (1966), however, did not simulate temperatures of early morning as well as it simulated maximum daily temperatures. This is indicated by the differences between observed and simulated morning temperatures at stations 3 in the Rouge and 4 in the Humber streams for the two days. Simulated temperatures in the Rouge stream on August 3, 1988, generally agreed with the spot temperatures taken with a mercury thermometer.

The daily range in temperature at station 1 in the Rouge stream in July and August 1987 and 1988 was 9–12°C (Figure 2). The constant temperature (9°C) and relatively large volume of groundwater discharging from the hatchery maintained the relatively low and narrow range of temperatures at station 1 throughout both summers.

The GISS climate-warming scenario increased maximum daily temperatures in the Rouge and Humber streams and moved the thermal habitat barriers (24°C) upstream. This reduced summer brook trout zones in the Rouge and Humber streams by 42 and 30% (Figure 3). The abrupt increase to about 16°C at station 1 in the "Air & gwt" profile of the Rouge stream was caused by an increase in the temperature of groundwater discharge from the hatchery. Because groundwater

TABLE 3.—Frequencies of occurrence of brook trout caught in lower sections of Humber stream, and maximum temperatures recorded for the month (1987) or the previous week (1988). Blanks indicate that sections or stations were not sapmled. Values in parentheses are recaptured marked brook trout from Centreville Creek.

	Number of fish by stream section and section length (m)					Maximum temperature (°C) by station and stream section		
Date	B 330	C1 400	C2 300	C3 275	D[a] 550	3 B–C1	4 C3	5 D
			1987[b]					
Jul 17		14		19		20	23	
Aug 14				18	0	20	23	24
17		37						
			1988					
Apr 4		27		13	10			
12		27		12	32		9	11
21				9(1)	8(2)	10	10	13
28						9	10	12
May 6		30		21(1)	32(3)	12	14	17
13				18(1)	49(11)	14	16	19
19		50		20(3)	22(12)	15	18	23
25				42(3)	58(16)	15	18	25
Jun 10		87(6)		44(4)	7(1)	17	18	25
15		75(5)	89(7)	24(1)	1	20	22	27
21	123(9)				0	21	22	26
30					0	20	21	26
Jul 13						22	23	27
Aug 4						22	23	28
12						22	24	27
17				10(1)	0	23	24	27

[a] All marked with adipose fin clips.
[b] In 1987, only 40–70% of each section was electrofished.

discharges to the Humber stream below station 1 from more than one source, the effect of elevated groundwater temperature on that stream was more subtle (Figure 3). The effect of elevated air temperature on maximum temperatures of both streams was less than the combined effects of elevated air and groundwater temperature. The effect of elevated air temperature alone was greater on the Humber stream than on the Rouge stream.

Discussion

Brook trout in the Rouge and Humber streams appear to avoid water temperatures above about 24°C. This upper avoidance temperature is consistent with the species' upper incipient lethal temperature of 25.4°C (Fry et al. 1946), and agrees with other studies of brook trout zonation in southern Ontario streams. Ricker (1934) pointed to 24°C as the barrier separating the brook trout–sculpin and centrarchid–cyprinid communities of Ontario streams. Recently, Barton et al. (1985) found that only fragmented populations of brook trout existed in streams in which 3-week means of maximum temperatures exceeded 22°C. Bowlby and Roff (1986), in a study of factors affecting brook trout biomass, found brook trout in a few stream reaches in which daily maximum temperatures reached 25°C, but daily temperatures in most of the streams did not exceed 22–23°C.

The tagging and temperature data collected in the Humber study area in 1988 suggest that brook trout moved out of Centreville Creek due to high water temperatures and took refuge in the Humber stream. Although it is possible that some brook trout from Centreville Creek moved downstream to cold tributaries, the significant finding is that brook trout left Centreville Creek when temperatures were close to their lethal level.

The general increase in the number of brook trout captured in sections D1–D3 of the Rouge stream throughout summer 1988 suggests that brook trout from sections E and F moved upstream as water temperatures increased in summer. The general decline in brook trout captured in section C after mid-June 1988 supports this hypothesis. Some fish from section C may have moved upstream to lower water temperatures above the tributary after temperatures in section C reached 21°C. If brook trout from section C moved upstream to avoid summer temperatures in section C, it follows that brook trout from section D1 may have been prevented from similar movement by the dam at station 5. It is unlikely that brook trout from section C moved downstream over the dam to the warmer sections below.

Climatic warming will likely increase both summer's length and temperatures, which means that brook trout in streams at low altitudes and low latitudes will spend longer periods in minimum thermal habitat. Habitat space has long been considered a determinant of the carrying capacity of a stream for salmonids (e.g., Chapman 1966; Burns 1971; Zalewski et al. 1985). If one assumes that all other factors that may affect the brook trout populations in the Rouge and Humber streams, such as competition from nonsalmonids and food supply (e.g., Flick and Webster 1975; Cada et al. 1987), do not change in a "warmer" climate, reductions in summer habitat like those simulated will likely lead to comparable reductions in the sizes of both brook trout populations.

Some summer brook trout zones in streams of southern Ontario may not be continuous, but may occur in patches (Barton et al. 1985) in association

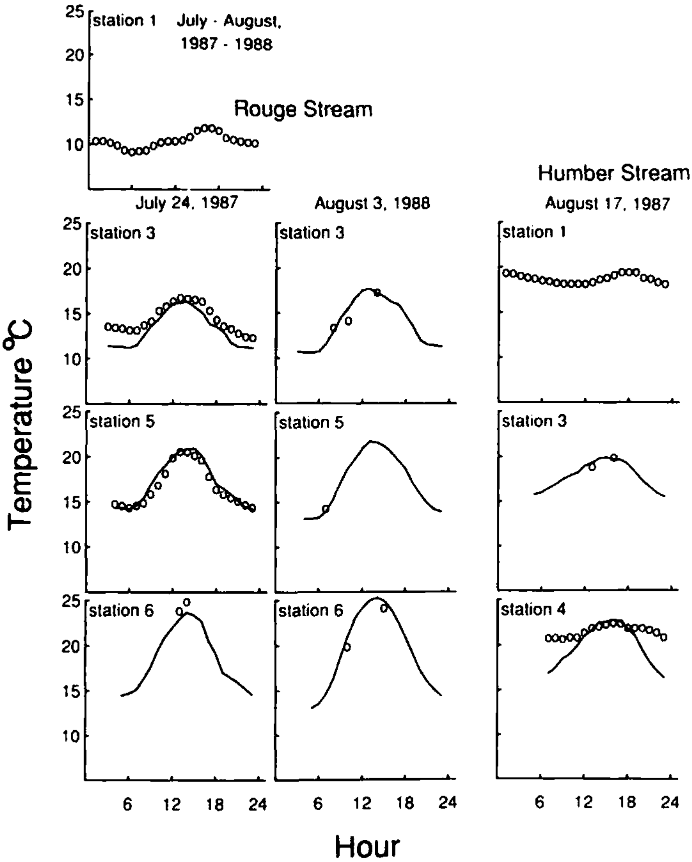

FIGURE 2.—Observed (open circles) and simulated (solid lines) temperatures in the Rouge stream for July 24, 1987, and August 3, 1988, and in the Humber stream for August 17, 1987. Observed temperatures were measured with thermographs (e.g., station 3, Rouge stream, July 24) or with a mercury thermometer (station 6, Rouge stream, July 24). Observed temperatures at station 1 in Rouge stream in 1988 were the same as those observed in 1987 due to the dominant influence of groundwater discharge from a hatchery.

with riparian vegetation and areas of groundwater upwelling. The simulations in my study suggest that climatic warming will shrink coldwater plumes associated with areas of groundwater upwelling in summer, and ultimately will shrink isolated refugia for brook trout. Presently continuous summer thermal habitat in some streams may become fragmented.

The differences between observed and simulated morning temperatures in the streams (Figure 2) likely arose because the temperature model does not incorporate terms in the energy equation to account for heat storage in the stream bed, banks, and adjacent vegetation. These surfaces act as sinks for short- and longwave radiation by day and as radiators by night to provide heat to streams and the blanket of air immediately above the ground. Other investigators have built such energy terms into their models (e.g., Bowles et al. 1977).

The different responses of the two streams to elevated summer air temperature of the GISS scenario reflects differences in their structural and hydrological properties. The Rouge stream is exposed to more direct solar radiation, which is the primary and dominant source of heat to surface waters. Thus, shade of the Humber stream likely permits the air mass (via evaporation, longwave radiation, conduction) to play a greater role in raising the stream temperature. Also, average water velocity is less in the Humber stream than in the Rouge stream. This, combined with the Humber stream's greater length (5 km), causes travel time of water through the Humber basin and, hence, exposure of the Humber stream to air to be greater

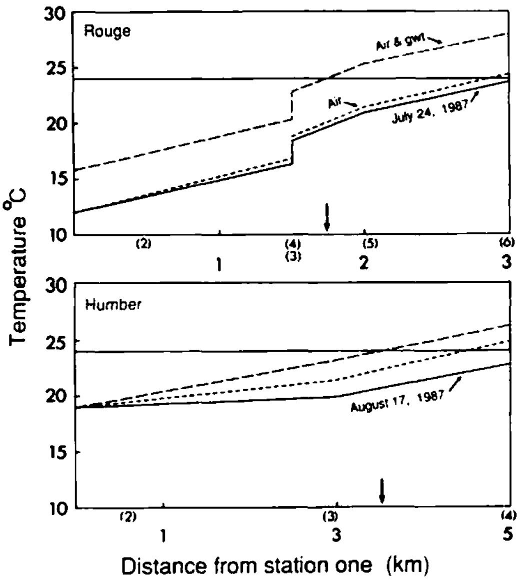

FIGURE 3.—Assessment of the potential effect of climatic warming on summer thermal habitat for brook trout in two southern Ontario streams. The longitudinal temperature profiles labeled July 24, 1987, and August 17, 1987 (solid lines), were constructed from the simulated maximum temperatures at the temperature stations for these days (Figure 2). Numbers in parentheses along the abscissas indicate approximate positions of temperature stations. The abrupt increase of about 2°C between stations 3 and 4 in the Rouge profile shows the effect of the tributary. Profiles marked "Air" (short dashes) and "Air & gwt" (long dashes) are simulated maximum temperatures when stream models were forced with elevated air temperature, and elevated air and groundwater temperatures, respectively. The horizontal line in each panel represents the thermal habitat barrier (24°C) of the stream. The arrows on the abscissas indicate the locations of the summer thermal habitat barrier and the lower ends of summer brook trout zones in the Goddard Institute for Space Studies (GISS) scenario.

than for the Rouge stream. The thermal inertia of the Rouge stream is greater than that of the Humber stream, due to the larger discharge, which contributed to the Rouge's lower sensitivity to scenario-adjusted air temperatures (equation 1).

My temperature models of the two streams may have underestimated the effect of elevated groundwater temperatures that result from climatic warming because stations 1 were not located at the absolute beginnings of the streams. Thus, the Humber model did not reflect the effect of changes in the temperature of discharged groundwater flowing to station 1, which was about 56% of flow to reach B (Table 1). The underestimate of the Rouge model is likely insignificant because that model embodied the large volume of groundwater discharge from the hatchery. Despite this potential limitation, my application of Delay and Seaders's (1966) temperature model provided good first approximations of the effect of climatic warming on maximum summer stream temperatures in the two streams.

Although I focused on the effects of changes in air and groundwater temperature on the thermal habitat of brook trout, brief mention of the potential effect of streamflow changes is warranted. The different scenarios of climatic warming (Smith 1989) project changes in seasonal precipitation for this region, but the direction and magnitude of projected changes among scenarios do not agree. If summer precipitation were to decrease, the temperature model used in my study (equation 1) shows clearly that a reduction in base flow would exacerbate the effects of increased air temperature. Reduced habitat volume alone would lower brook trout biomass and abundance (e.g., Kraft 1972).

Climatic warming will likely increase groundwater and summer air temperatures, and shrink summer habitat for brook trout in streams at low altitudes and latitudes in North America. However, because groundwater temperatures will always be lower than summer air temperatures, the cooling function of groundwater in streams will be maintained. The fate of a stream population of brook trout in a "warmer" climate will be determined by the volume of groundwater discharging to the stream and the space available to which the fish can retreat in summer.

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