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Effects of river flow fluctuations on groundwater discharge through brook trout, *Salvelinus fontinalis*, spawning and incubation habitats

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Abstract

The effects of short-term fluctuations in river discharge simulating a hydroelectricity peaking regime on the hydrogeological environment of the brook trout's reproductive habitats were examined. Fluctuating river levels altered shallow (≤ 2.5 m) groundwater pathways, chemistry, and flow potentials within the river bed at spawning and incubation sites. Rising river levels introduced river water into the bank where various degrees of mixing with groundwater occurred. Subsequent recessions of river levels increased the potentials for groundwater flow, particular in an offshore direction. The character of the river water – groundwater interaction appeared to be related to the hydrogeological nature of the river channel and adjacent catchment which varied among sites. The observations suggested hydroelectricity peaking regimes have potential negative impacts on brook trout reproduction.

Introduction

Many rivers and their watersheds are important to recreation, resource development, and energy production. However, these multiple uses of natural resources are not always compatible. The Nipigon River of northwestern Ontario, Canada, supports a world renowned brook trout, *Salvelinus fontinalis*, fishery (Scott & Crossman, 1979). The river also produces a significant quantity of hydroelectricity for Ontario. The majority of electricity is produced by manipulating the river discharges as a 'peaking' system. Peaking regimes require a maximum quantity of water to be stored behind dams until periods of peak energy demand when water is released to generate electricity. The result is a cycle defined by low river stage followed by a rapid increase in discharge and river levels persisting for variable periods, and a subsequent rapid return to a low river stage.

Peaking regimes typically have adverse affects on fish populations (see review by Burt & Mundie, 1986). Fluctuating river levels can cause populations to decline in response to unstable and transient habitats for free-swimming life history stages (Bain *et al.*, 1988) or possibly alterations of the hyporheic environment (White, 1990) utilized as incubation habitats. Spawning success will be jeopardized if declining river levels block access to spawning areas, or depths and flow rates decline below species specific minima (Reiser & Wesche, 1977; Smith, 1973). Incubation success has been maximized in controlled laboratory environments when embryos remain moist due to continual submergence (Becker *et al.*, 1983) and when water flow persists through the surrounding substrate (Reiser & White, 1983).

The presence of groundwater in the spawning and incubation habitat of brook trout appears to be critical for reproductive success (Curry *et al.*, 1991; Fraser, 1985; Gunn, 1986). Groundwater may mitigate the effects of de-watering events (Brick, 1986), but the effects of regulated river discharge on spawning brook trout adults and the groundwater environment of incubating embryos have never been described. The objective of the present study was to document changes in the hydrogeological environment of brook trout spawning and incubation habitats during short-term, river level manipulations. These observations would then be used to examine the potential impacts on the reproductive success of brook trout.

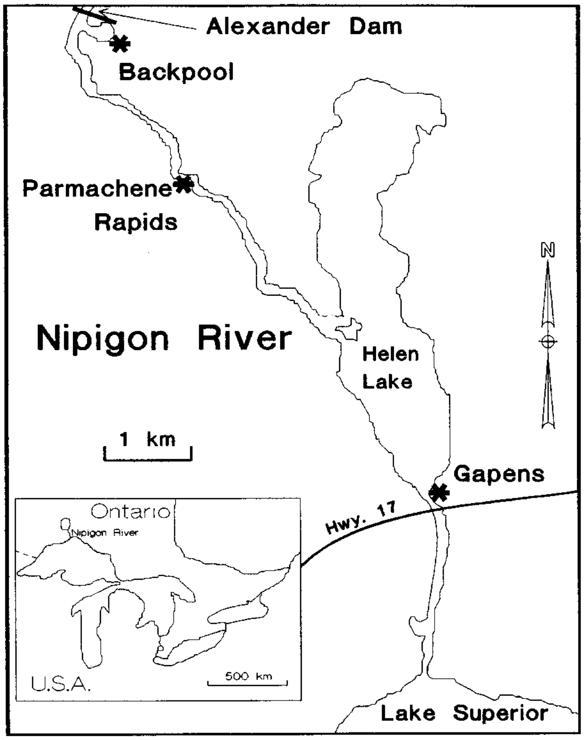

Fig. 1. Location of the Nipigon River and three brook trout spawning and incubation sites studied.

Methodology

Study site

The Nipigon River is located in a relatively young (< 10 000 yrs) region of glacio-fluvial deposits. The river falls 76 m from Lake Nipigon to Lake Superior in northwestern Ontario, Canada (Fig. 1). The river drains a total watershed of 23 000 km^2. It is short ($\approx$ 50 km), but of substantial discharge (100–600 m^3 s^{-1}). Three dams constructed on the river between 1920 and 1950 generate up to 240 megawatts of electricity for Ontario Hydro.

There are three known brook trout spawning sites in the 20 km reach between the final (downstream) dam at the Alexander Generating Station and Lake Superior (Fig. 1). There are no obstructions to brook trout movement in this section of river. All three spawning sites are located adjacent to steep sloping river banks ($\approx$45 slope and 20–40 m elevations). The slopes are treed with balsam fir (*Abies balsamea*), white birch (*Betula papyrifera*), poplar (*Populus spp.*), and some eastern white cedar (*Thuja occidentalis*).

The first site (= A), known as the Backpool, is located in the former river channel immediately below the Alexander Dam (Fig. 1). This near-stagnant pool ($\approx$ 5 ha) was the splash-pool of the original water fall and is now isolated from the present river by a narrow, 10–15 m wide channel. The gently sloping ($\approx 2°$) river bed at the spawning site is composed primarily of clay with various intermixed cobble-gravel bars. Brook trout spawning and incubation takes place on a 10 × 3 m gravel bar located 10 m offshore from the bank-full level. The bank-full level and spawning site correspond to $\approx$400 and 200 m^3 s^{-1} river discharges, respectively. The hydrological catchment adjacent to the spawning and incubation site is < 2 ha.

The second site (= B) is located at Parmachene Rapids (Fig. 1). The site is situated along the southwest bank at the end of a 200 m wide pool. The river bed slopes 10–20° and is composed primarily of intermixed sand, gravel, and cobbles with exposed clay lenses. Brook trout spawning occurs in a 15 × 10 m area < 10 m offshore (100–200 m^3 s^{-1} river levels) of the bank-full level (≈400 m^3 s^{-1} river level). The hydrological catchment adjacent to the spawning and incubation site was < 1 ha.

The third site (= C) is located at Gapens Pool at the outlet of Lake Helen (Fig. 1). The spawning area is situated in a large back-eddy (≈2 ha). The river bed in this area slopes 10–20° and is composed of primarily sand with small pockets (≈2 × 2 m) of gravel and cobble dispersed over 100–150 m of shoreline and within 20 m of the bank-full level. Several of the pockets are used by the brook trout as spawning and incubation sites. Unlike the other two sites, no clay lenses were observed. The adjacent catchment area is > 3 ha.

Methods

Mini-piezometers were used to measure hydraulic pressure heads (*i.e.*, the elevation at which the water pressure is at equilibrium with atmospheric pressure) and to sample water chemistry. Piezometers were constructed of flexible polyethylene tubing of 9.6 mm outside and 6.4 mm inside diameter. The slotted end was 10 cm in length with 7 horizontal openings (2 × 3 mm) cut into the tubing and covered with a double layer of 500 μm nylon (Nitex) screen. The piezometers were installed by inserting them into a metal pipe that had been driven into the river bed with a loose fitting, metal cap as described by Lee & Cherry (1978). The pipe was subsequently extracted substrate to collapse around the piezometer. The substrate was allowed to settle for 24 hrs prior to sampling.

Six piezometer nests were installed at each of the spawning sites on 21 (Backpool and Parmachene) and 22 (Gapens) September, 1991. Each nest consisted of two piezometers installed to depths of 1 and 2.5 m below grade. Three piezometer nests were installed perpendicular to the shore in two transects (= North and South transects). In each transect, piezometer nests were located at elevations corresponding to the river level at 113, 260, and 400 m^3 s^{-1} river discharges (see Figs 3 and 4). The two transects were sited in the outer thirds of the total spawning areas at the Backpool and Parmachene sites (10 m apart) and in the central area of the more expansive Gapens (13 m apart). Piezometers were labelled according to the site (A, B, or C), elevation (113, 260, or 400), transect (N or S), and depth (1 or 2.5 m). Five of the piezometer nests were installed at specific locations of brook trout redds (= nests) marked the previous year (piezometers A260N, A260S, B260S, C113N, and C113S).

The brook trout population in the Nipigon River appears to be declining. The activities and equipment of the present study had the potential to reduce spawning and incubation success; therefore, we chose to conduct and conclude our experiment immediately prior to spawning (early October) in an effort to mimimize our impact on reproduction. The groundwater monitoring began 22 September and was completed on 29 September, 1991. Ontario Hydro controlled discharge from the Alexander Dam to produce a simulated peaking cycle with river level stages sustained for approximately 24 hrs. One period each of maximum and minimum river stages were also acheived during the cycle (Fig. 2). Alterations of

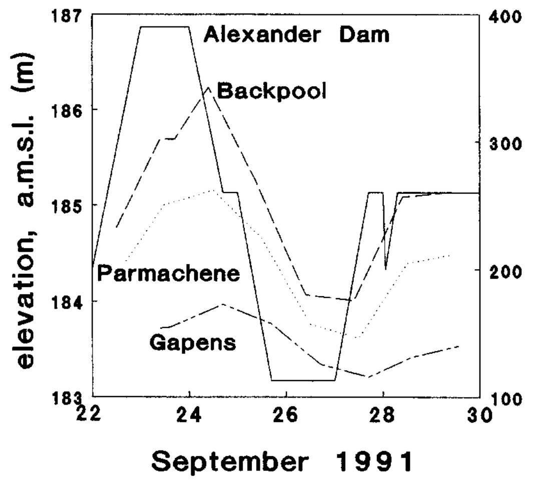

Fig. 2. Discharge from the Alexander Dam (m^3 s^{-1}) and river levels (m, a.m.s.l.) at three brook trout spawning and incubation sites in the Nipigon River, September 1991.

discharges occurred over the period 1800–2400 hr. Sampling occurred between 0900–1800 hr beginning with Backpool and proceeding downstream.

Hydraulic pressure head above the river level (mm) was measured daily in each piezometer with a manometer and occasionally a metered rule. River levels were monitored with Ontario Hydro staff gauges present at each site. The zero depths of these gauges at the Backpool (A), Parmachene (B), and Gapens (C) sites were 184.79, 184.31 and 183.82 m above mean sea level (a.m.s.l.), respectively. The datum was set to 0 m a.m.s.l. and the pressure heads were plotted for each transect

Table 1. Chemistry of the river and at 1 and 2.5 m within the substrate at three brook trout spawning and incubation sites in the Nipigon River, 22–29 September, 1991. Parameters are measured as mg l^{-1} as element or compound unless stated otherwise.

	Surface water			1 m			2.5 m		
	Mean	S.D.	*n*	Mean	S.D.	*n*	Mean	S.D.	*n*
Backpool									
Cond (μm cm^{-1}@25°C)	220	54	6	279	10	11	281	7	25
Hard (mg l^{-1} $CaCO_3$)	112	30	6	150	10	7	148	6	21
Ca	34	9	6	48	10	10	44	2	24
Mg	6.9	2.2	6	10.5	2.2	9	9.7	0.5	24
Na	2.1	0.6	6	2.3	0.9	10	1.8	0.1	24
K	1.2	0.5	6	2.8	1.4	10	2.0	0.2	24
Cl	2.0	1.1	6	1.4	0.7	9	0.9	0.1	24
Alk (mg l^{-1} $CaCO_3$)	112	30	6	154	10	11	149	6	25
pH	8.2	0.1	6	8.0	0.1	11	7.9	0.1	25
SO_4	3.25	1.00	6	4.51	0.33	10	4.67	0.39	25
NO_3 (mg l^{-1} N)	0.03	0.02	6	0.08	0.01	11	0.10	0.02	25
Parmachene									
Cond (μm cm^{-1}@25°C)	152	6	6	287	9	19	289	8	24
Hard (mg l^{-1} $CaCO_3$)	77	6	5	148	10	18	148	6	23
Ca	23	1	6	40	4	19	40	3	24
Mg	4.6	0.9	6	11.7	0.7	19	11.8	0.9	24
Na	1.4	0.2	6	2.1	0.1	19	2.1	0.4	24
K	0.6	0.1	6	2.0	0.2	19	2.0	0.3	24
Cl	1.1	0.4	6	1.1	0.3	19	1.1	0.2	24
Alk (mg l^{-1} $CaCO_3$)	76	2	6	148	5	19	148	10	24
pH	8.1	0.1	6	8.0	0.1	19	8.0	0.1	24
SO_4	2.46	0.61	6	8.12	0.37	18	7.80	1.68	24
NO_3 (mg l^{-1} N)	0.03	0.02	6	0.15	0.01	18	0.14	0.01	23
Gapens									
Cond (μm cm^{-1}@25°C)	154	3	5	552	61	29	557	60	30
Hard (mg l^{-1} $CaCO_3$)	78	2	5	226	32	25	218	27	26
Ca	24	1	5	63	8	29	60	8	30
Mg	4.4	0.1	5	17.3	3.0	29	15.3	2.2	30
Na	1.4	0.1	5	24.6	11.3	29	29.1	6.4	30
K	0.6	0.1	5	19.0	79.8	29	4.0	0.3	30
Cl	1.2	0.2	5	65.0	34.3	29	79.1	18.1	30
Alk (mg l^{-1} $CaCO_3$)	77	1	5	170	39	29	157	3	30
pH	8.2	0.1	5	8.0	0.1	29	8.0	0.1	30
SO_4	2.27	0.23	5	16.57	9.38	28	13.04	0.60	30
NO_3 (mg l^{-1} N)	0.02	0.01	5	0.38	0.20	29	0.50	0.04	30

at each sampling period. Isolines of pressure heads were determined by eye and the patterns of change during the study examined.

The vertical and horizontal (parallel to the river bed) hydraulic head differentials were calculated at each piezometer. Vertical differentials were calculated as the difference between the 1 m piezometer and the river level when the piezometer nest was submerged (1 m) and between the 2.5 and 1 m piezometers within a nest (2.5 m). Horizontal differentials were calculated between adjacent piezometer nests within a transect, *i.e.*, 400–260 and 260–113 levels at both the 1 and 2.5 m depths. Although attempts were made to relate differentials to river levels, the limited number of samples and heterogeneity of responses among piezometers limited analyses. The overall patterns of change were, therefore, examined by comparing differentials during submerged and exposed periods (ANOVA – SAS, 1985). Variances and residuals were examined to ensure the integrity of the statistical tests (Gilbert, 1989). No transformations of data were required.

Hydraulic conductivities ($K = \text{cm s}^{-1}$) were estimated following the methods of Lee & Cherry (1978) on 24 September when all piezometers were submerged. Collection bags were attached to piezometers and suspended at the river surface. The discharge of water was measured in a 500 ml graduated cylinder and the sampling time recorded with a stop-watch. Two samples were collected and the mean discharge, hydraulic gradient, and piezometer dimensions were used to calculate K (Hvorslev, 1951). Hydraulic conductivities were calculated for piezometers with discharge rates > 10 ml/h.

The vertical component of groundwater flux through the known locations of brook trout redds was examined using the basic Darcy equation (Freeze & Cherry, 1979). The flux was calculated between the 1 m piezometer and the river level using the vertical head differential and hydraulic conductivity. It was assumed the substrate between the piezometer tip and surface was homogenous and isotropic.

Water samples were collected six times during the study (Table 1). Samples were collected in 4 l plastic bags attached to the piezometers. The bags were filled by lowering them below the static water level in the piezometers. Where there was insufficient pressure, samples were collected using a siphon or by vacuum extraction.

Sample bags were rinsed with collected groundwater prior to collection for chemical analysis. Sampled water was placed in new, acid-washed bottles, refrigerated, and analyzed within several days by a government accredited laboratory. Analyses included conductivity, total hardness, calcium, magnesium, sodium, potassium, total alkalinity, pH, chloride, sulphate, total phosphate, total ammonium, and nitrate-nitrogen.

Conversion of analytical results to equivalent parts per million (EPM) was made to check ion balances. In addition, data were expressed as percentage of EPM to detect any significant changes in the ionic composition of the samples in response to changing river levels. The percentages of the total meq/l of cations and anions were plotted on DUROV plots to detect any significant changes in ionic composition (Freeze & Cherry, 1979).

Interactions between groundwater and river water were also examined at the Gapens site by plotting groundwater chloride concentrations against the river levels. These plots were summarized with linear regression analyses (Gilbert, 1989; SAS 1985).

Results

Ambient river

Discharges from the Alexander Dam ranged from 113–390 $m^3\ s^{-1}$, resulting in rates of river level fluctuations of 20–115 cm d^{-1} at each of the sites (Fig. 2). Changes were always most pronounced at the Backpool and least at the Gapens site.

The chemical composition of river water at all three sites was relatively similar during the fluctuations of the river (Table 1). The DUROV plots classify the river as calcium bicarbonate waters which reflects direct inputs of precipitation and freshly discharged groundwater (Fig. 5a).

Backpool

The results from the Backpool were complicated by certain hydrogeological factors. In the vicinity of the brook trout spawning and incubation area, there was a high potential for groundwater flow as indicated by consistent, vertical hydraulic head differentials that were substantially greater than the other sites (maximum = 130 cm, Table 2). The pressure heads, in combination with the clay substrate, resulted in poor seals developing around the piezometer nests at A400S, A113N, and A113S. Consequently, groundwater continually discharged through the surface around these piezometer nests during the study period and it was necessary to eliminate the 1 m piezometer data from all analyses.

Despite the substantial hydraulic pressure heads at the Backpool site, hydraulic conductivities were consistently low in comparison with the other sites (0.01–0.27 cm $s^{-1} \times 10^{-2}$ – Table 3). Groundwater pathways could not be determined from the present data. In the functioning piezometers, horizontal differentials were significantly greater at the 1 m, but not the 2.5 m depth when the piezometers were exposed (Table 2). Vertical differentials at the 2.5 m depth were similar during exposed and submerged periods. The gravel bar where the brook trout spawn at the 260 level remained wetted during the exposure period.

All chemical concentrations were elevated in the piezometer samples in comparison with the ambient river, indicating a groundwater source (Table 1). The groundwater within the river bed exhibited minor variability and was similar be-

Table 2. Horizontal, hydraulic pressure head differentials (cm) between adjacent piezometers within a transect (400–260 and 260–113) at 1 and 2.5 m depths below grade, and vertical differentials between 1–0 and 2.5–1 m depths during exposure and submersion of piezometers at three brook trout spawning and incubation sites and known redds in the Nipigon River, September 1991. Means ± standard deviations are presented.

Site	Depth (m)	Submerged	Exposed	P^1	*n*
Horizontal					
Backpool	1	10 ± 21	40 ± 22	<0.01	23
	2.5	9 ± 18	25 ± 39	0.14	31
Parmachene	1	3 ± 3	11 ± 10	0.03	23
	2.5	2 ± 3	7 ± 6	0.01	29
Gapens	1	1 ± 2	4 ± 4	0.01	28
	2.5	1 ± 3	2 ± 4	0.14	28
Redds – A200N & S	1	12 ± 23	46 ± 21	0.02	15
Redds – B200S, C100N & S	1	3 ± 4	20 ± 14	0.01	6
Vertical					
Backpool	1	39 ± 14	–	–	14
	2.5	43 ± 23	47 ± 31	0.66	44
Parmachene	1	5 ± 4	–	–	27
	2.5	4 ± 6	3 ± 6	0.58	39
Gapens	1	2 ± 1	–	–	30
	2.5	2 ± 1	2 ± 3	0.60	44
Redds – A200N & S	1	36 ± 15	–	–	10
Redds – B200S, C100N & S	1	3 ± 2	–	–	23

[1] H_0: submerged = exposed.

Table 3. Hydraulic conductivity (cm $s^{-1} \times 10^{-2}$) of substrate at 1 and 2.5 m below grade and along two transects at three brook trout spawning and incubation sites in the Nipigon River, 24 September, 1991.

	Depth (m)	Nominal river level ($m^3 s^{-1}$)		
		400	260	113
Backpool				
(north)	1	0.01	0.02	–
	2.5	0.13	0.25	0.09
(south)	1	–	0.27	–
	2.5	0.18	0.18	–
Parmachene				
(north)	1	2.64	0.23	–
	2.5	1.50	2.59	–
(south)	1	3.11	3.53	–
	2.5	2.17	3.27	2.10
Gapens				
(north)	1	1.53	3.90	2.65
	2.5	1.81	3.33	1.52
(south)	1	1.81	0.94	3.12
	2.5	2.65	1.34	1.51

tween depths during the river level fluctuations. Phosphate and ammonium were at or below trace levels in both groundwater and river water (<0.005 and <0.01 mg l^{-1}, respectively).

There was a greater similarity between the river bed groundwater and the ambient river in the Backpool than existed at the other sites. The similarity may be related to the enclosed nature of the site. With no direct flow of river water into this area, groundwater likely accounts for a large proportion of the surface water within the Backpool.

Parmachene

The changes in hydraulic pressure head at both transects at the Parmachene site suggested groundwater flow within the river bed was always directed offshore and towards the river column. The potential for groundwater movement was approximately vertical when the river level covered all piezometer nests (Fig. 3). As the river receded, the potential followed the river level to become near horizontal when river levels were below all piezometer nests (Fig. 4).

Horizontal head differentials were significantly greater at both depths when piezometers were exposed (Table 2). Vertical differentials were similar during exposed and submerged periods. In addition, the gravel bar where brook trout spawn in the vicinity of the 260 level piezometers remained wetted during the exposure periods.

Hydraulic conductivities within the Parmachene river bed ranged from 0.23–3.53 $\times 10^{-2}$ cm

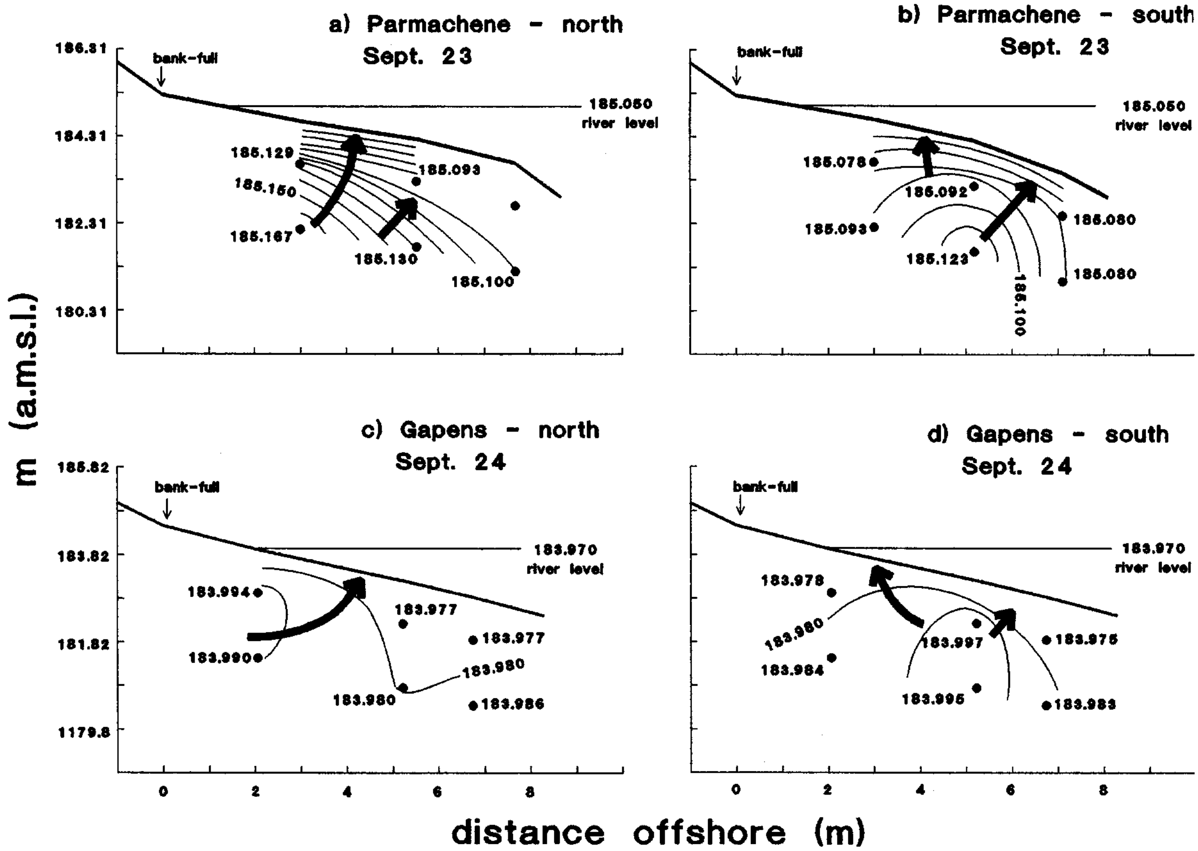

Fig. 3. Cross-sections perpendicular to the north-south river flow at two transects through the Parmachene and Gapens brook trout spawning and incubation areas after 36 hours of maximum flows. Solid circles indicate the location of the piezometers in the river channel. River levels (m – a.m.s.l.), hydraulic pressure heads in the responding piezometers (m – a.m.s.l.), estimated isolines of equal pressure (10 cm), and general direction of groundwater flow (arrows) are presented.

s^{-1} (Table 3). It is suspected the slow discharges (≈ 10 ml h^{-1}) at B113N1, B113N2.5, and B113S1 were related to the presence of clay lenses.

The concentrations of all chemical parameters within the river bed were elevated in comparison with the river (Table 1). The chemical composition of groundwater at both depths was consistent during the river level fluctuations. Nitrate appeared to be elevated in piezometer samples. Phosphates and ammonium were at or below trace levels in both groundwater and river water.

Gapens

Groundwater movement within the river bed at Gapens was similar to Parmachene during the river level fluctuations. Groundwater flow at both transects was directed towards the vertical when river levels were greatest (Fig. 3). Flow was more horizontal when river levels were reduced (Fig. 4).

Horizontal head differentials were significantly greater when the substrate was exposed at the 1 m but not at the 2.5 m depth (Table 2). differentials were similar during exposed and submerged periods. No wetted areas were observed during the low river levels, although such areas have been observed when river discharge declines to < 100 m^3 ^{-1}s (R. Swainson, unpublished data). Hydraulic conductivities in the river bed varied from $0.94–3.90 \times 10^{-2}$ cm s^{-1} (Table 3) which were similar to the Parmachene site.

The chemical composition of groundwater within the river bed was distinct from the ambi-

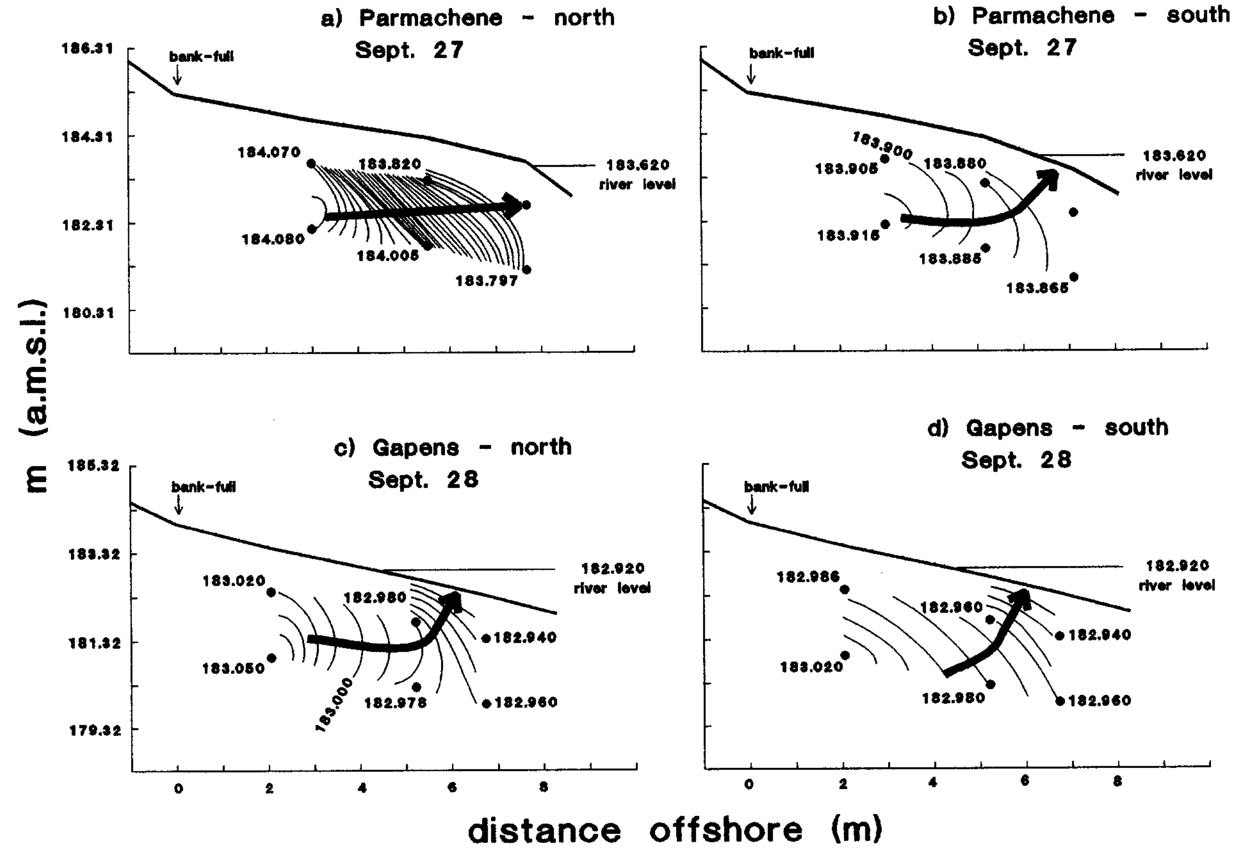

Fig. 4. Cross-sections perpendicular to the north-south river flow at two transects through the Parmachene and Gapens brook trout spawning and incubation areas after 36 hours of minimum flows. Solid circles indicate the location of the piezometers in the river channel. River levels (m – a.m.s.l.), hydraulic pressure heads in the responding piezometers (m – a.m.s.l.), estimated isolines of equal pressure (10 cm), and general direction of groundwater flow (arrows) are presented.

ent river at Gapens (Table 1). All parameters were elevated in the river bed in comparison with both the ambient river and with the other two sites. Phosphate and ammonium were at or below trace levels in both groundwater and river water. Nitrate concentrations in the groundwater were elevated to the 0.5 mg l^{-1} average for precipitation in northwestern Ontario (Ontario Ministry of Environment, 1988)

Sodium and chloride concentrations were distinctly elevated at Gapens. DUROV plots (Fig. 5)

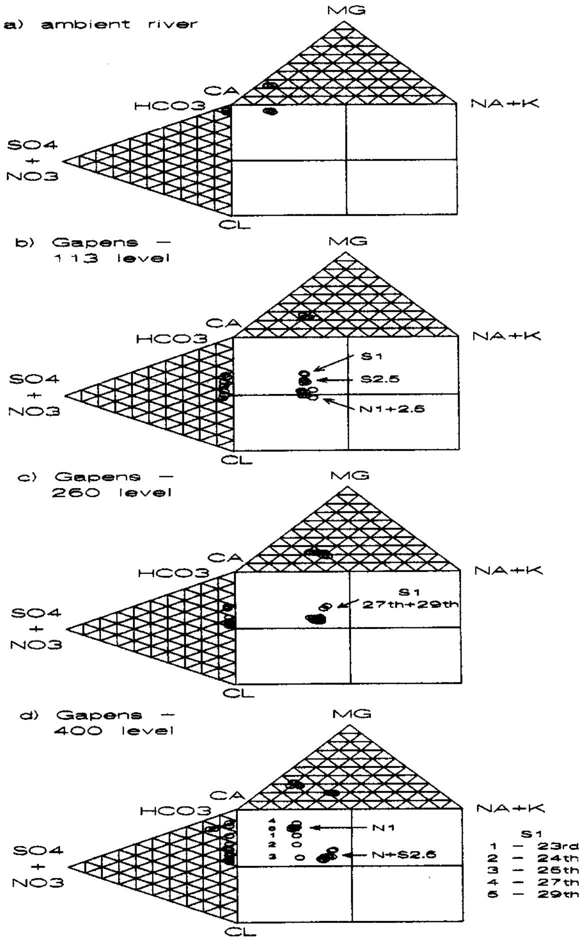

Fig. 5. DUROV plots indicating chemical composition of the ambient river at the Backpool, Parmachene, and Gapens sites (a), and the groundwater at 1 and 2.5 m below grade at the 113 (b), 260 (c), and 400 m^3 s^{-1} (c) river levels at the Gapens brook trout spawning and incubation site in the Nipigon River, 23–29 September, 1991. Circles represent % EPM (absolute error ≤10%).

indicated that groundwater in this spawning area is heavily influenced by sodium chloride contamination, probably associated with a salt storage facility for road de-icing activities in winter located ≈500 m east of the spawning site.

Groundwater and river water interaction

The elevated chloride levels in the groundwater samples at Gapens provided an opportunity to chemically examine the behaviour of groundwater and river water during river level fluctuations. In the 113 level piezometers, the DUROV plot displayed a degree of clustering indicating some mixing of groundwater and river water (Fig. 5b). The North and South transects appeared chemically different with the North exhibiting a greater influence of groundwater, *i.e.*, a greater concentration of chloride. Chloride levels displayed a significant, negative response to changing river levels at S2.5 ($P = 0.04$, $r^2 = 0.79$, $m = -0.21$, $n = 5$), indicating groundwater predominated at this site when river levels were low.

A stable groundwater composition existed at the 260 level indicating that no direct mixing with river-derived water occurred (Fig. 5c). A dilution

Table 4. Vertical, hydraulic pressure head differential (cm), specific discharge (cm $s^{-1} \times 10^{-2}$) measured when redds were submerged, and hydraulic conductivity (cm $s^{-1} \times 10^{-2}$) at 1 m below the surface of known brook trout redds in the Nipigon River, September 1991. Means, standard deviations, and ranges are presented.

Redd	Hydraulic conductivity	Hydraulic head differential	Specific discharge	n
A200N	0.02	46.2 ± 14.9 (36.0 – 72.0)	0.009 ± 0.003 (0.007 – 0.013)	5
A200S	0.27	25.9 ± 2.7 (23.0 – 30.0)	0.071 ± 0.007 (0.063 – 0.082)	5
B200S	3.53	5.1 ± 2.9 (1.5 – 10.0)	0.179 ± 0.102 (0.053 – 0.353)	7
C100N	2.65	2.0 ± 1.0 (0.7 – 3.5)	0.052 ± 0.027 (0.019 – 0.093)	8
C100S	3.12	2.1 ± 1.5 (0.5–4.2)	0.065 ± 0.048 (0.016 – 0.131)	8

of samples from S1 on September 27 and 29 could not be adequately explained. Chloride concentrations at the 1 m piezometers were significantly related to changing river levels ($P = 0.01$ and 0.01, $r^2 = 0.93$ and 0.93, $m = 0.16$ and 1.16, $n = 5$ and 5, N and S respectively) suggesting groundwater predominated at the 1 m depth during high river discharges.

Mixing of groundwater and river water appeared greatest at the 400 level. The water within the river bed exhibited distinct variability in ionic composition within (S1) and among piezometers (Fig. 5d). The greatest chloride levels in S1 were achieved on 24 and 25 September when river levels peaked (Fig. 2). The lowest levels occurred on 27 and 29 September when river levels were at a minimum ($P = 0.60$, $m = 0.61$, $n = 5$). Groundwater apparently predominated at S1 when river levels were high.

Brook trout redds

Horizontal head differentials at the 1 m depth were significantly greater when redds were exposed versus submerged (Table 2). The estimated K and specific discharge were lowest in the Backpool redds and similar among the remaining redds. The river bed water in the redds displayed variable responses to the river level fluctuations. In the redds at the Backpool (A200N and S) and Parmachene sites (B200S), hydraulic pressure head differentials at 1 m suggested groundwater flow potentials were unaltered by increasing river levels (Fig. 6); that is, river water quickly infiltrated groundwater pathways and pressure heads adjusted to this intrusion. When the river declined, the pressure head did not respond and groundwater flow potentials increased. The subsequent rise to pre-peaking river levels appeared to stabilize flow potentials at their pre-peaking levels.

In the redds at the Gapens site (C100N and S), the potentials for groundwater flow appeared directly linked to fluctuating river levels, but lagged ≈ 1 day behind. Both the lag and chloride analysis suggested that the intersection of the groundwater pathways and the intruding slug of river water was farther from the surface. The catchment at the Gapens sites was substantially larger than the other sites, thus, the water table at Gapens could exhibit a smaller angle to the horizontal and provide a greater region of unsaturated materials to be encountered by invading river water prior to mixing with groundwater.

Discussion

Hydrogeology

Groundwater discharge to lakes and rivers is common in regions of glacial deposits. Discharge is maximized at the shoreline (the interface between the surface water and lake or river bed) and declines at an exponential rate with distance offshore (Pfannkuch & Winter, 1984; Winter, 1974). In the present simulation of a hydroelectric 'peaking' regime, the rapidly fluctuating river levels altered the location of the shoreline and, consequently, the pattern of groundwater discharge. Overall, declining river levels decreased the vertical and increased the horizontal potential for groundwater discharge as the location of maximum discharge followed the receding shoreline. Subsequent increases in the river level reversed this pattern of groundwater movement in the nearshore zone. This pattern of response was most prominent at < 2.5 m within the river bed.

The spatial heterogeneity of the bank's hydrogeological structure influenced the degree of interaction between the groundwater and river water during the river level manipulation. Rising river water appeared to quickly infiltrate (< 1 day) groundwater pathways and not influence potentials for groundwater flow at the two upstream sites where small, relatively steep catchments existed. Hydraulic head was less responsive to receding river levels which increased the potentials for groundwater flow, particularly in an offshore direction.

Mixing of groundwater and intruding river water during rising river levels appeared to occur slower at the downstream Gapens site. After

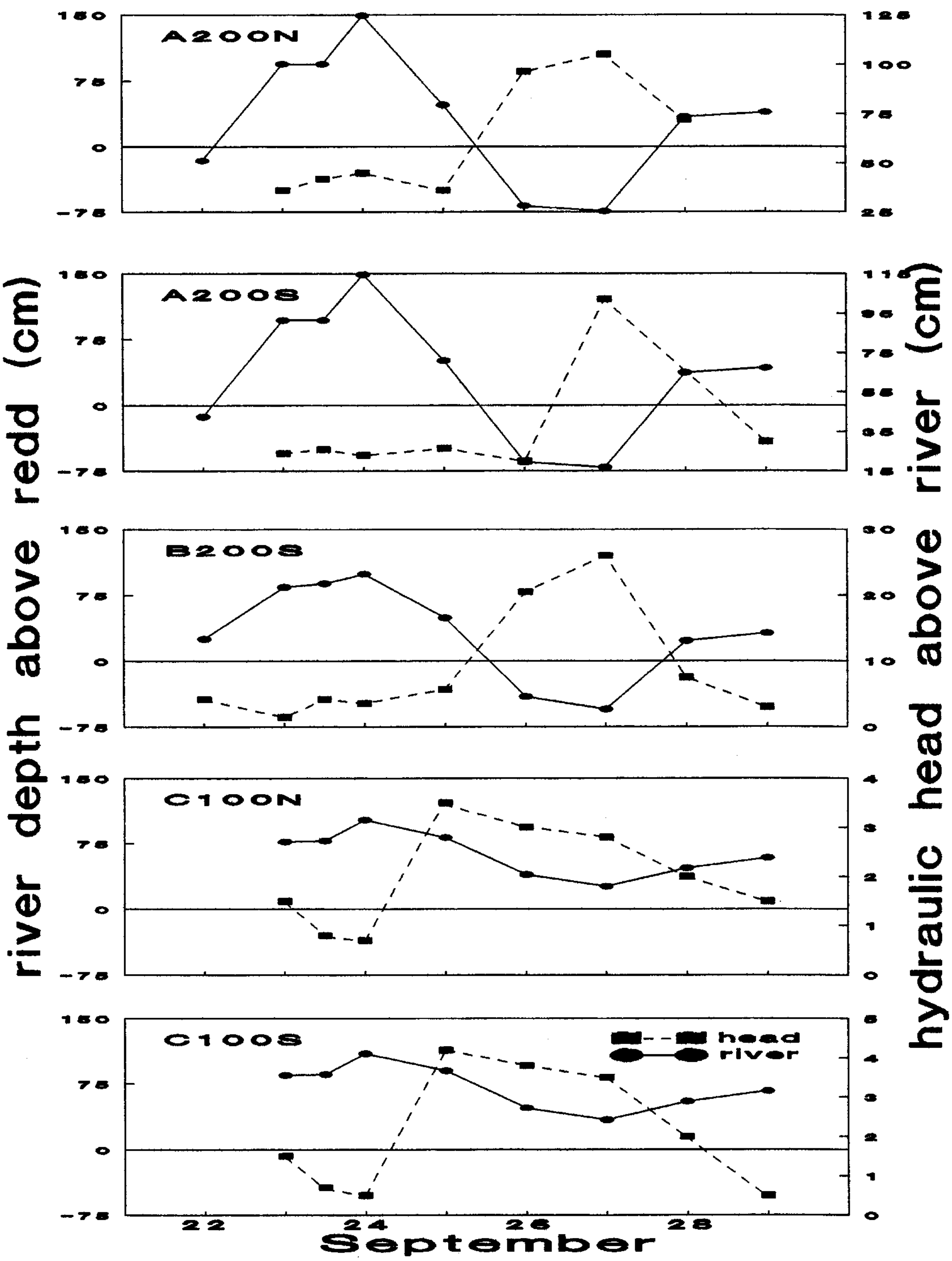

Fig. 6. River depth above redds and vertical hydraulic head differentials (1 m to river level) at five brook trout redds in the Nipigon River, 22–29 September, 1991.

about 1 day, the intruding river water slug appeared to have mixed with deeper groundwater that discharged farther offshore while shallower groundwater remained unaffected. The slug began to flush through shallower pathways and discharged to the nearshore zone when river levels receded.

These observations indicate the complexity of interactions in the vicinity of the hyporheic zone. Although some hydrological (White, 1990), chemical (Triska *et al.*, 1989), and biological (Godbout & Hynes, 1982) explorations of conditions in the hyporheic zone have been undertaken, our understanding of the interactions between groundwater and surface water remains tentative (Vervier *et al.*, 1992). It is apparent that rapid manipulations of river levels during peaking regimes can alter the physical and chemical nature of the hyporheic zone and, thus, potentially affect biological processes such as brook trout incubation in this environment.

Implications for brook trout reproductive success

Brook trout use various stimuli during the selection of spawning and incubation habitats. The selection may involve a critical minimum depth of water related to brook trout size (Smith, 1973). Stream velocity, substrate type, and cover are also important during site selection (Reiser & Wesche, 1977; Young *et al.*, 1989). The most critical stimulus, however, appears to be related to the chemical or physical nature of discharging groundwater and the persistence of these characteristics during the incubation period (Curry *et al.*, 1991; Fraser, 1985; Gunn, 1986). Consequently, hydroelectric peaking regimes will have direct impacts on brook trout spawning and incubation success, as suggested by the observed patterns of water movements within the river bed.

In the Nipigon River brook trout redds, rapidly declining river levels increased the potential for groundwater flow in varying degrees defined by the pattern of river level fluctuation and the site specific, hydrogeology and geomorphology of the river bed. These short term increases in discharge from the river bed would amplify the thermal or chemical gradients and may enhance brook trout spawning. However, the amplification period is probably too short in duration to influence spawning that occurs over a period of days for individual fish and months for populations (Power, 1980). Furthermore, the reduction in water depths may impede the physical activity of spawning or increase susceptibility of spawning fish to predators such as bald eagles (*Haliaeetus leucocephalus*).

Exposure of traditional spawning sites as a result of the peaking regime may have minimal effects on reproduction if new areas of discharging groundwater at lower elevations in the river channel become available to spawning trout. Similarly, increasing river levels could produce new spawning habitats at higher elevations in the river channel. There is evidence from population introductions that brook trout can establish new spawning and incubation habitats (Fraser, 1982). However, spawning at new areas of groundwater discharge located lower in the river channel has not been observed in the Nipigon River despite the 40+ years since the beginning of the generation of hydroelectricity. These new habitats would also jeopardized incubation success when river levels subsequently increased and altered flow patterns within the river bed. New sites located higher in the river channel would require substantial discharges to be sustained during the entire incubation period (fall-spring) to ensure successful incubation. In addition, there is no knowledge of the brook trout's ability to adjust the location of their spawning sites in response to the frequent changes in habitats resulting from a peaking regime.

Salmonid embryos require a continuous supply of oxygen to ensure successful incubation (Silver *et al.*, 1963). Oxygen can be delivered by the percolation of surface water (Vaux, 1968) or possibly groundwater (Sowden & Power, 1985) through the incubation habitat. The observed increase in the horizontal potential for flow within the river bed during low river stages suggests the supply of oxygenated water to embryos may be jeopardized. The effects of de-watering on salmonid redds depends on factors including developmental stage, duration of de-watering, and moisture content of incubation material. Nonetheless, even short-term (6 h de-watering is lethal to free-embryos and pre-emergent alevins (Becker *et al.*, 1983) and survival increases if incubation habitat remains moist (Reiser & White, 1983).

Brook trout redds located in areas of groundwater discharge may remain moist when exposed during the low river stage of a peaking cycle. The presence of wetted areas at the Nipigon River sites suggested groundwater flow to redds may not be totally eliminated during short-term events, but it is not known if sufficient flow rates and oxygen for successful incubation persist during substrate exposure. Brick (1986) indicated that rapid water level drawdowns and long-term low water stages will reduce the mitigating effects of groundwater on exposed incubation habitats of salmonids.

Also of considerable significance to the Nipigon River and other regulated, northern rivers is air temperature during the winter when brook trout incubation is ongoing. Exposed areas of groundwater seepage can remain unfrozen during winter, but seepage areas at the Parmachene site can freeze during periods of severe cold (R. Swainson, unpublished data). Because brook trout embryos are typically located in the upper 30 cm of substrate (Curry *et al.*, 1991; Snucins *et al.*, 1992), they will be extremely susceptible to freezing mortalities when redds are exposed.

An unexpected result of the present study is the sodium and chloride contamination of the groundwater aquifer feeding the brook trout spawning and incubation habitats at the Gapens site. Ambient and internal sodium and chloride concentrations are critical to the osmoregulation of fish embryos (Hoar & Randall, 1969). The significance of the ion levels in the brook trout incubation habitat at Gapens remains uncertain, but there is clearly a basis for concern. Many similar sources of groundwater contamination exist wherever concentrations of potential toxicants are stored, e.g., landfill waste sites, petroleum storage facilities, and domestic septic systems.

A peaking regime also has the potential to reduce survival of free-swimming alevins emerging from the river bed in spring. Emergence appears to be related to increases in groundwater discharge (Snucins *et al.*, 1992) and declining stream flows (Curry *et al.*, 1991). Peaking can be analogous to these natural, spring events and possibly resulting in the premature emergence of alevins not fully developed for free-swimming life. Premature alevins also may be more susceptibility to the augmented river flows of the peaking regime, natural spring flooding, or predators. It is the survival of these free-swimming, early life history stages that is critical for maintaining salmonid populations (Elliott, 1989).

The observed responses of the hyporheic waters beneath the brook trout incubation habitats indicate a potential exists for negative impacts on reproductive success resulting from rapid river level fluctuations caused by hydroelectricity peaking regimes. The consequences of greater durations of the varying river stages and the specific effects within individual redds remain to be tested.

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