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The Role of Hydraulic 'Dead Zones' in the Development of Phytoplankton in the Rideau River, Ontario

by

Jennifer Preece

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Abstract

Biomass of phytoplankton in large rivers may be maintained or even increased by inputs from hydraulic "dead zones". In some eutrophic rivers, dead zones can increase water retention time sufficiently for the development of algal concentrations substantially higher than in the main channel. "Seeding" of the main channel may then occur through the interchange of water between dead zones and the main channel. The objective of this thesis was to investigate the role of dead zones in the development of phytoplankton along the moderately eutrophic Rideau River.

In the first chapter, I compare the suspended algal communities in dead zones and the adjacent main channel of the Rideau, to evaluate the assumption that dead zones support higher phytoplankton biomass. Algal chlorophyll *a*, size structure, and nutrient concentrations were determined for dead zones and the main channel at 6 sites along the river in May, July and October 2000. Dead zones were characterized by abundant macrophytes in all seasons, and dense blooms of metaphyton in May and July. Total phosphorus and nitrogen concentrations were higher in dead zones than the main channel only in July, and there were no significant differences between dead zone and main channel soluble nutrients, overall. There was also no overall difference between total chlorophyll *a* in dead zones and the main channel, although some dead zone sites had substantially higher concentrations in May. Chlorophyll *a* contributed by algae >20 μm and >64 μm was significantly higher in dead zones in May, while the proportion of total chlorophyll *a* that was >64 μm was higher in dead zones in both May and July. Chlorophyll *a* was also more variable in dead zones than the main channel in July.

In the second chapter, I test the assumption that dead zones contribute algal biomass to the main channel of rivers. To do this, I examine the relationship between changes in main channel total chlorophyll *a* and the proportion of dead zone (inferred from the area of shallow macrophyte-dominated water) in 40 reaches along the Rideau, averaging approximately 2 km each. Over the entire river, the rate of change of chlorophyll *a* was not correlated with the proportion of shallow water in those reaches. However, there may be important differences between the upper section of the Rideau (above Kars) and the lower section (between Kars and Ottawa), now colonized by zebra mussels. There was a significant negative correlation between the percent of shallow water and the rate of change of chlorophyll *a* in the upper 29 reaches in July. This suggests that there are seasonal differences in the influence of dead zones on the development of phytoplankton in the Rideau, and that dead zones may not, in fact, contribute substantial phytoplankton biomass to the main channel of macrophyte-rich eutrophic rivers.

Résumé

Dans les grandes rivières, la biomasse phytoplanctonique peut être maintenue ou même augmentée par des apports venant de "zones mortes" hydrauliques. Dans certaines rivières eutrophiques, les zones mortes peuvent faire augmenter la période de rétention suffisamment pour permettre le développement de concentrations d'algues substantiellement plus élevées que dans le chenal principal. Le chenal principal pourrait ensuite être "ensemencé" par l'échange d'eau entre les zones mortes et le chenal principal. La présente thèse à pour objet d'étudier le rôle que jouent les zones mortes dans le développement du phytoplancton le long de la rivière Rideau, qui est moyennement eutrophique.

Dans le premier chapitre, je compare les communautés d'algues en suspension dans les zones mortes et dans le chenal principal adjacent de la rivière Rideau, afin d'évaluer la supposition que les zones mortes maintiennent une biomasse phytoplanctonique plus élevée que le chenal principal. La chlorophylle *a* et la composition selon la taille des algues, ainsi que les concentrations de nutriments ont été déterminées pour des zones mortes et pour le chenal principal à 6 sites le long de la rivière en mai, en juillet et en octobre 2000. Les zones mortes étaient caractérisées par une abondance de macrophytes en toute saison, ainsi que de denses efflorescences de métaphyton aux mois de mai et de juillet. Les concentrations de phosphore total et d'azote étaient plus élevées dans les zones mortes que dans le chenal principal en juillet, et, en général, il n'y avait aucune différence significative dans les nutriments solubles entre les zones mortes et le chenal principal. De plus, généralement, il n'y avait aucune différence significative entre la chlorophylle *a* totale des zones mortes et celle du chenal

principal, bien que certains sites dans les zones mortes aient des concentrations de chlorophylle *a* subsantiellement plus élevées en mai. La chlorophylle *a* fournie par les algues >20 µm et >64 µm était plus élevée, de façon significative, dans les zones mortes en mai, tandis que la proportion de chlorophylle *a* de >64 µm était plus grande dans les zones mortes en mai ainsi qu'en juillet. Les concentrations de chlorophylle *a* des zones mortes étaient aussi beaucoup plus variables que celles du chenal principal en juillet.

Dans le deuxième chapitre, j'examine la relation entre des changements de chlorophylle *a* totale dans le chenal principal et la proportion de zones mortes (déduite à partir de la superficie d'eau peu profonde dominée par des macrophytes) dans 40 tronçons, ayant chacun en moyenne une longueur d'environ 2 km, le long de la rivière Rideau, afin d'évaluer la supposition que les zones mortes fournissent de la biomasse d'algues au chenal principal des rivières. Sur toute l'étendue de la rivière, le taux de changement de chlorophylle *a* n'était pas en corrélation avec la proportion d'eau peu profonde de ces tronçons. Cependant, il y a peut-être d'importantes différences entre le cours supérieur de la rivière Rideau (en amont de Kars) et son cours inférieur (entre Kars et Ottawa), qui est maintenant colonisé par la moule zébrée. Au mois de juillet, le pourcentage d'eau peu profonde était inversement proportionnel au taux de changement de chlorophylle *a* dans les 29 tronçons du cours supérieur. Ceci suggère qu'il existe des différences saisonnières quant à l'influence des zones mortes sur le développement du phytoplancton dans la rivière Rideau, et que les zones mortes ne fournissent en fait peut-être pas de biomasse phytoplanctonique substantielle au chenal principal dans les rivière eutrophiques riches en macrophytes.

General Introduction

Phytoplankton in rivers is generally acknowledged to be comprised of organisms from several sources (Reynolds & Descy, 1996). Limnoplankton, derived from lakes and reservoirs, and benthic algae may be washed into stream flow (Reynolds, 1988; Reynolds & Glaister, 1993). Algae from these sources, however, often decline in abundance with downstream travel (Yang *et al.*, 1997). Other species, constituting the potamoplankton, or true river phytoplankton, are able to grow in the turbulent, turbid open-flow of rivers (Reynolds & Descy, 1996). Large lowland rivers support significant planktonic primary production and may be largely autotrophic (Descy & Gosselain, 1994; Lair *et al.*, 1999).

Potamoplankton growth is limited by the predominantly unidirectional flow in rivers (Reynolds, 1988). Unidirectional flow might be expected to lead to decreased phytoplankton abundance, through displacement of populations downstream, and increased dilution as discharge increases downstream. Higher discharge also may lead to increasing current velocity, erosion and carrying capacity, and thus increasing turbidity, limiting phytoplankton growth.

Given the constraints of unidirectional flow on phytoplankton population growth, how then are phytoplankton maintained at a given location, and how is it possible for phytoplankton abundance to actually increase downstream? Even allowing for enhancement of retention time due to turbulent mixing, increased biomass of potamoplankton may be far in excess of that predicted by *in situ* reproduction alone (Reynolds, 1988; Reynolds & Glaister, 1993; Reynolds & Descy, 1996). For example, Reynolds (1988) determined that in the Thames River, algal cells would have had to double every 8 to 9 minutes, in order to account for the increase in algal density that was

observed. Maintenance of, or increases in potamoplankton in downstream reaches may result from seeding or recruitment from hydraulic "dead zones" (Reynolds, 1988; 1994). Reynolds (1996) went so far as to entitle his 1996 Founders' Lecture to the British Phycological Society "Potamoplankters do it on the side".

Dead zones are areas of the river in which water is incompletely mixed with the bulk advective flow and may be formed by features such as embayments along the shore, side arms, or eddies behind obstructions such as river bends or islands (Reynolds *et al.*, 1994). A dead zone is characterized by very low current velocity, or even reverse flow, and may be viewed as a "pond within a river" (Reynolds, 1994). Dead zones may, like fluvial lakes, increase the diversity of habitat and biota in rivers (Hillbricht-Ilkowska, 1999). They can be important refuges from current or predation for invertebrates and juvenile fish (Hildrew *et al.*, 1991; Lancaster *et al.*, 1996; Sempeski & Gaudin, 1995) and constitute unique areas of rivers with respect to microbial degradation processes (Jones, 1996). Dead zones also may increase water retention time sufficiently for the development of higher algal concentrations through growth (Reynolds, 1988, Reynolds *et al.*, 1991).

The existence of dead zone sites with enhanced phytoplankton biomass has been shown using a variety of methods, including *in vivo* fluorometry, remote sensing and water sampling (Reynolds *et al.*, 1991). For example, Reynolds *et al.* (1991) measured a 1.5 to 2.5-fold enhancement of algal cells in areas of slow flow in the Severn, as compared to the main flow, and detected one large dead zone with a 43.4-fold increase in chlorophyll *a* over the main channel. However, not all studies have found higher algal biomass in dead zones. Wehr and Thorp (1997) found no difference in phytoplankton

biomass between mid-river and slow-flowing littoral zone habitats on the Ohio River. Dead zones also may support different communities of algae, characterized by slow-growing, larger species (Reynolds, 1994).

Interchange of water between the main flow and dead zones may increase algal concentrations in the main channel of the river. A number of studies have suggested a possible role of dead zones in seeding rivers with potamoplankton. Stoyneva (1994) concluded that midstream shallow areas and side arms of the Bulgarian Danube were important sources of potamoplankton to downstream in periods of low water. Lewis (1988) reported that peak phytoplankton density on the Orinoco River in Venezuela was associated with small changes in discharge during periods of low water, which flushed stagnant areas lying within the channel that had accumulated high plankton biomass. Köhler (1993, 1994) suggested that the main flow of the Spree River in Germany may be permanently re-inoculated with algae from "mixed reactors" formed by basins, pools and dead zones.

The objective of this study was to investigate the role of dead zones in the development of phytoplankton on the Rideau River, a medium-sized temperate lowland river in Eastern Ontario. Longitudinal and seasonal patterns of plankton development have been previously studied in the Rideau River (Basu & Pick, 1995, 1996, 1997; Yang *et al.*, 1997), but lateral patterns of phytoplankton biomass have not been investigated.

In chapter 1, I compare the biomass and size structure of suspended algae in the main channel and dead zones on the Rideau River, to determine if dead zones do in fact support higher concentrations of phytoplankton than the main channel. In chapter 2, I investigate the relationship between river morphometry (specifically, the proportion of

shallow, littoral "dead zones") and longitudinal changes in algal chlorophyll *a* in the Rideau River.

Comparison of phytoplankton biomass and size structure in the main channel and hydraulic 'dead zones' of the Rideau River

Introduction

Importation of phytoplankton from hydraulic "dead zone" areas along rivers has been hypothesized to maintain or increase phytoplankton populations in rivers (Köhler, 1993, 1994; Reynolds *et al.*, 1991; Stoyneva, 1994). Dead zones may increase water retention time enough to allow high concentrations of algal biomass to accumulate (Reynolds, 1988). Some studies have reported higher algal biomass in dead zones than in the main channel of rivers. For example, Reynolds *et al.* (1991) reported a dead zone on the Severn River with a 43.4-fold enhancement of algal chlorophyll *a* (Chl-*a*) over that of the adjacent main channel. However, other research has found dead zone algal biomass to be only slightly greater than in the main channel of rivers, and to consist of different species of algae (Spaink *et al.*, 1998). In fact, suspended algae in dead zones may sometimes originate from colonies of metaphyton, or from species which form benthic algal mats, which subsequently rise to the surface and fragment (Hudon *et al.*, 1996; Stoyneva, 1994). Alternately, there may be no detectable difference between main channel and dead zone algal abundance in some rivers, at least at most times of the year (Wehr & Thorp, 1997).

Shallow, eutrophic lakes may exist in either of two stable states: one is a clear-water state, associated with abundant aquatic vegetation, and the other is a turbid state, with high algal biomass (Jeppesen *et al.*, 1999). The macrophyte-dominated state is preferred, and considered to be indicative of a healthier ecosystem, but lakes may switch between these states. Phytoplankton dynamics in shallow rivers may be similar to those in shallow lakes (Reynolds *et al.*, 1994). At present, the Rideau River supports abundant aquatic macrophytes (Snetsinger *et al.*, 1998). As aquatic macrophytes may decrease

algal abundance, leading to a clear-water state in shallow aquatic systems, it is possible that dead zones on the Rideau River do not, in fact, support higher phytoplankton biomass than the main channel, as hypthesized by Reynolds (1991). However, aquatic macrophytes on the Rideau die back each fall (Spicer & Catling, 1990), so differences between main channel and dead zone algal biomass may exist only in some seasons.

I investigated dead zones and the adjacent main channel at six sites along the Rideau River, in mid-May, late July and early October 2000, to determine whether there were differences between suspended algal biomass, and community size structure in dead zones and the main channel. I tested the following hypotheses:

(1) Phytoplankton biomass differs between dead zones and the main channel. I predicted higher suspended algal biomass in dead zones in spring and fall, due to increased time for growth, but lower biomass in summer, due to the development of macrophytes in dead zones.

(2) Dead zones have higher concentrations of nutrients than the main channel, either through sustained inputs into a slowly flushed system, or increased microbial mineralization.

(3) Dead zones have different algal community composition than the main channel. I expected a higher proportion of slower-growing, larger-sized algal species in dead zones.

Material and Methods

Study area

The Rideau River is located in south-eastern Ontario, and flows from Lower Rideau Lake, at Smiths Falls, for approximately 110 km to empty into the Ottawa River at Ottawa (Figure 1.1). The Rideau drains a watershed of 3,830 km^2, and has an average annual discharge of 38.9 $m^3 s^{-1}$ (Water Survey of Canada, 1990). The underlying bedrock is mainly Palaeozoic limestone, dolomite and sandstone, which is overlain by Champlain Sea sediments and post-Champlain Sea alluvial and organic deposits (Geological Survey of Canada, 1982a, b). It is a moderately eutrophic, temperate lowland river, with mid-channel algal chlorophyll-*a* concentrations ranging throughout the year (and along its course) from about 2 to 27 $\mu g \cdot L^{-1}$ (Basu and Pick, 1995, 1997). Along its course, the river flows through forested land, which gives way to farmland, followed by increasing residential and urban development. Much of the river consists of shallow areas of low flow; approximately 40% (by area) of the river is 3 feet deep or shallower, and an additional 30% is between 3 and 6 feet deep (calculated from digitized navigational charts, Canadian Hydrographic Service, 1992). Aquatic macrophytes are abundant in these shallow littoral zones, and can reach nuisance levels, requiring mechanical harvesting, even in the navigation channel in some areas (Snetsinger *et al.*, 1998).

Field sampling

Six sites were sampled on the Rideau River, in May, July and October 2000 (Figure 1.1, Appendix 1.1). Sites A through C were located between Burritts Rapids and

Becketts Landing (Figure 1.2), while sites D through F were located between Kars and Long Island (Figure 1.3). At each site, the main channel and an adjacent dead zone area were sampled. The site co-ordinates were determined using a Magellan 2000 XL Satellite Navigator GPS.

Main channel sites were sampled across a bank-to-bank transect, at approximately one-third and two-thirds distances, and at mid-channel (Basu and Pick, 1996), while remaining in the navigation channel, where the depth exceeded 2.5 metres. Dead zone sites were sampled at 5 sub-sites at least 10 metres apart. Two sub-sites were located near the shore, one was located in the centre of the dead zone, and two were approximately mid-way between the centre of the dead zone and the edge of the navigation channel.

Water samples were taken at main channel sites with a 4 m integrated tube sampler, and at dead zone sites with a 1 L Nalgene bottle attached to a pole which was raised and lowered at a constant rate through the water column. Care was taken to avoid disturbing macrophytes, metaphyton or sediments when positioning the boat and when sampling water in shallow dead zone sites. Five water samples were collected in 2 or 4 L Nalgene bottles for suspended algal Chl-*a* in the main channel and dead zone at each site. In the main channel, water was sampled twice (approximately one-half hour apart) from the one-third distance and mid-channel sub-sites and once from the two-thirds distance sub-site, while in the dead zones water was sampled once from each sub-site. Water samples were collected in 300 mL clear polyethylene terephtalate glycol (PETG) bottles for nutrient analyses. In the main channel, three samples were taken, one each at the one-third, mid-channel and two-thirds distance sub-sites, except in May when only the one-

third distance and mid-channel were sampled. In each dead zone, three samples were taken, one each from a near-shore, central and near-channel sub-site, except in May when only the near-shore and central sub-sites were sampled.

Measurements of depth and Secchi depth were obtained at each sub-site using a Secchi disc. Light attenuation in the water column was calculated by measuring irradiance (μmol photons$\cdot m^{-2} \cdot s^{-1}$) with a LiCor 4π photometer (model LI-185B) at depth intervals of 0.5 or 0.25 m, at mid-channel and central dead zone sub-sites. Main channel current velocity was measured at one-third, mid-channel and two-thirds distances using a drifting drogue (Figure 1.4). I constructed the drogue using a modified version of a design employed by Baird and Associates (D. Scott, pers. communication), a local firm of consulting hydrologists. The drogue was suspended at a depth of approximately 0.6 of total channel depth (Wetzel & Likens, 1991) and deployed from the boat, which was anchored at bow and stern. The time taken for a measured length of floating line (attached to the drogue float) to play out was recorded and averaged for at least three trials. Current velocity was estimated at each dead zone sub-site in a similar manner, using a plastic bottle (filled with water until it floated mostly submerged) attached to a floating line, or by timing the progress of debris floating suspended in the water column.

Water temperature, conductance, pH, redox potential and dissolved oxygen concentration and percent saturation were measured at each sub-site using a Hydrolab Minisonde 4a water quality multiprobe. Readings were logged at 1 m depth intervals in the main channel, and 0.25 m intervals in dead zones, and averaged for the water column. Significant thermal stratification of the water column was not observed at any site sampled in 2000. Macrophytes were collected and identified at each dead zone, with

reference to mounted specimens and a species list prepared by the Canadian Museum of Nature (Richard & Gillespie, 1998).

Sediment analysis

Sediment was sampled at three sub-sites at each dead zone and main channel site in June 2000. Surface sediment cores were collected at one-third, mid-channel and two-thirds distances in the main channel, and near-shore, central and near-channel sub-sites in dead zones, using a Kajak-Brinkhurst (K-B) corer lowered from the boat. The top 2.5 cm of sediments was collected and kept refrigerated until analysed approximately 3 weeks later. The percent organic matter in the surface sediments was determined by weight-loss-on-ignition (LOI). Samples were dried overnight in a gravity oven at 95 C, to obtain dry weight (DW). They were then ignited in a muffle furnace at 500 C for 3 hours, and left to cool to room temperature in a desiccator, when ignition weight (IW) was determined. Percent organic matter was calculated as:

$$\% \text{ OM} = ((\text{DW} - \text{IW}) / \text{DW}) * 100.$$

Measurement of Chl-*a* concentration

Water samples were stored in darkness and filtered for suspended Chl-*a* within 12 hours of collection. Total Chl-*a* was estimated by filtering water through Poretics 0.2 μm polycarbonate membranes. To estimate Chl-*a* in larger size classes, water was also filtered in parallel through 2.0 and 20 μm Poretics polycarbonate membranes and 64 μm Nitex mesh. Vacuum pressure for filtration was maintained below 15 mg Hg, to minimize cell breakage. Filtered Chl-*a* samples were stored frozen at -18°C until

processed. Chl-*a* was extracted with DMSO and acetone (Burnison, 1980) and concentrations were estimated using a Turner Designs model 10-000R fluorometer, standardized according to Wetzel and Likens (1991), using the equation of Jeffrey and Humphrey (1975).

Nutrient concentrations

Nutrient analyses were performed by the Regional Municipality of Ottawa-Carleton Surface Water Quality Laboratories, using standard methods (Appendix 1.2). Water samples were analysed for total phosphorus (TP), soluble reactive phosphorus (RP), total Kjeldahl nitrogen (TKN), ammonia (NH_3), and nitrate+nitrite (NO_3+NO_2).

Data analysis

To statistically test the hypothesis that algal biomass in the different size classes was higher in dead zones than main channel sites, dead zone sites (n = 6) were compared to main channel sites (n = 6), using Model I ANOVA. 2-way factorial ANOVAs (General Linear Model, GLM) were carried out using Systat 7.0, with Chl-*a* as the dependent variable, and month (May, July and October), type (dead zone or main channel) and month*type as factors. Dependent variables were log-transformed if necessary to meet the assumptions of normality and homoscedasticity. Where these assumptions could not be met, non-parametric ANOVAs were used. *A priori* tests for differences between main channel and dead zones in each month were performed using pooled variance t-tests, with Dunn-Sidak adjusted probabilities. The difference in variability of total Chl-*a* between dead zones and main channel sites was tested in a

similar manner, with coefficient of variation (CV) of total Chl-*a* as the dependent variable. To test the hypothesis that dead zones contained a higher proportion of large-sized algae, the proportion of total Chl-*a* that was made up by netplankton (Chl-a > 64 μm) was compared between dead zones and main channel, in the same manner.

Separate ANOVAs were also carried out in a similar manner for each of the following dependent variables: TP, RP, TKN, NH_3, NO_3+NO_2, water temperature, % dissolved oxygen, pH, specific conductance, redox potential, and light extinction coefficient. Percent organic matter in sediments was compared between dead zones and main channel using 2-way ANOVA, with site, type and site*type as factors.

Tables summarizing 2-way ANOVAs and multiple comparisons between months are included in Appendices 1.4 to 1.7. Tables summarizing the results of *a priori* comparisons between main channel and dead zone sites are included in the text.

Results

Site characteristics

Main channel sites ranged in depth from approximately 4 metres to over 8 metres, while dead zone sites varied between 0.5 and 1 metre in depth (Table 1.1). There were no substantial differences in water depth at a given site between sampling months. Current velocity in the main channel was low, varying between 0.03 and 0.25 $m \cdot s^{-1}$ (Table 1.1). Current velocity was highest in May, ranging between 0.11 and 0.26 $m \cdot s^{-1}$, lower in July, between 0.05 and 0.16 $m \cdot s^{-1}$, and lowest in October, below 0.06 $m \cdot s^{-1}$. In the dead zones, current was below the detection limit of 0.01 $m \cdot s^{-1}$ in all months, although there was generally some slight water movement, particularly at the surface, due to waves and wind.

Average monthly discharge was considerably higher than the historical average discharge in May and July 2000 (Figure 1.5). In May and in July, the average discharges of the Rideau measured at Ottawa were 97.3 $m^3 \cdot s^{-1}$ and 28.2 $m^3 \cdot s^{-1}$ respectively, more than double the historical averages of 44.1 $m^3 \cdot s^{-1}$ and 12 $m^3 \cdot s^{-1}$ (Water Survey of Canada, 1990). By contrast, in October, the average discharge, 12 $m^3 \cdot s^{-1}$, was somewhat lower than the historical average of 19 $m^3 \cdot s^{-1}$.

Macrophytes were abundant in dead zones, but macrophyte species composition and density were found to be highly variable within dead zones, and between sampling seasons. Many of the species were found at all sites (Table 1.2). In general, the shallowest, near-shore sites had low macrophyte density in all seasons, and the deeper sites (nearest the main channel) were dominated by thick beds of *Myriophyllum spicatum* and *Potamogeton* spp. Sites of intermediate depth supported a variety of different species, such as *Vallisneria americana, Nymphaea odorata, Nuphar variegatum, Ceratophyllum demersum, Elodea canadensis, Lemna trisulca* and *Wolffia* sp. In May, the central and near-channel sites already had substantial macrophyte development, reaching the surface of the water in many places (Figure 1.6a). In particular, thick beds of *Potamogeton* spp. were found in May. In July, macrophyte growth was at its peak (Figure 1.6B, 1.7A), with *M. spicatum, Potamogeton* spp, *V. americana, N. odorata, N. variegatum, C. demersum,* and *E. canadensis* dominating. However, growth of epiphytic algae was heavy on macrophytes, particularly *Myriophyllum* and *Potamogeton*, and these macrophytes were beginning to show signs of decay. In October, macrophytes were still abundant, although there had been a decline in the density of some types, particularly *Potamogeton* spp., which had virtually disappeared. *L. trisulca* was particularly abundant

in October (Figure 1.7b), forming huge masses on the water surface and in the water column.

In addition to macrophytes, dense blooms of filamentous green algae (metaphyton), mainly *Spirogyra* spp. and some *Cladophora*, were present in all dead zones in May (Figure 1.8a). In addition, floating clumps of uprooted or fragmented macrophytes and algal mats were observed at most main channel sampling sites in May, presumably having been washed into the main flow from littoral zones due to the heavy rain and high discharge during this period. In July, dense blooms of metaphyton were still abundant in dead zones, and thick mats of *Hydrodictyon* and decaying *Spirogyra* had covered much of the surface area, particularly in regions where water was less than 1 metre deep (Figure 1.8b). By October, there was virtually no metaphyton present in any of the dead zones.

Secchi depth generally increased between sites A-C and sites D-F (Table 1.2, Figure 1.9). Secchi depth varied between 1.1 and 2.4 metres in the main channel, with the exception of site F in July, and sites D-F in October, when Secchi depth increased to between 3.7 and 4.0 metres. However, with only two exceptions, Secchi depth exceeded the depth of dead zone sites. In May, a Secchi depth of approximately 1 m was recorded in the deepest regions of the dead zone at site C, while in July, the Secchi depth in the dead zone at site A averaged 0.4 metres. Light extinction coefficients were somewhat higher on average in dead zones than in main channel sites in May and July (Figure 1.10), although the difference was not statistically significant ($p = 0.085$; $p = 0.07$, 1-tailed) (Table 1.3). Main channel water temperature varied between 12°C and 25.5°C over the sampling season (Table 1.1). There was no significant difference between main channel and dead zone water temperature in May

or October (Figure 1.11, Table 1.3), but in July water temperature was significantly higher in dead zones than the main channel. In July, water temperature in dead zones averaged 25.6 °C, approximately 2 °C higher than in the main channel.

Bottom sediments were very fine textured and loose, with a pudding-like consistency. Sediment colour was very dark, ranging from black (Munsell code 2.5Y 2.5/1) to greenish-black (10Y 2.5/1). When anchoring in dead zones, bubbles rose from disturbed sediments, accompanied by a swampy aroma. The average proportion of organic matter present in surface sediments varied between 13% to 32% in dead zones, and between 12% to 22% in the main channel (Figure 1.12). There were no significant differences between dead zone and main channel surface sediment organic matter at sites A to C (Table 1.4), but sediment organic matter was significantly higher in the dead zone than main channel at site D. Sediment cores could not be obtained in the main channel at sites E and F, where the bottom was rocky at all sub-sites.

Chemical parameters

Dissolved oxygen (percent saturation) was significantly higher in the water of dead zones than in the main channel in both May and July (Figure 1.13, Table 1.3). Dissolved oxygen ranged from 8.1 to 10.6 $mg \cdot L^{-1}$ (78% to 107% saturation) in the main channel and from 8.3 to 16.5 $mg \cdot L^{-1}$ (83% to 171%) in dead zones in May (Appendix 1.9). In July, dissolved oxygen was significantly lower than in May, ranging between 5.0 to 7.3 $mg \cdot L^{-1}$ (57% to 89%) in the main channel, and 4.4 to 9.5 $mg \cdot L^{-1}$ (54% to 115%) in dead zones. In October, there was no significant difference between dead zone and main channel dissolved oxygen. Dissolved oxygen ranged from 6.6 to 7.9 $mg \cdot L^{-1}$ (61% to

77%) in the main channel, and from 6.2 to 8.9 $mg \cdot L^{-1}$ (60% to 89%) in dead zones in October.

There were significant differences in pH, specific conductance and redox potential between months (Appendix 1.5a). pH was significantly higher in May (ranging between 8.2 and 9.2) than in July (7.1 to 8.4) or October (7.8 to 8.5). Specific conductance ranged from 317 to 405 $\mu S \cdot cm^{-1}$ in May, significantly higher than in July (223 to 329 $\mu S \cdot cm^{-1}$) and October (224 to 261 $\mu S \cdot cm^{-1}$). Redox potential was significantly lower in May and July (ranging from 269 to 463 mV) than in October (374 to 540 mV).

There was no significant difference overall between main channel and dead zone pH, (Appendix 1.5a), although pH was on average significantly higher in dead zones than the main channel in May (Table 1.3), ranging from 8.2 to 8.8 in the main channel, and from 8.3 to 9.2 in dead zones. Specific conductance and redox potential did not differ significantly between the main channel and dead zones overall.

Nutrients

Total phosphorus and total Kjeldahl nitrogen concentrations were both significantly higher overall in May and July than October (Appendix 1.6b). TP did not differ between dead zones and main channel sites in May, but TP was higher in dead zones in July and October (Figure 1.14, Table 1.5). Average dead zone TP was approximately 50% higher than in the main channel in July, and 11% higher in October. There was considerable variation between individual sites (Figure 1.15). In particular, TP was much higher in dead zones at sites A, C, D and E, than in the main channel in

July, while there was no difference at sites B and F. Average dead zone TKN was only significantly higher than in the main channel (by 17%), in July (Figure 1.16, Table 1.5). As with TP, there was site-to-site variation in the differences between dead zones and the adjacent main channel (Figure 1.17).

The soluble nutrients, reactive phosphorus, ammonia and nitrate-nitrite nitrogen did not differ significantly between dead zones and main channel sites, in any month (Figure 1.14, 1.16, Table 1.5). RP was significantly higher, overall, in July than in May, and NO_3+NO_2 was substantially higher in May than in either July or October (Appendix 1.6b). There was site-to-site variation in the differences between dead zone and main channel soluble nutrients, as there was for total nutrient concentrations (Figures 1.18, 1.19, and 1.20).

Chlorophyll-*a*

In May, mean total Chl-*a* (> 0.2 μm) was substantially higher in dead zones than the main channel (14.5 $\mu g \cdot L^{-1}$, compared to 9.2 $\mu g \cdot L^{-1}$) (Figure 1.21) although the difference was non-significant ($p = 0.08$, 1-tailed) (Table 1.6). Variability between samples was especially high in May. In dead zone sites, total Chl-*a* ranged from 2.4 to 52.8 $\mu g \cdot L^{-1}$; main channel total Chl-*a* was less variable, ranging between 5.0 and 18.4 $\mu g \cdot L^{-1}$ (Table 1.7). In July and October there was no significant difference between average main channel and dead zone total Chl-*a*. However, when total Chl-*a* was compared between dead zones and the main channel at individual sites (Figure 1.22), differences between the sites were evident. At sites A and C, there was no difference between the main channel and dead zone in any season. At sites B, D and E, average

total Chl-*a* was higher in dead zones than the adjacent main channel in May and October, but lower in July. At site F, where main channel total Chl-*a* was always the lowest, dead zone total Chl-*a* was higher in all seasons.

In May, mean Chl-*a* > 2.0 μm in dead zones was 8.5 $\mu g \cdot L^{-1}$, compared to 5.7 $\mu g \cdot L^{-1}$ in the main channel, but as for total Chl-*a*, the difference was (albeit marginally) non-significant ($p = 0.055$, 1-tailed). As with total Chl-*a*, there was no difference overall between dead zone and the main channel Chl-*a* > 2.0 μm in July or October.

Dead zones had, on average, significantly higher Chl-*a* > 20 μm than the main channel in May but there was no difference in July or October. In May, Chl-a > 20 μm averaged 5.4 $\mu g \cdot L^{-1}$ in dead zones, almost double the average of 2.3 $\mu g \cdot L^{-1}$ in the main channel. Chl-a > 64 μm was significantly higher overall in dead zones than the main channel in May, averaging 5.7 $\mu g \cdot L^{-1}$ and 0.9 $\mu g \cdot L^{-1}$ respectively, and also in July. There was no difference in October.

Variability in Chl-*a*

Total suspended algal biomass was spatially more variable in dead zones than main channel sites in May and July. In those months, the mean coefficient of variability (CV) of total Chl-*a* in dead zones was more than double that of the main channel (Figure 1.23, Table 1.8). The difference was statistically significant in July, but (marginally) non-significant in May ($p = 0.073$, 1-tailed). There was no significant difference between dead zone and main channel total Chl-*a* variability in October.

Differences in algal size

In May, all water samples taken at dead zone sites contained large, macroscopic filamentous green algae (Figure 1.24). By contrast, some main channel water samples at sites C, D and F contained no large filamentous algae, and all samples taken from the main channel at site E were without large filaments. In July and October, such large filaments were present only in some water samples taken from dead zone sites D to F (and one sample taken from the site B dead zone in July). No main channel samples contained macroscopic filamentous algae in July and October.

Chl-*a* > 64 μm contributed significantly more to total Chl-*a* in dead zones than in the main channel in May and July (Table 1.8). In May, Chl-*a* > 64 μm contributed an average of 35% of total Chl-*a* in dead zones, more than three times the percentage contributed in the main channel (Figure 1.25). In July, the average proportion of total Chl-*a* contributed by Chl-*a* > 64 μm had declined to 13% in dead zones, but was still three times higher than in the main channel.

Discussion

Higher algal biomass in dead zones of rivers has been hypothesized to occur (Reynolds, 1988; Köhler, 1993, 1994), but actually demonstrated in relatively few studies. Reynolds *et al.* (1991) found 1.5 to 2.5-fold higher Chl-*a* in slow-flowing areas of the Severn, and discovered one dead zone with a 43.4-fold enhancement over the main channel concentration. However, the work of Reynolds and colleagues was conducted on a highly eutrophic, algal-dominated river. In contrast, the Rideau River is characterized

by an abundant development of aquatic macrophytes (Snetsinger *et al.*, 1998), which might be expected to have an effect on phytoplankton biomass in dead zones.

Dead zones on the Rideau River were located in shallow areas, and were sites of abundant macrophyte and metaphyton development. Shallow water depth and low flow create conditions favourable for macrophyte colonization, either through direct effects, or by altering the river bed composition or nutrient content (Chambers *et al.*, 1991), but macrophytes may in turn calm the water column, decreasing current velocity still further.

Shallow lakes with high macrophyte development have been found to have lower phytoplankton densities than lakes with few macrophytes. Izaguirre & Vinocur (1994) found that lakes in the Salado River Basin with high macrophyte development had phytoplankton densities 6 times lower than lakes with low macrophyte development. Studies on shallow lakes with extensive littoral development indicate that primary productivity by macrophytes and epiphytic or epipelic algae may greatly exceed that by phytoplankton (Wetzel, 1975). In fact, some shallow eutrophic lakes have been found to alternate between dominance by submerged macrophytes and by phytoplankton (Mitchell, 1989; Perrow *et al.*, 1997; Jeppesen *et al.*, 1999). Attempts to change shallow eutrophic lakes from a phytoplankton-dominated to macrophyte-dominated state through biomanipulation are the focus of much recent research (Perrow *et al.*, 1997).

Macrophyte growth may decrease phytoplankton abundance or alter phytoplankton community composition through increased rates of sedimentation, competition for nutrients, shading, or through sheltering zooplankton. (Köhler, 1994; Perrow *et al.*, 1997; Hillbricht-Ilkowska, 1999; Jeppesen *et al.*, 1999).

Zooplankton biomass has been found to be negatively correlated with discharge, with biomass in rivers lower than in estuaries and tidal rivers, which in turn have lower biomass than lakes, but there can be considerable spatial heterogeneity in zooplankton distribution (Pace *et al.*, 1992; Viroux, 1999). Most studies on the impact of zooplankton in rivers have focussed on the main channel. There is disagreement on the extent of "top-down" control of phytoplankton, by grazers in rivers. Some studies have found substantial impacts on algal biomass of small grazers such as rotifers and ciliates (Lair *et al.*, 1999; Lair & Reyes-Marchant, 1997; Gosselain *et al.*, 1998). Slow growth rates and dilution and downstream washout of grazing organisms may prevent larger (> 64 μm) zooplankton from constraining faster-growing algal populations (Bothár & Kiss, 1990; Reynolds & Descy, 1996). However, substantial grazing has been reported in some rivers; grazing by mesozooplankton (> 210 μm) and micrometazoa (64-210 μm) was calculated as 20% and 45% of primary production, respectively, in the lower Hudson River estuary in fall (Lonsdale *et al.*, 1996). The extent of control exerted by zooplankton on phytoplankton may be seasonal, and controlled by other factors in addition to macrophyte abundance. The development of zooplankton may be limited by water temperature; in spring, water temperature may be too low to permit substantial zooplankton development, although phytoplankton can be abundant (Marneffe *et al.*, 1996).

Inshore habitats in rivers have been found to act as storage zones for zooplankton (Spaink *et al.*, 1998; Tans *et al.*, 1998; Reckendorfer *et al.*, 1999; Basu *et al.*, 2000a). Spaink *et al.* (1998) observed on the River Waal that the total biovolume of zooplankton was >100 times higher in the dead arm than in the main channel, and dominated by

crustaceans, while in the main channel crustaceans and rotifers were co-dominant. Basu *et al.* (2000a) found a nine-fold higher abundance of zooplankton (and greater mean crustacean size) at sites with dense aquatic macrophytes, than in open water sites in fluvial lakes in the St. Lawrence River. These fluvial lakes had similar dominant macrophyte taxa to the Rideau (*Myriophyllum* spp., *Potamogeton* spp., *E. canadensis*, *C. demersum* and *V. americana*.

Samples were collected during this study for analysis of zooplankton abundance in dead zones and the main channel of the Rideau River. In all sampling periods, there was a higher abundance of total zooplankton (due to higher numbers of macrozooplankton) in dead zones than the main channel (M. Demers, pers. communication). As with measurements of Chl-*a* and nutrients, there was considerable variability in zooplankton abundance and biomass between sites, particularly in July.

Differences in total Chl-*a*

Because of the possible impacts of macrophyte beds on dead zone phytoplankton, sampling on the Rideau River was conducted in spring, summer and fall. I hypothesized that in spring and fall, when macrophyte development was low, phytoplankton biomass would be higher in dead zones than in the main channel, but in mid-summer, dead zones would have lower phytoplankton biomass due to high macrophyte development.

This study found some differences between dead zone and main channel suspended algal biomass, as measured by Chl-*a* concentrations, in the Rideau River. However there was considerable variation between sites and between seasons. In May, some dead zones had considerably higher concentrations of total suspended Chl-*a*, as

hypothesized. Average total Chl-*a* was 57% higher in dead zones than the main channel in May. However, overall the difference was not highly significant. In July, when macrophyte development was at its maximum and I had hypothesized lower total Chl-*a* in dead zones, there was no significant difference. However, at 3 sites, mean total Chl-*a* was lower in dead zones than in the adjacent main channel. In October, contrary to my hypothesis, there was also no significant difference between average dead zone and main channel total Chl-*a* on the Rideau, although some dead zone sites had somewhat higher average total Chl-*a* than the adjacent main channel. It is possible that higher dead zone Chl-*a* was not observed in October because the autumn sampling period occurred before macrophytes had died back and similar processes were limiting phytoplankton development as in July.

Some other North American studies have found no differences, or only sporadic differences between algal biomass in the main channel and adjacent littoral zones. For example, Wehr and Thorp (1997) found no difference between phytoplankton densities in the main channel and slow-flowing littoral zones of the Ohio River in any month, except during April when chrysophyte densities were 2.4-fold higher in littoral zones. Basu *et al.*, (2000a, 2000b), by contrast, found significantly higher algal biomass in macrophyte beds in fluvial Lakes St. Francis and St. Pierre than in the main channel of the St. Lawrence in July 1997 and 1998, even in the presence of higher zooplankton biomass. However, the difference was not striking (3.3 $\mu g \cdot L^{-1}$ Chl-*a* in dense macrophytes, as compared to 2 $\mu g \cdot L^{-1}$ in open water and sparsely vegetated sites in 1998).

Differences in algal communities

While this study did not examine differences in taxonomic comparison of algae in main channel and dead zones, possible differences in community composition may be inferred from comparison of main channel and dead zone algae of different size classes. In both May and July, as hypothesized, there was a significant difference between the biomass of netplankton (algae > 64 μm) in dead zones and in the main channel. Overall, the proportion of total algal Chl-*a* contributed by Chl-*a* > 64 μm in dead zones was more than three times as high as that in the main channel. Dead zones had a more than 6-fold enhancement in Chl-*a* > 64 μm over the main channel in May, and a 3.5-fold enhancement in July. The higher proportion of larger-sized algae in dead zones in May and July than in the main channel may be partly attributed to suspended filamentous algae. In May, all water samples from dead zones contained large green algal filaments, but the occurrence of these filaments in main channel samples was lower. In July, such filaments were only seen in some dead zone samples, and in October, while some dead zone samples contained large algal filaments, there was very little metaphyton present in dead zones.

Phytoplankton assemblages have been found to differ between lakes with high and low macrophyte development; high numbers of species from periphyton and benthic communities were found in lakes colonized by macrophytes (Izaguirre & Vinocur, 1994). Similarly, Hudon *et al.* (1996) observed that phytoplankton biomass in the macrophyte-dominated fluvial Lakes St. Pierre and St. Francis on the St. Lawrence River contained less small, planktonic algae than the main river, and was enriched in filamentous chlorophytes such as *Spirogyra*, *Ulothrix*, *Oedogonium*, *Cladophora* and *Hydrodictyon*.

The higher algal biomass of fluvial lakes was therefore attributed to periphyton growth and resuspension rather than to plankton biomass accumulation. Stoyneva (1994) also concluded that there was a strong connection between benthic and planktonic communities on the Danube, with enhancement of the plankton by algae originating in benthic mats.

Other studies have also found differences between dead zone and main channel phytoplankton communities. Spaink *et al.* (1998) found a large difference in phytoplankton species composition between main channel and dead arm of the River Waal (a branch of the Rhine) in the Netherlands. The main channel was dominated by diatoms (*Cyclotella meneghiniana*, *Skeletonema potamos* and *Skeletonema subsalsum*), while the rear end of the dead arm was dominated by green algae, in particular *Pandorina morum*. The often cited Leighton dead zone of the Severn River studied by Reynolds *et al.* (1991) which had a 43.4 fold higher Chl-*a* concentration than the main channel, was actually dominated by the filamentous cyanobacterium, *Oscillatoria agardhii* Gomont., in contrast to the diatoms and green algae dominating the main channel.

The higher algal biomass in some dead zones than the main channel in May, and the higher proportion of netplankton in dead zones in both May and July can be at least partially attributed to inputs from metaphyton. Dense blooms of metaphyton, composed of filamentous green algae, were present in all dead zones in May and July but had disappeared by October. In May, the metaphyton was dominated by *Spirogyra* spp; algae in this genus are found in almost any kind of freshwater, and are among the most common of algae found in ponds, bog pools, and bays or backwaters of lakes and rivers (Canter-Lund & Lund, 1995). In July, dense mats of decaying *Spirogyra* and

Hydrodictyon blanketed large areas of dead zones on the Rideau. *Hydrodictyon*, or water net, favours eutrophic water, and can be a serious problem when very abundant, smothering and replacing wetland macrophytes (Canter-Lund & Lund, 1995). The development of "nuisance" mats of *Spirogyra, Cladophora* and *Hydrodictyon* has been a problem in the Rideau River for at least 30 years (Hamilton *et al.*, 1997).

The abundance of metaphyton in the Rideau is likely a result of high nutrient availability in shallow dead zones, and the relatively sheltered nature of these regions. McDougal *et al.* (1997) found that metaphyton development was triggered by nutrient inputs, whether added to the system or released from senescent macrophytes, and further aided by shelter from wind-driven displacement. They determined that mid-summer biomass of metaphyton in prairie wetlands (*Cladophora* sp. and *Enteromorpha intestinalis*) could equal or exceed macrophyte biomass, while phytoplankton and epipelon contributed very little (<5%) to total algal biomass overall. In addition to competing with phytoplankton for nutrients, metaphyton has also been found to shelter zooplankton such as cladocerans (Turner *et al.*, 1995) and is resistant to grazing by invertebrates and vertebrate herbivores (McDougal *et al.*, 1997).

The presence of dense metaphyton on the Rideau, in addition to vascular macrophytes, may account for a number of other differences between dead zones and the main channel. These include higher light extinction coefficients, higher water temperature, higher dissolved oxygen concentrations and pH, and higher variability in dead zone Chl-*a*.

Higher light extinction coefficients were calculated for water in some dead zones, than in the main channel in May and July (although overall the difference was not highly

significant). Blooms of filamentous green algae have been found to intercept light strongly. Light reaching the sediments may be reduced by more than 90% by peak blooms of filamentous green algae in the littoral zone of lakes (Turner *et al.*, 1995; McDougal *et al.*, 1997) and this shading may affect the abundance of other algae (Pillsbury & Lowe, 1999). While efforts were made to measure light extinction in open areas of dead zones, filamentous green algae were often present in the water column. In addition, the 4π design of the photometer detected incident, reflected and scattered light from above and below (Wetzel & Likens, 1991); light intensity was therefore probably influenced by proximity to nearby metaphyton and macrophytes.

In July, water temperature in dead zones was higher, by 2°C on average, than in the main channel. This may be partly due to the abundance of metaphyton and macrophytes, which inhibit water column mixing and the exchange of water between dead zones and the main channel. Filamentous algal clouds and mats have previously been found to increase water temperature and decrease water movement reaching the sediments (Turner *et al.*, 1995).

Dead zones on the Rideau were found to have significantly higher dissolved oxygen than the main channel in May and July. In May, dissolved oxygen percent saturation in dead zones reached as high as 171%, indicating high productivity in these regions. Dead zones also had slightly higher pH than the main channel in May. Increased pH in dead zones may be due to consumption of CO_2 during times of high productivity by macrophytes and algal communities (Wetzel, 1975).

Difference in variability of dead zones and main channel

This study found significantly higher variability of total Chl-*a* in dead zones than in the main channel in July and considerable variability in May (although there was no significant difference between dead zones and the main channel). This high variability may be partly attributable to the high proportion of netplankton, particularly filamentous algae, observed in dead zones in these months. Hudon *et al.* (1996) observed that large "periphytic" algae in Lake St. Pierre represented a large but highly variable proportion of the algal biomass. Larger algal cells may not be as homogeneously distributed in water as small cells, and clumps of filaments are common. Hamilton *et al.*, (1997) also observed fragmented filaments from algal mats in the water column of bays on the lower Rideau River, increasing plankton Chl-*a*.

In addition to variability attributable to the patchy distribution of large algal cells or clumps of filaments, there may be high variability in dead zones due to variations in the degree of hydrodynamic isolation of sampling sites from the main flow. Spaink *et al.* (1998) compared the main channel and a dead arm of the River Waal in the Netherlands in July and August 1995. Main channel Chl-*a* varied between 20 and 50 $\mu g\ L^{-1}$, while dead arm Chl-*a* varied between 10 and 80 $\mu g\ L^{-1}$. The highest concentrations of Chl-*a* in the dead arm were consistently found at the rear (furthest from the main channel), while concentrations at sites in the dead arm closer to the main channel were either similar to, or lower than Chl-*a* in the main channel. A further source of high variation is likely the extreme patchiness of conditions in dead zones. Macrophyte species distribution and density, as well as metaphyton were extremely patchy in dead zones on the Rideau.

Nutrients

Although total Chl-*a* was slightly higher (particularly at some sites) in dead zones than the main channel of the Rideau in May, TP was higher, overall, in dead zones only in July and October, by 50 % and 11% respectively, and TKN was higher in dead zones, by 17%, in July only. In fact, the differences are due to higher concentrations at a relatively few sites; at many sites the concentrations of TP and TKN were very similar in dead zones and the adjacent main channel. Concentrations of the soluble nutrients, RP, NH_3 and $NO_3 + NO_2$ did not differ between dead zones and the main channel in any month, overall, although there were also site-specific differences.

I had hypothesized that higher nutrient concentrations might be found in dead zones than the main channel, due to inputs from the adjacent land (through runoff or groundwater), or due to release from nutrients stored in sediments rich in organic matter. The sediments of dead zones on the Rideau were found to have a high organic matter content, and at three sites to be significantly higher in organic matter than the main channel bottom. In fact, at sites E and F, the main channel was rocky and no sediments could be collected, while the organic matter content of sediments in the dead zones these sites was the highest recorded, ranging between 25 - 40%. Hillbricht-Ilkowska (1999) also found that shallow fluvial lakes had highly organic bottom sediments, compared to the mainly inorganic sediments of the riverbed.

Phosphorus is usually found in much higher concentrations in the sediments than in the water column (Wetzel, 1975). However, nutrient cycling in dead zones may be complex, and vary from season to season. Macrophytes take up phosphorus from sediments, but may also release it to the water column. Algae on the sediments may be

able to use sediment phosphorus effectively. In fact, filamentous algae in the littoral zone of lakes can be a major site of phosphorus uptake, removing it from the water before it can reach the epilimnion of lakes. As macrophytes and filamentous algae decay, however, much phosphorus is rapidly released to open water (Turner *et al.*, 1995). Sediments may act as sinks for phosphorus under aerobic conditions, but under anaerobic conditions, particularly in mid-summer, phosphorus can be released from sediments to the overlying water (internal loading) (Wetzel, 1975). Fluvial lakes on the Krutynia River in Poland were found to act as sinks for TP in April and May (when production was high) and by June, some were exporters of TP (Hillbricht-Ilkowska, 1999). By August, most lakes were exporting TP, probably due to release from anaerobic organic-rich bottom sediments.

The cycling of nitrogen can also differ between the main channel and dead zones. Hillbricht-Ilkowska (1999) found significantly higher retention of nitrate (through uptake by vegetation and denitrification) in fluvial lakes than the river channel of the Krutynia. Filamentous green algal blooms have been found to have a significant seasonal effect on the nitrogen cycle in the littoral zone of lakes, through the flux of NH_3, taking it up rapidly during summer growth and releasing it again during decomposition in autumn (Turner *et al.*, 1995).

Higher TP was found in dead zones than the main channel of the Rideau in July and October, although there were no significant differences between dead zone and main channel suspended Chl-*a*. There was no significant difference between dead zone and main channel RP, so it seems unlikely that the excess phosphorus in dead zones was all in dissolved form. It is possible that there was a higher proportion of suspended particulate

matter (clay or dead organic matter) in dead zones than the main channel in July, possibly as a result of wave action from wind, or heavy boating traffic. Another explanation may involve different algal community composition in dead zones than the main channel. Phosphorus absorption is specific to different groups (and even species) of algae (Wetzel, 1975); algae in dead zones may have contained higher concentrations of phosphorus for a given concentration of Chl-*a* than the species dominating the main channel. Also, many algae are capable of "luxury" consumption of phosphorus far in excess of actual needs, when supplies are abundant (Wetzel, 1975). Although RP concentrations were not significantly different in dead zones than the main channel, it is likely that RP was being rapidly released from the sediments, and just as rapidly taken up by algae.

There was no significant difference between dead zone and main channel TP in May, despite the higher algal biomass found in dead zones in this month. Basu *et al.* (2000a) also found no difference in TP between vegetated and non-vegetated sites in fluvial lakes on the St. Lawrence in 1998 (although in July), despite higher algal biomass in the vegetated sites (but offered no explanation for this observation). As in July, it is possible that differences between main channel and dead zone community composition resulted in different TP uptake and storage of the different communities. However, this explanation requires that algae in the dead zones have less TP for a given amount of Chl-*a* than in the main channel, which is the opposite scenario from that proposed in July. Discharge was highest in May, and may have contributed to the presence of high concentrations of particulate matter, including dead organic matter, in the main channel, where it remained suspended due to turbulent mixing. This particulate matter may have settled more rapidly in dead zones, and therefore in dead zones a higher proportion of TP

may have been in living particulate matter than in the main channel. In addition, it is possible that in May, at least, water samples taken for nutrient analysis were either collected or analysed in a way that excluded or minimised the amount of large filamentous algae. Water samples may not have been sufficiently mixed before pouring off the aliquot for nutrient analysis; also, a smaller amount of water was used for nutrient analysis than for Chl-*a* analysis, which may have decreased the likelihood of sampling large algal filaments.

Differences among sites

In each month, there was variation between sites, with respect to differences between main channel and dead zone Chl-*a*. At sites A and C, there was no difference between the main channel and dead zone in any month. At sites B, D, and E, differences between dead zone and main channel mean Chl-*a* were evident; dead zones had higher Chl-*a* in May and October, and lower Chl-*a* in July. At Site F, the main channel had lower Chl-*a* than the dead zone in all months.

There may have been differences between dead zones, with respect to factors such as macrophyte species composition, affecting access of phytoplankton to light and nutrients, or abundance of grazers. However, the degree of hydrodynamic isolation of the different dead zones from the main channel likely played a large role. The dead zones at sites B and D were tucked behind islands, and at Site E, the dead zone was in a relatively protected side arm, while the dead zones at sites A and C may have been more exposed to exchange with the main flow. The existence of higher concentrations of Chl-*a* in dead zones than the main flow is, in itself, an indication that mixing with the main flow is

restricted. It is possible that the differences between dead zones and the main channel might have been even more pronounced, if sampling in May and July had not occurred in a year with discharge so much higher than average.

At site F, main channel Chl-a was always lower than at any other main channel site, as well as consistently lower than in the adjacent dead zone. A consistent increase in Secchi depth was also found between sites D and F, in all months. A consistent drop in main channel Chl-*a* has been noted in this area in previous years, and may be related to heavy zebra mussel colonization of the rocky channel bottom (Basu & Pick, 1997). Zebra mussels can exert high grazing pressure on river phytoplankton; Smith *et al.* (1998) found a 17-fold decrease in phytoplankton cell density in the Hudson River in New York, following invasion by *Dreissena polymorpha*. They estimated that zebra mussels filtered the entire water volume once every 2-3 days. In reaches heavily colonized by zebra mussels, dead zones with soft substrate may serve as refuges from filtration. Soft sediments were largely devoid of zebra mussels, as previously observed in lower regions of the Rideau by Hamilton *et al.* (1997), although any hard substrates such as site markers, sticks, and even some macrophytes were found to be colonized. Therefore, it is possible that if only the lower section of the Rideau River had been sampled, dead zones may have had significantly higher Chl-*a* than the main channel in all sampling months.

Effects of water depth

The dead zones studied on the Rideau River were all located in shallow areas. Some of the differences between dead zones and main channel sites, therefore, might be a consequence of water depth, and not simply differences in current velocity and water

retention time. Water depth is a particularly important parameter in determining the potential for growth of aquatic macrophyte beds, and thus in influencing the balance between plants and phytoplankton in lakes (Moss, 1997). However, it is difficult to separate the effects of hydrology and depth. Current velocity is also important in regulating aquatic macrophytes in flowing waters (Chambers *et al.*, 1991). The development of metaphyton is also limited by current, with groups such as *Spirogyra* forming masses in quiet ponds, pools or backwaters (Canter-Lund & Lund, 1995). Therefore, if we had studied shallow, fast flowing riffle zones, we would not have found the macrophyte assemblages and perhaps more importantly the metaphyton that dominated the shallow dead zones on the Rideau. As the differences that were found between dead zones and main channel of the Rideau were probably largely a result of the effects of the extensive macrophyte and metaphyton development found in the dead zones, it is reasonable to conclude that hydrology (and not merely depth) plays an important role in influencing the phytoplankton of dead zones.

Table 1.1 Physical parameters at the six study sites on the Rideau River in May, July and October 2000. Depth is given for the central sub-site at each sampling site. Current velocity, Secchi depth and temperature were averaged for each site (n = 3 in main channel, n = 5 in dead zones).

Parameter	Site A		Site B		Site C		Site D		Site E		Site F	
	Main	DZ	Main	DZ	Main	DZ	Main	DZ	Main	DZ	Main	DZ
Depth, m												
May	4.5	1.0	5.4	1.0	6.0	0.6	5.5	0.8	5.8	0.7	4.0	0.6
July	4.0	0.8	5.8	0.5	6.2	0.5	6.2	0.5	8.3	0.7	4.4	0.8
October	4.0	0.7	5.8	0.5	6.2	0.6	5.3	0.7	8.0	0.7	3.9	0.8
Current velocity, m s^{-1}												
May	0.26	<0.01	0.24	<0.01	0.11	<0.01	0.11	<0.01	0.14	<0.01	0.24	<0.01
July	0.06	<0.01	0.07	<0.01	0.05	<0.01	0.07	<0.01	0.16	<0.01	0.15	<0.01
October	0.06	<0.01	0.03	<0.01	0.04	<0.01	0.03	<0.01	0.04	<0.01	0.05	<0.01
Secchi depth, m												
May	1.4	n/a	1.4	n/a	1.1	n/a	2.0	n/a	2.0	n/a	2.4	n/a
July	1.5	n/a	1.5	n/a	1.9	n/a	1.7	n/a	1.8	n/a	3.7	n/a
October	2.4	n/a	2.0	n/a	2.0	n/a	3.7	n/a	3.9	n/a	4.0	n/a
Temperature,°C												
May	13.5	13.4	13.8	14.6	15.4	15.4	16.1	16.4	16.6	17.0	16.0	16.2
July	25.5	26.9	24.5	26.5	23.3	25.3	23.2	26.1	22.2	25.1	22.1	23.7
October	12.0	11.5	12.0	11.4	14.2	13.3	14.7	14.6	14.5	15.2	15.2	15.3

n/a – not available (dead zone sites were too shallow to allow Secchi depth measurement)

Table 1.2 Macrophytes observed at dead zone sites on the Rideau River in 2000.

Species	Dead Zone Site					
	A	B	C	D	E	F
Ceratophyllum demersum L.	X	X		X	X	X
Elodea canadensis Michx.	X	X		X	X	X
Lemna trisulca L.	X	X	X	X	X	X
Myriophyllum sibiricum Komorov.	X				X	
Myriophyllum spicatum L.	X	X	X	X		
Nuphar variegatum		X		X		
Nymphaea odorata Aiten.	X		X	X	X	X
Potamogeton crispus L.				X	X	X
Potamogeton richardsonii (Ar. Bennett) Rydb.	X	X	X	X	X	
Vallisneria americana L.	X	X	X	X	X	X
Wolffia sp.					X	X

Table 1.3 Summary of *a priori* comparisons between mean physical and chemical parameters in main channel and dead zone sites in May, July and October 2000. Comparisons are by pooled variance t-tests, with Dunn-Sidak adjusted probabilities. Positive t-statistics indicate higher mean values in dead zones than main channel. Six main channel and six dead zone sites were sampled.

Parameter	Month	t-statistic	p-value (2-tailed)
LA	May	2.101	0.175
	July	2.297	0.128
	Oct	0.420	0.968
Temp.	May	0.355	0.980
	July	2.133	**0.043**
	Oct	-0.227	0.995
% DO	May	2.892	**0.047**
	July	2.555	**0.083**
	Oct	-0.050	1.000
pH	May	2.443	**0.100**
	July	0.189	0.997
	Oct	0.697	0.876
SpCond	May	0.269	0.991
	July	0.823	0.814
	Oct	0.269	0.991
E_h	May	0.144	0.999
	July	-3.188	**0.029**
	Oct	1.191	0.597

LA = light attenuation (extinction coefficient); Temp. = water temperature; % DO = percent dissolved oxygen; SpCond = specific conductance; E_h = redox potential.

Table 1.4 *A priori* comparisons between percent organic matter in sediments from the main channel and dead zones at sites A-D on the Rideau River. Comparisons are by pooled variance t-tests, with Dunn-Sidak adjusted probabilities. Positive t-statistics indicate higher mean values in dead zones than main channel. Three samples were taken at each main channel and dead zone site.

Variable	Site	t-statistic	p-value (2-tailed)
% OM	A	-0.737	0.939
	B	-0.121	1.000
	C	0.324	0.997
	D	6.923	**0.024**

Table 1.5 Summary of *a priori* comparisons between main channel and dead zone nutrient concentrations in May, July and October 2000. Comparisons are by pooled variance t-tests, with Dunn-Sidak adjusted probabilities. Positive t-statistics indicate higher mean values in dead zones than main channel. Six main channel and six dead zone sites were sampled.

Nutrient	Month	t-statistic	p-value (2- tailed)
TP	May	0.319	0.986
	July	3.864	**0.009**
	October	2.903	**0.046**
RP	May	-1.860	0.253
	July	1.049	0.684
	October	-0.137	0.999
TKN	May	1.027	0.698
	July	2.448	**0.100**
	October	1.891	0.241
NH_3	May	-1.713	0.313
	July	0.079	1.000
	October	0.366	0.978
NO_3+NO_2	May	-1.157	0.618
	July	-0.344	0.982
	October	-1.263	0.552

Table 1.6 Summary of *a priori* comparisons between Chl-*a* concentrations in main channel and dead zone sites in May, July and October 2000. Comparisons are by pooled variance t-tests, with Dunn-Sidak adjusted probabilities. Positive t-statistics indicate higher mean values in dead zones than main channel. Six main channel and six dead zone sites were sampled.

Chl-*a* size fraction	Month	t-statistic	p-value (2- tailed)
> 0.2 μm	May	2.134	0.166*
	July	-0.321	0.985
	Oct	0.967	0.734
> 2.0 μm	May	2.386	0.110*
	July	0.639	0.901
	Oct	0.980	0.726
> 20 μm	May	5.004	**0.002**
	July	0.803	0.825
	Oct	1.456	0.440
> 64 μm	May	3.995	**0.008**
	July	5.985	**<0.001**
	Oct	1.967	0.215

* 1-tailed p-values are significant at $0.05<p<0.10$

Table 1.7 Comparison of Chl-*a* ($\mu g \cdot L^{-1}$) in main channel and dead zone sites in May, July and October 2000. Estimates are the mean and range of 30 samples.

Chl-*a* size fraction	Month	MAIN CHANNEL		DEAD ZONE	
		Mean	Range	Mean	Range
> 0.2 μm	May	9.2	5.0-18.4	14.5	2.4-52.8
	July	12.1	2.4-18.6	11.4	4.4-22.2
	Oct	5.6	1.8-9.5	6.8	2.6-9.6
> 2.0 μm	May	5.7	2.9-11.1	8.5	5.1-14.3
	July	7.5	1.6-13.1	8.5	2.9-19.2
	Oct	3.5	1.0-6.8	4.4	1.6-6.5
> 20 μm	May	2.3	0.3-5.2	5.4	1.7-17.7
	July	2.2	0.5-3.9	2.6	0.9-5.1
	Oct	1.0	0.2-3.0	1.4	0.3-3.6
> 64 μm	May	0.9	0.1-2.4	5.7	0.5-34.3
	July	0.4	0.1-0.9	1.4	0.4-6.1
	Oct	0.3	0.04-1.4	0.6	0.1-1.1

Table 1.8 Summary of *a priori* comparisons between main channel and dead zone (A) coefficient of variation (CV) of total Chl-*a*, and (B) proportion of total Chl-*a* > 64μm in May, July and October 2000. Comparisons are by pooled variance t-tests, with Dunn-Sidak adjusted probabilities. Positive t-statistics indicate higher mean values in dead zones than main channel. Six main channel and six dead zone sites were sampled.

	Variable	Month	t-statistic	p-value (2-tailed)
(A)	CV of total Chl-*a*	May	2.211	0.147
		July	2.639	**0.072**
		Oct	1.146	0.624
(B)	Proportion of Chl-*a* >64 μm	May	3.224	**0.027**
		July	5.200	**0.001**
		Oct	1.997	0.205

Figure 1.1 Location of sampling sites on the Rideau River. The main channel and an adjacent dead zone area were sampled at each site (A-F).

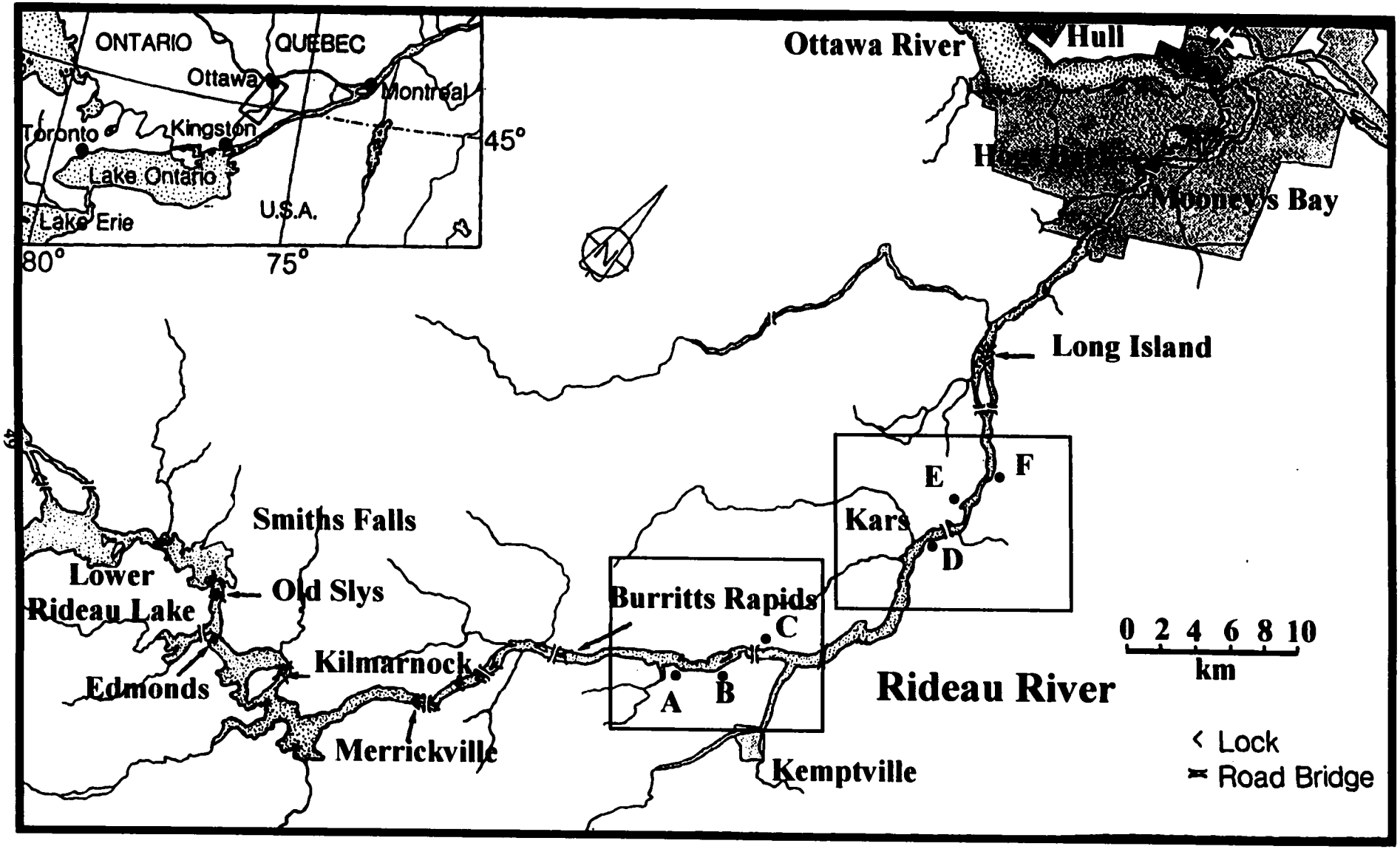
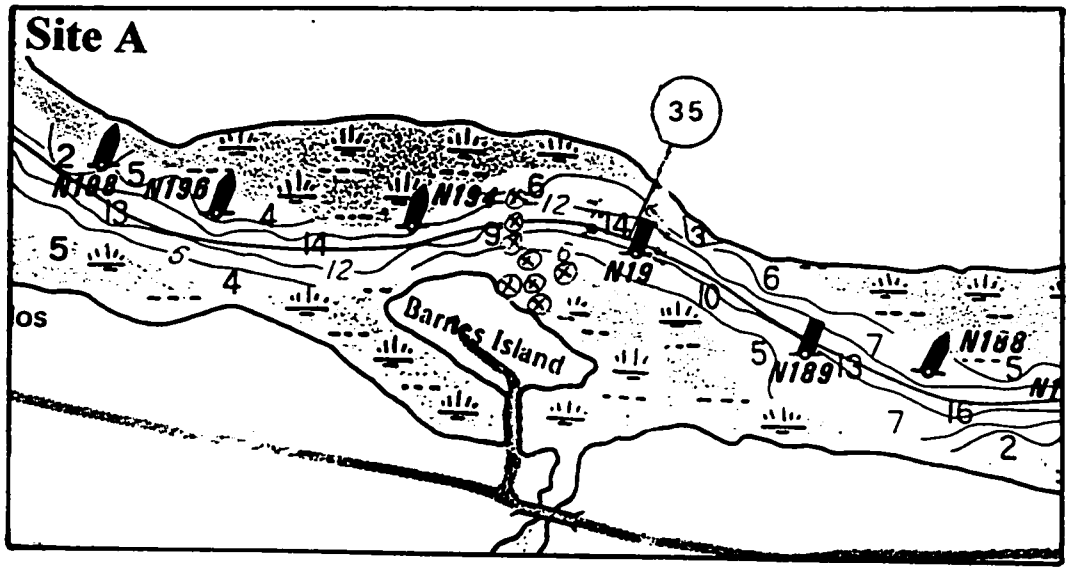
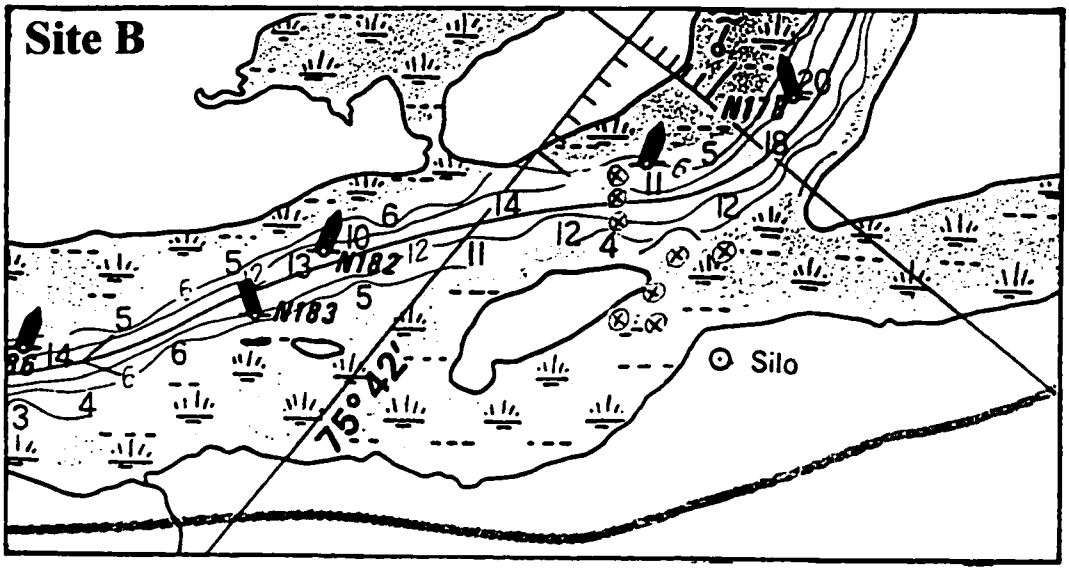
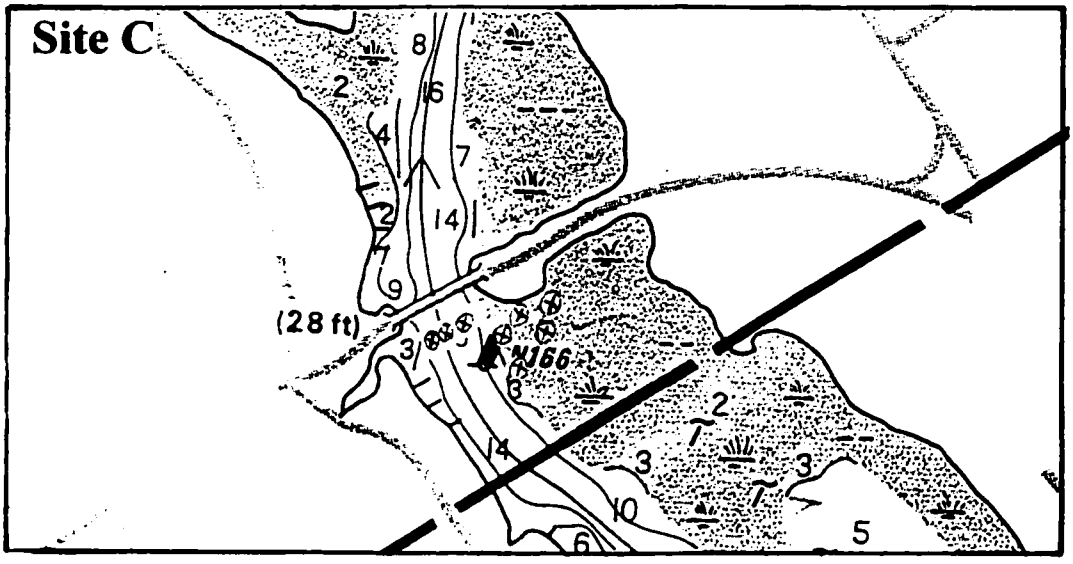

ONTARIO
QUEBEC
Ottawa
Montreal
Toronto
Kingston
Lake Ontario
Lake Erie
U.S.A.
45°
80°
75°
Ottawa River
Hull
Mooneys Bay
Long Island
Smiths Falls
Lower
Rideau Lake
Old Slys
Kilmarnock
Edmonds
Merrickville
Burritts Rapids
Kars
A
B
C
D
E
F
Rideau River
Kemptville
0 2 4 6 8 10
km
Lock
Road Bridge

Figure 1.2 Detail of sites A-C, between Burritts Rapids and Becketts Landing on the Rideau River. The approximate locations of sampling sub-sites are indicated by the symbol (x).







Statute Miles 1/2 1/4 0 1

Figure 1.3 Detail of sites D-F, between Kars and Long Island on the Rideau River. The approximate locations of sampling sub-sites are indicated by the symbol (x).

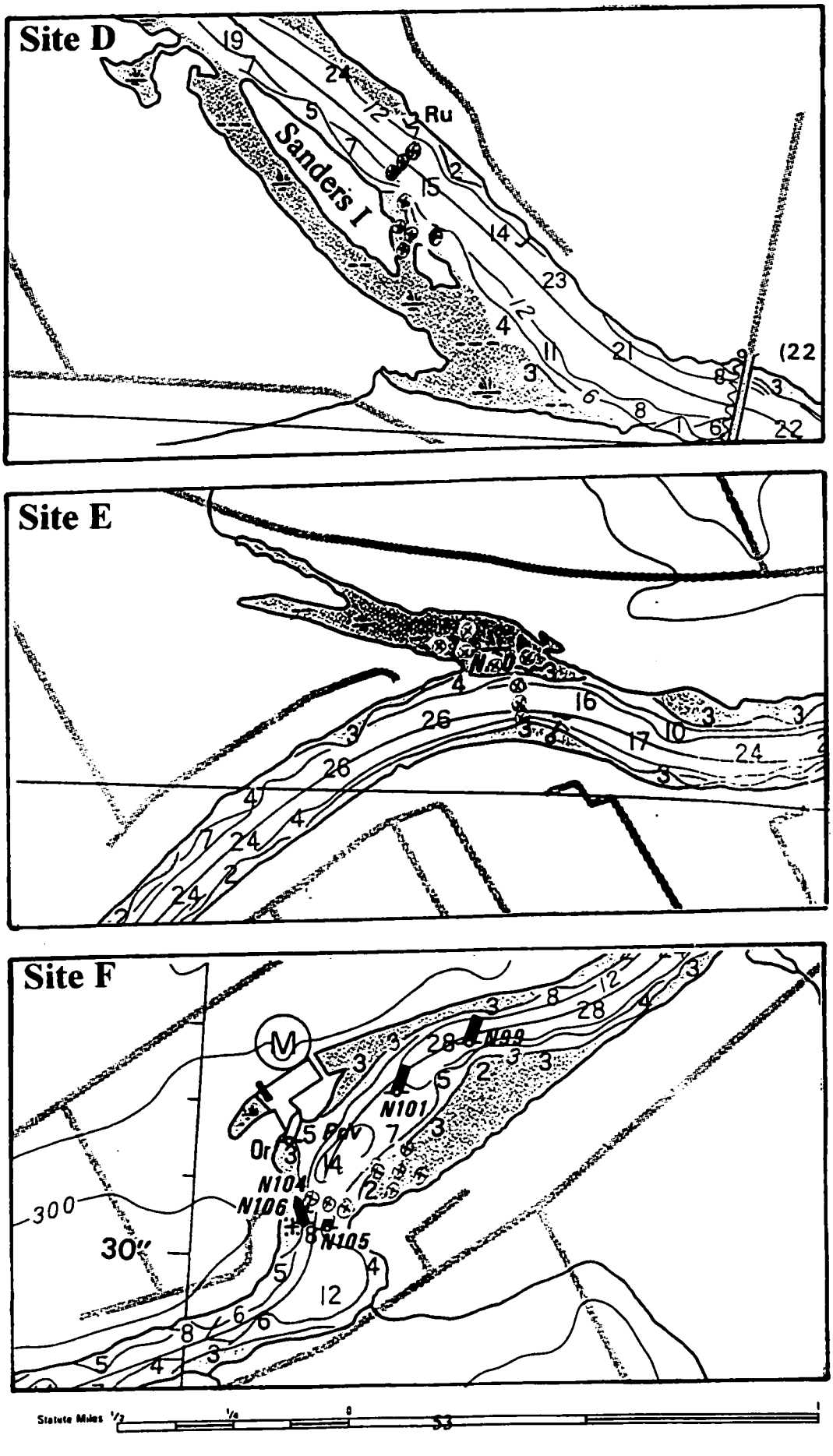

Site D
Sanders I
Ru
Site E
Site F
N99
N101
N104
N106
N105
Or
30"
300
Statute Miles

Figure 1.4 Drifting drogue used for current velocity measurement. The drogue is shown as it would appear when deployed from an anchored boat. The position of the float is adjustable, allowing the depth of the drogue to be varied, depending on the channel depth.

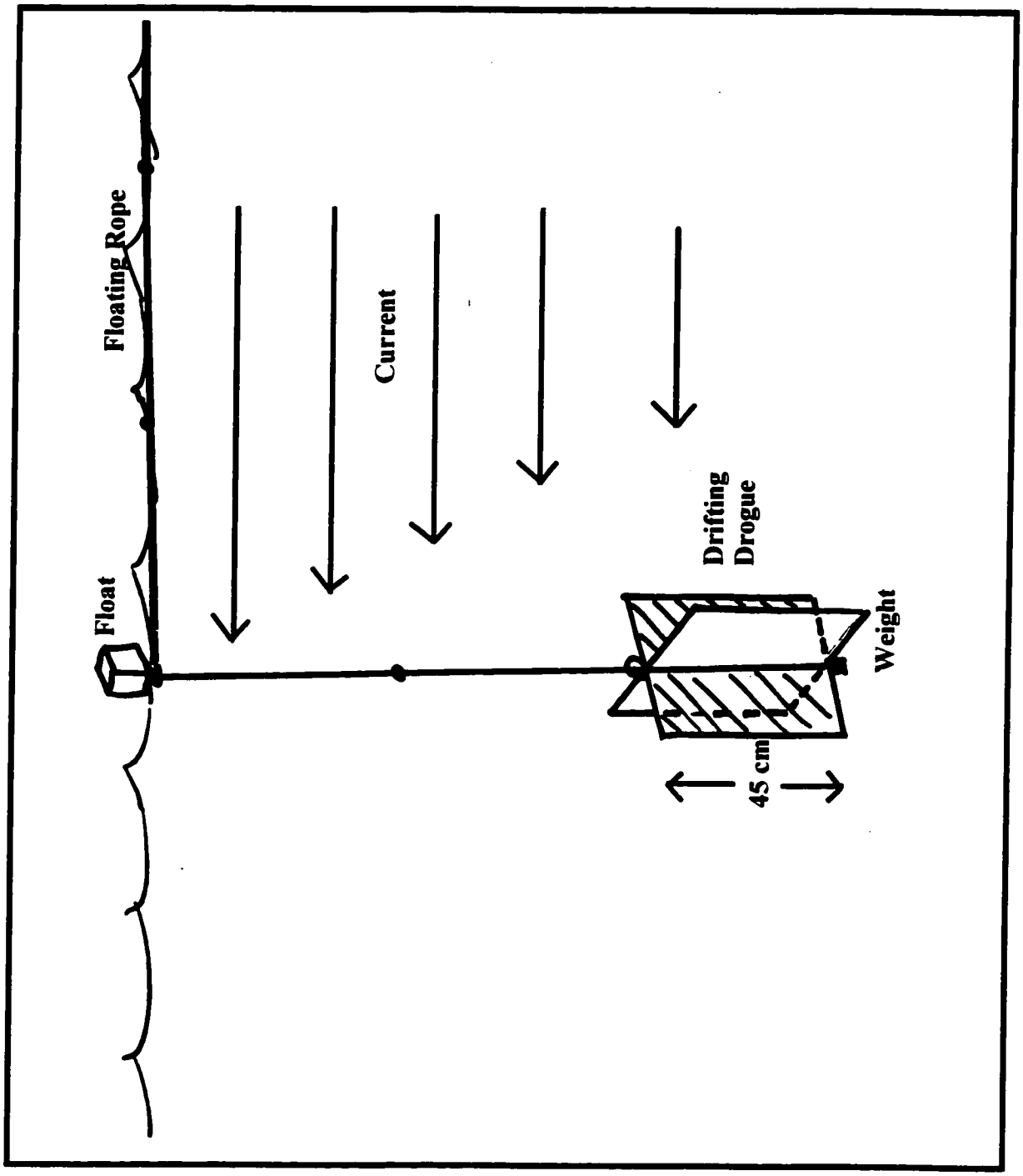

Floating Rope
Current
Float
Drifting
Drogue
Weight
45 cm

Figure 1.5 Comparison of historical mean monthly discharge with discharge measured in 2000, for the Rideau River at Ottawa. Historical mean monthly discharge is calculated from data for 1933 to 1990, except for the winter months, where records are available only from 1946 (December and April), or 1947 (January to March). Units are m^3s^{-1}.

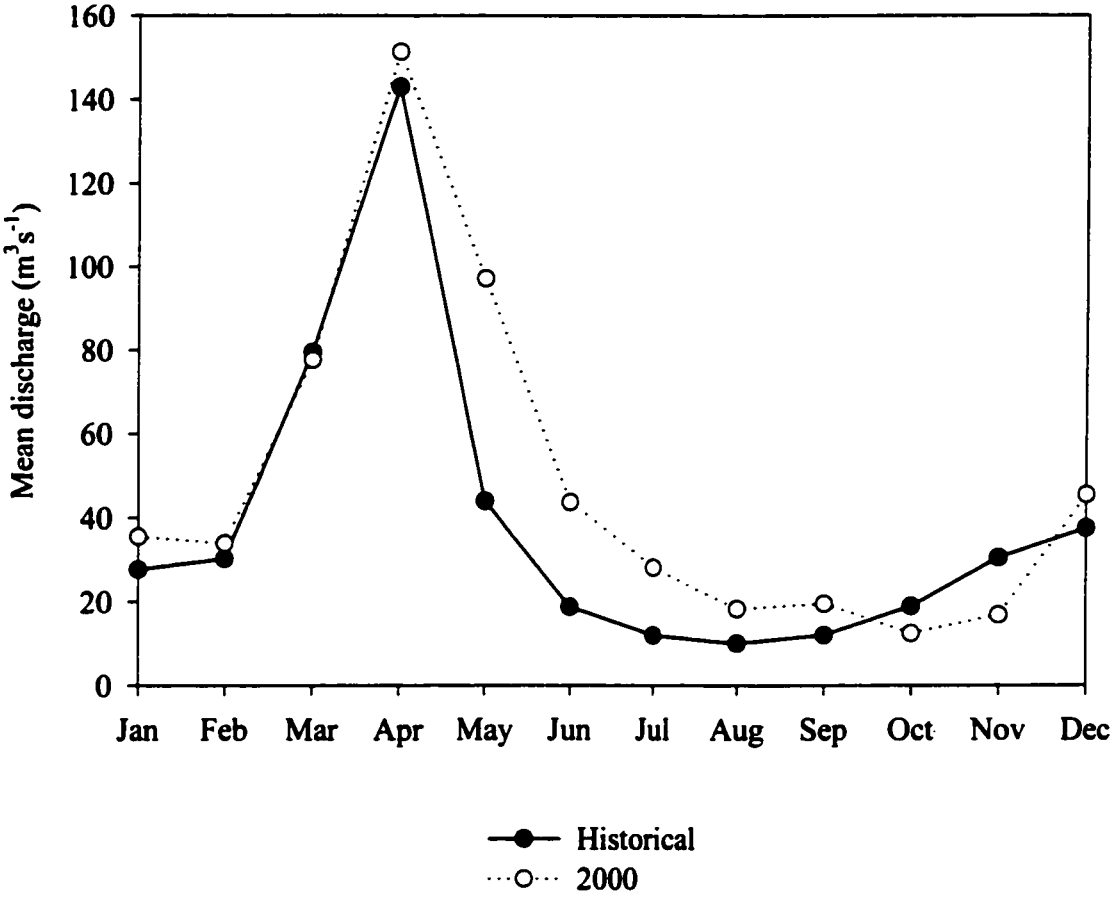

160
140
120
100
80
60
40
20
0
Mean discharge ($m^3 s^{-1}$)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Historical
2000

Figure 1.6 Macrophyte development in the dead zone at site C on the Rideau River, in (A) May 2000 (B) July 2000.

Figure 1.7 Submerged macrophytes in the dead zone at site D on the Rideau River in (A) July 2000 and (B) October 2000.

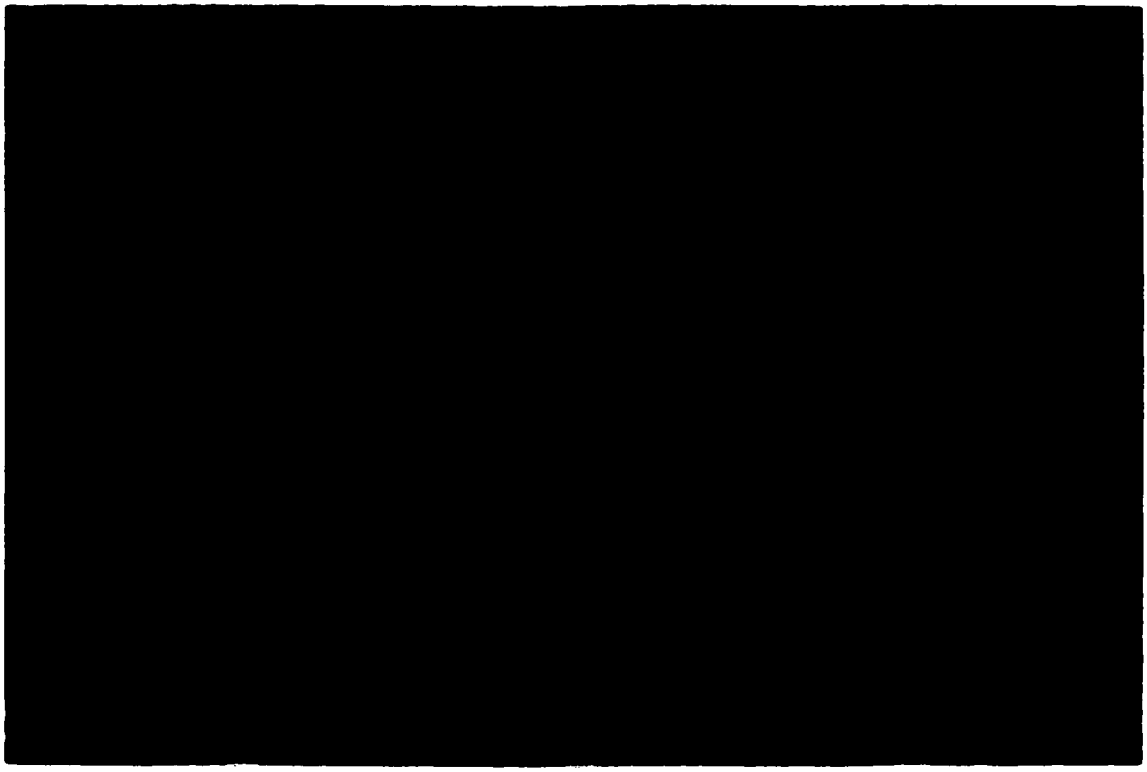
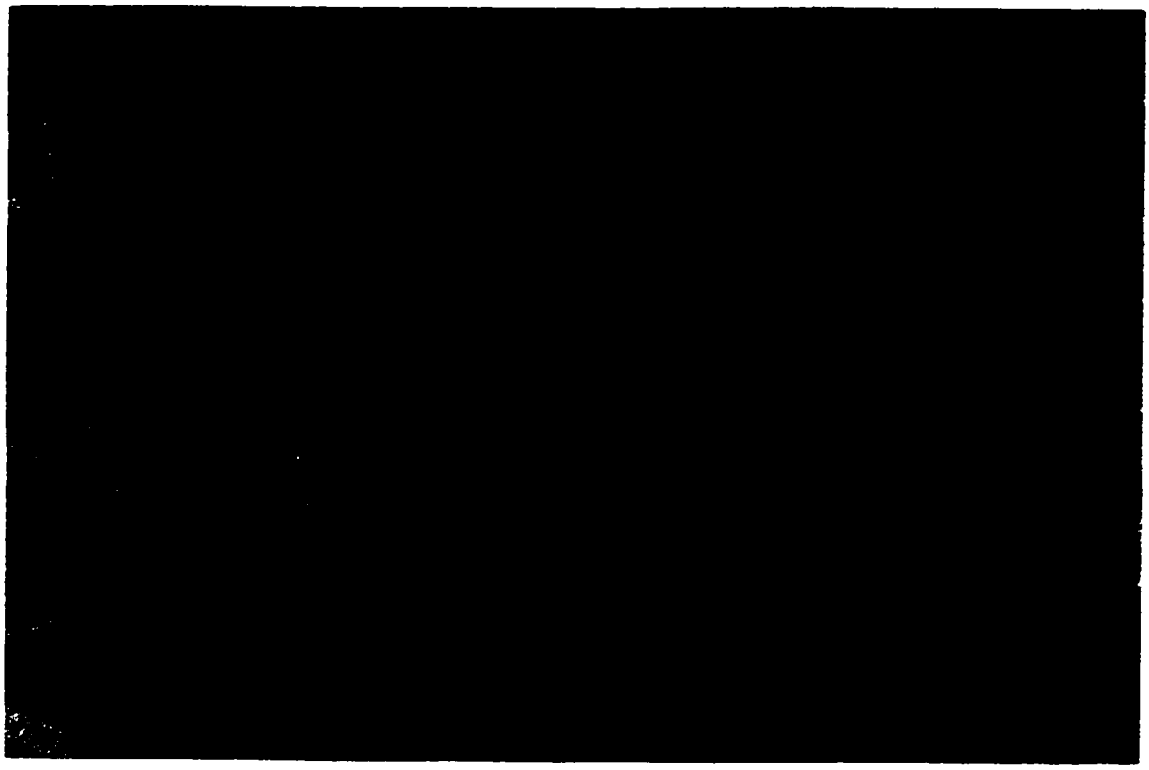


Figure 1.8 Metaphyton in the Rideau River, in May and July 2000.

(A) *Spirogyra* spp. sampled from the dead zone at Site A in May 2000. The specimen was photographed using phase contrast microscopy under 100x magnification. Width of the larger *Spirogyra* sp. filament is approximately 155 μm.

(B) Extensive macrophyte development, and thick mats of floating, decaying metaphyton in the dead zone at Site D in July 2000.



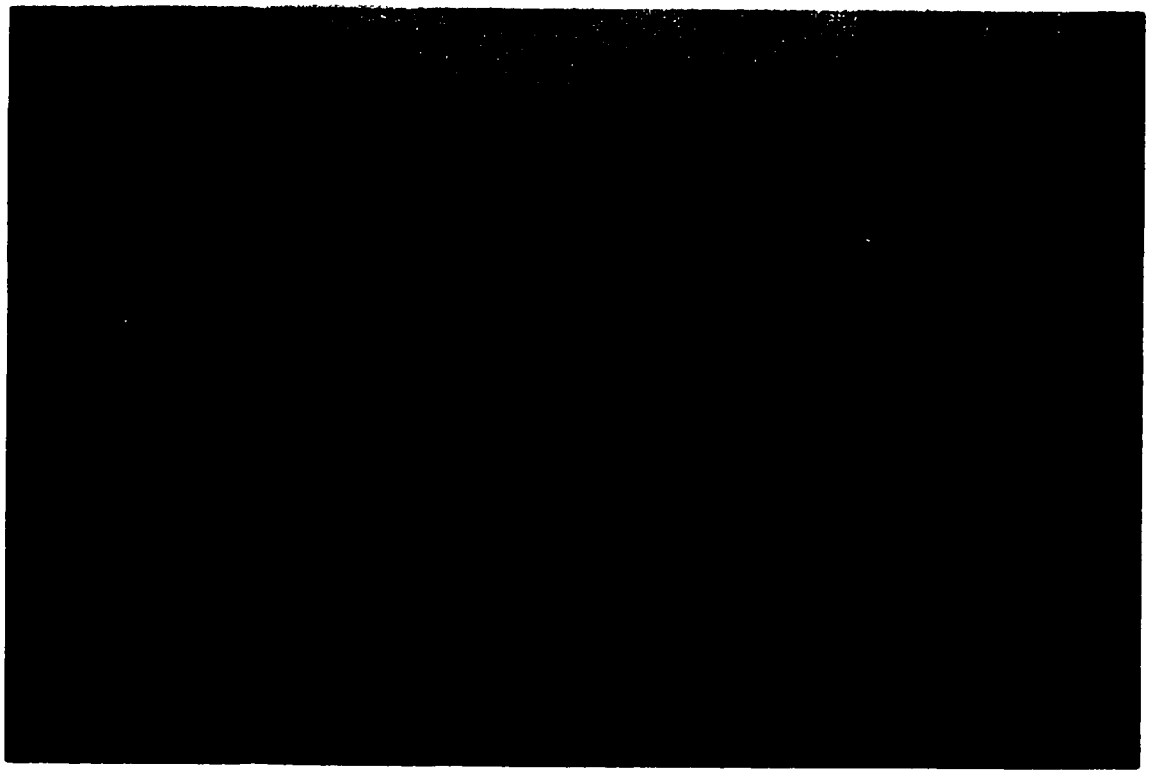


Figure 1.9 Secchi depth (in metres) measured in the main channel at sites A-F on the Rideau River, in May, July and October of 2000. Estimates represent the mean of three sub-sites, and include standard error.

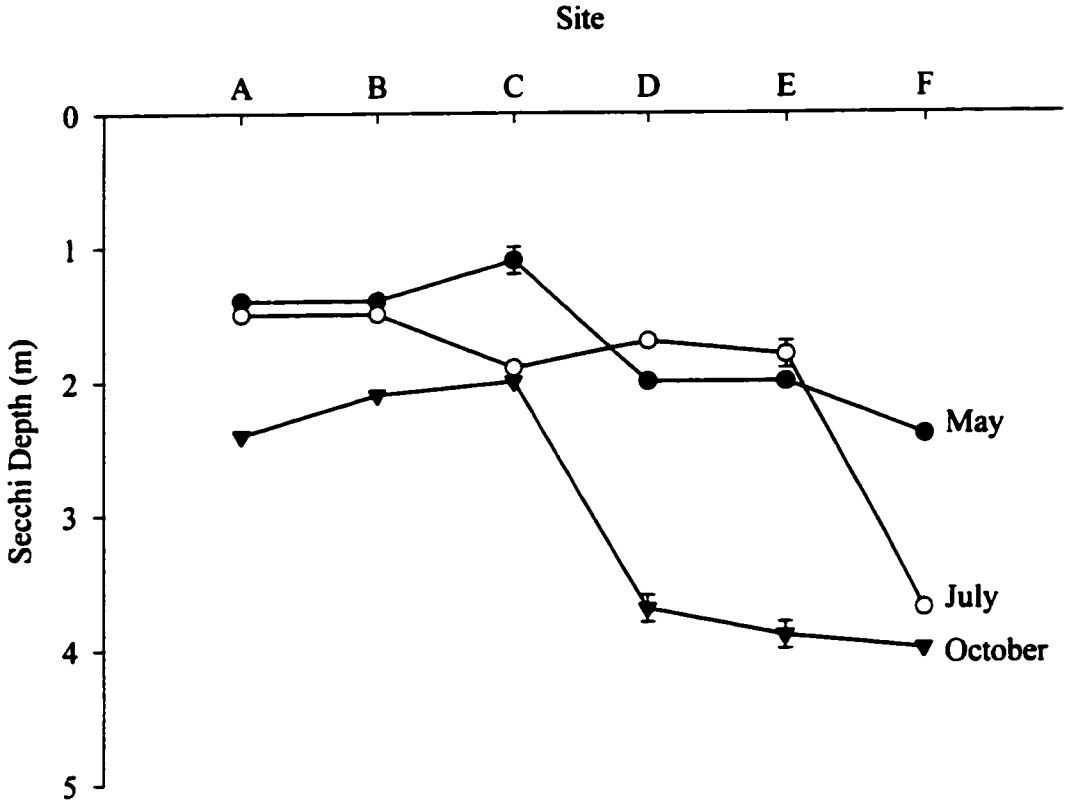

Site
A
B
C
D
E
F
0
1
2
3
4
5
Secchi Depth (m)
May
July
October

Figure 1.10 Light extinction coefficients (η) in the main channel and adjacent dead zones of the Rideau River in May, July and October 2000. Estimates represent the mean of six sites and include standard error.

$\eta = (\ln I_o - \ln I_z) / z$, where I_o = light intensity at surface and I_z = light intensity at depth z

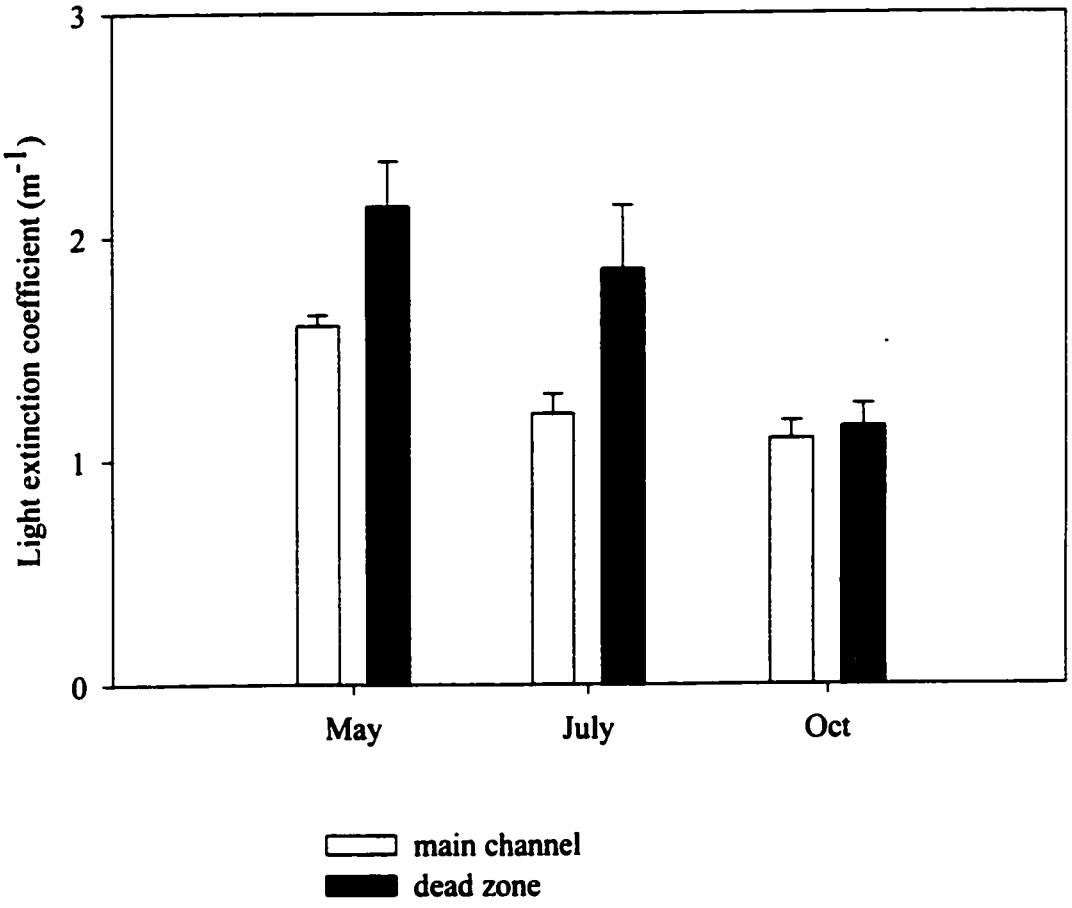

3
2
1
0
Light extinction coefficient (m-1)
May
July
Oct
main channel
dead zone

Figure 1.11 Water temperature in the main channel and dead zones of the Rideau River, in May, July and October 2000. Estimates represent the mean of six sites, and include standard error.

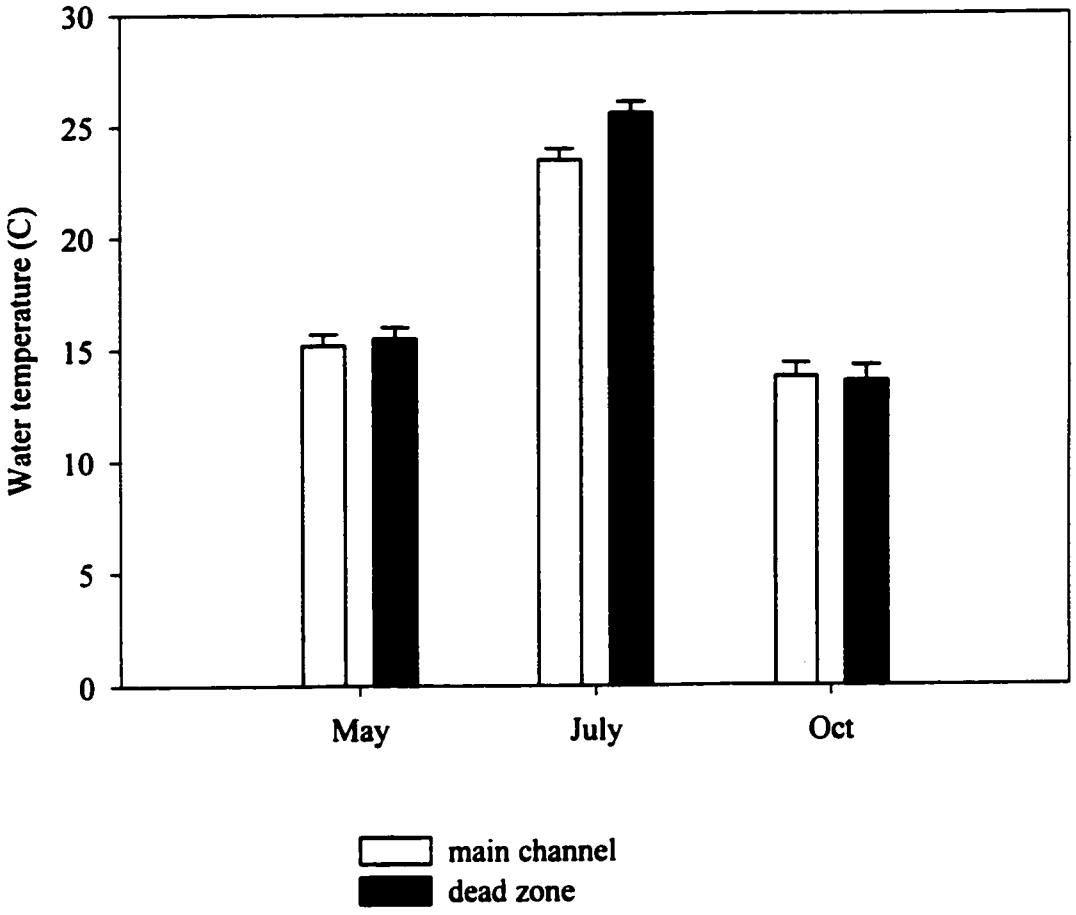

30
25
20
15
10
5
0
Water temperature (C)
May
July
Oct
main channel
dead zone

Figure 1.12 Sediment organic matter content in the main channel and dead zones at six sites on the Rideau River. Estimates represent the mean of 3 sub-sites (except site D, main channel, 2-subsites only), and include standard error. Sediment cores could not be obtained at main channel sites E and F, where the bottom was bedrock.

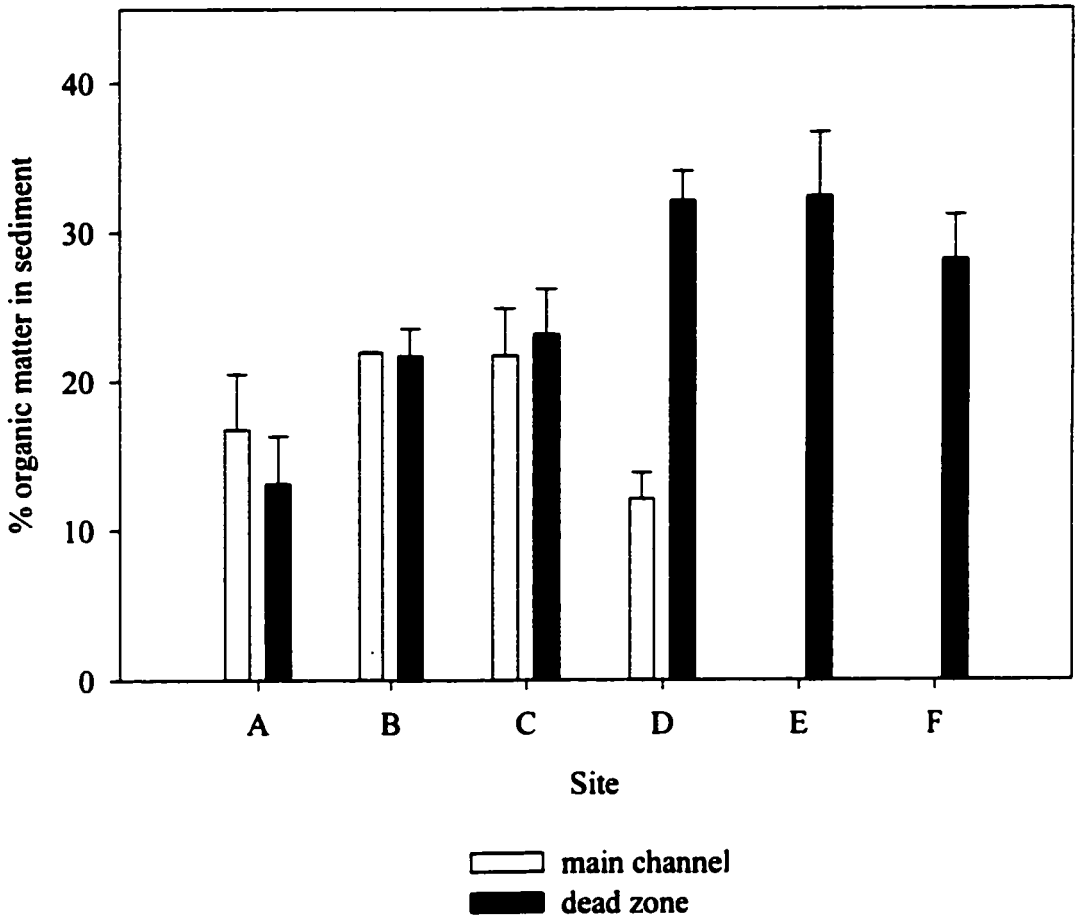

40
30
20
10
0
% organic matter in sediment
A
B
C
D
E
F
Site
main channel
dead zone

Figure 1.13 Dissolved oxygen (percent saturation) in the main channel and dead zones of the Rideau River, in May, July and October 2000. Estimates represent the mean of six sites, and include standard error.

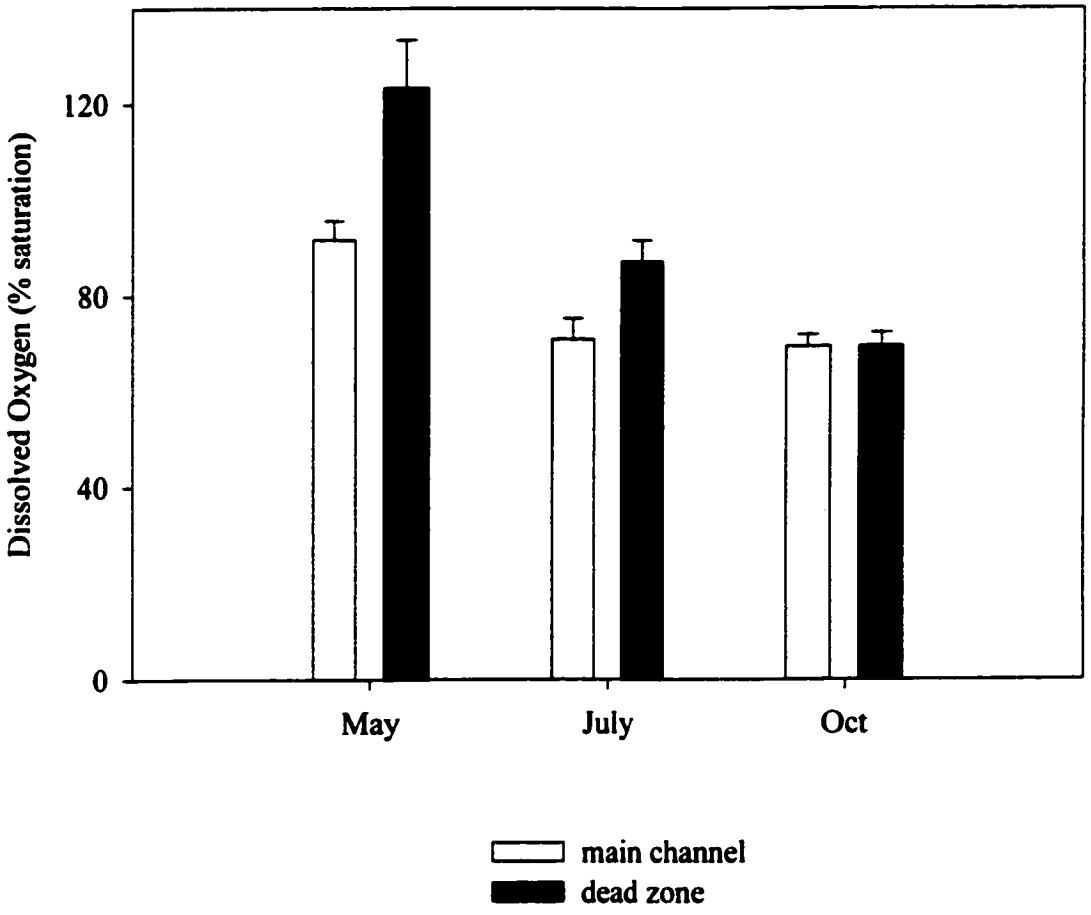

Dissolved Oxygen (% saturation)
120
80
40
0
May
July
Oct
main channel
dead zone

Figure 1.14 Comparison of (A) total phosphorus (TP) and (B) soluble reactive phosphorus (RP) concentrations in the main channel and dead zones, in May, July and October 2000. Estimates are the mean of 6 sites, and include standard error.

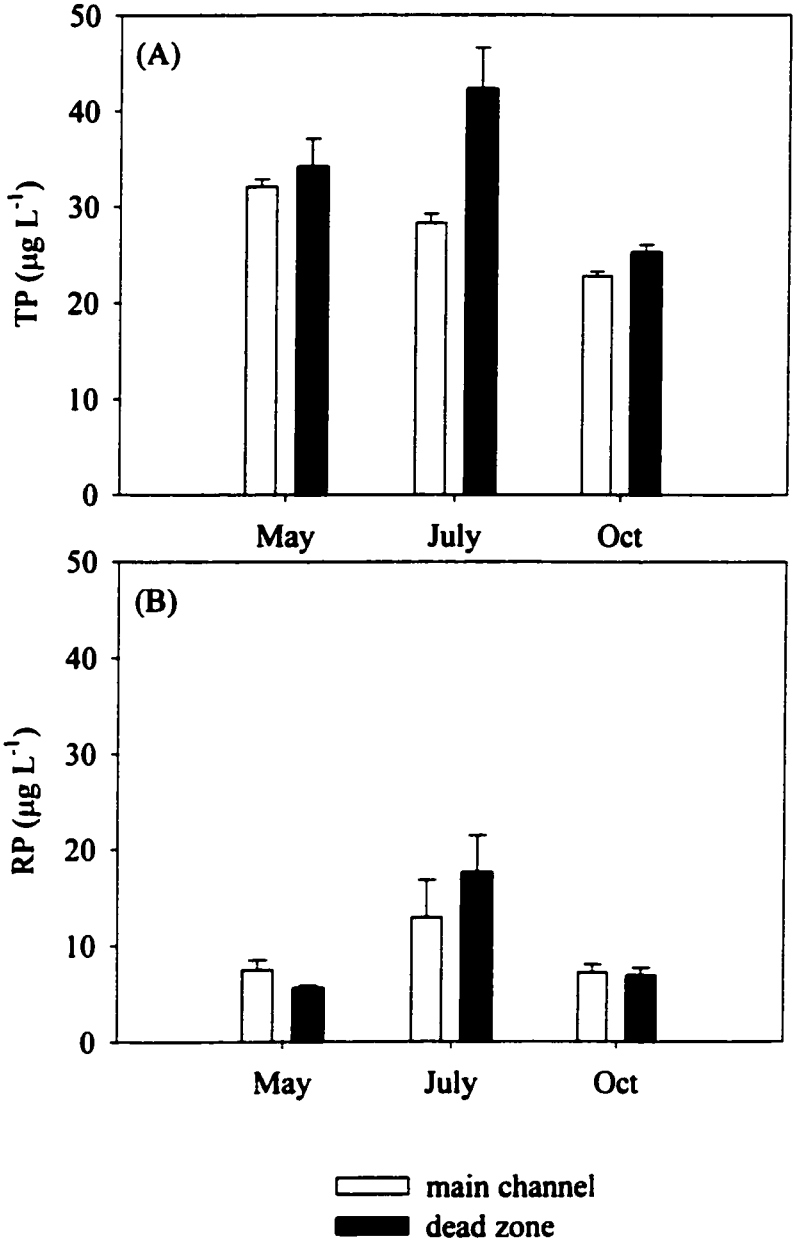

(A)
TP (µg L-1)
50
40
30
20
10
0
May
July
Oct
(B)
RP (µg L-1)
50
40
30
20
10
0
May
July
Oct
main channel
dead zone

Figure 1.15 Total phosphorus in the main channel and adjacent dead zones at six sites along the Rideau River, in May, July and October 2000. Estimates are the mean of 2 sub-sites in May, and 3 sub-sites in July and October, and include standard error.

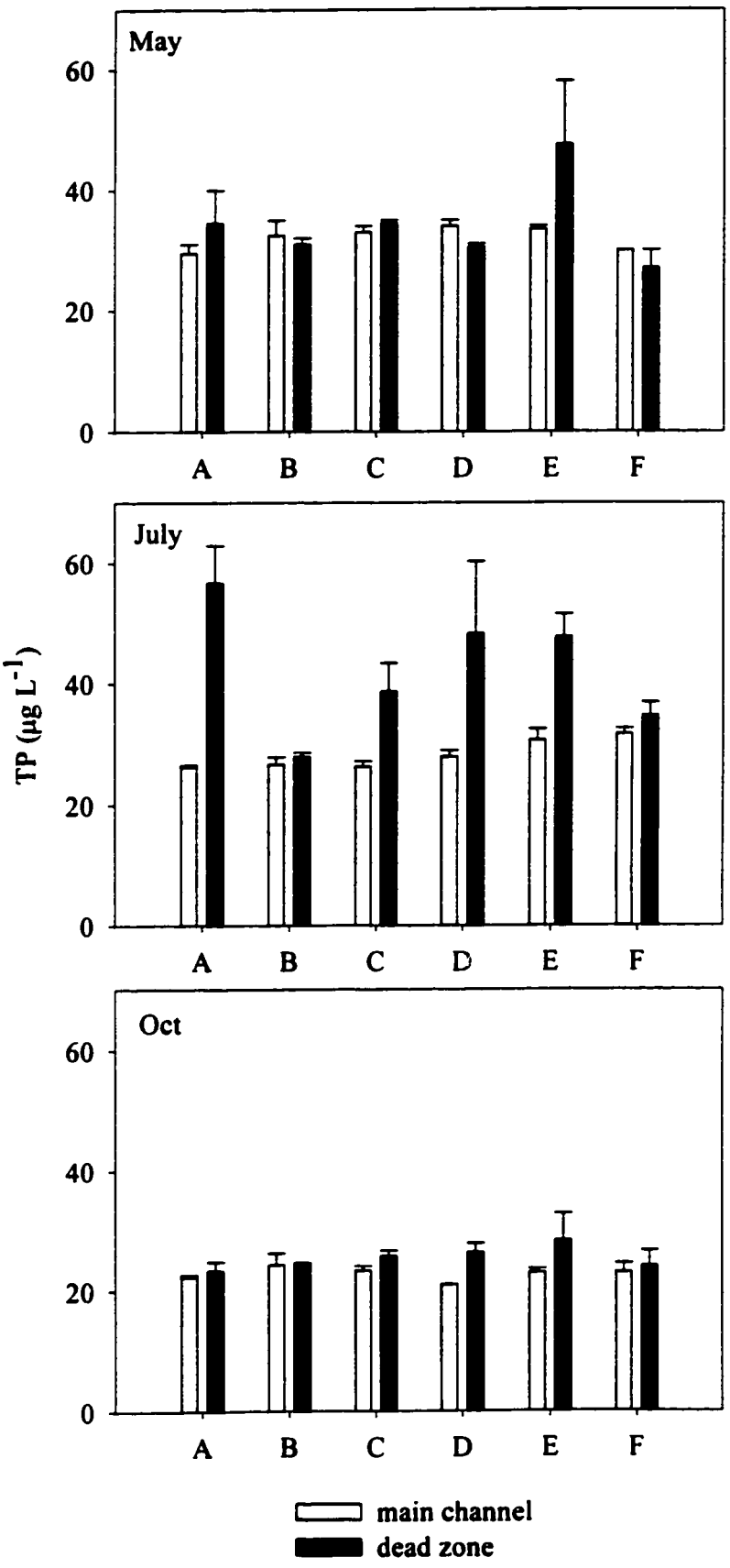

May
July
Oct
TP (µg L-1)
0
20
40
60
A
B
C
D
E
F
main channel
dead zone

Figure 1.16 Comparison of (A) total Kjeldahl nitrogen (TKN), (B) nitrate+nitrite (NO_3 + NO_2) and (C) ammonia (NH_3) nitrogen concentrations in the main channel and dead zones, in May, July and October 2000. Estimates are the mean of 6 sites, and include standard error. Note the different scales.

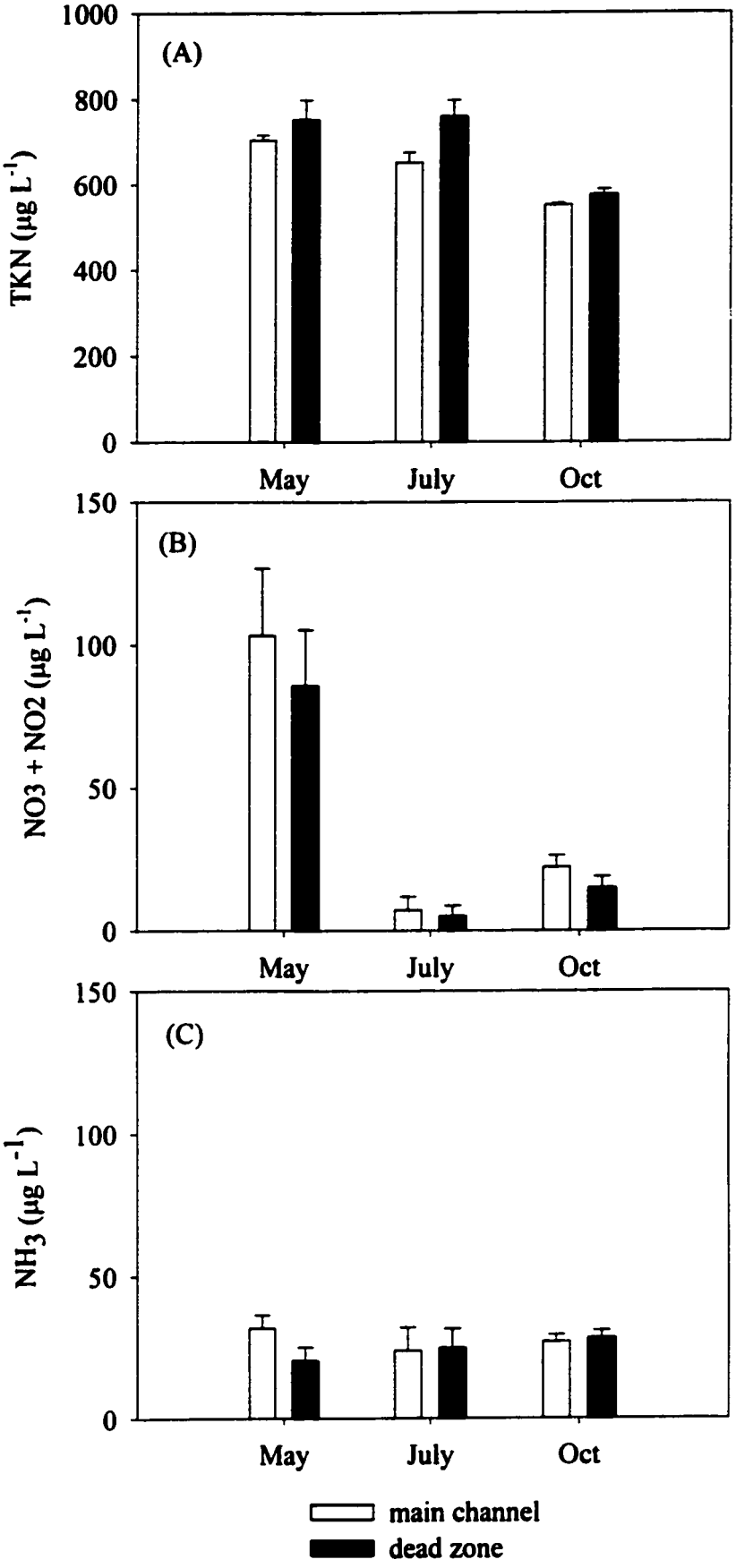

(A)
TKN (µg L-1)
1000
800
600
400
200
0
May
July
Oct
(B)
NO3 + NO2 (µg L-1)
150
100
50
0
May
July
Oct
(C)
NH3 (µg L-1)
150
100
50
0
May
July
Oct
main channel
dead zone

Figure 1.17 Total Kjeldahl nitrogen in the main channel and adjacent dead zones at six sites along the Rideau River, in May, July and October 2000. Estimates are the mean of 2 sub-sites in May, and 3 sub-sites in July and October, and include standard error.

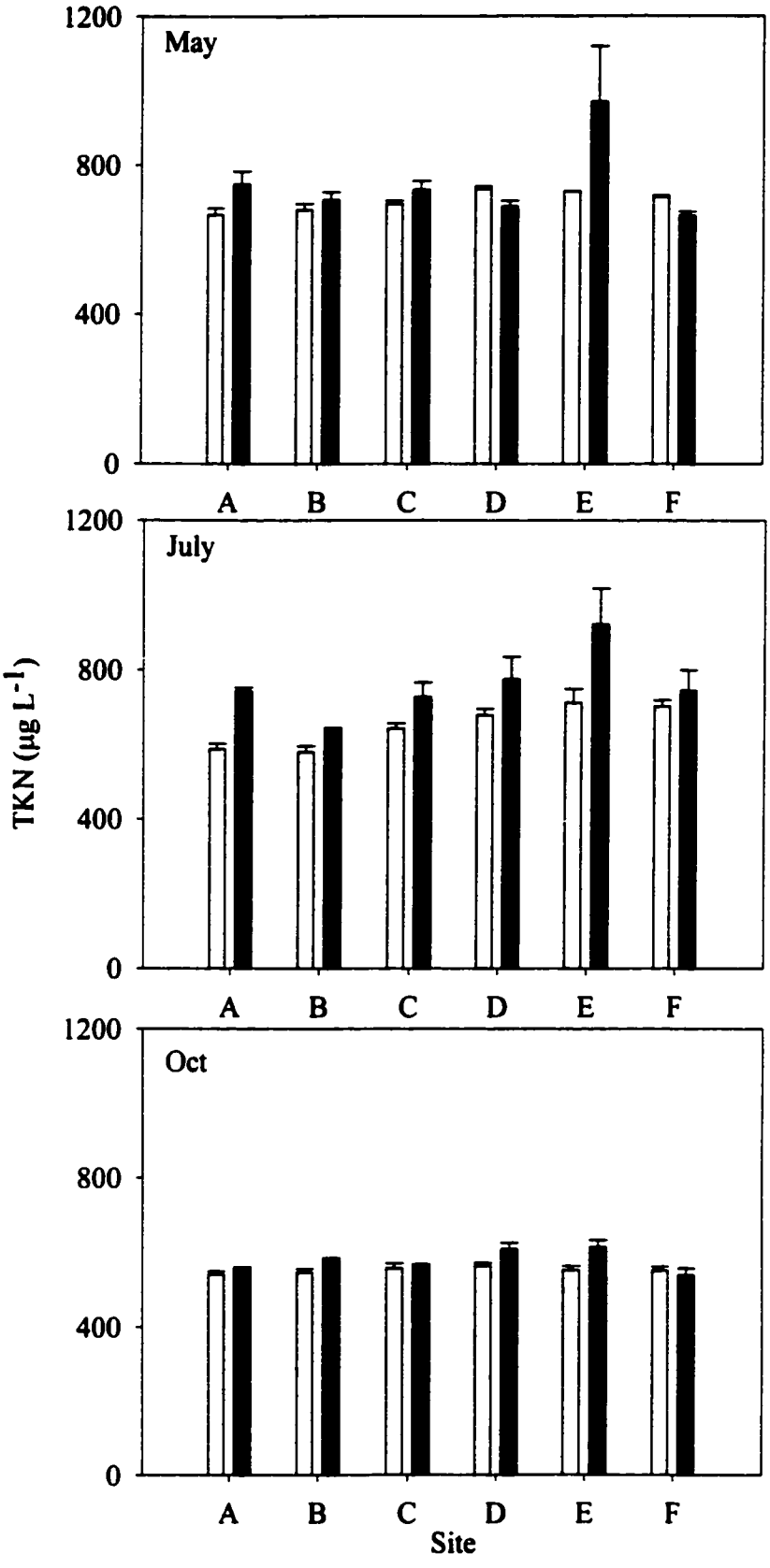

May
July
Oct
1200
800
400
0
A
B
C
D
E
F
TKN (µg L-1)
Site
main channel
dead zone

Figure 1.18 Soluble reactive phosphorus in the main channel and adjacent dead zones at six sites along the Rideau River, in May, July and October 2000. Estimates are the mean of 2 sub-sites in May, and 3 sub-sites in July and October, and include standard error.

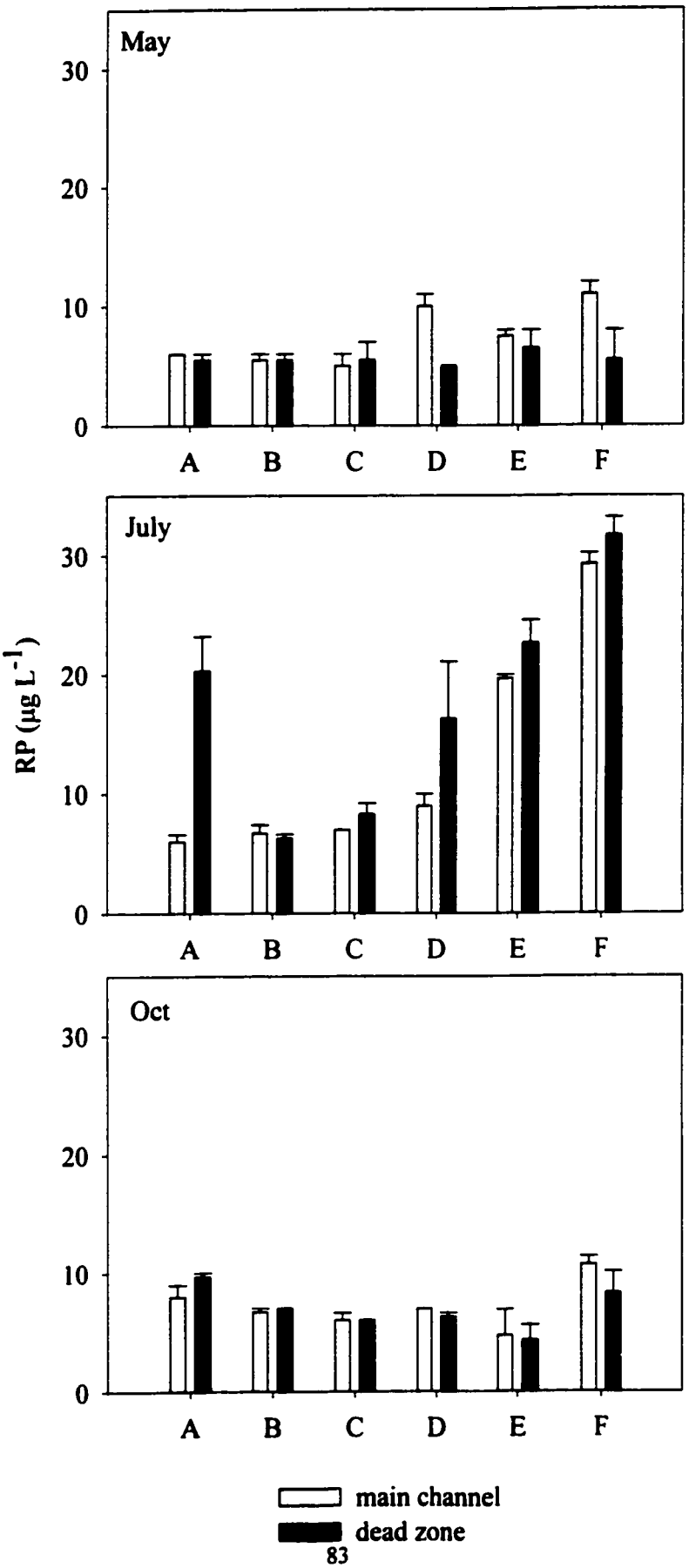

May
July
Oct
RP (µg L-1)
0
10
20
30
A
B
C
D
E
F
main channel
dead zone

Figure 1.19 Nitrate + nitrite nitrogen in the main channel and adjacent dead zones at six sites along the Rideau River, in May, July and October 2000. Estimates are the mean of 2 sub-sites in May, and 3 sub-sites in July and October, and include standard error.

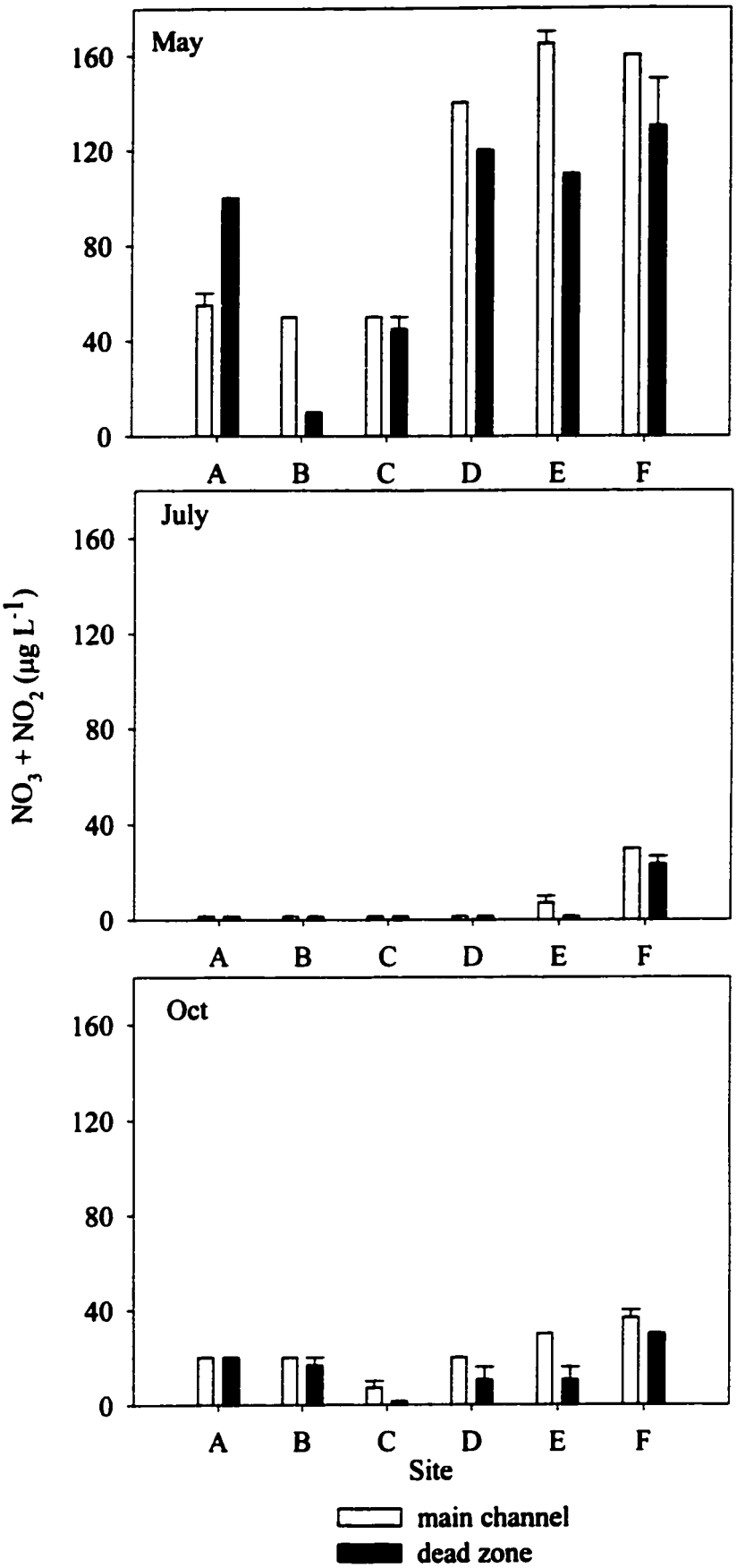

May
July
Oct
160
120
80
40
0
A
B
C
D
E
F
$NO_3 + NO_2$ (µg L^{-1})
Site
main channel
dead zone

Figure 1.20 Ammonia in the main channel and adjacent dead zones at six sites along the Rideau River, in May, July and October 2000. Estimates are the mean of 2 sub-sites in May, and 3 sub-sites in July and October, and include standard error.

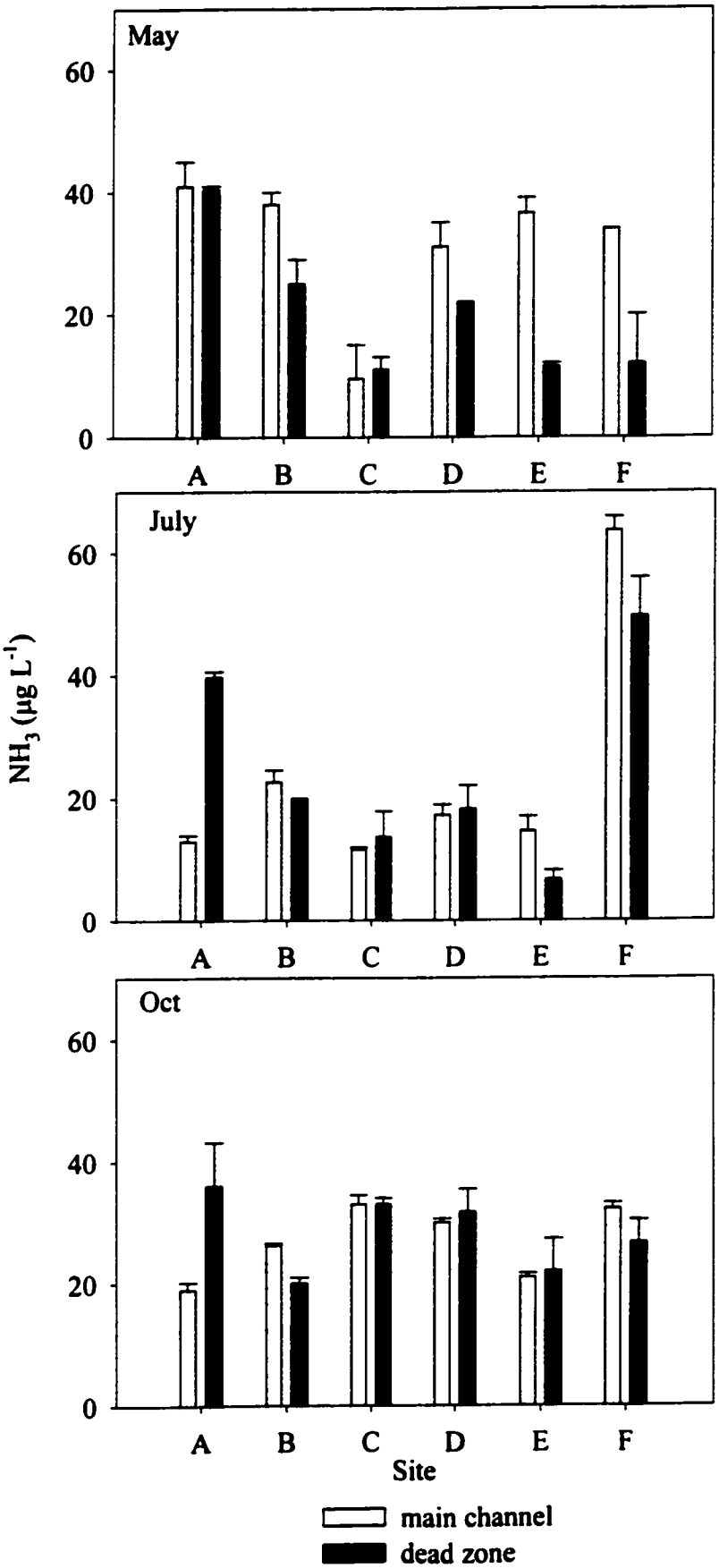

May
July
Oct
60
40
20
0
A
B
C
D
E
F
NH_3 ($\mu g\ L^{-1}$)
Site
main channel
dead zone

Figure 1.21 Chlorophyll-*a* at main channel and dead zone sites, in May, July and October 2000. Data are for algae retained on filters of (A) 0.2 μm, (B) 2.0 μm, (C) 20 μm and (D) 64 μm pore size. Estimates are the mean of six sites, and include standard error.

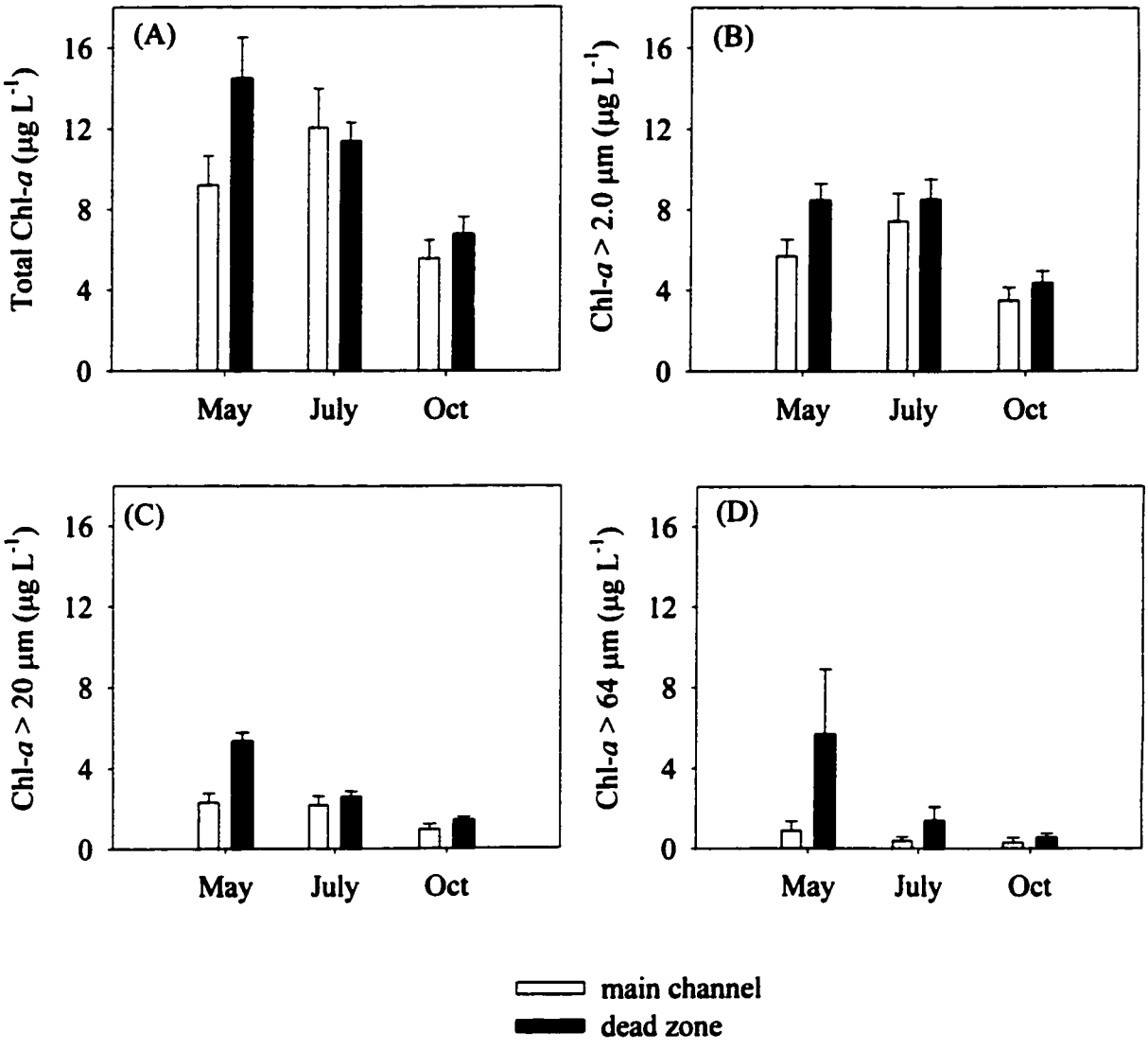

(A)
Total Chl-a (µg L-1)
16
12
8
4
0
May
July
Oct
(B)
Chl-a > 2.0 µm (µg L-1)
(C)
Chl-a > 20 µm (µg L-1)
(D)
Chl-a > 64 µm (µg L-1)
main channel
dead zone

Figure 1.22 Total chlorophyll *a* (> 0.2 μm) in the main channel and adjacent dead zones at six sites along the Rideau River, in May, July and October 2000. Estimates are the mean of 5 sub-sites and include standard error.

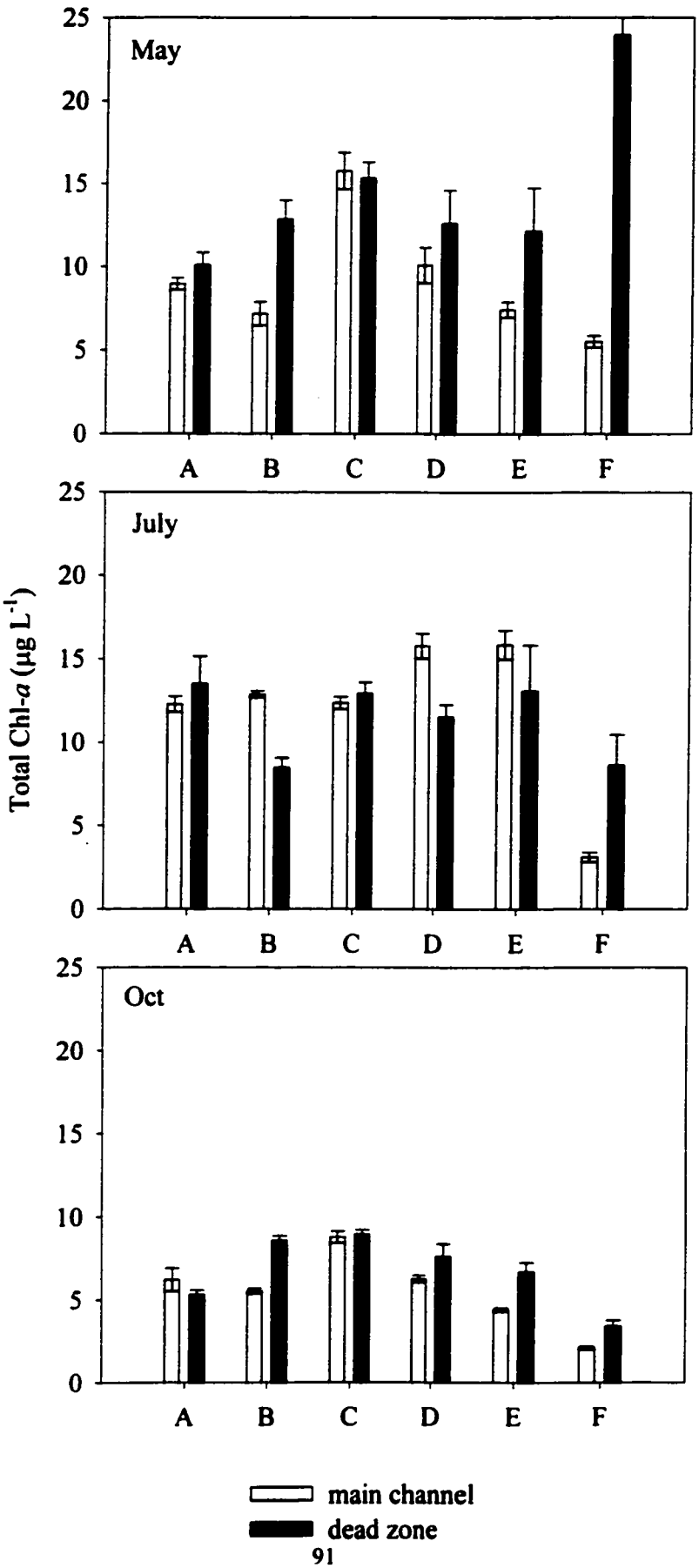

May
July
Oct
Total Chl-a (µg L-1)
25
20
15
10
5
0
A
B
C
D
E
F
main channel
dead zone

Figure 1.23 Variability in total chlorophyll *a* (> 0.2 μm) in the main channel and dead zones, in May, July and October 2000. Estimates represent the mean coefficient of variation (CV) of six sites, and include standard error.

CV = standard deviation / mean • 100 %; n = 5 sub-sites.

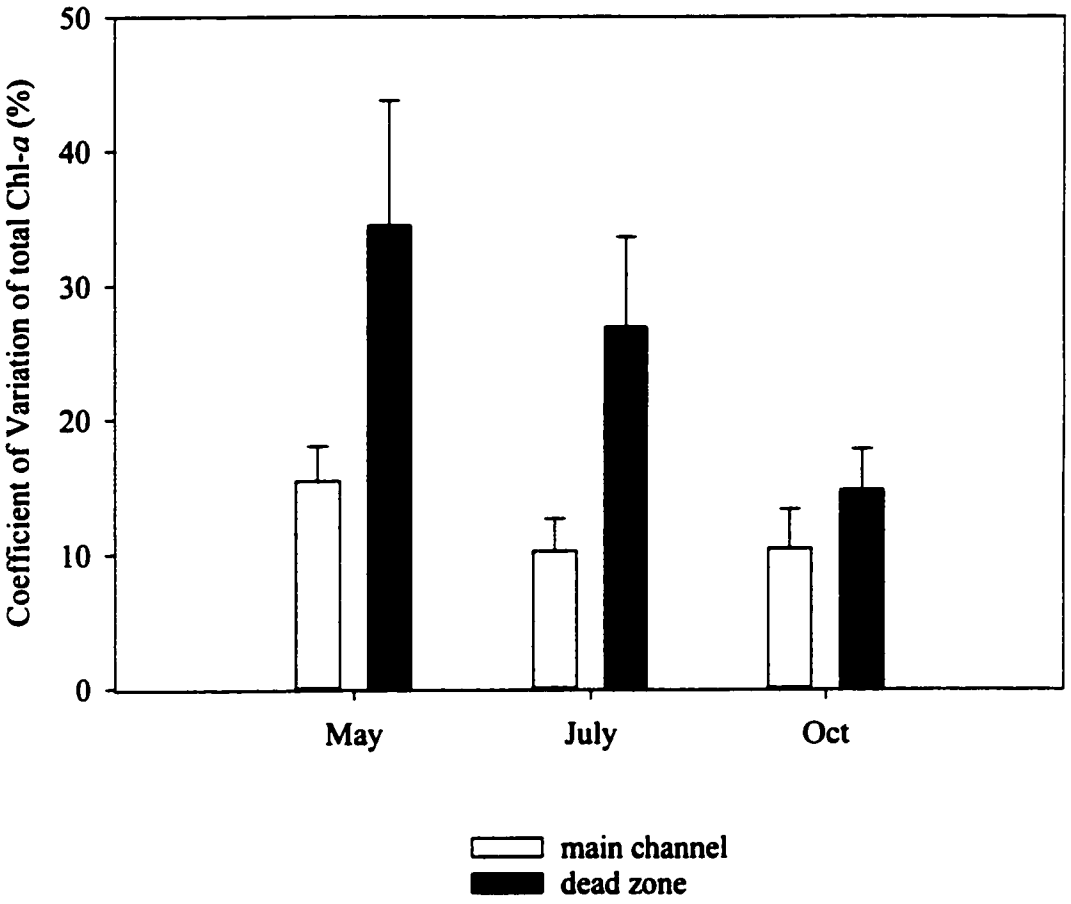

50
40
30
20
10
0
Coefficient of Variation of total Chl-a (%)
May
July
Oct
main channel
dead zone

Figure 1.24 Proportion of water samples in the main channel and dead zones containing macroscopic filamentous algae, in May, July and October 2000. Proportions were calculated from 5 samples at each site.

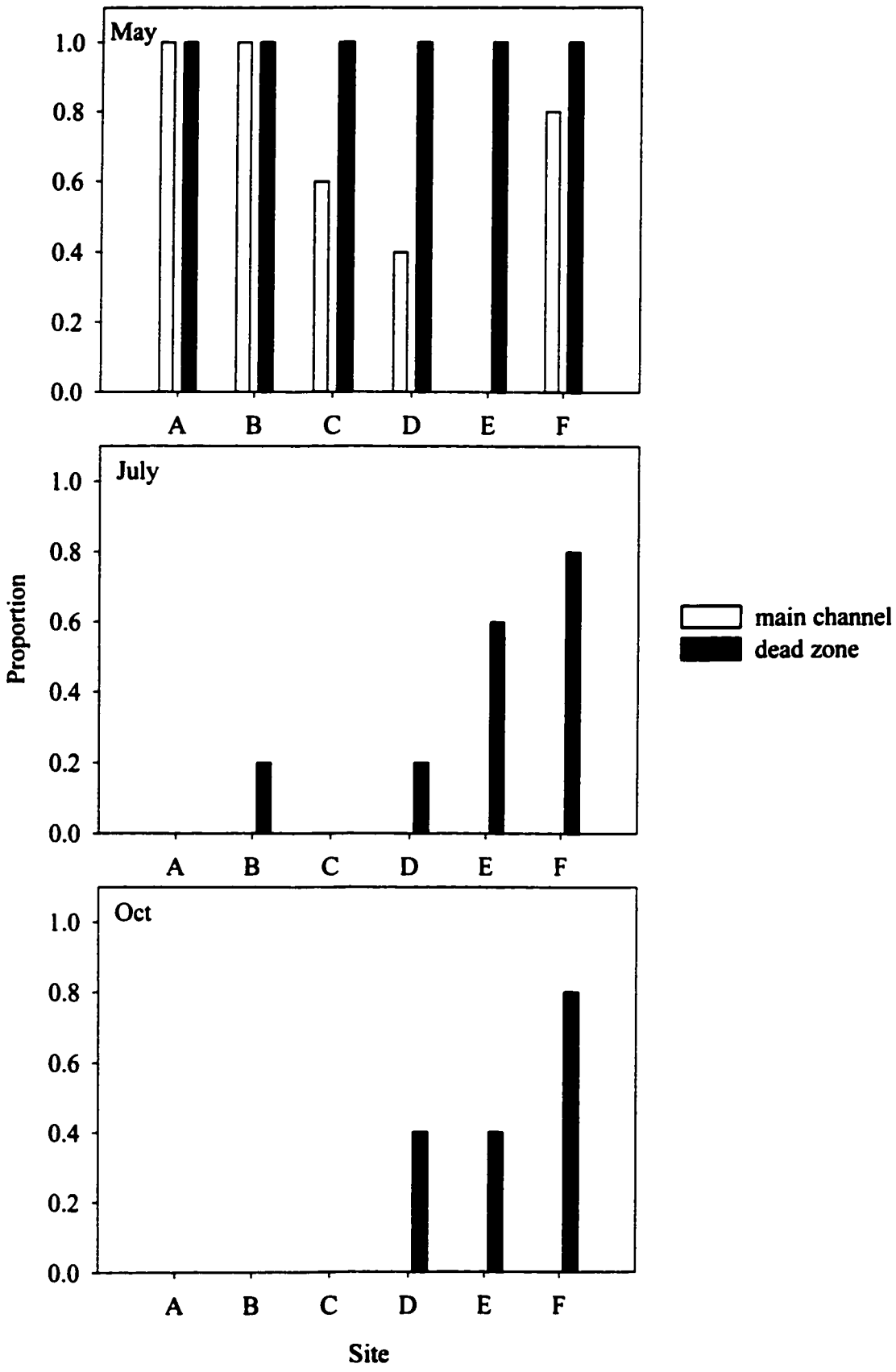
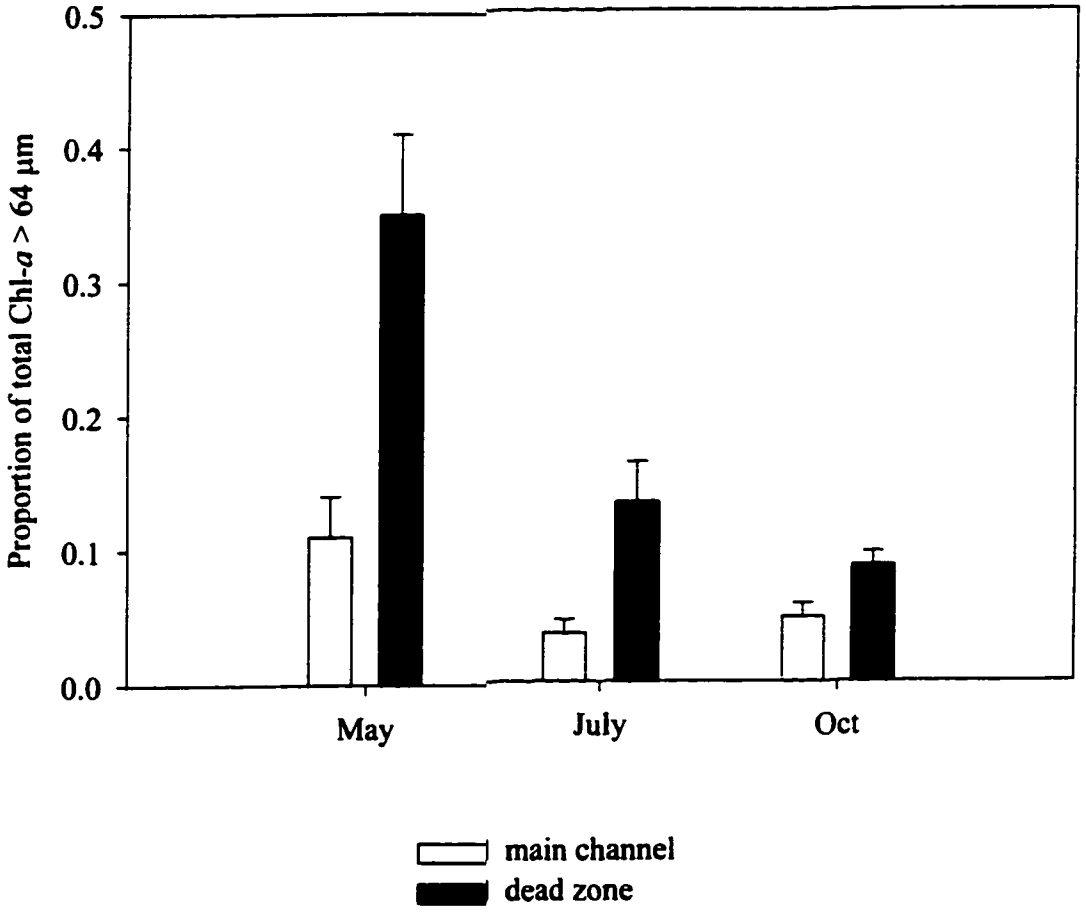

May
July
Oct
1.0
0.8
0.6
0.4
0.2
0.0
A
B
C
D
E
F
Proportion
Site
main channel
dead zone

Figure 1.25 Proportion of total chlorophyll *a* contributed by netplankton (Chl-*a* > 64 μm), in the main channel and dead zones, in May, July and October 2000. Estimates are the mean of six sites and include standard error.


0.5
0.4
0.3
0.2
0.1
0.0
Proportion of total Chl-a > 64 µm
May
July
Oct
main channel
dead zone

The relationship between river morphometry and longitudinal changes in chlorophyll *a* along the Rideau River

Introduction

The maintenance, and increase in density of river phytoplankton associated with downstream travel has been observed in large rivers, and attributed to importation from retentive areas, or dead zones (Reynolds, 1988; 1994; Descy & Gosselain, 1994; Köhler, 1994; Stoyneva, 1994; Lair & Reyes-Marchant, 1997). Dead zones, or areas of low flow, have been found in some instances to have higher suspended algal biomass than the main flow of the river (Reynolds *et al.*, 1991; Spaink *et al.*, 1998; Basu *et al.*, 2000a). However, the magnitude of the difference between dead zone and main channel algal biomass varied greatly. Dead zones in different rivers (or even different sections of the same river) contained from 1.5 to 43 times the biomass of the main channel (Basu *et al.*, 2000a; Spaink *et al.*, 1998; Reynolds *et al.*, 1991).

Some studies have shown that the main channel downstream of dead zone areas had higher algal biomass than the channel upstream (Stoyneva, 1994; Basu *et al.*, 2000a). However, other studies suggest that there may be little effect on downstream algal biomass. For example, Hudon *et al.* (1996) observed that resuspended periphyton from fluvial lakes on the St. Lawrence modified the dominant species composition of the St. Lawrence, but did not increase downstream biomass appreciably. They concluded that the shallow fluvial lakes were hydrodynamically isolated from the main flow, and that most of the algal production was retained and processed within the fluvial lakes.

Dead zones may also provide an inoculum of zooplankton to the main flow. Shallow littoral areas and dead zones have been found to have significantly higher zooplankton biomass that the main channel of rivers (Thorp *et al.*, 1994; Spaink *et al.*, 1998; Tans *et al.*, 1998; Reckendorfer *et al.*, 1999; Basu *et al.*, 2000a). In fact, some

dead zones may have zooplankton biomass as great as 100 times that in the main channel (Spaink *et al.*, 1998). Increases of zooplankton biomass in the main channel have also been attributed to importation from dead zones (Lair & Reyes-Marchant, 1997; Reckendorfer *et al.*, 1999; Basu *et al.*, 2000a). It is not clear therefore that exchange of water with dead zones would necessarily increase main channel algal biomass, as inputs of zooplankton may be more significant than inputs of algae.

On the Rideau River, increases in main channel phytoplankton biomass have been linked to increases in nutrients. Basu & Pick (1997) found that chlorophyll-*a* concentration (Chl-*a*) was best predicted by total phosphorus (TP) in the Rideau (R^2 = 0.43) in 1994 and 1995. Increases of main channel Chl-*a* have also been found to be associated with increased hydraulic retention time (Basu & Pick, 1995). However, the extent to which suspended algal biomass development in the main channel results from reproduction of phytoplankton in the main channel, or from inputs from the substantial dead zone areas adjacent to the channel has not been investigated.

In Chapter 1, I presented evidence that suspended algal biomass may, at least in spring, be higher in some dead zones than the main channel. Whether or not these dead zones contribute significantly to main channel suspended algal biomass, however, remains to be demonstrated. It is possible that there is little exchange of water between the dead zones and the main channel, as suggested by Hudon *et al.* (1996) in their study of the influence of fluvial lakes on the St. Lawrence. However, even if exchange is occurring, inputs of zooplankton from these dead zones may be more significant than inputs of algal biomass to the main channel, so the overall effect might conceivably be a decrease, rather than an increase in main channel phytoplankton density.

I hypothesised that in May and September, when Chl-*a* was expected to be higher in dead zones than the main channel, that there would be a positive correlation between the change in Chl-*a* over a given reach of the Rideau and the amount of dead zone in that reach. However, I expected to find a negative correlation in July, when dead zones were expected to have lower Chl-*a* than the main channel. To test this hypothesis, total Chl-*a* was sampled at intervals of approximately 2 km, in the main channel of the Rideau River from Smiths Falls to Ottawa, in May, July and September 2000. The change in Chl-*a* over each sampling reach was corrected for the estimated retention time in that reach, and analysed for any correlation with the amount of dead zone in that reach. Because dead zones were found wherever shallow, macrophyte-rich regions occurred on the Rideau River, the amount of dead zone was inferred from the area of shallow water, calculated using a digital bathymetric chart of the river.

Material and Methods

Field Sampling

A total of 41 sites were sampled on the Rideau River, between Smiths Falls and Ottawa (Appendix 2.1), in early May, late July and late September of 2000. These sites were originally selected in 1999 by Paul Hamilton of the Canadian Museum of Nature, in order to monitor changes in algal biomass and nutrient concentrations along the river. The sites were spaced at intervals of approximately 2 km, and included sites which were studied by Basu and Pick (1995, 1997) and sites which have been regularly sampled in past years by the Museum and the Regional Municipality of Ottawa-Carleton (RMOC) during ongoing monitoring of the river.

Sampling was carried out in collaboration with staff of the Research Division of the Canadian Museum of Nature. I accompanied them during their sampling on the Rideau, and was given the use of the samples and data they collected. In addition, I was allowed the use of their equipment and time to obtain additional samples for my own use in this project.

Site co-ordinates were determined using a Magellan 2000 XL Satellite Navigator GPS. Sampling was conducted at one location in the main channel at each site, with the exception of the RMOC sites (sites 4, 12, 16, 22, 25, 29, 35, 36 and 39). Those sites were sampled at two sites located in the main channel along a bank-to-bank transect, at roughly one-third and two-third distances across the river, at the locations regularly sampled by RMOC.

Water samples were collected from a depth of 0.5 metres, using a 3 L horizontal Van Dorn sampler. At each site, 3 water samples were obtained from the main channel for Chl-*a* analysis, with the exception of the RMOC sites, where 2 samples were obtained from the "A" location, nearer the right (when facing downstream) bank, and 1 sample was obtained from the "B" location closer to the left bank. Samples were obtained at intervals of 5 to 10 minutes.

Water for Chl-*a* analysis was immediately filtered through Whatman 934-AH glass microfibre filters, using a hand-operated pump. In May, 500 mL of water was filtered for each Chl-*a* sample, while in July and September, when algal biomass was lower, 1 litre was filtered for each sample. Care was taken to filter the samples rapidly, and to shade them from direct sunlight. The filters were immediately folded, wrapped in

aluminum foil, and placed between ice packs in an insulated cooler where they remained until being placed in a freezer at the end of the day.

Water samples were collected in 300 mL clear PETG bottles for phosphorus analysis. At each site (with the exception of the RMOC sites), two samples were taken for phosphorus analysis, one from each of the first two water samples collected for Chl-*a* analysis. At the RMOC sites, water for nutrient analyses was obtained from the first water sample collected at the "A" location, and from the sample taken at the "B" location.

Average current velocity was estimated at each site, using a drifting drogue, as described in Chapter 1. Estimates were calculated from at least 3 trials, conducted in the centre of the channel at each site (or the "A" site at each RMOC site). In May, current velocity was only estimated at 15 sites due to time constraints, and because on two days, sampling was simultaneously carried out from two boats, on two different regions of the river (and only one drogue was available).

Analysis of samples

Filters for Chl-*a* analysis were kept frozen until analysis. Samples from May were analysed within 6 weeks of collection, while samples from July and September were analysed within one month, and 2 weeks respectively. Chl-*a* was extracted with DMSO and acetone (Burnison, 1980) and concentrations were estimated using a Turner Designs model 10-000R fluorometer, and the equation of Jeffrey and Humphrey (1975).

Phosphorus analyses were performed by the RMOC Surface Water Quality Laboratories, using standard methods (Appendix 1.2).

Morphometry

An electronic (scanned, raster) version of the nautical chart of the Rideau River waterway (Canadian Hydrographic Service, 1992) was obtained from Nautical Data International, Inc. A vector version of the chart was created using ArcView 3.2 GIS software, by on-screen digitising of the depth contours, navigational channel, and sampling site locations. The digitised map was divided into sections, by extending a line across the channel, perpendicular to the shoreline, at each of the 41 sampling sites. These sections were designated sampling "reaches" for the purpose of further analysis; for example, reach 1 refers to the section of river between sampling sites 1 and 2.

In each reach, the length of navigational channel, and the area of water of different depth classes ("foreshore", 0-3 feet, 3-6 feet, 6-12 feet and 12-24 feet) was determined. The volume of water of each depth class was calculated using the average water depth for each depth class (1.5, 4.5, 9 and 18 feet, respectively) and the formula:

Volume = Surface area (m^2) x Depth (ft) x 0.3048 ($m \cdot ft^{-1}$).

The "foreshore" depth class was determined, while sampling along the river, to correspond either to areas of shallow water with dense submerged vegetation, or to areas of emergent vegetation. For the purpose of determining total volume, areas of foreshore were added to the 0-3 ft depth class. The mean width of each reach was calculated using the formula:

Mean width (m) = total area of reach (m^2) / length of navigation channel (m),

and the mean depth of each reach was calculated using the formula:

Mean depth (m) = volume (m^3) / surface area (m^2).

Data analysis

The relationship between changes in main channel Chl-*a* concentration over a given reach, and morphometric parameters (area and volume of shallow water) of the reach was investigated through non-parametric correlation analysis, by calculating Spearman rank correlation coefficients, using Systat 7.0. Several categories of shallow water were included: water 0-3 ft deep, 3-6 ft deep, and 0-6 ft (with and without "foreshore" included).

Because the reaches varied in length and in main channel current velocity, the change in Chl-*a* over each reach was corrected to reflect the travel time of water through that reach, before investigating possible correlations between the amount of dead zone (inferred from the amount of shallow water) and changes in Chl-*a*. Hydraulic retention time was calculated in two ways. The first method (Basu & Pick, 1995) assumes that mixing is complete, and that inflow equals outflow over the reach:

Retention time (hr) = Volume of reach (m^3) / Discharge ($m^3 \cdot s^{-1}$) / 3600 ($s \cdot hr^{-1}$).

Discharge values were obtained from the Water Survey of Canada, which maintains a continuous gauging site at Ottawa (station no. 02LA004). Discharge was assumed not to change appreciably along the length of the Rideau, and was calculated for each reach as the average of the daily discharge for the day prior to and the day of sampling (Basu & Pick, 1995; 1997). The second method assumes that retention time in the main channel is a reflection of average main channel velocity:

Retention time (hr) = length of channel (m) / Current velocity ($m \cdot hr^{-1}$).

Results

Chl-*a* concentration

The longitudinal patterns in Chl-*a* along the Rideau River in the sampling months of May, July and September are shown in Figure 2.1. Average total Chl-*a* on the Rideau River ranged between 0.8 and 13.8 $\mu g \cdot L^{-1}$ along the course of the river, and over the three periods sampled. Mean Chl-*a* was highest in May, averaging 7.8 $\mu g \cdot L^{-1}$ and declined in July to 5.4 $\mu g \cdot L^{-1}$ and again in September to 4.3 $\mu g \cdot L^{-1}$. Chl-*a* did not simply increase with downstream travel; there were stretches of increase and of decrease. However, the pattern of increase and decrease differed between months. In May, Chl-*a* rose steeply after Smiths Falls to a peak at site 6, decreased somewhat, and peaked again near Kemptville Creek; at site 27 (above Kars) Chl-*a* began to decrease, reaching a low at Ottawa. In July, Chl-*a* increased gradually from Smiths Falls to peak at site 30 (just below Kars), after which there was a steep drop, a slight increase near Blacks Rapids, and a decline again by Ottawa. In September, the development of Chl-*a* was similar to that in May, although the location of the peaks had shifted downstream somewhat, to site 10, and site 25 (Baxter Centre) respectively. The steep decline in Chl-a was also shifted downstream, to just below site 31.

Phosphorus

Average total phosphorus along the Rideau River varied between 11 and 48 $\mu g \cdot L^{-1}$, throughout the sampling period in 2000. The mean TP concentration along the river increased from 22 $\mu g \cdot L^{-1}$in May to 29 $\mu g \cdot L^{-1}$in July, and then decreased by September to 19 $\mu g \cdot L^{-1}$. As with Chl-*a*, the pattern of TP development along the length

of the river differed between months (Figure 2.2). In May, TP rose between Smith Falls and site 7, and remained fairly constant until site 27. TP then declined slightly from site 27 to Ottawa. In both July and September, TP concentrations rose gradually along the course of the river, from low values at Smiths Falls to maximum values at Ottawa.

Chlorophyll-*a* - TP relationship

When data for May, July and September were combined, there was no significant relationship between Chl-*a* and TP in the Rideau River (Figure 2.3). However, when the Chl-*a*-TP relationship was examined for each of the months separately (Figure 2.4), it was apparent that there were differences between the months, and that the relationships were not linear. The Rideau River downstream of Kars (site 29) is heavily colonized by zebra mussels (Martel, 1995). If only those sites above Kars were considered, there was a significant positive relationship between Chl-*a* and TP in both May and July, following log transformation of both variables (Figure 2.5).

Morphometric Parameters

The distance between sampling sites, calculated from the length of the main navigational channel, averaged approximately 2.2 km, but varied between 1.0 and 3.5 km (Table 2.1). The mean depth of reaches was 1.7 metres, (range 1.0-3.0 m) while the mean width was 317 metres (range 106-1333 m). The total surface area of "reach" between sampling sites averaged approximately 680,000 m^2, and ranged between 160,000 and 2,740,000 m^2 (Figure 2.6a). There were two stretches where the river widened out considerably; the first was between sites 4 (Edmunds Lock) and 12 (Merrickville), and

the second was between sites 18 (near The Catchall) and 27 (above Kars). The total volume of water in each reach averaged 1,130,000 m^3, and ranged between 370,000 and 2,740,000 m^3 (Figure 2.6b).

The surface area of water in each depth class ("foreshore", 0-3, 3-6, 6-12 or 12-24 feet) varied considerably between reaches (Figure 2.6a). In general, "foreshore" contributed substantially to total area only in those reaches with the highest total surface area, and area contributed by the 0-3 and 3-6 ft classes was generally highest in those reaches also. Very little of the Rideau River is deeper than 12 feet, and sites with such deeper areas were predominantly found downstream of site 20 (Barnes Island). Although these lower reaches had considerably lower total surface area than reaches in the upper part of the river, the high proportion of water in the deeper depth classes contributed to relatively high total water volume (Figure 2.6b). Therefore, the proportion of total water volume contributed by shallow water (less than 6 feet deep) declined more rapidly along the course of the river than did the proportion of total surface area contributed by shallow water (Figure 2.7).

Average mid-channel water velocity, measured with the drifting drogue, varied with sampling month, as well as between sites (Figure 2.8). In May, current velocity was only measured at 15 sites; where measured, current ranged between approximately 0.02 and 0.2 $m \cdot s^{-1}$. In July current velocity averaged 0.11 $m \cdot s^{-1}$ between Smiths Falls and Ottawa, ranging between 0.01 and 0.26 $m \cdot s^{-1}$. In September, average current velocity was 0.06 $m \cdot s^{-1}$, considerably lower than in July, although still ranging between 0.02 and 0.25 $m \cdot s^{-1}$.

However, the pattern of velocity measured along the course of the river was not consistent from month to month (showing differences in amplitude only). For example, there were several regions over which velocity increased in July (peaks), but decreased (valleys) in September.

Average discharge, measured at Ottawa, varied between the sampling months (Appendix 1.3). In May, the average daily discharge for the sampling days ranged between 51 and 58 $m^3 \cdot s^{-1}$. Average daily discharge was considerably lower in the July sampling period (31 to 42 $m^3 \cdot s^{-1}$), and lowest in September (16 to 21 $m^3 \cdot s^{-1}$).

Retention time calculated using reach volume and average discharge (RT), differed from retention time calculated from average mid-channel current velocity (RTV) in each month (Figure 2.9). In July and September, mean RTV (6.8 and 13.0 hr respectively) was lower than mean RT (9.3 and 16.0 hr respectively). However, in May, RTV was slightly higher than RT (6.5 hr, as compared to 5.6 hr). While RTV was generally lower than RT in a given reach, there were several reaches in which RTV was actually higher than RT, and these reaches were not consistent from month to month.

There was a positive correlation between RT and RTV in all months (Table 2.2). There was also a highly significant positive correlation between the change in Chl-*a* per hour calculated using RT (Δ Chl-*a*$\cdot hr^{-1}$ (RT)), and the change in Chl-*a* per hour calculated using RTV (Δ Chl-*a*$\cdot hr^{-1}$ (RT)) in all months (Table 2.2).

Correlations between changes in Chl-*a* and the proportion of shallow water

There were no correlations between the change in Chl-*a* (Δ Chl-*a*) measured over all 40 reaches and either the RT or RTV, except in September, when Δ Chl-*a* was positively correlated with RT (Table 2.2).

The rate of change in Chl-*a*, whether calculated using RT or RTV, was not correlated with the percent area (or volume) of shallow water (of any category) in the 40 reaches between Smiths Falls and Ottawa, in any month (Table 2.3, 2.4).

If only those 15 reaches for which velocity was measured in May were analysed, there were still no significant correlations between Δ Chl-$a \cdot hr^{-1}$ (RT) or Δ Chl-$a \cdot hr^{-1}$ (RTV) and the percentage of shallow water in May or July (Table 2.5, 2.6). However, there were positive correlations in September with the percent area (and volume) of water 0-3 ft deep (including "foreshore").

For the 29 reaches between Smiths Falls and Kars only (above the area of river suspected of being strongly influenced by heavy zebra mussel colonization), there was a significant negative correlation between Δ Chl-$a \cdot hr^{-1}$ (RT) and the percentage area of water 3-6 feet and 0-6 feet deep, in July (Table 2.7). No correlations were found in May or September.

Δ Chl-$a \cdot hr^{-1}$ (RTV) was also negatively correlated with the percent area of water 3-6 and 0-6 ft deep, (and with the percent volume of water in these categories) in July, and no significant correlations were found in September (Table 2.8). However, in May, in contrast to the result using Δ Chl-$a \cdot hr^{-1}$ (RT), Δ Chl-$a \cdot hr^{-1}$ (RTV) was positively correlated with the percent area or volume of water in several categories.

Discussion

Relationship between retention time (RT) and changes in Chl-*a*

Considerable longitudinal variation in Chl-*a* was found in the Rideau River in 2000. As previously observed by Basu and Pick (1995), there were stretches of river over which net increases and net decreases of Chl-*a* occurred. Basu and Pick (1995) investigated changes in Chl-*a* over 3 reaches of approximately 8 km in length, and found that changes in Chl-*a* were related to the retention time (RT) of water in a given reach. RT was estimated by dividing the total water volume by the average discharge in each reach. This method of calculating retention time may overestimate the actual retention time of water in the main channel, particularly in stretches where a high proportion of the total water volume is in areas of very low flow. It is possible, therefore, that the retention time calculated by Basu and Pick (1995) for the "long retention reach" was overestimated and that there was not in fact any correlation with true retention time. When changes in Chl-*a* were investigated over shorter sections of the river (1 to 3.5 km in length) in this study, I found no correlation with RT, except in September, when there was a significant, but low positive correlation. Such lack of correlation may indicate that there are other factors, besides residence time in a reach, responsible for increases in main channel Chl-*a*. Basu et al. (2000a) estimated water retention time separately for the littoral zones and main channel of fluvial lakes on the St. Lawrence river, after observing that wide, shallow littoral areas had much lower current velocity than the central channel. On the Rideau River, as discussed in Chapter 1, current velocity in shallow, macrophyte-rich dead zones was consistently below the detection limit of 0.01 $m \cdot s^{-1}$. Average mid-channel current velocity along the length of the river was usually considerably higher,

ranging from 0.01 to 0.26 $m \cdot s^{-1}$. For this reason, a second method of estimating retention time of water in the main channel, (RTV), based on average main-channel current velocity, was also used in this study. Retention time has been calculated from distance and mean flow velocity in other studies (Bahnwart et al., 1999). However, while it may reflect retention time in the main channel more accurately than RT, it likely underestimates true retention time, because of the presence of retentive features and lateral and longitudinal mixing of water due to eddies, crosscurrents and backflows (Reynolds, 1988).

Comparison of RT and RTV

As expected, in most cases, RTV was lower than RT in a given reach, although there were instances in each month where RTV was actually higher than RT. There are several possible explanations for this observation. The method of measuring average main-channel current velocity, using the drifting drogue, may have led to some erroneously low velocity measurements. Current velocity is highly variable within a river channel (Reynolds, 1988), and velocity measurements were only made at one location for each site; the exact location of the sampling site undoubtedly varied between sampling months. In addition, since velocity was measured at depths of up to about 5 metres at some sites, it is possible that macrophytes (which were not visible at such depth) restricted the movement of the drogue at times. The navigation channel provides ideal growing conditions for Eurasian watermilfoil (*M. spicatum*), which may grow at depths of up to 6 m in the Rideau River (Snetsinger *et al.*, 1998).

There were also differences in the pattern of RTV along the river in different months due to considerable variability in the pattern of current velocity measured along the course of the river from month to month. In particular, there were several sites at which, in July, current velocity increased from the previous site, but decreased from the previous site in May and September. This may be an indication of changes in the effective channel size, due to maximum development of macrophytes in mid-summer. Dense macrophyte beds may contribute to large volumes of water with very low flow, which might lead to increased water velocity in the open channel.

I expected that if RT overestimated true main-channel retention time more in reaches with a high proportion of shallow areas of low flow, than in narrower, deeper reaches, that there would not be a particularly strong correlation between RT and RTV. There was, however, a significant positive correlation between RT and RTV in each of the months. The method of calculating RT from volume and discharge assumes not only that water in a given reach is fully mixed, and flowing at the same rate, but that discharge is constant along the length of the river. This assumption is likely invalid, and as a result discharge is probably overestimated in the upper reaches of the Rideau. This is the same region where there is an extremely high proportion of shallow, very slowly flowing water. I had assumed that the volume of water that was actually flowing in this region would be greatly overestimated, leading to overestimates of main channel retention time. However, as discharge may also be overestimated in this part of the river, the net result may be that retention time is not overestimated relative to the downstream section of the river.

As there was a highly significant positive correlation between Δ Chl-*a*·hr^{-1} (RT) and Δ Chl-*a*·hr^{-1} (RTV), it is not surprising that there was close agreement between the correlations obtained using the two methods of calculating retention time (at least when the same set of sites was analysed).

Correlations between changes in Chl-*a* hr^{-1} and the proportion of shallow water

Whether changes in Chl-*a*·hr^{-1} were calculated using RT or RTV, there was no correlation between the rate of change in Chl-*a* and the percent of shallow water in reaches between Smiths Falls and Ottawa in any month. In contrast, I had hypothesised positive correlations for May and September, and a negative correlation in July. However, after repeating the analysis using only those sites for which RTV had been calculated in May, I observed that the resulting correlations differed, depending on the set of sites being analysed.

A consistent decline in mid-channel total Chl-*a* was observed downstream of Kars in all sampling months in this study. Basu and Pick (1997) also observed a significant decline in phytoplankton biomass downstream of Kars, which they suggested may be due to feeding by the exotic zebra mussel (*Dreissena polymorpha*), which has been found at high densities in the lower regions of the Rideau below Kars (Martel, 1995). I found no significant relationship between log-transformed Chl-*a* and TP (for all sampling months in 2000 combined), unlike Basu & Pick (1997), who found a significant positive relationship in 1994 and 1995). However, when data from each month were examined separately there was a significant positive relationship between log-transformed Chl-*a* and TP in May and July after sites downstream of Kars were removed. This indicates

that there are differences between the two sections of the river, possibly partially attributable to the influence of zebra mussels.

For this reason, I decided to examine the correlation between the rate of change of Chl-*a* and the percent of shallow water for reaches above Kars only. Once again, there was no significant correlation in September, whether RT or RTV was used to calculate Δ Chl-*a*·hr^{-1}. However, as hypothesized, in this section of the river there were significant negative correlations in July, using both methods of calculating Δ Chl-*a*·hr^{-1}. As when the entire river was analysed, there was no significant correlation in May, when RT was used to calculate Δ Chl-*a*·hr^{-1}.

The negative correlation between the rate of change of Chl-*a* and the percent of shallow water in July supports my hypothesis that shallow littoral "dead zones" are not contributing to increases in main channel Chl-*a* in summer, and may in fact be responsible for declines, at least in the section of the Rideau above Kars. No significant overall difference was actually found between main channel and dead zone Chl-*a* in July (Chapter 1), although Chl-*a* was lower in some dead zones than the main channel. However, even if Chl-*a* was not lower in dead zones, there could still be a significant negative effect of dead zones on main channel Chl-*a*, if dead zones are sources of high zooplankton biomass. Other researchers have found significantly higher biomass of zooplankton in dead zones, and evidence of export of zooplankton to the main channel (Thorp *et al.*, 1994; Spaink *et al.*, 1998; Tans *et al.*, 1998; Reckendorfer *et al.*, 1999; Basu *et al.*, 2000a).

There was no clear evidence of a correlation in May or in September, between the change in Chl-*a* in the main channel and the proportion of shallow water, although a

positive correlation had been hypothesised. In May, when changes in Chl-*a*·hr^{-1} were calculated using RT, there was no correlation whether all 40 reaches or only reaches above Kars were analysed. A positive correlation was found using changes in Chl-*a*·hr^{-1} calculated from RTV, for sites above Kars only. However, the sample size was extremely small (n = 11), and I had already observed that results differed, depending on the choice of sites being analysed. In September, no significant correlations were found between changes in Chl-*a*·hr^{-1} calculated using either RT or RTV and the proportion of shallow water, either when all 40 sites or the 29 sites above Kars were analysed. I would have expected to see a positive correlation in May, especially since some dead zones were found to have higher Chl-*a* than the main channel (although they were extremely variable, and there was not a statistically significant difference overall). The lack of clear positive correlations in September is not quite so surprising, however, as no significant difference was found between dead zone and main channel Chl-*a* (Chapter 1).

There are a number of reasons why significant correlations might not be found between the proportion of dead zones in a reach and changes in Chl-*a* in the main channel, even if those dead zones have higher algal biomass. Dead zones may be in virtual isolation from the main channel for much of the time, and exports of algal biomass from them may be episodic (Reynolds & Descy, 1996) and possibly of short duration, occurring during times of blooms, high rainfall, periods of high discharge, or even during slight changes in discharge during periods of low flow (Lewis, 1988). Reynolds *et al.* (1991) determined that the Leighton Reach dead zone on the Severn would have had to be in relative isolation from the main channel for upwards of 25 days, to develop the high population of *Oscillatoria* observed. Hudon *et al.* (1996) found that fluvial lakes on the

St. Lawrence had increased algal biomass due to the growth and resuspension of periphyton, but algal biomass was not increased downstream of these fluvial lakes. They suggested that, at least in summer, the lakes were in hydrodynamic isolation from the main channel. Similarly, Basu *et al.* (2000b) found no significant difference in phytoplankton between the inflow and outflow for either fluvial Lake St. Francis or Lake St. Pierre in summer of 1997, although they did observe a slight increase through Lake St. Pierre in 1998 (Basu *et al.*, 2000a).

Hamilton *et al.* (1997) hypothesised that the break-up and dispersal of algal mats on the Rideau was linked to seasonal changes in light and temperature as well as to current flow. Therefore it may be possible to detect an impact on main channel Chl-*a* only at certain times; these may not have coincided with the times when the Rideau River was sampled in this study. Yang *et al.* (1997) investigated differences in algal size structure in the Rideau between July and September of 1993 (when discharge was considerably lower than in 2000), and although they found an increase in large planktonic taxa with downstream travel there was no evidence of high benthic input. In my study, however, while differences in size structure of phytoplankton with downstream travel were not investigated, fragments of macrophytes and algal mats were found in the main channel later in May. This may indicate that organic matter periodically enters the main channel from dead zone areas, although not perhaps at the time when I was sampling for this study.

Inputs of algal biomass from shallow dead zone areas may be occurring during the sampling period, but we may not detect them. Algal-rich water, contributed by dead zones, might not necessarily result in net increases in main channel Chl-*a* if high losses

balance inputs. Phytoplankton communities that have developed in dead zones may be so different from those in the main channel that they may be poorly adapted to conditions in the main channel. This has been observed for limnoplankton (phytoplankton from lakes) which typically decrease in abundance after entering rivers (Reynolds & Glaister, 1993). Algal species from the main channel may not adapt well to conditions in stagnant dead zones, and therefore may not establish new populations capable of enhancing the development of phytoplankton in the river as a whole (Köhler, 1997). Spaink *et al.* (1998) concluded that backwaters probably had little influence on the phytoplankton of the main channel of the River Waal, due to the large difference in species composition between the dead arm and main channel.

Algal density may not increase with travel downstream because of high losses to grazing. While there is debate as to the role of zooplankton in controlling riverine phytoplankton (Bothár & Kiss, 1990; Reynolds & Descy, 1996), rotifer densities have been found to be capable of causing declines in phytoplankton in the main channel of some rivers such as the Loire River in France (Lair & Reyes-Marchant, 1997). Lonsdale *et al.* (1996) observed a substantial impact on phytoplankton by mesozooplankton in the Lower Hudson River. However, Basu and Pick (1997) found no evidence that grazing by zooplankton had a significant effect on phytoplankton biomass in the Rideau. Grazing by zebra mussels may have a large impact in rivers, however. Smith *et al.* (1998) observed a 17-fold decrease in phytoplankton cell density in the Hudson River of New York, following invasion by *D. polymorpha.* Basu and Pick (1997) observed a significant decline in phytoplankton biomass downstream of Kars, which they suggested may be due to feeding by *D. polymorpha.* Bahnwart *et al.* (1999) observed that phytoplankton

biomass in the eutrophic lowland Warnow River in Germany decreased upon travel from fluvial lakes into shallow river stretches, possibly due to increased contact with filtering benthic feeders in addition to enhanced sedimentation resulting from the filtering effect of submerged macrophytes.

The absence of consistent strong relationships between changes in algal biomass and dead zone abundance may also be due to low precision in estimates of the rate of change of Chl-*a*. The inability to detect a real effect, or low statistical power, may result from high variance in the dependent variable (SPSS Inc. 2000). A power analysis, using estimates of precision, could determine if there was sufficient power to detect significant correlations. However, the precision of estimates of the rate of change of Chl-*a* was not determined, due to lack of information on the precision of bathymetric measurements.

Even if dead zones do not export high concentrations of algal biomass to the main channel, they may still be important in the development of phytoplankton in rivers. The effect of dead zones on the development of phytoplankton in the main channel may go beyond a simple enhancement of biomass through exchange of algal-poor main channel water with algal-rich dead zone water. Dead zones may serve as reservoirs of "seed" propagules. Recruitment of algal cells from sediment, whether resting stages such as asexual spores or cysts, or vegetative cells that have settled out of the water column, may be important in maintaining communities which subsequently develop in the main channel. A number of studies have reported a dynamic connection between the phytobenthos and phytoplankton in rivers and shallow lakes (Stoyneva, 1994; Schelske *et al.*, 1995; Hansson, 1996; Sanderson & Frost, 1996). For example, Reynolds and Descy (1996) observed that certain species of diatoms can grow either attached to surfaces or

suspended in the plankton, and that dead zones may serve as storage zones for algae which produce resting stages, such as species of *Aulacoseira* and *Stephanodiscus*. Therefore, while dead zones may not contribute high algal biomass, they may nevertheless play an important role in maintaining algal populations in rivers.

Table 2.1 Morphometric parameters for 40 reaches (approximately 2 km length) along the Rideau River, from Smiths Falls to Nepean Creek.

Reach	Volume ($m^3 \cdot 10^6$)	Area ($m^2 \cdot 10^6$)	Channel Length (m)	Mean Depth (m)	Mean Width (m)
1	0.53	0.29	2130	1.85	134
2	0.66	0.40	1773	1.64	228
3	0.47	0.26	1018	1.82	253
4	1.61	1.61	2816	1.00	573
5	2.05	1.81	2001	1.14	903
6	0.73	0.68	1960	1.07	348
7	1.67	1.50	2155	1.11	698
8	2.74	2.74	2054	1.00	1333
9	1.54	1.02	2087	1.51	488
10	1.45	0.96	2088	1.51	462
11	1.22	1.17	2414	1.04	485
12	0.72	0.51	2532	1.43	200
13	0.82	0.36	1826	2.25	199
14	0.45	0.26	2209	1.72	119
15	0.63	0.31	1737	2.04	178
16	0.82	0.42	3536	1.94	119
17	0.44	0.28	2283	1.58	121
18	0.86	0.66	2399	1.30	277
19	0.86	0.75	2196	1.15	339
20	1.15	0.84	2250	1.37	372
21	0.94	0.57	1937	1.64	296
22	2.17	1.19	2418	1.83	492
23	2.73	1.34	2214	2.04	603
24	1.89	0.90	2078	2.10	434
25	2.44	1.05	2978	2.33	351
26	1.30	0.77	1974	1.68	392
27	1.08	0.35	1873	3.04	189
28	1.25	0.48	2202	2.60	219
29	0.82	0.29	1895	2.84	152
30	0.75	0.27	1834	2.73	150
31	0.75	0.32	2264	2.31	143
32	1.07	0.37	2606	2.90	142
33	0.53	0.24	2307	2.16	106
34	1.32	0.47	2111	2.81	222
35	0.92	0.39	2687	2.37	145
36	1.02	0.37	2271	2.72	165
37	0.66	0.26	1677	2.55	155
38	0.94	0.39	1865	2.41	210
39	0.82	0.33	2296	2.51	142
40	0.37	0.16	1397	2.31	116
sum	45.21	27.36	86347.95		
average	1.13	0.68	2159	1.65	317

Table 2.2 Correlations between retention times (RT and RTV), between ΔChl-*a* & RT or RTV, and between Δ Chl-*a*·hr^{-1} (calculated using RT) and Δ Chl-*a*·hr^{-1} (calculated using RTV), for reaches located between Smiths Falls and Ottawa. The critical values of Spearman rank correlation coefficients (r_s) are 0.446, 0.267 and 0.264 for n = 15, 39 and 40, and $\alpha = 0.05$.

Correlation	**May**	**July**	**Sept**
RT & RTV	**0.635**** (n = 15)	**0.564***** (n = 39)	**0.593***** (n = 40)
ΔChl-*a* & RT	0.117 (n = 40)	0.213 (n = 40)	**0.307*** (n = 40)
ΔChl-*a* & RTV	0.429 (n = 15)	-0.096 (n = 39)	0.124 (n = 40)
Δ Chl-*a*·hr^{-1} (RT) & Δ Chl-*a*·hr^{-1} (RTV)	**0.971***** (n = 15)	**0.948***** (n = 39)	**0.988***** (n = 40)

* 0.025<p<0.05; ** 0.01<p<0.005; ***p < 0.0005

Table 2.3 Correlations between Δ Chl-*a*·hr^{-1} (calculated from RT) and percent area (and volume) of shallow water for reaches located between Smiths Falls and Ottawa (n = 40). The critical value of Spearman rank correlation coefficient (r_s) is 0.264, for n = 40 and α = 0.05.

Measure of shallow water	**Δ Chl-*a*·hr^{-1} (calculated using RT)**		
	May	**July**	**Sept**
% area 0-3 ft	-0.245	0.040	-0.227
% area 3-6 ft	0.192	-0.173	0.088
% area 0-6 ft	0.059	-0.135	-0.098
% area 0-3 ft (incl. foreshore)	0.010	0.273	0.182
% area 0-6 ft (incl. foreshore)	0.217	0.094	0.208
% vol 0-3 ft	-0.133	0.077	-0.086
% vol 3-6 ft	0.193	-0.133	0.067
% vol 0-6 ft	0.165	-0.128	0.005
% vol 0-3 ft (incl. foreshore)	0.099	0.229	0.200
% vol 0-6 ft (incl. foreshore)	0.239	-0.017	0.130

Table 2.4 Correlations between Δ Chl-*a*·hr^{-1} (calculated from RTV) and percent area (and volume) of shallow water for reaches located between Smiths Falls and Ottawa. The critical values of Spearman rank correlation coefficients (r_s) are 0.446, 0.267 and 0.264, for n = 15, 39 and 40, and $\alpha = 0.05$.

Measure of Shallow water	**Δ Chl-*a*·hr^{-1} (calculated using RTV)**		
	May (n = 15)	**July (n = 39)**	**Sept (n = 40)**
% area 0-3 ft	-0.079	-0.090	-0.259
% area 3-6 ft	0.386	-0.194	0.084
% area 0-6 ft	0.225	-0.235	-0.117
% area 0-3 ft (incl. foreshore)	0.211	0.267	0.191
% area 0-6 ft (incl. foreshore)	0.339	0.065	0.227
% vol 0-3 ft	0.121	-0.081	-0.106
% vol 3-6 ft	0.393	-0.165	0.075
% vol 0-6 ft	0.386	-0.194	0.008
% vol 0-3 ft (incl. foreshore)	0.400	0.202	0.216
% vol 0-6 ft (incl. foreshore)	0.350	-0.041	0.149

Table 2.5 Correlations between Δ Chl-*a*·hr^{-1} (calculated from RT) and percent area (and volume) of shallow water for only those reaches in which velocity was measured in May (n = 15). The critical value of Spearman rank correlation coefficient (r_s) is 0.446, for n = 15 and $\alpha = 0.05$.

Measure of shallow water	Δ Chl-*a*·hr^{-1} (calculated using RT) May	July	Sept
% area 0-3 ft	-0.125	0.204	0.093
% area 3-6 ft	0.339	-0.018	0.182
% area 0-6 ft	0.171	0.071	0.204
% area 0-3 ft (incl. foreshore)	0.246	0.286	**0.482***
% area 0-6 ft (incl. foreshore)	0.350	0.154	0.396
% vol 0-3 ft	0.014	0.282	0.118
% vol 3-6 ft	0.354	-0.075	0.143
% vol 0-6 ft	0.350	-0.036	0.118
% vol 0-3 ft (incl. foreshore)	0.404	0.304	**0.554****
% vol 0-6 ft (incl. foreshore)	0.321	0.146	0.239

* $0.025<p<0.05$; ** $0.01<p<0.025$

Table 2.6 Correlations between Δ Chl-*a*·hr^{-1} (calculated from RTV) and percent area (and volume) of shallow water for only those reaches in which velocity was measured in May (n = 15). The critical value of Spearman rank correlation coefficient (r_s) is 0.446, for n = 15 and α = 0.05.

Measure of shallow water	Δ Chl-*a*·hr^{-1} (calculated using RTV) May	July	Sept
% area 0-3 ft	-0.079	0.236	0.082
% area 3-6 ft	0.386	-0.161	0.232
% area 0-6 ft	0.225	-0.071	0.218
% area 0-3 ft (incl. foreshore)	0.211	0.254	**0.489***
% area 0-6 ft (incl. foreshore)	0.339	-0.018	**0.471***
% vol 0-3 ft	0.121	0.179	0.129
% vol 3-6 ft	0.393	-0.221	0.204
% vol 0-6 ft	0.386	-0.193	0.182
% vol 0-3 ft (incl. foreshore)	0.400	0.171	**0.582****
% vol 0-6 ft (incl. foreshore)	0.350	-0.032	0.318

* $0.025<p<0.05$; ** $0.01<p<0.025$

Table 2.7 Correlations between Δ Chl-*a*·hr^{-1} (calculated from RT) and percent area (or volume) of shallow water for reaches between Smiths Falls and Kars. The critical value of Spearman rank correlation coefficient (r_s) is 0.312, for n = 29 and $\alpha = 0.05$.

Measure of shallow water	Δ Chl-*a*·hr^{-1} (calculated using RT) May	July	Sept
% area 0-3 ft	-0.256	0.070	-0.216
% area 3-6 ft	0.246	**-0.369***	0.034
% area 0-6 ft	0.085	**-0.323***	-0.199
% area 0-3 ft (incl. foreshore)	-0.020	0.252	0.173
% area 0-6 ft (incl. foreshore)	0.234	-0.061	0.186
% vol 0-3 ft	-0.089	-0.012	-0.102
% vol 3-6 ft	0.192	-0.300	0.015
% vol 0-6 ft	0.158	-0.269	-0.062
% vol 0-3 ft (incl. foreshore)	0.152	0.100	0.170
% vol 0-6 ft (incl. foreshore)	0.240	-0.201	0.041

* $0.025<p<0.05$

Table 2.8 Correlations between Δ Chl-*a*·hr^{-1} (calculated from RTV) and percent area (or volume) of shallow water for reaches between Smiths Falls and Kars. The critical values of Spearman rank correlation coefficients (r_s) are 0.536, 0.317 and 0.312, for n = 15, 28 and 29 and $\alpha = 0.05$.

Measure of shallow water	Δ Chl-*a*·hr^{-1} (calculated using RTV) May (n = 11)	July (n = 28)	Sept (n = 29)
% area 0-3 ft	-0.027	-0.063	-0.216
% area 3-6 ft	0.518	**-0.361****	0.034
% area 0-6 ft	0.464	**-0.428*****	-0.199
% area 0-3 ft (incl. foreshore)	0.391	0.274	0.173
% area 0-6 ft (incl. foreshore)	**0.600****	-0.056	0.186
% vol 0-3 ft	0.436	-0.182	-0.102
% vol 3-6 ft	**0.536***	**-0.331****	0.015
% vol 0-6 ft	0.482	**-0.338****	-0.062
% vol 0-3 ft (incl. foreshore)	**0.709******	0.102	0.170
% vol 0-6 ft (incl. foreshore)	0.482	-0.211	0.041

* p = 0.05; ** 0.025<p<0.05; *** 0.01<p<0.025; **** p = 0.01

Figure 2.1 Total chlorophyll *a* in the main channel of the Rideau River, sampled at sites extending from Smiths Falls (site 1) to Nepean Creek (site 41), in May, July and September 2000. Bars represent the mean of 3 samples; estimates include standard error. The x-axis is not to scale

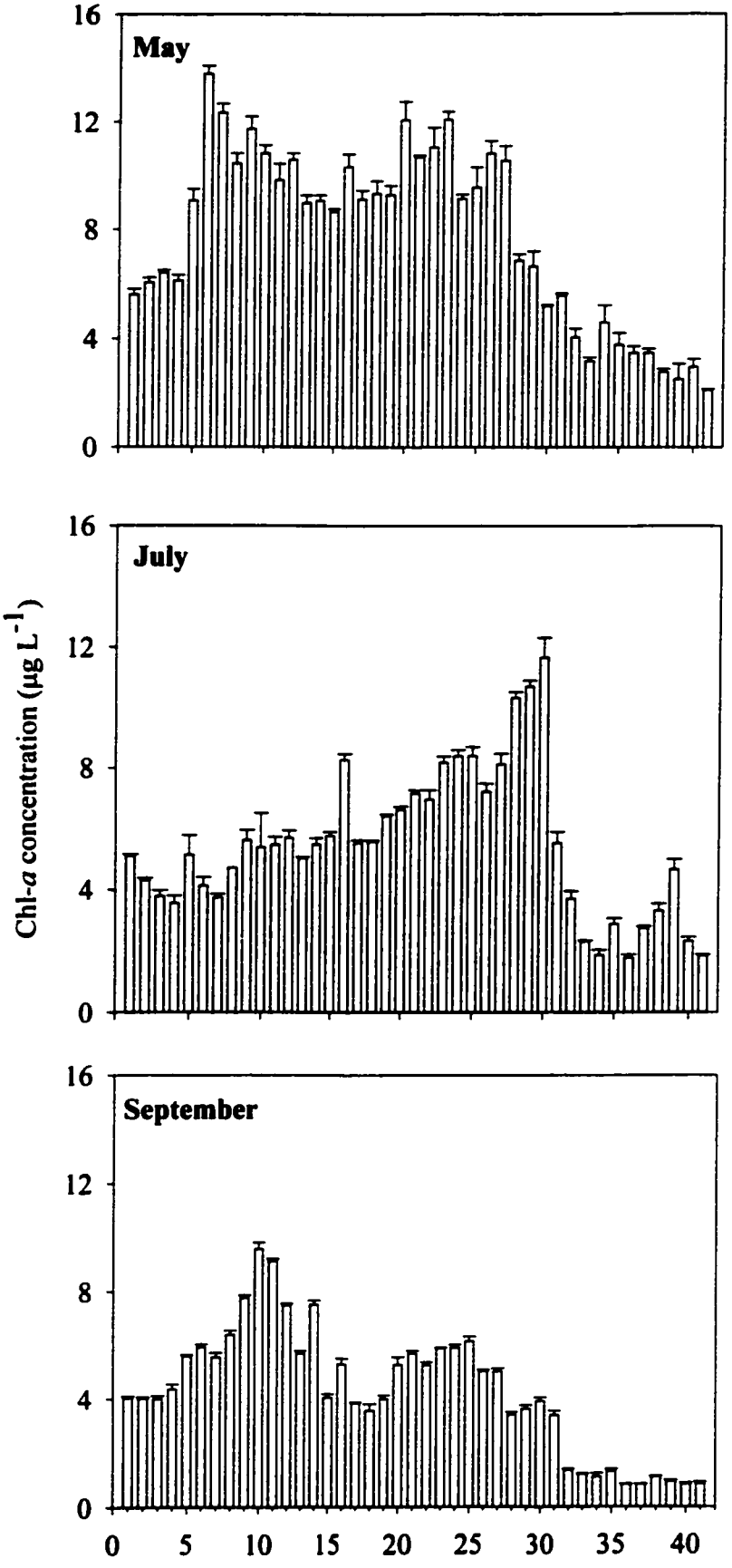

May
July
September
Chl-a concentration (µg L-1)
Site
0
4
8
12
16
0
5
10
15
20
25
30
35
40

Figure 2.2 Total phosphorus concentration in the main channel of the Rideau River, sampled at sites extending from Smiths Falls (site 1) to Nepean Creek (site 41), in May, July and September 2000. Bars represent the mean of 2 samples; estimates include standard error. The x-axis is not to scale.

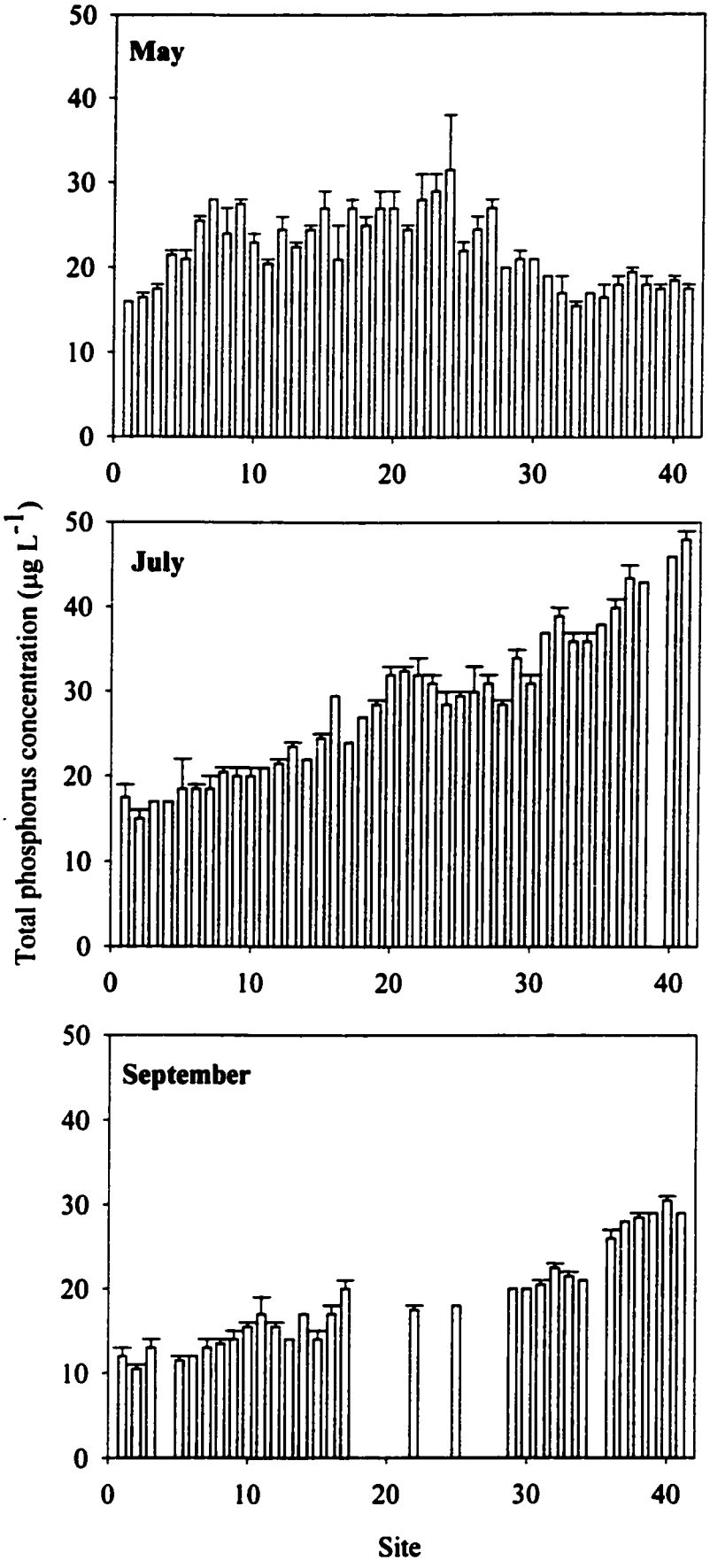

May
July
September
Total phosphorus concentration (µg L-1)
Site
0
10
20
30
40
50

Figure 2.3 Relationship between total phosphorus (TP) and total chlorophyll *a* (Chl-*a*) in the Rideau River between Smiths Falls and Ottawa, in 2000. Data for the sampling periods in May, July and September are combined. TP and Chl-*a* are log transformed.

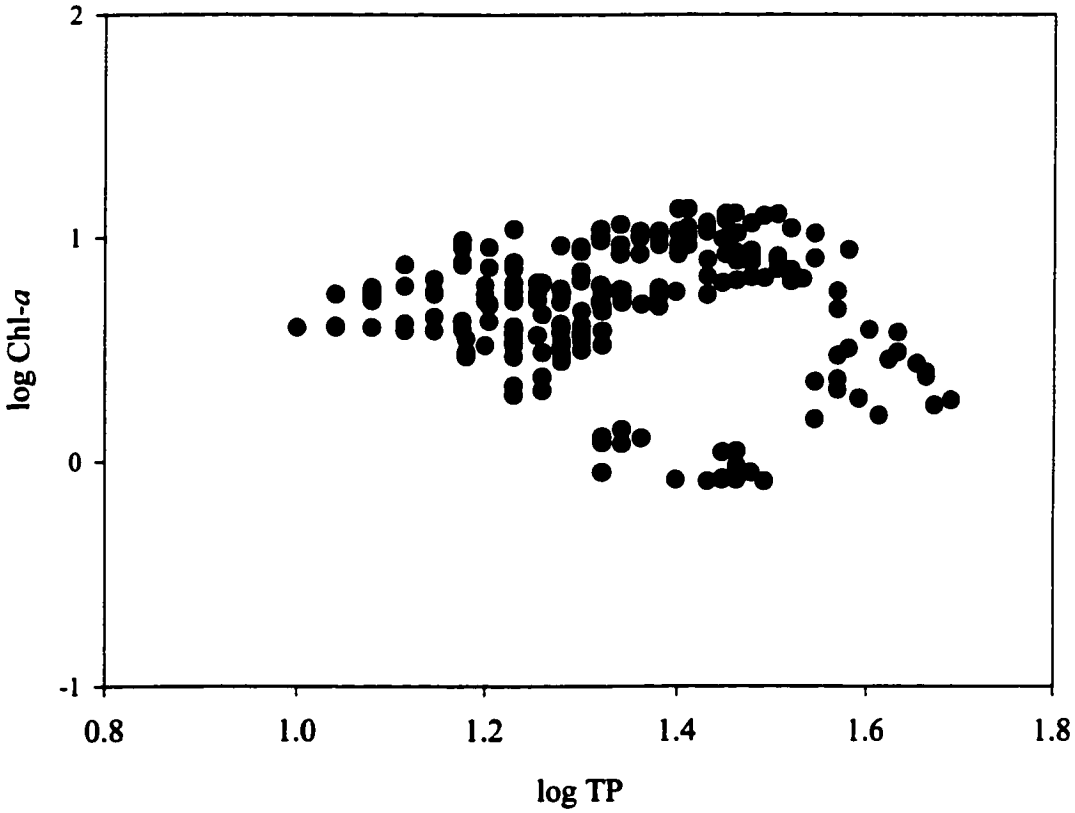

2
1
0
-1
log Chl-a
0.8
1.0
1.2
1.4
1.6
1.8
log TP

Figure 2.4 Relationship between TP and Chl-*a* in the Rideau River between Smiths Falls and Ottawa, in May, July and September 2000. TP and Chl-*a* are log transformed.

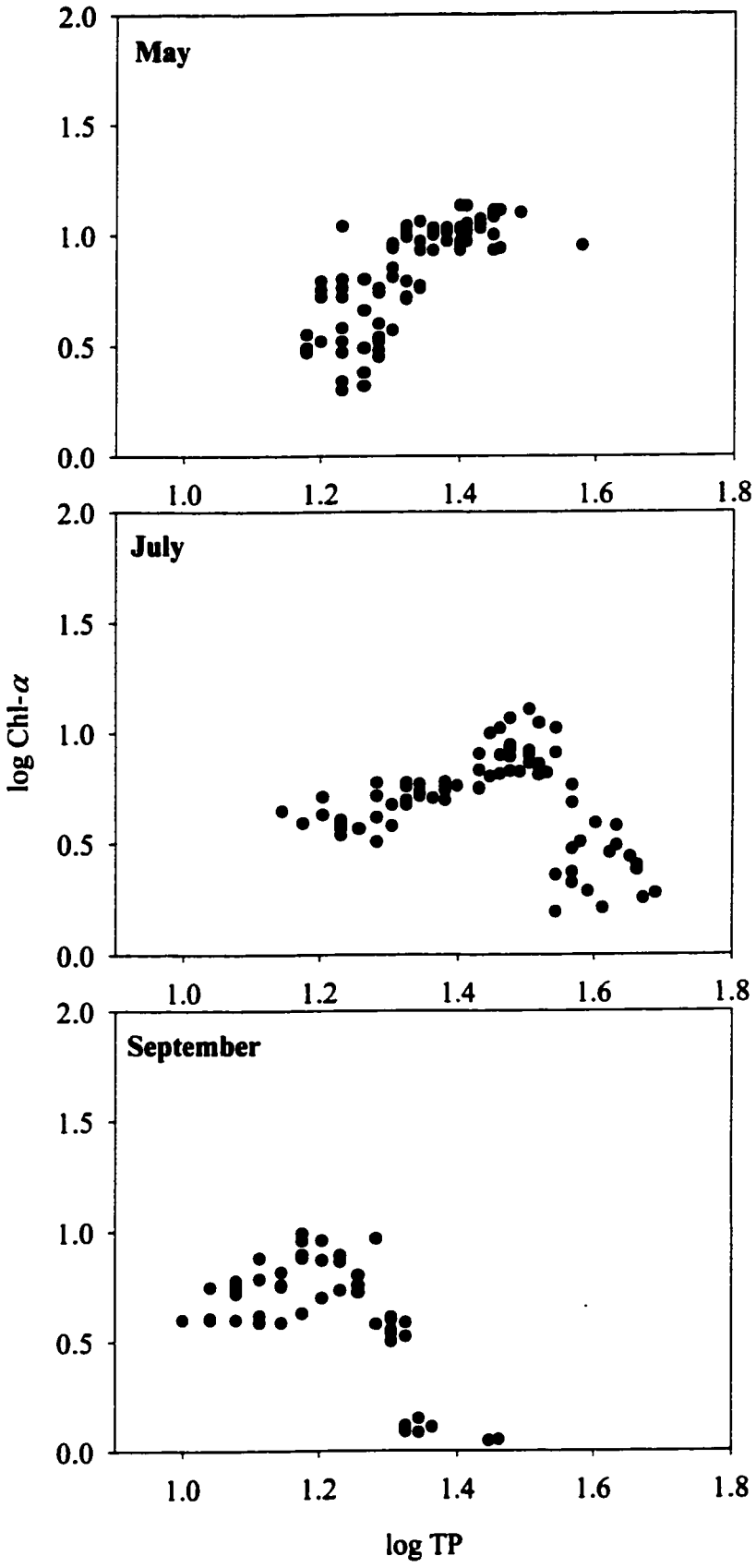

May
July
September
log Chl-α
log TP
2.0
1.5
1.0
0.5
0.0
1.0
1.2
1.4
1.6
1.8

Figure 2.5 Relationships between TP and Chl-*a* in the Rideau River between Smiths Falls (site 1) and Kars (site 30), in May, July and September 2000. TP and Chl-*a* are log transformed.

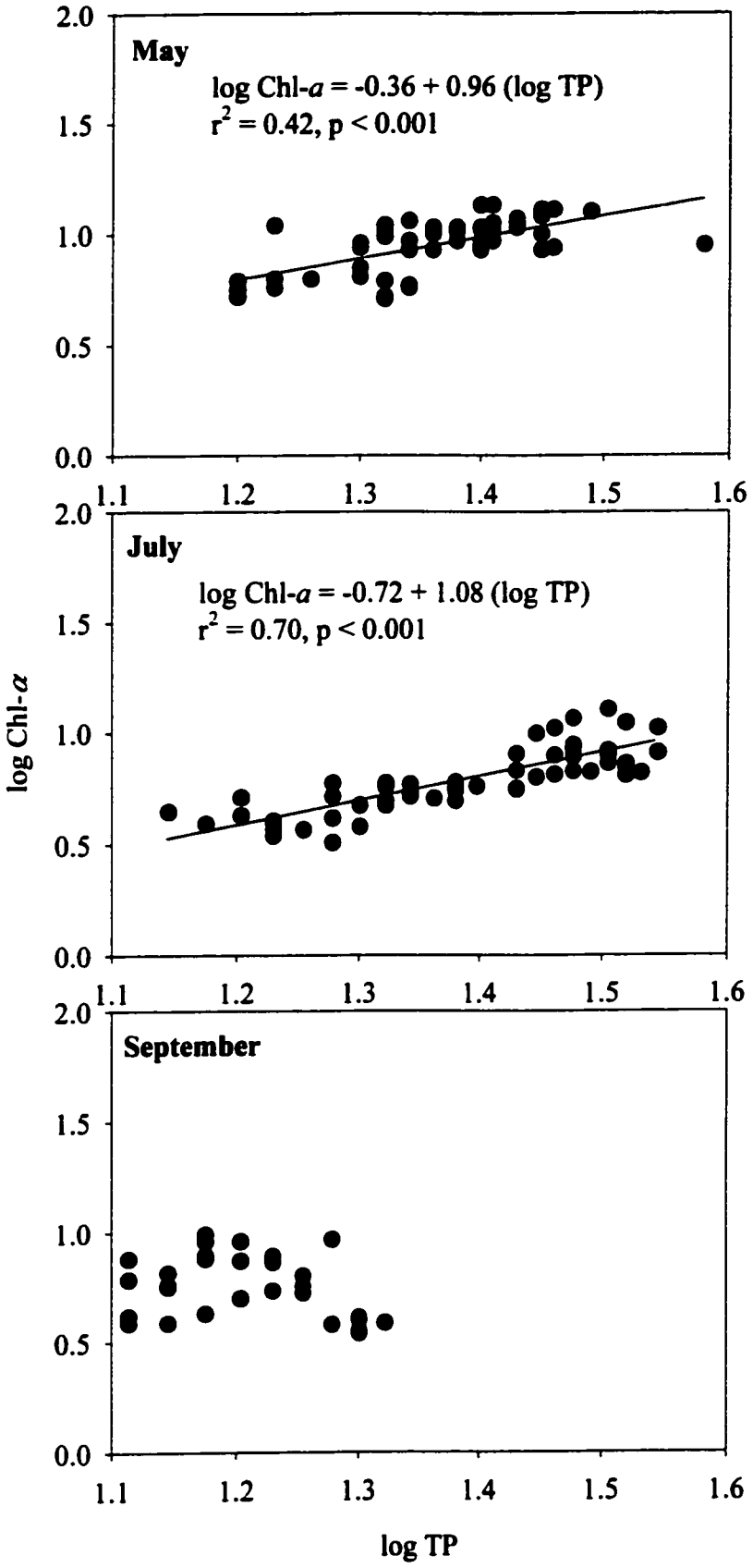

May
log Chl-a = -0.36 + 0.96 (log TP)
r2 = 0.42, p < 0.001
July
log Chl-a = -0.72 + 1.08 (log TP)
r2 = 0.70, p < 0.001
September
log Chl-a
log TP
2.0
1.5
1.0
0.5
0.0
1.1
1.2
1.3
1.4
1.5
1.6

Figure 2.6 Total surface area (A) and total volume (B) of water in each sampling reach along the Rideau River, from Smiths Falls (reach 1) to Ottawa (reach 40). Stacked bars illustrate the contribution to total surface area and volume of water of different depth classes. "Foreshore" indicates shallow water with abundant submerged or emergent vegetation. Depth classes are in feet; surface area is measured in $m^2 \cdot 10^6$ (km^2) and volume is measured in $m^3 \cdot 10^6$. The x-axis is not to scale.

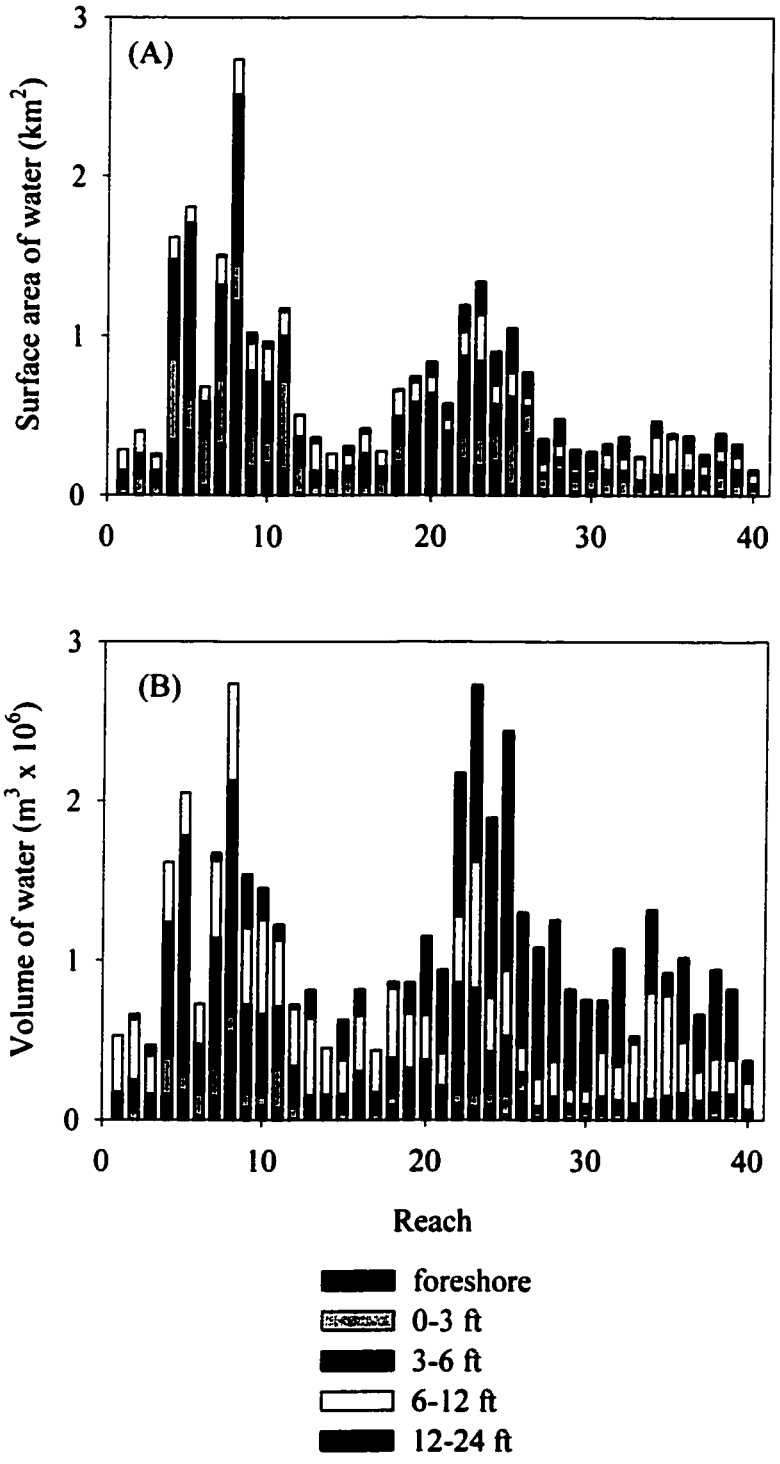

(A)
Surface area of water (km^2)
3
2
1
0
0
10
20
30
40
(B)
Volume of water (m^3 x 10^6)
3
2
1
0
0
10
20
30
40
Reach
foreshore
0-3 ft
3-6 ft
6-12 ft
12-24 ft

Figure 2.7 Percentage of (A) surface area, and (B) volume of shallow water (0-6 feet deep), in each reach on the Rideau River from Smiths Falls (reach 1) to Ottawa (reach 40). The x-axis is not to scale.

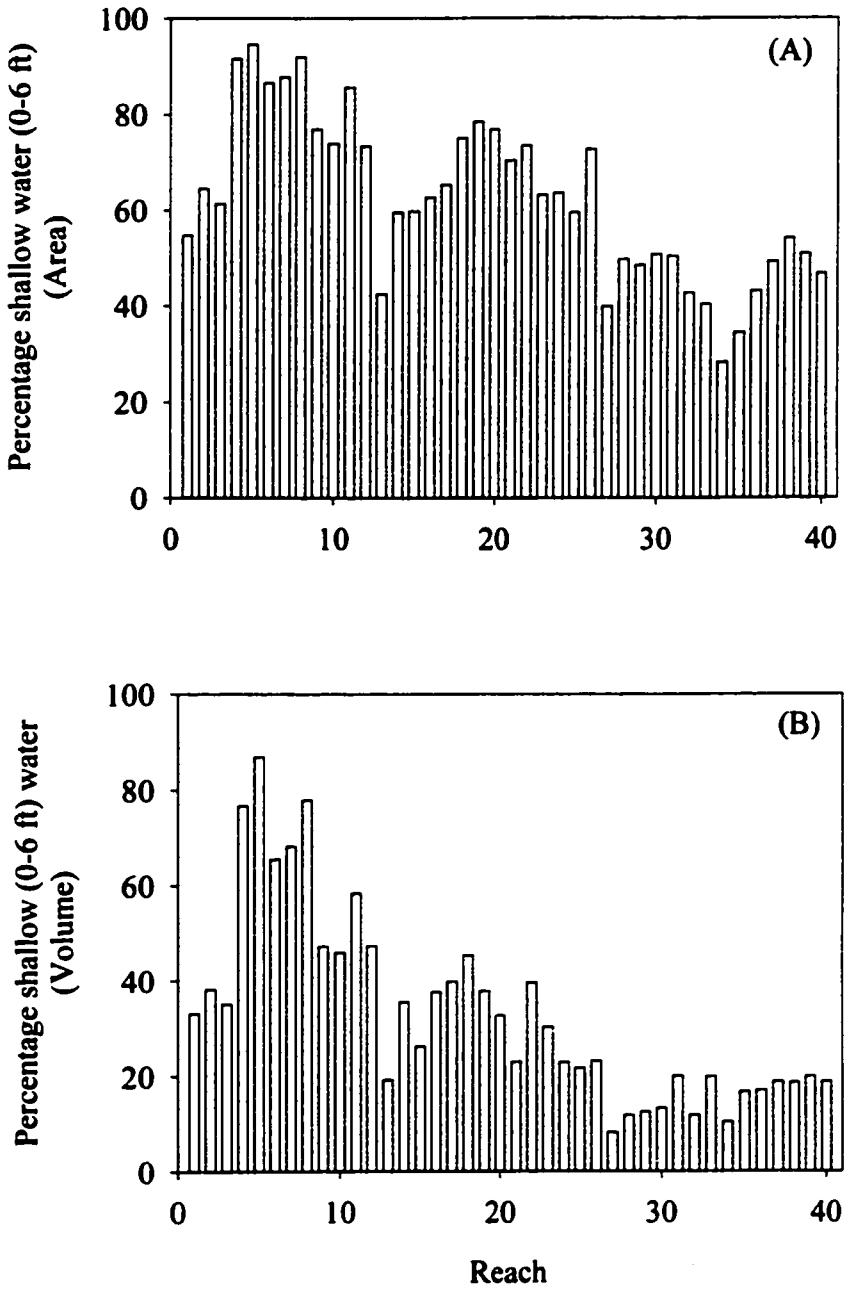

(A)
Percentage shallow water (0-6 ft) (Area)
100
80
60
40
20
0
0
10
20
30
40
(B)
Percentage shallow (0-6 ft) water (Volume)
100
80
60
40
20
0
0
10
20
30
40
Reach

Figure 2.8 Average current velocity measured in the main channel of the Rideau River, in May, July and September 2000. Current was measured in $m \cdot s^{-1}$, using a drifting drogue, and is the average of at least three trials. The x-axis is not to scale.

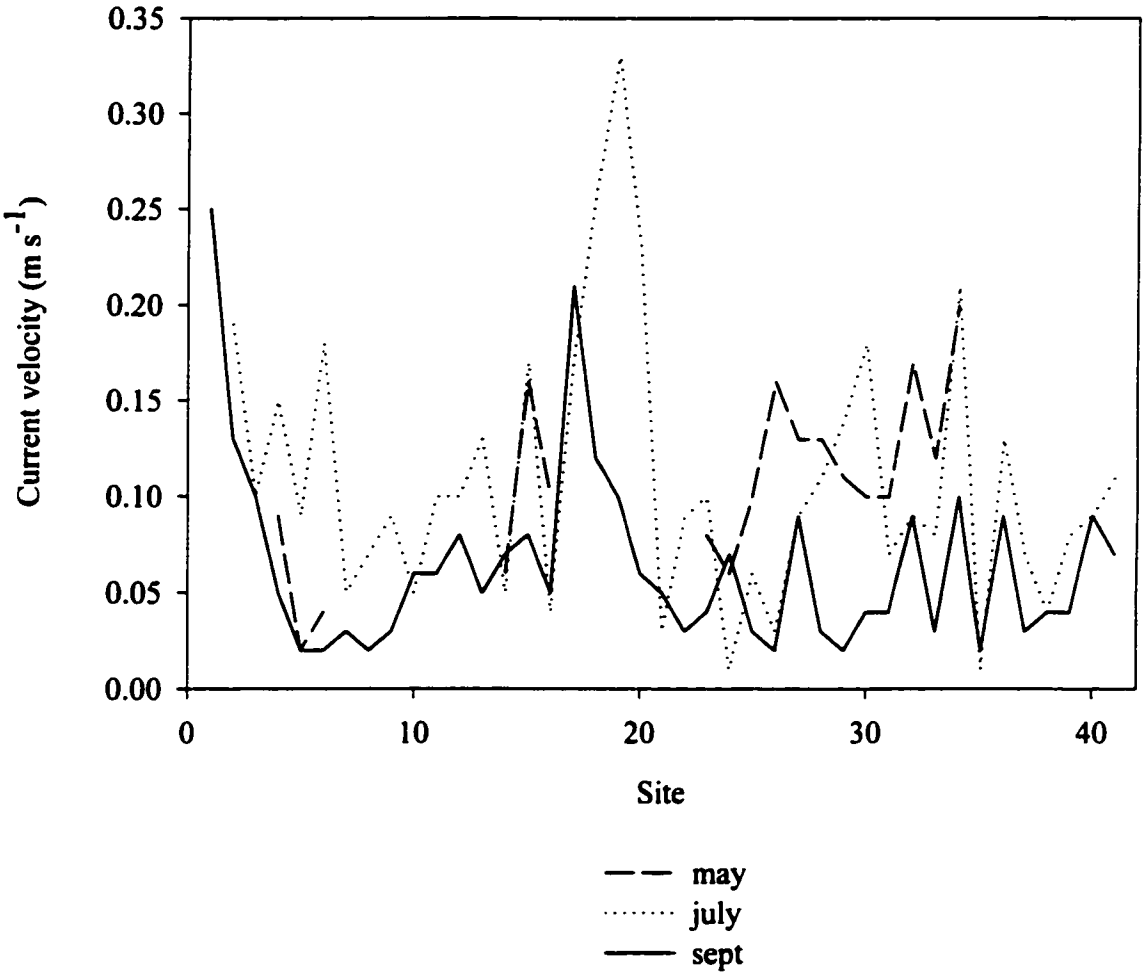
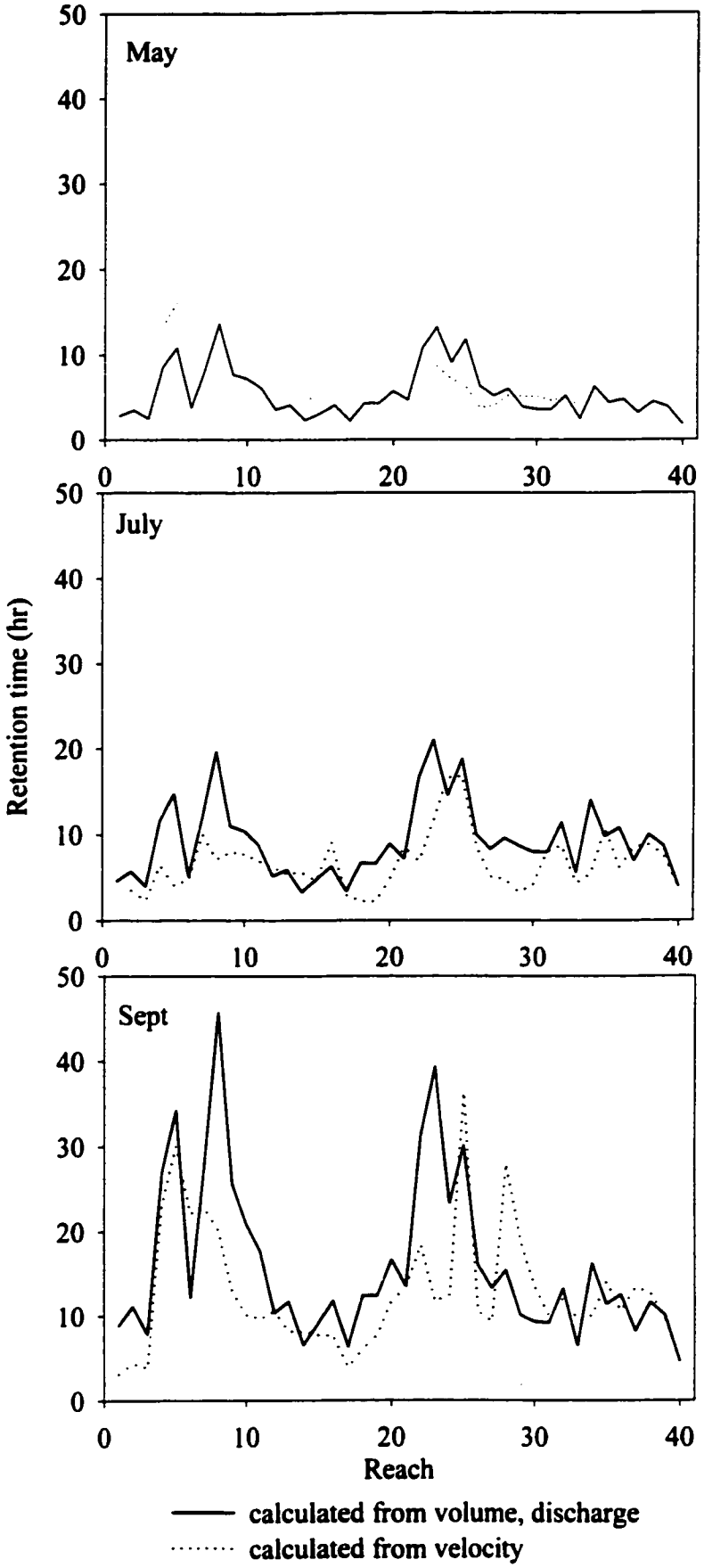

0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Current velocity (m s-1)
0
10
20
30
40
Site
may
july
sept

Figure 2.9 Retention time for reaches along the Rideau River, from Smiths Falls (reach 1) to Ottawa (reach 40), in May, July and September 2000. Retention time (in hours) was calculated either from (a) reach volume and average discharge, or (b) average main channel velocity. The x-axis is not to scale.


May
July
Sept
Retention time (hr)
Reach
0
10
20
30
40
50
calculated from volume, discharge
calculated from velocity

Summary and Conclusions

Contrary to the prediction that dead zones allow the accumulation of high concentrations of phytoplankton relative to the main channel (Reynolds *et al.*, 1991), suspended algal biomass (estimated from chlorophyll *a*) in the Rideau River was not consistently higher in dead zones than in the main channel. Dead zones were characterized by abundant aquatic macrophytes in May, July and October. In May and July, considerable suspended algal biomass in dead zones was contributed by netplankton, particularly filamentous green algae (metaphyton). Recent studies in fluvial lakes on the St. Lawrence River have also shown enrichment of plankton by similar resuspended periphytic algal species (Hudon *et al.*, 1996).

Dead zones have been hypothesized to play a role in maintaining or enhancing phytoplankton communities in rivers, through exports of algal-rich water to the main channel (Reynolds, 1994; Köhler, 1994). However, I found no correlation between changes in main channel chlorophyll *a* and the proportion of shallow littoral dead zones along the entire course of the Rideau River. The export of high concentrations of algal biomass from dead zones may occur infrequently, or may be significant at only certain locations. In addition, the algae found in dead zones may be ill-adapted to conditions in the main channel, and may decline in abundance with downstream travel, as has been found for limnoplankton originating in lakes (Yang *et al.*, 1997). In the upper section of the river, above Kars, by contrast, there was a significant negative correlation, in July, between changes in main channel chlorophyll *a* and the proportion of shallow littoral dead zones. This may indicate that dead zones can actually contribute to declines, rather than increases in main channel phytoplankton density, in some seasons.

Even if dead zones do not contribute substantially to downstream increases in phytoplankton in the Rideau, they are an important component of this river. Research on turbid and clear-water shallow lakes indicates that macrophyte-rich dead zones on rivers such as the Rideau may play an important role in maintaining clear-water conditions (Jeppesen *et al.*, 1999). Dead zones may also have an important role in the maintenance of phytoplankton populations from year to year, by providing storage zones for the resting stages of certain algae. These shallow littoral zones also increase the diversity of habitat and biota on the river. They support abundant aquatic macrophytes, providing habitat and refuge from current and predation for invertebrates and fish (Hillbricht-Ilkowska, 1999; Lancaster *et al.*, 1996; Sempeski & Gaudin, 1995; Snetsinger *et al.*, 1998).

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Appendix 1.1 Location of sampling sites on the Rideau River (determined using GPS).

Site	Latitude	Longitude
A (Main)	45°01.38N	075°42.78W
A (Dead Zone)	45°01.34N	075°42.75W
B (Main)	45°01.93N	075°41.83W
B (Dead Zone)	45°01.87N	075°41.85W
C (Main)	45°02.85N	075°40.78W
C (Dead Zone)	45°02.95N	075°40.79W
D (Main)	45°09.40N	075°38.32W
D (Dead Zone)	45°09.38N	075°38.22W
E (Main)	45°10.92N	075°38.10W
E (Dead Zone)	45°10.87N	075°38.17W
F (Main)	45°12.13N	075°38.58W
F (Dead Zone)	45°12.21N	075°38.60W

Appendix 1.2 Methods used by RMOC for nutrient analyses

Nutrient	Method
TP	MOE method The Determination of Total Phosphorus in Surface Waters and Precipitation by Colourimetry. 1989. Kjeldahl digest followed by colourimetric analysis on an autoanalyser (molybdate/ascorbic acid procedure).
RP	MOE method RNDNPP-103DC2-PPO4FR.1 Automated colourimetry (molybdate/ascorbic acid procedure).
TKN	MOE method The Determination of Total Kjeldahl Nitrogen in Surface Water, Precipitation and Soil Extracts by Colourimetry. 1989. Kjeldahl digest followed by colourimetric analysis on an autoanalyser (phenat/nitroprusside/hypochlorite procedure).
NH_3	MOE method RNDNP-E3174A.1 Automated colourimetry (phenat/nitroprusside/hypochlorite procedure).
NO_2+NO_3	EPA method 300.0 Ion chromatography

Appendix 1.3 2000 mean daily discharges (in $m^3 \cdot s^{-1}$) for the Rideau River at Ottawa. (Preliminary data, supplied by Environment Canada)

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	32.1	19.6	131	133	58.3	62.7	53.8	18.6	12.5	14.2	16.6	43.7
2	15.5	19.3	119	113	58.4	61.9	55.2	18.1	12.2	15.7	16.2	37.7
3	14.1	19.4	110	92.6	56.9	42	54.7	17.6	12.5	15.9	15.8	33
4	16.5	20	99.9	131	54.7	24.1	37.3	24.3	12.4	17.9	10.1	30.6
5	35.6	20.2	83.8	167	51.3	18.9	25.9	24	12.3	19.7	7.61	25.6
6	40.5	19.5	73.8	155	48.8	24.6	18.8	23.9	12.5	19.6	11.8	20
7	30.4	18.5	68	138	53.7	25.2	22.6	24.4	13.3	19.7	14.7	21.8
8	25.5	16.6	59.1	190	81.1	27.2	21.9	29.4	13.5	19.2	13.4	32.8
9	24.7	18.6	49.5	237	134	32.6	21.9	35.8	16.4	19.1	11.6	39.2
10	23.3	17.4	66.9	231	153	36.7	23.2	31.1	18.1	19.1	15.8	50.1
11	50	18.5	64.6	244	159	39.1	20.5	22	23.2	17.3	14.8	22.7
12	68.3	19.7	60	225	142	40.4	17.2	21.3	23.9	15	14.1	18.6
13	47.5	19.1	50.5	212	125	38.1	13.9	19.6	23.4	12.4	13.8	31
14	44.3	19.5	43.7	210	97.2	36.9	16.3	17.5	23.8	11.9	15.1	36.7
15	53.7	21.1	44	187	87.5	40.3	20.4	16.6	29.8	11.9	16.6	46.2
16	50.7	21.6	58.5	151	68.2	41.3	21.6	13.3	25.8	10.1	17.2	37.1
17	41.5	21.3	80.8	111	53.7	43.2	30.7	8.08	23.5	8.32	16.4	15
18	56.8	20.6	79.2	87.8	76.2	39.2	41.5	9.07	24.6	8.72	15.9	25
19	59.8	20.9	71.5	82.1	142	30.7	35.9	10.8	26.5	8.85	15.1	35
20	57.1	21.2	45.2	78.6	139	26.2	28.6	9.88	26.2	8.7	14.1	44.3
21	55.9	20.9	43.8	102	132	29.1	28.4	10.3	26.1	8.08	13.3	45.4
22	45.5	20.5	45.4	175	109	28.9	32.8	14.5	25	8.05	12.3	37.2
23	34.7	20.1	51.1	226	92.5	33.1	34	18.5	24.7	7.41	11.7	46.2
24	29	23	55.2	217	104	34.5	33.4	18.2	24.3	6.77	10.8	56.3
25	22.6	48.8	56.3	179	146	62.8	33.7	18.1	20.8	7.52	9.53	64.4
26	22.1	60.6	57.9	139	167	99.6	26.4	17.8	17.8	7.75	12.6	79.5
27	23.7	89.3	62.6	97.9	132	97.9	19.4	16.8	15.5	7.87	21.6	89.9
28	20.6	161	73.1	83.5	90.6	81.3	23.8	15.6	15.5	7.7	36.7	83.9
29	19.3	147	186	73.2	67.1	64	21.6	15.8	15.8	7.34	44.5	93.2
30	18.9		174	69.3	69	51.3	21.2	13.1	15.4	10.8	46.5	87.2
31	18.8		146		67.1		18.7	13.9		15.4		79.8
avg	**35.5**	**33.9**	**77.8**	**151.3**	**97.3**	**43.8**	**28.2**	**18.3**	**19.6**	**12.5**	**16.9**	**45.5**
Year average	**48.4**											

Appendix 1.4a 2-way factorial GLM model for percent organic matter measured in sediments (top 2.5 cm) from main channel and dead zones at (A) sites A – D and (B) sites A – C on the Rideau River.

	Variable	Effect	Model r^2	F-ratio	df	p-value (2-tailed)
(A)	% OM	site	0.716	3.712	3	**0.035**
		type		5.236	1	**0.037**
		type*site		6.887	3	**0.004**
(B)	% OM	site	0.453	4.474	2	**0.035**
		type		0.125	1	0.730
		type*site		0.424	2	0.664

Appendix 1.4b Tukey HSD pairwise comparisons of percent organic matter in sediments from sites A-D on the Rideau River.

Variable	Comparison	Mean Difference	MSE	df	p-value (2-tailed)
% OM	A-B	6.912	20.788	15	0.080
	A-C	7.543			**0.052**
	A-D	7.191			0.088
	B-C	0.632			0.995
	B-D	0.279			1.000
	C-D	-0.352			0.999

Appendix 1.5a Summary of 2-way factorial GLM models for mean physical and chemical parameters measured in main channel and dead zones (n = 6 sites) in May, July and October 2000. Mean parameters at each site were calculated from water column averages at 3 subsites (main channel), or 5 subsites (dead zones).

Parameter	Effect	Model r^2	Test Statistic	df	p-value (2-tailed)
LA	month	0.627	H = 16.67	2	**p < 0.001**
	type		H = 3.16	1	**0.05<p<0.10**
	type*month		H = 1.49	2	0.25<p<0.50
Temp.	month	0.935	F-ratio = 211.711	2	**p < 0.001**
	type		F-ratio = 2.471	1	p = 0.126
	type*month		F-ratio = 2.371	2	p = 0.111
	month	0.925	F-ratio = 195.006	2	**p < 0.001**
	type		F-ratio = 2.276	1	p = 0.141
% DO	month	0.732	H = 21.2	2	**p < 0.001**
	type		H = 2.706	1	**p = 0.10**
	type*month		H = 1.70	2	0.25<p<0.50
pH	month	0.779	H = 21.43	2	**p < 0.001**
	type		H = 1.175	1	0.25<p<0.50
	type*month		H = 1.528	2	0.25<p<0.50
SpCond	month	0.750	H = 25.87	2	**p < 0.001**
	type		H = 0.225	1	0.75<p<0.90
	type*month		H = 0.137	2	0.90<p<0.95
E_h	month	0.754	F-ratio = 41.936	2	**p < 0.001**
	type		F-ratio = 0.164	1	p = 0.689
	type*month		F-ratio = 3.912	2	**p = 0.031**

LA = light attenuation; Temp. = water temperature; % DO = percent dissolved oxygen; SpCond = specific conductance; E_h = redox potential;

Appendix 1.5b Summary of Tukey HSD pairwise comparisons of mean physical and chemical parameters (n = 6) in May, July and October 2000.

Parameter	Comparison	Mean Difference	MSE	df	p-value (2-tailed)
LA	May-July	-9.708	114.250	34	p = 0.081
	July-Oct	8.083			p = 0.168
	May-Oct	17.792			**p = 0.001**
Temp	May-July	-9.187	2.107	32	**p < 0.001**
	July-Oct	-10.873			**p < 0.001**
	May-Oct	-1.687			**p = 0.020**
% DO	May-July	12.750	111.0	35	**p = 0.015**
	July-Oct	-6.750			p = 0.272
	May-Oct	-19.50			**p < 0.001**
pH	May-July	0.794	0.161	35	**p < 0.001**
	July-Oct	0.285			p = 0.204
	May-Oct	-0.509			**p = 0.010**
SpCond	May-July	14.583	111.0	35	**p = 0.005**
	July-Oct	-6.833			p = 0.264
	May-Oct	-21.417			**p < 0.001**
E_h	May-July	-25.304	1097.288	30	p = 0.165
	July-Oct	92.343			**p < 0.001**
	May-Oct	117.647			**p < 0.001**

LA = light attenuation; Temp. = water temperature; % DO = percent dissolved oxygen; SpCond = specific conductance; E_h = redox potential;

Appendix 1.6a Summary of 2-way factorial GLM models for average nutrient concentrations measured in main channel and dead zone (n = 6 sites) in May, July and October 2000.

Nutrient	Effect	Model r^2	Test Statistic	df	p-value (2 tailed)
TP	month	0.79	H = 17.57	2	**p < 0.001**
	type		H = 3.35	1	**0.05<p<0.10**
	month*type		H = 1.92	2	0.25<p<0.5
RP	month	0.39	H = 8.64	2	**0.01<p<0.025**
	type		H = 0.16	1	0.5<p<0.75
	month*type		H = 2.23	2	0.25<p<0.5
TKN	month	0.64	F-ratio = 22.03	2	**p < 0.001**
	type		F-ratio = 7.525	1	**p = 0.010**
	month*type		F-ratio = 0.286	2	p = 0.286
NH_3	month	0.084	F-ratio = 0.197	2	p = 0.822
	type		F-ratio = 0.505	1	p = 0.483
	month*type		F-ratio = 0.918	2	p = 0.410
NO_3+NO_2	month	0.714	H = 19.96	2	**p < 0.001**
	type		H = 0.64	1	0.25<p<0.5
	month*type		H = 0.10	2	p = 0.95

Appendix 1.6b Summary of Tukey HSD pairwise comparisons of average nutrient concentrations between months (n = 6).

Nutrient	Comparison	Mean Difference	MSE	df	p-value (2-tailed)
TP	May-July	0.917	133.8	29	0.979
	July-Oct	-16.667			**0.004**
	May-Oct	-17.583			**0.002**
RP	May-July	-13.792	138.07	28	**0.020**
	July-Oct	-9.458			0.138
	May-Oct	4.333			0.643
TKN	May-July	22.792	4293.52	30	0.674
	July-Oct	-141.117			**<0.001**
	May-Oct	-163.908			**<0.001**
NH3	May-July	1.733	167.688	30	0.943
	July-Oct	3.317			0.806
	May-Oct	1.583			0.952
NO_3+NO_2	May-July	20.750	130.8	29	**<0.001**
	July-Oct	8.500			0.181
	May-Oct	-12.250			**0.036**

Appendix 1.7a Summary of 2-way factorial GLM models for average chlorophyll *a* concentrations measured in main channel and dead zone (n = 6 sites) in May, July and October 2000.

Chl-*a* size fraction	Effect	Model r^2	Test Statistic	df	p-value (2 tailed)
> 0.2 μm	month	0.483	F-ratio = 10.347	2	**p < 0.001**
	type		F-ratio = 2.773	1	p = 0.106
	type*month		F-ratio = 2.288	2	p = 0.119
	month	0.404	F-ratio = 9.576	2	**p = 0.001**
	type		F-ratio = 2.566	1	p = 0.119
> 2 μm	month	0.477	F-ratio = 10.831	2	**p < 0.001**
	type		F-ratio = 4.435	1	**p = 0.044**
	month*type		F-ratio = 0.653	2	p = 0.528
	month	0.455	F-ratio = 11.072	2	**p < 0.001**
	type		F-ratio = 0.041	1	**p = 0.041**
> 20 μm	month	0.766	F-ratio = 29.181	2	**p < 0.001**
	type		F-ratio = 20.854	1	**p < 0.001**
	month*type		F-ratio = 9.400	2	**p = 0.001**
> 64 μm	month	0.764	H = 11.51	2	**0.001<p<0.005**
	type		H = 10.29	1	**0.001<p<0.005**
	month*type		H = 1.11	2	0.5<p<0.75

Appendix 1.7b Summary of Tukey HSD pairwise comparisons of average Chl-*a* concentrations (n = 6) in May, July and October 2000.

Chl-*a* size fraction	Comparison	Mean Difference	MSE	df	p-value (2-tailed)
> 0.2 μm	May-July	0.129	12.188	30	0.995
	July-Oct	-5.549			**0.001**
	May-Oct	-5.678			**0.001**
> 2.0 μm	May-July	-0.906	4.921	32	0.582
	July-Oct	-4.059			**<0.001**
	May-Oct	-3.153			**0.004**
> 20 μm	May-July	1.447	0.728	30	**0.001**
	July-Oct	-1.210			**0.004**
	May-Oct	-2.657			**<0.001**
> 64 μm	May-July	8.917	129.420	30	0.151
	July-Oct	-6.792			0.323
	May-Oct	-15.708			**0.006**

Appendix 1.8 Main channel and adjacent dead zone physical characteristics

Depth & Secchi depth (m); current ($m \cdot s^{-1}$); temp (°C); LA = light extinction (m^{-1}); % OM = percent organic matter in sediments. BD = below detection; n/a = not able to measure

Month	Site	Type	subsite	Depth	Secchi	Current	Temp	LA
May	A	Main	C1	4.50	1.4	0.25	13.55	1.44
May	A	Main	L	4.00	1.4	0.25	13.56	
May	A	Main	R1	3.50	1.5	0.29	13.48	
May	B	Main	C1	5.40	1.4	0.26	13.74	1.48
May	B	Main	L	3.75	1.4	0.21	13.80	
May	B	Main	R1	5.50	1.5	0.25	13.72	
May	C	Main	C1	6.00	1.2	0.13	15.25	1.63
May	C	Main	L	3.80	1.2	0.09	15.56	
May	C	Main	R1	5.50	1.0	0.09	15.37	
May	D	Main	C1	5.50	2.0	0.15	15.92	1.67
May	D	Main	L	5.70	2.0	0.11	16.01	
May	D	Main	R1	4.00	2.0	0.07	16.22	
May	E	Main	C1	5.80	2.0	0.17	16.43	1.73
May	E	Main	L	5.80	2.0	0.18	16.42	
May	E	Main	R1	2.70	2.0	0.07	16.82	
May	F	Main	C1	4.00	2.4	0.30	15.98	1.68
May	F	Main	R1	4.40	2.4	0.20	15.94	
May	A	DZ	A	0.75	bottom	BD	13.30	
May	A	DZ	B	1.00	bottom	BD	13.40	
May	A	DZ	C	1.00	bottom	BD	13.40	2.34
May	A	DZ	D	1.20	bottom	BD	13.48	
May	A	DZ	E	1.10	bottom	BD	13.49	
May	B	DZ	A	0.50	bottom	BD	14.54	
May	B	DZ	B	0.60	bottom	BD	14.72	
May	B	DZ	C	0.95	bottom	BD	14.47	1.61
May	B	DZ	D	1.00	bottom	BD	14.50	
May	B	DZ	E	1.10	bottom	BD	14.60	
May	C	DZ	A	0.50	bottom	BD	15.16	
May	C	DZ	B	0.50	bottom	BD	15.46	
May	C	DZ	C	0.63	bottom	BD	15.82	2.52
May	C	DZ	D	1.20	1.0	BD	15.24	
May	C	DZ	E	2.20	1.1	BD	15.14	
May	D	DZ	A	0.50	bottom	BD	15.90	
May	D	DZ	B	0.60	bottom	BD	16.34	
May	D	DZ	C	0.75	bottom	BD	16.43	2.77
May	D	DZ	D	1.10	bottom	BD	16.57	
May	D	DZ	E	0.80	bottom	BD	16.71	
May	E	DZ	A	0.37	bottom	BD	16.83	
May	E	DZ	B	0.50	bottom	BD	16.81	
May	E	DZ	C	0.70	bottom	BD	16.97	2.03
May	E	DZ	D	1.00	bottom	BD	17.31	
May	E	DZ	E	1.00	bottom	BD		
May	F	DZ	A	0.66	bottom	BD	15.50	
May	F	DZ	B	0.80	bottom	BD	16.27	
May	F	DZ	C	0.55	bottom	BD	16.55	1.56
May	F	DZ	D	0.75	bottom	BD	16.73	
May	F	DZ	E	0.65	bottom	BD	15.96	

Month	Site	Type	subsite	Depth	Secchi	Current	Temp	LA	% OM
July	A	Main	C1	4.00	1.5	0.04	25.29	0.96	17.27
July	A	Main	L	3.50	1.5	0.06	25.37		22.92
July	A	Main	R1	3.00	1.4	0.06	25.82		10.00
July	B	Main	C1	5.80	1.5	0.06	24.55	1.18	21.88
July	B	Main	L	4.70	1.5	0.07	24.55		21.93
July	B	Main	R1	5.40	1.4	0.06	24.42		22.01
July	C	Main	C1	6.20	1.9	0.04	23.25	1.55	23.62
July	C	Main	L	5.50	1.9	0.03	23.36		26.05
July	C	Main	R1	5.40	1.9	0.08	23.35		15.57
July	D	Main	C1	6.20	1.7	0.07	22.87	1.25	13.86
July	D	Main	L	6.40	1.7	0.07	22.77		n/a
July	D	Main	R1	3.50	1.7	0.03	23.92		10.37
July	E	Main	C1	8.30	1.7	0.22	22.04	1.33	n/a
July	E	Main	L	8.30	1.8	0.18	22.10		n/a
July	E	Main	R1	5.50	2.0	0.07	22.48		n/a
July	F	Main	C1	4.40	3.7	0.14	22.09	1.00	n/a
July	F	Main	L	3.50	bottom	0.14	22.21		n/a
July	F	Main	R1	4.50	3.7	0.15	22.00		n/a
July	A	DZ	A	0.50	0.3	BD	26.97		6.76
July	A	DZ	B	0.50	0.3	BD	27.51		
July	A	DZ	C	0.80	0.4	BD	26.56	2.97	16.94
July	A	DZ	D	0.90	0.6	BD	26.93		
July	A	DZ	E	0.80	0.5	BD	26.66		15.61
July	B	DZ	A	0.30	bottom	BD	26.66		21.86
July	B	DZ	B	0.30	bottom	BD	26.56		
July	B	DZ	C	0.50	bottom	BD	26.89	1.33	24.85
July	B	DZ	D	0.80	bottom	BD	26.44		
July	B	DZ	E	0.90	bottom	BD	26.10		18.44
July	C	DZ	A	0.50	bottom	BD	25.34		17.07
July	C	DZ	B	0.50	bottom	BD	25.38		
July	C	DZ	C	0.75	bottom	BD	25.47	1.54	26.36
July	C	DZ	D	1.00	bottom	BD	25.16		
July	C	DZ	E	1.00	bottom	BD	25.26		26.09
July	D	DZ	A	0.30	bottom	BD	26.60		36.00
July	D	DZ	B	0.40	bottom	BD	26.29		
July	D	DZ	C	0.50	bottom	BD	25.74	1.98	30.89
July	D	DZ	D	0.85	bottom	BD	25.86		
July	D	DZ	E	1.00	bottom	BD	25.91		29.41
July	E	DZ	A	0.40	bottom	BD	24.92		31.25
July	E	DZ	B	0.50	bottom	BD	25.25		
July	E	DZ	C	0.70	bottom	BD	24.99	2.27	40.32
July	E	DZ	D	0.75	bottom	BD	25.12		
July	E	DZ	E	1.00	bottom	BD	25.21		25.60
July	F	DZ	A	0.75	bottom	BD	22.86		34.12
July	F	DZ	B	0.70	bottom	BD	23.91		
July	F	DZ	C	0.75	bottom	BD	23.80	1.07	25.41
July	F	DZ	D	0.75	bottom	BD	24.21		
July	F	DZ	E	0.80	bottom	BD	23.50		25.00

Month	Site	Type	subsite	Depth	Secchi	Current	Temp	LA
Oct	A	Main	C1	4.00	2.4	0.06	12.01	1.18
Oct	A	Main	L	4.50	2.4	0.06	12.01	
Oct	A	Main	R1	3.00	2.4	0.06	12.04	
Oct	B	Main	C1	5.80	2.1	0.03	11.98	1.28
Oct	B	Main	L	3.50	2.0	0.05	11.93	
Oct	B	Main	R1	5.00	2.1	0.02	12.02	
Oct	C	Main	C1	6.20	2.0	0.04	14.20	1.18
Oct	C	Main	L	4.90	2.0	0.04	14.12	
Oct	C	Main	R1	5.50	2.0	0.05	14.18	
Oct	D	Main	C1	5.30	3.8	0.03	14.68	1.25
Oct	D	Main	L	5.80	3.5	0.03	14.68	
Oct	D	Main	R1	5.20	3.8	0.03	14.71	
Oct	E	Main	C1	8.00	3.8	0.03	14.50	0.86
Oct	E	Main	L	8.00	bottom	0.06	14.65	
Oct	E	Main	R1	6.50	4.0	n/a	14.47	
Oct	F	Main	C1	3.90	bottom	0.04	15.26	0.84
Oct	F	Main	L	3.60	bottom	0.03	15.21	
Oct	F	Main	R1	4.10	4.0	0.06	15.18	
Oct	A	DZ	A	0.50	bottom	BD	11.60	
Oct	A	DZ	B	0.40	bottom	BD	11.33	
Oct	A	DZ	C	0.70	bottom	BD	11.36	1.47
Oct	A	DZ	D	0.70	bottom	BD	11.54	
Oct	A	DZ	E	0.80	bottom	BD	11.61	
Oct	B	DZ	A	0.40	bottom	BD	11.65	
Oct	B	DZ	B	0.40	bottom	BD	11.07	
Oct	B	DZ	C	0.50	bottom	BD	11.35	1.34
Oct	B	DZ	D	0.50	bottom	BD	11.49	
Oct	B	DZ	E	0.70	bottom	BD	11.65	
Oct	C	DZ	A	0.55	bottom	BD	13.09	
Oct	C	DZ	B	0.40	bottom	BD	13.13	
Oct	C	DZ	C	0.60	bottom	BD	13.13	0.97
Oct	C	DZ	D	1.00	bottom	BD	13.30	
Oct	C	DZ	E	1.30	bottom	BD	13.92	
Oct	D	DZ	A	0.50	bottom	BD	14.56	
Oct	D	DZ	B	0.50	bottom	BD	14.54	
Oct	D	DZ	C	0.70	bottom	BD	14.50	1.13
Oct	D	DZ	D	1.10	bottom	BD	14.72	
Oct	D	DZ	E	1.20	bottom	BD	14.63	
Oct	E	DZ	A	0.50	bottom	BD	14.76	
Oct	E	DZ	B	0.50	bottom	BD	14.90	
Oct	E	DZ	C	0.70	bottom	BD	15.01	1.21
Oct	E	DZ	D	0.80	bottom	BD	15.28	
Oct	E	DZ	E	0.80	bottom	BD	15.95	
Oct	F	DZ	A	0.70	bottom	BD	14.97	
Oct	F	DZ	B	0.50	bottom	BD	15.23	
Oct	F	DZ	C	0.80	bottom	BD	15.35	0.80
Oct	F	DZ	D	0.80	bottom	BD	15.62	
Oct	F	DZ	E	0.80	bottom	BD	15.54	

Appendix 1.9 Chemical parameters measured for main channel and adjacent dead zone.
DO = dissolved oxygen ($mg \cdot L^{-1}$); SpCond = specific conductance ($\mu S \cdot cm^{-1}$); E_h = redox potential (mV)

Month	Site	Type	subsite	DO%	DO	pH	SpCond	E_h
May	A	Main	Cl	96.3	10.0	8.6	318.0	388.3
May	A	Main	L	96.5	10.0	8.6	317.4	382.1
May	A	Main	Rl	95.8	10.0	8.5	318.3	380.2
May	B	Main	Cl	98.8	10.2	8.6	317.6	358.4
May	B	Main	L	98.7	10.2	8.6	318.0	379.0
May	B	Main	Rl	97.2	10.1	8.6	318.7	361.0
May	C	Main	Cl	104.0	10.4	8.8	328.6	366.0
May	C	Main	L	106.5	10.6	8.8	329.1	331.6
May	C	Main	Rl	105.4	10.5	8.8	328.0	358.6
May	D	Main	Cl	81.9	8.1	8.2	356.1	358.6
May	D	Main	L	82.9	8.2	8.2	350.8	287.4
May	D	Main	Rl	82.6	8.1	8.2	343.1	327.7
May	E	Main	Cl	82.9	8.1	8.2	346.6	358.6
May	E	Main	L	84.2	8.2	8.2	345.7	361.8
May	E	Main	Rl	77.8	8.6	8.2	348.8	340.5
May	F	Main	Cl	83.0	8.2	8.2	353.3	394.3
May	F	Main	Rl	82.3	8.1	8.2	353.1	383.6
May	A	DZ	A	96.8	10.1	8.4	329.3	450.0
May	A	DZ	B	98.7	10.3	8.5	328.6	400.3
May	A	DZ	C	96.9	10.1	8.5	326.5	397.0
May	A	DZ	D	99.0	10.3	8.6	327.3	385.0
May	A	DZ	E	97.7	10.2	8.6	327.1	382.8
May	B	DZ	A	150.1	15.3	9.2	325.9	363.5
May	B	DZ	B	144.8	14.7	9.2	326.3	354.0
May	B	DZ	C	150.8	15.4	9.2	328.6	366.7
May	B	DZ	D	144.2	14.7	9.2	341.9	371.7
May	B	DZ	E	142.4	14.5	9.2	338.3	370.7
May	C	DZ	A	109.3	11.0	8.9	328.3	408.0
May	C	DZ	B	114.3	11.4	8.9	327.7	392.0
May	C	DZ	C	129.3	12.8	9.1	323.8	377.5
May	C	DZ	D	107.3	10.8	8.9	326.8	380.0
May	C	DZ	E	86.3	8.7	8.6	340.2	342.2
May	D	DZ	A	97.3	9.6	8.3	337.4	396.5
May	D	DZ	B	98.6	9.7	8.4	336.9	388.0
May	D	DZ	C	92.4	9.0	8.4	336.5	341.5
May	D	DZ	D	97.5	9.5	8.4	335.2	343.0
May	D	DZ	E	105.0	10.2	8.6	334.9	307.3
May	E	DZ	A	141.3	13.7	9.0	396.1	355.0
May	E	DZ	B	147.3	14.3	9.2	405.3	284.5
May	E	DZ	C	150.4	14.5	9.1	378.9	310.0
May	E	DZ	D	171.3	16.5	9.2	366.4	271.5
May	F	DZ	A	148.4	14.8	9.1	342.7	397.0
May	F	DZ	B	146.7	14.4	9.1	343.7	366.0
May	F	DZ	C	136.5	13.3	9.0	342.4	357.0
May	F	DZ	D	163.3	15.9	8.8	338.2	381.5
May	F	DZ	E	83.5	8.3	8.3	353.3	392.0

Month	Site	Type	subsite	DO%	DO	pH	SpCond	E_h
July	A	Main	C1	86.1	7.2	8.0	224.5	412.2
July	A	Main	L	85.8	7.1	8.0	224.9	404.8
July	A	Main	R1	89.3	7.3	8.0	225.7	410.7
July	B	Main	C1	76.8	6.4	8.0	225.6	367.2
July	B	Main	L	76.6	6.4	8.0	226.3	396.5
July	B	Main	R1	75.7	6.3	8.0	224.8	428.2
July	C	Main	C1	68.8	5.8	7.9	242.3	429.7
July	C	Main	R1	71.1	6.0	7.9	239.5	463.4
July	D	Main	C1	72.0	6.1	7.8	256.2	410.4
July	D	Main	L	69.0	5.9	7.8	259.5	397.6
July	D	Main	R1	75.8	6.3	7.9	255.0	413.3
July	E	Main	C1	59.0	5.1	7.7	263.4	399.8
July	E	Main	L	59.0	5.1	7.7	263.9	397.6
July	E	Main	R1	69.2	5.9	7.8	261.3	402.8
July	F	Main	C1	57.7	5.0	7.5	264.6	409.8
July	F	Main	L	58.3	5.1	7.5	264.6	396.0
July	F	Main	R1	56.7	4.9	7.5	264.4	444.4
July	A	DZ	A	105.9	8.5	8.1	231.7	371.0
July	A	DZ	B	94.5	7.5	7.8	239.2	369.5
July	A	DZ	C	92.4	7.4	7.9	232.6	350.7
July	A	DZ	D	96.1	7.7	7.9	234.4	387.3
July	A	DZ	E	105.1	8.5	8.1	232.5	389.0
July	B	DZ	A	73.0	5.8	7.4	264.5	268.5
July	B	DZ	B	94.7	7.6	8.3	227.2	312.0
July	B	DZ	C	100.9	8.0	8.3	226.8	357.0
July	B	DZ	D	107.0	8.6	8.4	224.0	359.0
July	B	DZ	E	100.0	8.0	8.4	222.9	319.3
July	C	DZ	A	57.1	4.6	7.5	248.7	435.5
July	C	DZ	B	64.5	5.3	7.6	243.9	437.0
July	C	DZ	C	59.2	4.8	7.5	250.0	367.5
July	C	DZ	D	91.7	7.5	8.2	232.0	372.3
July	C	DZ	E	92.4	7.6	8.1	232.4	351.3
July	D	DZ	A	92.9	7.4	7.1	278.3	428.5
July	D	DZ	B	102.4	8.2	7.6	270.7	407.0
July	D	DZ	C	89.7	7.3	7.6	266.8	411.5
July	D	DZ	D	90.6	7.3	7.9	259.6	407.7
July	D	DZ	E	104.2	8.4	8.1	257.0	388.3
July	E	DZ	A	68.8	5.7	7.4	320.6	384.5
July	E	DZ	B	82.5	6.7	7.3	319.6	368.0
July	E	DZ	C	115.5	9.5	8.1	329.2	372.3
July	E	DZ	D	79.6	6.5	8.0	284.4	308.0
July	E	DZ	E	54.3	4.4	7.7	300.6	316.0
July	F	DZ	A	73.4	6.3	7.8	268.0	332.7
July	F	DZ	B	91.0	7.7	8.0	263.8	335.0
July	F	DZ	C	83.0	7.0	7.9	264.2	357.0
July	F	DZ	D	89.8	7.5	8.1	263.6	374.0
July	F	DZ	E	65.5	5.5	7.7	264.5	343.7

Month	Site	Type	subsite	DO%	DO	pH	SpCond	E_h
Oct	A	Main	C1	61.0	6.6	8.0	226.3	518.8
Oct	A	Main	L	61.3	6.6	8.0	225.8	521.0
Oct	A	Main	R1	61.8	6.7	8.0	225.6	515.3
Oct	B	Main	C1	63.3	6.8	8.0	224.8	492.7
Oct	B	Main	L	64.4	7.0	8.1	224.7	498.0
Oct	B	Main	R1	62.9	6.8	8.0	224.6	514.3
Oct	C	Main	C1	68.9	7.1	8.2	225.5	462.5
Oct	C	Main	L	68.7	7.1	8.2	225.3	472.0
Oct	C	Main	R1	67.7	7.0	8.2	225.7	458.1
Oct	D	Main	C1	74.5	7.7	8.2	235.6	497.2
Oct	D	Main	L	72.4	7.4	8.3	237.3	499.2
Oct	D	Main	R1	73.0	7.4	8.2	235.9	499.4
Oct	E	Main	C1	77.3	7.9	8.1	237.1	373.5
Oct	E	Main	L	76.4	7.8	8.1	236.8	388.0
Oct	E	Main	R1	73.8	7.6	8.1	237.2	406.3
Oct	F	Main	C1	73.7	7.4	8.1	237.7	428.0
Oct	F	Main	L	74.5	7.5	8.1	237.7	418.8
Oct	F	Main	R1	74.6	7.6	8.1	237.5	430.2
Oct	A	DZ	A	60.6	6.6	8.0	224.1	540.3
Oct	A	DZ	B	60.6	6.7	8.0	224.0	535.8
Oct	A	DZ	C	60.4	6.6	8.0	224.2	530.7
Oct	A	DZ	D	62.1	6.8	8.1	224.1	526.5
Oct	A	DZ	E	62.1	6.8	8.1	224.2	523.6
Oct	B	DZ	A	68.9	7.5	8.4	224.6	517.0
Oct	B	DZ	B	67.0	7.4	8.2	226.1	518.7
Oct	B	DZ	C	68.9	7.6	8.3	226.7	517.5
Oct	B	DZ	D	69.0	7.6	8.3	226.4	515.0
Oct	B	DZ	E	70.0	7.6	8.3	225.1	515.0
Oct	C	DZ	A	65.1	6.9	8.1	225.9	518.3
Oct	C	DZ	B	68.6	7.2	8.2	225.6	512.0
Oct	C	DZ	C	67.0	7.1	8.1	227.0	508.7
Oct	C	DZ	D	69.3	7.3	8.2	226.3	495.0
Oct	C	DZ	E	69.7	7.2	8.2	225.7	472.8
Oct	D	DZ	A	60.6	6.2	7.8	238.0	525.0
Oct	D	DZ	B	60.3	6.2	7.9	237.2	521.3
Oct	D	DZ	C	61.0	6.2	7.9	236.8	519.0
Oct	D	DZ	D	71.1	7.2	8.2	236.5	510.7
Oct	D	DZ	E	71.0	7.2	8.2	236.5	508.3
Oct	E	DZ	A	76.9	7.8	8.1	238.6	481.8
Oct	E	DZ	B	81.0	8.2	8.3	260.8	466.0
Oct	E	DZ	C	79.0	8.0	8.1	205.7	441.6
Oct	E	DZ	D	74.8	7.5	8.2	243.1	446.8
Oct	E	DZ	E	89.5	8.9	8.5	242.2	400.0
Oct	F	DZ	A	66.6	6.7	7.9	238.0	487.3
Oct	F	DZ	B	75.3	7.6	8.2	236.8	468.3
Oct	F	DZ	C	76.4	7.7	8.2	237.1	470.7
Oct	F	DZ	D	77.8	7.8	8.2	238.6	440.0
Oct	F	DZ	E	76.2	7.6	8.2	237.6	438.7

Appendix 1.10 Nutrient concentrations (mg L^{-1}) measured for main channel and adjacent dead zone. BD = below detection. Minimum detection limits: NH_3 and NO_3+NO_2 - 0.003; RP - 0.002; TKN - 0.01; TP - 0.005.

Month	Site	Type	subsite	NH3	NO3+NO2	RP	TKN	TP
May	A	Main	C1	0.045	0.050	0.006	0.684	0.031
May	A	Main	R1	0.037	0.060	0.006	0.648	0.028
May	B	Main	C1	0.040	0.050	0.006	0.696	0.035
May	B	Main	R1	0.036	0.050	0.005	0.663	0.030
May	C	Main	C1	0.015	0.050	0.004	0.704	0.034
May	C	Main	R1	0.004	0.050	0.006	0.688	0.032
May	D	Main	C1	0.035	0.140	0.011	0.731	0.033
May	D	Main	R1	0.027	0.140	0.009	0.743	0.035
May	E	Main	C1	0.039	0.160	0.008	0.730	0.033
May	E	Main	R1	0.034	0.170	0.007	0.730	0.034
May	F	Main	C1	0.034	0.160	0.012	0.718	0.030
May	F	Main	R1	0.034	0.160	0.010	0.711	0.030
May	A	DZ	A	0.041	0.100	0.006	0.783	0.040
May	A	DZ	C	0.040	0.100	0.005	0.713	0.029
May	B	DZ	A	0.029	0.010	0.006	0.685	0.030
May	B	DZ	C	0.021	0.010	0.005	0.727	0.032
May	C	DZ	A	0.013	0.050	0.007	0.710	0.034
May	C	DZ	C	0.009	0.040	0.004	0.757	0.035
May	D	DZ	A	0.022	0.120	0.005	0.674	0.030
May	D	DZ	C	0.022	0.120	0.005	0.704	0.031
May	E	DZ	A	0.011	0.110	0.005	0.822	0.037
May	E	DZ	C	0.012	0.110	0.008	1.119	0.058
May	F	DZ	A	0.004	0.110	0.003	0.655	0.024
May	F	DZ	C	0.020	0.150	0.008	0.674	0.030
July	A	Main	C1	0.012	BD	0.006	0.598	0.027
July	A	Main	L	0.012	BD	0.005	0.607	0.026
July	A	Main	R1	0.015	BD	0.007	0.560	0.026
July	B	Main	C1	0.025	BD	0.006	0.555	0.025
July	B	Main	L	0.019	BD	0.006	0.578	0.026
July	B	Main	R1	0.024	BD	0.008	0.609	0.029
July	C	Main	C1	0.012	BD	0.007	0.669	0.026
July	C	Main	L	0.011	BD	0.007	0.640	0.025
July	C	Main	R1	0.012	BD	0.007	0.622	0.028
July	D	Main	C1	0.019	BD	0.008	0.669	0.027
July	D	Main	L	0.014	BD	0.008	0.712	0.027
July	D	Main	R1	0.019	BD	0.011	0.657	0.030
July	E	Main	C1	0.018	0.010	0.020	0.712	0.034
July	E	Main	L	0.010	BD	0.020	0.776	0.030
July	E	Main	R1	0.016	0.010	0.019	0.648	0.028
July	F	Main	C1	0.062	0.030	0.029	0.673	0.033
July	F	Main	L	0.061	0.030	0.031	0.706	0.032
July	F	Main	R1	0.068	0.030	0.028	0.730	0.030
July	A	DZ	A	0.040	BD	0.025	0.758	0.069
July	A	DZ	C	0.041	BD	0.021	0.743	0.052
July	A	DZ	D	0.038	BD	0.015	0.729	0.049
July	B	DZ	A	0.020	BD	0.006	0.647	0.029

Month	Site	Type	Subsite	NH3	NO3+NO2	RP	TKN	TP
July	B	DZ	C	0.020	BD	0.007	0.634	0.028
July	B	DZ	E	0.020	BD	0.006	0.642	0.027
July	C	DZ	A	0.022	BD	0.010	0.761	0.046
July	C	DZ	C	0.009	BD	0.008	0.772	0.040
July	C	DZ	E	0.010	BD	0.007	0.650	0.030
July	D	DZ	A	0.018	BD	0.026	0.890	0.072
July	D	DZ	C	0.025	BD	0.012	0.748	0.040
July	D	DZ	E	0.012	BD	0.011	0.687	0.033
July	E	DZ	A	0.004	BD	0.024	1.001	0.054
July	E	DZ	C	0.009	BD	0.025	1.032	0.048
July	E	DZ	E	0.007	BD	0.019	0.732	0.041
July	F	DZ	A	0.041	0.020	0.029	0.783	0.033
July	F	DZ	C	0.046	0.020	0.032	0.815	0.039
July	F	DZ	E	0.062	0.030	0.034	0.638	0.032
Oct	A	Main	Cl	0.021	0.020	0.007	0.528	0.022
Oct	A	Main	L	0.017	0.020	0.007	0.542	0.022
Oct	A	Main	Rl	0.019	0.020	0.010	0.555	0.023
Oct	B	Main	Cl	0.027	0.020	0.007	0.539	0.023
Oct	B	Main	L	0.026	0.020	0.007	0.564	0.028
Oct	B	Main	Rl	0.026	0.020	0.006	0.536	0.022
Oct	C	Main	Cl	0.031	0.010	0.006	0.536	0.022
Oct	C	Main	L	0.032	BD	0.005	0.553	0.024
Oct	C	Main	Rl	0.036	0.010	0.007	0.582	0.024
Oct	D	Main	Cl	0.030	0.020	0.007	0.571	0.021
Oct	D	Main	L	0.029	0.020	0.007	0.549	0.021
Oct	D	Main	Rl	0.031	0.020	0.007	0.571	0.021
Oct	E	Main	Cl	0.022	0.030	0.003	0.546	0.024
Oct	E	Main	L	0.020	0.030	0.009	0.539	0.022
Oct	E	Main	Rl	0.021	0.030	0.002	0.572	0.023
Oct	F	Main	Cl	0.032	0.040	0.012	0.540	0.021
Oct	F	Main	L	0.034	0.040	0.010	0.544	0.022
Oct	F	Main	Rl	0.031	0.030	0.010	0.570	0.026
Oct	A	DZ	A	0.049	0.020	0.009	0.559	0.026
Oct	A	DZ	C	0.035	0.020	0.010	0.561	0.023
Oct	A	DZ	E	0.024	0.020	0.010	0.543	0.021
Oct	B	DZ	A	0.018	0.020	0.007	0.588	0.024
Oct	B	DZ	D	0.021	0.020	0.007	0.579	0.025
Oct	B	DZ	E	0.021	0.010	0.007	0.571	0.024
Oct	C	DZ	A	0.034	BD	0.006	0.558	0.026
Oct	C	DZ	C	0.034	BD	0.006	0.572	0.027
Oct	C	DZ	E	0.031	BD	0.006	0.556	0.024
Oct	D	DZ	A	0.036	BD	0.006	0.641	0.029
Oct	D	DZ	C	0.024	0.010	0.006	0.591	0.024
Oct	D	DZ	E	0.035	0.020	0.007	0.592	0.026
Oct	E	DZ	A	0.030	0.020	0.007	0.645	0.037
Oct	E	DZ	C	0.012	BD	0.003	0.615	0.026
Oct	E	DZ	E	0.024	0.010	0.003	0.579	0.022
Oct	F	DZ	A	0.023	0.030	0.005	0.514	0.020
Oct	F	DZ	C	0.023	0.030	0.009	0.529	0.023
Oct	F	DZ	E	0.034	0.030	0.011	0.573	0.029

Appendix 1.11 Chl-*a* concentration (μg L^{-1}) measured for suspended algae retained on filters of 0.2, 2.0, 20 and 64 μm pore size. NA = not available (missing sample)

Month	Site	Type	subsite	Chl-*a* 0.2	Chl-*a* 2	Chl-*a* 20	Chl-*a* 64
May	A	Main	C1	8.89	5.14	3.15	1.15
May	A	Main	C2	8.24	6.24	3.05	1.29
May	A	Main	L	NA	NA	NA	NA
May	A	Main	R1	8.63	4.28	2.80	1.36
May	A	Main	R2	10.06	4.89	4.19	1.74
May	B	Main	C1	8.09	5.21	3.12	0.97
May	B	Main	C2	5.97	4.23	3.49	0.95
May	B	Main	L	5.01	NA	3.37	2.37
May	B	Main	R1	8.50	7.16	2.42	1.18
May	B	Main	R2	8.26	4.84	5.16	2.23
May	C	Main	C1	12.88	8.32	2.45	0.86
May	C	Main	C2	18.36	11.14	3.07	0.57
May	C	Main	L	18.36	9.99	3.61	0.35
May	C	Main	R1	14.71	9.21	3.19	0.34
May	C	Main	R2	14.49	8.74	2.55	0.60
May	D	Main	C1	11.51	5.39	1.93	0.83
May	D	Main	C2	8.23	5.46	1.96	0.48
May	D	Main	L	12.60	5.96	1.83	0.43
May	D	Main	R1	11.05	7.22	2.37	1.10
May	D	Main	R2	6.94	5.10	1.59	0.52
May	E	Main	C1	6.76	3.14	0.62	0.25
May	E	Main	C2	8.43	10.46	1.65	0.66
May	E	Main	L	7.49	3.84	0.80	0.50
May	E	Main	R1	6.08	4.24	1.11	0.35
May	E	Main	R2	8.33	3.71	0.33	0.11
May	F	Main	C1	5.43	3.97	0.68	0.16
May	F	Main	C2	5.41	2.94	1.64	1.16
May	F	Main	L	NA	NA	NA	NA
May	F	Main	R1	5.81	3.04	2.02	0.23
May	F	Main	R2	6.52	3.34	0.80	1.70
May	A	DZ	A	10.95	6.81	2.77	2.12
May	A	DZ	B	7.13	9.63	4.52	3.47
May	A	DZ	C	11.04	7.12	3.10	NA
May	A	DZ	D	10.64	5.88	1.93	0.48
May	A	DZ	E	10.70	5.50	11.96	1.29
May	B	DZ	A	9.47	5.67	3.76	3.77
May	B	DZ	B	10.95	6.93	3.24	4.72
May	B	DZ	C	13.54	6.36	6.85	10.99
May	B	DZ	D	15.05	6.44	2.80	1.49
May	B	DZ	E	15.21	6.07	5.49	4.49
May	C	DZ	A	14.24	9.97	3.39	0.85
May	C	DZ	B	15.97	11.83	4.71	3.16
May	C	DZ	C	18.49	11.83	11.99	16.40
May	C	DZ	D	15.27	13.30	3.15	2.21
May	C	DZ	E	12.60	9.48	2.37	1.35
May	D	DZ	A	7.83	5.14	3.34	1.29

Month	Site	Type	subsite	Chl-*a* 0.2	Chl-*a* 2	Chl-*a* 20	Chl-*a* 64
May	D	DZ	B	13.17	6.24	2.50	1.56
May	D	DZ	C	19.75	10.66	8.29	8.20
May	D	DZ	D	12.23	8.81	6.78	3.80
May	D	DZ	E	9.93	5.50	3.44	2.64
May	E	DZ	A	2.37	7.22	1.71	1.04
May	E	DZ	B	11.81	5.43	2.25	2.56
May	E	DZ	C	16.19	8.46	5.36	5.17
May	E	DZ	D	13.42	8.23	13.11	16.18
May	E	DZ	E	16.83	14.03	5.63	16.74
May	F	DZ	A	7.31	5.24	2.06	0.99
May	F	DZ	B	17.63	8.33	5.16	3.35
May	F	DZ	C	52.81	14.26	17.65	34.34
May	F	DZ	D	16.74	11.26	2.45	1.62
May	F	DZ	E	25.23	12.65	8.98	12.57
July	A	Main	C1	11.34	6.59	1.29	0.16
July	A	Main	C2	11.55	6.72	1.22	0.19
July	A	Main	L	11.66	6.83	1.74	0.37
July	A	Main	R1	13.51	7.80	1.99	0.16
July	A	Main	R2	13.31	8.48	1.42	0.19
July	B	Main	C1	12.28	7.22	2.12	0.21
July	B	Main	C2	12.80	5.55	2.19	0.31
July	B	Main	L	13.41	6.83	2.16	0.22
July	B	Main	R1	12.80	7.61	1.94	0.26
July	B	Main	R2	13.10	7.42	2.01	0.21
July	C	Main	C1	11.55	6.63	1.87	0.39
July	C	Main	C2	13.51	7.71	2.35	0.37
July	C	Main	L	12.38	6.93	2.06	0.34
July	C	Main	R1	11.66	6.59	1.41	0.24
July	C	Main	R2	12.69	6.83	1.78	0.41
July	D	Main	C1	17.56	11.08	3.07	0.54
July	D	Main	C2	16.46	10.09	3.82	0.71
July	D	Main	L	16.86	11.08	3.51	0.70
July	D	Main	R1	13.82	9.05	2.72	0.52
July	D	Main	R2	14.23	10.79	3.31	0.52
July	E	Main	C1	15.25	11.82	3.86	0.88
July	E	Main	C2	18.56	13.11	3.31	0.59
July	E	Main	L	17.06	11.40	3.55	0.59
July	E	Main	R1	14.74	9.86	3.85	0.51
July	E	Main	R2	13.72	10.70	3.42	0.61
July	F	Main	C1	3.01	1.61	0.78	0.16
July	F	Main	C2	3.56	1.71	0.85	0.36
July	F	Main	L	3.94	1.99	0.65	0.25
July	F	Main	R1	2.37	1.81	0.52	0.10
July	F	Main	R2	2.70	1.66	0.75	0.28
July	A	DZ	A	13.00	12.95	2.61	0.99
July	A	DZ	B	19.19	19.22	3.88	1.09
July	A	DZ	C	11.44	11.73	2.23	1.19
July	A	DZ	D	9.56	7.95	3.80	0.85

Month	Site	Type	subsite	Chl-*a* 0.2	Chl-*a* 2	Chl-*a* 20	Chl-*a* 64
July	A	DZ	E	14.36	10.98	3.62	2.19
July	B	DZ	A	7.30	6.44	1.63	0.41
July	B	DZ	B	8.81	6.98	2.27	2.22
July	B	DZ	C	8.60	7.07	2.19	0.66
July	B	DZ	D	10.40	7.84	2.63	0.46
July	B	DZ	E	7.41	6.51	2.21	0.87
July	C	DZ	A	14.54	10.98	3.80	1.01
July	C	DZ	B	13.31	9.80	3.16	1.40
July	C	DZ	C	13.82	9.60	3.35	0.98
July	C	DZ	D	10.72	6.88	1.18	0.61
July	C	DZ	E	12.28	8.09	2.16	0.59
July	D	DZ	A	12.28	8.52	3.33	1.41
July	D	DZ	B	13.51	9.95	3.57	1.78
July	D	DZ	C	9.87	6.29	2.82	0.75
July	D	DZ	D	12.18	8.14	2.58	1.51
July	D	DZ	E	9.87	9.48	5.06	1.13
July	E	DZ	A	9.56	12.84	0.88	6.06
July	E	DZ	B	16.66	13.48	3.71	4.27
July	E	DZ	C	7.95	5.40	1.06	0.44
July	E	DZ	D	9.03	8.52	2.39	1.65
July	E	DZ	E	22.20	4.35	1.88	1.28
July	F	DZ	A	NA	7.85	1.65	0.92
July	F	DZ	B	6.75	4.38	1.86	1.02
July	F	DZ	C	9.56	6.49	2.11	1.68
July	F	DZ	D	13.87	4.49	3.12	1.28
July	F	DZ	E	4.40	2.92	1.19	1.22
Oct	A	Main	C1	5.23	3.47	1.15	0.36
Oct	A	Main	C2	5.44	3.97	1.46	0.50
Oct	A	Main	L	5.48	4.04	1.41	0.22
Oct	A	Main	R1	6.03	3.58	1.31	0.55
Oct	A	Main	R2	8.91	6.78	3.04	1.37
Oct	B	Main	C1	5.49	3.24	1.25	0.46
Oct	B	Main	C2	5.58	3.66	1.29	0.37
Oct	B	Main	L	6.10	3.82	1.47	0.54
Oct	B	Main	R1	5.23	3.61	1.24	0.42
Oct	B	Main	R2	5.32	3.35	1.31	0.31
Oct	C	Main	C1	8.66	5.69	1.46	0.42
Oct	C	Main	C2	9.49	6.30	1.81	0.48
Oct	C	Main	L	9.41	6.22	1.60	0.57
Oct	C	Main	R1	7.56	5.24	1.51	0.47
Oct	C	Main	R2	8.83	5.77	1.66	0.54
Oct	D	Main	C1	6.62	3.34	0.56	0.15
Oct	D	Main	C2	6.28	3.22	0.57	0.09
Oct	D	Main	L	6.71	3.42	0.39	0.08
Oct	D	Main	R1	5.54	2.90	0.65	0.11
Oct	D	Main	R2	6.19	3.10	0.57	0.08
Oct	E	Main	C1	4.28	3.18	0.36	0.08
Oct	E	Main	C2	4.54	2.90	0.43	0.08

Month	Site	Type	subsite	Chl-*a* 0.2	Chl-*a* 2	Chl-*a* 20	Chl-*a* 64
Oct	E	Main	L	4.49	3.07	0.42	0.08
Oct	E	Main	R1	4.07	3.15	0.22	0.07
Oct	E	Main	R2	4.69	2.61	0.48	0.08
Oct	F	Main	C1	1.81	0.95	0.23	0.04
Oct	F	Main	C2	2.27	1.18	0.25	0.07
Oct	F	Main	L	2.33	1.26	0.26	0.07
Oct	F	Main	R1	2.02	1.19	0.28	0.07
Oct	F	Main	R2	2.04	1.00	0.21	0.07
Oct	A	DZ	A	6.24	3.87	1.95	0.86
Oct	A	DZ	B	4.87	3.27	1.31	0.52
Oct	A	DZ	C	5.14	3.09	1.37	0.49
Oct	A	DZ	D	4.79	3.44	0.99	0.58
Oct	A	DZ	E	5.58	3.74	1.46	0.49
Oct	B	DZ	A	9.24	5.41	2.86	0.99
Oct	B	DZ	B	7.90	5.65	1.06	0.67
Oct	B	DZ	C	8.07	5.30	1.56	0.77
Oct	B	DZ	D	8.74	6.04	1.91	0.64
Oct	B	DZ	E	8.99	5.89	2.02	0.96
Oct	C	DZ	A	8.63	6.54	1.39	1.02
Oct	C	DZ	B	9.24	6.10	2.43	0.71
Oct	C	DZ	C	9.57	6.34	1.50	0.58
Oct	C	DZ	D	9.24	5.73	1.87	0.54
Oct	C	DZ	E	8.07	5.53	1.57	0.49
Oct	D	DZ	A	9.08	5.28	1.90	1.10
Oct	D	DZ	B	7.65	4.64	0.98	0.58
Oct	D	DZ	C	5.23	3.24	0.89	0.46
Oct	D	DZ	D	6.88	3.77	0.93	0.24
Oct	D	DZ	E	9.33	5.79	1.54	0.46
Oct	E	DZ	A	7.46	5.77	3.56	0.39
Oct	E	DZ	B	6.49	3.61	0.61	0.41
Oct	E	DZ	C	8.38	4.75	0.57	0.43
Oct	E	DZ	D	5.84	3.61	0.66	0.44
Oct	E	DZ	E	5.23	4.24	0.56	0.19
Oct	F	DZ	A	3.02	1.61	0.66	0.09
Oct	F	DZ	B	NA	1.61	0.30	0.19
Oct	F	DZ	C	2.62	2.34	1.12	0.61
Oct	F	DZ	D	3.56	1.76	0.87	0.17
Oct	F	DZ	E	4.42	3.00	1.62	0.53

Appendix 2.1 Location of sampling sites on the Rideau River.

Site	Description	Latitude	Longitude
1	Smiths Falls N502	44°53.81N	76°01.44W
2	Smiths Falls N474	44°53.45N	75°59.82W
3	Otter Creek N458	44°52.84N	75°59.20W
4	Edmunds Lock	44°52.35N	75°58.76W
5	N422	44°52.18N	75°56.91W
6	N403	44°53.12N	75°56.36W
7	N392	44°52.43N	75°55.56W
8	N374	44°52.09N	75°54.58W
9	N356	44°52.20N	75°53.03W
10	N342	44°53.26N	75°52.65W
11	N326	44°54.27N	75°52.19W
12	Merrickville N305	44°54.97N	75°50.83W
13	Merrickville N284	44°55.73N	75°49.87W
14	Clowes Lock	44°56.70N	75°49.38W
15	Lower Nicholsons N253	44°57.69N	75°49.15W
16	Burritts Rapids N247	44°58.46N	75°48.67W
17	N227	44°59.33N	75°46.43W
18	N222	45°00.14N	75°45.51W
19	The Catchall	45°00.94N	75°43.97W
20	Barnes Island N191	45°01.43N	75°42.62W
21	Libby Island N175	45°02.30N	75°41.80W
22	Kemptville	45°02.83N	75°40.81W
23	Kemptville Creek N160	45°03.62N	75°39.37W
24	N152	45°04.52N	75°38.41W
25	Baxter Centre N144	45°05.46N	75°37.86W
26	N129	45°06.88N	75°37.44W
27	N121	45°07.76N	75°38.09W
28	N118	45°08.61N	75°38.60W
29	Kars Bridge N113	45°09.71N	75°38.03W
30	Long Reach	45°10.58N	75°37.79W
31	Long Reach	45°11.34N	75°38.10W
32	N99	45°12.54N	75°39.11W
33	Long Island N91	45°13.21N	75°40.09W
34	Long Island N69	45°14.10N	75°41.03W
35	Long Island Locks	45°14.95N	75°42.19W
36	Jock River	45°16.27N	75°42.08W
37	Gloucester Glen	45°17.51N	75°41.91W
38	N44	45°18.38N	75°41.73W
39	Blacks Rapids	45°19.25N	75°41.78W
40	Ottawa Int'l Airport	45°20.47N	75°41.88W
41	Nepean Creek	45°21.10N	75°42.09W

Appendix 2.2 Chlorophyll-*a* concentration ($\mu g \cdot L^{-1}$) measured for total suspended algae sampled in the main channel of the Rideau River, 2000.

Site	Sample	May Chl-*a*	July Chl-*a*	Sept Chl-*a*
1	A	5.27	5.18	3.97
1	B	5.62	5.12	4.14
1	C	5.97	5.01	4.05
2	A	6.13	4.26	3.97
2	B	5.74	4.43	4.03
2	C	6.32	4.26	4.09
3	A	6.35	3.91	3.97
3	B	6.32	4.03	3.86
3	B	6.57	3.45	4.20
4	A	5.74	3.91	4.03
4	B	6.44	3.10	4.37
4	C	6.20	3.68	4.66
5	A	8.52	3.91	5.58
5	B	8.75	5.41	5.52
5	C	9.90	6.10	5.70
6	A	13.45	4.14	5.75
6	B	13.53	3.68	5.98
6	C	14.36	4.60	6.10
7	A	12.08	3.91	5.24
7	B	12.99	3.80	5.75
7	C	11.96	3.57	5.70
8	A	9.67	4.72	6.10
8	B	10.82	4.72	6.55
8	C	10.82	4.72	6.55
9	A	11.27	5.98	7.58
9	B	12.65	4.95	7.86
9	C	11.28	5.92	7.86
10	A	10.36	7.01	9.11
10	B	11.39	3.22	9.79
10	C	10.70	5.92	9.84
11	A	9.21	5.70	9.05
11	B	11.05	4.95	9.28
11	C	9.21	5.75	9.05
12	A	10.82	6.04	7.41
12	B	10.36	5.24	7.58
12	C	n/a	5.81	7.52
13	A	8.52	4.95	5.64
13	B	9.44	5.06	5.64
13	C	8.98	5.06	5.87
14	A	8.98	5.41	7.29
14	B	9.44	5.18	7.80
14	C	8.75	5.87	7.46
15	A	8.75	5.98	4.26
15	B	8.52	5.75	3.86
15	C	8.75	5.58	4.03
16	A	11.05	8.03	5.00
16	B	10.47	8.15	5.70

Site	Sample	May Chl-*a*	July Chl-*a*	Sept Chl-*a*
16	C	9.44	8.66	5.18
17	A	9.38	5.47	3.86
17	B	8.49	5.47	3.80
17	C	9.50	5.70	3.86
18	A	10.12	5.52	3.04
18	B	9.32	5.58	3.74
18	C	8.51	5.64	3.86
19	A	8.70	6.50	3.80
19	B	9.29	6.32	4.20
19	C	9.84	6.44	3.97
20	A	10.75	6.67	4.72
20	B	13.02	6.44	5.58
20	C	12.42	6.78	5.52
21	A	10.65	7.24	5.58
21	B	10.80	7.29	5.64
21	C	10.63	7.01	5.87
22	A	10.50	7.58	5.41
22	B	12.49	6.72	5.29
22	C	10.15	6.61	5.06
23	A	11.85	8.49	5.92
23	B	12.65	7.80	5.87
23	C	11.73	8.32	5.87
24	A	8.98	8.03	5.81
24	B	8.98	8.71	6.10
24	C	9.44	8.49	5.87
25	A	10.36	8.37	6.32
25	B	10.24	7.92	6.32
25	C	8.06	8.94	5.81
26	A	9.90	7.24	5.01
26	B	11.28	6.78	5.12
26	C	11.28	7.69	4.95
27	A	10.13	7.92	5.06
27	B	9.90	8.83	4.84
27	C	11.62	7.69	5.18
28	A	7.13	9.96	3.39
28	B	6.44	10.53	3.28
28	C	7.02	10.53	3.57
29	A	5.85	11.10	3.45
29	B	6.39	10.53	3.57
29	C	7.71	10.53	3.86
30	A	5.24	11.67	4.09
30	B	5.17	12.80	3.97
30	D	5.21	10.53	3.68
31	A	5.52	4.84	3.16
31	B	5.70	5.81	3.33
31	C	5.57	5.98	3.68
32	A	3.54	3.91	1.28
32	B	3.95	3.22	1.40
32	C	4.65	4.03	1.40
33	A	3.32	2.35	1.22

Site	Sample	May Chl-*a*	July Chl-*a*	Sept Chl-*a*
33	B	2.95	2.29	1.21
33	C	3.27	2.35	1.18
34	A	3.35	1.56	0.90
34	B	5.26	2.11	1.30
34	C	5.18	1.99	1.15
35	A	3.12	2.99	1.37
35	B	3.61	2.52	1.21
35	C	4.58	3.16	1.40
36	A	3.05	1.62	0.82
36	B	3.59	1.93	0.84
36	C	3.81	1.87	0.86
37	A	3.44	2.76	0.85
37	B	3.74	2.70	0.84
37	C	3.25	2.87	0.82
38	A	2.95	3.80	1.12
38	B	2.80	3.10	1.11
38	C	2.60	3.10	1.13
39	A	1.98	4.03	0.93
39	A	2.32	4.95	1.01
39	B	3.07	5.06	0.93
40	A	2.42	2.52	0.82
40	B	3.35	2.11	0.90
40	C	3.12	2.40	0.82
41	A	2.09	1.89	0.97
41	B	2.17	1.79	0.84
41	C	2.07	1.89	0.80

Appendix 2.3 Total phosphorus concentrations ($mg \cdot L^{-1}$) measured at 41 sites along the Rideau River in May, July and September 2000. n/a – result not obtained from RMOC.

Site	Sample	TP		
		May	July	Sept
1	A	0.016	0.016	0.011
1	B	0.016	0.019	0.013
2	A	0.016	0.016	0.01
2	B	0.017	0.014	0.011
3	A	0.018	0.017	0.012
3	B	0.017	0.017	0.014
4	A	0.022	0.017	n/a
4	C	0.021	0.017	n/a
5	A	0.022	0.015	0.011
5	B	0.02	0.022	0.012
6	A	0.025	0.018	0.012
6	B	0.026	0.019	0.012
7	A	0.028	0.017	0.012
7	B	0.028	0.02	0.014
8	A	0.021	0.021	0.013
8	B	0.027	0.02	0.014
9	A	0.027	0.021	0.013
9	B	0.028	0.019	0.015
10	A	0.024	0.019	0.016
10	B	0.022	0.021	0.015
11	A	0.02	0.021	0.015
11	B	0.021	0.021	0.019
12	A	0.023	0.022	0.016
12	C	0.026	0.021	0.015
13	A	0.023	0.024	0.014
13	B	0.022	0.023	0.014
14	A	0.025	0.022	0.017
14	B	0.024	0.022	0.017
15	A	0.029	0.024	0.015
15	B	0.025	0.025	0.013
16	A	0.017	0.035	0.016
16	C	0.025	n/a	0.018
17	A	0.026	0.024	0.021

Site	Sample	TP		
		May	July	Sept
17	B	0.028	0.024	0.019
18	A	0.024	0.027	n/a
18	B	0.026	0.027	n/a
19	A	0.029	0.029	n/a
19	B	0.025	0.028	n/a
20	A	0.025	0.033	n/a
20	B	0.029	0.031	n/a
21	A	0.024	0.032	n/a
21	B	0.025	0.033	n/a
22	A	0.025	0.034	0.017
22	C	0.031	0.03	0.018
23	A	0.027	0.03	n/a
23	B	0.031	0.032	n/a
24	A	0.038	0.03	n/a
24	B	0.025	0.027	n/a
25	A	0.023	0.029	0.018
25	C	0.021	0.03	0.018
26	A	0.023	0.033	n/a
26	B	0.026	0.027	n/a
27	A	0.026	0.032	n/a
27	B	0.028	0.03	n/a
28	A	0.02	0.029	n/a
28	B	0.02	0.028	n/a
29	A	0.022	0.033	0.02
29	C	0.02	0.035	0.02
30	A	0.021	0.03	0.02
30	B	0.021	0.032	0.02
31	A	0.019	0.037	0.02
31	B	0.019	0.037	0.021
32	A	0.015	0.038	0.023
32	B	0.019	0.04	0.022
33	A	0.016	0.037	0.021
33	B	0.015	0.035	0.022
34	A	0.017	0.035	0.021
34	B	0.017	0.037	0.021
35	A	0.015	0.037	n/a
35	C	0.018	n/a	n/a
36	A	0.017	0.039	0.027

Site	Sample	TP		
		May	July	Sept
36	C	0.019	0.041	0.025
37	A	0.019	0.045	0.028
37	B	0.02	0.042	0.028
38	A	0.017	0.043	0.029
38	B	0.019	0.043	0.028
39	A	0.017	n/a	0.029
39	C	0.018	n/a	n/a
40	A	0.018	0.046	0.031
40	B	0.019	0.046	0.03
41	A	0.018	0.047	0.029
41	B	0.017	0.049	0.029

Appendix 2.4 Area of water ($m^2 \cdot 10^3$) of each depth class (units are feet) for 40 consecutive reaches along the Rideau River, from Smiths Falls to Nepean Creek.

Reach	'foreshore"	0-3	3-6	6-12	12-24
1	6.4	36.5	113.6	129.3	0.0
2	7.2	107.5	146.5	138.2	5.5
3	2.7	54.1	101.4	88.5	11.3
4	350.1	512.0	615.3	136.7	0.0
5	407.2	203.9	1096.7	98.1	0.0
6	58.2	304.8	226.7	91.6	0.0
7	323.0	408.2	587.0	176.5	8.6
8	1218.5	224.8	1073.0	220.9	0.0
9	180.1	201.3	402.2	175.0	60.3
10	202.0	139.6	371.4	215.8	35.3
11	164.9	558.9	279.5	151.1	17.2
12	15.0	169.0	188.2	131.4	3.8
13	0.7	59.6	93.8	177.3	31.4
14	3.6	55.4	98.0	106.8	0.0
15	0.0	96.1	88.4	78.6	45.4
16	0.0	58.9	204.8	128.2	28.9
17	0.0	80.5	100.1	95.9	0.0
18	207.2	112.9	178.4	158.0	7.3
19	503.9	17.9	63.3	125.9	34.5
20	543.3	11.9	88.9	104.5	88.9
21	348.2	21.6	34.7	75.8	94.0
22	226.1	144.0	504.3	151.7	163.7
23	186.0	175.6	482.9	288.7	202.4
24	215.8	171.4	187.1	123.3	204.5
25	70.4	285.0	267.4	149.9	273.7
26	391.0	123.7	47.9	58.5	152.4
27	39.5	75.9	26.2	64.6	148.2
28	165.1	33.3	41.6	82.0	160.1
29	23.1	75.3	41.6	35.5	113.0
30	33.8	66.3	39.6	32.8	102.3
31	5.7	75.2	82.4	102.6	57.9
32	0.0	98.1	59.6	78.8	133.0
33	0.0	33.1	65.5	137.5	8.1
34	4.9	44.4	83.1	242.6	93.7
35	0.0	32.6	101.5	229.7	25.1
36	0.8	52.3	108.4	117.6	95.4
37	0.0	55.8	72.1	67.6	64.1
38	30.0	97.1	85.3	78.5	100.7
39	4.2	66.7	95.4	80.6	79.3
40	5.4	31.4	39.1	61.7	24.4
sum	5944.2	5172.4	8583.1	4988.4	2674.6
%	21.7	18.9	31.4	18.2	9.8

Appendix 2.5 Volume of water ($m^3 \cdot 103$) of each depth class (units are feet) for 40 consecutive reaches along the Rideau River, from Smiths Falls to Nepean Creek.

Reach	'foreshore"	0-3	3-6	6-12	12-24
1	2.9	16.7	155.8	354.6	0.0
2	3.3	49.2	200.9	379.0	30.4
3	1.3	24.7	139.1	242.7	62.1
4	160.1	234.1	844.0	375.1	0.0
5	186.2	93.2	1504.2	269.2	0.0
6	26.6	139.4	311.0	251.4	0.0
7	147.7	186.6	805.1	484.2	47.2
8	557.1	102.8	1471.7	606.0	0.0
9	82.3	92.0	551.6	480.2	331.0
10	92.4	63.8	509.4	591.8	193.7
11	75.4	255.5	383.3	414.6	94.1
12	6.9	77.3	258.1	360.5	20.8
13	0.3	27.2	128.7	486.3	172.5
14	1.7	25.3	134.5	292.9	0.0
15	0.0	43.9	121.3	215.7	249.1
16	0.0	26.9	281.0	351.8	158.6
17	0.0	36.8	137.3	263.1	0.0
18	94.7	51.6	244.7	433.4	39.8
19	230.4	8.2	86.9	345.4	189.1
20	248.4	5.5	121.9	286.6	488.0
21	159.2	9.9	47.6	208.0	515.7
22	103.4	65.8	691.7	416.0	898.0
23	85.0	80.3	662.4	792.0	1110.3
24	98.7	78.3	256.7	338.3	1121.9
25	32.2	130.3	366.8	411.3	1501.7
26	178.7	56.6	65.7	160.4	836.3
27	18.1	34.7	36.0	177.3	813.3
28	75.5	15.2	57.0	224.8	878.5
29	10.6	34.4	57.0	97.3	620.1
30	15.5	30.3	54.3	89.9	561.5
31	2.6	34.4	113.1	281.5	317.9
32	0.0	44.9	81.8	216.1	729.5
33	0.0	15.1	89.8	377.2	44.7
34	2.2	20.3	114.0	665.5	514.0
35	0.0	14.9	139.2	630.2	137.4
36	0.4	23.9	148.7	322.5	523.3
37	0.0	25.5	98.9	185.6	351.9
38	13.7	44.4	117.0	215.4	552.2
39	1.9	30.5	130.8	221.1	435.3
40	2.5	14.3	53.6	169.3	134.1

Appendix 2.6 Percent area of sampling reaches composed of water of each depth class. Depth units are feet.

Reach	"foreshore"	0 – 3	3 – 6	6 – 12	12 - 24
1	2.2	12.8	39.7	45.2	0.0
2	1.8	26.6	36.2	34.1	1.4
3	1.1	21.0	39.3	34.3	4.4
4	21.7	31.7	38.1	8.5	0.0
5	22.5	11.3	60.7	5.4	0.0
6	8.5	44.7	33.3	13.4	0.0
7	21.5	27.2	39.0	11.7	0.6
8	44.5	8.2	39.2	8.1	0.0
9	17.7	19.8	39.5	17.2	5.9
10	21.0	14.5	38.5	22.4	3.7
11	14.1	47.7	23.9	12.9	1.5
12	3.0	33.3	37.1	25.9	0.7
13	0.2	16.4	25.9	48.9	8.7
14	1.4	21.0	37.2	40.5	0.0
15	0.0	31.1	28.7	25.5	14.7
16	0.0	14.0	48.7	30.5	6.9
17	0.0	29.1	36.2	34.7	0.0
18	31.2	17.0	26.9	23.8	1.1
19	67.6	2.4	8.5	16.9	4.6
20	64.9	1.4	10.6	12.5	10.6
21	60.6	3.8	6.0	13.2	16.4
22	19.0	12.1	42.4	12.7	13.8
23	13.9	13.1	36.2	21.6	15.2
24	23.9	19.0	20.7	13.7	22.7
25	6.7	27.2	25.6	14.3	26.2
26	50.5	16.0	6.2	7.6	19.7
27	11.2	21.4	7.4	18.2	41.8
28	34.3	6.9	8.6	17.0	33.2
29	8.0	26.1	14.4	12.3	39.2
30	12.3	24.1	14.4	11.9	37.2
31	1.8	23.2	25.5	31.7	17.9
32	0.0	26.6	16.1	21.3	36.0
33	0.0	13.6	26.8	56.3	3.3
34	1.0	9.5	17.7	51.8	20.0
35	0.0	8.4	26.1	59.1	6.4
36	0.2	14.0	29.0	31.4	25.5
37	0.0	21.5	27.8	26.0	24.7
38	7.7	24.8	21.8	20.1	25.7
39	1.3	20.4	29.2	24.7	24.3
40	3.3	19.4	24.1	38.1	15.1

Appendix 2.7 Percent volume of sampling reaches composed of water of each depth class. Depth units are feet.

Reach	"foreshore"	0 – 3	3 – 6	6 – 12	12 - 24
1	0.5	3.2	29.4	66.9	0.0
2	0.5	7.4	30.3	57.2	4.6
3	0.3	5.3	29.6	51.7	13.2
4	9.9	14.5	52.3	23.3	0.0
5	9.1	4.5	73.3	13.1	0.0
6	3.7	19.1	42.7	34.5	0.0
7	8.8	11.2	48.2	29.0	2.8
8	20.4	3.8	53.8	22.1	0.0
9	5.4	6.0	35.9	31.2	21.5
10	6.4	4.4	35.1	40.8	13.3
11	6.2	20.9	31.3	33.9	7.7
12	0.9	10.7	35.7	49.8	2.9
13	0.0	3.3	15.8	59.7	21.2
14	0.4	5.6	29.6	64.5	0.0
15	0.0	7.0	19.3	34.2	39.5
16	0.0	3.3	34.3	43.0	19.4
17	0.0	8.4	31.4	60.2	0.0
18	11.0	6.0	28.3	50.1	4.6
19	26.8	1.0	10.1	40.2	22.0
20	21.6	0.5	10.6	24.9	42.4
21	16.9	1.0	5.1	22.1	54.8
22	4.8	3.0	31.8	19.1	41.3
23	3.1	2.9	24.3	29.0	40.7
24	5.2	4.1	13.6	17.9	59.2
25	1.3	5.3	15.0	16.8	61.5
26	13.8	4.4	5.1	12.4	64.4
27	1.7	3.2	3.3	16.4	75.3
28	6.0	1.2	4.6	18.0	70.2
29	1.3	4.2	7.0	11.9	75.7
30	2.1	4.0	7.2	12.0	74.7
31	0.3	4.6	15.1	37.6	42.4
32	0.0	4.2	7.6	20.2	68.0
33	0.0	2.9	17.0	71.6	8.5
34	0.2	1.5	8.7	50.6	39.1
35	0.0	1.6	15.1	68.4	14.9
36	0.0	2.3	14.6	31.7	51.4
37	0.0	3.9	14.9	28.0	53.2
38	1.5	4.7	12.4	22.9	58.6
39	0.2	3.7	16.0	27.0	53.1
40	0.7	3.8	14.3	45.3	35.9

Appendix 2.8 Discharge and retention time of sampling reaches in the Rideau River, in May, July and September 2000

Reach	Volume (m^3)	Discharge ($m^3 \cdot s^{-1}$)			Retention time (hr)		
		May	July	Sept	May	July	Sept
1	530006.7	53.0	32.3	16.7	2.8	4.6	8.8
2	662871.7	53.0	32.3	16.7	3.5	5.7	11.1
3	469839.3	53.0	32.3	16.7	2.5	4.0	7.8
4	1613263.2	53.0	38.7	16.7	8.5	11.6	26.9
5	2052817.5	53.0	38.7	16.7	10.8	14.7	34.2
6	728331.6	53.0	38.7	16.7	3.8	5.2	12.2
7	1670806.1	55.8	38.7	16.7	8.3	12.0	27.9
8	2737593.4	55.8	38.7	16.7	13.6	19.6	45.7
9	1537236.3	55.8	38.7	16.7	7.7	11.0	25.6
10	1451199.4	55.8	38.7	19.3	7.2	10.4	20.9
11	1222904.2	55.8	38.7	19.3	6.1	8.8	17.6
12	723595.4	55.8	38.7	19.3	3.6	5.2	10.4
13	815105.6	55.8	38.7	19.3	4.1	5.9	11.7
14	454337.9	55.8	38.7	19.3	2.3	3.3	6.5
15	630053.8	55.8	36.1	19.3	3.1	4.8	9.1
16	818221.6	55.8	36.1	19.3	4.1	6.3	11.8
17	437203.1	55.8	36.1	19.3	2.2	3.4	6.3
18	864297.4	55.8	36.1	19.3	4.3	6.7	12.4
19	859875.4	55.8	36.1	19.3	4.3	6.6	12.4
20	1150258.8	55.8	36.1	19.3	5.7	8.9	16.6
21	940322.1	55.8	36.1	19.3	4.7	7.2	13.5
22	2174883.2	55.8	36.1	19.3	10.8	16.7	31.3
23	2730070.9	57.7	36.1	19.3	13.2	21.0	39.3
24	1893947.3	57.7	36.1	22.6	9.1	14.6	23.3
25	2442275.6	57.7	36.1	22.6	11.8	18.8	30.1
26	1297745.4	57.7	36.1	22.6	6.3	10.0	16.0
27	1079323.0	57.7	36.1	22.6	5.2	8.3	13.3
28	1251099.0	57.7	36.1	22.6	6.0	9.6	15.4
29	819409.3	57.7	26.2	22.6	3.9	8.7	10.1
30	751400.7	57.7	26.2	22.6	3.6	8.0	9.3
31	749405.5	57.7	26.2	22.6	3.6	8.0	9.2
32	1072217.9	57.7	26.2	22.6	5.2	11.4	13.2
33	526759.7	57.7	26.2	22.6	2.5	5.6	6.5
34	1316132.8	57.7	26.2	22.6	6.3	14.0	16.2
35	921749.9	57.7	26.2	22.6	4.4	9.8	11.4
36	1018758.7	58.4	26.2	22.6	4.8	10.8	12.5
37	661893.4	58.4	26.2	22.6	3.2	7.0	8.2
38	942774.5	58.4	26.2	22.6	4.5	10.0	11.6
39	819584.1	58.4	26.2	22.6	3.9	8.7	10.1
40	373843.6	58.4	26.2	22.6	1.8	4.0	4.6

Appendix 2.9 Calculation of change in Chl-*a* per hour (retention time estimated from total volume and discharge), for reaches along the Rideau River in May, July and September 2000.

Reach	Retention time (hr)			Δ Chl-*a*			Δ Chl-*a*·hr^{-1}		
	May	July	Sept	May	July	Sept	May	July	Sept
1	2.8	4.6	8.8	0.44	-0.79	-0.03	0.158	-0.172	-0.003
2	3.5	5.7	11.1	0.36	-0.52	-0.02	0.104	-0.091	-0.002
3	2.5	4.0	7.8	-0.30	-0.23	0.35	-0.122	-0.057	0.044
4	8.5	11.6	26.9	2.94	1.57	1.24	0.348	0.136	0.046
5	10.8	14.7	34.2	4.72	-1.00	0.34	0.439	-0.068	0.010
6	3.8	5.2	12.2	-1.44	-0.38	-0.38	-0.377	-0.074	-0.031
7	8.3	12.0	27.9	-1.90	0.96	0.84	-0.228	0.080	0.030
8	13.6	19.6	45.7	1.29	0.90	1.37	0.095	0.046	0.030
9	7.7	11.0	25.6	-0.91	-0.24	1.81	-0.119	-0.021	0.071
10	7.2	10.4	20.9	-1.00	0.08	-0.45	-0.138	0.008	-0.022
11	6.1	8.8	17.6	0.77	0.23	-1.63	0.126	0.026	-0.092
12	3.6	5.2	10.4	-1.61	-0.67	-1.79	-0.447	-0.129	-0.172
13	4.1	5.9	11.7	0.08	0.46	1.81	0.020	0.078	0.154
14	2.3	3.3	6.5	-0.39	0.29	-3.47	-0.172	0.088	-0.531
15	3.1	4.8	9.1	-0.60	2.51	1.24	-0.191	0.517	0.137
16	4.1	6.3	11.8	1.05	-2.73	-1.46	0.258	-0.434	-0.124
17	2.2	3.4	6.3	0.20	0.04	-0.29	0.092	0.011	-0.046
18	4.3	6.7	12.4	-0.04	0.84	0.44	-0.009	0.126	0.036
19	4.3	6.6	12.4	2.78	0.21	1.29	0.649	0.032	0.104
20	5.7	8.9	16.6	-1.37	0.55	0.42	-0.239	0.062	0.025
21	4.7	7.2	13.5	0.36	-0.21	-0.44	0.077	-0.029	-0.032
22	10.8	16.7	31.3	1.03	1.23	0.63	0.095	0.074	0.020
23	13.2	21.0	39.3	-2.95	0.21	0.04	-0.224	0.010	0.001
24	9.1	14.6	23.3	0.42	0.00	0.23	0.046	0.000	0.010
25	11.8	18.8	30.1	1.27	-1.17	-1.13	0.108	-0.062	-0.037
26	6.3	10.0	16.0	-0.27	0.91	0.00	-0.043	0.091	0.000
27	5.2	8.3	13.3	-3.69	2.20	-1.62	-0.710	0.264	-0.122
28	6.0	9.6	15.4	-0.21	0.38	0.21	-0.035	0.039	0.014
29	3.9	8.7	10.1	-1.44	0.95	0.29	-0.365	0.109	0.029
30	3.6	8.0	9.3	0.39	-6.12	-0.52	0.108	-0.767	-0.056
31	3.6	8.0	9.2	-1.55	-1.82	-2.03	-0.429	-0.229	-0.220
32	5.2	11.4	13.2	-0.87	-1.39	-0.15	-0.168	-0.122	-0.012
33	2.5	5.6	6.5	1.41	-0.44	-0.09	0.556	-0.079	-0.014
34	6.3	14.0	16.2	-0.82	1.01	0.21	-0.129	0.072	0.013
35	4.4	9.8	11.4	-0.29	-1.09	-0.49	-0.065	-0.111	-0.043
36	4.8	10.8	12.5	0.00	0.97	0.00	0.000	0.090	0.000
37	3.2	7.0	8.2	-0.70	0.56	0.28	-0.222	0.079	0.035
38	4.5	10.0	11.6	-0.38	1.35	-0.17	-0.085	0.135	-0.014
39	3.9	8.7	10.1	0.56	-2.34	-0.10	0.144	-0.268	-0.010
40	1.8	4.0	4.6	-0.85	-0.49	0.02	-0.478	-0.123	0.004

Appendix 2.10 Calculation of change in Chl-*a* per hour (retention time estimated from main channel current), for reaches along the Rideau River, in May, July and September, 2000.

Site	Current ($m \cdot s^{-1}$)			Reach	Retention time (hr)			Δ Chl-*a* ($\mu g \cdot l^{-1}$)			Δ Chl-*a*·hr^{-1}		
	May	July	Sept		May	July	Sept	May	July	Sept	May	July	Sept
1			0.25										
2		0.19	0.13	1			3.07	0.44	-0.79	-0.03			-0.01
3		0.10	0.10	2		3.49	4.31	0.36	-0.52	-0.02		-0.15	0.00
4	0.09	0.15	0.05	3		2.28	3.80	-0.30	-0.23	0.35		-0.10	0.09
5	0.02	0.09	0.02	4	13.18	6.43	22.96	2.94	1.57	1.24	0.22	0.24	0.05
6	0.04	0.18	0.02	5	16.12	4.10	30.02	4.72	-1.00	0.34	0.29	-0.24	0.01
7		0.05	0.03	6		4.75	22.09	-1.44	-0.38	-0.38		-0.08	-0.02
8		0.07	0.02	7		10.01	22.79	-1.90	0.96	0.84		0.10	0.04
9		0.09	0.03	8		7.08	20.07	1.29	0.90	1.37		0.13	0.07
10		0.05	0.06	9		7.95	12.89	-0.91	-0.24	1.81		-0.03	0.14
11		0.10	0.06	10		7.68	10.10	-1.00	0.08	-0.45		0.01	-0.04
12		0.10	0.08	11		6.91	9.63	0.77	0.23	-1.63		0.03	-0.17
13		0.13	0.05	12		6.18	10.53	-1.61	-0.67	-1.79		-0.11	-0.17
14	0.06	0.05	0.07	13		5.46	8.14	0.08	0.46	1.81		0.08	0.22
15	0.16	0.17	0.08	14	5.63	5.55	8.08	-0.39	0.29	-3.47	-0.07	0.05	-0.43
16	0.10	0.04	0.05	15	3.72	4.57	7.70	-0.60	2.51	1.24	-0.16	0.55	0.16
17		0.17	0.21	16		9.10	7.65	1.05	-2.73	-1.46		-0.30	-0.19
18		0.26	0.12	17		2.93	3.83	0.20	0.04	-0.29		0.01	-0.08
19		0.33	0.10	18		2.24	6.03	-0.04	0.84	0.44		0.37	0.07
20		0.23	0.06	19		2.17	7.65	2.78	0.21	1.29		0.10	0.17
21		0.03	0.05	20		4.81	11.74	-1.37	0.55	0.42		0.11	0.04
22		0.09	0.03	21		8.54	13.36	0.36	-0.21	-0.44		-0.02	-0.03
23	0.08	0.10	0.04	22		6.87	18.35	1.03	1.23	0.63		0.18	0.03
24	0.06	0.01	0.07	23	8.64	11.62	11.66	-2.95	0.21	0.04	-0.34	0.02	0.00
25	0.10	0.06	0.03	24	7.12	16.55	12.41	0.42	0.00	0.23	0.06	0.00	0.02
26	0.16	0.03	0.02	25	6.29	16.79	36.26	1.27	-1.17	-1.13	0.20	-0.07	-0.03
27	0.13	0.09	0.09	26	3.73	8.60	10.46	-0.27	0.91	0.00	-0.07	0.11	0.00
28	0.13	0.11	0.03	27	4.03	5.08	9.29	-3.69	2.20	-1.62	-0.92	0.43	-0.17
29	0.11	0.14	0.02	28	5.22	4.79	27.91	-0.21	0.38	0.21	-0.04	0.08	0.01
30	0.10	0.18	0.04	29	5.10	3.28	18.81	-1.44	0.95	0.29	-0.28	0.29	0.02
31	0.10	0.07	0.04	30	5.11	4.12	13.48	0.39	-6.12	-0.52	0.08	-1.49	-0.04
32	0.17	0.09	0.09	31	4.62	8.05	10.04	-1.55	-1.82	-2.03	-0.34	-0.23	-0.20
33	0.12	0.08	0.03	32	4.93	8.72	12.01	-0.87	-1.39	-0.15	-0.18	-0.16	-0.01
34	0.20	0.21	0.10	33	3.93	4.36	9.55	1.41	-0.44	-0.09	0.36	-0.10	-0.01
35		0.01	0.02	34		5.37	9.99	-0.82	1.01	0.21		0.19	0.02
36		0.13	0.09	35		10.70	14.00	-0.29	-1.09	-0.49		-0.10	-0.03
37		0.07	0.03	36		6.15	10.54	0.00	0.97	0.00		0.16	0.00
38	0.07	0.04	0.04	37		8.53	13.35	-0.70	0.56	0.28		0.07	0.02
39		0.08	0.04	38		8.82	12.66	-0.38	1.35	-0.17		0.15	-0.01
40		0.09	0.09	39		7.65	9.81	0.56	-2.34	-0.10		-0.31	-0.01
41	0.16	0.11	0.07	40		3.94	4.81	-0.85	-0.49	0.02		-0.12	0.00