Stream ecosystem health in rural mixed land-use watersheds

Marie Claire Brisbois, Rob Jamieson, Robert Gordon, Glenn Stratton, and Ali Madani

Abstract: A paired stream approach was used to assess ecosystem health in two rural Nova Scotia streams (Thomas Brook and Sharpe Brook) with varying land-use practices. The objectives of the study were to assess stream health within an agricultural catchment, the Thomas Brook Watershed, and to identify parameters that could be used to characterize the impacts of agricultural land use on stream ecosystem health within intensively farmed watersheds in Nova Scotia. General water quality (nutrient concentrations, turbidity, pH, temperature) and the hydrology of both watersheds were monitored from May to October 2006. In addition, continuous dissolved oxygen (DO) and chlorophyll *a* data were collected in both streams, and benthic invertebrate populations were characterized during the study period. Diurnal DO data were analyzed to determine photosynthesis and respiration ratios. Macroinvertebrate data provided information on productivity, and on a number of other relevant metrics. Findings determined that agricultural land-use generally led to high nutrient concentrations, large dissolved oxygen variability, turbid waters, high chlorophyll *a* content, and impacted macroinvertebrate populations in streams. Forested land-use demonstrated typically unimpacted conditions. It was concluded that DO dynamics and macroinvertebrate metrics would be very useful for providing a generalized assessment of stream health in agricultural watersheds.

Key words: stream health, agriculture, water quality, macroinvertebrates.

Résumé : Une approche de jumelage de ruisseaux jumelés a été utilisée pour évaluer la santé des écosystèmes dans deux ruisseaux ruraux de Nouvelle-Écosse (le ruisseau Thomas et le ruisseau Sharpe) qui ont des utilisations du territoire différentes. Les objectifs de cette étude étaient d'évaluer la santé des ruisseaux dans un bassin hydrologique agricole, le bassin hydrologique du ruisseau Thomas, et d'identifier les paramètres qui pourraient être utilisés pour caractériser les impacts de l'utilisation du territoire sur la santé des écosystèmes des ruisseaux dans les bassins hydrologiques fortement agricoles de Nouvelle-Écosse. La qualité générale de l'eau (concentrations en nutriments, turbidité, pH, température) ainsi que l'hydrologie des deux bassins hydrologiques ont été surveillés de mai à octobre 2006. De plus, les données continues d'oxygène dissous et de chlorophylle *a* ont été collectées dans les deux ruisseaux; les populations d'invertébrés benthiques ont été caractérisées durant cette période d'étude. Les données d'oxygène dissous diurnes ont été analysées afin de déterminer les rapports de photosynthèse et de respiration. Les données sur les macro-invertébrés ont fourni de l'information sur la productivité ainsi que sur certains autres paramètres pertinents. Les conclusions ont déterminé que l'utilisation agricole du territoire engendrait généralement des concentrations élevées en nutriments, une grande variabilité de l'oxygène dissous, des eaux turbides, un contenu élevé en chlorophylle *a* et qu'il y avait un impact sur les populations de macro-invertébrés dans les ruisseaux. L'utilisation forestière du territoire montre peu d'impact sur les conditions. Il a été conclu que la dynamique de l'oxygène dissous et les paramètres des macro-invertébrés pourraient être très utiles pour fournir une évaluation générale de la santé des ruisseaux dans les bassins hydrographiques agricoles.

Mots-clés : santé des ruisseaux, agriculture, qualité de l'eau, macro-invertébrés.

Introduction

Water quality is an issue of growing concern as global demand for water increases and freshwater resources become increasingly impacted. Many rural streams, especially those in agricultural regions, experience eutrophic conditions as a result of excessive nutrient inputs from agricultural activities or human wastes (Wilcock et al. 1995; Young and Huryn

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1999; Berka et al. 2001). The impacted water systems exhibit a number of undesirable features locally, and also impact higher order streams, reservoirs, lakes and ultimately, ocean waters.

There are a wide range of symptoms of eutrophication resulting from agricultural land use. High nutrient concentrations in streams can lead to an increase in algal growth. Aside from being aesthetically unpleasant, large algal biomasses can disrupt dissolved oxygen (DO) cycling leading to anoxic conditions that are toxic to aquatic life (Mason 1991; Young and Huryn 1999; CCME 2004). Waterways can become choked leading to water stagnation and deposition of stream sediment loads. Surface algae can prevent incoming sunlight from reaching subsurface depths, which can affect benthic life. The result is a disruption of the entire aquatic ecosystem.

Agricultural activities affect stream ecosystem health in other manners. Intensive farming makes soils more susceptible to erosion, resulting in high stream sediment loads. Streams are also subject to contamination by pathogens and pesticides (Wauchope 1978). Application of pH agents to soils can alter stream pH levels in ways that are intolerable to established aquatic communities (Simmons et al. 1996). The removal of riparian vegetation exacerbates these problems by eliminating natural buffer strips.

While the above issues are well documented, the development of environmental standards and robust assessment methods for agricultural watersheds have not been forthcoming. It is difficult to set numerical guidelines for typical agricultural pollutants such as nitrogen (N), phosphorous (P), and sediments, as these pollutants cause impacts that are difficult to quantitatively characterize. As well, numeric criteria must be developed on a regionally specific basis because reference conditions often vary according to parent materials and background conditions. The development of environmental performance standards for agricultural watersheds require regionally based comparative watershed studies.

Monitoring and remediation efforts on the Thomas Brook agricultural watershed in rural Nova Scotia have been ongoing since 2001. The watershed is one of seven watersheds included in the Agriculture and Agri-Food Canada (AAFC) Watershed Evaluation of Beneficial Management Practices (WEBs) program. The goal of the WEBs program is to investigate the value and effectiveness of agricultural beneficial management practices (BMPs) at the watershed scale. Tattrie et al. (2004) previously reported on concentrations and loading of nutrients within the watershed. They observed that Thomas Brook possessed elevated levels of P and N. Phosphorus loading to the stream was driven by surface runoff events while nitrate-nitrogen (NO_3-N) concentrations were highest during baseflow periods, when groundwater was the primary source of streamflow.

An objective of this study was to assess the health of Thomas Brook and produce an ecosystem report for managers of the Thomas Brook WEBs program. In the process of developing this assessment, a second objective, that of identifying suitable parameters for inclusion in a regionally specific, rapid assessment methodology for the determination of stream health, was undertaken. A paired watershed approach was applied with specific focus on the suitability of employing community metabolism measurements and macroinvertebrate population dynamics assessments.

Methods

Study sites

Experimental data were gathered from two tributaries of the Cornwallis River in the Annapolis Valley region of Nova Scotia, Canada, an area dominated by agricultural activity (Fig. 1). The Thomas Brook catchment is located on the north side of the valley. The stream originates on North Mountain and is underlain by basalt and various silt and clay-stones. The Sharpe Brook catchment, which served as a reference watershed in this study as it has a flow regime that is comparable to Thomas Brook, is located on the southern side, originating on South Mountain. Granite, slate, and quartzite underlay the watershed (Trescott 1968). Both watersheds and their respective water sampling sites are illustrated in Fig. 2.

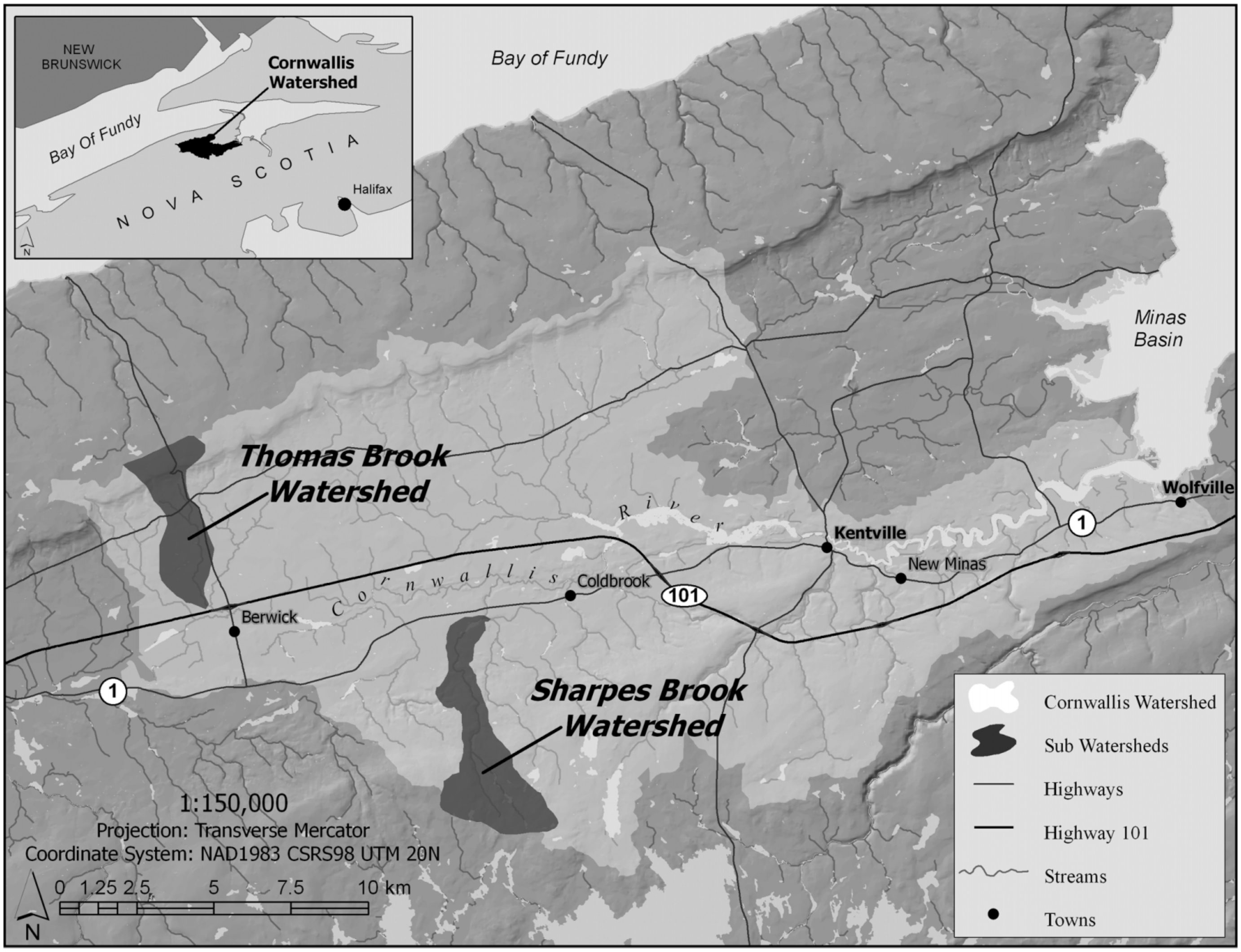
The Thomas Brook basin drains an area of 760 ha. The brook is approximately 5.8 km in length and 2 m in width at the outlet. It is characterized by two branches in the upper reaches that converge approximately one third of the distance through the watershed (Jamieson et al. 2003). Soils are fine grained reddish-brown sandy loams (Blomidon Naturalists Society 1993). Pasture, cropland, forage, a dairy operation, and residential land use dominate the watershed. The dairy operation consists of approximately 150 cows. Both manure and inorganic fertilizers are applied to cropland throughout the watershed. Approximately 70% of land use is agricultural or agricultural support. The remainder is residential with some forest on the valley wall. Riparian vegetation has been removed along approximately 57% of the brook and several reaches have been mechanically straightened.

Sharpe Brook, 15 km from Thomas Brook, has a drainage area of 1300 ha. It is approximately 6.5 km in length and the width varies throughout the basin from <1 m to approximately 4 m in the lower reaches. There are two major tributaries in the headwaters that converge one third of the way through the watershed. Soils are thin, poorly drained and acidic (Agriculture Canada 1989; Blomidon Naturalists Society 1993). Land use is primarily undeveloped forest (~75%) or residential (~20%) with limited quarrying in the upper reaches. Sharpe Brook has functioning riparian zones along approximately 98% of the study reach length.

Monitoring methods

Data were gathered during a five month period from May 2006 to September 2006. This involved the installation of YSI 6920 Multi Parameter Water Quality Monitors (YSI Hydrodata Inc. Letchworth, Hertfordshire, UK) near the outlet of each watershed. The YSI sondes were used to continuously measure in vivo chlorophyll *a* content, DO and water temperature (*T*). Weekly grab samples were collected at sampling sites shown in Fig. 2 for NO_3^--N, total phosphorous (TP), DO, *T*, chlorophyll *a*, pH, and turbidity. Nitrate-nitrogen and TP were analyzed using Standard Method 4110 (2000 version) and Standard Method 4500-P (1999 version), respectively (APHA 2000). Chlorophyll samples were analyzed using USEPA Method 445.0 (USEPA 1997) to deter-

Fig. 1. Thomas and Sharpe Brook Watershed locations in Nova Scotia, Canada.



mine concentrations of extracted chlorophyll *a*. Extracted chlorophyll *a* data were related to corresponding in vivo chlorophyll data gathered by grab sample using a fluorometer (Turner Designs Inc., Sunnyvale, CA 94085), and to the monitors, to correct for variability in the in vivo data resulting from in-stream interference.

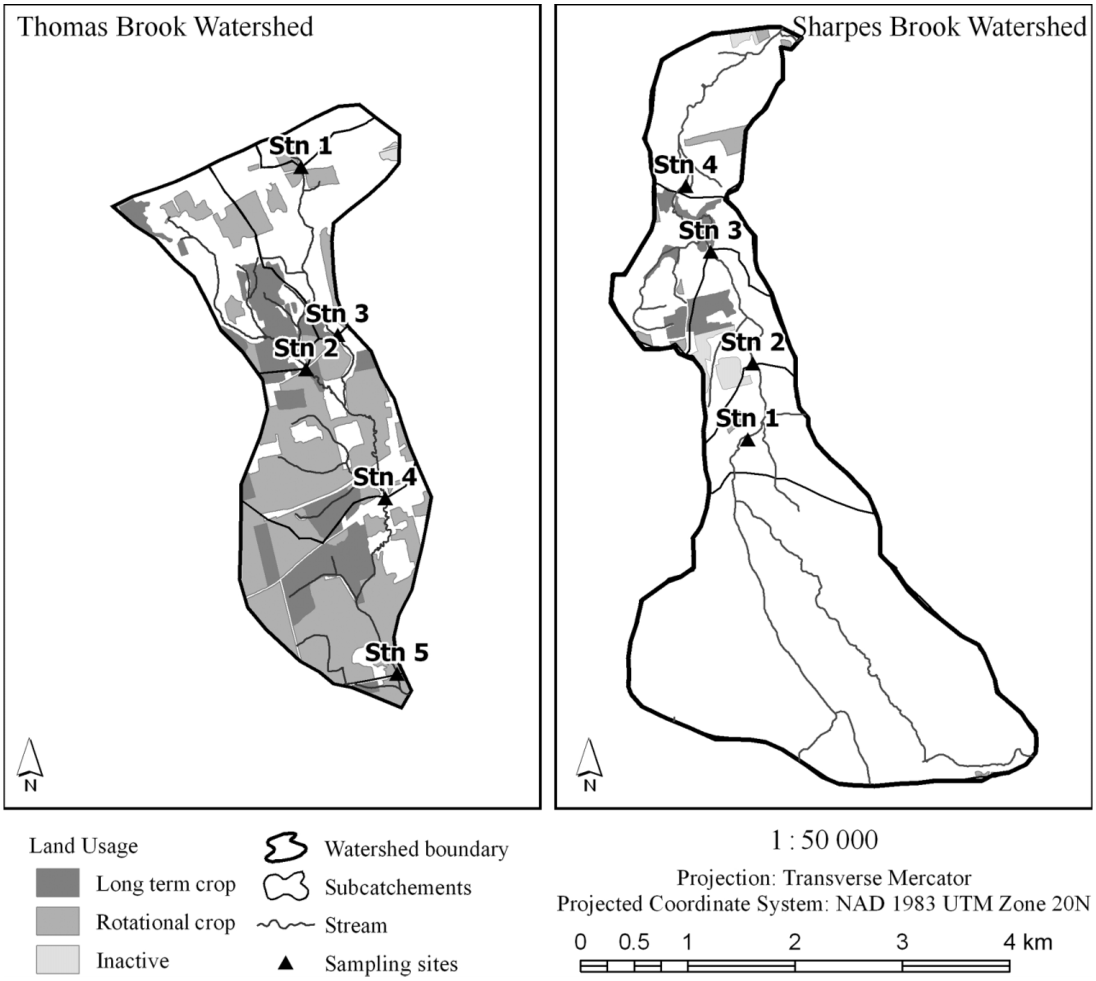
Flow rates were monitored using a Price current meter and the velocity-area method (CGSB 1991). Water level was measured continuously at a v-notch weir at Sharpe Brook site 2 using a HOBO U20 Water Level Logger (Onset Computer Corporation, Pocasset Mass.). Water level measurements were related to discharge values obtained by manual measurements and a stage-discharge relationship was developed. A regression equation was developed to relate the continuous flow measured at site 2 to flow rates manually measured at the outlet of the Sharpe Brook watershed (site 4). Agriculture and Agri-food Canada operate a continuous flow gauging station at the outlet of the Thomas Brook watershed.

Macroinvertebrate surveys were conducted on three dates (31 May, 20 July, and 25 September 2006) over the sampling period using USEPA methodology (Barbour et al. 1999). Three sites in each watershed were sampled. Sites were chosen to reflect the diversity of habitats (pools, riffles, runs) available within the study areas while retaining a geographical basis for valid comparative analysis between the two streams. Three sub-samples were collected at each site to acknowledge any differences in pool, riffle, and run habitats. A 500 μm standard size surber net was used. Sub-samples were combined in a bucket and the net was rinsed into the bucket using stream water. Macroinvertebrates and stream bed materials containing smaller organisms were transferred to jars using tweezers. Stream water was included so that samples were not biased against small, swimming organisms. Samples were preserved using 70% ethanol, identified and enumerated.

Bed sediment samples were collected at all sample sites (Fig. 2) and analyzed to determine particle size distribution by mechanical sieve analysis. Coarse bed material size distribution was only determined at Sharpe Brook as sieve analysis of Thomas Brook sediments revealed predominantly fine grained substrates. Sites were analyzed at Sharpe Brook according to the pebble count technique (Wolman 1954).

Air temperature, solar radiation, and precipitation values were obtained from a weather station operated by Agriculture and Agri-Food Canada at Thomas Brook site 5.

Fig. 2. Watershed land use and sampling sites for Thomas and Sharpe Brooks. Inactive refers to agricultural land that has not been cultivated for several years. The remaining non-shaded areas represent undisturbed (forested) land use.



Data analysis

Delta method for dissolved oxygen

Diurnal DO curves were analyzed using the delta method to obtain estimates of gross primary production (GPP), respiration (R), and re-aeration (Chapra and Di Toro 1991). Re-aeration coefficient values (k) were computed by plotting the change in DO concentration against the DO deficit during the night when photosynthesis (GPP) values are zero. The slope of this graph gives k in units of h^{-1}. A mass balance approach proposed by Odum (1956) was then used to obtain values for GPP and R:

$$[1] \qquad \frac{\mathrm{d[DO]}}{\mathrm{d}t} = \mathrm{GPP}(t) - R(t) + k \times (\mathrm{DO_{sat}} - \mathrm{DO})$$

where DO is the dissolved oxygen concentration (mg L^{-1}), GPP is the rate of gross primary production or photosynthesis (mg L^{-1} h^{-1}), R is the rate of respiration (mg L^{-1} h^{-1}), k is the re-aeration coefficient (h^{-1}), and $\mathrm{DO_{sat}}$ is the DO concentration at saturation (mg L^{-1}).

During the night, when GPP ceases in the absence of solar radiation, this equation reduces to

$$[2] \qquad \frac{\mathrm{d[DO]}}{\mathrm{d}t} = -R(t) + k \times (\mathrm{DO_{sat}} - \mathrm{DO})$$

This equation can be solved to obtain a nighttime average value for R and corrected for variation in temperature by applying the following equation (Chapra 1997):

$$[3] \qquad R(t) = R \times 1.08^{(T - T_\mathrm{a})}$$

where T is the water temperature (°C) and T_a is the night time averaged temperature over the period for which R was determined (°C).

Using average hourly temperatures, hourly $R(t)$ values were computed and substituted into eq. [1] to obtain hourly estimates of GPP(t) during daylight hours. The GPP(t) values were averaged to obtain a daily GPP estimate.

Estimates of k using the delta method in small streams are often inaccurate because of small-scale variability in flow patterns and mechanical reaeration (Young and Huryn 1999). It is therefore desirable to reinforce data using an alternative method. The Surface Renewal Model (SRM) provides another estimate of k using water velocity and depth. A mass transfer coefficient was determined using the following equation (Owens 1974):

$$f_{(20\,^{\circ}\mathrm{C})} = 50.8 \times V^{0.67} \times H^{-0.85} \quad [4]$$

where f is the mass transfer coefficient (cm h^{-1}), V is the water velocity (cm s^{-1}), and H is mean stream depth (cm). The re-aeration coefficient (k) is determined as follows:

$$k_{(20\,^{\circ}\mathrm{C})} = \frac{f_{(20\,^{\circ}\mathrm{C})}}{H_a} \quad [5]$$

where H_a is the mean reach depth (cm).

The $k_{(20\,^{\circ}\mathrm{C})}$ value can be adjusted for temperature by using the following formula (Elmore and West 1961):

$$k_{(T\,^{\circ}\mathrm{C})} = k_{(20\,^{\circ}\mathrm{C})} \times 1.024^{(T-20)} \quad [6]$$

Values of k computed by the SRM method were then substituted into eq. [1] to determine GPP and R.

Paired t tests were used to compare data sets from Thomas and Sharpe Brooks for nutrients, turbidity, DO, and chlorophyll a. Linear regression analysis was performed to assess the relationship between nutrients and chlorophyll a concentration.

Macroinvertebrate data were analyzed using a number of different metrics. Family biotic index (FBI) was computed as follows (Hilsenhoff 1988):

$$\mathrm{FBI} = \sum_{i=0}^{s} n(i) \times t(i) \div \sum_{i=0}^{s} n(i) \quad [7]$$

where n is the number of individuals, t is the tolerance value for a given family, and s is the number of families included in the analysis.

Percent Ephemeroptera (E), Plecoptera (P), and Trichoptera (T) is a valuable metric because individuals within EPT families tend to have lower pollution tolerances (Resh and Grodhaus 1983). This metric is numerically represented as follows:

$$\%\ \mathrm{EPT} = \left[\frac{\left(\sum \mathrm{E} + \sum \mathrm{P} + \sum \mathrm{T}\right)}{\sum n_{\mathrm{j}}}\right] \times 100 \quad [8]$$

where E is the number of Ephemeroptera, P is the number of Plecoptera, and T is the number of Trichoptera.

Chironomidae are considered pollution tolerant and are therefore useful as indicators (Dance and Hynes 1980). Percentage Chironimidae was calculated as follows:

$$\%\ \mathrm{Chironomidae} = \left(\frac{\sum \mathrm{Chironomidae}}{\sum n_j}\right) \times 100 \quad [9]$$

Functional feeding groups (FFG) were also used to quantify a number of metrics. The ratios between individual FFGs, or combinations of FFGs can provide a wide range of ecosystem information. Photosynthesis to R ratios can be established by examining the ratio of shredders and scrapers to total collectors. Values greater than 0.75 are indicative of autotrophic conditions (Merritt and Cummins 1978).

The ratio of coarse particulate organic matter (CPOM) to fine particulate organic matter (FPOM) is indicative of the functioning of riparian systems as measured by shredder associations. It is determined by the ratio of shredders to total collectors. During the fall–winter period, functioning riparian zones are described by ratios of >0.5. During the spring and summer, this ratio is >0.25 (Merritt and Cummins 1978). Channel stability is estimated through the ratio of scrapers and filtering collectors to shredders and gathering collectors. When this ratio is >0.5, it is indicative of a high proportion of stable substrates such as bedrock, boulders, cobbles, and large woody debris (Merritt and Cummins 1978). Photosynthesis to R (GPP/R) ratios were also computed by averaging GPP and R values from the delta method and SRM method. These values were used to generate numerical GPP/R estimates.

Results and discussion

General watershed and climate characteristics

Sharpe Brook sites were characterized by gravel and cobble sediments (2–256 mm) in the headwaters, with sediment size decreasing downstream. Thomas Brook had a high fraction of gravel and cobble in the headwaters, but exhibited rapidly decreasing coarse fractions as agricultural activity increased. Bed sediments in Thomas Brook in the lower part of the watershed were predominantly fine grained. Increasing fractions of sand and silt within bed sediments are expected with increasing land disturbance (Burkhead et al. 1997; Sutherland et al. 2002).

Maximum daily incoming solar radiation levels were relatively constant from May to September with a minimum monthly average value of 12.5 MJ m^{-2} d^{-1} in September and a maximum of 16.2 MJ m^{-2} d^{-1} in August. Air temperature peaked in July. Average maximum daily air temperatures ranged from 20 °C to 25 °C. Rainfall levels were characteristic of normal averages for the study sites and average daily maximum rainfall varied monthly from 0.7 mm in June to 5.3 mm in July.

Hydrology

At Sharpe Brook, the minimum flow rate over the study period was 0.14 m^3 s^{-1}, the maximum was 5.45 m^3 s^{-1}, and the average was 0.96 m^3 s^{-1}. At Thomas Brook, values ranged from 0.01 m^3 s^{-1} to 2.08 m^3 s^{-1} with an average of 0.20 m^3 s^{-1}. Hydrographs and rainfall levels are shown in Fig. 3. The hydrological characteristics of Thomas Brook, as compared to Sharpe Brook, appear consistent with that of watersheds impacted by agricultural land use. Typical impacts, as shown in Fig. 3, include flashier hydrograph responses and lower baseflow levels (Harker et al. 2003)

General water quality (nutrients, turbidity, pH)

Peak TP concentrations were observed following storm flow events in Thomas Brook. Sharpe Brook site 4 experienced a large peak in TP concentrations from the end of August to the middle of September, reaching levels as high as 3.94 mg L^{-1} before decreasing again. The cause of this peak is not known but may be attributable to point source inputs (i.e., wildlife activities) upstream of Sharpe Brook site 3. Concentrations of TP and NO_3^--N at the watershed outlets at Thomas Brook site 5 and Sharpe Brook site 4 are given in Table 1.

According to Wetzel (2001), TP in unimpacted streams is generally between 0.01 and 0.05 mg L^{-1}. Environment Can-

Fig. 3. Average daily flow and rainfall at Thomas and Sharpe Brooks.

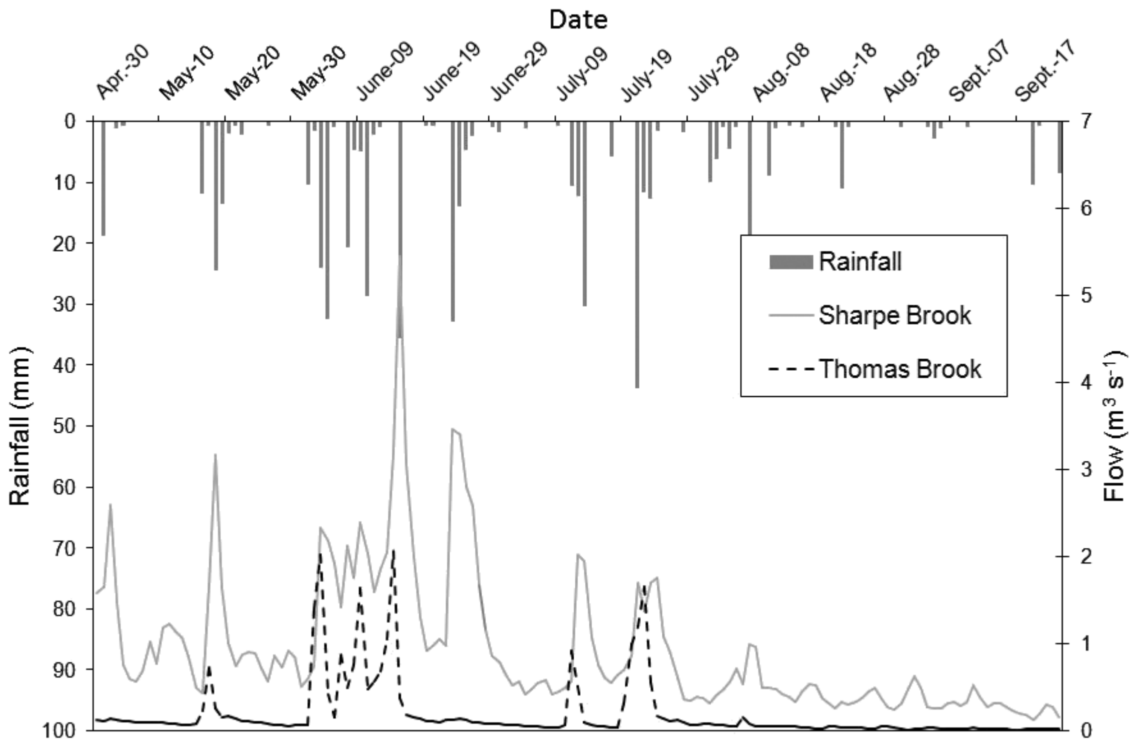


Table 1. Summary of water quality data for Thomas Brook (TB) and Sharpe Brook (SB).

Location	Site		TP[a] (mg L^{-1})	NO_3^--N (mg L^{-1})	Turbidity (NTU)	pH	Chlorophyll *a* (µg L^{-1})
Thomas Brook	TB1	Mean	<0.06	0.28	1.1	6.9	-
		St dev	-	0.39	2.3	0.3	-
	TB2	Mean	0.11	1.03	7.2	7.4	-
		St dev	-	0.44	7.0	0.2	-
	TB3	Mean	<0.06	0.65	6.3	7.4	-
		St dev	-	0.21	7.2	0.2	-
	TB4	Mean	<0.06	1.81	12.8	7.3	-
		St dev	-	0.61	15.5	0.2	-
	TB5	Mean	0.07	2.00	18.9	7.4	3.5
		St dev	-	0.65	23.6	0.3	7.9
Sharpe Brook	SB1	Mean	<0.06	0.03	0.3	5.8	-
		St dev	-	0.01	1.4	0.4	-
	SB2	Mean	<0.06	0.07	0.2	5.9	-
		St dev	-	0.18	0.9	0.5	-
	SB3	Mean	0.07	0.03	0.3	6.1	-
		St dev	-	0.02	1.0	0.2	-
	SB4	Mean	0.35	0.09	0.7	6.3	0.6
		St dev	-	0.10	1.2	0.3	1.2

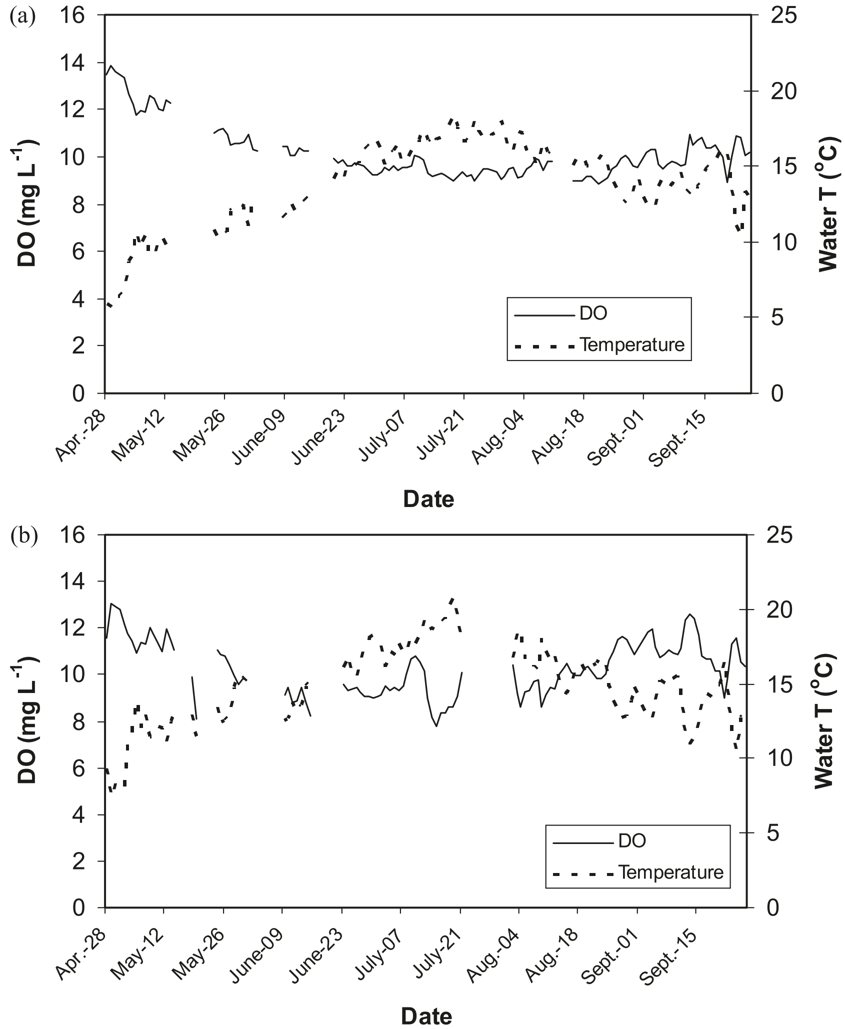
[a]TP detection limit is 0.06 mg L^{-1}.

ada uses trigger ranges for the evaluation of TP which state that eutrophication occurs between 0.035 and 0.1 mg L^{-1}. The detection limit for the methodology used in this study was 0.06 mg L^{-1} TP. Any concentrations detected above 0.06 mg L^{-1} therefore indicated some degree of impairment.

Total P levels were most often at, or only slightly above, the detection limit for all sites except Thomas Brook site 2. Thomas Brook site 2 exceeded the eutrophication trigger range with an average TP concentration of 0.11 mg L^{-1}, probably as a result of milkhouse washwater and manure from an adjacent dairy operation. Levels above 0.10 mg L^{-1} are considered hyper-eutrophic (CCME 2004). Total P levels in Thomas Brook are consistent with those found in other agricultural watersheds (Lenat and Crawford 1994; Royer et al. 2004).

Turbidity values were significantly higher for Thomas Brook. Average turbidity at the outlet was 18.9 NTU at Thomas Brook and 0.7 NTU at Sharpe Brook. Turbidity values between Thomas and Sharpe Brooks yielded statistically significant differences.

Fig. 4. Daily averaged DO and water temperature at (*a*) Sharpe Brook site 4 and (*b*) Thomas Brook site 5.



Sharpe Brook NO_3^-- N concentrations tended to follow flow patterns indicating both groundwater and stormflow movement. Average Sharpe Brook concentrations were always <2.9 mg L^{-1}. At Thomas Brook, NO_3^-- N concentrations were highest during base flow periods indicating NO_3^-- N transport through groundwater. At Thomas Brook sites 4 and 5, maximum NO_3^-- N concentrations were >2.9 mg L^{-1} indicating that aquatic life was, at times, at risk. The maximum acceptable concentration of NO_3^--N according to the Canadian Water Quality Guideline for the Protection of Aquatic Life is 2.9 mg L^{-1} (CCME 2006). Statistical analysis showed that NO_3^--N concentrations in Thomas Brook were significantly higher ($p < 0.005$) than in Sharpe Brook. Nitrate-nitrogen concentrations are consistent with those published by Tattrie et al. (2004), stating that NO_3^--N levels were highest in the lower reaches of Thomas Brook where agricultural cropping dominates local land use.

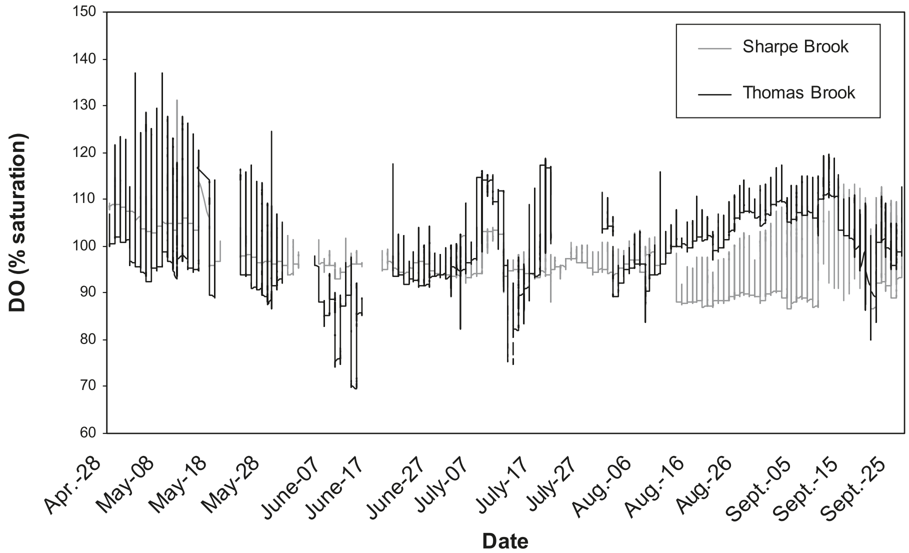
Average pH levels differed between the two streams and are shown in Table 1. Thomas Brook was consistently neutral while Sharp Brook was slightly acidic. Results are likely due to differences in underlying bedrock composition but the addition of manures and liming agents in Thomas Brook could have influenced pH as well.

Dissolved oxygen dynamics

At Sharpe Brook, DO values ranged from 8.6 mg L^{-1} to 13.5 mg L^{-1} over the summer. The average diurnal amplitude ranged from 0.4 mg L^{-1} to 2.1 mg L^{-1}. At Thomas Brook, DO ranged from 3.5 mg L^{-1} to 13.4 mg L^{-1}. The average diurnal amplitude ranged from 0.8 mg L^{-1} to 6.9 mg L^{-1}. Daily averaged data are presented in Fig. 4.

Dissolved oxygen data for both Thomas Brook and Sharpe Brook are shown in Fig. 5 to demonstrate the range of diurnal variations over the summer. During very high flow events, equipment was removed from the stream to prevent damage, causing breaks in the data set. In general, Thomas Brook tended to show more variable DO concentrations with a greater diurnal range, especially during the spring and early summer. High variability in Sharpe Brook at the end of the summer is likely the result of the accumulated growth of benthic algae over the summer, as noted by visual inspection. Two-tailed *t* tests examining differences between DO averages on monthly time steps, indicated that differences between the two streams were always statistically significant (p < 0.005) for the 5 month sampling period.

Fig. 5. Diurnal DO cycling for (*a*) Thomas and (*b*) Sharpe Brooks.



Higher diurnal DO variations are expected for nutrient enriched streams as nutrients promote in-stream growth of chlorophyll containing biomass. This increased biomass will photosynthesize during the day. At night, decomposers feeding on biomass elevate respiration, lowering DO levels. This pattern was also seen by Wang et al. (2003) who observed diurnal DO amplitudes from 5 to 7 mg L^{-1} over a summer sampling period on an agricultural stream in Indiana. Diurnal DO amplitudes measured on an urban stream in the same study averaged only 3 mg L^{-1}. Wilcock et al. (1998) studied 23 agricultural streams in Lowland New Zealand and found average minima of 4 mg L^{-1} and maxima of 10–12 mg L^{-1} resulting in amplitudes of 6–8 mg L^{-1}. As with Thomas Brook, if the recorded minimum values persist for a prolonged period of time, aquatic life may suffer.

Stream biology

Re-aeration coefficients, photosynthesis, respiration, and P/R ratios

Both the delta method and the SRM method were used to estimate the re-aeration coefficient and then substituted into Odum's mass balance approach, (eq. [2]), to determine GPP and *R*. Values for *k* were similar for both the delta and SRM methods. At Sharpe Brook, *k* values were between 0.67 and 1.13 h^{-1}. Thomas Brook *k* values ranged from 0.33 to 1.13 h^{-1} over the summer. The *k* will largely be determined by individual stream morphology and mechanical aeration, however values for small agricultural streams have been found to range from 0.23 to 0.64 h^{-1} (Butcher and Covington 1995; Wilcock et al. 1998; Young and Huryn 1999).

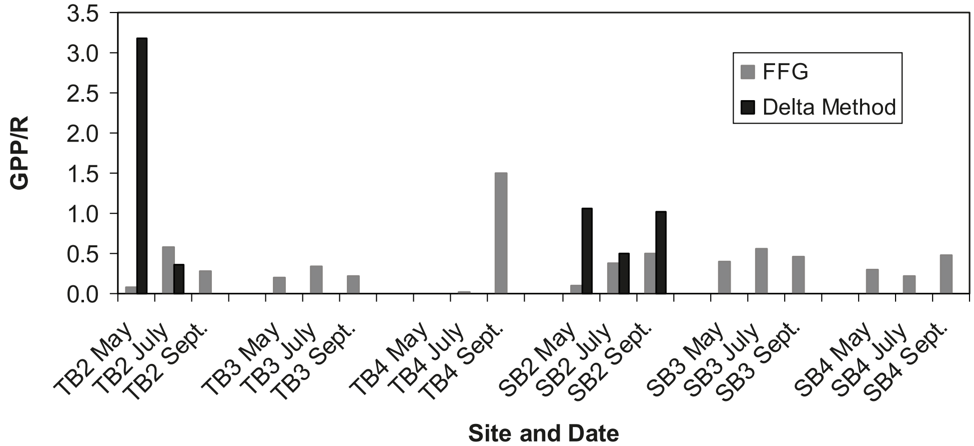
At Sharpe Brook, respiration rates ranged from 0.25 to 1.55 mg L^{-1} h^{-1} while GPP rates ranged from 0.13 to 0.88 mg L^{-1} h^{-1}. Average respiration values at Thomas Brook ranged from 0.22 to 0.67 mg L^{-1} h^{-1}. Photosynthesis values exhibited a larger range from 0.11 to 3.08 mg L^{-1} h^{-1}.Young and Huryn (1999) found that GPP peaked (approximate GPP = 0.58 mg L^{-1} h^{-1}) in spring or summer for most of their study streams. They also noted the highest *R* levels in their undisturbed catchments (approximate R = 2.08 mg L^{-1} h^{-1}). Studies of forested catchments have consistently found that large organic matter inputs from vegetated riparian areas result in low GPP/*R* ratios (Chaessman 1985; Naiman et al. 1987; Marzolf et al. 1994; Young and Huryn 1999).

Measurement of ecosystem level processes such as GPP and *R* are useful because they are representative of integrated responses to a variety of disturbances on a catchment scale (Bunn et al. 1999). Depression of GPP and elevation of *R* can occur as a result of high benthic sediment loads in pasture sites with low percentage riparian cover (Bunn et al. 1999). Clear-cut streams in the Cascade Mountains, Oregon, had very high respiration rates in sediments (Murphy et al. 1981). High sediment levels, reflected by high turbidity levels in Thomas Brook, may be causing similar effects resulting in the low GPP levels seen over the summer months ($0.11 < \text{GPP} < 0.18$).

Higher variability in photosynthesis and respiration values in Thomas Brook is consistent with findings in the literature. Hornberger et al. (1976) correlated variability in productivity with enrichment. They concluded that small changes in environmental conditions (% riparian cover, land use, etc.) resulted in significant changes in productivity when dealing with a large biomass. Bunn et al. (1999) also found that percentage riparian cover and land use accounted for much of the variation in metabolism rates.

Figure 6 contains estimated values for GPP/*R* ratios. Thomas Brook exhibited strongly autotrophic conditions in the spring (average GPP/*R* = 6.55). By summer, values were highly heterotrophic reaching a low in July of 0.27. Low GPP/*R* values indicate that DO patterns are strongly influenced by respiration by chlorophyll containing biomass and microbial communities (Wilcock et al. 1999). Values increased towards the end of the summer. Data from monitoring instrumentation deployed downstream of Thomas Brook site 3 in early July provided DO data that yielded a GPP/*R* of 3.75. This downstream location has a well developed riparian zone and average turbidity was low (2.0 NTU) enabling the growth of photosynthesizing materials. It also

Fig. 6. Gross primary production / respiration (GPP/R) ratios computed using functional feeding group (FFG) ratios and using the delta method.



received runoff from an adjacent corn field and may therefore have experienced increased productivity as a result of nutrient inputs.

Sharpe Brook experienced the same general pattern of autotrophy in the spring and fall and heterotrophy in the summer months. Values however, were much less extreme with a maximum autotrophic GPP/*R* of 1.47 in May. The minimum summer value was also moderate (GPP/*R* of 0.52 in June). Dissolved oxygen data from the probe deployed at Sharpe Brook site 3 in mid-July produced a GPP/*R* of 0.49. This value is consistent with findings in the rest of the watershed.

In many forested watersheds globally, ecosystems are consistently characterized by net consumption of carbon and are therefore considered heterotrophic (GPP/R < 1) (Vannote et al. 1980; Bunn et al. 1999). In accordance with these findings, Sharpe Brook was heterotrophic for the span of time during which full canopy cover was present. Agricultural land use often results in GPP/*R* ratios <1 (Wiley et al. 1990; Young and Huryn 1996; Wilcock et al. 1998) as a result of heterotrophic respiration when the metabolic balance is dominated by decomposition (Wilcock et al. 1998), however Young and Huryn (1999) found that autotrophy occurred most often in catchments that had been adapted for agriculture (GPP/R = 1.5).

Williams et al. (2000) found GPP/*R* to be highest for a stream sampled 3 km downstream from a sewage treatment plant outflow pipe. It was hypothesized that increased nutrient loading resulted in increased productivity. Odum (1956) typically associated autotrophic communities with polluted streams. Autotrophy however, can occur in the spring time before full foliage cover is established as is likely with Sharpe Brook. Streams like Thomas Brook, with low riparian coverage, are also subject to higher production rates because of the lack of stream shading (Vannote et al. 1980; Bunn et al. 1999; Young and Huryn 1999). Compounded seasonal and riparian effects are probably responsible for the extremely high ratios seen at Thomas Brook.

High turbidity at agricultural sites has been recorded by others and is expected to reduce GPP levels by limiting light availability (Vannote et al. 1980; Wiley et al. 1990; Richards et al. 1993; Young and Huryn 1996; Young and Huryn 1999).

Although GPP and *R* are commonly used as stream health indicators, they are not considered to provide adequate estimations of stream health on their own (Bunn et al. 1999). The open system method used here, characterized by the continuous measurement of oxygen concentrations in an open stream system, requires high productivity values to compensate for atmospheric and mechanical re-aeration effects. In small, forested streams where GPP values are usually low and re-aeration rates are high, this condition is rarely met (Bunn and Davies 1990). As well, estimation of k by use of graphical or analytical methods has been shown to consistently underestimate re-aeration values. This occurs because factors such as localized turbulence and morphological variations are often overlooked during calculations (Young and Huryn 1999). Using a combination of velocity-depth equations has been shown to produce a more accurate estimate of k (Wilcock 1982) but it may ultimately be best to rely on the ratio of GPP to *R* that appear to be unaffected by variations in k (Young and Huryn 1999).

Chlorophyll *a*

Chlorophyll *a* concentrations in Sharpe Brook were consistently low. When corrected for in stream effects a large number of chlorophyll *a* concentrations were non-detectable. The maximum concentration at Sharpe Brook occurred in May at 11 μg L^{-1}. Average values were closer to 2 μg L^{-1}. At Thomas Brook, averages were slightly higher and extreme maxima were much higher. The maximum value temporally coincided with the Sharpe Brook maximum, but was much higher (257 μg L^{-1}). Thomas Brook averages were close to 4 μg L^{-1}. Average and maximum chlorophyll *a* data from the outlets of each watershed are shown in Table 2.

High flow events were generally followed by peaks in chlorophyll *a* concentration in a manner consistent with the dislodging of benthic chlorophyll materials into suspension during these periods. A two-tailed *t* test was used to compare the two sites; *p*-values were always <0.05 indicating significant differences.

Chlorophyll *a* concentrations were plotted against computed photosynthesis rates to investigate the relationship between photosynthesizing material and in vivo chlorophyll *a*

Table 2. Weekly in vivo chlorophyll *a* data at Thomas Brook site 5 and Sharpe Brook site 4.

	Thomas Brook		Sharpe Brook	
Date (Week beginning on month/day)	Average chl *a* ($\mu g\ L^{-1}$)	Maximum chl *a* ($\mu g\ L^{-1}$)	Average chl *a* ($\mu g\ L^{-1}$)	Maximum chl *a* ($\mu g\ L^{-1}$)
05/07	4.8	10.3	<0.1	1.1
05/14	4.4	9.5	<0.1	5.6
05/21	53.8	256.9	1.8	11.2
05/28	4.3	7.3	0.2	2.8
06/04	3.6	7.3	<0.1	2.7
06/11	12.1	25.8	2.5	5.0
06/18	10.3	23.3	2.0	4.4
06/25	3.1	8.6	0.9	2.4
07/02	3.7	10.3	1.5	2.9
07/09	1.5	9.1	<0.1	3.6
07/16	6.5	30.1	0.4	2.5
07/23	3.3	29.8	2.4	3.9
07/30	-	-	2.5	4.2
08/06	3.4	4.5	0.3	1.7
08/13	3.5	5.5	0.9	2.6
08/20	2.3	3.7	<0.1	0.7
08/27	3.1	4.8	<0.1	<0.1
09/03	2.1	3.3	<0.1	<0.1
09/10	2.3	3.2	<0.1	<0.1
09/17	2.1	8.5	<0.1	<0.1
09/24	2.6	3.8	<0.1	<0.1

content. The strength of this relationship provides an indication of the relative importance of in vivo materials as opposed to benthic materials in determining overall stream productivity (USEPA 1997). In both Thomas Brook and Sharpe Brook, the relationship was very weak (R^2 = 0.16 and R^2 = 0.15, respectively).

In Sharpe Brook, low turbidity levels, combined with wide, shallow, gravel and cobble streambeds, contributed to the fact that a large proportion of the chlorophyll *a* contained within the stream system is benthic in nature. These benthic populations are generally anchored on stable substrates that are less susceptible to erosion than those in streams with finer bed materials. Highly stable substrates are less likely to contribute to stream sediment load, even under high flow conditions and as a result, the only chlorophyll in the water column results from a small fraction of mobile chlorophyll containing compounds, or from benthic chlorophyll that has been sheared away from bed materials.

With high nutrient concentrations, it is logical that an increase in production will be observed as algal biomass increases. High turbidity levels in Thomas Brook probably keep benthic chlorophyll values low, especially in the downstream reaches where sediment input rates due to erosion were high.

Chlorophyll *a* concentrations are one of the primary parameters used to assess the trophic status of lake ecosystems (CCME 2004). However, in lotic systems, the relationship between increasing levels of agricultural activity and water column chlorophyll *a* levels is influenced by many factors (nutrient levels, turbidity, bed substrate, riparian conditions), which make it difficult to use this parameter as a primary indicator of stream ecosystem functioning.

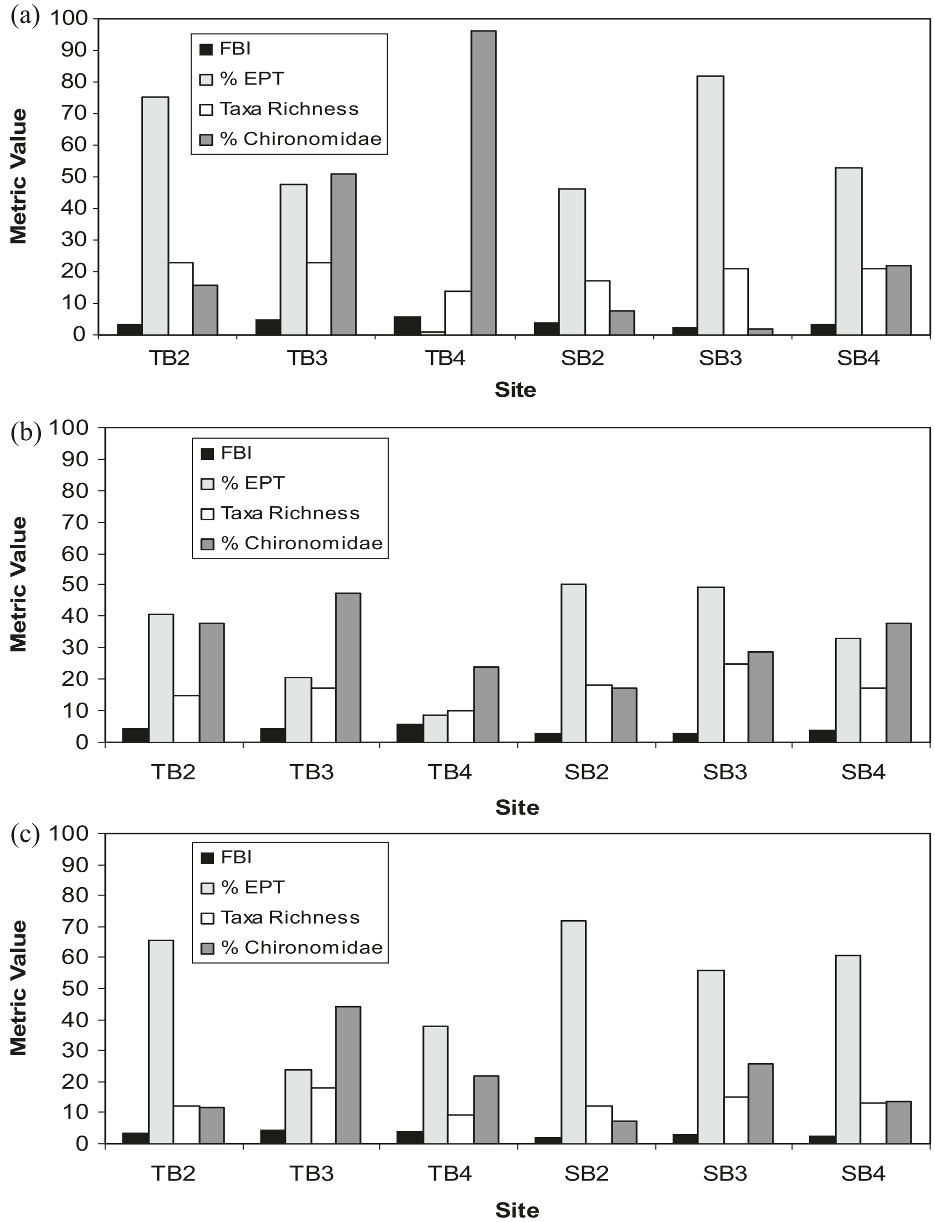
Macroinvertebrates

The family biotic index (FBI) is an invertebrate metric that assesses water quality based on the relative numbers of specific species and their assigned pollution tolerance values. High FBI index values (FBI = 7.26–10.00) indicate impaired or “very poor” water quality. At the other end of the spectrum is low FBI values (FBI = 0.00–3.75) that represent “excellent” conditions (Hilsenhoff 1987).

Family biotic index values at Sharpe Brook indicated “excellent” to “very good” (FBI = 0.0–3.75 and 3.76–4.25, respectively) water quality conditions for the duration of the study (Fig. 7). Thomas Brook results were more variable, most likely as a result of the variability in bed and canopy conditions. “Excellent” conditions (FBI = 0.0–3.75) were found at Thomas Brook site 2 in May and in September, and at Thomas Brook site 4 in September. The remainder of the Thomas Brook samples were indicative of “good” conditions (FBI = 4.26–5.00) with the exception of Thomas Brook site 4 in May and July when samples indicated “fair” to “poor” conditions (FBI = 5.01–7.25). These results are consistent with those reported by Lenat and Crawford (1994) from their examination of forested versus agricultural stream sites.

Percentage Ephemeroptera, Plecoptera, and Trichoptera (%EPT) values are useful because Ephemeroptera, Plecoptera, and Trichoptera species tend to be sensitive to stress resulting from organic pollutants (Resh and Grodhaus 1983). The lowest values, indicative of the greatest degree of impairment, were seen at Thomas Brook sites 3 and 4. The average Thomas Brook value was 35.7%. Values for Sharpe Brook were generally higher with an average of 55.8%. Low EPT taxa richness at agricultural streams is

Fig. 7. Macroinvertebrate metric values for Thomas Brook and Sharpe Brook in (*a*) May 2006, (*b*) July 2006, and (*c*) September 2006.



often observed and is usually accompanied by an increase in other, more tolerant, taxa like Chironomidae (Dance and Hynes 1980; Richards et al. 1993; Lenat and Crawford 1994; Peitz 2003).

Chironomidae are often abundant in streams experiencing organic pollution and are identified as pollution tolerant. Large populations are generally indicative of stream impairment when observed in conjunction with decreased EPT fractions (Resh and Grodhaus 1983; Peitz 2003). The highest Chironomidae values were seen at Thomas Brook sites 3 and 4. Average Chironomidae values were 39.0% at Thomas Brook and 18.0% at Sharpe Brook. The most extreme example of an impacted relationship was at Thomas Brook site 4 where low EPT (1.2%) was observed in conjunction with high Chironomidae (96.1%).

High taxa richness values are usually associated with healthy ecosystems supporting diverse macroinvertebrate communities. They indicate that niche space, habitat, and food sources are adequate to support diverse populations (Resh and Grodhaus 1983; Barbour et al. 1999). The lowest values were seen at Thomas Brook sites 2 and 4 but overall average values for the two streams were similar. Thomas Brook taxa richness was an average of 15.7 species. At Sharpe Brook, this average was 17.7 species. This implies that, for these streams, taxa richness may not be a useful indicator.

Welch et al. (1977) found that Chironomidae replace Ephemeroptera and Plecoptera in agricultural streams. Ephemeroptera, Plecoptera, Trichoptera, and Chironomidae values observed at Thomas Brook and Sharpe Brook are consistent with these results. Observations by Dance and Hynes (1980) with respect to reduced numbers of Ephemeroptera and Plecoptera in agricultural areas also correlate well with results for this study.

Functional feeding group ratios reflect conditions of stress because instability in the food source will result in unbalanced feeding group relationships (Barbour et al. 1999). Functional feeding group ratios yielded GPP/*R* ratios that were almost exclusively heterotrophic for Sharpe Brook, and heterotrophic to strongly heterotrophic for Thomas Brook. These values are shown in Fig. 6. Thomas Brook site 4 exhibited strong autotrophy in September, but was the only site in the study to do so. In general, results are comparable to GPP/*R* values resulting from DO curve fitting methods on corresponding dates. There is some variability however, likely resulting from errors in the estimation of k in small order streams (Merritt and Cummins 1978).

CPOM/FPOM ratios, indicative of the level of riparian zone impaction, suggest healthy buffer zones at Sharpe Brook sites 3 and 4. Thomas Brook sites were all characterized by impaired riparian functioning (high erosion rates, lack of streamside vegetation, absent canopy cover, etc.) with the exception of Thomas Brook site 3 in May and September. Low CPOM/FPOM ratios are also associated with large filter-feeder communities. These communities are able to survive as a result of the high proportion of suspended particulate organic matter resulting from inefficient riparian buffering. High proportions of filter-feeders are commonly found in agricultural streams. Scraper populations are generally low as high turbidity prevents the growth of benthic algae (Lenat 1984; Nerbonne and Vondracek 2001). At Thomas Brook, CPOM/FPOM <0.25 at most sites indicating that filter-feeders groups dominate the macroinvertebrate community (Merritt and Cummins 1978).

Channel stability ratios indicate stable substrates for all Sharpe Brook sites (Merritt and Cummins 1978). This is expected for the gravel and cobble bed materials observed there. Thomas Brook sites have a greater tendency to exhibit unstable substrates with Thomas Brook sites 3 and 4 both exhibiting instability at some point. This is consistent with observations of riparian impaction or removal at Thomas Brook as riparian zones stabilize channel materials. Stable channels are more resistant to bed and bank erosion (Hill 1976; Kauffman and Krueger 1984; Brooker 1985) and therefore contribute less sediment to the stream load, leading to more stable conditions for invertebrate populations to successfully colonize (Lenat 1984; Barbour et al. 1999).

Conclusions

This study used the reference watershed approach to assess the health of a small stream, Thomas Brook, which drains a predominantly agricultural watershed in the Annapolis Valley, Nova Scotia. A key objective of the study was to identify parameters and metrics that would be most useful for classifying the impacts of agricultural activity on stream health in this geographic area. The water quality and hydrology of Thomas Brook were typical of streams impacted by agricultural activity (i.e., elevated nutrient concentrations, increased turbidity and finer bed materials, flashy runoff responses with lower baseflows).

As compared to a forested reference watershed, Sharpe Brook, dissolved oxygen concentrations in Thomas Brook showed significant diurnal variability. Analysis of DO variability in Thomas Brook yielded GPP/*R* ratios indicative of autotrophic conditions in the spring and heterotrophic conditions in the summer. Macroinvertebrate analyses yielded an assessment of "fair" conditions in Thomas Brook. Reduced populations of intolerant species and increased pollution tolerant populations were observed and impaired riparian function and instable channel substrates were identified. In comparison, Sharpe Brook reflected a typical pristine system with healthy macroinvertebrate communities and habitats. Continuous monitoring of in vivo chlorophyll *a* concentrations provided little information on water quality or ecosystem health in continuously flowing rural streams.

In summary, this study showed that Thomas Brook is a moderately impaired aquatic ecosystem. The strongest indicators of impairment were the amplitude of diurnal fluctuations in dissolved oxygen, differences in community metabolism, and the various metrics provided by the macroinvertebrate analysis. These parameters should be included within future studies aimed at assessing and classifying the health of streams in agricultural watersheds in Nova Scotia.

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