EXPORT COEFFICIENT MODELING AND BIOASSESSMENT IN TWO TRIBUTARIES OF THE GRAND RIVER, SOUTHERN ONTARIO, CANADA

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Biology

Waterloo, Ontario, Canada, 1998

0-612-38283-4

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ABSTRACT

Since eutrophication became a widely used term in the late 1940's, much research effort has been directed towards understanding eutrophication in lakes. Comparatively little, however, is known about the eutrophication process in rivers despite large increases in the concentrations of nitrogen and phosphorus measured in rivers worldwide. Consequently, there is a real need to address the problem of increased nutrient loads delivered to lotic systems. To investigate nitrogen and phosphorus loading to streams in the Grand River watershed, empirical models were constructed to predict diffuse sources of these nutrients and assessements were made of epilithic diatom and macroinvertebrate communities to determine relationships with water quality and land use. The streams selected for investigation were chosen based on land use in their watersheds. The upper half of the Laurel Creek watershed and the Carroll Creek watershed are rural and land use is mainly agricultural, whereas the lower half of the Laurel Creek watershed is under urban development.

An export coefficient modeling approach was used to assess the influence of land use on phosphorus and nitrogen loading to Laurel Creek and Carroll Creek. Models were constructed for the 1995-1996 water year and calibrated with ± 3 % of observed concentrations. Runoff from urban areas contributed most to the loading of phosphorus to Laurel Creek and atmospheric deposition was an important source of nitrogen. In the Carroll Creek watershed, runoff from non-row crops contributed most to both nitrogen and phosphorus loading. When the Laurel Creek models were assessed by running them for the 1977-1978 water year, using water quality and land use data collected independently, predicted concentrations were within ± 7 % of observed concentrations. The Carroll Creek phosphorus model was developed using the export coefficients chosen for Laurel Creek, with slight modifications, and it is likely that these coefficients will perform well in other areas of the Grand River watershed, with similar catchment characteristics and land use. This requires confirmation by testing the coefficients in other subcatchments. Different export coefficients were used in two nitrogen models, however, because the measured nitrogen concentration in Carroll Creek was much higher

than in Laurel Creek. It is thus clear that further study is required to investigate the use of export coefficient modeling to model nitrogen inputs in this area.

The taxonomic structure of epilithic diatom and macroinvertebrate communities in Laurel Creek and Carroll Creek was related to both water chemistry and watershed land use. These communities can thus be used as indicators of stream water quality and surrounding land use. Although land use and water chemistry predictors were independently related to diatoms and macroinvertebrates, a close link was observed between land use, water chemistry and the biota. Relationships between epilithic diatoms and total nitrogen and total phosphorus concentrations were sufficiently strong to develop weighted-averaging regression and calibration models for inferring stream water concentrations of these nutrients. The models were accurate within ± 2.4 μg/l for phosphorus and ± 2.0 mg/l for nitrogen. The models were found to be reliable and performed better than other nutrient diatom-inference models. Epilithic diatoms can clearly be used to monitor total nitrogen and total phosphorus in these streams.

Overall, there is potential for the results of export coefficient modeling and bioassessment to be related. Nutrient concentrations predicted empirically could thus be used further to predict impacts on the structure and functioning of stream communities. Furthermore, these relationships could be used to assess the impact of proposed development, changes in land use or nutrient control strategies, on stream health as determined by the biota. These approaches have utility for evaluating eutrophication, in particular nonpoint sources of nutrients, in temperate watersheds.

ACKNOWLEDGEMENTS

I would very much like to thank my supervisor, Dr. Hamish Duthie, for his support and kind encouragement throughout this study. I am also grateful for advice from my committee, Drs. Colin Mayfield, George Dixon and Neil Hutchinson, and would also like to thank Dr. Brian Moss for his input when I started this project.

I am also indebted to other members of the Biology Department who helped me with advice, equipment and lab facilities, including Drs. Bill Taylor, Ralph Smith and Dave Barton, and the graduate secretaries along the way, Marion Brown, Elizabeth Harnum and Sheri Thomas, and also Fran Filipitsch and Chris Lorentz, for their patience and help. I would like to thank Janet Waite, Dale Weber, Ron Socha and Jim Tremain for being so helpful throughout, and Dr. John Semple for advice on my diatom photos.

I would also like to thank Dr. Roland Hall for statistical and editorial advice, and Dr. Jeanette O'Hara Hines for help throughout with statistics and experimental design.

For their invaluable assistance in the lab and the field, I would like to thank Jodi Kerr and Brian Campbell, with a special thanks to Scott Pilcher for all the time he put in helping me. Thanks also go to Dean Fitzgerald for help with selecting my sites, exploring the streams and sampling, and Bruce Kilgour for taking me on a tour of Laurel Creek and for statistical advice. I would also like to acknowledge Martha Guy, Jane Almond and Jeff Hudson for introducing me to the joys of phosphorus (!) and Gen Carr and Sebastien Lamontagne for input when I started modeling. In particular, I would like to thank Raphael Tymowski for help in the field, lab, darkroom and graphics room. I also acknowledge Jane Almond, Paul Slaweck and Rick Baldwin for sorting and identifying the macroinvertebrates. Thanks also to Chris Scholey for making diatom counting and writing up so entertaining, and Dan Campbell for helping me with algal and plant identifications.

More thanks go out to Liz Leedham and Keith Warriner for introducing me to the University and involving me in the Tri-Council project. I acknowledge Brian Whitehead (OMOEE) for water chemistry data, and the staff at the Grand River Conservation Authority for advice, data and reports, with a special thanks to Pete Mason. I also acknowledge all the people at OMAFRA who talked to me about farming in the area, and the farmers on Carroll Creek who took the time to answer my questions. I would like to thank Susan Motkaluk and Irene Shuftis (City of Waterloo) for Laurel Creek maps, John Fischer (Environment Canada) for Laurel Creek data, Brian Smith (Ontario Climate Centre) for precipitation data and Sue Sanders (Water Survey of Canada) for discharge data. A very special thanks to Bruce Pond (OMNR) for providing me with the Carroll Creek land use data.

I am grateful for funding received from NSERC and the Tri-Council funded University of Waterloo Eco-Research project, as well as for scholarships received from the University of Waterloo.

A very big thank you to all the members of the Portly Penguin Tea Room for helping me enjoy my time at Waterloo.

I would also like to thank Pat and Chuck Potter for their help and assurance. And, of course, many thanks to Rachael Fletcher for seeing me through another character building time, eh?

In particular I would like to thank Kevin Pitts for being there for me, and his parents, Sharon and Ted, for their support and for giving me a home away from home.

DEDICATION

I dedicate this thesis to my parents for their constant support and encouragement.

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1. INTRODUCTION

1.1 General introduction

Eutrophication is the term used to describe the biological effects of an increase in the concentration of plant nutrients on aquatic ecosystems (Harper, 1992). The key nutrients responsible for eutrophication are nitrogen and phosphorus. The term has become widely used since the late 1940's when scientists began to realize that nutrients entering and accumulating in freshwater systems from anthropogenic sources were having deleterious effects on these systems. Since that time, much research effort has been directed towards understanding eutrophication in lakes. Comparatively little is known about the eutrophication process in rivers. However, rivers worldwide have doubled their content of nitrogen and phosphorus as a result of the effects of man, with local increases in Western Europe and North America of up to 50 times (Harper, 1992). Consequently, there is a real need to address the problems of increased nutrient loads delivered to lotic systems.

Elevated loads of phosphorus and nitrogen can have many negative effects on aquatic ecosystems (Carpenter et al., 1998). One of the most important consequences is the increased growth of algae and aquatic macrophytes. The senescence and decomposition of these organisms, as well as nocturnal oxygen consumption by community respiration, create oxygen shortages resulting in fish kills. In some freshwater systems, blooms of cyanobacteria in particular are a prominent symptom of eutrophication (Carpenter et al., 1998). These blooms contribute to a wide range of water quality problems including summer fish kills, foul odours and unpalatability of drinking water. Furthermore, certain cyanobacteria release toxins that can kill livestock and may pose a serious health threat to humans.

Nitrogen and phosphorus are discharged to rivers from a variety of point and nonpoint sources (Carpenter et al., 1998; Heathwaite et al., 1996). Point sources of nutrients arise through the discharge of industrial effluent and domestic sewage (Heathwaite et al., 1996).

Industrial processes producing high concentrations of nitrogen and phosphorus include steel production, petroleum production and refining, pulp and paper, organic and inorganic chemicals, plastics and fertilizer production. Nonpoint sources of nutrients include runoff from urban areas, highways, forests, pasture, cropland, and rangeland, and inputs from atmospheric sources (Carpenter et al., 1998; Hipp et al., 1993).

In most developed areas of the world, sewage and industrial effluents are treated to reduce nitrogen and phosphorus concentrations prior to discharge, and the management of freshwater systems to improve water quality has for decades been directed toward reducing point source loadings of these nutrients (Sharpley et al., 1993). However, nonpoint sources, particularly from agricultural activities, have superseded point source loadings in many countries (Carpenter et al., 1998; Duda, 1993). Eutrophication controls have mainly focused on point sources because nonpoint sources are difficult to monitor since they involve the interaction of a wide range of human-influenced variables, such as land use, fertilizer application, soil type and the hydrological pathways linking the land to rivers and lakes (Heathwaite et al., 1996). As point source loadings have been systematically reduced, diffuse loadings have become proportionally more important in overall water quality management.

Traditionally, excessive phosphorus inputs have been viewed as the primary cause of freshwater eutrophication (Schindler, 1977). It is possible, however, that in shallow lakes, especially those dominated in their pristine state by macrophytes, and in some river systems, eutrophication has largely been driven by nitrogen inputs (Moss, 1998; Rott et al., 1998). In their study on the Grand River, Rott et al. (1998) attributed progressing eutrophication from the 1960's to the 1990's mainly to significant increases in nitrates. They found that areas of the Grand River continue to experience elevated nutrient levels despite efforts to control inputs from point sources. The consequent luxuriant growths of macrophytes and macroalgae are a current management issue, and there is a need to address the sources and effects of nitrogen and phosphorus loading to streams in the Grand River watershed.

The aim my research was to model inputs of nitrogen and phosphorus to tributaries of the Grand River, and to determine the manifestation of these inputs in their effect on the biota. I selected two streams, Laurel Creek and Carroll Creek, to provide a comparison between rural and urban land uses. Diffuse phosphorus and nitrogen loads to these streams from their catchments were modeled using export coefficients. Assessments were made of epilithic diatom and macroinvertebrate communities in these streams to determine relationships with water quality and land use, and assess their utility in river monitoring. These approaches were then compared to make recommendations for an overall framework for monitoring eutrophication in the Grand River watershed.

1.2 Export coefficient modeling

The approach I used to model nitrogen and phosphorus inputs to the streams from nonpoint sources was export coefficient modeling. Unlike traditional methods for assessing the impact of land use change on water quality, which involve the development of detailed physically-based models, export coefficient models are very simple (Johnes, 1996). The export coefficient modeling approach aims to predict the concentrations of total nitrogen and total phosphorus at any site in a stream as a function of the export of nutrients from each nutrient source in the watershed above that site (Johnes and Heathwaite, 1997). The models are constructed using data collected on land cover, such as the area of urban and agricultural land, and the input of nutrients through atmospheric deposition. Export coefficients are derived from the literature and results of field experiments to determine the loss of nutrients from each identifiable source to the stream. Such models provide an effective means of evaluating the impact of land use and land management on water quality for surface waters on an annual basis (Johnes, 1996).

In Chapter 2, I describe an export coefficient model I developed to predict and evaluate phosphorus loading to Laurel Creek from nonpoint sources. Although recent improvements in this approach have successfully adapted the conventional use of export coefficients to accurately predict nitrogen and phosphorus loading to rivers (Johnes, 1996; Johnes and Heathwaite, 1997), these models did not include runoff from urban areas. Urban runoff can, however, be an important source of nutrients to nearby watercourses (Hipp et al., 1993) and there is a need to evaluate diffuse inputs to urbanized streams. In Chapter 3 I then outline export coefficient models I constructed to predict nitrogen loads to Laurel Creek, and nitrogen and phosphorus loads to Carroll Creek.

1.3 Biological assessments

There are two important arguments in favour of biological monitoring of freshwater systems. Firstly, because organisms have an integrating response to their environment, fluctuations in water quality, which may be missed by intermittent chemical analysis, are recorded. Secondly, it can be argued that if we wish to maintain healthy, diverse biological communities, it is more appropriate to monitor the aquatic community rather than physicochemical variables only (Cox, 1991; Hynes, 1963).

The choice of bioindicator group must satisfy certain criteria. These include, (i) that each taxon has precise ecological limits to its range which do not vary unpredictably, (ii) that the ranges can be defined, and (iii) that the taxon can be consistently identified (Cox, 1991; Hellawell, 1977). These criteria are met by a range of organisms. Within any such group however, the better understood and more precise the ecological requirements of individual taxa, the more accurate the predictions from the presence of particular associations.

Epilithic diatoms

Despite the fact that algae are the main primary producers of most rivers in temperate regions (Whitton, 1991) algal methods for monitoring have generally been considered less important than microbiological, fish and invertebrate-based methods. Where algal-based methods have been put to practical use however, they have been shown to be successful (Whitton, 1991). Furthermore, over the last decade, numerous studies have demonstrated the sensitivity of algae to various human impacts (e.g. Maier and Rott, 1988; Pipp and Rott, 1994; Rott et al., 1998) and algae are included in national river surveys worldwide (Whitton et al. 1991). Many practical approaches to algal-based methods for monitoring rivers are in routine use or are currently being tested.

The algal community of low order streams predominantly comprises sessile, benthic species (Round, 1981). This community can be referred to by the term "periphyton", which is defined as "...a complex community of microbiota attached to inorganic or organic, living or dead substrata, including algae, bacteria, fungi, inorganic and organic detritus" (Wetzel, 1983). The periphyton is normally a well structured community consisting of organisms of a large size spectrum, ranging from a few microns to several centimetres (Rott, 1991). The long-term response of periphyton communities to environmental stress is primarily a change in species composition (Rott, 1991; Round, 1993). Periphyton algae in general and diatoms in particular are especially suitable organisms to monitor the effects of both organic pollution and eutrophication on rivers (Rott et al., 1998).

According to Round (1981), the periphyton can be sub-divided into:
1) Epilithic forms: algae living on rocks;
2) Epiphytic forms: algae living on vascular plants or other algae;
3) Epipelic forms: algae living in or on the surface of soft, muddy sediments;
4) Epipsammic forms: algae live in or on the surface of sandy sediments.

Apart from the saprobic system and observations on particular species, such as *Cladophora glomerata*, taxonomically based methods involving algae are largely restricted to diatoms (Whitton, 1991). The most widely used methods involve the epilithic diatoms (Round, 1991a and 1991b). Epilithic diatom communities fit the aforementioned criteria required of indicator organisms in that they are present throughout the length of a river, they grow in a specific, well-defined habitat, they react to changes in water quality, they are free of life-cycle stages which may cause the indicator organism to be absent over certain periods, and they are identifiable and floras are available (Round, 1993). Diatoms can also be stored on permanent microscopic slide mounts, providing long-term access to samples. Numerous studies have demonstrated the sensitivity of benthic diatoms to nitrogen and phosphorus concentrations, illustrating their suitability as indicators of the biological effects of eutrophication (e.g. Kelly and Whitton. 1995; Pan et al., 1996; Rott et al., 1998; Round, 1991b).

Macroinvertebrates

Of all the potential groups of freshwater organisms that have been considered for use in biological monitoring, benthic macroinvertebrates are most often recommended (Hellawell, 1986). They mainly consist of aquatic insects, mites, molluscs, crustaceans and annelids, and there are many advantages of using these organisms in water quality monitoring (Resh et al., 1996). Like epilithic diatoms, they fulfill the criteria required of indicator organisms. They are ubiquitous throughout river habitats, sensitive to water quality, react quickly to peturbations in the environment, are generally sedentary in nature allowing spatial analysis of disturbance effects, qualitative sampling and analysis techniques are simple and well developed, and the taxonomy of many groups is well known and identification keys are available.

It should be noted, however, that changes in the structure of stream epilithic diatom and macroinvertebrate communities induced by water quality changes can be masked by other factors (Lowe and Pan, 1996; Resh et al., 1996). Macroinvertebrates in particular are influenced by physical substrate features, they have specialized habitat niches and specific food requirements (Round, 1993). On the other hand, epilithic diatom responses may be influenced by top-down forces acting on the community (Lowe and Pan, 1996). For example, elevated nutrient concentrations may result in an increase in algal productivity, which in turn encourages grazing. Thus, biological monitoring data are most valuable when more than one component of the biota are assessed.

In Chapter 4, I use changes in the structure of macroinvertebrate and epilthic diatom communities in Laurel Creek, to assess the influence of urbanization on water quality. As well as evaluating community composition, I determine periphyton biomass and assign macroinvertebrate functional feeding groups. I then consider the results of biological and water quality monitoring on the stream, in the context of current management strategies in place for the watershed.

I take these approaches further in Chapter 5, and evaluate the relationships between the structure of these communities in Laurel Creek and Carroll Creek and stream water quality and catchment land use. There is growing recognition that stream communities have potential as biological signatures of catchment condition and such associations have been evaluated for macroinvertebrates (e.g. Allan et al., 1997, Richards et al., 1996). However, few studies have focused on stream diatom communities or both groups simultaneously, and evaluating these relationships has relevance for developing macroinvertebrate and diatom indicators as monitoring and assessment tools for water resources planning and management.

I then use weighted-averaging regression and calibration in Chapter 6, to develop and evaluate models for inferring total phosphorus and total nitrogen concentrations in Laurel Creek and Carroll Creek using epilithic diatoms. Using these methods, I assess the utility of diatoms for monitoring eutrophication in these streams.

Finally, in Chapter 7 I compare the export coefficient modeling approaches presented in Chapters 2 and 3 to the biological assessments presented in Chapters 4 to 6, and make recommendations towards developing an overall framework for monitoring eutrophication in the Grand River watershed.

1.4 Objectives

The objectives my research were four-fold:

(1) To evaluate and predict phosphorus and nitrogen inputs to Laurel Creek and Carroll Creek from their catchments using export coefficient modelling.

(2) To determine the distribution and structure of epilithic diatom and macroinvertebrate communities in these streams, and how they relate to water quality and catchment land use.

(3) To evaluate relationships between nitrogen and phosphorus concentration and epilithic diatom communities.

(4) To compare these approaches for monitoring rivers and make recommendations towards developing a framework for monitoring eutrophication in the Grand River watershed.

1.5 Hypotheses

The following hypotheses were examined:

(1) An export coefficient modeling approach will effectively describe nitrogen and phosphorus loading to Carroll Creek and Laurel Creek.

(2) There are measurable relationships between both epilithic diatom and macroinvertebrate communities and catchment land use and water quality in these streams.

(3) There are measurable relationships between epilithic diatoms and total nitrogen and total phosphorus concentrations in streams.

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2. EXPORT COEFFICIENT MODELING TO ASSESS PHOSPHORUS LOADING IN AN URBAN WATERSHED [1]

2.1 Abstract

An export coefficient modeling approach was used to assess the influence of land use on phosphorus loading to a Southern Ontario stream. A model was constructed for the 1995-1996 water year and calibrated within ± 3 % of the observed mean concentration of total phosphorus. It was found that runoff from urban areas contributed most to the loading of phosphorus to the stream. When the model was assessed by running it for the 1977-1978 water year using water quality and land use data collected independently, agreement within ± 7 % was obtained. The model was then used to forecast the impact of future urban development proposed for the watershed in terms of phosphorus loading, and to evaluate the reduction in loading resulting from several urban best management practices (BMP). It was determined that phosphorus removal will have to be applied to all the urban runoff from the watershed to appreciably reduce stream phosphorus concentration. Of the BMP's assessed, an infiltration pond design resulted in the greatest phosphorus load reduction, 50 % from the 1995-1996 baseline.

2.2 Introduction

The importance of phosphorus in the eutrophication of fresh waters has been well documented (Lee et al., 1978). Phosphorus is the key limiting nutrient for aquatic plant growth in many freshwater systems. Increased phosphorus loading to these systems may cause excessive algal and macrophyte growth, and consequent environmental degradation. Phosphorus loads originate from a variety of anthropogenic point and nonpoint sources, of which urban and agricultural runoff and sewage effluent are particularly important.

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[1] Based on a paper submitted to the Journal of the American Water Resources Association. Co-author H.C. Duthie.

The export coefficient modeling approach was originally developed in North America to predict nutrient inputs to lakes and streams (Beaulac and Reckhow, 1982; Dillon and Kirchner, 1975; Omernik 1976; Rast and Lee, 1983; and Reckhow et al., 1980). The use of nutrient export coefficients for estimating loads of nitrogen and phosphorus is based on a knowledge that, for a given climatological regime, specific land use types will yield or export characteristic quantities of these nutrients to a downstream waterbody over an annual cycle (Rast and Lee, 1983). Knowing the area of land in a watershed devoted to specific uses and the quantities of nutrients exported per unit area of these uses (i.e.: the nutrient export coefficients) it is possible to estimate total annual loads of phosphorus and nitrogen to a waterbody from non-point sources.

Recently, this technique has been successfully modified and used to determine nutrient loads to surface waters in Britain (Johnes, 1996; Johnes and Heathwaite, 1997; Johnes et al., 1994; and Johnes, et al., 1996) and was used to estimate nutrient loading from nonpoint sources to rivers in Northern Canada (Chambers and Dale, 1997). Export coefficient modeling has a number of advantages over more detailed, process-based, modeling techniques, in particular the simplicity of model format and operation of the model using a spreadsheet (Johnes, 1996). The approach relies on data from readily available sources, has relatively few data requirements, can be easily calibrated and provides a relatively inexpensive, robust means of evaluating the impact of land use and land management on nutrient loading to surface waters.

The objectives of this study were 1) to construct a phosphorus export coefficient model for the Laurel Creek watershed, 2) to forecast the impact, in terms of phosphorus loading, of future urban development proposed for the watershed, and 3) to illustrate how this approach might be used for watershed land use planning and decision making.

2.3 Site description

Laurel Creek is approximately 20 km long with a watershed area of 74.4 km^2 (see Fig.1). It flows into the Grand River in Southern Ontario, which is in the Lake Erie watershed. The topography varies from gentle, long slopes (0-3% simple) to short and steep slopes (>12% complex) (GRCA, 1993). The most common soils are members of the Brant Waterloo and Burford Fox associations, loam with some silt loam and clay sand formed on outwash and lacustrine deposits (Presant and Wicklund, 1971).

Laurel Creek drains most of the land area within the City of Waterloo and much of the lower half of the watershed is under urban development. Land use in the upper half of the watershed is largely agricultural, consisting mainly of commercial crop production (GRCA, 1993). Urban development is currently extending into the agricultural area, and further expansion is planned to accommodate the forecasted population growth in the watershed (City of Waterloo,1988; 1998).

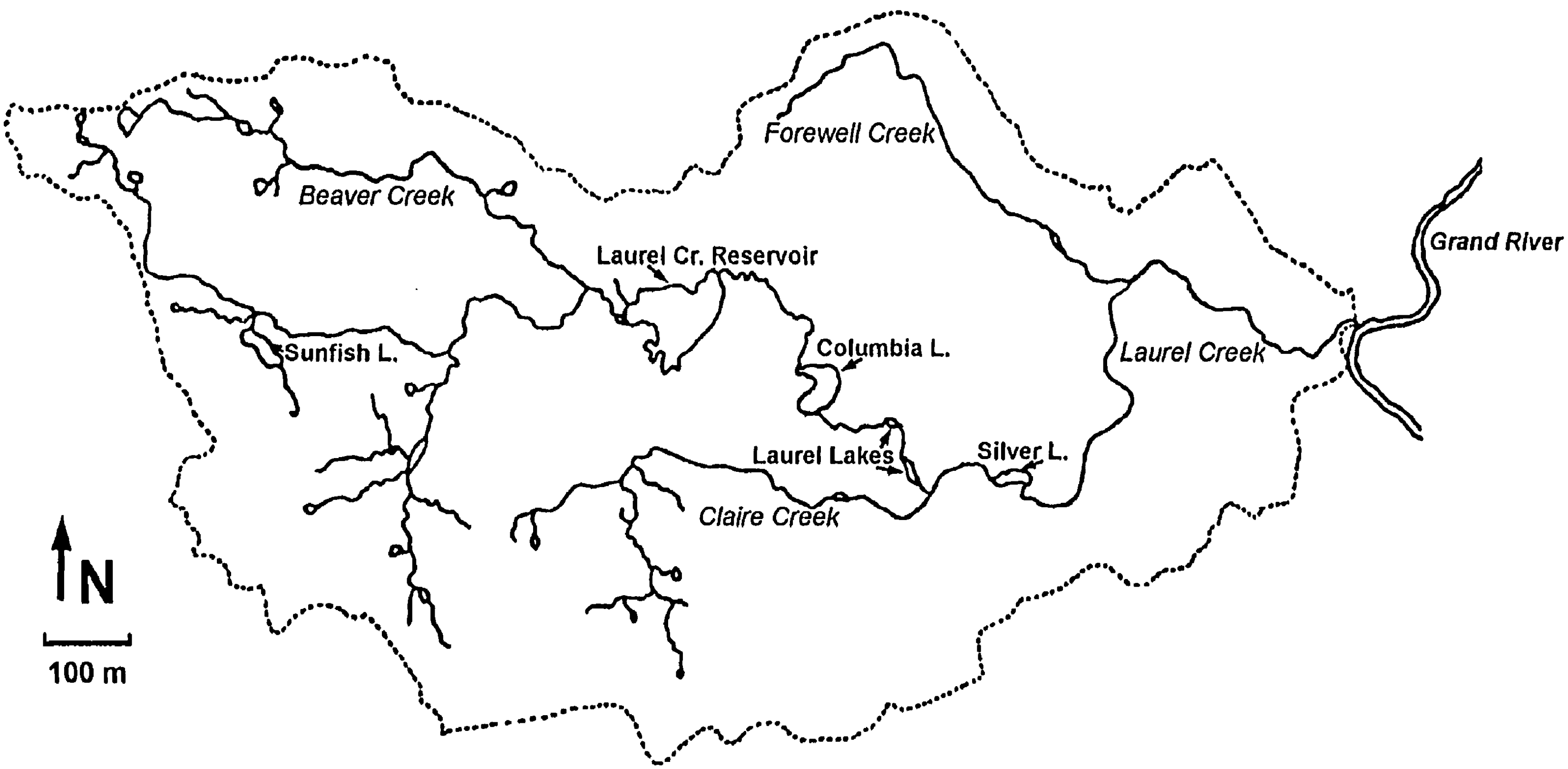
2.4 Methods

2.4.1 Modeling procedure

The modeling procedure used, based on that outlined by Johnes (1996), Johnes et al. (1996) and Reckhow et al. (1980), is briefly presented here and outlined in more detail in Chapter 3. A simple empirical model was constructed for the 1995-1996 water year, with total phosphorus load transported by the stream predicted as the sum of the export of phosphorus from each nutrient source in the watershed. The model equation used for the Laurel Creek watershed was:

$$L = \sum_{i=1}^{n} E_i A_i + P \qquad (1)$$

Figure 1. Map of the Laurel Creek watershed showing watershed boundary



where L was the nutrient load delivered to the stream; E was the export coefficient selected for nutrient source i; A was the area of the watershed occupied by land use type i; and P was the input of nutrients from precipitation. The export coefficient, E_i, expressed the rate at which phosphorus was transported from each land use type in the watershed and was selected from the literature. The phosphorus load exported to the stream from inputs through precipitation (P) was calculated as:

$$P = daQ \tag{2}$$

where d was the areal deposition rate of phosphorus in kg/ha/yr, a was the area of the watershed and Q was the percentage of total annual rainfall lost to runoff.

Using measurements of total annual discharge, the model predictions were expressed as mean annual concentration of total phosphorus in the stream. The model was then calibrated against observed total phosphorus concentration. A sensitivity analysis was conducted to determine which of the export coefficients exerted greatest influence over model output. Each of the export coefficients was, in turn, altered by 10 % while the other coefficients were kept constant, and the overall change in the model prediction was assessed. This information was used to revise the selection of those coefficients exerting greatest control over model output. The model was then run again with the new export coefficients and calibrated against the phosphorus data collected until the model predicted with ± 5 % of observed loads.

The calibration procedure was then objectively assessed by running the model for the 1977-1978 water year using independent data collected in the Laurel Creek watershed on changing land use, agricultural practice and total phosphorus load. Phosphorus data was available for 1970-1978 but prior to 1977 combined sewage overflows were discharged to the creek, and the model was only run for the 1977-1978 water year. To run the model over the entire period would have involved selecting and calibrating new coefficients for phosphorus in sewage, and an objective assessment of model calibration would not have been achieved. Assessment of the model should ideally be carried out over several years to establish a relationship between predicted and observed phosphorus loads, but water quality data for the 1978-1995 period was not available for Laurel Creek.

Finally, the model was used to forecast the impact, in terms of phosphorus load, of future urban development in the watershed. To illustrate how this approach can be used in watershed land use planning and decision making, several best management practices (BMP) designs for phosphorus removal from urban runoff were assessed using the model.

2.4.2 Water chemistry, precipitation & discharge.

To determine the observed total phosphorus load, water samples were collected at the mouth of Laurel Creek weekly, biweekly or monthly over the 1995-1996 water year. The water year ran from September, 1 1995 to August, 31 1996, starting from the month with the lowest mean discharge (Gordon et al., 1994). Sampling intensity was focused to include several storm and snow melt events and a total of 21 samples were analyzed. Water was collected in hydrochloric acid-rinsed bottles, and total phosphorus concentration was measured as phosphate using the ascorbic acid method following oxidation with persulfate under pressure (Parsons et al., 1984). Total phosphorus data for 1970-1978 were obtained from the Ontario Ministry of Environment and Energy and phosphorus was analyzed according to standard methods outlined in their analytical protocol (OMOEE, 1981). Sample size for this data ranged from 11 – 16 per year. Precipitation data for 1970-1997, measured at the Waterloo-Wellington station, was obtained from the Ontario Climate Centre, Environment Canada.

Discharge data were collected by the Water Survey of Canada. The gauged site on Laurel Creek is located upstream of the mouth of the creek, so downstream discharge had to be estimated. Discharge measurements were made, under varying flow conditions, at the mouth of the creek over a two month period in 1997, to develop a relationship with discharge at the gauged site ($R^2 = 0.94$) (Winter, unpublished data). Estimates obtained using this relationship agreed closely with those calculated by adjusting for the difference in watershed area between the two sites, using an equation outlined in Gordon et al. (1994).

2.4.3 Land use

Land use in the Laurel Creek watershed for 1995-1996 was compiled using maps from the Ontario agricultural resource inventory (OMAF, 1983), maps and information contained in GRCA (1993), data collected in the 1996 agricultural census (Statistics Canada, 1996), and the 1997 City of Waterloo zoning map. Land use for the 1977-1978 model was determined using Grand River Conservation Authority reports and maps (MacMillan, 1978; Veale, 1981) and information from the 1976 agricultural census (Statistics Canada, 1976). A report obtained from the City of Waterloo (1998) was used to ascertain the staging of future urban development in the watershed.

2.5 Results and discussion

2.5.1 Export coefficient selection

The export coefficient for the loading of phosphorus from woodland areas in the watershed was selected to reflect the forest type, which was mainly mixed deciduous, and geology. A value of 0.1 kg/ha/year was chosen based on Dillon and Kirchner's 1975 study on Ontario watersheds. Chambers and Dale (1997) summarize export coefficients for 198 North American watersheds primarily draining crops, and calculated an average of 0.3 kg/ha/yr (S.E. ± 0.02 kg; range 0.1-0.39). Soil erosion and, consequently, total phosphorus loss in runoff, are greater in row crops than non-row crops. Based on the large proportion of non-row crops grown in the Laurel Creek watershed (mainly a mixed grain system which usually consists of oats and barley, and may include wheat), a lower export coefficient of 0.25 kg/ha/yr was selected. Grazing in the watershed is not intense and pasture areas are generally unimproved. A coefficient of 0.2 kg/ha/yr was selected, which was the lowest value in the range for Canadian pasture areas presented by Chambers and Dale (1997). The input of phosphorus to the watershed via atmospheric deposition, 0.2 kg/ha/yr, was taken from Kuntz (1980). The percentage of total annual rainfall lost to runoff was 30 % (Winter, unpublished data). Reckhow et al. (1980) list urban export coefficients ranging from 0.19 to 6.23 kg/ha/yr (mean 1.91, S.D. 1.79). A relatively low export coefficient of 0.5 kg/ha/yr was selected to reflect the large proportion of low-density and mid-density residential development. Combined sewage overflow is diverted from Laurel Creek and some urban stormwater runoff from the watershed thus bypasses the stream.

Export coefficients for rural populations using phosphorus-free detergents were not available and phosphorus inputs from septic systems were not included in this model. Vollenweider (1971) and Reckhow et al., (1980) state that 50 % to 100 % of the phosphorus input to aquatic systems from human waste is due to phosphorus containing detergents. These are no longer used in Canada and it was thus assumed that septic tanks are not an important source of phosphorus in the watershed. Aquatic birds are also potential contributors of phosphorus to urban lakes at certain times of year (Manny et al., 1994; Moore et al., 1998). These have not been quantified for the man-made lakes in the Laurel Creek system and were not included in this model.

2.5.2 Export coefficient model

The export coefficient model for Laurel Creek predicted within ± 3 % of observed total phosphorus load (Table 1 and Fig. 2). Runoff from the urban area contributed most to the loading of phosphorus, followed by commercial crop production. On conducting a sensitivity analysis, phosphorus concentrations in Laurel Creek were found to be most strongly determined by export from urban areas, cropland and atmospheric sources respectively (Table 2). These observations correspond to those made by Rast and Lee (1983) who determined that, for U.S. waterbodies, the annual loading of phosphorus from urban areas was twice that from rural/agricultural areas. Beaulac and Reckhow (1982) found that average annual phosphorus loading from urban areas was higher than from areas of non-row crops and pasture.

Table 1. Export coefficient model for Laurel Creek constructed for the 1995-1996 water year

Nutrient source	Area (ha)	Phosphorus input (kg/ha/yr)	Phosphorus export coefficient (kg/ha/yr)	Phosphorus load (kg)
Urban	3073		0.5	1537
Crops	3263		0.25	816
Pasture	105		0.2	21
Woodland	676		0.1	68
Atmospheric	7441	0.2	30 % of input	446
Total predicted load				2888

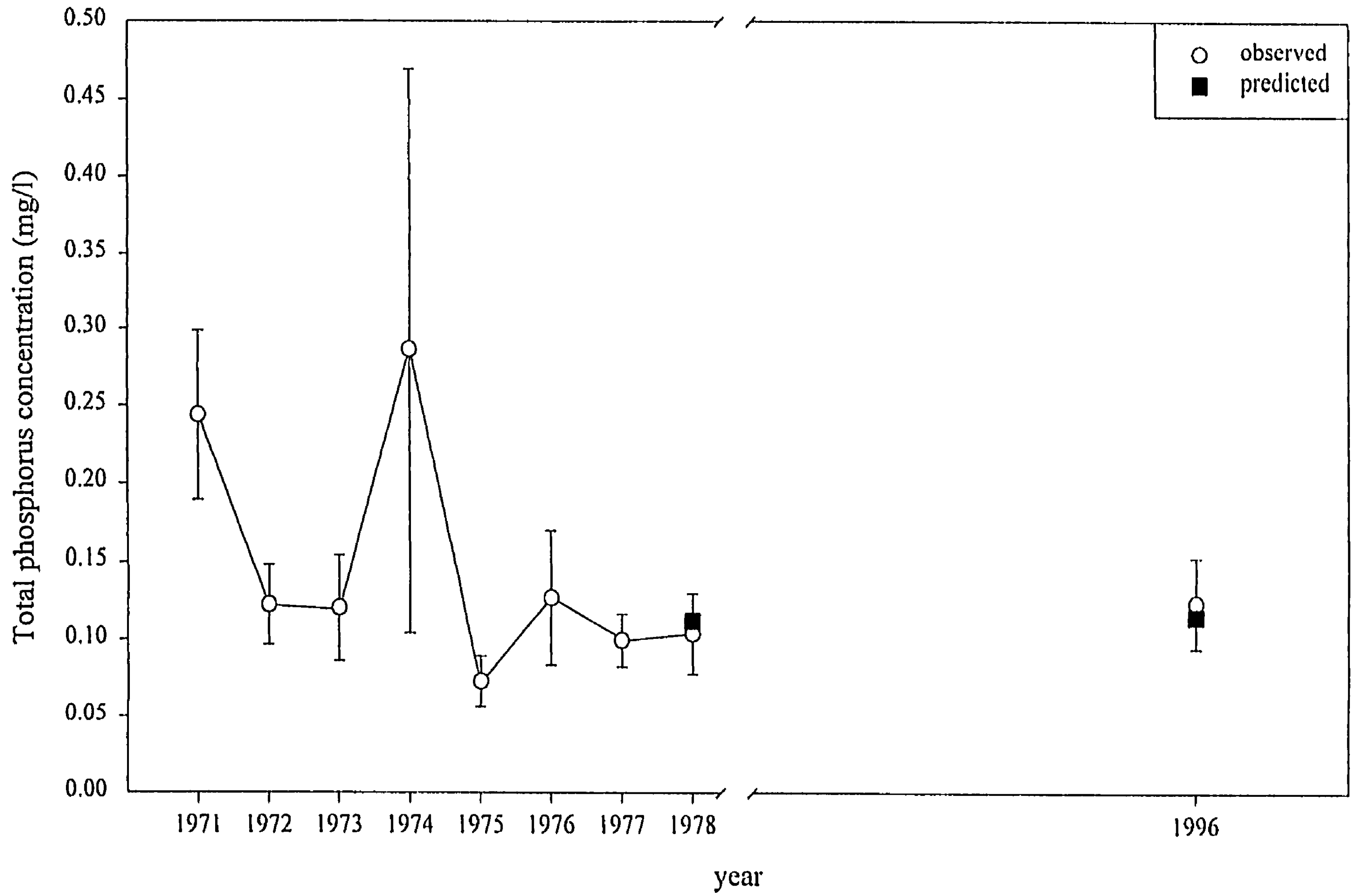
Table 2. Sensitivity analysis for the Laurel Creek export coefficient model

Nutrient source	% Change in model output by adjustment of each export coefficient by 10%
Urban	5.30
Crops	2.84
Pasture	0.07
Woodland	0.24
Atmospheric	1.55

On assessing the model by running it using independent data collected for the 1977-1978 water year, the prediction was within ± 7 % of observed phosphorus concentration (Table 3 and Fig. 2). Between 1977 and 1996, the urban area increased by 864 ha, encroaching on the agricultural and woodland areas. This increase in urban development resulted in an increase of 423 kg in the annual total phosphorus load to Laurel Creek.

Phosphorus loading from urban areas originates from a variety of sources, including runoff from roads, parking lots, roofs, lawns and driveways (Bannermann *et al.*, 1993). Inputs may be in soluble forms of phosphorus or bound to particles of dust and dirt, and

Figure 2. Laurel Creek total phosphorus concentration from 1970-1978 and 1996, showing mean annual measured concentrations for each water year (+/- 1 S.E.) and mean annual concentrations predicted using the export coefficient model.



may enter nearby streams directly, through uncontained runoff, or via storm-sewer outfalls. In residential areas, like those predominant in the Laurel Creek watershed, lawns

Table 3. Assessment of Laurel Creek export coefficient model using 1977-1978 data

Nutrient source	Area (ha)	Phosphorus input (kg/ha/yr)	Phosphorus export coefficient (kg/ha/yr)	Phosphorus load (kg)
Urban	2181		0.5	1019
Crops	3504		0.25	876
Pasture	295		0.2	59
Woodland	959		0.1	96
Atmospheric	7441	0.2	30 % of input	446
Total predicted load				2568

are the major source of phosphorus (Bannermann *et al.*, 1993). Urban populations in North America generally place emphasis on lawn landscapes and, in certain high maintenance areas, yearly phosphorus applications may exceed 100 kg/ha (Hipp *et al.*, 1993).

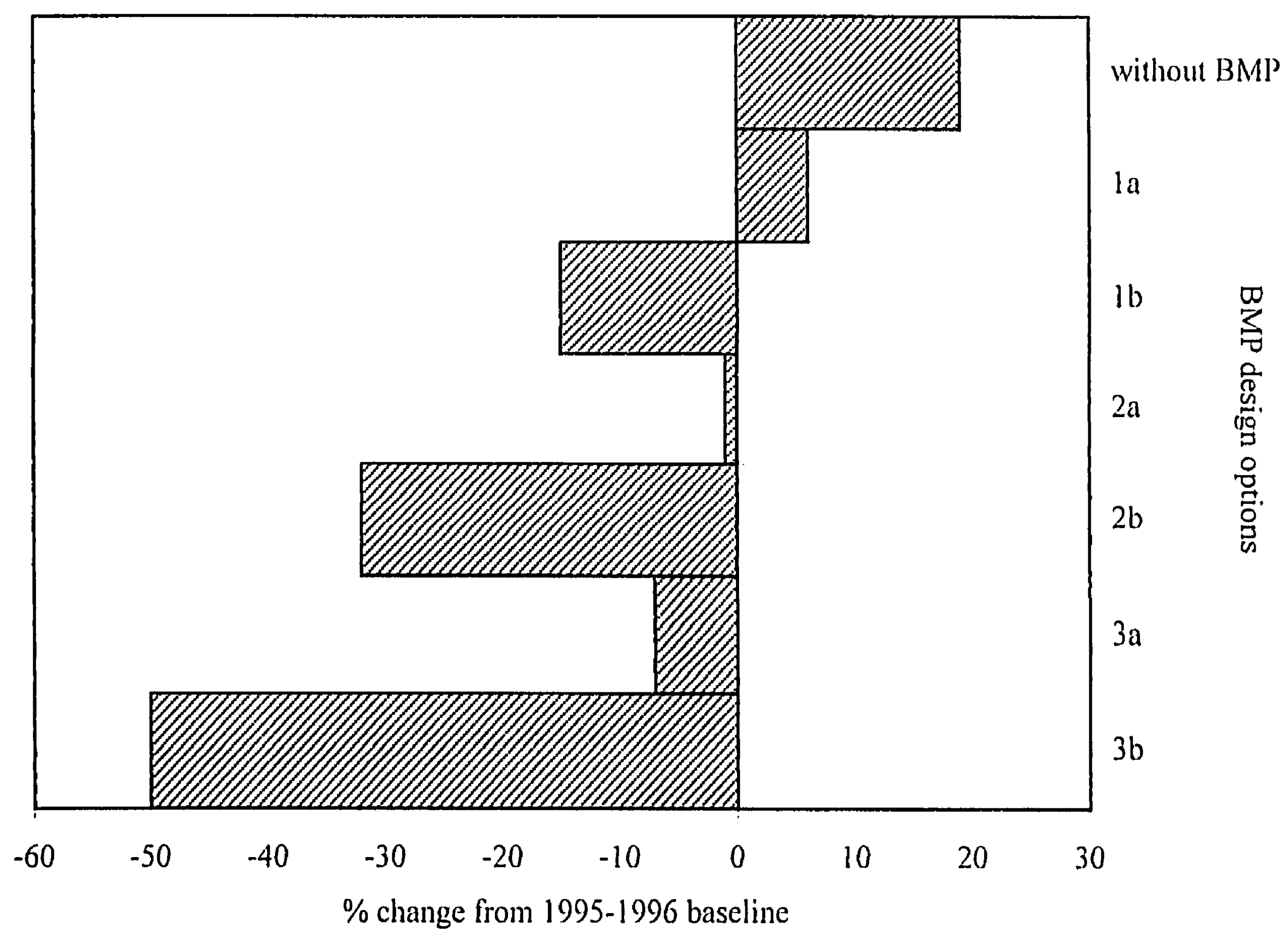
Before the bypass of the combined sewage overflow from Laurel Creek to the Grand River in 1977, mean annual total phosphorus concentrations in Laurel Creek were highly variable (Fig. 2). Combined sewage overflows discharge partially treated or untreated sewage and urban stormwater to streams or lakes during periods of high flow, such as snowmelt and stormevents (Sullivan et al., 1978). Prior to 1974 there was no phosphorus removal at the sewage treatment plant, and in 1971 and 1974 the highest concentrations, 0.24 and 0.37 mg/l respectively, and greatest variability were observed. Mean annual concentrations ranged between 0.07 and 0.13 mg/l from 1974 -1996. Before the bypass was put in, combined sewage overflow clearly dominated phosphorus loading to Laurel Creek, particularly during certain years, and would have been related to the frequency of storm and snowmelt events.

Using the model to forecast total phosphorus loads resulting from urban development planned for the Laurel Creek watershed, a potential increase in total phosphorus loads up to 3423 kg was predicted. representing a 19 % increase from 1995-1996 loads (Fig. 3). Urban land use at this time would occupy 4906 ha. 66 % of the watershed area.

The current. past and predicted future phosphorus concentrations are considerably higher than 0.03-0.05 mg/l. the Ontario Ministry of Environment and Energy guideline for allowable total phosphorus in rivers and streams to prevent excessive aquatic plant growth (GRCA, 1982). The nuisance growth of aquatic plants is a management concern in the Grand River watershed because of the associated reduction in aesthetic quality and degradation of fish habitat. At certain periods during the summer, nocturnal plant respiration results in dissolved oxygen levels falling below requirements for fish survival (Mason et al., 1989). Oxygen deficits also limit the natural ability of the Grand River to assimilate sewage effluent discharge from the major urban centers along the river (Draper & Weatherbe, 1995). Reducing the input of phosphorus to the Grand River is an ongoing management concern. and the importance of non-point sources is increasingly being recognized.

There are several management options to reduce the loading of phosphorus from the existing and planned urban development. One option to reduce phosphorus runoff from lawns and gardens is to grow resource-efficient plants that are well adapted to the area and thus have lower water and chemical input requirements (Hipp et al., 1993). Kentucky bluegrass (*Poa pratensis*), one of the most widely used turfgrasses in Ontario, for example, requires fertile soils, whereas creeping red fescue (*Festuca rubra*) is more tolerant of infertile conditions (OMAF, 1981). Improved, low maintenance, turfgrass cultivars are continually being developed (Schultz, 1989). Indigenous vegetation, which is adapted to the area, requires less maintenance than other plants and the use of such species in landscaping should be actively encouraged. Where fertilizers are needed, homeowners, gardening firms and landscapers should be encouraged not to over-fertilize. To most effectively educate such consumers, sales representatives and others interacting closely with consumers must first be educated (Latimer et al., 1996).

Figure 3. Model forecasting of changes in phosphorus loading to Laurel Creek resulting from future urban development. Three BMP design options for phosphorus removal from urban runoff were evaluated, 1) an extended detention pond system, 2) a forest filter strip, and 3) an infiltration pond design (see text for full explanation). These designs were evaluated for a) runoff from new urban development, and b) all urban runoff.



Other options to control runoff tend to be either structurally intensive and expensive or nonstructural and less costly. These include infiltration practices such as porous or permeable pavements, infiltration basins and infiltration trenches; sedimentation practices such as detention basins and retention basins; wetland systems; and vegetated buffer strips (Scholze, 1993). A control program for stormwater discharges must be developed, focusing on the water quality problems caused by phosphorus for sites along the creek (Lee and Jones-Lee, 1993). These have been evaluated in a recent watershed study (GRCA, 1993) and should be considered in developing and implementing BMP's. Typically, a combination of practices will be required to effectively control phosphorus loading from the urban area (Scholze et al., 1993).

The degree of phosphorus removal by three BMP designs from Schueler (1987), presented in the Laurel Creek watershed study (GRCA, 1993), were evaluated using the Laurel Creek model (Fig. 3). BMP design 1 is an extended detention pond system, where first-flush runoff volume was detained for 6-12 hours, with an estimated phosphorus removal of up to 40 %. BMP design 2 is a 100 ft wide forest filter strip with level spreader, with an estimated phosphorus removal of up to 60 %. BMP design 3 is an infiltration pond design which exfiltrates one inch runoff volume per impervious acre and removes up to 80 % of the phosphorus. These were considered for a) runoff from the proposed new development; and b) all urban runoff, including that from proposed development.

Applying these management options to the new urban development only would have little (up to -7 % change from the1995-1996 load) impact on the Laurel Creek phosphorus load. BMP designs 2 and 3, when applied to all the urban runoff, would result in appreciable reductions in phosphorus load, -33 % and -50 % respectively. Phosphorus concentration would thus be reduced to approximately 0.08 mg/l or 0.06 mg/l, closer to the 0.03-0.05 mg/l target for the Grand River (GRCA, 1982). To evaluate these options fully, their cost and removal rates for other pollutants of concern would need to be considered, as would combinations of design options.

2.5.3 Model limitations

An important limitation of the export coefficient modeling approach in general is that the export coefficients selected cannot be verified fully for the research site without considerable expenditure on field experimental work (Johnes. 1996). A further limitation is that given the importance of hydrological pathways in determining nutrient delivery to surface waters, and the variations in available transport mechanisms over the annual cycle, the model cannot predict in real time. Another limitation is that phosphorus uptake in the stream is not included in the model as it is highly variable and difficult to quantify, but it can be considerable in certain streams at certain times of year (Mulholland et al., 1997). The buffering capacity of riparian vegetation is also not, at present, included in the model because data are not available as generally applicable retention coefficients for these zones (Johnes, 1996).

There are several specific limitations of the model developed for the Laurel Creek system. An important one is that only phosphorus loading was considered in this model, but there are many other pollutants in urban and agricultural runoff that may potentially degrade water quality. Examples from agricultural and urban development are pesticides and nitrogen, and from highways and the urban area, heavy metals, road salts and petroleum hydrocarbons (Marsalek et al., 1997 and Skinner et al., 1997). These pollutants should also be evaluated and considered in developing BMP's for controlling stormwater discharges and agricultural runoff to Laurel Creek. A further limitation is that phosphorus retention and release coefficients for the shallow, eutrophic, surface-release reservoirs in the system were not included in the model as generally applicable coefficients for such systems were not available. Finally, the objective assessment phase of the modeling procedure was limited to one year and results thus have to be interpreted with caution when used in a management context.

2.6 Conclusions

Despite the limitations of the model developed, export coefficient modeling provided a simple, reliable approach to evaluate phosphorus loading to Laurel Creek. The model was calibrated within ± 3 % of observed loads for 1995-1996, and when objectively assessed by running it for the 1977-1978 water year, the predicted load was within ± 7 % of the observed load. The model provided a simple tool for forecasting, in terms of phosphorus loading, the impact of future urban development planned for the Laurel Creek watershed. Several urban BMP designs were evaluated for phosphorus removal, and it was determined that phosphorus removal will have to be applied to all the urban runoff from the watershed to appreciably reduce concentrations in Laurel Creek.

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3. EXPORT COEFFICIENT MODELING TO ASSESS NITROGEN AND PHOSPHORUS LOADING TO CARROLL CREEK, AND NITROGEN LOADING TO LAUREL CREEK

3.1 Abstract

Export coefficient modeling was used to assess phosphorus and nitrogen loading to Carroll Creek and nitrogen loading to Laurel Creek. Models were constructed for the 1995-1996 water year and calibrated within ± 3 % of observed concentrations. The Carroll Creek phosphorus model was developed using the export coefficients presented for Laurel Creek in the previous chapter, with some modification to separate row and non-row crops and to account for the intensity of grazing in the watershed. Although data were not available to assess the model, it was based on the Laurel Creek which proved reliable when objectively assessed. and it is likely that these coefficients will perform well in other areas of the Grand River watershed with similar land use and watershed characteristics. Overall, non-row crops contributed most to the loading of phosphorus to Carroll Creek. and atmospheric deposition and row crops were also important sources. Assessment of the Laurel Creek nitrogen model using 1977-1978 data was successful, predictions were within ± 6 % of observations. To calibrate the Carroll Creek model. however, very different export coefficients were required because the measured nitrogen concentration in Carroll Creek was much higher than in Laurel Creek. Atmospheric sources contributed most to the loading of nitrogen to Laurel Creek, followed by runoff from urban areas and non-row crops. Non-row crops contributed most to the loading of nitrogen to Carroll Creek, and row-crops and atmospheric deposition were also important sources. However, since the coefficients were so different in the models, it is clear that they are not widely applicable to other areas of the Grand River watershed and further study is required to investigate the use of export coefficient modeling to model nitrogen inputs in this area.

3.2 Introduction

Traditional approaches for assessing the impact of land use change on water quality have involved the development of detailed physically based models (Johnes, 1996). Such models predict changes in water quality in real time and work well in small watersheds, and in the watersheds for which they were constructed. They are, however, expensive to construct and difficult to calibrate, owing to their high data requirements. In addition, these models attempt to predict nitrate or orthophosphate concentrations in surface waters. To evaluate nutrient loading from nonpoint sources, manageable, relatively inexpensive models are desirable, provided they are accurate and capable of prediction. They also need to be able to predict total nitrogen and total phosphorus concentrations in order to assess the total load delivered to the waterbody.

In the1970's, a number of investigators in North America developed models for quantitatively estimating and evaluating the loading of nutrients to streams and lakes using export coefficients (Beaulac and Reckhow, 1982; Dillon and Kirchner, 1975; Omernik, 1976; Rast and Lee, 1983; Reckhow and Simpson, 1980; Reckhow et al., 1980). The use of nutrient export coefficients for estimating loads of nitrogen and phosphorus is based on the knowledge that, for a given climatological regime, specific land use types will yield or export characteristic quantities of these nutrients to a downstream waterbody over an annual cycle (Rast and Lee, 1983). Knowing the area of land in a watershed devoted to specific uses and the quantities of nutrients exported per unit area of these uses (i.e.: the nutrient export coefficients) it is possible to estimate total annual loads of phosphorus and nitrogen to a waterbody from nonpoint sources.

The export coefficient modeling approach, therefore, aims to predict the concentrations of total nitrogen and total phosphorus at any site in the surface water drainage network of a drainage basin as a function of the export of nutrients from each nutrient source in the catchment above that site (Johnes, 1996). Recently, export coefficient modeling has been successfully modified and used in Britain (Johnes, 1996; Johnes and Heathwaite, 1997). It has also been adapted to allow determination of nutrient loadings delivered to lakes in England and Wales, in the development of a new lake classification and monitoring scheme for the National Rivers Authority (Johnes et al.,1994), and was used to estimate nutrient loading from nonpoint sources to rivers in Northern Canada (Chambers and Dale, 1997). The models developed for rivers in Britain predicted total nitrogen and total phosphorus concentration with high precision (>95 % of the variance in observed data explained) (Johnes et al., 1996). One recent study incorporated export coefficient modeling into a computer based model, WATERSHEDSS, using geographical information systems to evaluate nutrient loading under alternative land treatment scenarios (Osmond et al., 1997). The export coefficient modeling approach has a number of very clear advantages over more detailed, process-based modeling approaches, in particular the simplicity of the model format and the operation of the model using a spreadsheet system. The model provides an effective means of evaluating the impact of land use and land management on water quality for surface waters on an annual basis (Johnes, 1996). The model predicts and is calibrated against total nitrogen and total phosphorus concentration data, thereby reducing the problems inherent in predicting the concentration of individual nutrient fractions which may be highly labile.

Since this approach was developed, the only use of export coefficient modeling to evaluate nutrient loading to rivers in Canada has been in the Northern River Basins study (Chambers and Dale, 1997). The effectiveness of such models when constructed to predict the loss of nitrogen and phosphorus from complex British catchments (Johnes et al., 1994 ;1996) demonstrates the potential of this approach in the management of nonpoint source loading of nutrients to Canadian rivers. Recently, developments in this approach have focused on agricultural rather than urban nonpoint sources of nutrients, yet urban runoff may contain significant levels of nitrogen and phosphorus (Hipp et al., 1993).

The aim of this and the previous chapter, was to adapt the export coefficient modeling approach to evaluate nitrogen and phosphorus loading to two tributaries (one half urban/half rural and one rural) of the Grand River from nonpoint sources. In chapter 7, this evaluation of eutrophication was compared to the results of an assessment of stream benthic diatoms and macroinvertebrates. In the previous chapter, export coefficient modeling was used to assess the influence of land use phosphorus loading to Laurel Creek. The objectives in this chapter were 1) to construct and evaluate a nitrogen export coefficient model for Laurel Creek, 2) to construct and evaluate nitrogen and phosphorus export coefficient models for Carroll Creek and 3) to discuss these models and the model presented in the previous chapter.

3.2 Site descriptions

3.3.1 Laurel Creek

Laurel Creek is approximately 20 km long with a watershed area of 74.4 km^2. It flows into the Grand River in Southern Ontario, which is in the Lake Erie watershed. The topography varies from gentle, long slopes to short and steep slopes (GRCA, 1993). Laurel Creek drains most of the land area within the City of Waterloo and much of the lower half of the watershed is under urban development. Land use in the upper half of the watershed is largely agricultural, consisting mainly of commercial crop production (GRCA, 1993). The most common soils in the agricultural area are members of the Brant Waterloo and Burford Fox associations, loam with some silt loam and clay sand formed on outwash and lacustrine deposits (GRCA, 1993; Presant and Wicklund, 1971). Five impoundments exist along Laurel Creek, some with a relatively high water storage capacity.

3.3.2. Carroll Creek

Carroll Creek is approximately 20 km long with a watershed area of 69.2 km^2. It is also a tributary of the Grand River, flowing into the river about 2 km downstream of the town of Elora. Land use throughout the watershed is predominantly agricultural, consisting of crop and livestock production. The topography is mainly gently rolling, with some short and irregular steep slopes (Hoffman et al., 1963). The most important soils is the area are silt, clay and sandy loams of the Harriston series, in particular Brant Harriston asscociations, and of the Huron series, formed on glacial till and lacustrine deposits.

3.4 Methods

3.4.1 Modeling procedure

The modeling procedure used was based on that outlined by Johnes (1996), Johnes et al. (1996) and Reckhow et al. (1980) (Fig. 1). Information was obtained from existing databases on discharge, land use and catchment characteristics for the 1995-1996 water year. Rates of nitrogen and phosphorus export from each type of land use were then selected from the available literature.

Using this information, simple empirical models were constructed in a spreadsheet to predict total phosphorus and total nitrogen load transported the streams as the sum of the export from each nutrient source in their watersheds. For both study watersheds, the model equation used was:

$$L = \sum_{i=1}^{n} E_i A_i + P \qquad (1)$$

where L was the nutrient load delivered to the stream (kg); E was the export coefficient selected for nutrient source i (kg/ha); A was the area of the watershed occupied by land use type i (kg); and P was the input of nutrients from precipitation (kg). P was calculated as:

$$P = daQ \qquad (2)$$

where d was the annual areal deposition rate of phosphorus or nitrogen (kg/ha). a was the area of the watershed (ha) and Q was the percentage of total annual rainfall lost to runoff. Q was calculated as:

$$Q = (R / p) * 100 \tag{3}$$

where R was the mean annual runoff (mm) and p was the total annual precipitation (mm). R was calculated using the equation:

$$R = (F / a) * 1000 \tag{4}$$

where F is the mean annual flow volume (million m^3) and a is the catchment area (km^2).

Using measurement of total annual discharge. the model predictions were expressed as mean annual stream concentrations. The models were then calibrated against observed concentrations. A sensitivity analysis was conducted for each model to determine which of the export coefficients exerted greatest control over model output. Each of the coefficients was, in turn, altered by 10 % while the other coefficients were kept constant, and the overall change in model output assessed. This information was used to revise the selection of those coefficients exerting greatest control over model output. The model was then run again with the new export coefficients and calibrated against the observed data until the model predicted within ± 5 % of measured concentrations. For each land use type, extreme land use changes were then assessed by comparing the change in model output if that land use type were to cover the entire watershed area.

For the Laurel Creek nitrogen model, the calibration procedure was objectively assessed by running the model for the 1977-1978 water year, using independent data collected in the Laurel Creek watershed on changing land use, discharge, agricultural practice and

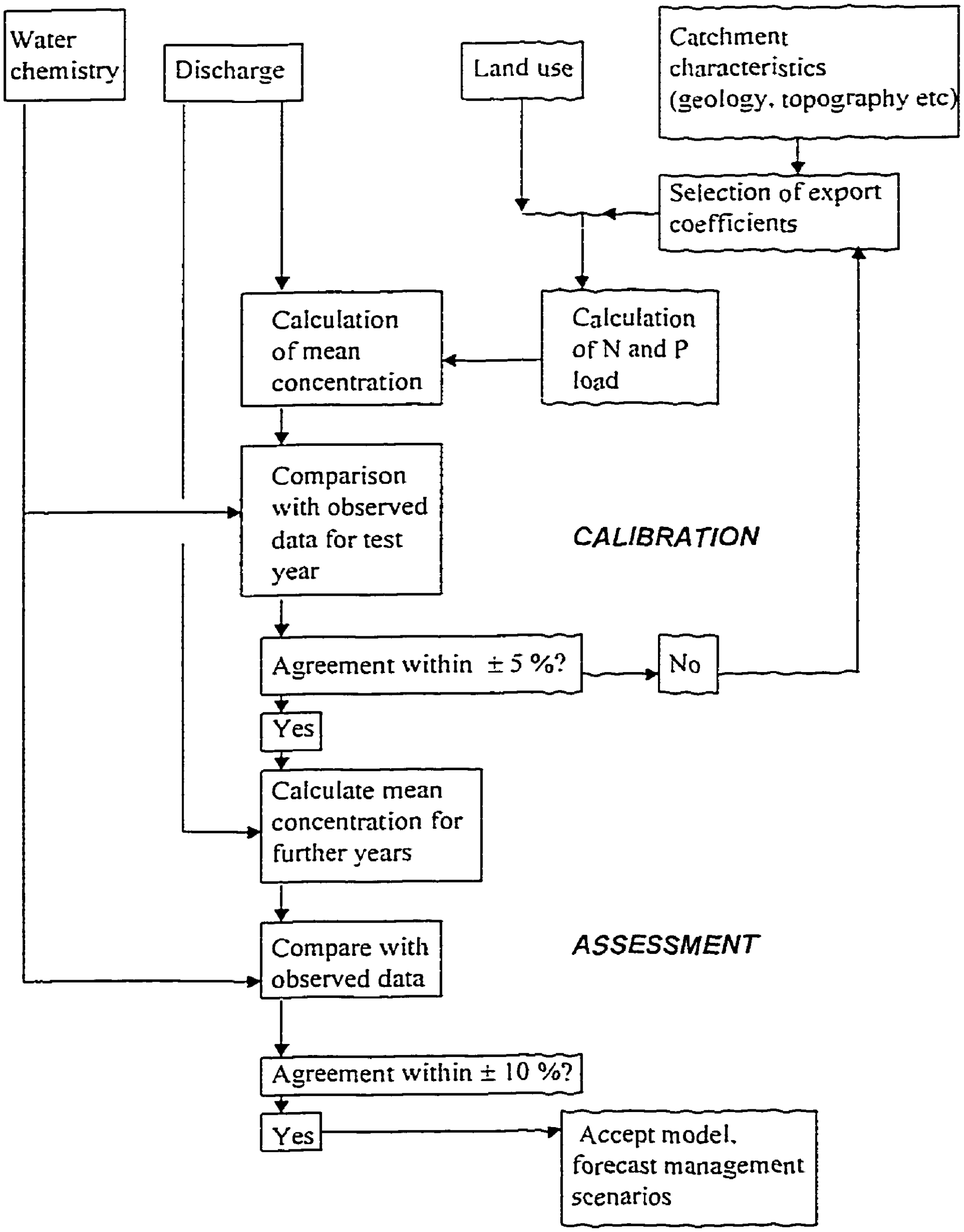

Figure 1. Flow diagram of the export coefficient modeling procedure (adapted from Johnes et al., 1996)

total nitrogen concentration. For reasons outlined in the previous chapter, this was the only year for which the model could be objectively assessed. Assessment of the model should ideally be carried out over several years to establish a relationship between predicted and observed concentrations. Past data were not available to assess the Carroll Creek model.

3.4.2 *Water chemistry, precipitation and discharge*

To determine mean annual concentrations of total nitrogen and total phosphorus, water samples were collected at a sampling frequency varying from weekly to monthly over the 1995-1996 water year. The water year ran from September 1, 1995 to August 31, 1996, starting from the month with the lowest mean discharge (Gordon et al., 1994). Samples were collected at the mouth of both streams, and sampling intensity was adjusted throughout the year to include storm and snow melt events. A total of 21 samples were analyzed for phosphorus and 19 for nitrogen. Water was collected in 10% hydrochloric acid-rinsed bottles, and total phosphorus concentration was measured as phosphate using the ascorbic acid method following oxidation with persulfate under pressure (Parsons et al., 1984). Total nitrogen concentration was measured as nitrate following digestion with sodium hydroxide and sulfuric acid under ultraviolet light (Technicon, 1984). Blanks were run in all analyses and the limits of detection were 0.2 μg/l for phosphorus and 1 mg/l for nitrogen. Total kjeldahl nitrogen, nitrate and nitrite data for 1977-1978 (total of 12 samples) were obtained from the Ontario Ministry of the Environment and Energy and analyzed according to standard methods outlined in their analytical protocol (OMOEE, 1981). Total nitrogen concentration was calculated by adding these forms of nitrogen (Ameel et al., 1993). Precipitation data were obtained from the Ontario Climate Centre, Environment Canada for the stations closest to Laurel Creek, Waterloo-Wellington, and to Carroll Creek, Glen Allan.

Discharge data for Laurel Creek were compiled by the Water Survey of Canada, and for Carroll Creek by the Grand River Conservation Authority. The gauges on both streams were located upstream of the mouth, so downstream discharge had to be estimated. Discharge measurements were made, under varying flow conditions, at the mouth of both streams over a two month period in 1997, to develop a relationship with the gauged site

($R^2 = 0.94$ for Laurel Creek and $R^2 = 0.84$ for Carroll Creek). Estimates obtained using this relationship agreed very closely with those calculated by adjusting for the difference in watershed area between the two sites, using an equation outlined in Gordon et al. (1994). Mean annual discharge for the Laurel Creek watershed was calculated using the relationship developed using measurements downstream. For the Carroll Creek watershed, discharge was calculated by adjusting for watershed area, using the equation:

$$Q_1 = Q_2 \, (A_1/A_2) \tag{5}$$

where Q_1 = mean annual discharge for the ungauged site, Q_2 = mean annual discharge for the gauged site, and A_1 and A_2 are the areas of the ungauged and gauged watersheds, respectively.

3.4.3 Land use

Land use in the Laurel Creek watershed for 1995-1996 was compiled using: maps from the Ontario agricultural resource inventory (OMAF, 1983); maps and information contained in GRCA (1993); data collected in the 1996 agricultural census (Statistics Canada, 1996); and the 1997 City of Waterloo zoning map. Land use for the 1977-1978 model was determined using Grand River Conservation Authority reports and maps (MacMillan, 1978; Veale, 1981) and information from the 1976 agricultural census (Statistics Canada, 1976). Land use in the Carroll Creek watershed was entered into a geographical information systems (GIS) database by Bruce Pond, Wildlife and Natural Heritage Science Section, Ontario Ministry of Natural Resources, using satellite imagery and the Ontario agricultural resource inventory. For all models, data collected from maps were used to determine the extent of land under crop production, and the areas of specific crop types were then calculated using Statistics Canada data on the proportions of crops grown in each township.

3.5 Results

3.5.1 Phosphorus export coefficient selection

With three exceptions, the export coefficients for phosphorus used in the Carroll Creek model were the same as those used in the Laurel Creek model outlined in the previous chapter. Total annual rainfall lost to runoff in the Carroll Creek watershed was 37%. Based on a series of interviews with farmers owning property directly adjacent to the creek, it was determined that grazing was intense on the creek banks, and a higher coefficient of 0.5 kg/ha/yr was used to reflect the export from grazed areas on Carroll Creek. This value is used by Chambers and Dale (1997) for areas of pasture under intense grazing. Row crops and non-row crops were considered separately in the Carroll Creek model, and an export coefficient of 0.3 kg/ha/yr was selected to reflect the input of phosphorus from row crops since soil erosion and, consequently, total phosphorus runoff is greater in row crops than non-row crops (Chambers and Dale, 1997). As for Laurel Creek, inputs of phosphorus from septic tanks were not included in the model. The urban coefficient was used to account for runoff from built up areas and highways.

3.5.2 Nitrogen export coefficient selection

Laurel Creek

To express the transfer of nitrogen from woodland areas in Laurel Creek, an export coefficient of 3 kg/ha/yr was selected. This was the mean value calculated by Chambers and Dale (1997) for export from North American watersheds and within the range for deciduous forests (1.37-4.01 kg/ha/yr) listed in Reckhow et al. (1980). For cropland, coefficients of 6 kg/ha/yr and 8 kg/ha/yr were selected for non-row crops and row crops respectively. These export coefficients are within the North American coefficients for row crops (2.81-79.6) and non-row crops (0.97-38.22) published by Reckhow et al. (1980) for loam, sandy clay loam and silt loam soils. For the pasture areas, an export coefficient of 3.5 kg/ha/yr was selected, which is the mean value for Canadian pasture summarized by Chambers and Dale (1997). To express transfer from urban land uses in the watershed, an export coefficient of 5.5 kg/ha/yr was selected, which is in the range of those presented by Reckhow et al. (1980) for low density residential areas (1.48-9.48). The input in nitrogen in precipitation, 12.4 kg/ha/yr, was taken from Kuntz (1980) and the percentage of precipitation lost to runoff was 30%. The nutrient content of rainfall was derived from this study because it was the most thorough investigation available Great Lakes area. However, given the reported increases in atmospheric nitrogen deposition over the last century (Vitousek et al., 1997) it is likely that the nitrogen coefficient would now be higher than it was 18 years ago. European export coefficient models (Johnes, 1996; Johnes et al., 1996) also use atmospheric nutrient levels measured in the 1980's and could not be used to obtain more recent estimates.

Inputs from septic tanks in the watershed were not included in the nitrogen models for Laurel Creek or Carroll Creek because no information was available on the failure rates of these systems in the area and general rates of nitrogen loading from septic tanks are scarce. Jones et al. (1977) and Reckhow et al. (1980) investigate the binding of phosphorus to soils and the movement of phosphorus from septic tanks, but such comprehensive studies are not available for nitrogen. Johnes (1996) includes loading from septic tanks in her export coefficient models, and assumes that all septic tanks in the watershed discharge to the waterbody of interest annually. Although septic tanks likely contribute to nitrogen in these creeks, there is no data available to confirm that they fail with such regularity. Assuming a 100 % failure rate, using an export coefficient for nitrogen of 2.49 kg per capita/yr (Johnes, 1996) the total potential input of nitrogen from the rural population of the watersheds would be 3793 kg for Carroll Creek and 2393 kg for Laurel Creek. For this calculation, the rural population was estimated using the 1996 agricultural census (Statistics Canada, 1996).

Carroll Creek

For the Carroll Creek watershed the same export coefficient for woodland areas was used, and the coefficient for urban areas used in the Laurel Creek model was used to express runoff from built up areas and highways. The input from atmospheric sources was also the same, but 37% of the annual rainfall was lost to runoff.

Agricultural land use is intense throughout the Carroll Creek watershed, and the measured annual average nitrogen concentration was seen to be a lot higher than in Laurel Creek (7.5 mg/l versus 2.74 mg/l). Using the Laurel Creek coefficients to calculate the load of nitrogen to Carroll Creek the predicted loads were 142,000 kg (-66 %) lower that observed loads. In order, therefore, to calibrate the Carroll Creek model, higher export coefficients for crops and pasture had to be used than for the Laurel Creek watershed.

An export coefficient of 35 kg/ha/yr was selected for the export of nitrogen from row crops, and a coefficient of 27 kg/ha/yr was selected for non-row crops. These are within the published ranges for row and non-row crops on loam and silt loam soils (Reckhow et al., 1980). To reflect the export of nitrogen from grazed areas, a coefficient of 15 kg/ha/yr was selected which is in the range for pasture presented by Reckhow et al., 1980 for North American pastures (1.48-30.85 kg/ha/yr).

3.5.3 Carroll Creek phosphorus export coefficient model

The total predicted phosphorus load delivered to Carroll Creek over the 1995-1996 water year was 2236 kg (Table 1). This was within ± 3 % of the observed levels (Fig. 3). The mean annual observed concentration was 0.08 mg/l (S.D. ± 0.10). Of the nutrient sources included in the model, non-row crops contributed most (1106 kg). Atmospheric deposition (512 kg) and row crops (471 kg) were also important sources.

The sensitivity analysis performed indicated that phosphorus concentration in Carroll Creek was most strongly determined by export from non-row crops, followed by atmospheric deposition and export from row crops (Table 2). These sources were most sensitive to a 10 % change in their export coefficients. The model was also sensitive to extreme changes in watershed. and the greatest increases in phosphorus loading would result if the entire watershed was urbanized or converted to pasture.

Table 1. Phosphorus export coefficient model for Carroll Creek constructed for the 1995-1996 water year

Nutrient source	Area (ha)	Phosphorus input (kg/ha/yr)	Phosphorus export coefficient (kg/ha/yr)	Phosphorus load (kg)
Urban	70		0.5	35
Pasture	98		0.5	49
Row crops	1570		0.3	471
Non-row crops	4424		0.25	1106
Woodland	629		0.1	63
Atmospheric	6922	0.2	0.37	512
Total predicted load				2236

Table 2. Sensitivity analysis for the Carroll Creek phosphorus export coefficient model

Nutrient source	% change in model output by adjustment of each export coefficient by 10 %	% change in model output if nutrient source were to cover entire watershed area
Urban	0.16	78
Pasture	0.22	79
Row crops	2.12	17
Non-row crops	4.95	2
Woodland	0.28	-45

3.5.4 Laurel Creek nitrogen export coefficient model

The total load of nitrogen delivered to Laurel Creek over the 1995-1996 water year was predicted to be 68251 kg, which was within ± 1 % of the measured levels (Table 3 and Fig. 2). The mean annual observed concentration was 2.74 mg/l (S.D. ± 0.74).

Table 3. Nitrogen export coefficient model for Laurel Creek constructed for the 1995-1996 water year

Nutrient source	Area (ha)	Nitrogen input (kg/ha/yr)	Nitrogen export coefficient (kg/ha/yr)	Nitrogen load (kg)
Urban	3073		5.5	16902
Pasture	106		3.5	371
Row crops	841		8	6728
Non-row crops	2423		6	14538
Woodland	677		3	2031
Atmospheric	7441	12.4	0.3	27681
Total predicted load				68251

Atmospheric sources contributed most to this load (27681 kg), followed by urban runoff (16902 kg), non-row crops (14538 kg) and row crops (6728 kg). These sources were also most sensitive to a 10 % change in their export coefficients (Table 4). Nitrogen loading to the stream would be substantially reduced if the entire watershed were converted to woodland or pasture, and increased if the watershed were developed for row-crop

Table 4. Sensitivity analysis for the Laurel Creek nitrogen export coefficient model

Nutrient source	% change in model output by adjustment of each export coefficient by 10 %	% change in model output if nutrient source were to cover entire watershed area
Urban	2.48	1
Pasture	0.05	-27
Row crops	0.99	28
Non-row crops	2.13	6
Woodland	0.30	-27
Atmospheric	4.06	

production. An assessment of the model by running it using independent data collected for the 1977-1978 water year resulted in a predicted load of 67725 kg, which was within ± 6 % of observed concentrations when converted using annual discharge (Table 5 and Fig. 2). The mean annual measured concentration was 2.58 mg/l (S.D. ± 0.62).

Figure 2. Observed concentrations of nitrogen and phosphorus versus those predicted using the export coefficient models for Laurel Creek and Carroll Creek.

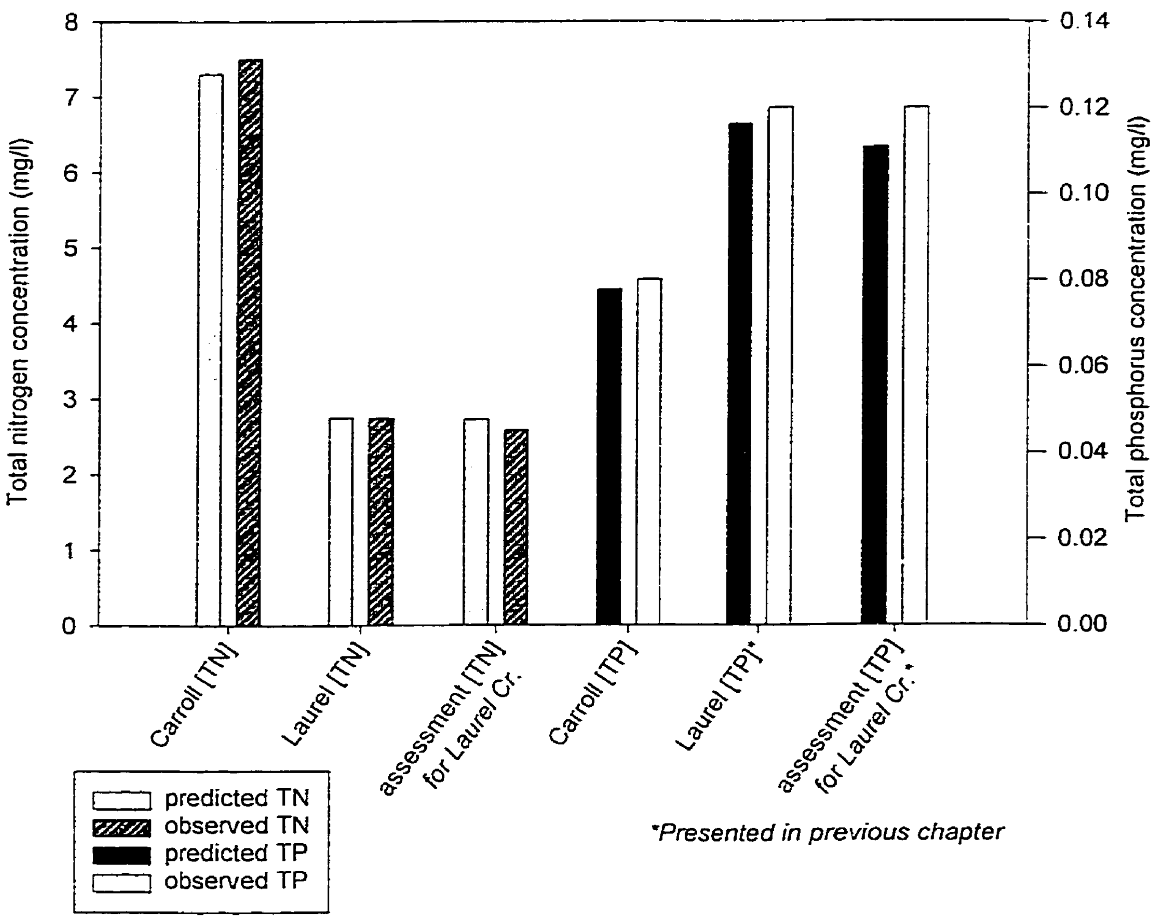

Table 5. Assessment of Laurel Creek nitrogen export coefficient model using 1977-1978 data

Nutrient source	Area (ha)	Nitrogen input (kg/ha/yr)	Nitrogen export coefficient (kg/ha/yr)	Nitrogen load (kg)
Urban	2181		5.5	11996
Pasture	295		3.5	1033
Row crops	1557		8	12456
Non-row crops	1947		6	11682
Woodland	959		3	2877
Atmospheric	7441	12.4	0.3	27681
Total predicted load				67725

3.5.5 Carroll Creek nitrogen export coefficient model

The predicted load of nitrogen delivered to Carroll Creek over the 1995-1996 water year was 209898 kg, which was within ± 3 % of the measured levels (Table 6 and Fig. 2). The observed mean annual concentration was 7.50 mg/l (S.D. ± 2.82). Non-row crops contributed most to this load (119448 kg). and row crops (54950 kg) and atmospheric deposition (31758 kg) were also important. These sources were also most sensitive to a 10 % change in their export coefficients (Table 7). Converting the entire watershed to woodland or urban development would reduce nitrogen loading considerably, whereas converting the entire watershed to row crop production would increase nitrogen loading.

Table 6. Nitrogen export coefficient model for Carroll Creek constructed for the 1995-1996 water year

Nutrient source	Area (ha)	Nitrogen input (kg/ha/yr)	Nitrogen export coefficient (kg/ha/yr)	Nitrogen load (kg)
Built up	70		5.5	385
Pasture	98		15	1470
Row crops	1570		35	54950
Non-row crops	4424		27	119448
Woodland	629		3	1887
Atmospheric	6922	12.4	0.37	31758
Total predicted load				208918

Table 7. Sensitivity analysis for the Carroll Creek nitrogen export coefficient model

Nutrient source	% change in model output by adjustment of each export coefficient by 10 %	% change in model output if nutrient source were to cover entire watershed area
Built up	0.02	-72
Pasture	0.07	-35
Row crops	2.62	31
Non-row crops	5.69	4
Woodland	0.09	-75
Atmospheric	1.43	

3.6 Discussion

3.6.1 Evaluation of the models

A range of factors may affect export rates of nutrients to a stream from agricultural areas, in particular soil type and structure, extent and timing of crop cover, tillage practices, fertilizer application and rainfall (Johnes et al., 1996). Open-pored sandy soils, for example, lose much more nitrogen by leaching than clay or organic-rich soils. Nutrients move to streams from their watersheds via surface runoff, natural subsurface flow and subsurface tile flow (Sharpley et al., 1993). The mechanisms by which this movement occurs are rainfall- and irrigation-induced erosion, leaching and runoff. In urban areas, nutrients are generally exported via surface runoff because paved surfaces are impervious to water and prevent infiltration. Urban inputs enter streams through uncontained runoff or via storm-sewer outfalls (Banneramann et al., 1993). Phosphorus inputs from urban and agricultural areas may be in soluble organic and inorganic forms, or bound to particulate material (Sharpley et al., 1993) whereas inputs of nitrogen to streams are largely in soluble forms (Heathwaite et al., 1996).

Loads of these nutrients delivered to surface waters from agricultural systems arise through inputs of fertilizers and manure to areas of crop and livestock production (Haygarth et al., 1998; David et al., 1997). It is difficult to maintain the fine balance of available nutrients required to satisfy crop needs and at the same time minimize leaching losses, and loading from these systems occurs because nutrients are generally added at rates that exceed crop requirements. Excess nutrients accumulate in agricultural areas and may eventually enter rivers, streams and groundwater. Nitrate contamination of surface and groundwaters as a result of over-fertilization, for example, is an environmental problem throughout Europe and North America (David et al., 1997; Johnes and Burt, 1993), and there is concern that excess phosphorus accumulating in soils in areas of intensive agriculture may lead to an increase in phosphorus losses to the aquatic environment (Haygarth et al., 1998). Phosphorus and nitrogen loads are also delivered to surface waters from urban areas, originating from sources such as runoff from roads, parking lots, roofs, lawns and driveways (Bannermann et al., 1993; Hipp et al., 1993).

Given the diversity in agricultural and urban land use intensity, the numerous factors that potentially affect the rates of delivery of nitrogen and phosphorus from these sources, and the complex pathways of nutrient transfer to surface waters, it is not surprising that there is great variation in export coefficients reported in the literature (Johnes et al., 1996). In the studies reviewed by Reckhow et al. (1980), for example, the nitrogen export from non-row crops ranged from 0.97-38.22 kg/ha/yr, and the phosphorus export from non-row crops ranged from 0.1-8.08 kg/ha/yr. Selecting coefficients based on specific land use category (such as low versus high density residential and corn versus soybean production) fertilizer application rate, soil type, annual precipitation and water runoff did not greatly improve the range in estimates. Nitrogen export from corn, for example, grown on loam or silt loam soil, with fertlizer application rates between 100-112 kg/ha/yr, with an annual precipitation of 57-65 cm/yr and a water runoff rate of 8.6-10 cm/yr, ranged from 2.81-79.6 kg/ha/yr. When calculated as a percentage of fertilizer input, the reported export of nitrogen from corn ranged from 3-152 %.

To keep the models simple and usable throughout the Grand River watershed, I elected to use fairly broad land use categories, and calibrated the models using coefficients within the ranges of those published. The selection of coefficients was very subjective, based on my interpretation of the published numbers. The assessment phase of modeling was therefore essential to independently evaluate the effectiveness of the models. This was possible for the Laurel Creek models. but not for the Carroll Creek models. The Laurel Creek models for phosphorus and nitrogen performed well when run using independent data collected for the 1977-1978 water year. These models therefore appear reliable, with the caveat that the assessment was only run for one year. Since the Carroll Creek phosphorus model, when constructed using similar coefficients to those used for the Laurel Creek model. predicted concentrations within ± 3 % of observed concentrations. it also seems reliable. The nitrogen models. however. were very different for the two watersheds. Despite similarities in the types of crops grown. tillage system. geology. soils and topography between the two watersheds. observed concentrations of nitrogen were much higher in Carroll Creek than Laurel Creek. and coefficients for the loading of nitrogen from cropland had to be chosen to reflect this. Although part of the Laurel Creek watershed is used for agriculture, urban development is encroaching on the rural area and each year less land is being used for crops. The fact that agriculture is intense and the predominant land use in the Carroll Creek watershed is a likely explanation for the higher nitrogen concentrations measured.

On interviewing 18 farmers with properties adjacent to Carroll Creek on their farming practices, it was determined that most farmers used much higher levels of fertilizer than the recommended rates, particularly on corn. It is possible that there was more nitrogen input to the Carroll Creek than the Laurel Creek watershed which would account for higher export rates, but, as Laurel Creek farmers were not questioned, this could not be substantiated. Phosphorus fertilizers, however. were also applied at much higher levels than those recommended, yet measured stream concentrations were consistently similar to those observed in agricultural areas on Laurel Creek. Nevertheless it is possible that more nitrogen fertilizer is applied to crops in Carroll Creek watershed than in the Laurel Creek watershed and that this is running off into the creek.

Another possible source of nitrogen to Carroll Creek was from feedlots and manure piles located in close proximity to the creek. Most farmers with properties adjacent to the creek reported manure storage within 500 m of the stream, generally as a pile on a cement pad. These are extremely prone to the runoff of manure and would contribute to nitrogen loading to Carroll Creek. No data was collected from farmers with property on Laurel Creek, and no details of the amounts of manure stored were obtained, so this data could not be included as components in the models. It is possible that the input of nitrogen from these sources to Carroll Creek was greater than to Laurel Creek. Feedlots and manure storage areas, however, contribute extremely high levels of both phosphorus and nitrogen (Reckhow et al., 1980) and since phosphorus levels were not elevated in Carroll Creek, it is unlikely that these were the sources of the higher nitrogen load.

According to artificial drainage maps drawn by OMAF in 1982, half of the agricultural land in the Carroll Creek watershed is tile drained. Tile drainage has been shown to increase the loss of nitrate from fertilized fields to surface waters (Baker and Johnson, 1983; Tan et al., 1993), particularly during high rainfall years (David et al., 1997). In a study by David et al. (1997), over a six year period an average 49% of the annual field inorganic nitrogen pool was leached through tile drains and seepage, and exported to a nearby river. This was as much as 85%, however, during 1996, a high rainfall year. An estimated 40% of the agricultural area of the Laurel Creek watershed, however, is also tile drained. The proportion of tile drained land on Carroll Creek is therefore only slightly higher than on Laurel Creek, but the total annual precipitation in 1995-1996 was 1045.7 mm at the station closest to the Laurel Creek watershed, and 1108.7 mm at the station closest to the Carroll Creek watershed. Of this precipitation, an estimated 37 % was lost to runoff in the Carroll Creek watershed versus 30 % in the Laurel Creek watershed. This is a surprising result given that the area urban development with impervious surfaces is much higher in Laurel Creek than in Carroll Creek. Mean annual runoff tends to decrease as watershed area increases (Gordon et al., 1992) but since the Laurel Creek watershed area is only 5 km^2 greater than the Carroll Creek watershed, this is unlikely to be a significant factor. A more likely explanation is water storage and flow regulation resulting from the reservoirs on the Laurel Creek system (GRCA. 1993). These influence the mean annual flow used to calculate mean annual runoff (equation 4), and the proportion of rainfall lost to runoff may actually be greater than that calculated using this equation. Nevertheless. the higher rainfall together with the slightly greater proportion of land tile drained, may have led to a greater export of nitrogen to Carroll Creek than to Laurel Creek. Phosphorus is also transported to nearby streams via tile drains. but, unlike nitrogen. phosphorus is prone to sorption from the water as it percolates through the soil to the tile (Sharpley et al.. 1995). Most phosphorus is lost is surface rather than subsurface runoff. which might explain why phosphorus concentrations in Carroll Creek were not elevated when compared to agricultural areas on Laurel Creek.

Nitrate is highly soluble and very mobile. making is highly susceptible to leaching through soil with infiltrating water (Hallberg and Keeney. 1993). It is thus a common contaminant of groundwater. and the most extensive source of nitrate delivered to groundwater is agriculture. Nitrate leaching in relation to fertilization has been documented for many crops (Hallberg and Keeney, 1993) and it is possible that long term, intensive agriculture in the Carroll Creek watershed has led to nitrate contamination of the groundwater. which then enters the stream via subsurface flow and contributes to measured concentrations. Since the export coefficient modeling approach does not directly include inputs from groundwater, and no measurements of groundwater inputs were made, it was not possible to separate out and account for these sources.

The estimated rural population discharging sewage to septic tanks was greater in the Carroll Creek than the Laurel Creek watershed (1523 versus 961) which might also have contributed to the higher measured concentrations of nitrogen in Carroll Creek. A study by Burton et al. (1977) found that the export of nitrogen was higher from a suburban watershed in South Florida than from urban and agricultural watersheds and concluded that this might be due to septic drainage. However, since failure rates for septic tanks in the Laurel Creek and Carroll Creek watersheds have not been investigated, they were not included as nutrient sources in these models. In a worst case scenario, assuming a 100 %

failure rate, the input from septic tanks in Carroll Creek only represents 2 % of the annual load and was predicted to be only 1400 kg higher than septic inputs to Laurel Creek. It is therefore unlikely that loading from septic tanks could account for the elevated nitrogen concentrations observed in Carroll Creek.

Another possible explanation for lower observed concentrations of nitrogen in Laurel Creek than in Carroll Creek is that the proportion of nitrogen removed through denitrification was greater in Laurel Creek. Bacterial denitrification represents a potentially significant pathway for the permanent removal of nitrogen from river systems (Hill, 1979). Denitrification is affected by a number of environmental factors. The process requires anaerobic conditions and is influenced by temperature and pH. It proceeds slowly at low temperatures and in acidic conditions (Wetzel, 1983).
The lower half of Laurel Creek is warmer than Carroll Creek during the summer months which might enhance denitrification. Biological oxygen demand was also higher in the lower half Laurel Creek than in Carroll Creek which would increase the likelihood of sediments becoming anoxic. An important difference between the Laurel Creek and the Carroll Creek watershed is the presence of the impoundments on Laurel Creek, which might increase denitrification rates. The sediments of these shallow, eutrophic reservoirs reportedly become anaerobic during the summer (GRCA, 1993) which would substantially increase the opportunity for denitrification. Rates of denitrification in both rivers and lakes have not been well studied, and are very variable, both spatially and temporally (Hill, 1979; Seitzinger, 1988). They were thus not included in the models.

The higher concentrations of nitrogen measured in Carroll Creek were probably a consequence of several of these factors. The intensity of agriculture of Carroll Creek, causing over-fertilization, groundwater contamination, and runoff in tile drains, as well as higher precipitation and runoff and a greater rural population serviced by septic tanks, are likely explanations. These, together with the possibility for increased rates of denitrification in Laurel Creek, are all plausible reasons. Since these inputs were not measured and incorporated in the model directly. they are reflected in the higher coefficients selected for crops grown in the Carroll Creek watershed.

The supply of nitrogen and phosphorus from atmospheric deposition is potentially a significant source of nutrients for aquatic ecosystems (Jassby et al., 1994) and atmospheric inputs were found to be important sources of nutrients in all models. and the most important source of nitrogen to Laurel Creek. This observation is common in studies of nutrient loading to lakes and rivers. In their study of forested stream catchments in Central Ontario, Dillon et al. (1991) found that atmospheric deposition and nitrogen and phosphorus typically exceeded catchment export, and Jassby et al. (1994) conclude that atmospheric deposition provides most of the total annual nitrogen load to Lake Tahoe and a significant portion of the phosphorus load. Johnes and Heathwaite (1997) and Johnes (1996) found that atmospheric inputs were important sources of nitrogen and phosphorus to rivers in Britain. Emission and deposition of NOx in particular have increased over the last century, and have been correlated with the rising use of fossil fuels and artificial fertilizers due to increases in human population density, industrial activity and agriculture (Vitousek et al., 1997). It is likely that these sources become will increasingly important as the use of fossil fuels continues to increase.

On comparing the Laurel Creek and Carroll Creek models. urban land use is more important in terms of phosphorus loading and agricultural land use in terms of nitrogen loading. There is a possibility, however, that the loading of phosphorus from the agricultural land will increase if phosphorus is accumulating in the soil due to over-fertilization. High soil phosphorus contents may eventually lead to an increase in the phosphorus losses to the streams because the soil becomes saturated with phosphorus and is unable to retain further inputs (Haygarth et al., 1998). The current observations for phosphorus correspond to those made by Rast and Lee (1983) who determined that, for U.S. waterbodies, the annual loading of phosphorus from urban areas was twice that from rural/agricultural areas. They estimated the export of nitrogen, however, to be the same from urban and rural/agricultural areas, whereas Beaulac and Reckhow (1982) found that the average export of nitrogen from row crops, mixed agriculture and, to a lesser extent, non-row crops were higher than from urban areas. The land use covering the greatest area of the Carroll Creek watershed was non-row crop production, which mainly consisted of a mixed grain system, usually made up of oats and barley. Row crops, mainly corn and soybeans, also occupied a substantial area.

Sensitivity analysis

A sensitivity analysis is a test of a model in which the value of a single variable or parameter is changed (while all others remain constant), and the impact of this change on the dependent variable is observed (Kothandaraman and Ewing, 1969). This approach permits a comparison of model response with response anticipated from theory, which serves to (a) aid in confirming that the model is consistent with theory, (b) indicate the effect of errors in each of the sensitive parameters or variables, (c) identify sensitive parameters or variables that must be reliably estimated, (d) indicates the relationships between control variables and decision variables to help ensure that a change in a control variable can have a desirable effect on the decision variable, and (e) identify any regions where desirable levels of the decision variables are insensitive to possible errors of estimation in the model variables and parameters (Reckhow and Chapra, 1983). Model documentation should include sensitivity analysis that can be used to evaluate the appropriateness of the model to the issue of concern.

For the simple models presented in this chapter, sensitivity analysis was also simple and the outcome of changing various parameters was predictable. The analysis reflects both the area of the nutrient source and the size of the export coefficient and gives an indication of the relative importance of each nutrient source in the study watersheds. It identified those coefficients most important in determining model output, and these were first altered to calibrate predictions to observed levels. For the Carroll Creek watershed, model outputs for phosphorus and nitrogen are dominated by export from non-row crops, row crops and atmospheric sources, since a minor change in the export coefficients for these sources resulted in the greatest change in model output. The most extreme changes in model outputs, through scenarios where each nutrient source covers the entire watershed, result from built-up, pasture and woodland areas, since these are the nutrient sources currently covering the smallest land area. This outcome for this, extreme, sensitivity analysis had less to do with export coefficients and more to do with relative changes in land cover under each scenario.

In contrast, the parameters exerting greatest control over model output for phosphorus (presented in the previous chapter) and nitrogen in the Laurel Creek watershed are urban development, cropland and atmospheric sources. Atmospheric sources are relatively more important in the Laurel Creek nitrogen model than in the Carroll Creek model because the export coefficients reflecting the transport from the other nutrient sources are lower. The most extreme changes in the Laurel Creek nitrogen model output, on running scenarios where each nutrient source covers the entire watershed result from row-crop, pasture and woodland areas, since these are the nutrient sources currently covering the smallest areas. The change in model output on converting the entire watershed to woodland is greater for the Carroll Creek nitrogen model than for the Laurel Creek model, even though the coefficient reflecting the export of nitrogen from woodland areas is the same. This is because the coefficients for the other nutrient sources in the Carroll Creek watershed (in particular those for row and non-row crops) are much higher than in the Laurel Creek watershed.

Uncertainty analysis is another approach that can be used to evaluate model performance and gives an indication of model error (Reckhow and Chapra, 1983; Reckhow et al., 1980). Uncertainty may be caused by natural fluctuations inherent in a characteristic such as the variation in flow or stream nutrient concentration. This uncertainty can be incorporated into the export coefficient modeling approach by using most likely, high and low export coefficients. These coefficients can be selected by calibrating models for annual mean nutrient concentration and for values ± 1 standard deviation around the mean. Such uncertainty analysis was beyond the scope of this study but would be useful given the stochastic nature of hydrological processes and water chemistry.

3.6.2 Model limitations

Quality of the data

The limitations of these models arise firstly because they are approximations of reality, and discrepancies between the models and reality are inevitable. and secondly through limitations in the data used to create them. No model is better than the data used for its construction. calibration and assessment (Johnes et al., 1996). For these models there are three sources of data: those obtained from existing databases and maps to determine land use, precipitation and discharge; the measured data used for calibration and assessment; and those on export coefficients coupled with the subjective judgment necessary in their use. Any individual element in these could be in error but because the models are made up of so many elements, they have a considerable robustness (Johnes et al., 1996). The assumptions made are that meteorological and discharge data are reliable. and that maps have been drawn accurately. An additional source of error arises through the conversion of discharge to account for runoff from areas downstream of the gauged sites. Since two alternative methods of performing this calculation yielded very similar results, the estimates are considered acceptable. The data drawn from agricultural censuses collected by Statistics Canada rely on accurate reporting by farmers. Although this data might not be strictly accurate, proportions calculated on a township basis are likely to be reliable because of the high number of farms reporting.

In the calibration and assessment phases of modeling, it is assumed that the measured concentrations of nitrogen and phosphorus in the streams reflect mean annual concentrations. Obviously the more observations on which this annual mean is based, the more accurate it will be. Ideally a continuous sampler would be set up and numerous samples analyzed to calculate an annual mean concentration based on all storm and snowmelt events, and on baseflow measurements. Due to financial and time constraints this was not feasible, but samples were taken as often as possible, both during baseflow and during storm and snowmelt events. However, there is no way to ascertain that the annual mean estimates are accurate and because samples were only collected at an intensity varying from weekly to monthly, phosphorus and nitrogen values presented may in fact represent baseflow nutrient loads. Such infrequent sampling tends to underestimate inputs under elevated flow conditions (Cullen et al., 1988). The samples analyzed by the OMOEE for 1977-1978 were also only collected once or twice each month and may represent low flow concentrations.

The greatest difficulties in export coefficient modeling come in the selection of appropriate export coefficients since, despite the coverage of these in the literature, judgment and experience are necessary for the selection of appropriate values in the relevant published ranges (Johnes et al., 1996). The coefficients selected for the export of phosphorus from these catchments performed well, both when assessed by running the Laurel Creek model for the 1977-1978 water year and when applying them to the Carroll Creek watershed. The selection of the coefficients for nitrogen were more of a problem, however, and, although the Laurel Creek model performed well on assessment, the Laurel Creek and Carroll Creek models were very different and should not be used for management purposes without further evaluation.

Further limitations

There are several important in-stream and in-lake processes that affect measured concentrations of nitrogen and phosphorus which were not included in the models. The impoundments on Laurel Creek are shallow, eutrophic, surface-release reservoirs, for which no generally applicable retention and release coefficients are available for phosphorus or nitrogen. As well as influencing denitrification rates as discussed above, the internal loading of phosphorus from the sediments of such lakes may be substantial, particularly under anoxic conditions (Nürnberg, 1994). On the other hand, nutrients are also retained in lake sediments. A long-term study on a shallow eutrophic lake in Finland, for example, found that the lake retained >80 % of its nutrient load (Ekholm et al., 1997). The retention of phosphorus in rivers may also be important. In a study by Hill (1981) on Duffin Creek in Ontario, for example, there was considerable retention of phosphorus in the river channel, particularly during summer low flows. The retention observed reflected both binding to sediments and uptake by aquatic macrophytes and algae. The buffering capacity of riparian vegetation is also not, at present, included in the model because generally applicable retention coefficients are not available for these zones (Johnes, 1996). Riparian areas, in particular wetlands, have been recognized globally for their value in nutrient removal (Brix, 1994; Haycock et al., 1993). However, in tile drained areas tile lines generally discharge directly to creeks and drains, and would have to be diverted into such buffer zones to reduce nutrient loading.

Given the range in coefficients from specific land use types and the complex nature of the movement of nutrients through the landscape, it seems incorrect to state, as mentioned in the introduction, that "for a given climatological regime, specific types of land uses...will yield or export characteristic quantities of these nutrients to a downstream waterbody over an annual cycle" (Rast and Lee, 1983). Yet, on assessment using independently collected data, models constructed based on this principle gave predictions consistently close ($R^2 = 0.95$) to observed concentrations of both nitrogen and phosphorus when constructed for numerous river watersheds throughout Britain (Johnes et al., 1996). Although there were problems with the nitrogen models, the phosphorus models constructed for Carroll Creek and Laurel Creek are reliable. It would appear then, that models constructed using this approach are often effective, but, given their empirical nature, there is no way of knowing why they work. Since we do not know why they work we also cannot predict when, or why, they might fail to work (Lehman, 1986) and they should be used with caution in stream and lake management. On the other hand, predictive limnology based on empirical approaches has been instrumental in the successful program of eutrophication control on the Great Lakes (Peters, 1986).

3.7 Conclusions

Despite these limitations, the phosphorus models developed in this and the previous chapter proved reliable and provide an inexpensive, simple approach to evaluate phosphorus loading to Laurel Creek and Carroll Creek. The Carroll Creek model presented in this chapter was constructed using the export coefficients used in the Laurel Creek model, with some modification to separate row and non-row crops and account for the intensity of grazing in the watershed, and predictions were within ± 3 % of observed loads. Although data were not available to assess this model, it was based on the Laurel Creek model which performed well when objectively assessed, and it is likely that these coefficients will perform well in other areas of the Grand River watershed of similar land use and watershed characteristics. The export coefficients used in nitrogen models, however, were very different in the two watersheds, and these models may be poor predictors of nitrogen loading. The nitrogen load predicted by the Laurel Creek model was within ± 6 % of the observed concentration when assessed for the 1977-1978 water year, but, since the coefficients were so different in the Carroll Creek model, it is clear that they are not widely applicable to other areas in the Grand River watershed.

3.8 Future work

To improve and assess these models further it would be necessary to construct models for other areas in the Grand River watershed using the same coefficients and evaluate their performance. Watersheds with a long-term water chemistry and discharge records should be selected, with varying proportions of urban and agricultural land use. Given the complexity of internal lake processes that influence water chemistry, ideally rivers without reservoirs on them should be used.

At present these models have been constructed using a simple spreadsheet, but, using a GIS approach, there are ways in which this method could be refined (Johnes and Heathwaite, 1997). The spatial distribution of different land use types could be mapped and linked to key factors controlling nutrient export such as hydrology, soil type and topography. This could be linked, via export coefficients and discharge data, to observed concentrations of nitrogen and phosphorus, and the model could be used to establish areas where management should be targeted to provide the most efficient control of nutrient loading. Using GIS would enable the development of a fully distributed export coefficient model rather than the simple lumped model presented here.

The strength of the export coefficient modeling approach derives from the prediction of total annual export rates of total nitrogen and phosphorus (Johnes, 1996). Such models are useful at a catchment scale and can be used to answer a number of important management questions. In particular, they can be used to reconstruct nutrient loading prior to phases of intensification and as such provide a baseline against which to gauge future loads. They can also be used to forecast possible impacts of future land use and land management on phosphorus and nitrogen export rates. However, the scope of such models are limited because they do not take into account important processes controlling the movement of nutrients along nonpoint source pathways. Detailed, process-based models that include nutrient dynamics are necessary to fully evaluate nonpoint source nutrient control strategies, but such models are impractical in large catchments because of their high data requirements. Therefore, what is ultimately required to evaluate diffuse sources of nutrients at the catchment scale is a combination these approaches (Johnes and Hodgkinson, 1998).

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4. EFFECTS OF URBANIZATION ON WATER QUALITY, PERIPHYTON AND INVERTEBRATE COMMUNITIES IN A SOUTHERN ONTARIO STREAM[1]

4.1 Abstract

Changes in periphyton and macroinvertebrate community structure along a stream system were used to assess the effects of urbanization on water quality. Epilithic diatom and macroinvertebrate samples collected in 1995 and 1996 from Laurel Creek, a rapidly urbanizing watershed in Southern Ontario, were related to measured water quality variables using canonical correspondence analysis (CCA) and principle components analysis (PCA). A distinct separation between urban and rural sites was observed in the ordinations, and sites also differed in terms of macroinvertebrate functional feeding groups. Water quality changes resulting from urban and agricultural development in the watershed are exacerbated by the presence of impoundments and have had fundamental effects on the benthic community of Laurel Creek. Major restoration will be required to improve water and habitat quality in the stream, in particular the rehabilitation of several impoundments. The implementation of urban stormwater and agricultural runoff controls and minimization of erosion from areas currently under urban development are imperative to prevent further deterioration in stream condition.

4.2 Introduction

Changes in land use in watersheds under agricultural and urban development have led to fundamental changes in the structure and functioning of stream communities (Allan, 1995). Wherever significant human settlement has occurred, stream habitats have been altered in terms of both physical and chemical characteristics. The effects of agricultural land use on streams include the runoff of agricultural chemicals, sediment loading due to increased erosion, and alterations in channel morphology (Skinner et al., 1997).

[1] Based on a paper published by the Canadian Water Resources Journal 23:245-257. Co-author H.C. Duthie

Urbanization in stream watersheds reduces soil permeability, thus altering stream hydrology (Andoh, 1994). Another important source of pollution in both rural and urban areas is highway runoff (Marsalek et al., 1997; Smith and Kaster, 1983). Stormwater runoff from highways and urban areas contains particulate material and many chemicals, including nutrients, road salts, heavy metals and petroleum hydrocarbons (Marsalek et al., 1997).

In southern Ontario, impoundments are often used for flood control. Impoundments have significant effects on streams, including changes in the physical and chemical conditions downstream of the dam. In particular, modification of the temperature and flow regimes have been documented, and downstream water quality changes such as elevated nutrient concentrations are also observed (Allan, 1995). The biological effects of impoundments are considerable, and have been well described (Spence and Hynes, 1971; Lehmkuhl, 1972; Ward and Stanford, 1987).

Benthic algae and macroinvertebrates possess many attributes that make them ideal organisms to employ in water quality monitoring investigations (Lowe and Pan, 1996; Hellawell, 1986). Of all the potential groups of freshwater organisms used in biological monitoring, benthic macroinvertebrates are most often utilized and many methods of community analysis exist (Hellawell, 1986). Benthic algae, however, are at the base of the grazing aquatic food web, and occupy a pivotal position at the interface of the chemical-physical and biotic components (Lowe and Pan, 1996). Effects observed at this level either directly or indirectly influence the rest of the aquatic community. Diatoms in particular are the most abundant autotrophic organisms in rivers, colonizing all available surfaces, and are a major source of food for protozoa, invertebrates and young fish (Round, 1993). The use of diatoms in water quality assessments has been described in many studies and much support has been given to this approach (e.g.: Kelly et al., 1995; Pan et al., 1996; Rott et. al., 1998; and Round, 1993). Although biological monitoring data are most valuable when more than one group of organisms of the aquatic community are analyzed (Lowe and Pan, 1996), studies most often focus on one group.

The objective of this study was to assess diatom and macroinvertebrate community structure in relation to land use. in a stream system affected both by agricultural and urban development and by the presence of impoundments. These results are discussed in the context of current management strategies in place for the watershed.

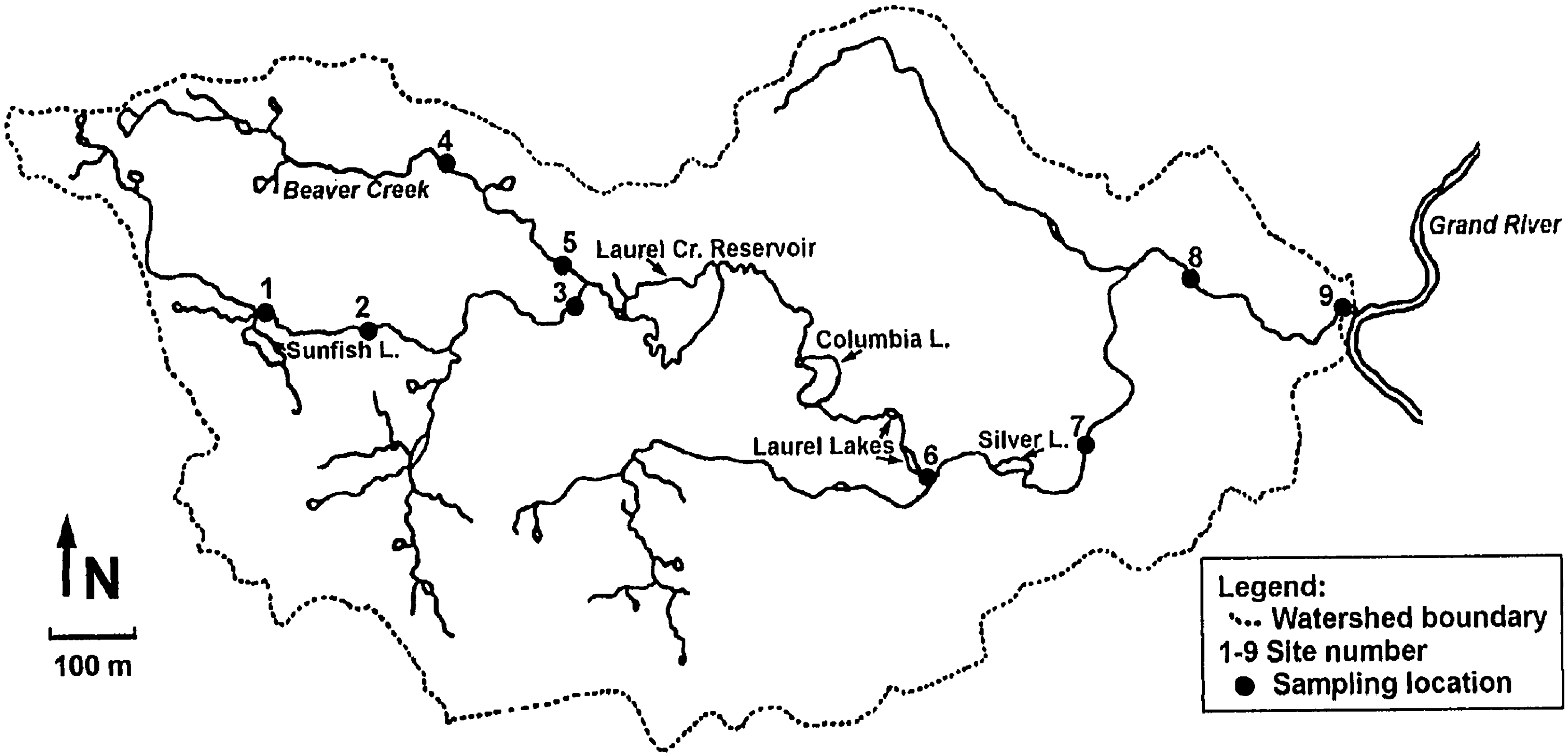
4.3 Site description

Laurel Creek is approximately 20 km long with a catchment area of about 74 km^2 (Fig.1). Historically it was a stream with high water clarity and quality (GRCA, 1993), but its character has been profoundly altered by agricultural and urban development and by the construction of impoundments.

Approximately half of the watershed is under residential, industrial and commercial development. especially in the lower half (GRCA, 1993). The urban land use consists of a broad range of types including residential. industrial and commercial. The upper part of the watershed is predominantly agricultural. consisting of cash crops and pasture, with several areas of woodlot and wetland. Five impoundments exist along Laurel Creek. the largest of which are Laurel Creek Reservoir and Columbia Lake. These discharge from their surface waters, releasing warm, phosphorus-rich water downstream (GRCA, 1993).

The health and quality of Laurel Creek have been the focus of much concern and debate in recent years. The GRCA (1993) Laurel Creek Watershed Study identified issues of concern in the watershed, and concluded that the aquatic habitat in Laurel Creek is degraded in many areas. Key components of the management strategy include the protection of lands that play an important role in enhancing and protecting environmental conditions in the watershed, and setting targets for stormwater runoff (GRCA, 1993). The study also identified sections of the creek and the impoundments, including Laurel Creek Reservoir, Columbia Lake, Laurel Lakes and Silver Lake, as requiring rehabilitation to improve water quality. Action undertaken to date includes the establishment of a detailed

Figure 1: Map of Laurel Creek watershed showing sites sampled



monitoring program in the western portion of the watershed to assess the impact of current and future urban development. Major rehabilitation work is presently being undertaken on Silver Lake. As yet there are no formal proposals in place for the rehabilitation of the other impoundments.

Sites studied on Laurel Creek were selected to reflect varying proportions of upstream urban and agricultural land use and the influence of impoundments (see Fig.1). Sites 1, 2 and 3 are located in the headwaters of the creek, upstream of Laurel Creek Reservoir, and were only sampled in the second field season. Sites 4 and 5 are located on the Beaver Creek tributary of the Creek, upstream of the reservoir. At these sites, the streams are first and second order, and are impacted by agriculture and low density residential land use. Sites 6, 7, 8 and 9 are located downstream of the major impoundments and in the urban center. The stream at site 6 is third order and at the rest of the sites are fourth order. Site 6 is located downstream of Laurel Creek Reservoir, Columbia Lake and Laurel Lake, and site 7 is located downstream of these reservoirs and Silver Lake. Average summer water quality values for all sites are shown in Table 1. In the analysis below, sites 1 to 5 were classified as rural and sites 6 to 9 were classified as urban.

4.4 Methods

4.4.1 Water quality analysis

Samples for water quality analysis were collected in hydrochloric acid-rinsed plastic bottles every two weeks from May to September in 1995 and 1996. Soluble reactive phosphorus was analyzed using the ascorbic acid method, after filtration through a 0.45 μm membrane filter. Total phosphorus concentration was measured as phosphate using the ascorbic acid method following oxidation with persulfate under pressure (Parsons et al., 1984). Total nitrogen concentration was measured as nitrate following digestion with sodium hydroxide and sulfuric acid under ultraviolet light (Technicon, 1984). Alkalinity, nitrate, ammonia, total suspended solids and biological oxygen demand were analyzed according to standard methods (APHA, 1989) and conductivity, pH and temperature were measured in the field.

4.4.2 Periphyton chlorophyll a *analysis*

The periphyton sampler used was developed by Duthie and Jones (1990), and consisted of an enclosed brush attached to a 100 ml syringe barrel. It can be used underwater, scraping an area of 4.9 cm^2. Samples were collected once a month from May to September in 1995 and 1996 (except June 1996) at sites 4 to 9. At each site, three samples were collected and pooled in a plastic container. On returning to the laboratory, samples were filtered onto a 4.5 cm Whatman GF/F filter, placed in a small plastic petri dish and frozen. Samples were later analyzed according to the methods of Burnison (1980). Spectrophotometric readings were taken in a 4 cm cuvette at 480, 630, 647, 664 and 750 nm. Samples were then acidified for phaeophytin correction. Pigment concentrations were calculated using Jeffrey and Humphrey's (1975) equations.

4.4.3 Epilithic diatom sampling

Epilithic diatom samples were collected once a month at all sites. Samples were collected from riffle habitats by pooling scrapings from 3 to 5 rocks, depending on size, into a plastic container. On returning to the laboratory samples were preserved in 10% ethanol. Samples were later treated in 10% hydrocholoric acid for ten minutes, and then in hydrogen peroxide for one hour. Samples were neutralized, and dried onto 22 mm square coverslips. Coverslips were mounted onto slides using Hyrax ® or Naphrax diatom mount. Two hundred diatoms were counted for each slide and identified to species following Krammer and Lange-Bertalot (1986-1991), and also Patrick and Reimer (1966, 1975) and Sims (1996). At two sites downstream of the impoundments (sites 6 and 7) there was evidence of an increase in the number of planktonic species in the epilithic samples. The species found are also commonly found in the plankton of Laurel Creek Reservoir and Columbia Lake (Hopper, 1997). They were significantly more abundant at these sites than at other sites, and in order to provide an unbiased assessment of the epilithon, the planktonic species were excluded in the counts of two hundred for analysis. This is a valid approach for planktonic species that are not components of the epilithon (F.E. Round, pers. comm.) and the taxa excluded were: *Aulacoseira granulata*, *Asterionella formosa*, *Cylostephanos dubius*, and *Stephanodiscus sp.*. Rare taxa (those occurring in abundances of ≤1 %) were not included in data analysis.

4.4.4 Macroinvertebrate sampling

Samples of the macroinvertebrate community were collected in May, July and late September / early October in 1995 and 1996. Samples were collected for sites 4 to 9 in 1995, and for sites 4, 5, 6, 7, and 9 in 1996. At each site, riffle habitats were sampled using a modified Hess sampler (Hess, 1941). A 530 cm^2 round bucket was used with a 240 µm screen on the upstream side. The 240 µm net arm was placed at the downstream side, which had a removable container with a 240 µm mesh screen at the bottom. Samples were collected by placing the sampler on the substrate and thoroughly stirring up the substrate in the bucket and washing the sample to the container. The contents of the container were then washed into a 500 µm sieve box, and panned into an attached jar. This was the largest mesh size used for collecting and sorting. Samples were preserved in 10 % buffered formalin. The invertebrates were identified to order or family, and assigned to a functional feeding group, using Merritt and Cummins (1996a and 1996b), Pennak (1989) and Cummins (1973). As for the epilithic diatom data, rare taxa (those occurring in abundances of ≤1% at a site) were deleted for multivariate analysis.

4.4.5 Statistical analyses

ANOVA's were used to assess differences in periphyton chlorophyll and total phosphorus, total soluble reactive phosphorus and total suspended solid concentrations at Laurel Creek sites (Wilkinson, 1992). Data were tested for deviations from normality and homogeneity of variance. Based on these tests, the data were log_{10} transformed to fulfill the assumptions for ANOVA. The ANOVA model used was a randomized block design. to block against the effects of date and so account for seasonal effects. Post-hoc tests were conducted via the Tukey procedure to determine significant differences between sites.

Multivariate statistical analyses were conducted using CANOCO version 3.1 (Ter Braak, 1990). Detrended correspondence analysis was first used to determine the maximum amount of variation in the diatom and macroinvertebrate data. Based on the gradient lengths obtained, I decided that a test based on a unimodal response model was most appropriate for analysis of the diatom data and a linear method for the macroinvertebrate data.

Canonical correspondence analysis (CCA) was therefore used to explore relationships between the epilithic diatom taxa and measured water quality variables. On assessing colinear environmental variables, it was found that none of the environmental variables had variance inflation factors > 20, indicating that they all contributed uniquely to the ordination (Ter Braak, 1990). Canonical coefficients and approximate *t*-tests were then used to identify environmental variables which were important in explaining the directions of variance in the distribution of the diatom taxa. The significance of the CCA axes was assessed using Monte Carlo permutation tests (99 random permutations).

The macroinvertebrate data were analyzed using principle components analysis (PCA). The analysis was performed on taxonomic group data that were $\log_{10}$ transformed.

4.5 Results

4.5.1 Water quality and periphyton chlorophyll

Several water quality parameters show a distinct difference between sites in rural (sites 1 to 5) and in urban (sites 6 to 9) areas (Table 1). Conductivity, temperature, total

Table 1. Mean summer water chemistry values for Laurel Creek sampling sites. Sites 1 to 5 are classified as rural and sites 6 to 9 are classified as urban.

	Sites								
Variable	1	2	3	4	5	6	7	8	9
Conductiviity (μS)	583.5	521.8	559.3	556.8	561.9	605.1	724.8	875.5	961.9
pH	8.0	8.0	7.9	7.4	7.7	7.7	7.7	8.0	8.0
Temperature (^{o}C)	15.0	15.5	15.0	17.4	16.5	20.6	20.3	19.5	19.0
Total phosphorus (μg/l)	28.2	27.8	54.2	48.4	55.8	144.7	155.8	101.0	84.5
Soluble reactive phosphorus (μg/l)	11.0	10.0	27.7	18.3	25.2	4.5	15.2	7.8	13.6
Alkalinity (mg/l CaCO3)	252.0	228.5	241.3	250.5	249.1	196.0	193.9	194.5	205.5
Biological oxygen demand (mg/l)	1.2	1.0	1.3	2.2	1.5	5.3	5.7	4.1	3.3
Total suspended solids (mg/l)	6.5	6.6	7.7	5.0	9.4	48.5	52.7	30.1	29.1
Total nitrogen (mg/l)	3.11	2.34	2.01	2.22	2.72	2.10	2.72	2.93	2.22
Nitrate (mg/l)	1.90	1.50	1.23	1.04	1.30	0.75	0.85	1.28	1.13
Ammonia (mg/l)	0.30	0.30	0.29	0.21	0.18	0.31	0.30	0.16	0.15

phosphorus concentration, biological oxygen demand and total suspended solid concentration were higher at the urban sites. Alkalinity and soluble reactive phosphorus were higher at the rural sites.

Total phosphorus and total suspended solid concentrations showed significant differences between urban and rural sites (p <0.01), with the highest concentrations being found at urban sites 6 and 7, which were just downstream of impoundments (Figs. 2a and 2b). Soluble reactive phosphorus was higher for rural than for urban sites and these differences were significant (p <0.01) (Fig.2c). Periphyton chlorophyll a did not differ significantly between sites (p 0.33) (Fig. 2d).

4.5.2 Epilithic diatom community

After deleting colinear variables, CCA identified ten environmental variables that each explained significant (p <0.05) directions of variance in the diatom data along one or more of the first three CCA axes (Fig. 3). These were conductivity (cond), pH, temperature (temp), total phosphorus (TP), soluble reactive phosphorus (SRP), alkalinity (alk), biological oxygen demand (BOD), total suspended solids (TSS), total nitrogen (TN) and nitrate (NO_3). The eigenvalues for CCA axes 1, 2 and 3 (0.63, 0.27 and 0.22 respectively) constrained to these environmental variables were significant (p <0.01), and were similar to those obtained for unconstrained DCA (0.75, 0.42, 0,26). The species-environmental correlations for axes 1, 2 and 3 were high (0.93, 0.79 and 0.69 respectively). The ten environmental variables thus accounted for the major gradients in the composition of the epilithic diatom community at the Laurel Creek sites studied.

CCA axis 1 was correlated with temperature (r = -0.66). Axis 2 was correlated with total phosphorus and alkalinity (r = -0.57 and 0.52 respectively). Biological oxygen demand and total suspended solids were also correlated with axis 2 (r = -0.45 and -0.46 respectively).

Figure 2. Mean (+ 1 SE; n = 18) 1995 and 1996 summer values of a) total phosphorus; b) total suspended solids; c) soluble reactive phosphorus; and d) periphyton chlorophyll for Laurel Creek sites.

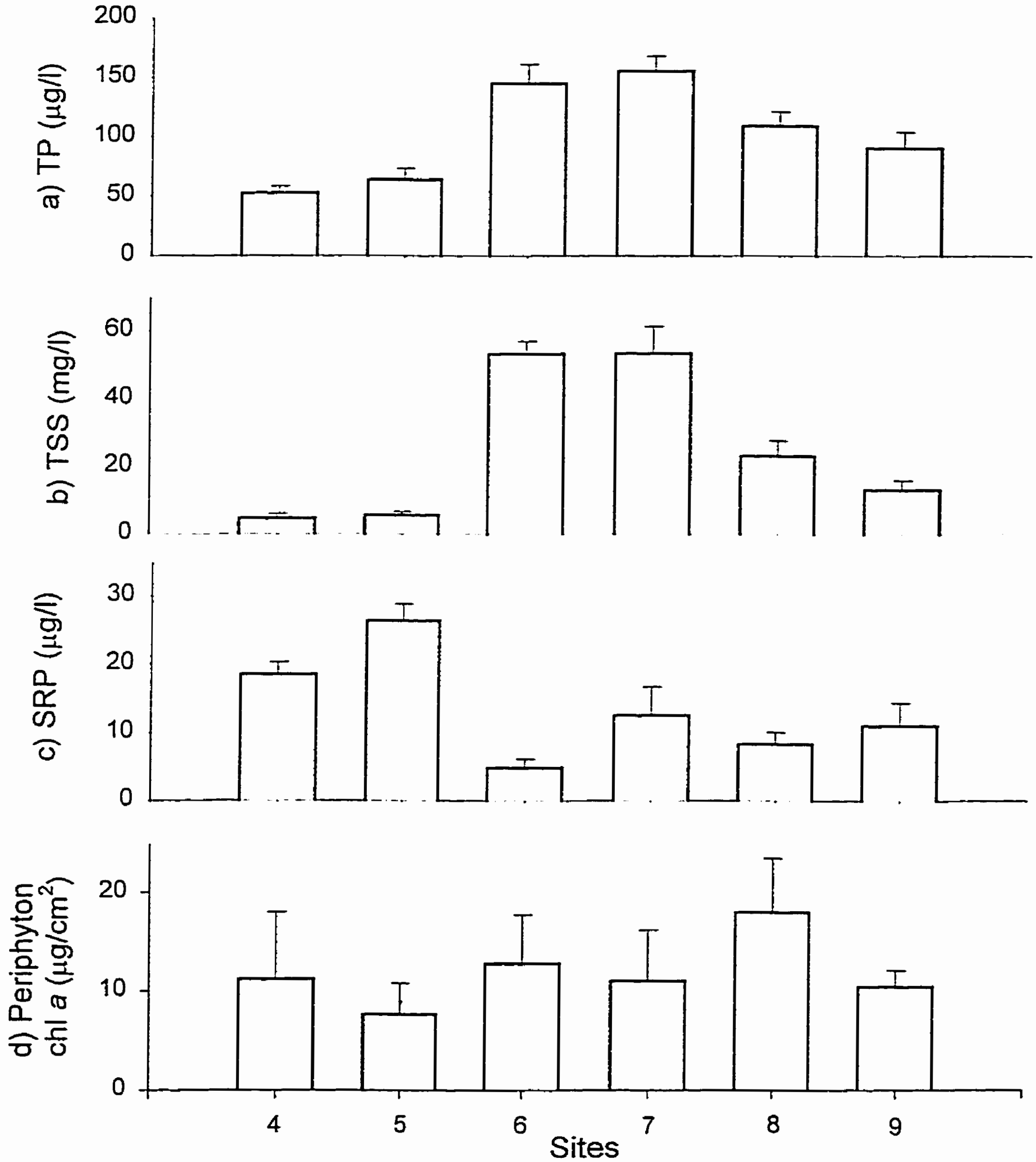
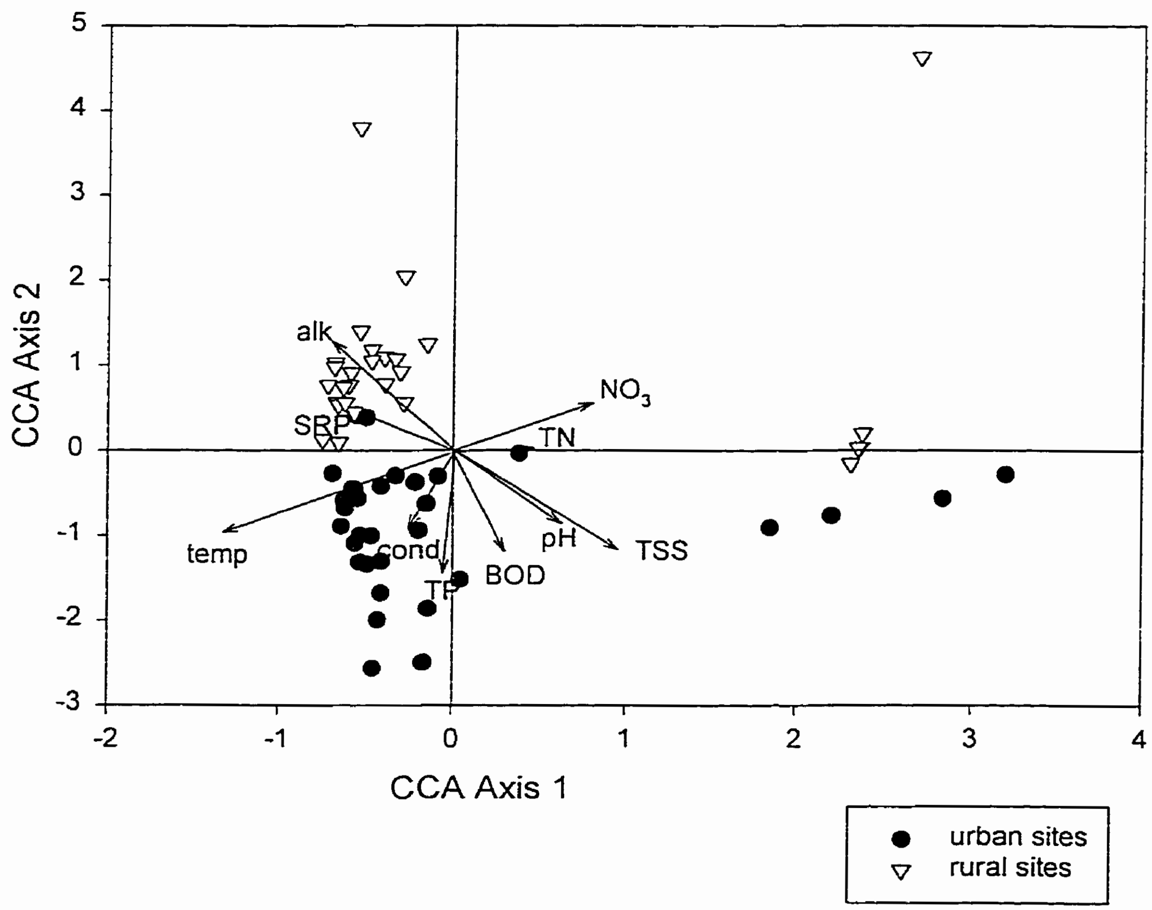


Figure 3. Sample scores obtained in CCA ordination of 1995 and 1996 Laurel Creek epilithic diatom data. Urban and rural sites are represented by symbols and environmental biplot scores are multiplied by two and represented by arrows.



In the CCA plot of the samples scores for Laurel Creek epilithic diatoms, urban and rural sites are separated in ordination space. CCA axis 2 separates the sites, urban sites being positioned towards the bottom of the biplot and rural sites towards to top.

4.5.3 Macroinvertebrate taxonomic groups

A distinct difference in the proportion of the macroinvertebrate functional feeding groups is observed between urban and rural sites in both 1995 and 1996 (Fig. 4). In urban sites the relative proportion of deposit feeders (Oligochaeta) was higher than in rural sites, and the proportion of taxa classified as filtering collectors (Simuliidae and Bivalvia) was also higher.

In the PCA biplot rural and urban sites show separation in ordination space based on their macroinvertebrate taxonomic composition (Fig. 5). The abundance of Oligochaeta (olig), Simuliidae (sim) and Nematoda (nem) are positively correlated. Given the distance of Oligochaeta from the intercept, this group is more important in indicating site differences between urban and rural sites. Platyhelminthes (plat) was also important. The groups most abundant at urban sites are negatively correlated with many of those most abundant at rural sites (Coleoptera, col; Tipulidae, tip; Empididae, emp; Hydracarina, hyd; Tabanidae, tab; Gastropoda, gast; and Megaloptera, meg). Of these groups, Coleoptera was most important in indicating differences between rural and urban sites. Other groups plotted are: Isopoda (iso), Chironomidae (chir), Bivalvia (biv), Ephemeroptera (eph) and Trichoptera, (tric).

4.6 Discussion

According to the river continuum concept (Vannote et al., 1980), under pristine conditions, the first and second order sites on Laurel Creek would obtain most of their energy inputs from terrestrial sources and consequently have a higher proportion of macroinvertebrate shredders than the downstream sites. Furthermore, periphyton

Figure 4. Relative abundance of invertebrate functional feeding groups for Laurel Creek (df = deposit feeders; f = filterers; g=gatherers; s=scrapers; om=omnivores; p=predators; sh=shredders; and co=collectors).

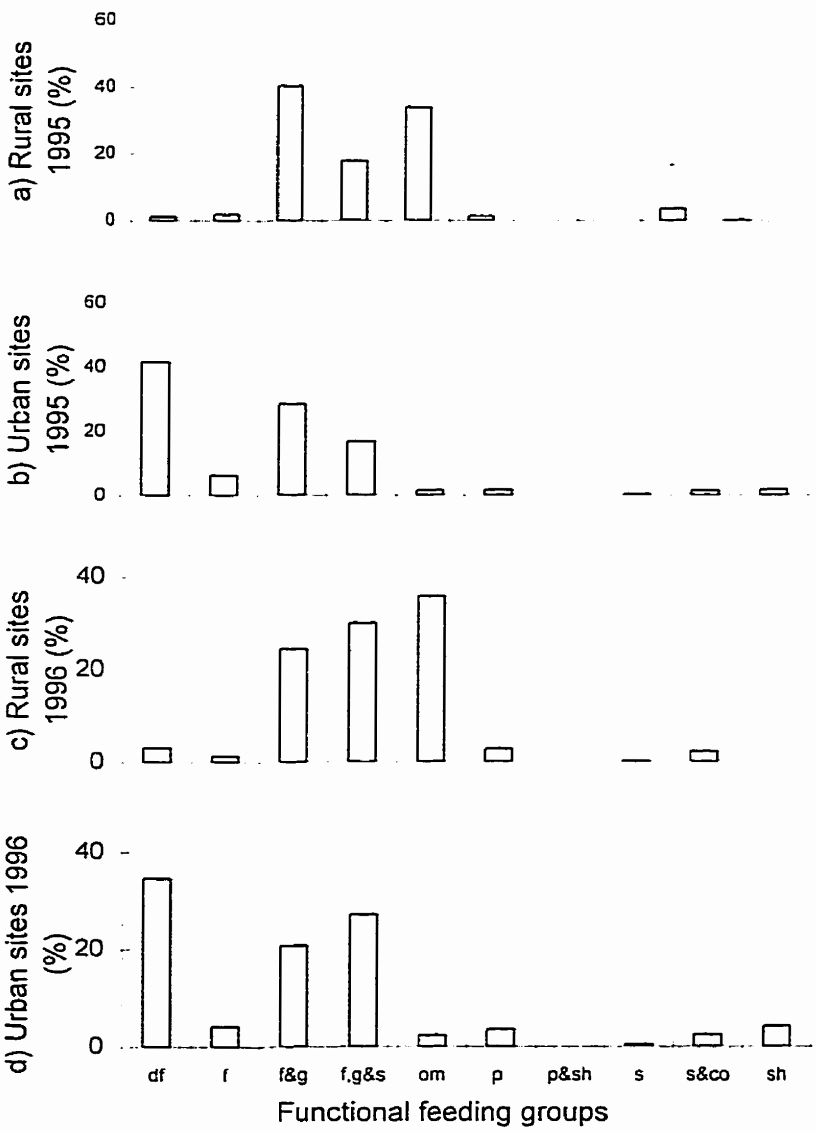
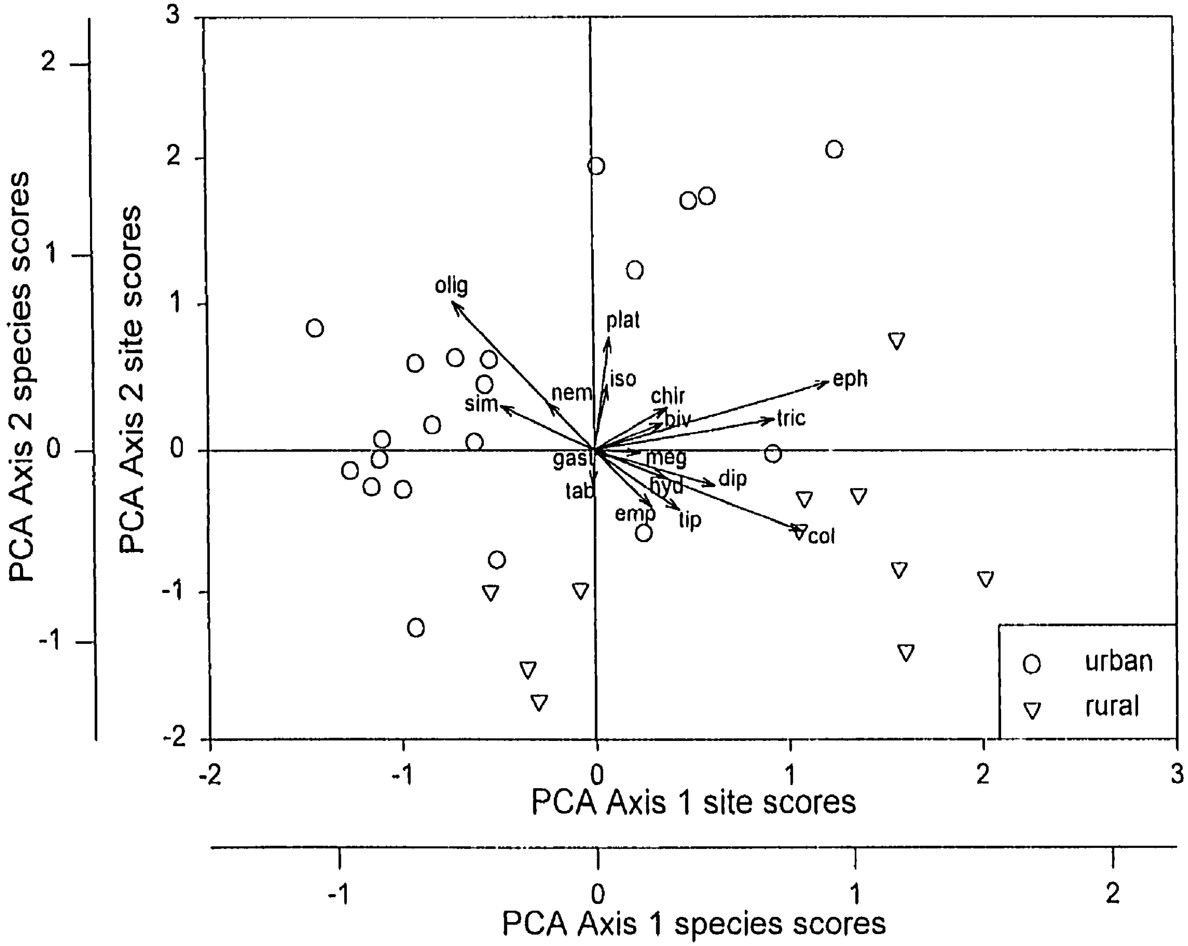


Figure 5. Biplot of species and site scores from PCA on 1995 and 1996 Laurel Creek benthic macroinvertebrate data. The arrows represent species scores (see text for full names of taxonomic groups), and the symbols represent site scores.



biomass would be greater at the higher order sites. as would the proportion of grazers. In the Laurel Creek system however, human activity has modified this relationship. The clearing of land for agricultural and urban development and associated runoff and erosion have modified the creek in the headwaters. altering energy inputs to the system. The construction of impoundments downstream has created lentic environments permitting plankton production.

The results obtained clearly indicate that the macroinvertebrate and periphyton communities in Laurel Creek, which are highly influenced by the effects of land use in the watershed, are also affected by the impoundments. Agricultural land use in rural sites results in higher soluble reactive phosphorus levels than downstream. Runoff from highways and the urbanized area in the lower half of the watershed result in an increase in conductivity and, together with surface-release from the impoundments, cause an increase in suspended solids, total phosphorus and biological oxygen demand.

The increase in downstream suspended solid concentration contrasts with the more common effect of impoundments, which is to markedly increase water clarity downstream as a result of the settling of particulate material in the reservoir (Ward and Stanford, 1987). The increase in total suspended solids observed may be due in part to the export of reservoir plankton during the summer months. Phytoplankton has been shown to contribute to the water-borne particulate load in Laurel Creek (Hopper, 1997). Other reservoir studies have noted currents in turbidity that run from the inlet stream to the reservoir outlet causing the release of suspended materials (Ward and Stanford, 1987). Siltation of the impoundments on the Laurel Creek system is a recognized management problem in the watershed resulting from erosion due to urban and agricultural development upstream, and it is likely that some of the sediments that have built up are being washed downstream via such currents.

Despite the higher total phosphorus concentrations observed in the urban area, periphyton chlorophyll *a* did not increase significantly. The proportion of soluble reactive phosphorus was significantly lower in urban than in rural sites indicating that much of the phosphorus at the urban sites was bound to particulate material and not biologically available. Moreover, elevated suspended solid concentrations may have decreased light penetration to the substrate at these sites and in turn might have reduced periphyton biomass. Other studies have also found that periphyton biomass is generally poorly related to nutrient concentrations (Cattaneo, 1987; Cattaneo et al., 1993) and attribute this to the influence of other biotic and abiotic variables such as substrate type, water velocity and grazing pressure. Because of the inherent variability in periphyton biomass, the taxonomic structure of the community is more effectively related to water chemistry (Cattaneo et al., 1993).

Based on analysis of diatom species and periphyton genera found (unpublished data), the impoundments and urban run-off result in nutrient and mild organic pollution in Laurel Creek. Bacterial and nutrient inputs from large populations of waterfowl are also a likely source (GRCA, 1993). The percent cover of *Cladophora* was higher in urban than in rural sites (Winter, unpublished data). The growth of *Cladophora* has been shown to be promoted by increases in phosphorus levels. *Cladophora* is tolerant of mild organic pollution (Hellawell, 1986). The percent cover was also high for rural sites, however, indicating the impact of agricultural land use at these sites.

According to the multivariate statistical analysis, urban and rural sites on Laurel Creek clearly differed in terms of their epilithic diatom and macroinvertebrate community composition. In the epilithic diatom analysis, temperature was seen to be an important variable, as was total phosphorus, biological oxygen demand and total suspended solids. This coincides with the observations made on the impact of land use and the impoundments on the system.

Urban and rural sites showed distinct differences in the distribution of macroinvertebrate taxa. The higher proportion of deposit feeders at the urban sites reflects the influence of suspended solid load and flow characteristics downstream of the impoundments. These organisms are found in soft sediments. rich in organic matter and commonly live in sites receiving organic enrichment. feeding on organic detritus and its associated microflora (Peckarsky et al.. 1990). Fine sediment build up must have occurred between the rocks of the riffle habitats sampled to provide a suitable substrate for this group of organisms. Moreover. the increase in filtering collectors observed downstream of the reservoirs reflects an increase in the suspended food particles at these sites. These organisms are also favoured by the substrate stability that is characteristic of the regulated flow conditions downstream of impoundments (Ward and Stanford. 1987).

4.7 Conclusions

I conclude that the Laurel Creek system has been severely impacted by land use in the watershed and by the reservoirs. Urban and agricultural land uses in the Laurel Creek watershed differentially influence water quality. which in turn influences benthic macroinvertebrate and periphyton community structure. The effects of development in the watershed are exacerbated by several impoundments on Laurel Creek. in particular Laurel Creek Reservoir and Columbia Lake. Higher levels of total phosphorus. total suspended solids. biological oxygen demand and conductivity were observed for urban sites, as were higher summer temperatures. These water quality parameters, together with habitat alterations resulting from flow regulation downstream of the impoundments and the clearing of land for development, have had fundamental effects on the benthic community of the creek, profoundly influencing community structure and function. Major rehabilitation work will be required to improve water and habitat quality in the stream.

The rehabilitation work being carried out on Silver Lake will undoubtedly have a positive influence downstream. Until controls are in place upstream, however. Laurel Creek will remain degraded and Silver Lake will continue to experience the sediment build up problems that have led to the dredging required in current restoration efforts. To avoid this and to improve water quality, major effort is required, in particular the implementation of urban stormwater and agricultural runoff controls and the minimization of erosion from areas currently under urban development. As recommended in the Laurel Creek Watershed study, rehabilitation work on Laurel Creek Reservoir, Columbia Lake and the Laurel Lakes is also required (GRCA, 1993). Suggested structural changes, such as replacing the reservoirs with wetland areas and natural streams, bypassing the reservoirs and taking water directly from upstream to downstream or dredging sediments, would reduce warming, sediment loading and nutrient inputs from the impoundments. If the Watershed Management Strategy (GRCA, 1993) is not implemented Laurel Creek habitat and water quality will continue to deteriorate with a concomitant change in the resident fauna and flora.

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5. THE INFLUENCE OF LAND USE AND WATER QUALITY ON EPILITHIC DIATOMS AND MACROINVERTEBRATES IN LAUREL CREEK AND CARROLL CREEK[1]

5.1 Abstract

Epilithic diatom and macroinvertebrate communities in streams are effective biomonitors of interactions between water quality and catchment land use. Canonical correspondence analysis identified significant ($p < 0.05$) relationships between epilithic diatom and macroinvertebrate communities, and several water quality and watershed land use variables, in the rural Carroll Creek watershed and in the semi-urban Laurel Creek watershed, both tributaries of the Grand River, Ontario. In particular the concentrations of total phosphorus, total nitrogen and total suspended solids were important, as was the proportion of the subwatershed area classified as urban or agricultural. The relative influences of water chemistry and land use predictors on these communities were quantified using variance partitioning analysis, based on partial constrained ordination. Most of the variance in the biotic data could be explained by the joint influence of land use and water chemistry (29 % for diatoms and 39 % for invertebrates). On using distance downstream as a covariable to remove upstream-downstream effects, this shared variance was reduced (22% for diatoms and 26 % for invertebrates) indicating that the influence of land use on water chemistry was partly a geographical phenomenon. Overall, these relationships demonstrate the utility of macroinvertebrates and diatoms as indicators of catchment land use.

5.2 Introduction

The development of natural landscapes in watersheds for agricultural and urban uses has led to fundamental changes in the structure and functioning of stream communities (Allan, 1995). Since Hynes (1975) concluded that the valley rules the stream, it is

[1] Based on a paper submitted to the Canadian Journal of Fisheries and Aquatic Sciences. Co-author H.C. Duthie.

increasingly recognized that watershed land use is an important determinant of stream biotic communities. Richards et al. (1996) indicated that stream communities could be used effectively to develop biological signatures of catchment condition. Although several studies have evaluated relationships between watershed land use and stream macroinvertebrates (e.g. Allan et al., 1997; Richards et al., 1996; Quinn et al., 1997; Townsend et al., 1997) few studies have focused on stream diatom communities (e.g. Leland, 1995), or both groups simultaneously. Many studies have, however, used diatoms to monitor runoff from various land uses as it is reflected in the environmental conditions of streams (e.g. Pan et al., 1996; Rott et al., 1998). Diatoms are also commonly used in paleolimnological studies to estimate historical changes in watershed land use (e.g. Hall et al., 1998; Hall and Smol, 1996). Given their sensitivity to the resultant changes in stream water quality, and that they have been related to land use in paleolimnological studies (sensu Hall et al., 1998), it would appear that diatom communities at stream sites could also be directly related to catchment land use.

Epilithic diatoms and macroinvertebrates possess many attributes that make them ideal organisms to employ in stream monitoring investigations (Resh et al., 1996; Round, 1993). Benthic macroinvertebrates are the group of freshwater organisms most often utilized in biological monitoring, and many methods of community analysis exist (Resh et al., 1996). In recent years however, it has become evident that benthic algae in general (Lowe and Pan, 1996) and epilithic diatoms in particular (Round, 1993) are also useful for monitoring river water quality. Both macroinvertebrates and epililthic diatoms occur throughout a range of river habitats, are easily sampled, are sensitive to water quality and react quickly to peturbation of the environment, the taxonomy of many groups is well known and identification keys are available (Resh, 1996; Round, 1993). Multivariate analytical approaches, such as canonical correspondence analysis, are increasingly being used in river monitoring, and provide sophisticated techniques to assess the influence of water chemistry and land use variables on stream communities. Variance partitioning analysis (sensu Borcard et al., 1992) is a relatively new technique that uses these approaches to quantify the relative influence of multiple factors on biological assemblages (Hall et al., 1998; Richards et al., 1996).

The objectives of this study were to assess the relationships between macroinvertebrate and epilithic diatom communities and stream water chemistry, to evaluate the influence of land use on these organisms, and to compare the relative influence of water quality and land use factors. Two stream catchments with contrasting urban and rural land uses were compared. Overall, this study will investigate the utility of these organisms in developing biological signatures of watershed land use. Evaluating these relationships has relevance for developing macroinvertebrate and diatom indicators as monitoring and assessment tools for water resources planning and management.

5.3 Site description

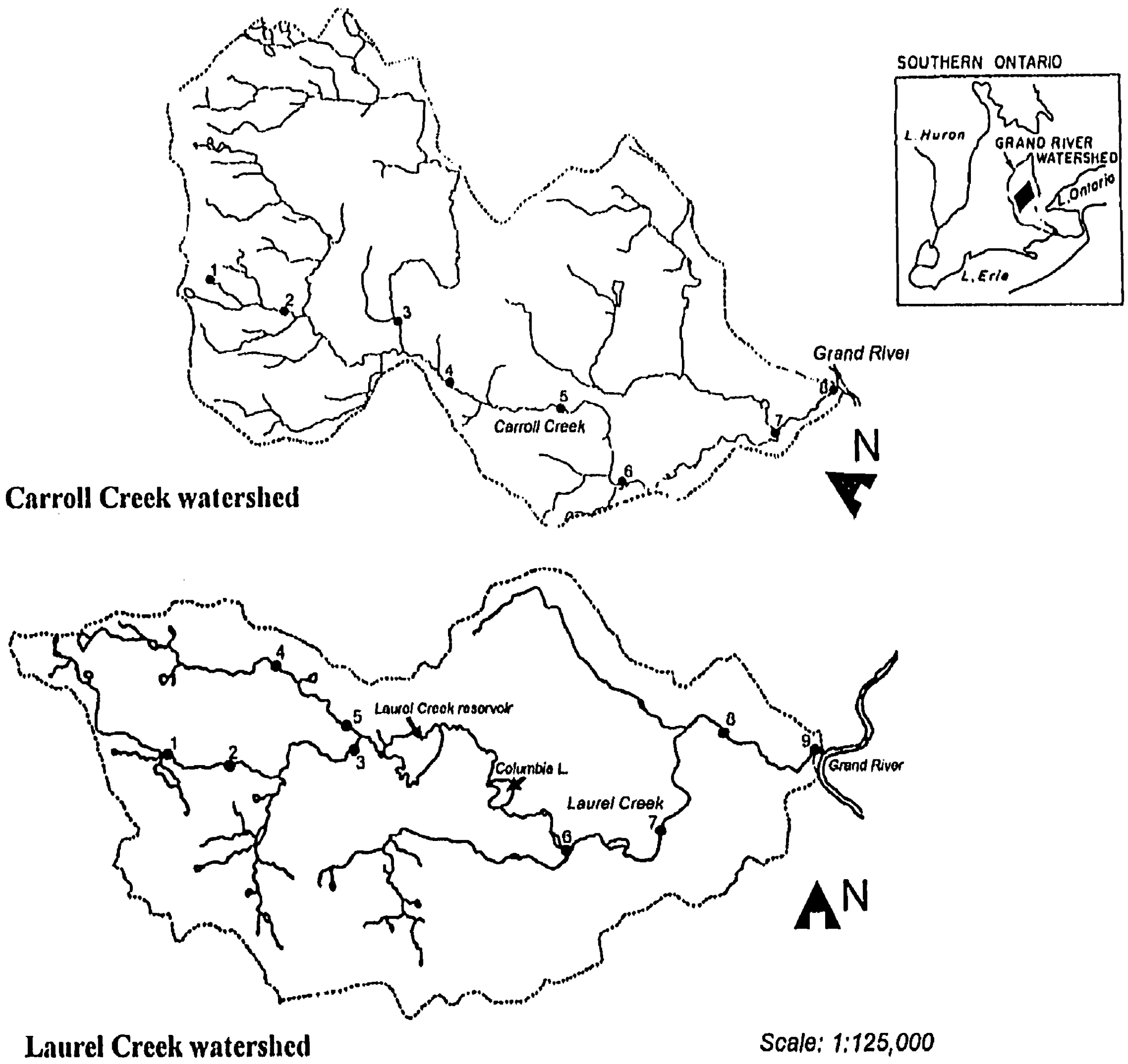
The study sites (Fig.1) were selected to provide a comparison between a partly urban and a rural watershed. Laurel Creek is approximately 20 km long with a watershed area of about 74 km^2. Land use in the upper part of the watershed is rural (sites 1-5, first and second order), consisting mainly of crop production, and areas of pasture and woodland. The lower half of the watershed is under urban development (sites 6-9, third and fourth order), mainly residential with some commercial and industrial uses. The effects of urban and agricultural development on stream water quality and habitat are exacerbated by the presence of several impoundments on Laurel Creek (Chapter 4). Carroll Creek is approximately 20 km long with a watershed area of 69 km^2. Land use in the watershed is entirely rural, consisting of commercial crop and livestock production, and areas of pasture and woodland. On Carroll Creek, site 1 is first order, sites 2 and 3 are second order, sites 4-7 are third order and site 8 is fourth order.

5.4 Methods

5.4.1 Field and laboratory methods

Water samples were collected in hydrochloric acid-rinsed plastic bottles every two weeks from May to September in 1995 and 1996 and monthly from October 1996 – February

Figure 1. Geographic location and maps of the Laurel Creek and Carroll Creek watersheds



1997. Alkalinity. nitrate. ammonia. total suspended solids and biological oxygen demand were analyzed according to standard methods (APHA. 1989) and conductivity. pH and temperature were measured in the field. Soluble reactive phosphorus was analyzed using the ascorbic acid method. after filtration through a 0.45 μm filter. and total phosphorus was measured using the ascorbic acid method following oxidation with persulfate under pressure (Parsons, *et al.*. 1984). Total nitrogen concentration was measured as nitrate following digestion with sodium hydroxide and sulfuric acid under ultraviolet light (Technicon. 1984).

A series of land use variables were determined for the sites: the percentage of the subwatershed that was tile drained. the percentage mapped as urban. cropland. pasture or woodland. and the number of stormsewers in the subwatershed upstream of a site. These were calculated using maps from the Ontario agricultural resource inventory (OMAF, 1983). maps and information contained in GRCA (1993). and the current City of Waterloo storm sewer and zoning maps. Land cover information for the Carroll Creek watershed was entered into a geographical information systems (GIS) database. using satellite imagery and the Ontario agricultural resource inventory, by Bruce Pond. Ontario Ministry of Natural Resources.

Epilithic diatom samples were collected once a month over the sampling period and prepared using techniques described in Chapter 4. For each sample, at least two hundred diatoms were counted and identified to species following Krammer and Lange-Bertalot (1986-1991), and also Patrick and Reimer (1966, 1975) and Sims (1996). At sites downstream of the impoundments on Laurel Creek (sites 6 and 7) there was evidence of an increase in the number of planktonic species in the epilithic samples. The species found are also commonly found in the plankton of Laurel Creek Reservoir and Columbia Lake (Hopper, 1997). They were significantly more abundant at these sites than at other sites, and, in order to provide an unbiased assessment of the epilithon, the planktonic species were excluded from the counts. This is a valid approach for planktonic species that are not components of the epilithon (F.E. Round, pers. comm.) and the taxa excluded were: *Aulacoseira granulata. Asterionella formosa. Cylostephanos dubius*, and *Stephanodiscus sp.*

Macroinvertebrate samples were collected in May. July and late September / early October in 1995 and 1996. Samples were collected at Carroll Creek sites 2 to 8 in 1995 and sites 2, 4, 5, 7 and 8 in 1996. Laurel Creek sites 4 to 9 were sampled in 1995 and sites 4, 5, 6, 7 and 9 were sampled in 1996. At each site samples were collected using a modified Hess sampler (Hess, 1941). as described in Chapter 4. The invertebrates were identified to order or family using Merritt and Cummins (1996a). Peckarsky et al. (1990) and Pennak (1989).

5.4.2 Data analysis

Diatom and macroinvertebrate taxa were included in ordinations if they were present in a minimum of 3 samples and achieved >1 % abundance in at least one sample. Ordinations were performed using CANOCO version 3.1 (Ter Braak, 1990). Detrended correspondence analysis (DCA) was used to determine the maximum amount of variation in the invertebrate and the diatom data. Based on this analysis it was determined that. for each data set. subsequent constrained ordinations should be based on a unimodal response model, such as canonical correspondence analysis (CCA).

In the ordinations used to explore the relationships among the distribution of diatom and invertebrate taxa and the measured water quality variables. season (spring. summer, fall and winter) was entered as a nominal variable. Since samples were collected over a two year period, it is likely that there was considerable seasonal variation in the biota and the environment. This seasonal variation was not the prime research question. however, and, using partial CCA with season as a covariable, the relationships between the biota and environmental data were evaluated after removing the influence of season on community composition (Ter Braak and Verdonschot. 1995).

Watershed land cover did not vary measurably over the sampling period, and subsets of invertebrate and diatom data were developed to relate community structure to land use and account for this lack of variation. To develop the subsets, a series of CCAs were run to establish which month, average of months for each year and each season, or overall average provided the best relationships between the biotic data and the measured water quality and land use variables. Based on this assessment, averages of 1996 data were used. Since the sample number was reduced in the subsets, a series of preliminary CCAs with forward selection were run to identify those measured environmental variables most important in explaining directions of variation in the diatom and invertebrate data.

I used variance partitioning analysis (CCA with and without the use of covariables) to determine the total variance in the diatom and invertebrate communities explained by: 1) water chemistry predictors alone, 2) land use predictors alone, 3) an interaction between land use and water chemistry predictors, and 4) that remaining unexplained by factors related to land use and water quality (Borcard et al., 1992; Hall et al., 1998). Upstream effects are important in virtually all processes in running waters, and, in order to assess to what extent upstream-downstream effects influenced these relationships, this analysis was repeated using distance downstream as a covariable.

5.5 Results

5.5.1 Water chemistry and land use characteristics

The water chemistry values presented for sites on Carroll Creek and Laurel Creek are calculated as means for the entire study period (Table 1). Conductivity, total phosphorus concentration, biological oxygen demand and total suspended solid concentration were higher in the urban area on Laurel Creek than at the other, rural, sites. Total phosphorus concentration was lowest at upstream sites on Carroll Creek (sites 1 and 2) and on Laurel Creek (sites 1 and 2). Soluble reactive phosphorus concentration was also lowest at site 1 on Carroll Creek, but at other rural sites was generally similar to or greater than the mean

Table 1. Average (n = 21) water chemistry characteristics of study sites and summary statistics.

	Cond-uctivity (µS)	pH	Total phosphorus (µg/l)	Soluble reactive phosphorus (µg/l)	Alkalinity (mg/l $CaCO_3$)	Biological oxygen demand (mg/l)	Total suspended solids (mg/l)	Total nitrogen (mg/l)	Nitrate (mg/l)
Carroll Creek sites:									
1	527.8	7.6	10.8	5.0	263.9	1.2	1.1	3.5	2.3
2	585.9	7.8	22.9	12.0	282.7	1.7	3.8	7.6	3.6
3	631.5	7.9	37.8	15.2	258.6	2.3	3.2	5.7	3.6
4	593.6	7.8	38.3	14.4	253.6	2.5	2.8	5.3	2.9
5	590.3	8.0	45.9	25.2	251.0	2.9	3.8	4.5	2.9
6	535.7	8.1	41.2	21.3	228.5	2.7	3.5	3.9	2.3
7	583.8	8.2	40.1	17.1	238.4	2.4	4.1	7.7	4.5
8	571.2	8.1	37.1	14.3	241.7	2.5	3.6	8.4	4.7
Laurel Creek sites:									
1	583.4	8.0	28.2	11.0	252.0	1.2	6.5	3.1	1.9
2	528.7	8.0	27.8	8.8	225.9	1.8	9.7	2.1	1.4
3	571.4	7.9	44.1	21.8	238.2	2.1	6.5	2.0	1.4
4	556.6	7.4	48.4	18.3	250.6	2.1	5.0	2.2	1.0
5	561.7	7.7	55.8	25.2	249.1	1.5	9.5	2.6	1.3
6	643.4	7.8	123.5	8.0	205.1	4.9	42.4	2.2	1.1
7	748.7	7.8	135.7	14.5	204.4	5.2	72.2	2.6	1.2
8	875.5	8.0	101.0	7.8	194.4	4.1	30.1	2.9	1.3
9	1000.3	7.9	78.5	12.5	214.1	3.5	32.2	2.3	1.4
average	638.0	7.9	57.3	15.2	236.9	2.8	15.4	4.3	2.4
standard deviation	167.6	0.3	44.9	13.8	36.8	1.8	30.8	3.3	1.9
minimum	410.0	7.0	5.4	1.2	130.0	0.3	0.0	0.6	0.3
maximum	1403.0	8.7	214.6	65.1	337.8	7.8	291.1	16.6	8.2

concentration at urban sites. Alkalinity was higher in rural sites than urban sites, in particular at upstream sites on Carroll Creek. Total nitrogen and nitrate concentrations were higher in the Carroll Creek than in the Laurel Creek system, with the highest values recorded at sites 6 and 7. The variation in the measured variables observed in the summary statistics, reflects both seasonal effects and site characteristics.

The proportion of cropland in the Carroll Creek subwatersheds indicates the intensity of agriculture in this area (Table 2). Only site 1 on Carroll Creek has relatively large areas of woodland in its watershed. The rural sites on Laurel Creek (sites 1-5) have varying proportions of agriculture and woodland in their catchments. Agriculture is more intense at sites 4 and 5 than at sites 1-3, and site 2 in particular has large area of woodland in its

Table 2. Subwatershed land use characteristics of study sites

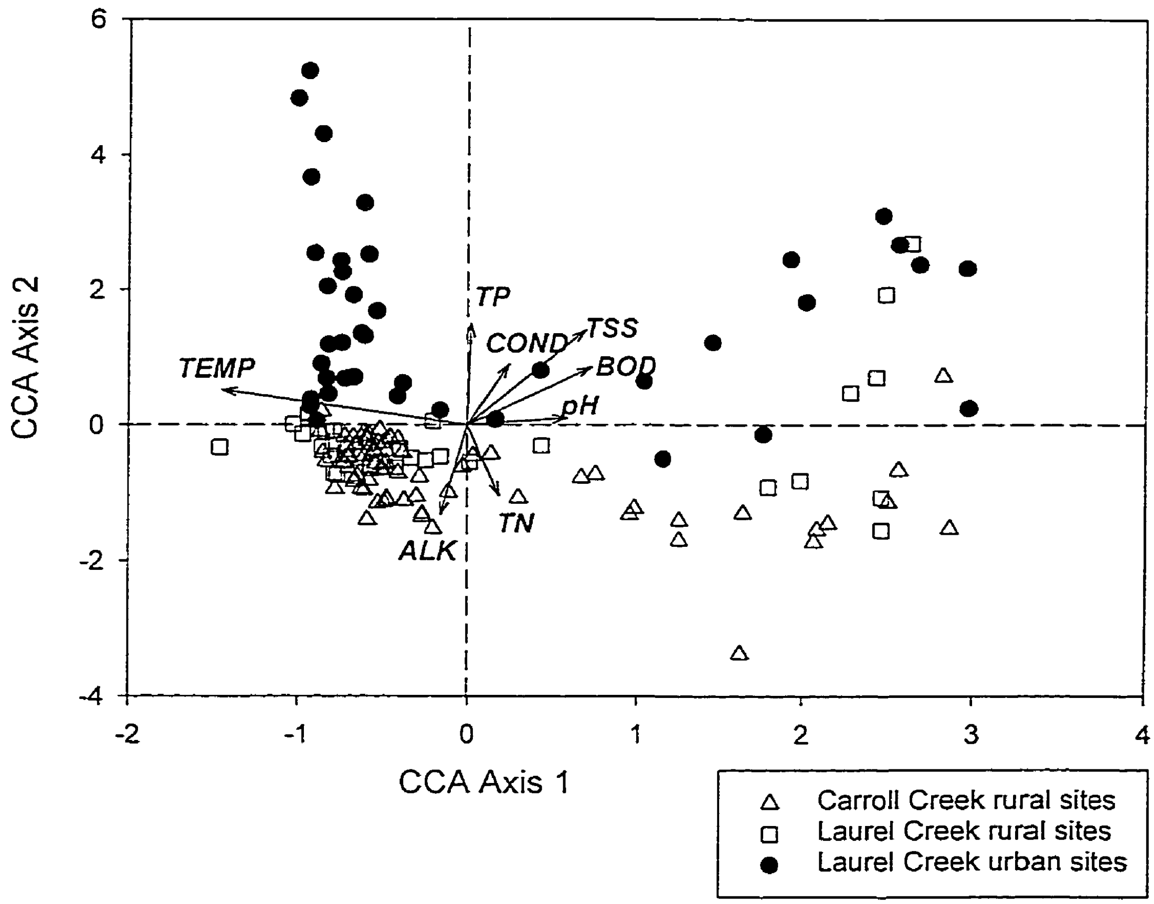
	Proportion of land in subwatershed classified as:					Number of storm-sewer outlets upstream
	Urban	Pasture	Crop-land (%)	Wood-land	Tile-drained	
Carroll Creek sites:						
1	0	0	57	43	0	0
2	0	0	85	15	23	0
3	3	0	92	4	54	0
4	0	0	90	9	77	0
5	0	2	87	7	30	0
6	0	17	73	10	53	0
7	0	2	92	4	5	0
8	0	0	81	14	23	0
Laurel Creek sites:						
1	3	4	46	33	9	0
2	0	4	21	74	0	0
3	2	2	49	12	21	0
4	0	4	71	25	61	0
5	0	4	79	10	34	0
6	49	0	29	4	12	3
7	64	0	22	3	9	35
8	90	0	0	0	0	44
9	58	0	0	0	0	2

subwatershed. Sites 6-9 on Laurel Creek have varying amounts of urban land cover in their catchments. Urbanization is particularly intense at sites 7-9.

5.5.2 Diatom species distribution and water quality gradients

Eight environmental variables were identified in CCA (temperature, TEMP; total phosphorus, TP; conductivity, COND; biological oxygen demand, BOD; total suspended solids, TSS; pH; total nitrogen, TN; and alkalinity, ALK) that each explained significant (p <0.05) directions of variance in the diatom data along one or more of the first two CCA axes (Fig. 2). The eigenvalues for the CCA axes 1 (0.43) and 2 (0.21) were significant (p <0.01), but were lower than eigenvalues extracted by DCA (0.61, 0.38).

Figure 2. Canonical correspondence analysis biplot of sample scores obtained in the ordination of all epilithic diatom data. Urban and rural sites are represented by symbols. The arrows indicate water quality variables (biplot scores were multiplied by 2) that are significantly ($p<0.05$) correlated with the distribution of diatoms at these sites.



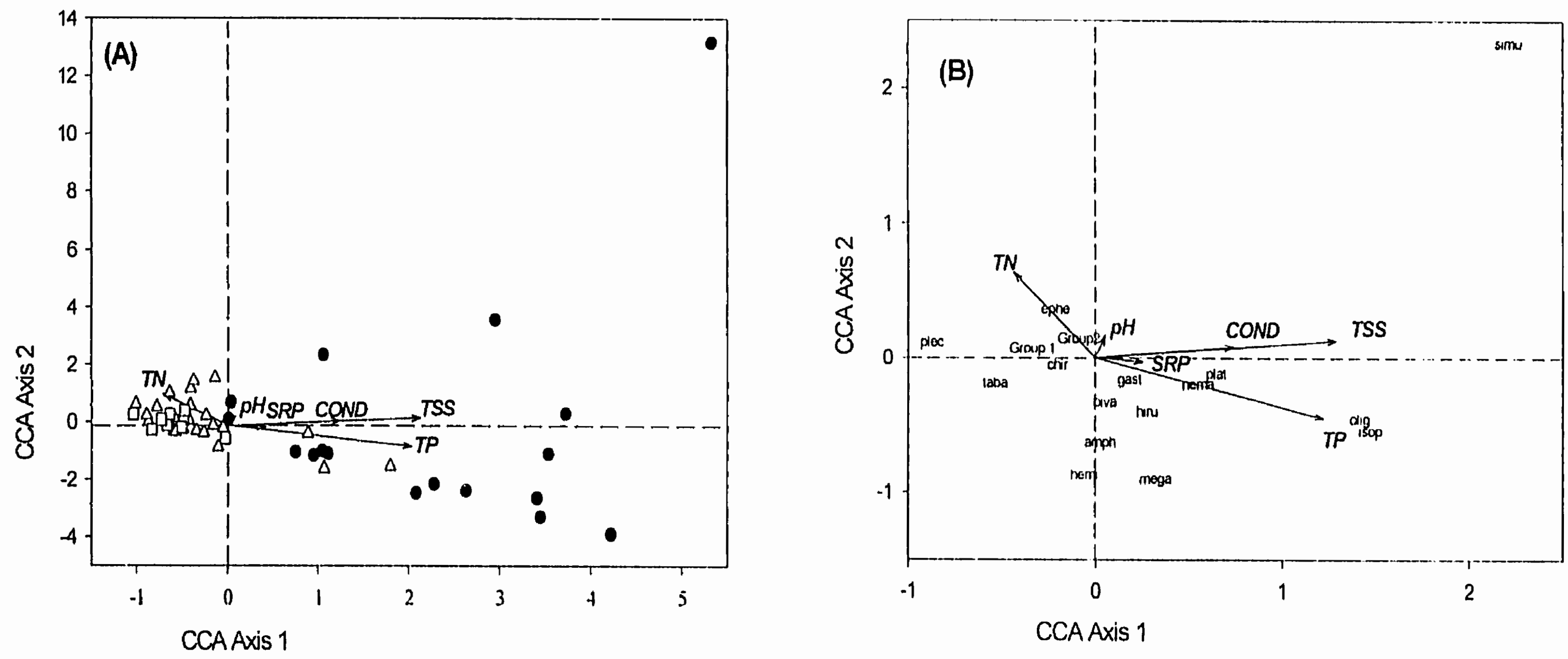
The environmental variables thus only accounted for part of the variation in species composition extracted by DCA. CCA axis 1 was highly correlated with temperature and, to a lesser extent, biological oxygen demand and total suspended solids. CCA axis 2 was highly correlated with total phosphorus, total suspended solids and alkalinity. With the exception of points on the right hand side of the plot, most of which represent samples collected in May 1996, urban and rural sites are separated in ordination space along axis 2. May 1996 was a month with unseasonably high discharge rates and frequent storm events, which might explain why different patterns were observed in the diatom assemblages. In terms of diatom species composition, rural sites on Laurel Creek are similar to Carroll Creek sites.

5.5.3 Distribution of macroinvertebrate taxonomic groups and water quality gradients

CCA identified six environmental variables (total nitrogen, pH, conductivity, total suspended solids, total phosphorus and soluble reactive phosphorus, SRP) that each explained significant ($p < 0.05$) directions of variance in the macroinvertebrate data along one or more of the first two CCA axes (Fig. 3A, 3B). The eigenvalues for the CCA axes 1 (0.31) and 2 (0.11) were significant ($p < 0.01$) and similar to those extracted by DCA (0.39, 0.14). The water chemistry variables thus accounted for the major gradients in the composition of macroinvertebrate assemblages in this data set. CCA axis 1 was highly correlated with total suspended solids, total phosphorus and conductivity and CCA axis 2 was highly correlated with total nitrogen and total phosphorus.

Urban and rural sites were generally separated along CCA axis 1 (Fig. 3A). Macroinvertebrate taxa on the right side of the ordination plot represent those most abundant at urban sites, and those on the left side were more abundant at rural sites (Fig. 3B). Simuliidae, Oligochaeta and Isopoda were indicative of conditions at urban sites, whereas Plecoptera, Tabanidae and Ephemeroptera were more abundant at rural sites.

Figure 3: Canonical correspondence analysis biplot for all macroinvertebrate data. The arrows indicate water quality variables (biplot scores were multiplied by 2.5) that are significantly (p<0.05) correlated with the distribution of macroinvertebrates. (A) Urban and rural sites are represented by symbols[a]. (B) Species scores are represented by invertebrate order or family[b].



[a]Carroll Creek sites are represented by triangles; Laurel Creek rural sites are represented by squares and urban sites by closed circles.
[b]iso-Isopoda; sim-Simuliidae; plat-Platyhelminthes; olig-Oligochaeta; nem-Nematoda; biv-Bivalvia; gast-Gastropoda; chir-Chironomidae; plec- Plecoptera; taba - Tabanidae; group 1- Ephemeroptera, Diptera, Tipulidae, Coleoptera, Hydracarina; group 2-Empididae, Trichoptera.

5.5.4 Diatom species distribution and land use characteristics

A CCA of the diatom data identified four land use variables (the proportion of urban land, pasture and woodland, and the number of storm sewers upstream) that each explained significant (p <0.05) directions of variance along one or more of the first three CCA axes (Fig. 4). The eigenvalues for the CCA axes 1 (0.29) and 2 (0.11) were significant ($p < 0.04$) and similar to those obtained by DCA (0.31, 0.14), indicating that the land use variables accounted for the main variation in species composition in this data subset extracted by DCA. CCA axis 1 was highly correlated with the proportion of urban land, cropland and the number of storm sewers, and CCA axis 2 was highly correlated with the area of woodland. In terms of diatom species distribution, urban and rural sites were separated along CCA axis 1, and the Laurel Creek rural sites and Carroll Creek sites were somewhat separated along CCA axis 2. The separation of the rural sites along axis 2 is related to the proportion of woodland in the subwatershed, which was highest for Carroll Creek site 1 and Laurel Creek sites 1, 2 and 4.

5.5.5 Land use characteristics and distribution of macroinvertebrate taxonomic groups

CCA of the subset of macroinvertebrate data identified three land use variables (the proportion of urban land and pasture and the number of storm sewers) that each explained significant (p <0.05) directions of variance along one or more of the first three CCA axes (Fig. 5A, 5B). The eigenvalues for the CCA axes 1 (0.33) and 2 (0.14) were significant (p <0.01) and similar to those obtained by DCA (0.38, 0.10), indicating that, as with the diatom data subset, these land use variables accounted for the major gradients observed in the macroinvertebrate assemblages. CCA axis 1 was highly correlated with the area of urban land and, to a lesser extent, the area of pasture, whereas CCA axis 2 was highly correlated with the number of storm sewers upstream. Although the relative proportion of pastureland in the subwatersheds was relatively low, grazing was fairly intense and was generally located in the riparian zone, particularly at sites on Carroll Creek. This might explain why pasture was related to the composition of macroinvertebrate communities at rural sites.

Figure 4. Canonical correspondence analysis biplot of the samples scores obtained in the ordination of 1996 epilithic diatom data. Urban and rural sites are represented by symbols and numbers represent site number. The arrows indicate land-use parameters (biplot scores were multiplied by 1.5) that are significantly (p<0.05) correlated with the distribution of diatoms at these sites.

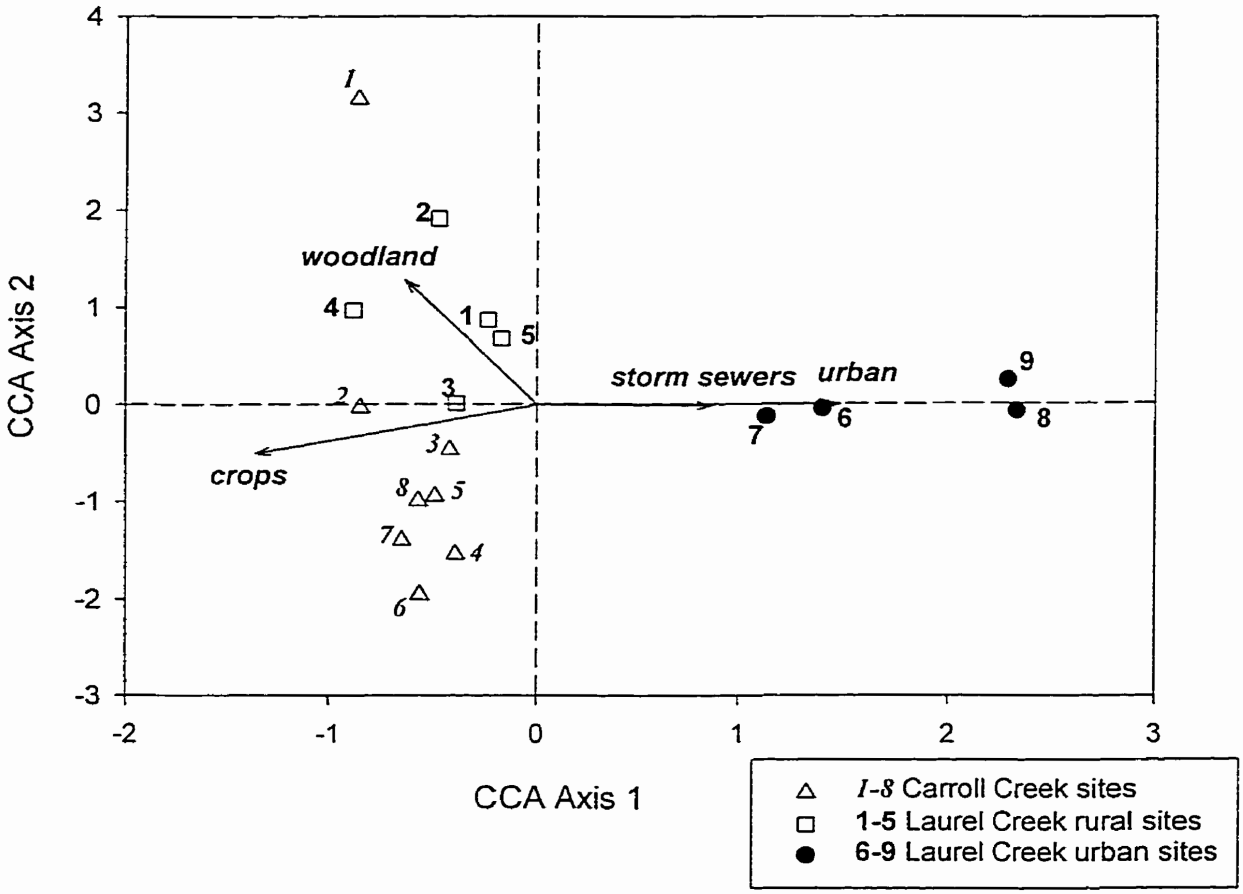
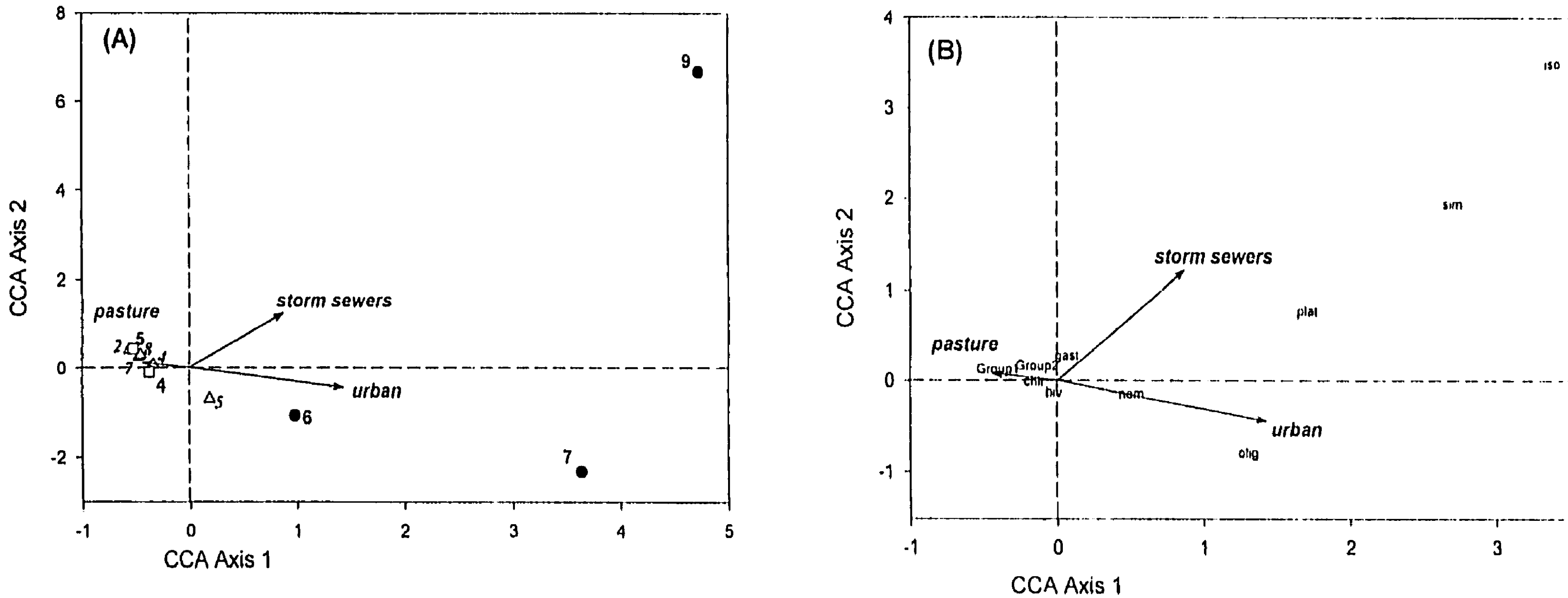


Figure 5. Canonical correspondence analysis biplot for 1996 macroinvertebrate data.The arrows indicate land use parameters (biplot scores were multiplied by 1.5) that are significantly ($p < 0.05$) correlated with the distribution of macroinvertebrates. (A) Urban and rural sites sample scores are represented by symbols[a] and numbers represent site number. (B) Species scores are represented by invertebrate order or family[b].



[a]Carroll Creek sites are represented by triangles; Laurel Creek rural sites are represented by squares and urban sites by closed circles.
[b]iso-Isopoda; sim-Simuliidae; plat-Platyhelminthes; olig-Oligochaeta; nem-Nematoda; biv-Bivalvia; gast-Gastropoda; chir-Chironomidae; group 1-Plecoptera, Ephemeroptera, Tipulidae, Coleoptera, Hydracarina; group 2-Empididae, Trichoptera.

Urban and rural sites were separated along CCA axis I reflecting differences in the macroinvertebrate assemblages at these sites (Fig. 5A). Isopoda, Simuliidae, Platyhelminthes and Oligochaeta were most abundant at urban sites, whereas Plecoptera, Ephemeroptera, Tipulidae, Hydracarina and Coleoptera were most abundant at rural sites (Fig. 5B).

5.5.6 Partitioning of the variance in diatom and macroinvertebrate assemblages between land use factors and water quality factors

Preliminary CCAs with forward selection identified water chemistry and land use variables that explained the greatest amount of variance in the subsets of biotic data. Based on this analysis, the water chemistry variables used for the diatom data were conductivity, pH, total phosphorus, total suspended solids and total nitrogen. For the invertebrate data, conductivity and total phosphorus were found to be most important. The land use parameters identified for the diatom subset were the proportion of urban land, cropland, woodland and pasture, and the number of storm sewers. For the invertebrate subset, the proportion of urban land and the number of storm sewers were used.

For both diatom and macroinvertebrate communities, factors associated with water chemistry explained more of the variance in the biotic data than factors associated with land use alone (Table 3). The joint influence of water chemistry and land use explained the largest proportion of variance in the diatom and macroinvertebrate data. The percent variance explained by the interaction between land use and water chemistry decreased, and unexplained variance increased, when distance downstream was used as a covariable to remove the influence of upstream effects.

Table 3. Results of variance partitioning using partial CCA. The percent variance in the macroinvertebrate and diatom data explained by land use and water quality predictors alone, by the interaction between predictors, and that remaining unexplained, are presented. The analysis was repeated using distance downstream as a covariable to remove upstream effects.

	% Variance explained by predictors			
Predictors	Diatom data	Diatom data with distance downstream covariable	Macro-invertebrate data	Macroinvertebrate data with distance downstream covariable
Land use	17	17	13	13
Water quality	23	21	24	25
Interaction	29	22	39	26
Unexplained	31	40	24	36

5.6 Discussion

The results clearly indicate that epilithic diatom and macroinvertebrate communities in Laurel Creek and Carroll Creek can be related to both water chemistry and watershed land use. The land use data were useful for predicting major patterns of macroinvertebrate and diatom community composition, indicating these groups could be used to indicate watershed conditions at stream sites in this area.

The water chemistry characteristics of the sites largely reflect runoff from surrounding agricultural and urban areas. Higher levels of soluble reactive phosphorus, nitrate and total nitrogen at rural sites, particularly in the Carroll Creek watershed, are a result of runoff from cropland and pasture. Suspended solid load was lowest at the headwater site on Carroll Creek, which drained the greatest area of woodland and lowest area of cropland. This observation is similar to that of Allan et al. (1997) who found that stream sediment concentrations increased as the proportion of agricultural to forest land cover increased. Loads at rural sites on Laurel Creek, however, were higher despite relatively high proportions of woodland and low proportions of cropland at these sites. It is likely that there are differences in land management in the riparian zone and in the distribution of land uses in these subwatersheds that influence sediment load. Urban and highway runoff in areas of the Laurel Creek watershed also contribute to suspended solid load, as well as causing elevated conductivity, biological oxygen demand and total phosphorus. Stream temperatures were also higher at Laurel Creek urban sites, but the importance of temperature in relation to diatom distribution is likely to be partly due to extreme seasonal changes, and further exaggerated by differences in the time of day when sites were sampled. Alkalinity was higher at rural sites, and most likely reflects the infiltration of alkaline groundwater to these sites.

The joint influence of water chemistry and land use explained most of the variance in the biotic data, indicating a close link between water chemistry, land use and the composition of stream communities. However, land use effects independent of changes in water chemistry also impact the biota in these streams. In addition to altering stream chemical characteristics, surrounding agricultural and urban land uses impact stream habitat through direct modification of the stream channel and through alteration in discharge patterns and erosion rates. In many areas of Laurel Creek in particular, stream sections have been channelized, re-routed and concrete-lined. For about 500 m the creek flows underground. Such physical alterations profoundly influence the composition of stream communities (Allan, 1995). Furthermore, the removal of the vegetative cover along riverbanks in areas of agricultural and urban development affects stream biota by altering energy supply and reducing inputs of woody debris. Riparian vegetation is a potentially important source of organic material to streams, and woody debris provides a valuable structural element to the channel (Quinn et al., 1997; Richards et al.,1993).

Water chemistry changes that are independent of land use also impact the biota in these streams. Modifications of water chemistry might be taking place through internal processes. Phosphorus uptake and denitrification, for example, may significantly alter nutrient concentrations in some stream systems (Hill, 1979 and 1981). The geology of the catchment will also influence water quality. The most likely explanation in this study, however, is the influence of the impoundments on Laurel Creek. As discussed in Chapter 4, the surface-release reservoirs discharge warm, phosphorus and particulate rich water to downstream sites during the summer months. The lakes also attract large populations of waterfowl that input nutrients and bacteria. Substantial changes in water quality thus occur in the reservoirs, independent of surrounding land use.

Upstream-downstream effects as well as catchment influences are important in stream systems. Many concepts in river ecology, such as the river continuum concept (Vannote et al., 1980) and the nutrient spiraling concept (Webster and Patten, 1979), are based on upstream-downstream linkages. The river continuum concept describes how energy pathways vary along a continuous gradient from headwaters to mouth, and how structural and functional characteristics of stream communities adapt to these changes, while the nutrient spiraling concept describes the cycling of nutrients in running water. An element occurring in the water column as dissolved, available, nutrient is transported downstream as a solute and is then incorporated into the biota, and eventually is returned to the water column in dissolved form. Since the cycle involves downstream transport, it is described as a spiral. When such upstream linkages were removed from the variance partitioning analysis, the proportion of unexplained variance increased and proportion of variance shared between water chemistry and land use decreased. The water chemistry / land use interaction thus seems to have a geographic trend, and to some extent reflects these upstream-downstream effects.

The unexplained variance observed reflects the influence of unmeasured environmental factors on the biota, as well as biotic influences such as competition and predation, and, for the diatom community, invertebrate grazing. An important environmental variable impacting stream assemblages that was not included in this analysis is flow rate (Biggs, 1995). Several catchment features were also not considered, in particular surficial geology, that influence macroinvertebrate and periphyton assemblages through their control over channel morphology and hydrologic patterns. In fact, Richards et al. (1996) found that these features masked land use in their study of macroinvertebrate assemblages in Michigan.

As discussed further in Chapter 4, some of the invertebrate taxa most commonly found at urban and rural sites differed in terms of their functional feeding strategies. Simuliidae, indicative of conditions at urban sites, are generally filtering collectors (Merritt and Cummins, 1996b), and reflect elevated levels of suspended food particles at these sites. The impoundments on Laurel Creek enhance the production of planktonic organisms during the summer months (Hopper, 1997), which are released to downstream sites, encouraging the establishment of filtering collectors at urban sites on the stream. These organisms are also favoured by the substrate stability characteristic of the regulated flow conditions downstream of impoundments (Ward and Stanford, 1987). Oligochaeata were also common at urban sites and inhabit soft sediments, rich in organic matter, feeding on organic detritus and its associated microflora (Peckarsky et al., 1990). These organisms are indicators of organic enrichment, and fine sediment build up must have occurred between the rocks of the riffles sampled to provide them with a suitable substrate. Plecoptera and Ephemeroptera were most common at rural sites, and members of these groups are generally scrapers, gathering collectors, predators or shredders (Merritt and Cummins, 1996b), and are generally less tolerant of organic pollution than the groups found at the urban sites (Resh et al., 1996). These taxa are predominantly obligate erosional species, whose clinging and scraping behaviours are most suitable in larger substrate materials (Richards et al., 1997) and their absence in the urban sites confirms the sedimentation of riffles at these sites

5.7 Conclusions

The results indicate that taxonomic structure of epilithic diatom and macroinvertebrate communities in these streams was related to both water chemistry and watershed land use. My findings indicate that these communities can be used as indicators of water chemistry and watershed conditions at stream sites. These observations clearly demonstrate the importance of watershed land use characteristics as determinants of stream biotic communities and their utility as indicators of catchment conditions.

Land use practices influenced stream habitat quality, which in turn affected the stream assemblages. Urban and rural sites were distinctly different in terms of their macroinvertebrate and epilithic diatom communities, reflecting differences in physical and chemical habitat properties at these sites. Physiochemical and relatively coarse watershed land use data predicted the major gradients in epilithic diatom and macroinvertebrate community composition. Although land use and water chemistry were independently related to these communities, a close link was observed between land use, water chemistry and the biota. This joint influence of land use and stream water chemistry on community composition was found partly to be due to upstream-downstream effects.

These findings clearly demonstrate the growing recognition of the importance of watershed characteristics in the structuring of stream communities. They show that there are measurable relationships between diatom and macroinvertebrate community composition and land use in this area, and it is likely that such relationships will be observed for other stream systems. Studies elsewhere have found that land use patterns strongly influenced variation in stream macroinvertebrate assemblage structure (Quinn et al., 1997; Richards et al., 1996). My study outlines how surrounding land use strongly influenced variation in diatom as well as macroinvertebrate community composition in the streams studied, indicating that both groups of organisms can be used effectively as monitors of watershed land use.

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6. WEIGHTED-AVERAGING REGRESSION AND CALIBRATION MODELS FOR INFERRING TOTAL PHOSPHORUS AND TOTAL NITROGEN USING EPILITHIC DIATOMS FROM LAUREL CREEK AND CARROLL CREEK

6.1 Abstract

Relationships between epilithic diatoms and total nitrogen and total phosphorus were sufficiently strong to develop weighted-averaging regression and calibration models for inferring stream water concentrations of these nutrients in Laurel Creek and Carroll Creek. These models were accurate within ± 2.4 µg/l for total phosphorus and ± 2 mg/l for total nitrogen. An evaluation of the goodness of fit of these models with and without bootstrapping indicated that these models performed better than other nutrient models for which similar assessments were made. Models were improved when seasonal variation was removed by using average water quality and diatom data. Overall, epilithic diatoms can clearly be used to monitor total nitrogen and total phosphorus concentrations in these streams.

6.2 Introduction

The use of diatom taxonomic composition to infer environmental conditions using weighted-averaging regression and calibration modeling has, until recently, largely been restricted to paleolimnological studies on lakes. In such studies, diatoms have proved to be powerful indicators of environmental change, and models can be developed to infer past water quality conditions using diatom assemblages (Dixit et al., 1992). Sedimentary diatoms have been used extensively in studies dealing with lake acidification and recovery, and are extremely useful as indicators of pH changes in lakes (Battarbee et al., 1990). More recently, diatom inference models have been developed to quantitatively infer lake water trophic variables (e.g. Christie and Smol, 1993; Cumming et al., 1995; Hall and Smol, 1992 & 1996; Reavie et al., 1995).

Despite the success of such approaches in lentic systems, diatom species distributions in streams in relation to environmental conditions have not been well established (Pan et al., 1996). Given that diatoms are extremely useful in river monitoring (Round, 1993), and the utility of diatom weighted-averaging regression and calibration modeling in lake studies, there is a need to investigate the use of such inference approaches in streams. Pan et al. (1996), developed diatom inference models for pH and total phosphorus in streams in the Appalachian Mountains, and found that the relationship between diatoms and environmental variables were robust and quantifiable. To date, no such models evaluating diatom responses to nitrogen concentrations in streams have been published.

Diatoms are sensitive indicators of trophic status in rivers and lakes (Cumming et al., 1995; Kelly and Whitton, 1995). As a resident biotic component in streams, species rich diatom assemblages can integrate temporal variation in nutrient concentrations. It is difficult to accurately monitor nitrogen and phosphorus levels in rivers due to transient and episodic changes in storage, transport and inputs of these nutrients (Cattaneo and Prairie, 1994). Taking regular measurements of total nitrogen and total phosphorus and correlating them with diatom data can provide useful inference models for these nutrients that can subsequently be used to infer concentrations. Such models reduce the need for expensive, and labor intensive, water chemistry data collection. Furthermore, if samples are collected from a variety of stream sites that span gradients in nitrogen and phosphorus, species optima and tolerances calculated using weighted-averaging regression and calibration can be used to develop indices of eutrophication (sensu Kelly and Whitton, 1995). To create a trophic index, the species optima and tolerances can be classified using cluster analysis and each cluster can be assigned an ordinal or nominal rank based on species preference with respect to nitrogen and phosphorus (Lowe and Pan, 1996).

The objectives in this chapter were to develop and evaluate weighted-averaging regression and calibration models for inferring total phosphorus and total nitrogen concentrations in Laurel Creek and Carroll Creek using epilithic diatom community structure. Using these methods, I assessed the utility of diatoms for monitoring eutrophication in these streams, and, as well as advancing our knowledge of stream diatom species distribution in relation to phosphorus concentration, I developed stream nitrogen inference models that, to date, have not been published in the literature.

6.3 Site description

As outlined in the previous chapter, the study sites were both located in the Grand River watershed in Southern Ontario. Laurel Creek is approximately 20 km long with a catchment area of about 74 km^2. Land use in the upper part of the watershed is rural, consisting mainly of cropland, and areas of pasture and woodland. The lower half of the watershed is under urban development. As outlined in Chapter 4, the effects of urban and agricultural development on stream water quality and habitat are exacerbated by the presence of several impoundments on Laurel Creek. Carroll Creek is approximately 20 km long with a catchment area of 69 km^2. Land use in the watershed is rural, consisting of commercial crop and livestock production, and areas of pasture and woodland.

6.4 Methods

6.4.1 Diatoms and water chemistry

Samples of epilithic diatoms were collected monthly from sites on Laurel Creek and Carroll Creek from May to September in 1995 and from May 1996 to February 1997, using methods described in Chapter 4. Water samples were collected every two weeks from May to September and monthly over the rest of the sampling period. Total phosphorus concentration was measured as phosphate using the ascorbic acid method, following oxidation with persulfate under pressure (Parsons et al., 1984). Total nitrogen concentration was measured as nitrate following digestion with sodium hydroxide and sulfuric acid under ultraviolet light (Technicon, 1984). Alkalinity, nitrate, ammonia, total suspended solids and biological oxygen demand were analyzed using standard methods (APHA, 1989) and conductivity, pH and temperature were measured in the field.

Epilithic diatom samples were collected monthly from riffle habitats by pooling rock scrapings from 3 to 5 rocks. Slides were prepared using methods outlined in Chapter 4. and at least 200 valves were counted on each slide. and identified to species following Krammer and Lange-Bertalot (1986-1991). and also using Patrick and Reimer (1966, 1975) and Sims (1996). *Aulacoseira granulata*, *Asterionella formosa*, *Cyclostephanus dubius* and *Stephanodiscus sp.* were excluded from counts because they were determined to be planktonic species that were not components of the epilithon. and were found exclusively at sites on Laurel Creek downstream of impoundments. This is a valid approach (F.E. Round, pers. Comm). and was used to provide an unbiased assessment of the epilithon at these sites.

6.4.2 Data analysis

Diatom species were included in ordinations and calibration models if they were present in 3 samples and in made up >1 % of the count in one sample. All water quality variables except pH, temperature and alkalinity were log-transformed due to their extremely skewed distributions. Ordinations were performed using CANOCO version 3.1 (Ter Braak, 1990). Detrended correspondence analysis (DCA) was used to calculate the maximum amount of variation in the diatom data, and it was determined that a technique based on a unimodal response model would be appropriate for analysis. Canonical correspondence analysis (CCA) was therefore used to evaluate relationships with environmental variables. Rare species were downweighted in all ordinations. Canonical coefficients and approximate *t*-tests were used to identify the variables that each explained significant directions of variance in the distribution of diatom taxa. In all CCAs, the taxon scores were scaled to be weighted averages of the site scores (Ter Braak, 1990). The significance of the CCA axes was assessed using Monte Carlo permutation tests (99 random permutations).

Unusual samples

Before beginning the analysis, ordination was used to screen the data to detect any unusual or 'outlier' samples. Outlier samples may have an unusual diatom assemblage or an unusual combination of environmental variables (Hall & Smol, 1992). An outlier was detected and deleted from the final CCA and calibration model if (i) the sample score fell outside the 95 % confidence limits about the sample score means in both a DCA of the species data and a principle components analysis (PCA) of the environmental data in the full data set; or (ii) the sample had an environmental variable with extreme (>x5) influence detected by CCA.

Regression and calibration of diatoms and total nitrogen and total phosphorus

To develop reliable water chemistry inference models from diatom data there must be a strong statistical relationship between diatoms and the variable to be modeled. The strengths of the relationships between total nitrogen and total phosphorus and diatoms for this data set were assessed using constrained and partially constrained CCAs (TerBraak & Verdonschot, 1995). Constrained CCAs were first run, using total nitrogen and total phosphorus in turn as a single environmental variable. Species composition was thus constrained to one variable alone, and reliable inference models can be developed if the ratio of the first (constrained) eigenvalue (λ_1) to the second (unconstrained) eigenvalue (λ_2) is high (Hall and Smol, 1996).

Partially constrained CCAs and Monte Carlo permutation tests (99 random permutations) were then run to examine the individual, independent, effect of total nitrogen and total phosphorus in turn on the distribution of diatom species. In this analysis, the first ordination axis was constrained to each variable alone after the influences of the other variables were partialled out (TerBraak & Verdonschot, 1995).

Weighted-averaging (WA) regression is a technique that can be used to estimate the optima of diatom taxa to a water chemistry variable (Cumming et al., 1995). A taxon's optimum can be defined as an estimate of the value along an environmental gradient at which a taxon consistently achieves its highest abundance relative to other taxa. A weighted average can be used to estimate the optimum of a taxon along an environmental gradient using the following equation:

$$\text{WA optimum for taxon } k\ (U_k) = \frac{\sum_{i=1}^{n} Y_{ik}X_i}{\sum_{i=1}^{n} Y_{ik}} \qquad (1)$$

where Y_{ik} is the abundance of taxon k in sample i from a site, and X_i is the value of the environmental variable of interest at the stream site when sample i was collected (Line and Birks, 1990). The tolerance of a taxon is the standard deviation of the optima and can be calculated using the following equation:

$$\text{WA tolerance for taxon } i\ (Ti) = \sqrt{\frac{\sum_{i=1}^{n} Y_{ik}(X_i - U_k)^2}{\sum_{i=1}^{n} Y_{ik}}} \qquad (2)$$

A WA estimate for each sample from every site is simply calculated as the average of the U_k of all taxa in that sample, weighted by their relative abundances, using the equation:

$$\text{WA estimate for sample } i\ (Zi) = \frac{\sum_{i=1}^{n} Y_{ik}U_k}{\sum_{i=1}^{n} Y_{ik}} \qquad (3)$$

WA- regression and calibration were performed to calculate diatom species total nitrogen and total phosphorus optima and develop inference models for these variables, using the computer program WACALIB version 3.3 (Line et al., 1994). In WA modeling using this method, averages are taken twice, once in WA-regression and once in WA-calibration (Birks et al., 1990). This results in shrinkage of the range of the inferred variable. To correct for this, a simple linear deshrinking was done by regressing the initial inferred values of estimated optima for the training set, Z_i, on the observed values, X_i, using a classical linear regression model.

Errors associated with model inferences were estimated from 999 bootstrap cycles. Bootstrapping is a computer resampling procedure in which the *n* samples used in the calibration form a data pool (Lowe and Pan, 1996). In each bootstrap cycle, a subset of *n* samples are randomly selected from the data pool and used to calculate WA-estimates. The same procedure is repeated, in this case 999 times. A distribution of WA-estimates can then be created and standard errors calculated (root mean square error, RMSE). As outlined in Hall et al. (1996), models were assessed using (i) the correlation between diatom-inferred values with and without bootstrapping, (ii) the apparent RMSE of prediction, and (iii) the bootstrap RMSE.

Models were first developed, and assessed, for the full 126 sample set. Then, in order to evaluate the models further, the data set was sorted randomly and 84 samples used to develop calibration models. The remaining 42 samples were then used to test the accuracy of the calibration models. The total nitrogen and total phosphorus concentrations estimated for the test set were compared to measured concentrations using regression analysis.

Finally, models were developed using mean values of the diatom and water chemistry data collected during the summer months (from May to September in 1995 and 1996). Mean values were used in order to evaluate how models would compare when seasonal variation in diatom and environmental data was removed. To develop the subset of mean values, a series of CCAs were run to establish which month, average of months for each year or season, or overall average, provided the strongest relationships between total nitrogen and total phosphorus and the diatom data. It was found that the relationships were strongest using overall averages of data collected over both summer field seasons.

6.5 Results

Deleting rare diatom taxa reduced the number of species in the analysis from 146 to 68. Removing outlier samples further decreased the number of diatom species to 66, and, of the 154 collected, 126 samples were used in analysis.

6.5.1 Canonical correspondence analysis

Eight environmental variables were identified in CCA (temperature, TEMP; total suspended solids, TSS; total phosphorus, TP; conductivity, COND; biological oxygen demand, BOD; pH; total nitrogen, TN; and alkalinity, ALK) that each explained significant (p <0.05) directions of variance in the diatom data along one or more of the first two CCA axes (Fig.1). The eigenvalues of the CCA axes 1 (0.22) and for CCA axis 2 (0.17) dropped somewhat from those obtained in DCA (0.53 and 0.27) indicating that the environmental variables only accounted for part of the variation in the species data extracted by DCA. When sampling month was entered as a nominal variable and used as a covariable to remove seasonal effects from the analysis, the eigenvalues extracted by CCA (0.28 and 0.17) and DCA (0.48 and 0.24) were closer, indicating that some of the unexplained variance in the species data was due to seasonal variation in water chemistry and diatoms. However, the eigenvalues extracted by CCA were significant (p <0.01) and the variance explained by the first two CCA axes was 12 %, which is similar to relationships of 11 to 18 % reported for other lake and stream studies (Pan et al., 1996). Based on the canonical coefficients and approximate t-tests, CCA axis 1 was highly correlated with total nitrogen and temperature and CCA Axis 2 was highly correlated with total susended solids, total phosphorus and alkalinity.

As was also seen in Chapter 5, urban and rural sites separated in ordination space along CCA axis 2 (Fig. 2). There is some further divergence of rural sites along CCA axis 1. This separation reflects the impact of watershed land use on water chemistry, which in turn influences diatom community structure. Those diatom species whose scores fall at the top of the plot of species scores (Fig. 1) were those that are most common at urban

Figure 1. CCA diagram showing species scores obtained in the ordination of epilithic diatom data in 126 samples. Diatom species are represented by open circles. Diatom names are presented in Table 1. Arrows indicate environmental variables (biplot scores were multiplied by 2.5) that are significantly ($p < 0.05$) correlated with diatom distribution.

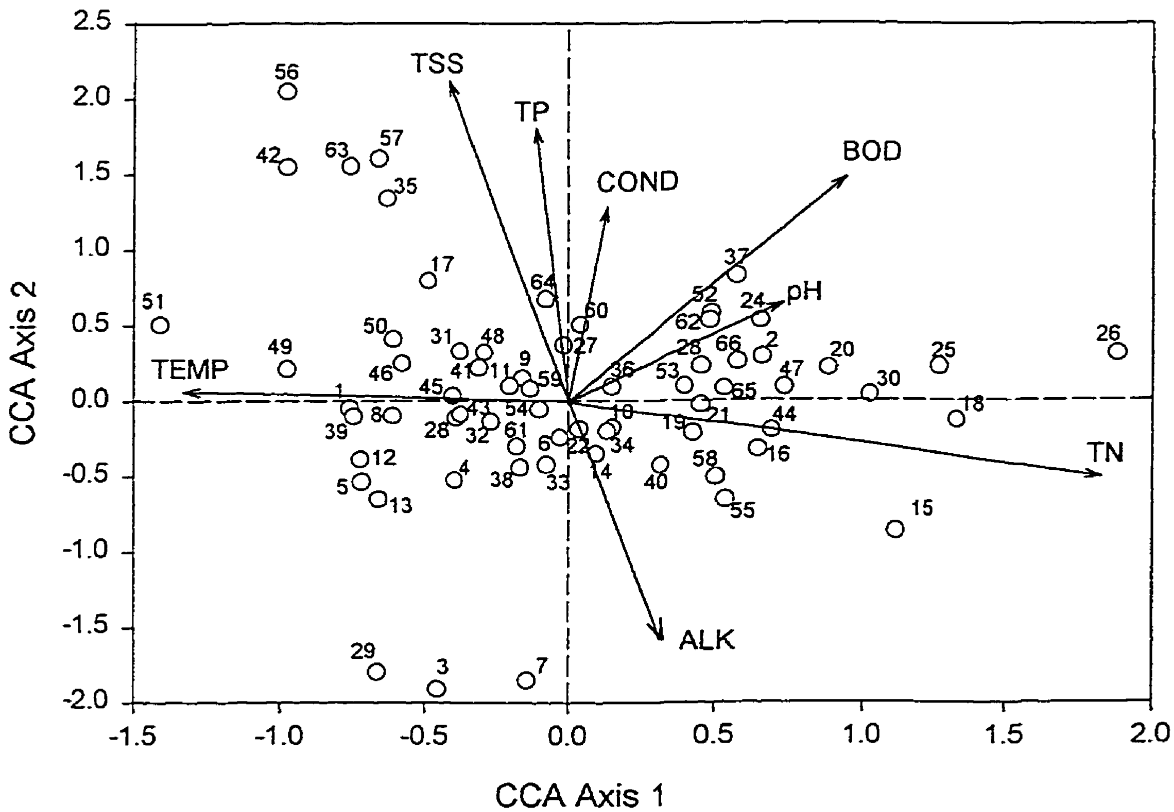
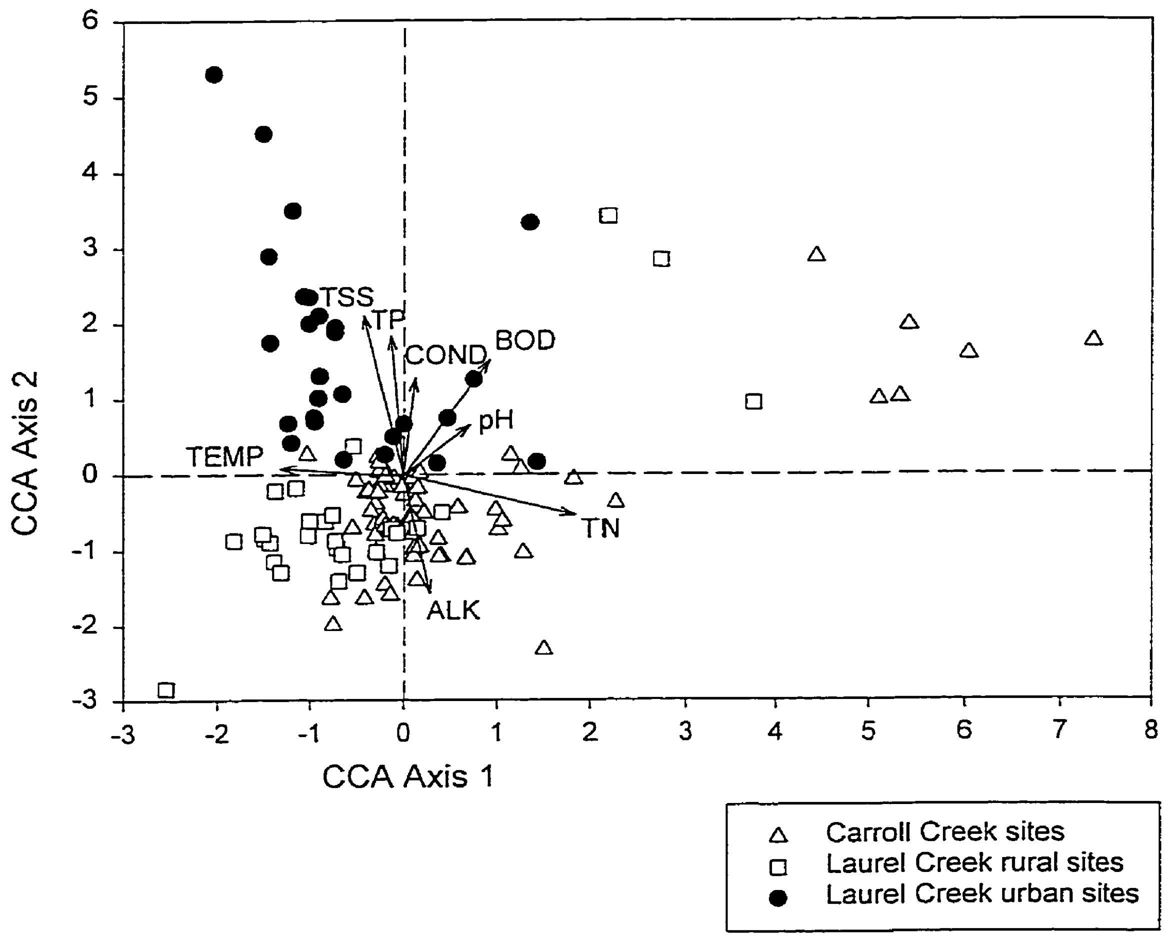


Figure 2. CCA ordination of the 126 sample set. Urban and rural sites are represented by symbols. The arrows indicate environmental variables (biplot scores were multiplied by 2.5) that are significantly (p <0.05) correlated with the distribution of diatoms at these sites.



sites and include *Nitzschia incognita*. *Navicula schroeteri*. *Navicula viridula*. *Nitzschia solita* and *Nitzschia inconspicua*. Those species whose scores fall at the bottom of the plot were most common at rural sites. Those predominantly found at Laurel Creek rural sites were *Achnanthes lauenbergiana*. *Cocconeis placentula* and *Cyclotella menenghiniana* while *Cymbella reichardtii*. *Diatoma tenuis*. *Nitzschia heufleuriana* and *Gomphonema olivaceum* were mainly found at Carroll Creek sites.

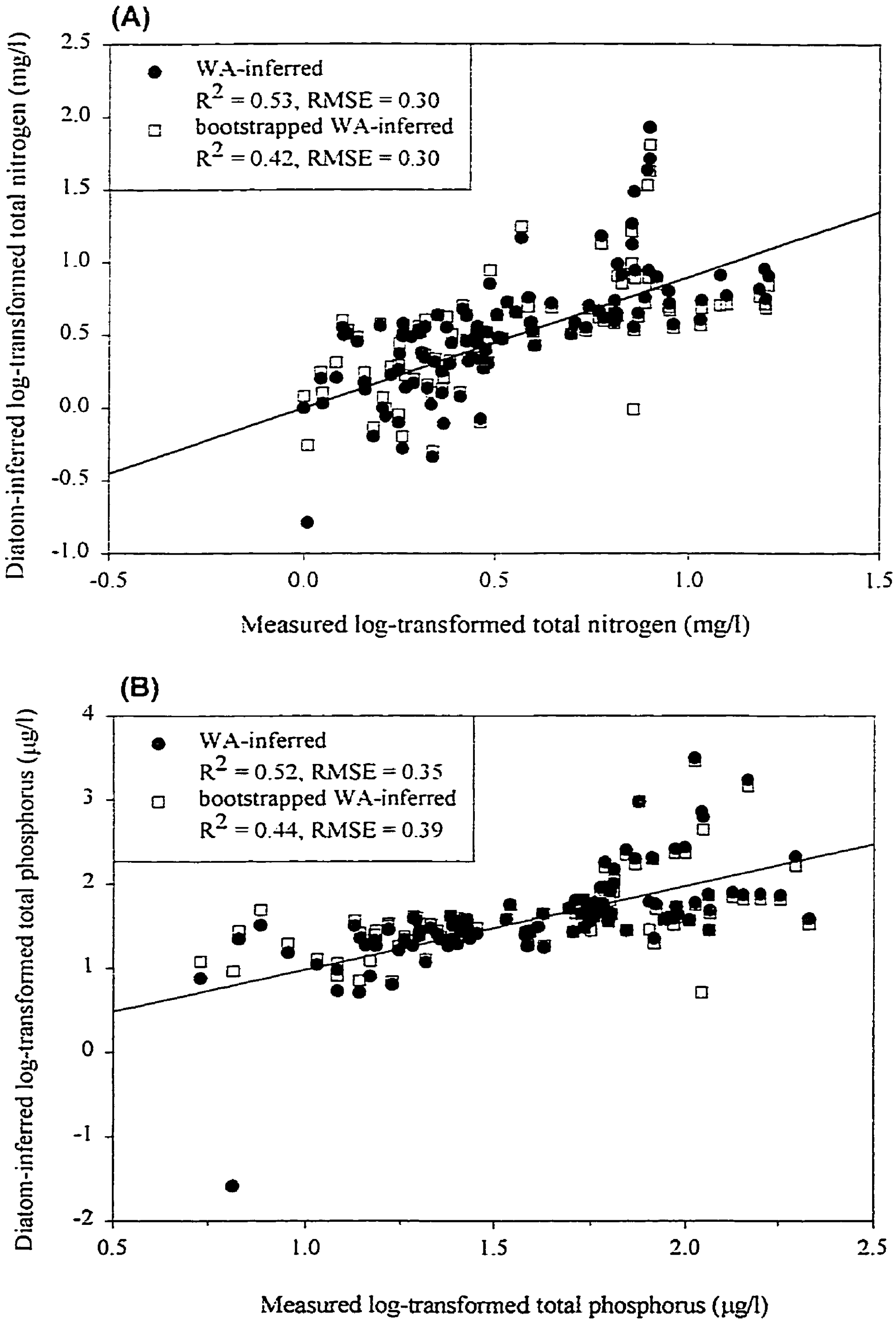
6.5.2 Inference models for total nitrogen and total phosphorus

On assessing the strengths of relationships between total nitrogen concentration. TN. total phosphorus concentration. TP and diatoms using constrained CCAs it was determined that TN was slightly more strongly correlated with diatom community structure than TP ($\lambda_1/\lambda_2 = 0.32$ versus 0.21). Partially constrained ordinations and Monte Carlo permutation tests indicated that significant (p <0.01) and independent responses of diatoms to both TP and TN. The values for λ_1/λ_2 in the constrained CCAs are slightly lower than those determined in paleolimnological TP models developed for lakes by Hall and Smol (1992 & 1996) and Reavie and Smol (1995). that ranged from 0.36 to 0.44. and in a TN model developed by Christie and Smol (1993). 0.40. However. since the relationships between diatoms and both TN and TP were significant and independent for this data set. I conclude that they were strong enough to develop inference models.

To develop robust and reliable WA inference models. realistic optima of diatom species must be estimated along the environmental gradients of interest (Hall and Smol, 1996). One way to assess whether the optima are realistic is to compare goodness of fit (R^2 and RMSE of prediction) between measured versus WA-inferred values estimated with and without bootstrapping. If the goodness of fit between measured and inferred values is much weaker when estimated using bootstrapping, then the species optima are not clearly defined by the WA technique (Hall and Smol, 1996).

My 126 stream site calibration set reliably estimated the optima of the diatom taxa along the TN and TP gradients (Fig. 3A and 3B). In all graphs. the R^2 values represent the

Figure 3. The relationship between measured and diatom-inferred stream (A) total nitrogen and (B) total phosphorus concentration using weighted-averaging regression and calibration models and classical deshrinking, with and without bootstrapping. R^2 values are shown, and in each case are significant ($p < 0.01$). RMSE is the root mean square error of prediction. The straight line was drawn at 1:1 ratio.



coefficient of determination of regression between diatom-inferred and measured TN or TP. The differences between correlations (0.53 vs. 0.42 for TN; 0.52 vs. 0.44 for TP) and root mean squared errors (0.30 vs. 0.30 for TN; 0.35 vs. 0.39 for TP), were small when compared with TP inference models developed for streams (Pan et al., 1996) and for lakes (Hall and Smol, 1996). However, the R^2 values were lower than those in the aforementioned studies for TP (0.62 and 0.63), and than those in Christie and Smol (1993) for TN (0.75).

The gradient of TN ranged from 1- 16.29 mg/l, and of TP ranged from 5.36 – 214.78 µg/l (Fig. 3A and 3B). Along these gradients, the diatom inference models provide fairly close estimates of measured TP, accurate within ± 2.24 µg/l. For TN however, the standard error of ± 2.00 mg/l was higher when compared with the range in measured values.

The TN and TP optima and tolerances are listed for the 66 common diatom taxa, together with the effective number of occurrences (Hill's N2) on which these are based (Table1). Hill's N2 is an estimate of the number of samples that, in practice, influence the weighted average of that species (Cumming et al., 1992). For TN, optima range from 1.61 mg/l for *Nitzschia amphibia* to 12.13 mg/l for *Nitzschia heufleuriana*. Optima for TP range from 7.71 mg/l for *Achnanthes stolida* to 118.85 mg/l for *Nitzschia solita*. Taxa with small tolerances for the environmental variable of interest are considered good indicators of the variable (Lowe and Pan, 1996). Based on their optima and tolerances, *Navicula lanceolata*, *Navicula schroeterii*, and *Nitzschia inconspicua* are good indicators of high phosphorus conditions. *Nitzschia amphibia*, *Nitzschia constricta*, and *Nitzschia solita* are also good indicators of high phosphorus, however, these species also indicate low nitrogen conditions. *Cymbella affinis* is a good indicator of low phosphorus, and *Navicula pupula* and *Nitzschia constricta* are good indicators of low nitrogen. *Achnanthes stolida* is a good indicator of low nitrogen and low phosphorus conditions.

The results of running a set of one third of the samples to test the calibration based on the other two thirds are similar to the results obtained on bootstrapping (Fig. 4A and 4B). The correlations between diatom inferred and measured log-transformed TN and TP were

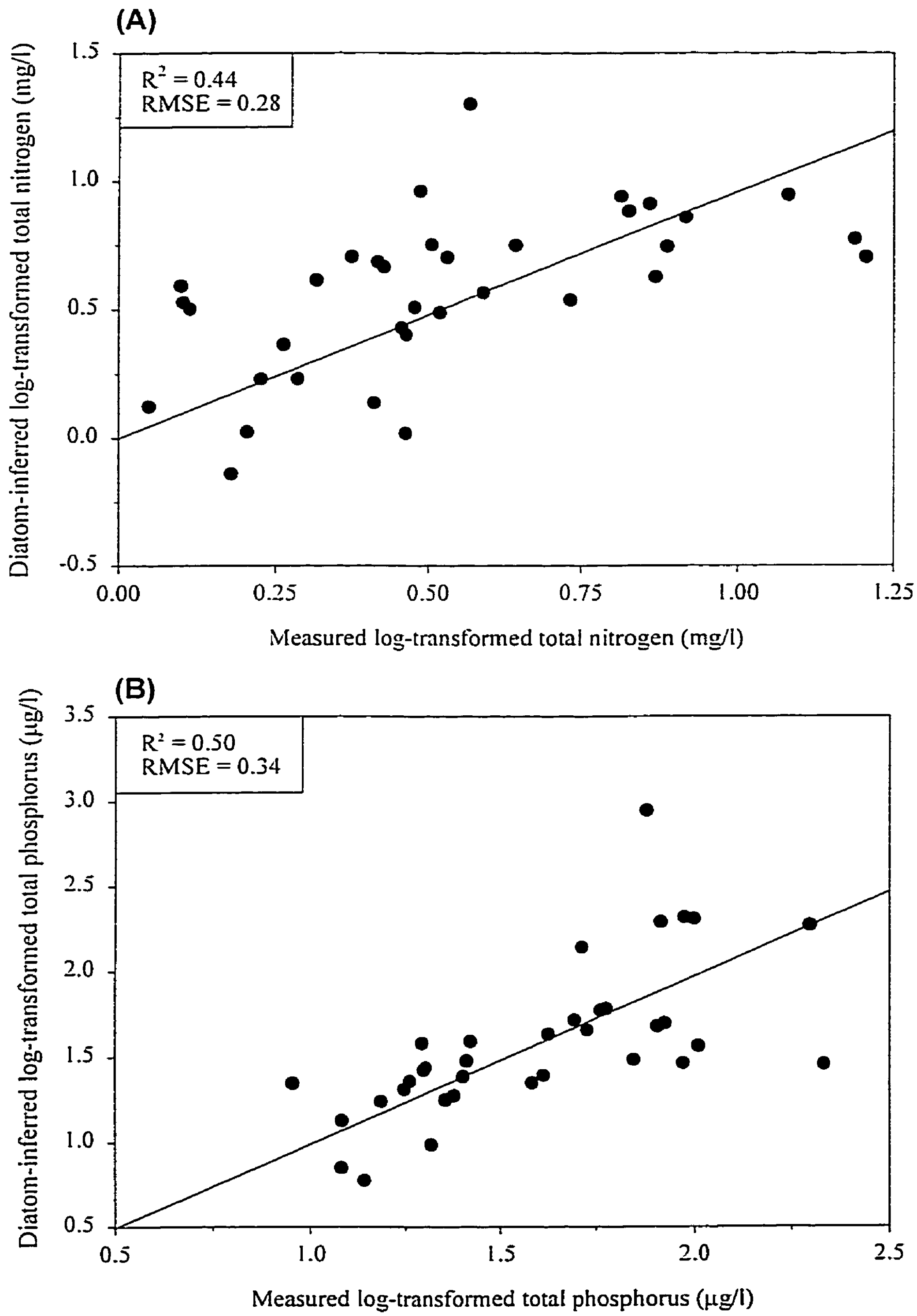
Table 1. The optima and tolerances for total nitrogen and total phosphorus concentration and effective number of occurences (Hill's N2) of the diatom taxa used in ordinations and WA regression and calibration models.

Taxon	[TN] (mg/l)		[TP] (µg/l)		Hill's
	Optimum	Tolerance	Optimum	Tolerance	N2
1 *Achnanthes conspicua* A. MAYER	1.99	1.51	52.12	2.41	21.8
2 *Achnanthes delicatula* (KÜTZING) GRUNOW	4.46	1.93	49.77	2.61	5.9
3 *Achnanthes laevis* ØSTRUP	2.52	1.42	10.38	1.82	3.9
4 *Achnanthes lanceolata* (BRÉBISSON) GRUNOW	2.43	1.72	31.62	2.13	28.9
5 *Achnanthes lauenbergiana* HUSTEDT	2.13	1.51	33.19	2.59	8.9
6 *Achnanthes minutissima* KÜTZING	3.53	2.07	35.24	2.31	85.4
7 *Achnanthes stolida* KRASSKE	2.13	1.51	7.71	1.83	2.3
8 *Achnanthes trinodis* (W.SMITH) GRUNOW	2.32	1.75	38.37	1.80	4.9
9 *Amphora pediculus* (KÜTZING) GRUNOW	3.06	1.88	46.88	2.33	68.5
10 *Caloneis bacillum* (GRUNOW) CLEVE	3.55	1.71	35.56	2.19	23.5
11 *Cocconeis pediculus* EHRENBERG	2.99	2.18	51.29	2.52	28.8
12 *Cocconeis placentula* EHRENBERG	1.89	1.65	43.35	1.80	24.0
13 *Cyclotella menenghiniana* KÜTZING	1.73	2.06	38.46	2.06	5.9
14 *Cymbella affinis* KÜTZING	4.43	2.07	16.03	1.58	6.4
15 *Cymbella reichardtii* KRAMMER	5.61	2.25	9.14	3.41	1.6
16 *Cymbella silesiaca* BLEISCH	6.12	1.95	36.73	2.25	23.1
17 *Cymbella sinuata* GREGORY	2.28	1.78	56.75	2.63	22.2
18 *Diatoma tenuis* AGARDH	5.78	1.87	39.81	2.17	6.8
19 *Diatoma vulgaris* BORY	5.62	2.04	16.56	1.87	5.9
20 *Fragilaria brevistriata* GRUNOW	5.12	2.48	24.66	2.36	3.5
21 *Fragilaria capucina* (DESMAZIÈRES) KÜTZING	4.22	1.98	41.50	2.20	25.3
22 *Fragilaria construens* (EHRENBERG) GRUNOW	3.13	2.08	44.36	2.34	8.8
23 *Fragilaria pinnata* EHRENBERG	2.34	1.73	53.70	2.11	8.0
24 *Fragilaria tenera* (W.SMITH) LANGE-BERTALOT	2.63	1.32	53.95	2.50	2.8
25 *Fragilaria ulna* (NITZSCH) LANGE-BERTALOT	5.70	1.92	41.59	2.16	17.7
26 *Gomphonema olivaceum* (HORNEMANN) BRÉBISSON	6.70	1.52	54.58	1.68	11.3
27 *Gomphonema parvulum* KÜTZING	2.59	1.76	56.75	2.67	18.7
28 *Gyrosigma acuminatum* (KÜTZING) RABENHORST	5.50	2.13	46.88	2.50	8.8
29 *Melosira varians* AGARDH	3.33	1.17	16.75	1.90	3.5
30 *Meridion circulare* GRÉVILLE	4.55	1.59	42.76	1.85	6.9
31 *Navicula capitata* EHRENBERG	2.73	2.00	65.61	2.59	8.8
32 *Navicula capitatoradiata* GERMAIN	2.99	2.09	33.27	2.46	36.6
33 *Navicula cryptocephala* KÜTZING	3.17	2.02	30.55	2.41	25.3
34 *Navicula cryptotenella* LANGE-BERTALOT	4.31	1.90	35.97	2.06	44.1
35 *Navicula eliginensis* (GREGORY) RALFS	2.43	1.99	95.72	2.77	4.6
36 *Navicula gregaria* DONKIN	3.42	1.98	53.83	1.86	33.5
37 *Navicula lanceolata* (AGARDH) EHRENBERG	3.23	1.70	62.52	1.58	10.8
38 *Navicula sp.*aff. *N. meniscula* SCHUMANN	3.44	1.62	39.36	1.98	7.9
39 *Navicula pupula* KÜTZING	1.91	1.26	47.53	2.41	7.3
40 *Navicula reichardtiana* LANGE-BERTALOT	4.73	1.91	34.43	2.09	29.2
41 *Navicula saprophila* LANGE-BERTALOT & BONIK	2.81	1.90	41.98	2.43	22.9
42 *Navicula schroeteri* MEISTER	2.06	1.44	102.33	1.45	4.9
43 *Navicula sp.*aff. *seminuloides* HUSTEDT	1.79	1.17	45.92	1.47	2.1

Table 1. (*concluded*)

Taxon	[TN] (mg/l)		[TP] (µg/l)		Hill's N2
	Optimum	Tolerance	Optimum	Tolerance	
44 *Navicula tripunctata* (O.F. MÜLLER) BORY	5.82	1.89	39.17	1.99	31.7
45 *Navicula trivialis* LANGE-BERTALOT	2.40	1.56	50.00	2.49	14.2
46 *Navicula venetata* KÜTZING	2.62	1.74	48.19	3.20	8.7
47 *Navicula viridula* KÜTZING	4.72	1.83	55.59	1.89	8.3
48 *Nitzschia acicularis* (KÜTZING) W.SMITH	3.56	1.88	55.08	2.20	6.8
49 *Nitzschia amphibia* GRUNOW	1.61	1.47	69.82	1.64	11.1
50 *Nitzschia capitellata* HUSTEDT	2.59	1.87	52.12	2.36	10.3
51 *Nitzschia constricta* KÜTZING (RALFS)	1.82	1.17	70.31	1.43	2.8
52 *Nitzschia dissipata* var. *media* (KÜTZING) GRUNOW	3.86	2.47	48.53	2.24	12.3
53 *Nitzschia dissipata* var. *dissipata* (KÜTZING) GRUNOW	4.09	1.84	49.89	2.07	43.6
54 *Nitzschia fonticola* GRUNOW	2.81	1.62	33.57	2.04	18.8
55 *Nitzschia heufleuriana* GRUNOW	12.13	2.83	18.49	2.30	1.5
56 *Nitzschia incognita* LEGLER & KRASSKE	2.35	1.24	100.00	3.73	1.1
57 *Nitzschia inconspicua* GRUNOW	2.08	1.37	115.35	1.48	12.2
58 *Nitzschia linearis* (AGARDH) W. SMITH	5.28	2.36	30.97	1.85	9.6
59 *Nitzschia palea* (KÜTZING) W. SMITH	3.71	1.99	34.36	2.52	30.7
60 *Nitzschia pusilla* GRUNOW emend LANGE-BERTALOT	3.40	1.81	60.26	2.47	8.3
61 *Nitzschia recta* HANTZSCH	3.22	1.98	32.89	1.91	18.3
62 *Nitzschia sociabilis* HUSTEDT	3.98	1.95	51.40	2.13	18.6
63 *Nitzschia solita* HUSTEDT	1.91	1.45	118.85	1.76	10.3
64 *Rhoicosphenia abbreviata* (AGARDH) LANGE-BERTALOT	2.79	1.78	57.94	1.95	14.2
65 *Surirella angustata* KÜTZING	4.20	2.36	44.36	2.55	5.6
66 *Surirella brebissoni* KRAMMER & LANGE-BERTALOT	4.50	1.91	50.58	1.96	15.1

Figure 4. The relationship between measured and diatom-inferred stream (A) total nitrogen and (B) total phosphorus concentration for a test set made up of 42 samples, using a calibration set made up of 84 samples. R^2 values are significant (p <0.01), and the line was drawn at a 1:1 ratio. RMSE is the root mean square error of prediction.



0.44 and 0.50 respectively, and data points are evenly spread around a 1:1 line. The root mean square error of prediction was ± 1.91 mg/l for TN and ± 2.19 μg/l for TP.

When seasonal variation was removed from the data set by using summer 1995 and 1996 mean values, the inference models constructed were better than those using the full data set (Fig. 5A and 5B). The goodness of fit between diatom inferred and measured log transformed TN and TP were similar with and without bootstrapping (R^2 0.82 vs. 0.76 and RMSE 0.09 vs. 0.12 for TN; R^2 0.76 vs. 0.61, RMSE 0.11 vs. 0.19 for TP), indicating that species optima were estimated reliably. The gradient of TN ranged from 2.10 to 8.74 mg/l, and TP ranged from 13.16 to 154.88 μg/l. The correlations between inferred and measured log transformed TN and TP were high, 0.82 and 0.76 respectively.

6.5.3 Plots of mean number of individuals counted for eight diatom species, and total nitrogen and total phosphorus

The mean (+ 1 S.E.) number of individuals counted of eight diatom species were plotted for sites on Carroll Creek and Laurel Creek (the site numbers are equivalent to those Fig.1 in Chapter 5), together with plots of mean (± 1 S.E.) TN and TP (Fig. 6 A-H). There was good agreement between the abundance of species at sites, which varied considerably in their mean TN and TP, their optima and tolerances for TN and TP presented in Table 1, and their position in the CCA plot of species scores (Fig. 1). *Achnanthes minutissima* was the diatom species was most commonly counted at all sites, and was common throughout the range of TN and TP (Fig. 6A). It should be noted that there are several ecotypes of *Achnanthes minutissima* (Lange-Bertalot, 1991), and I was unable to consistently separate the individual varieties. I therefore grouped them in this analysis, and it is likely that there would be more differentiation in the abundance of this species between sites if it were separated into the various forms. The abundance of *Caloneis bacillum* also showed no relationship with TN or TP (Fig. 6B). These species are not good indicators of TN or TP, and they were located in the middle of the CCA plot, indicating that they were indifferent to the measured water quality variables and common at all sites (Fig. 1). *Cymbella reichardtii* was found at many of the stream sites,

Figure 5. The relationship between measured and diatom-inferred stream (A) total nitrogen and (B) total phosphorus for average 1995 and 1996 summer data, with and without bootstrapping. R^2 values are shown and in each case are significant ($p < 0.01$), and the line was drawn at a 1:1 ratio. RMSE is the root mean square error of prediction.

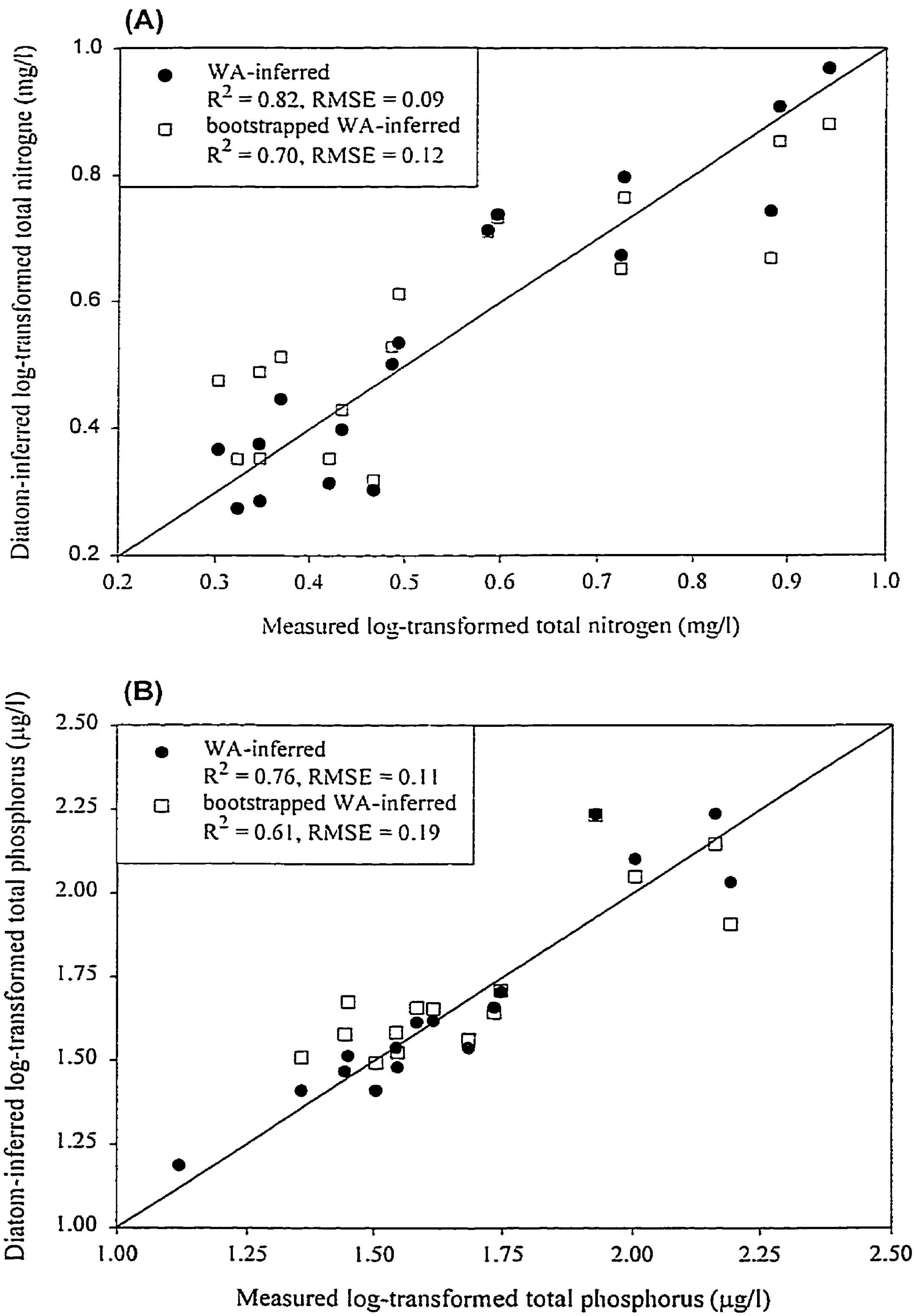
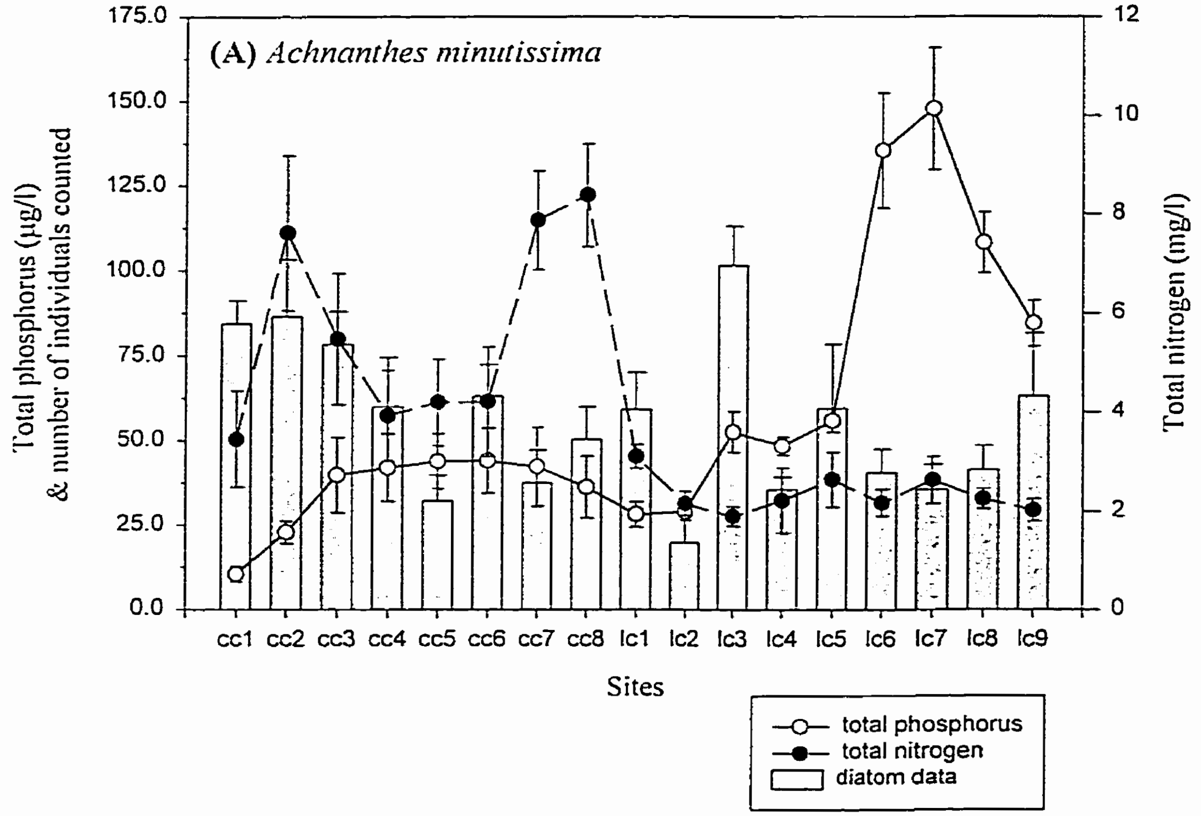


Figure 6 (A-H). Mean (± 1 S.E.) number of diatom individuals counted, total nitrogen and total phosphorus concentrations for Carroll Creek (cc) and Laurel Creek (lc) sites over the sampling period. Site numbers are equivalent to those presented in Chapter 5, Figure 1. Note that the number of diatom valves counted are plotted on either the total nitrogen or the total phosphorus scale.



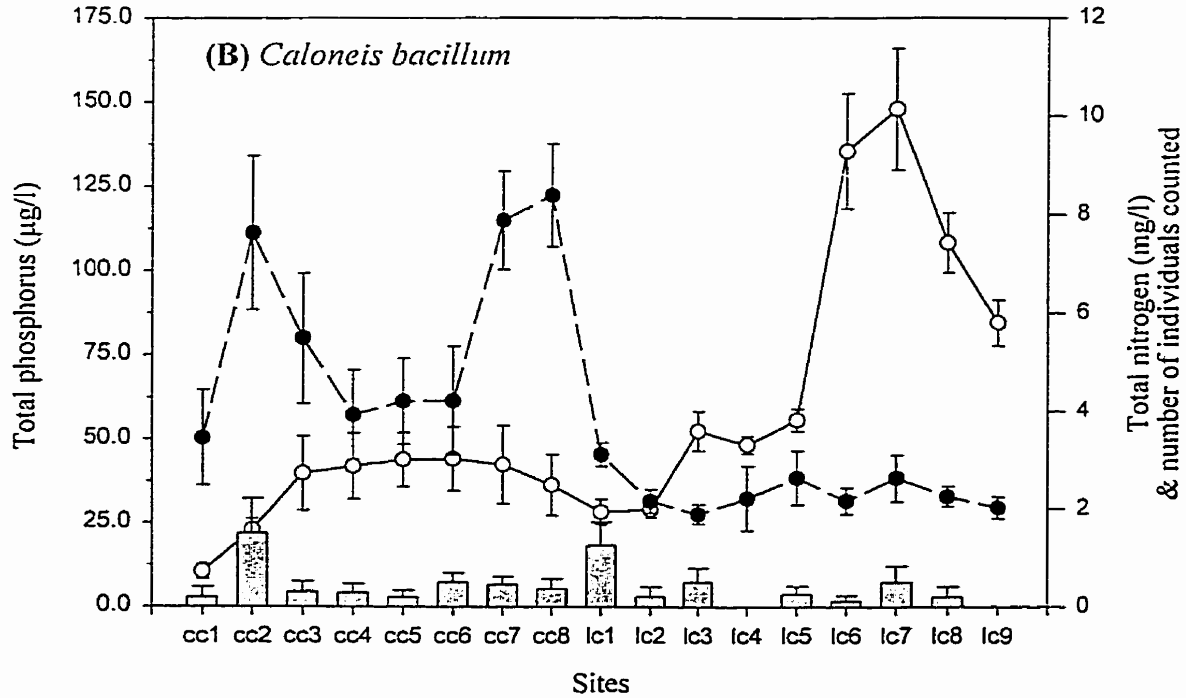
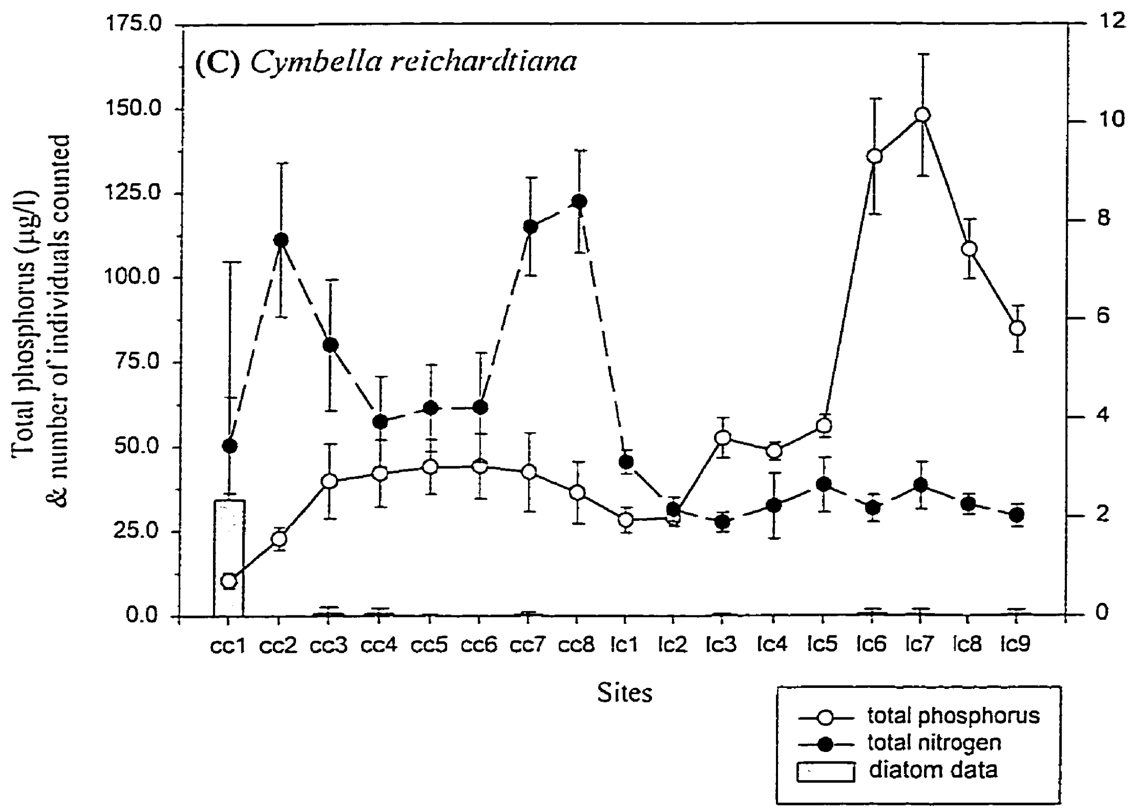


Figure 6. (*continued*)



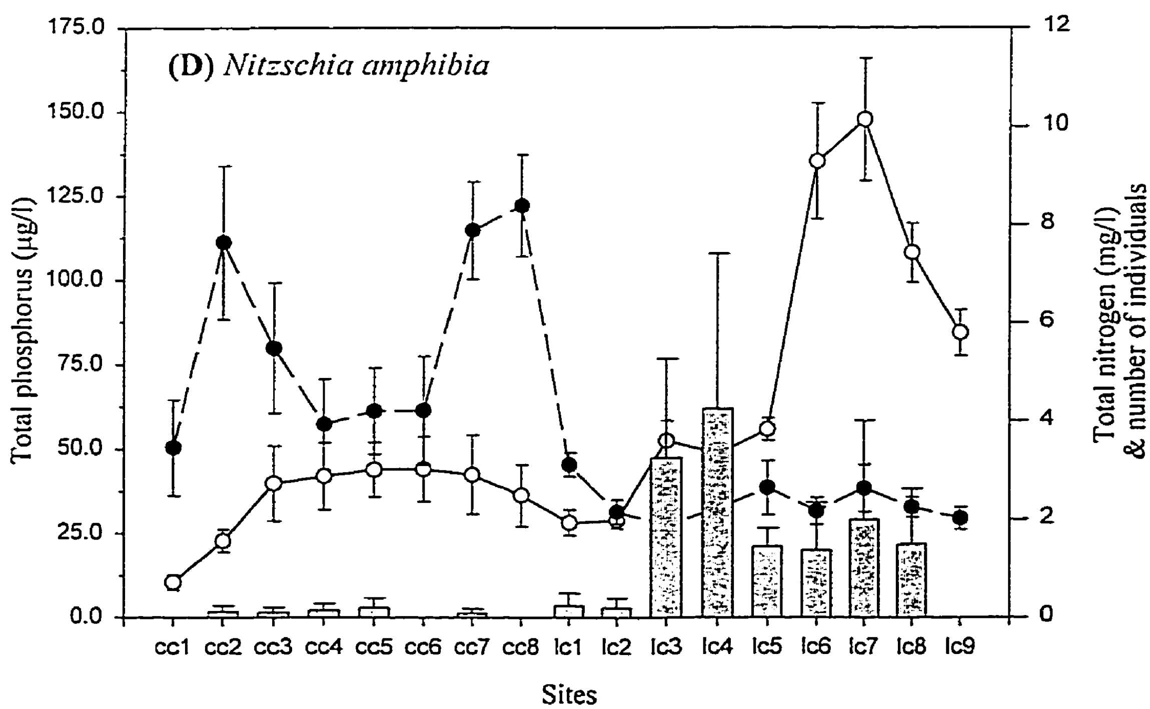
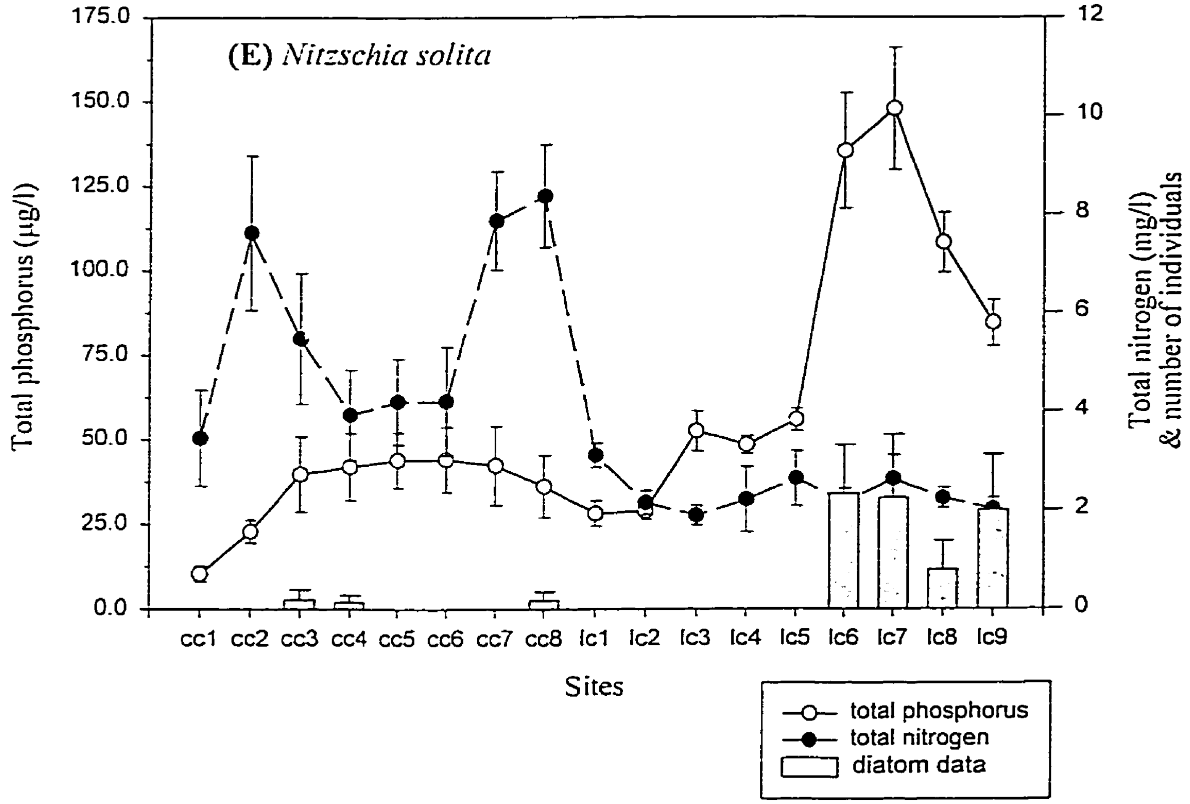


Figure 6. (*continued*)



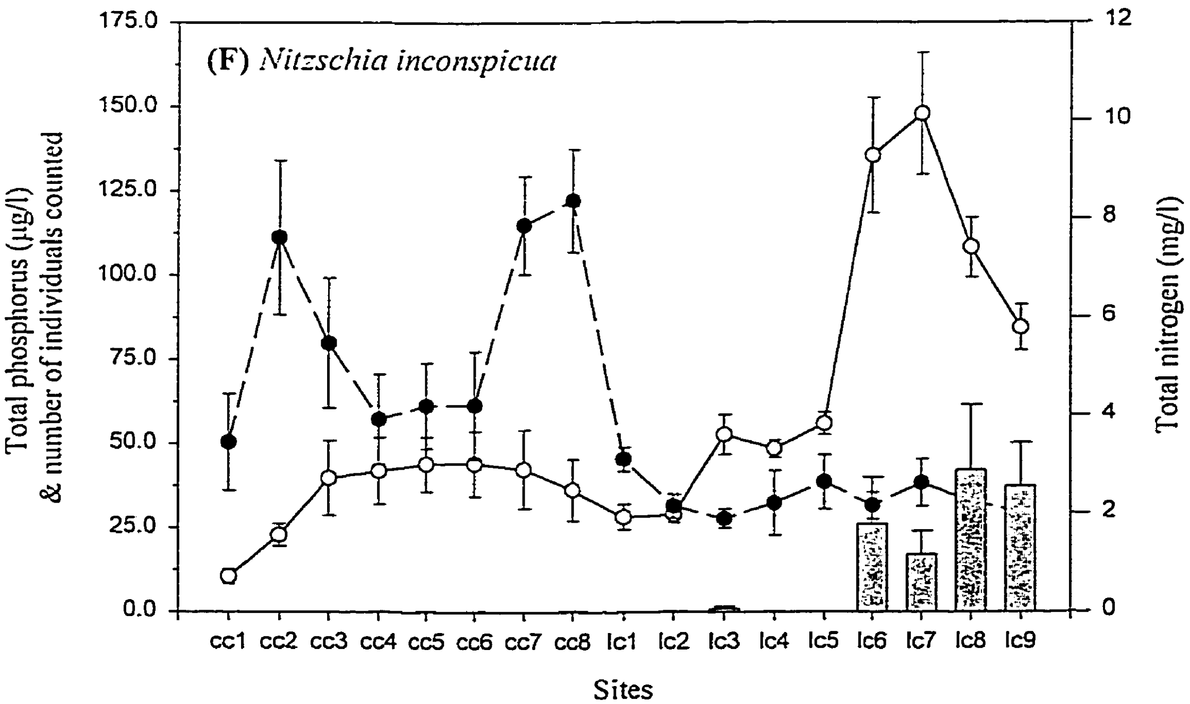
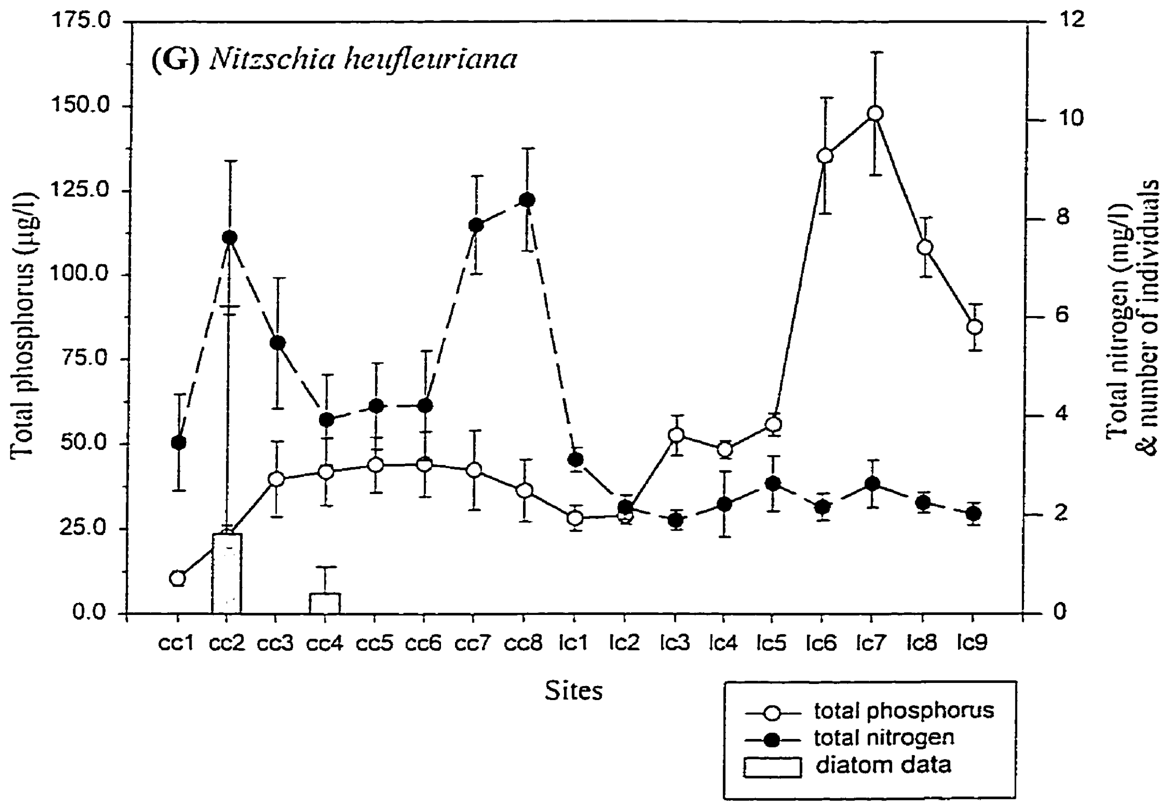
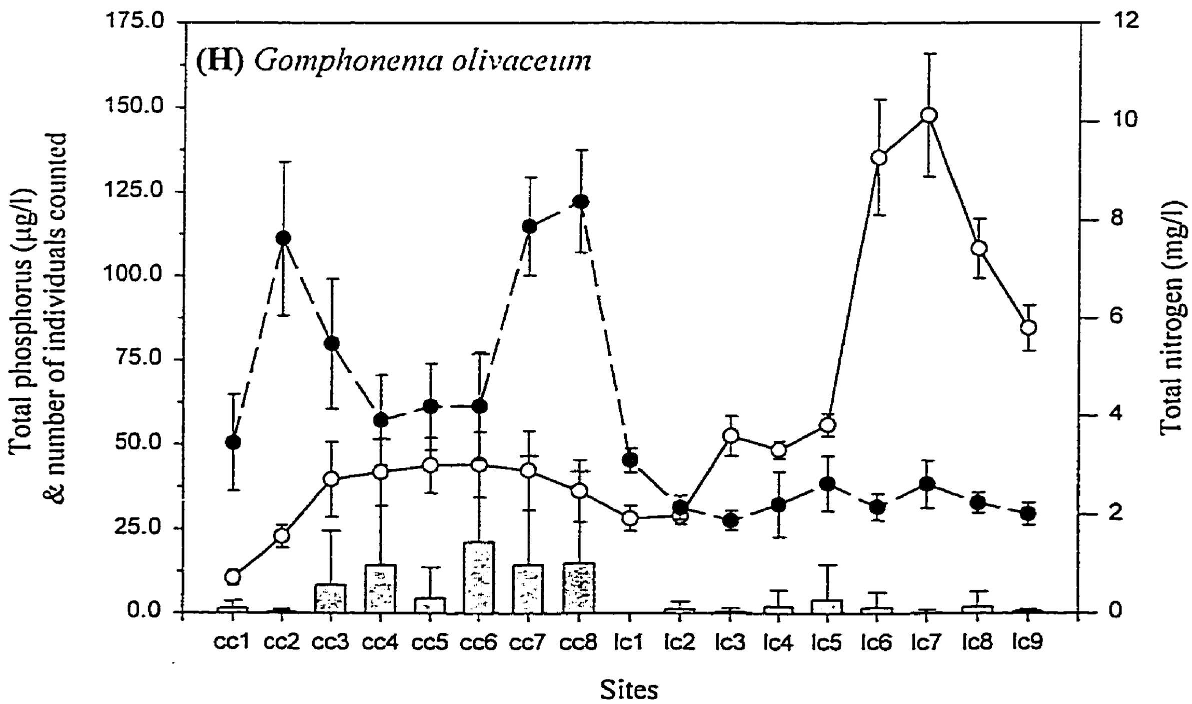


Figure 6. (*concluded*)





but predominantly at the headwater site on Carroll Creek, which was the site with the lowest measured mean TP (Fig. 6C). This species is a good indicator of low TP. *Nitzschia amphibia* was most abundant at sites on Laurel Creek (Fig 6D) and indicates low TN conditions. This species is also an indicator of high TP however, and was fairly abundant at urban sites on Laurel Creek that had high mean TP. *Nitzschia solita* was most abundant at urban sites on Laurel Creek with high mean TP (Fig. 6E) and is an indicator of high TP. To a lesser extent, however, this species was also an indicator of low TN. *Nitzschia inconspicua* was a good indicator of high TP, and was most commonly found at the high-phosphorus urban sites on Laurel Creek (Fig. 6F). *Nitzschia heufleuriana* and *Gomphonema olivaceum* had high optima of TN, but also had relatively high tolerances, denoting that they are not good indicators of TN. *Nitzschia heufleuriana* was only found at rural sites on Carroll Creek, and was most common at Carroll Creek site 2 which had a high mean TN concentration (Fig. 6G). However, this species was not found at Carroll Creek sites 7 and 8, which had the highest mean TN and TP concentrations. *Gomphonema olivaceum* was common at all sites, but was most abundant at sites on Carroll Creek that had higher mean TN than those on Laurel Creek (Fig. 6H). The counts of this species showed no relationship with TN at Carroll Creek sites.

6.6 Discussion

The results clearly demonstrate that epilithic diatoms can be related to total nitrogen and total phosphorus concentrations in Laurel Creek and Carroll Creek. Although the correlations between measured and diatom-inferred total phosphorus and total nitrogen were lower than those observed in other models, assessment indicated that, unlike in other studies where similar assessments were made, the models were reliable.

Although numerous studies have reported that nutrients, particularly phosphorus, are important for algal growth, the development of nutrient regression and calibration models has not been particularly successful (Pan et al., 1996). In these models, the coefficient of determination of regression between diatom-inferred and measured total nitrogen or total phosphorus concentration was low when compared with models relating diatoms to pH

(Battarbee, 1990). The poor performance of these models may be due to temporal variablity in nutrient concentration, particularly in streams, and the importance of other environmental variables in structuring diatom communities. This study, however, illustrates their utility in monitoring eutrophication in rivers.

The gradient of total nitrogen was small in the data set presented in this chapter, and although the gradient of total phosphorus was larger, there were relatively few samples at the low end of the range. It is likely that both models would be improved if more sites were added to increase the range, particularly at the low end. This would also be required to use the models further and construct indices of eutrophication.

I classified the sites according to OECD total phosphorus eutrophication ratings (OECD, 1982) and evaluated the performance of the total phosphorus model in terms of its ability to predict the trophic status. The model predicted mesotrophic (10-35 μg/l TP) and eutrophic (35-100 μg/l) samples correctly at a rate of 76 % and 57 % respectively. This percentage seems high given the seasonal variation in the data set. For oligotrophic (<10 μg/l) and hypereutrophic (> 100μg/l) samples, the model predicted poorly, with 20 % and 33 % correct predictions respectively. However, as stated previously, most of the samples were collected from mesotrophic and eutrophic sites which limits the ability of the model to predict the trophic status of sites at the low and high ends of the phosphorus gradient. Furthermore, excessive inputs of phosphorus under eutrophic and hypereutrophic conditions may be causing problems in using diatoms to predict concentrations at these sites. High levels of phosphorus can cause algal blooms and shifts in algal assemblage composition from dominance by diatoms to dominance by other algal groups (Schindler, 1974). At some sites during the summer months, I observed an apparent dominance of the periphyton by the green alga *Cladophora sp.* A model based solely on diatoms may not be able to predict such among-divisional shifts (Pan et al., 1996) which would limit the utility, during the summer months in particular, of the model at certain sites. Also, total phosphorus was seen to be somewhat correlated with total suspended solids indicating that measured total phosphorus might not always reflect levels that are biologically available.

A more fundamental problem with using diatoms as indicators of eutrophication is the implication that shifts of diatom species to nutrient loading may represent only an initial phase of the response to increased nutrient levels (Pan et al., 1996). It has been noted, for example, that diatom assemblages become uniform at certain phosphorus concentrations (Reavie et al., 1995). Presumably species present under high nutrient levels are tolerant of eutrophic conditions, and species composition will not respond markedly to further increases in nutrient concentrations. Because of this problem, it has been concluded that effective diatom-based inference models for total phosphorus may be limited to low and medium ranges of phosphorus concentration (Pan et al., 1996). My results somewhat contradict these observations in that the models constructed proved relatively reliable despite the high proportion of eutrophic sites in the data set.

On taking an overall average of measured and diatom-inferred total phosphorus concentrations, the model predicted trophic status (OECD, 1982) accurately for 11 out of the 17 sites sampled. Both the nitrogen and the phosphorus models predicted particularly poorly for the site on Laurel Creek downstream of Columbia Lake, lc6, at urban sites lc8 and lc9, and at Carroll Creek sites cc4 and cc5 which were located in areas of direct cattle access. It is likely that at these sites other water chemistry and physical variables were relatively more important in structuring the diatom community than total nitrogen and total phosphorus concentration. The predictability of nutrient concentrations at these sites was highly temporally variable. Successfully developing total nitrogen and total phosphorus diatom-inference models for streams in this area may force the selection of sites where other abiotic influences are not so extreme.

Nevertheless, the models constructed for these systems were more reliable than other, similar, phosphorus models developed for lakes and other stream systems in terms of their estimation of species optima (e.g. Hall and Smol, 1996; Pan et al., 1996). Diatoms were generally good indicators of total nitrogen and total phosphorus in these streams. The ecological optima of the species were high when compared with those observed in other studies on lakes (Christie and Smol, 1993; Hall and Smol, 1992 & 1996; and Reavie et al., 1995) which reflects the eutrophic nature of these streams. However, of the species found in this study, all those included in a list of phosphorus optima and tolerances published by Pan et al. (1996) for Appalachian streams were in the ranges of values presented. These were *Achnanthes minutissima*, *Achnanthes lanceolata*, *Navicula capitata*, *Navicula cryptotenella*, *Navicula venetata*, *Nitzschia palea* and *Nitzschia sociabilis*.

Growth experiments on diatoms have only been done on a limited number of species, most of which are planktonic (van Dam et al., 1994). There is thus insufficient autoecological data to confirm the observed species optima and tolerances, or to assign experimentally determined values. Certainly, the fact that the optima of these stream species, and of others listed in Pan et al. (1996), are higher than those in the lake studies outlined above indicates the need to further investigate diatom relationships to nutrients in lotic systems. It is likely that optima and tolerances vary geographically and between habitats, and that to develop effective inference models for streams, extensive measurements over various ecoregions will be required.

However, as mentioned above for total phosphorus, the measured nutrient concentrations may not necessarily reflect the amounts biologically available, and species optima may be overestimated. Species optima may also be modified because changes in nutrient levels might indirectly influence diatoms. Observed nutrient concentrations might indirectly alter the composition of diatom communities by increasing competition with other algal groups such as green and blue-green algae (Schindler, 1974), and by modifying the structure of macroinvertebrate populations and the balance between autrotrophs and heterotrophs (Allan, 1995). Furthermore, if the phosphorus is bound to suspended particles, a reduction in light penetration to the substrate, due to attenuation by particulate material in the water column, might be correlated with elevated levels of phosphorus. In fact, it might be these influences that cause measurable shifts in diatom community composition that are, even if not directly, related to nitrogen and phosphorus concentrations. Without these influences, increased nutrient concentrations might not measurably affect diatom community structure at eutrophic sites where algae are already adapted to high nutrient conditions.

6.7 Conclusions

Relationships between diatoms and total nitrogen and total phosphorus in Laurel Creek and Carroll Creek were sufficiently strong to develop weighted-averaging regression and calibration models for inferring stream water concentrations of these nutrients. These models were accurate within ± 2.4 μg/l for total phosphorus and ± 2 mg/l for total nitrogen.

Based on an evaluation of the goodness of fit with and without bootstrapping, the total nitrogen and total phosphorus models were found to be relatively robust and reliable. The models performed better than other nutrient models for which similar assessments were made. Diatoms can therefore be used to monitor total nitrogen and total phosphorus in these streams.

The models were improved when seasonal variation in the data was removed by using average water quality and diatom data. This indicates that reliable models could be constructed for these streams by correlating mean values of frequent total nitrogen and total phosphorus measurements with diatom community composition. However, in order to create usable models and diatom indices of eutrophication in the Grand River watershed, more samples from oligotrophic sites are required to improve predictions of low nutrient concentrations. Functional models might also require sites where other environmental variables excessively confound the influence of total nitrogen and total phosphorus on diatoms to be excluded. It is likely though, that using mean values to reduce temporal variability in nutrient concentrations will improve predictions for such sites as well.

Overall, epilithic diatoms can clearly be related to total nitrogen and total phosphorus concentrations in Laurel Creek and Carroll Creek and have utility as monitors of stream eutrophication in the Grand River watershed.

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7. SUMMARY AND CONCLUSIONS

Epilithic diatom and macroinvertebrate community assessment and export coefficient modeling (ECM) both provide useful, but very different, methods of evaluating the impact of watershed land use and nutrient loading on Laurel Creek and Carroll Creek.

Using the ECM approach, I constructed models for predicting phosphorus and nitrogen loading to the streams. The phosphorus models proved reliable, and provide a simple, inexpensive approach to evaluate phosphorus loading to these streams. Moreover, there is potential for developing useful models for predicting nitrogen loads to streams in this area, and using this approach to estimate nutrient loading to streams in the Grand River watershed, with similar land use and watershed characteristics, under various land development and management scenarios. Such evaluation can include an assessment of proposed nutrient control strategies. Through this approach, nutrient sources are identified and loadings from each source quantified.

However, at present the ECM approach does not incorporate any in-stream processes or impacts on the biota. Yet if our desire is to maintain healthy, diverse biological communities, it is more appropriate to monitor the aquatic community rather than physicochemical variables only. To determine whether these nutrient loads affect the structure and functioning of stream communities, some measure of the stream biota must be included in analysis. There were measurable relationships between both watershed land use and water quality and structure of epilithic diatom and macroinvertebrate communities in Laurel Creek and Carroll Creek, indicating that both groups of organisms could be effectively used as monitors of catchment conditions and water quality. Furthermore, relationships between diatoms and total phosphorus and total nitrogen in these streams were sufficiently strong to develop weighted-averaging regression and calibration models for inferring stream nutrient concentrations of these nutrients. Diatoms therefore have utility as monitors of eutrophication in the Grand River watershed.

The advantage of using biological monitoring over the empirical nutrient loading model, or simply taking physicochemical measurements, is that aquatic organisms integrate all of the influential biotic and abiotic parameters in their habitat and provide a continuous record of environmental quality. Although the mechanisms responsible for decline or local extinction of populations may be difficult to define, the populations' responses give unambiguous signals about the quality of the habitat (Lowe and Pan, 1996). As outlined in Chapter 2, there are many pollutants other than nitrogen and phosphorus in urban and agricultural runoff that may potentially degrade water and habitat quality. Examples include pesticides, heavy metals, road salts and petroleum hydrocarbons (Marsalek et al., 1997; Skinner et al., 1997). As well as developing specific indicators of nitrogen and phosphorus therefore, biological monitoring has utility for providing information on the overall impact of land use and water quality on these communities, and for indicating sites where more intensive investigation of pollution sources is required.

However, although there were measurable relationships between the biota and both water quality and land use variables, and diatoms in particular were useful indicators of eutrophication, since the biota respond to a range of biotic and abiotic variables such correlations do not demonstrate causality. To demonstrate causal relationships between organisms and water quality there is a need for extensive experimental data (Cox, 1991). In terms of evaluating eutrophication, such monitoring does not quantify sources of nutrients or provide a means for quantitatively assessing strategies for controlling and minimizing nitrogen and phosphorus loads.

Given the nature of ECM and biological monitoring, it seems that to effectively monitor eutrophication, evaluate various land use and land management scenarios, and quantify nutrient loads while maintaining an overall picture of stream heath, both approaches should be employed. Presumably, if export coefficient models were constructed for sufficient sites in the Grand River watershed, relationships could be developed between the "driving variables" nitrogen and phosphorus and "derivative variables" like trophic status scores or indices developed using diatoms and/or macroinvertebrates, or estimates of peak periphyton biomass (sensu Johnes et al., 1994). In this way, nutrient concentrations predicted using export coefficient models could be used to predict impacts on the structure and functioning of stream communities.

7.1 Recommendations towards developing a framework for monitoring eutrophication in the Grand River watershed

1. ECM provides a reliable, simple, inexpensive approach to evaluate phosphorus and nitrogen loading to rivers and has potential for application in the Grand River watershed. Export coefficients used in a model constructed to determine phosphorus loading to Laurel Creek proved reliable on independent assessment, and performed well when used for Carroll Creek. It is likely that these coefficients can be used in other areas of the Grand River watershed with similar land use and watershed characteristics. The nitrogen export coefficients, however, were very different for the Laurel Creek and Carroll Creek models, indicating that these models may be poor predictors of nitrogen loading, and that these coefficients are not widely applicable in other areas of the Grand River watershed. To develop this approach further, it it would be necessary to construct models for other subwatersheds, using the same coefficients, and evaluate their performance. Such investigation will identify whether the same coefficients express the export of nutrients from other areas. In order to do this effectively, watersheds with long-term water chemistry and discharge records should be chosen, with varying proportions of urban and agricultural land use. Given the complexity of internal lake processes that influence nutrient concentrations, rivers without reservoirs on them should ideally be used. However, since many impoundments exist in the Grand River watershed, useful export coefficient models will eventually have to include reservoir-altered systems. Measurements at the inlet and outlet of a number of reservoirs should be made to allow the calculation of nutrient retention/release rates that can be incorporated into export coefficient models.

2. Epilithic diatom and macroinvertebrate community composition could be related to water chemistry and watershed land use in Laurel Creek and Carroll Creek. Such

relationships should be evaluated at other sites in the Grand River watershed, with varying proportions of forest, agricultural and urban land cover in their catchments. Partitioning variance in the stream assemblages based on various land uses would then enable the use of these communities to develop biological signatures of watershed land use. Furthermore, phosphorus and nitrogen were significantly correlated with the distribution of diatoms and invertebrates at the sites investigated indicating their utility as indicators of eutrophication.

3. The relationship between diatoms and total nitrogen and total phosphorus in Laurel Creek and Carroll Creek were sufficiently strong to develop weighted-averaging regression and calibration models for inferring stream water concentrations of these nutrients, indicating that diatoms can be used to monitor total nitrogen and total phosphorus in these streams. Moreover, Rott et al. (1998) found that diatom analysis discriminated between the impacts on river water quality of treated urban wastewaters and diffuse nutrient sources from farmland in the Grand River. Thus, diatom-based methods of assessment clearly have utility for monitoring eutrophication throughout the Grand River watershed. Using the weighted averaging techniques described in Chapter 6, reliable inference models could be constructed for sites in the Grand River watershed to infer total nitrogen and total phosphorus concentration based on epilithic diatom community structure. To develop reliable models, mean values of frequent total nitrogen and total phosphorus measurements should be correlated with diatom community structure. Sites should be selected that are distributed homogeneously along a gradient from low to high concentrations of these nutrients, in particular sufficient samples are required from oligotrophic sites for useful predictions of low nutrient conditions. Finding oligotrophic sites will present a challenge given the extent of agricultural and urban land use throughout the Grand River watershed, and the domestic sewage discharged along the length of the river. Blue Springs Creek, a stream in the Grand River watershed that flows into the Eramosa River just south of Rockwood, is a one possibility (Peter Mason, GRCA, pers. comm.) as are the headwaters of the Grand River north of Luther Lake. Functional diatom inference models might also require the exclusion of sites where other environmental variables

excessively confound the influence of total nitrogen and total phosphorus on diatoms. Examples identified in this study were those in urban areas and sites where cattle were allowed direct access to the stream. However, using mean water quality values to reduce temporal variability in nutrient concentrations might improve predictions for such sites. Overall, the results of diatom-inference modeling could be used to develop calibration models to infer concentrations of nitrogen and phosphorus, or could be used to develop an index of eutrophication.

4. Indices developed using diatoms or macroinvertebrates, could be related to mean annual total nitrogen and total phosphorus concentrations predicted using ECM for sites in the Grand River watershed. Nutrient concentrations predicted empirically could thus be used in turn to predict impacts on the structure and functioning of stream communities. Furthermore, these relationships could be used to assess the impact of proposed development, changes in land use, or nutrient control strategies, on stream health as determined by the biota.

5. Overall, these approaches would further our knowledge of the impact of eutrophication on streams in the Grand River watershed, and would provide valuable information on nonpoint sources of nutrients to the river. These sources are inadequately incorporated in the current Grand River Simulation Model (CH2M, 1996), a model used to predict the impact of nutrients on the Grand River by simulating the growth of aquatic plants and algae caused by these loads, and the consequent sags in dissolved oxygen concentration. Improving estimates of nonpoint sources of nitrogen and phosphorus to the Grand River for use in water resources planning and management are essential if eutrophication is to be controlled.

7.2 Conclusions

1. ECM provided a simple, reliable approach to evaluate phosphorus loading to Laurel Creek and Carroll Creek. Both models were calibrated with ± 3 % for the 1995-1996 water year, and when the Laurel Creek model was objectively assessed by running it

for the 1977-1978 water year. the predicted load was within ± 7 % of the observed load. The Carroll Creek model was constructed using the export coefficients used for Laurel Creek. with some modification to separate row and non-row crops and account for the intensity of grazing in the watershed. It is likely that these phosphorus coefficients will perform well when assessed for other areas in the Grand River watershed of similar land use and watershed characteristics.

2. The Laurel Creek export coefficient model provided a simple tool for forecasting, in terms of phosphorus loading. the impact of future urban development planned for the Laurel Creek watershed. Several urban best management practice designs were evaluated. and it was determined that phosphorus removal will have to be applied to all the urban runoff from the watershed to appreciably reduce concentrations in Laurel Creek. Overall. this approach proved useful for evaluating the impact of phosphorus control strategies on mean annual phosphorus concentration in Laurel Creek.

3. The export coefficients used in the models constructed to predict nitrogen loads to Laurel Creek and Carroll Creek were very different in the two watersheds, and these models may be poor predictors of nitrogen loading. The total nitrogen concentration predicted for Laurel Creek was within ± 6 % of the observed concentration when objectively assessed for the 1977-1978 water year. However, since the coefficients were so different in the Carroll Creek model it is clear that they are not widely applicable to other areas in the Grand River watershed. The higher concentrations of nitrogen measured in Carroll Creek were most likely due to several factors. The intensity of agriculture of Carroll Creek, causing over-fertilization, groundwater contamination, and runoff in tile drains, as well as higher precipitation and runoff and a greater rural population serviced by septic tanks, are likely explanations. These, together with the possibility for increased rates of denitrification in Laurel Creek, are all plausible reasons. Since these inputs were not measured and incorporated in the model directly, they are reflected in the higher coefficients selected for crops grown in the Carroll Creek watershed.

4. Evaluation of macroinvertebrates and periphyton in Laurel Creek indicated that the stream has been severely impacted by land use in the watershed and by the presence of several reservoirs in the system. Urban and agricultural land uses in the Laurel Creek watershed differentially influence water quality. which in turn influence the structure and functioning of macroinvertebrate and periphyton communities. The effects of development in the watershed are exacerbated by the presence of several impoundments on the creek, in particular Laurel Creek Reservoir and Columbia Lake. Higher levels of total phosphorus, total suspended solids, biological oxygen demand and conductivity were observed for urban sites. as were higher summer temperatures. These water quality parameters, together with habitat alterations resulting from flow regulation downstream of the impoundments and the clearing of land for development, have had fundamental effects on the benthic community of Laurel Creek. If the watershed management strategy (GRCA, 1993) is not implemented, Laurel Creek habitat and water quality will continue to deteriorate with a concomitant change in the resident fauna and flora.

5. The taxonomic structure of epilithic diatom and macroinvertebrate communities in Laurel Creek and Carroll Creek was related to both water chemistry and watershed land use. My findings indicate that these communities can be used as indicators of water quality and land use. Furthermore, these observations clearly demonstrate the importance of watershed land use characteristics as determinants of stream biotic communities and their utility as indicators of catchment conditions. Although land use and water chemistry were independently related to diatoms and macroinvertebrates, a close link was observed between land use, water chemistry and the biota. Studies elsewhere have found that land use patterns strongly influenced variation in stream macroinvertebrate assemblage structure (Quinn et al., 1997; Richards et al., 1996). My study outlines how surrounding land use strongly influenced variation in diatom as well as macroinvertebrate community composition in the streams studied, indicating that both groups of organisms can be used effectively as monitors of watershed land use.

6. Relationships between diatoms and total nitrogen and total phosphorus in Laurel Creek and Carroll Creek were sufficiently strong to develop weighted-averaging regression and calibrations models for inferring stream water concentrations of these nutrients. These were accurate within ± 2.4 μg/l for total phosphorus and ± 2 mg/l for total nitrogen. The models were found to be reliable based on an evaluation of the goodness of fit with and without bootstrapping, and performed better than other nutrient models for which similar assessments were made. Models were improved when seasonal variation was removed by using average water quality and diatom data. Overall, epilithic diatoms can clearly be used to monitor total nitrogen and total phosphorus in these streams.

7. The results of ECM and bioassessment could be related, and nutrient concentrations predicted empirically could thus be used further to predict impacts on the structure and functioning of stream communities. Furthermore, these relationships could be used to assess the impact of proposed development, changes in land use or nutrient control strategies, on stream health as determined by the biota. These approaches have utility for evaluating eutrophication, in particular nonpoint sources of nutrients, in the Grand River watershed.

7.3 References

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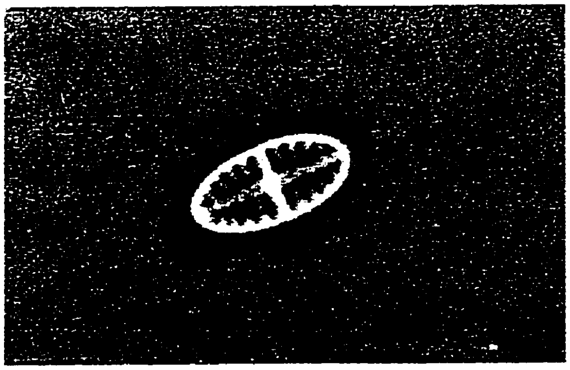
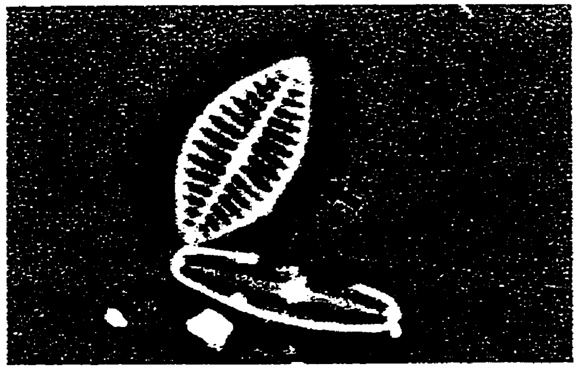
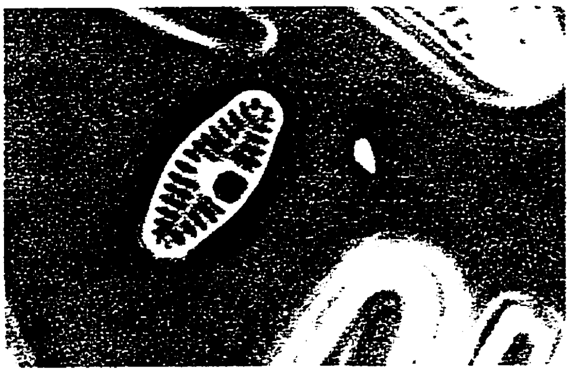
Appendix 1
Photographs of selected diatom valves
from Carroll Creek and Laurel Creek rock scrapings



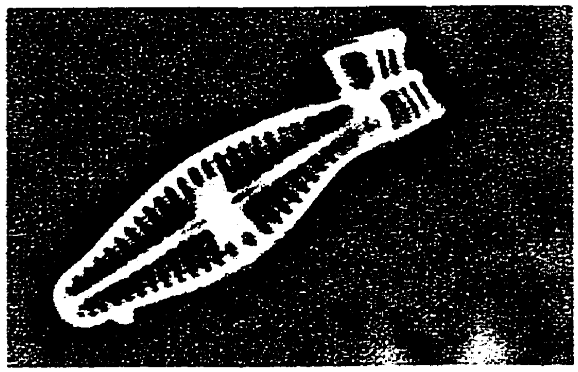
Achnanthes conspicua A. MAYER
Length: 8.0um



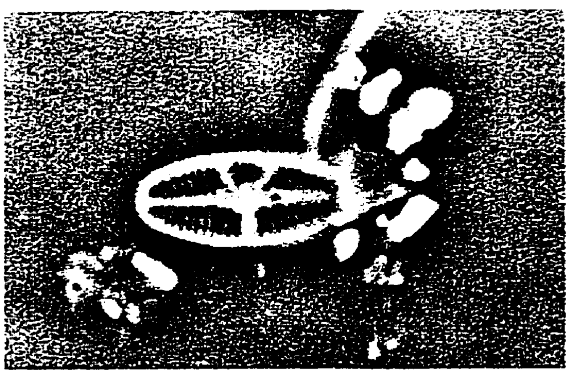
Achnanthes clevei GRUNOW
Length: 8.8um



Achnanthes lanceolata (BRÉBISSON) GRUNOW
Length: 8.8um
Side without raphe

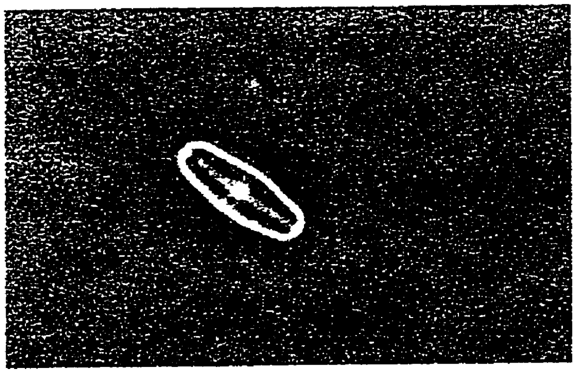


Achnanthes lanceolata (BRÉBISSON) GRUNOW
Length: 16.0um
Side with raphe

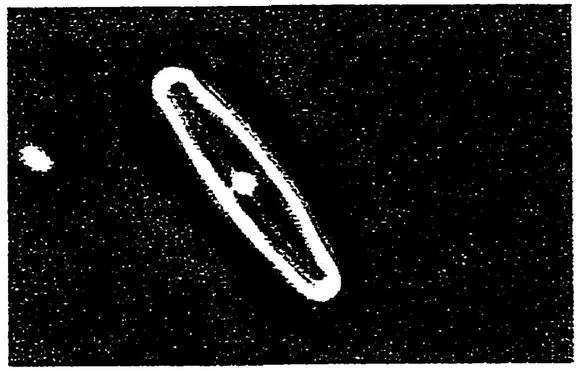


Achnanthes lauenbergiana HUSTEDT
Length: 9.6um
Side without raphe

Achnanthes lauenbergiana HUSTEDT
Length: 9.6um
Side with raphe

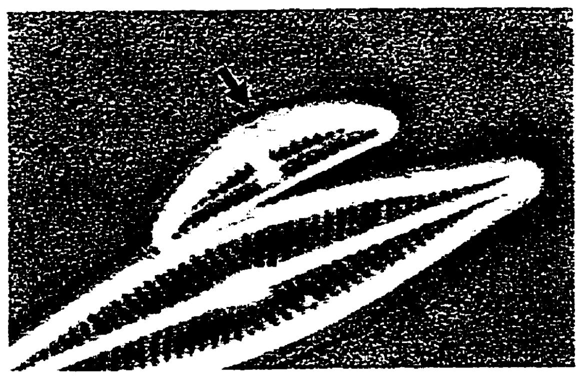


Achnanthes minutissima KŪTZING
Length: 7.0um

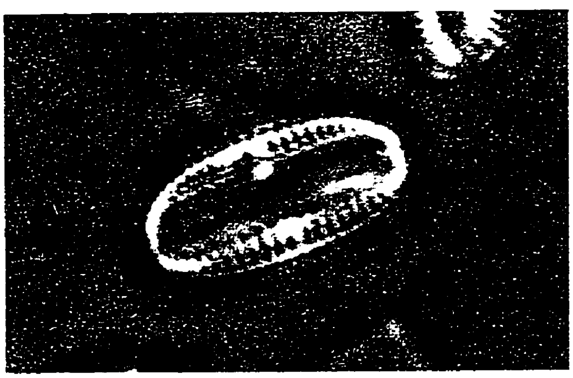


Achnanthes minutissima KŪTZING
Length: 13.6um

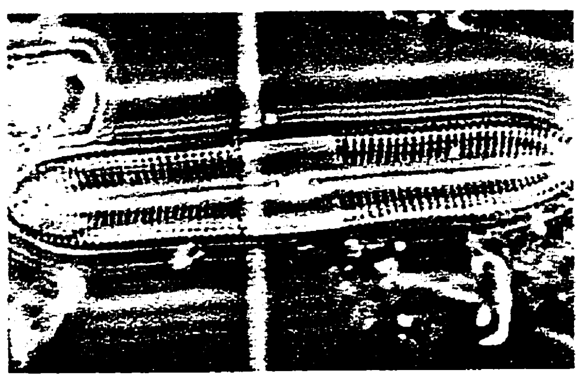
Achnanthes minutissima KŪTZING
Length: 7.0um



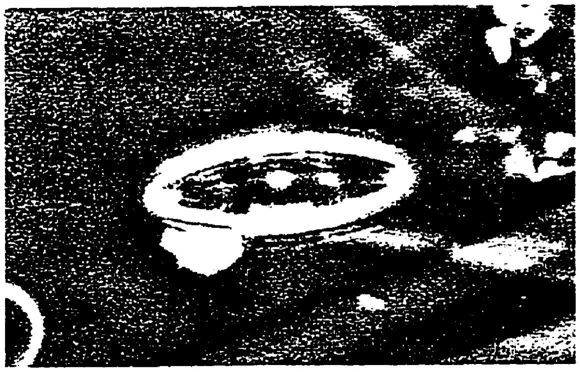
Amphora pediculus (KŪTZING) GRUNOW
Length: 11.4um



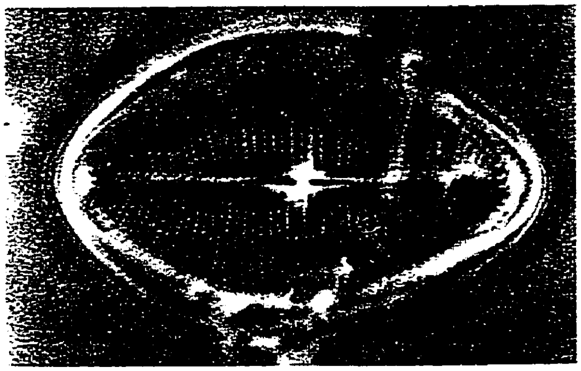
Amphora pediculus (KŪTZING) GRUNOW
Length: 12.8um



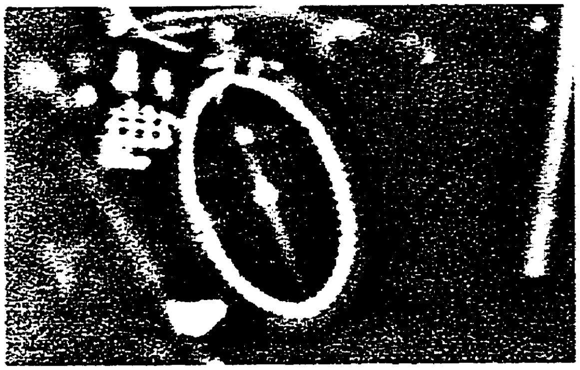
Caloneis bacillum (GRUNOW) CLEVE
Length: 37.6um



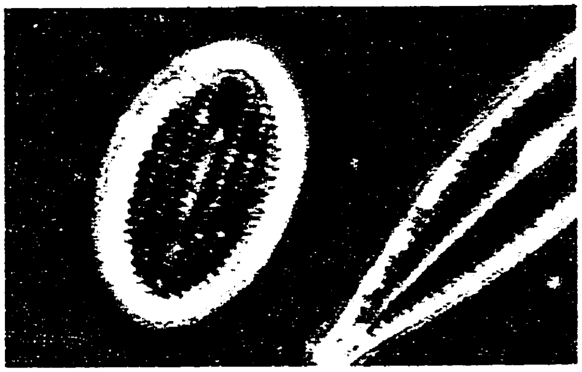
Caloneis bacillum (GRUNOW) CLEVE
Length: 12.0um



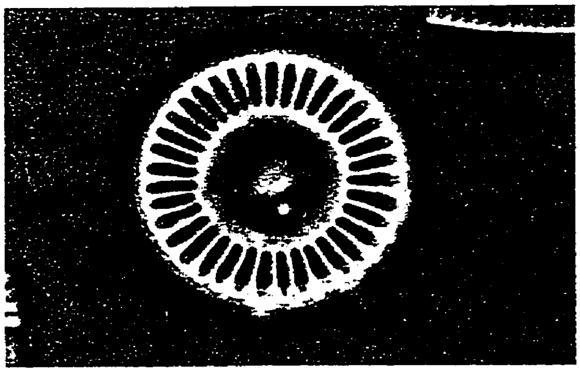
Cocconeis pediculus EHRENBERG
Length: 30.0um



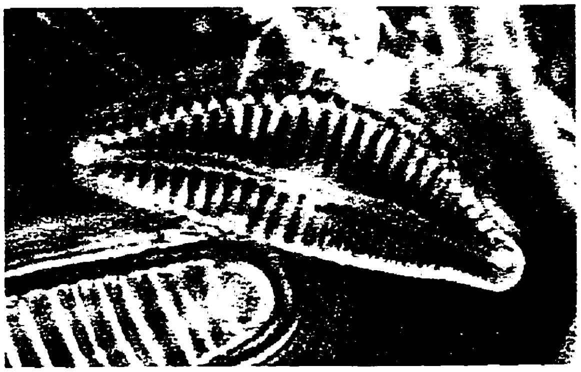
Cocconeis placentula EHRENBERG
Length: 12.8um



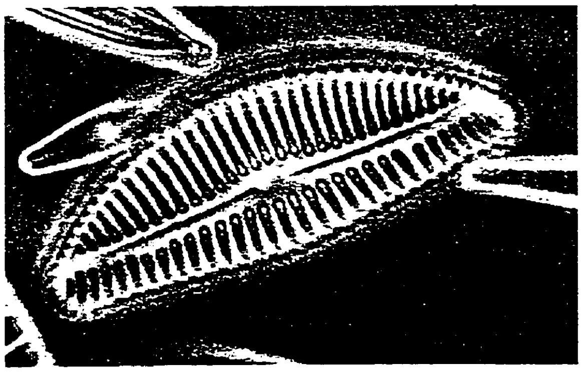
Cocconeis placentula var *euglypta* EHRENBERG
Length: 15.4um



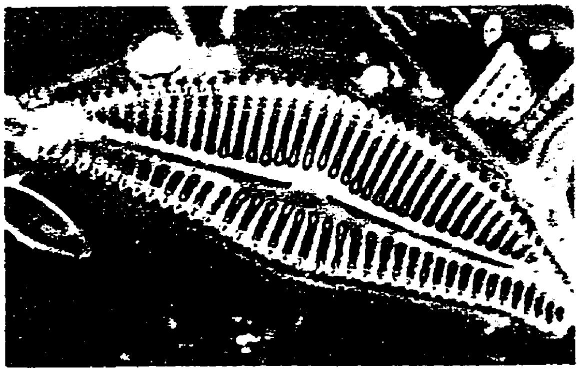
Cyclotella menenghiniana KÜTZING
Length: 16.0um



Cymbella affinis KÜTZING
Length: 21.6um

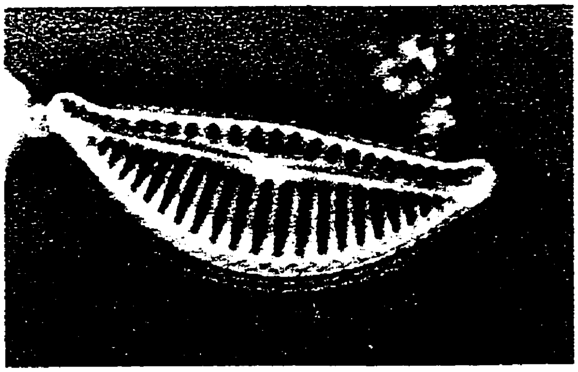


Cymbella caespitosa (KÜTZING) BRUN
Length: 32.0um

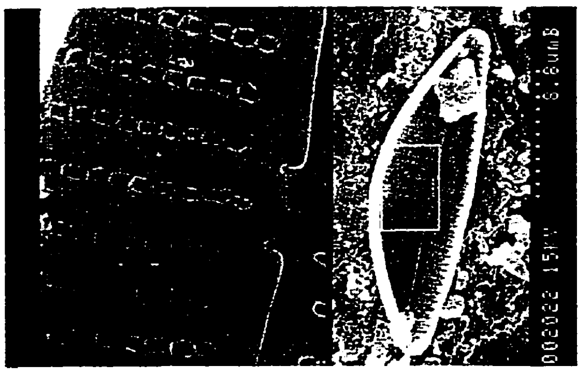


Cymbella prostrata (BERKELEY) BRUN
Length: 37.6um

Cymbella reichardtii KRAMMER
Length: 8.0um

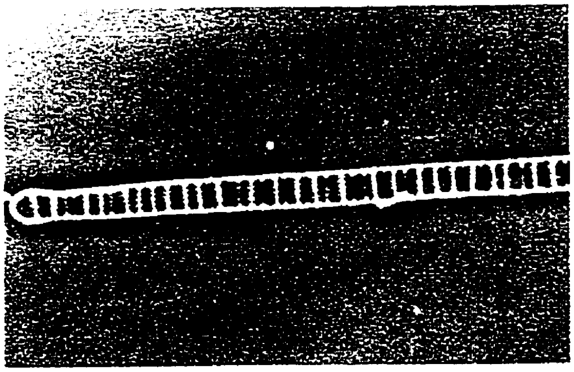


Cymbella silesiaca BLEISCH
Length: 22.0um Width: 7.0um

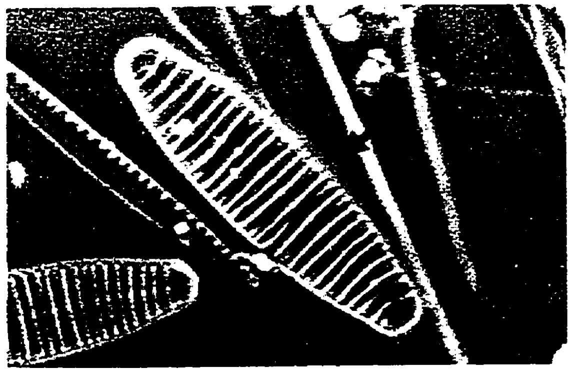


Cymbella silesiaca BLEISCH

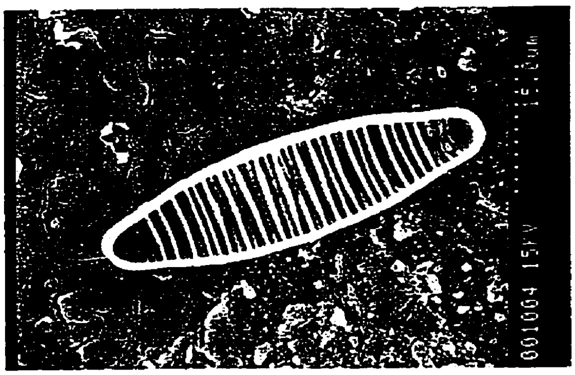
Cymbella sinuata GREGORY
Length: 13.6um



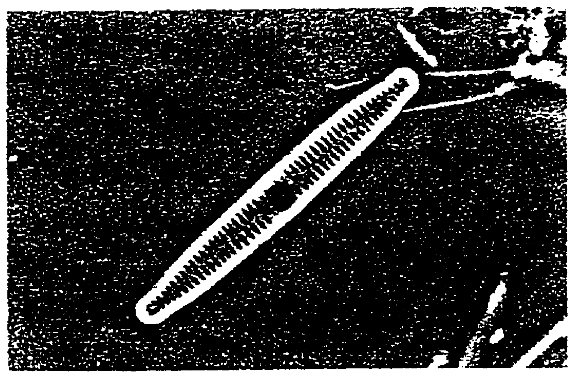
Diatoma tenuis AGARDH
Length: 56.0um



Diatoma vulgaris BORY
Length: 39.0um



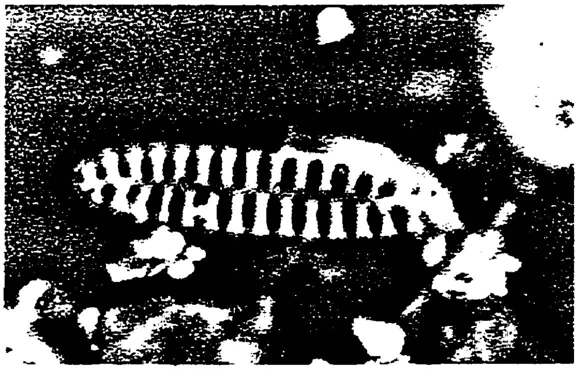
Diatoma vulgaris BORY



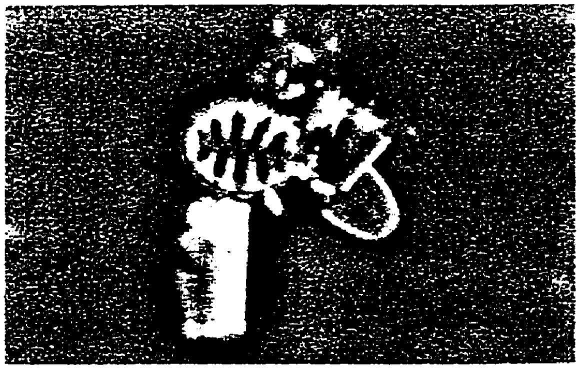
Fragilaria capucina DESMAZIÈRES
Length: 34.0um

Fragilaria construens (EHRENBERG) GRUNOW
Length: 12.0um

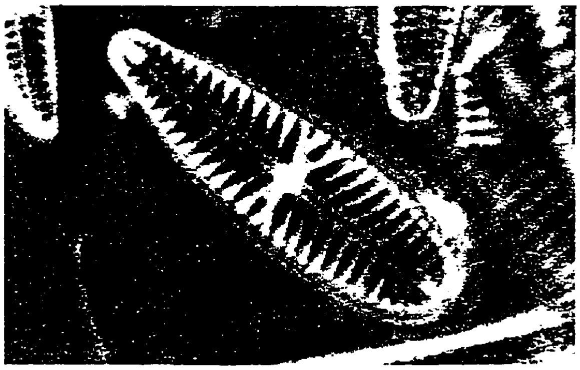
Fragilaria construens (EHRENBERG) GRUNOW
Length: 8.0um



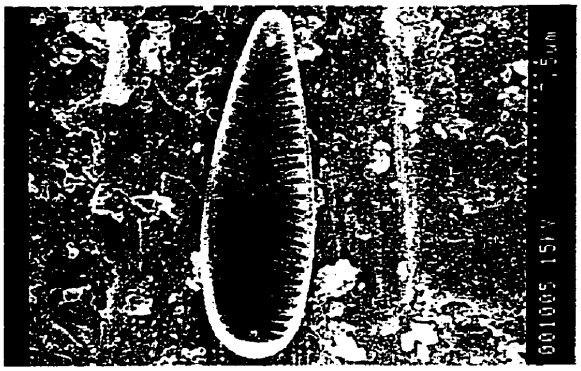
Fragilaria pinnata EHRENBERG
Length: 16.8um



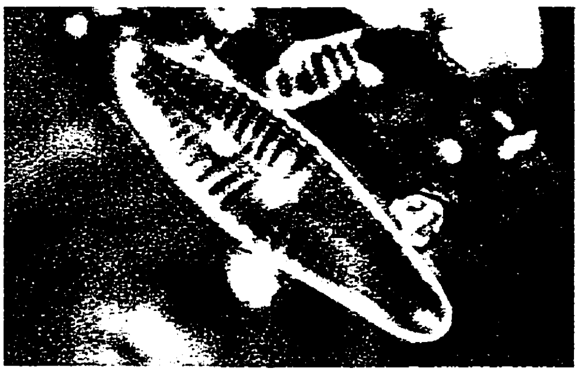
Fragilaria pinnata EHRENBERG
Length: 5.6um



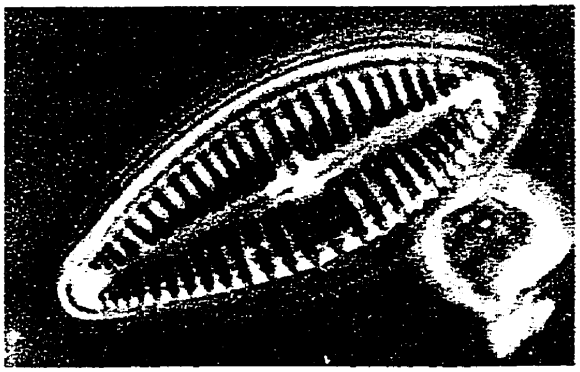
Gomphonema olivaceum var *olivaceum* (HORNEMANN) BRÉBISSON
Length: 12.0um



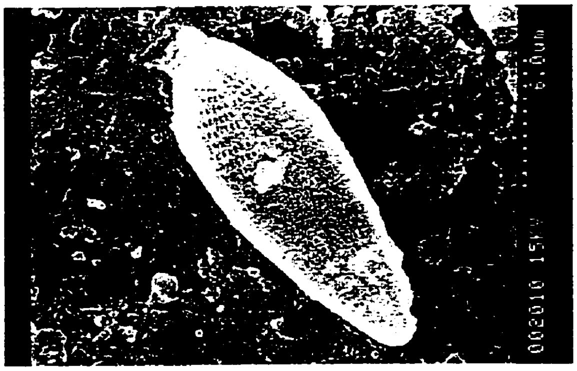
Gomphonema olivaceum var *olivaceum* (HORNEMANN) BRÉBISSON



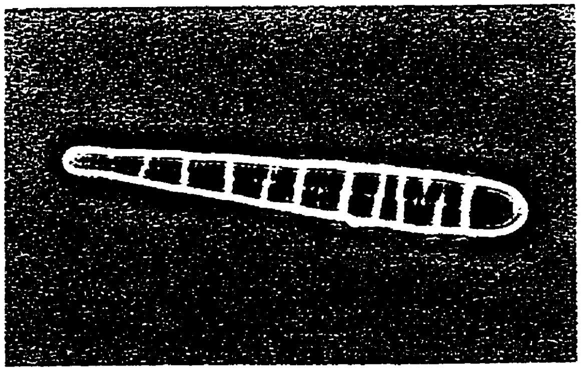
Gomphonema parvulum KÜTZING
Length: 20.0um Width: 6.0um



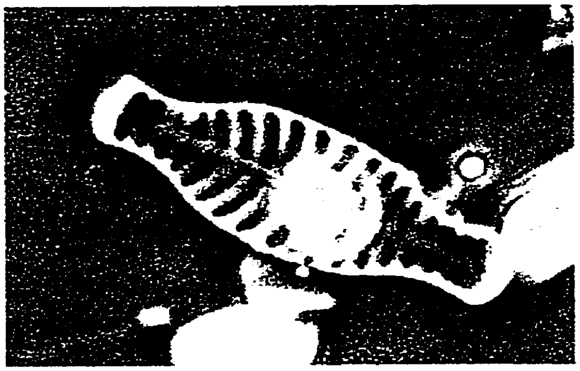
Gomphonema parvulum KÜTZING
Length: 22.0um Width: 9.0um



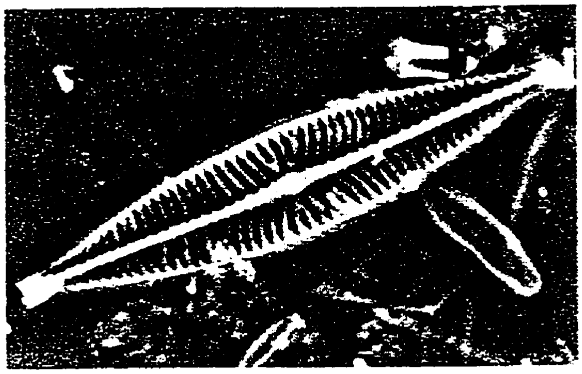
Gomphonema parvulum KÜTZING



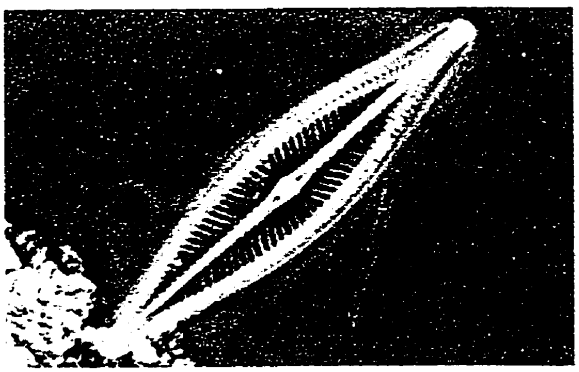
Meridion circulare (GRÉVILLE) AGARDH
Length: 44.0um



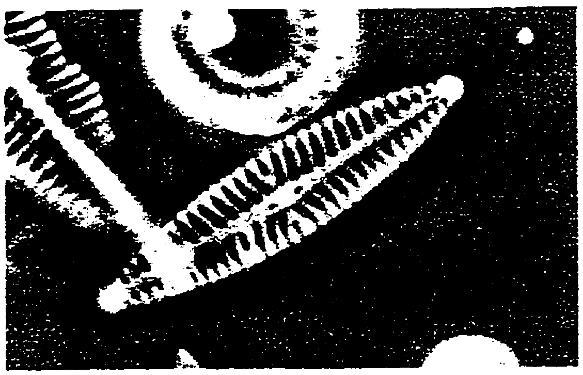
Navicula capitata EHRENBERG
Length: 20.0um



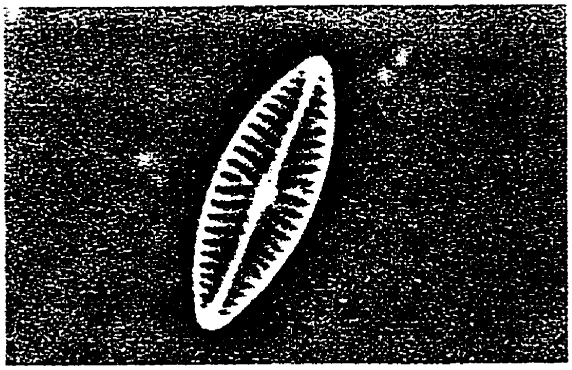
Navicula capitatoradiata GERMAIN
Length: 37.6um



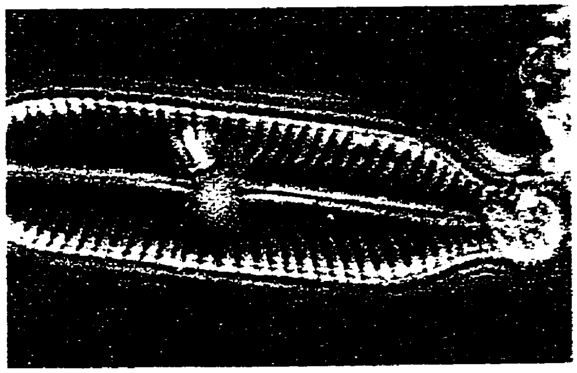
Navicula cryptocephala KÜTZING
Length: 46.4um



Navicula cryptotenella LANGE-BERTALOT
Length: 20.0um

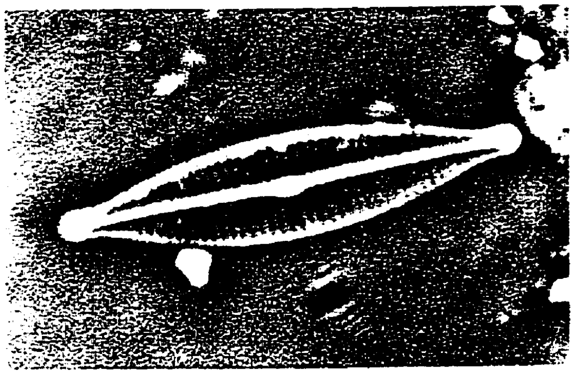


Navicula cryptotenella LANGE-BERTALOT
Length: 13.6um

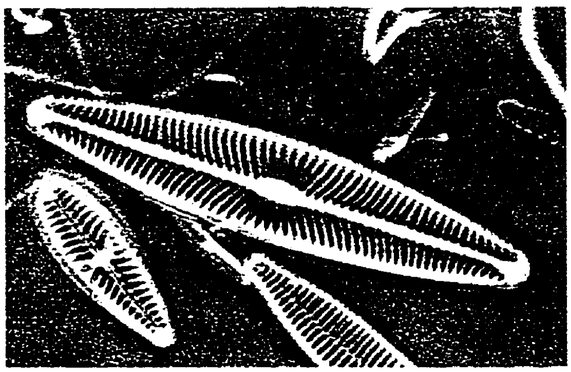


Navicula eliginensis (GREGORY) RALFS
Length: 36.0um

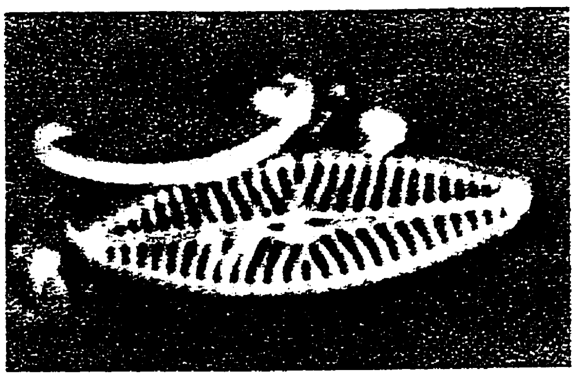
Navicula eliginensis (GREGORY) RALFS
Length: 26.4um



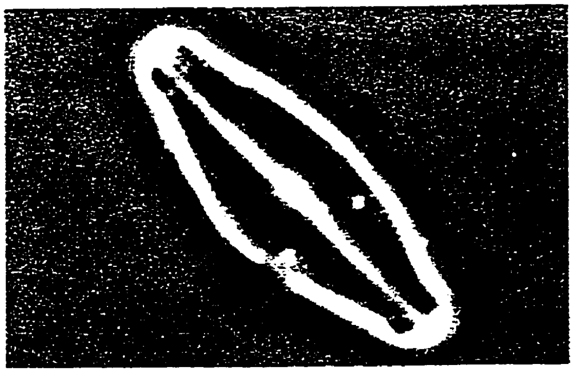
Navicula gregaria DONKIN
Length: 24.0um Width: 6.0um



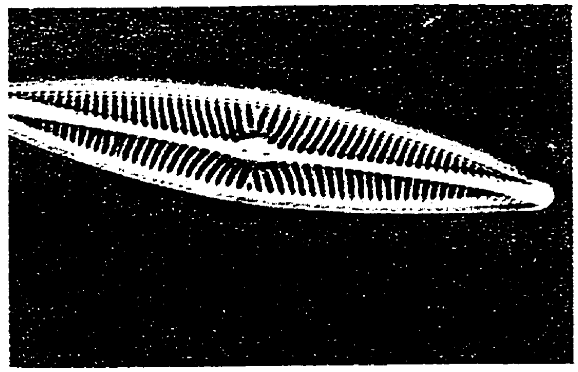
Navicula lanceolata (AGARDH) EHRENBERG
Length: 44.8um



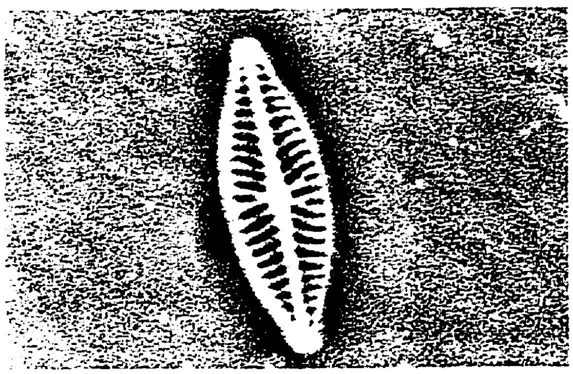
Navicula sp. aff. *N. meniscula* SCHUMANN
Length: 20.0um



Navicula pupula KÜTZING
Length: 20.0um



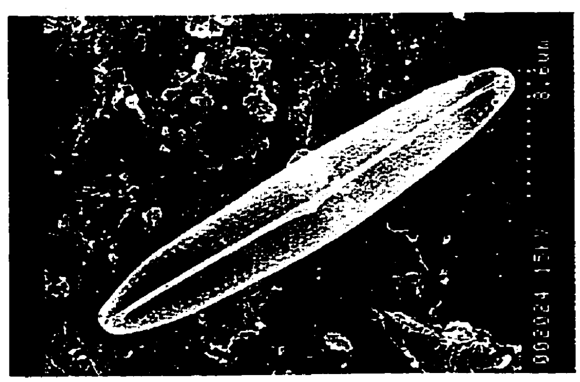
Navicula radiosa KÜTZING
Length: 50.4um



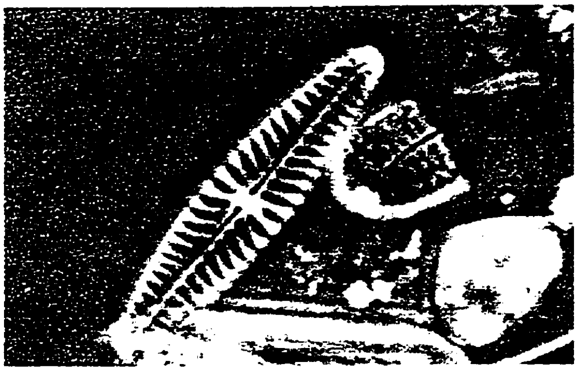
Navicula reichardtiana LANGE-BERTALOT
Length: 15.0um

Navicula saprophila LANGE-BARTELOT & BONIK
Length: 7.2um

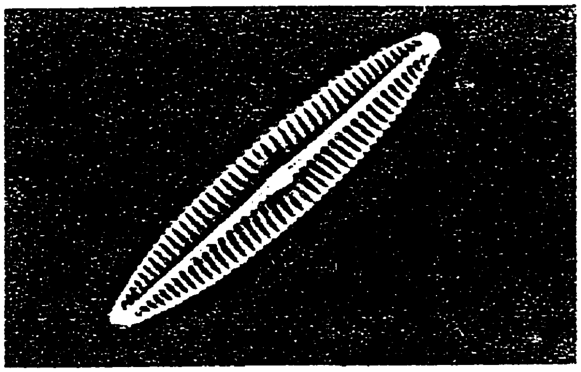
Navicula schroeteri MEISTER
Length: 34.0um



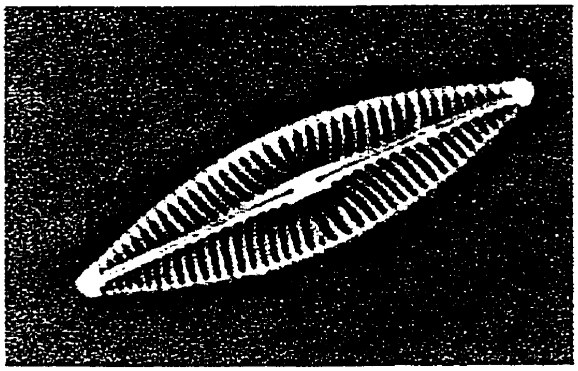
Navicula schroeteri MEISTER



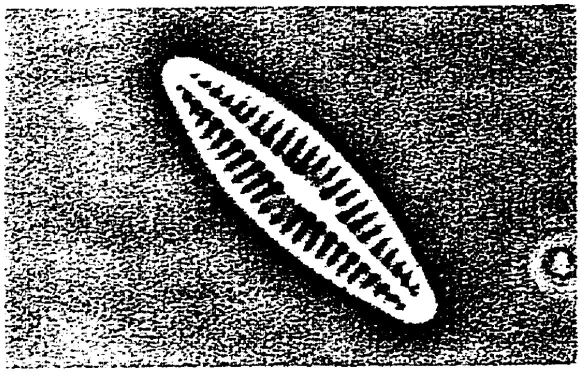
Navicula sp. aff. *N. tenelloides* HUSTEDT
(possibly *N. seibigii* LANGE-BERTALOT)
Length: 24.8um



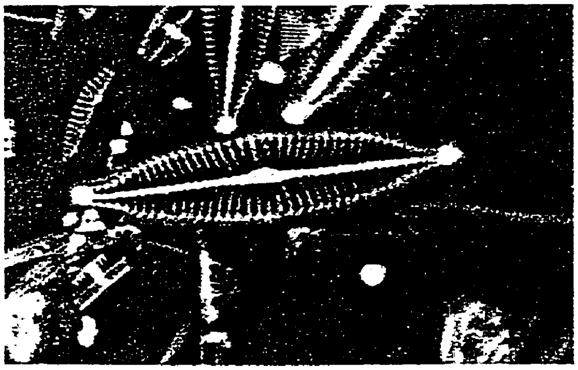
Navicula tripunctata (O.F. MÜLLER) BORY
Length: 40.0um



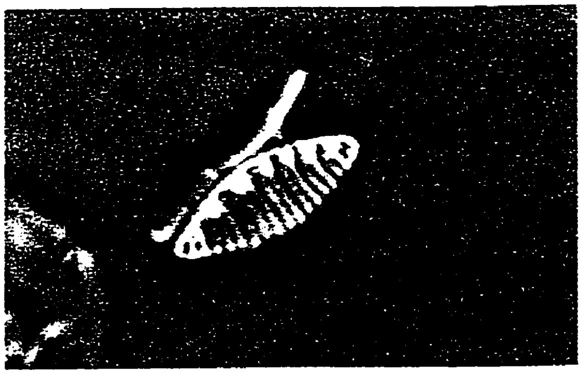
Navicula trivialis LANGE-BERTALOT
Length: 31.0um



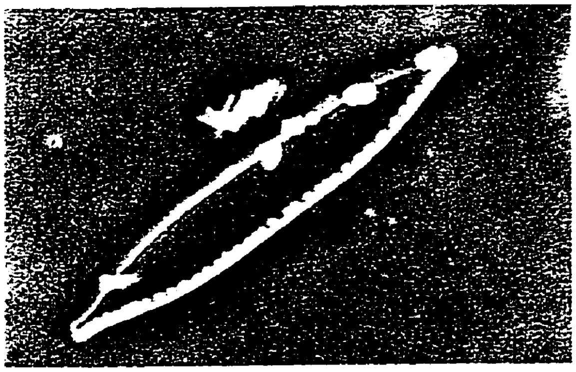
Navicula veneta KÜTZING
Length: 16.8um



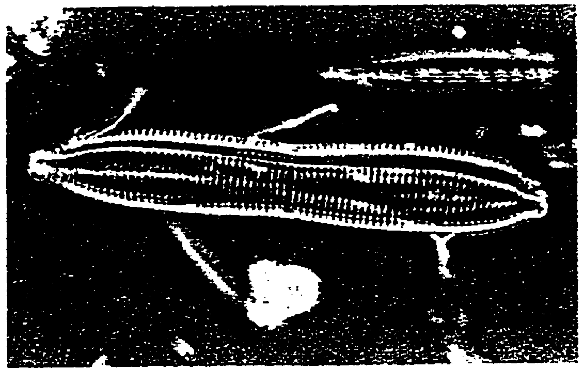
Navicula viridula KÜTZING
Length: 36.0um



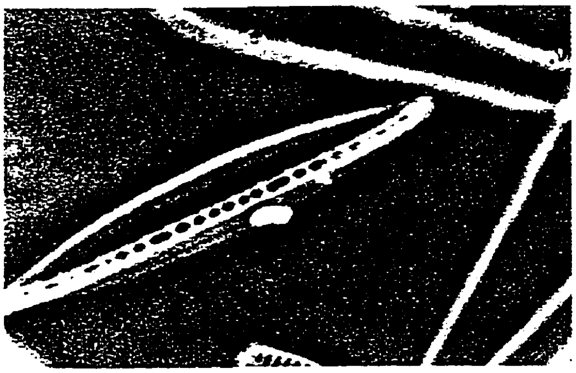
Nitzschia amphibia GRUNOW
Length: 10.4um



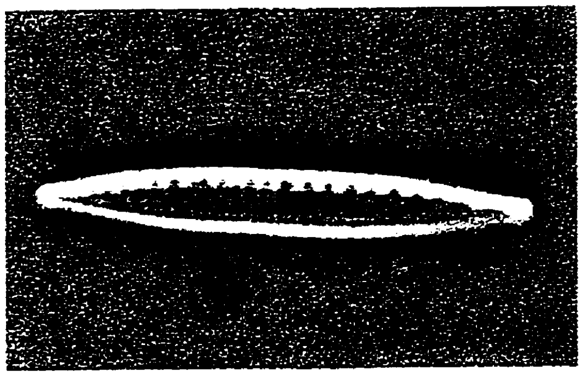
Nitzschia capitellata HUSTEDT
Length: 30.0um



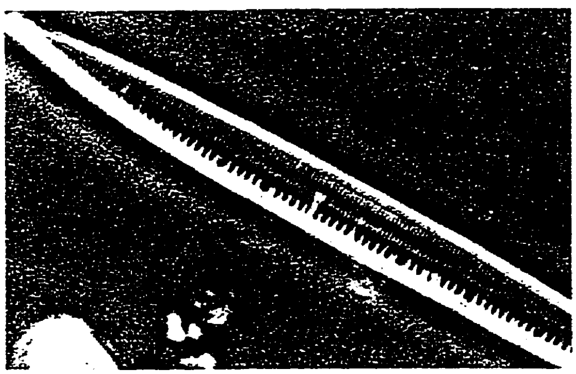
Nitzschia constricta KÜTZING (RALFS)
Length: 40.0um



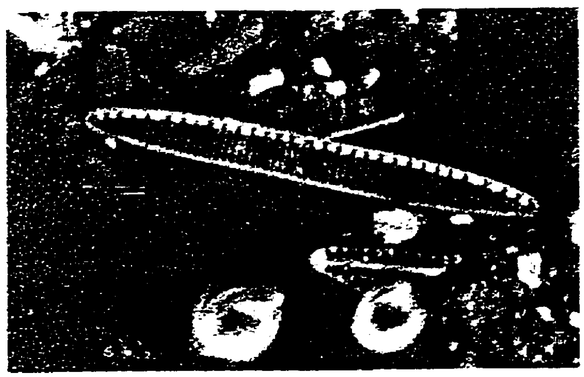
Nitzschia dissipata var. *dissipata* (KÜTZING) GRUNOW
Length: 28.0um



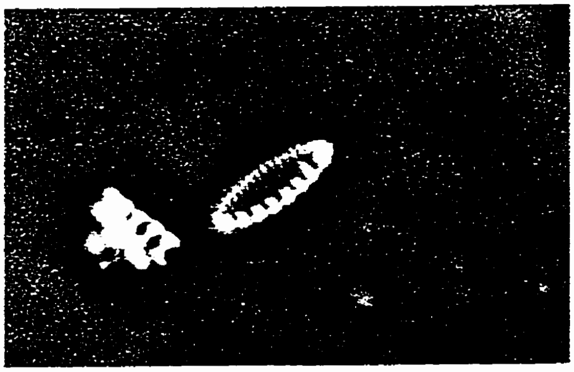
Nitzschia fonticola GRUNOW
Length: 24.0um



Nitzschia heufleuriana GRUNOW
Length: 44.0um



Nitzschia incognita LEGLER & KRASSKE
Length: 28.8um

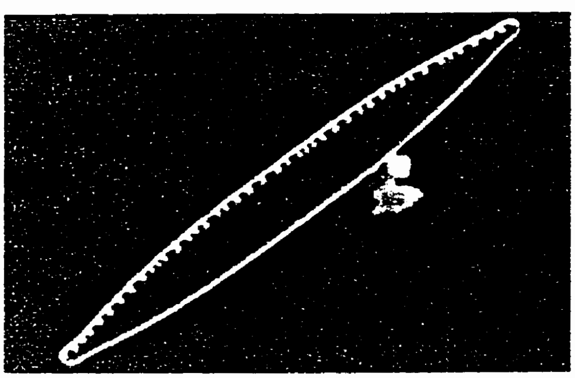


Nitzschia inconspicua GRUNOW
Length: 6.4um

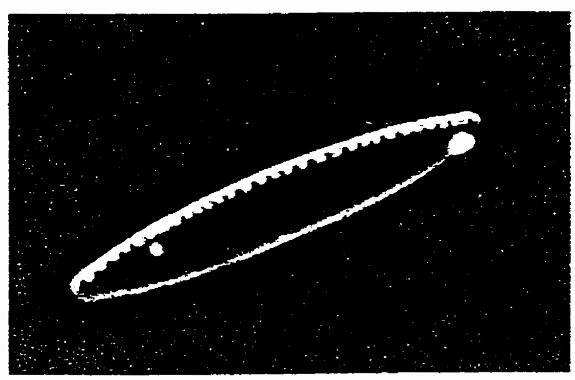
Nitzschia inconspicua GRUNOW
Length: 8.0um

Nitzschia inconspicua GRUNOW

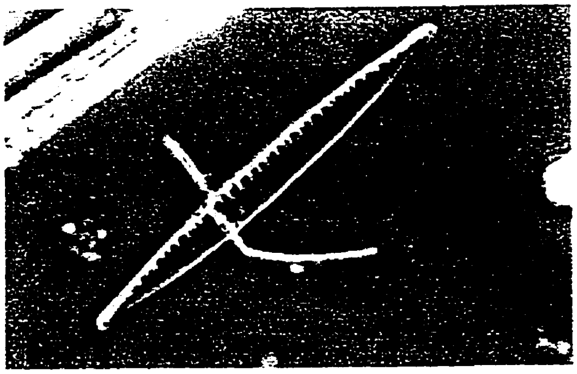
Nitzschia linearis (AGARDH) W. SMITH
Length: 22.0um



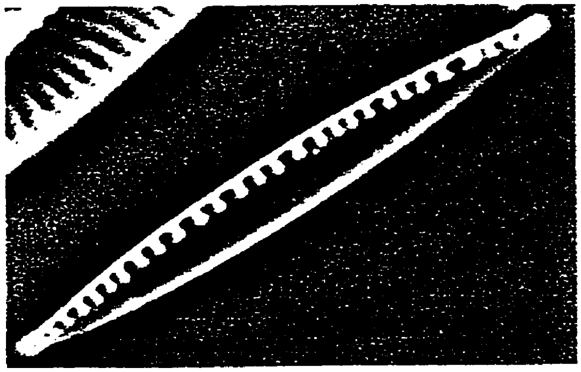
Nitzschia palea (KUTZING) W. SMITH
Length: 36.0um



Nitzschia pusilla GRUNOW emend LANGE-BERTALOT
Length: 22.0um

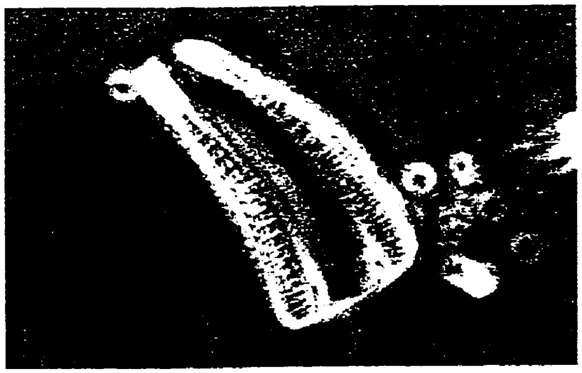


Nitzschia recta HANTZSCH
Length: 43.0um

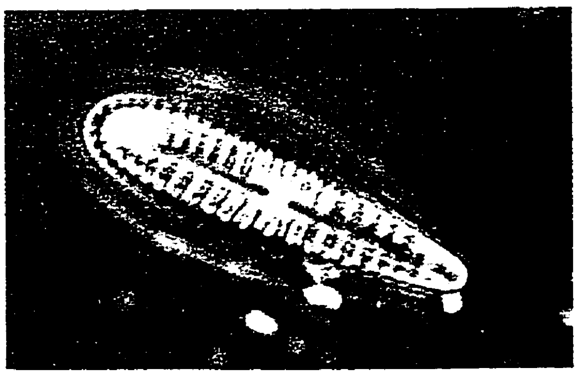


Nitzschia sociabilis HUSTEDT
Length: 29.6um

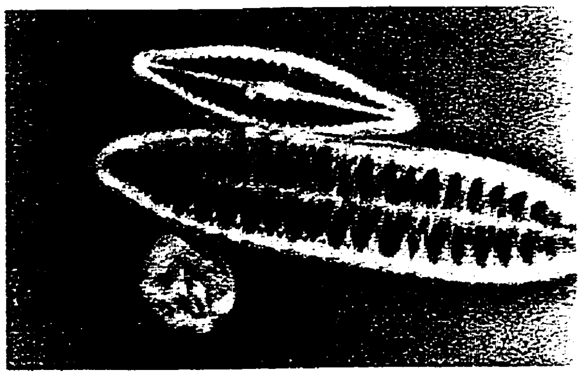
Nitzschia solita HUSTEDT
Length: 25.6um



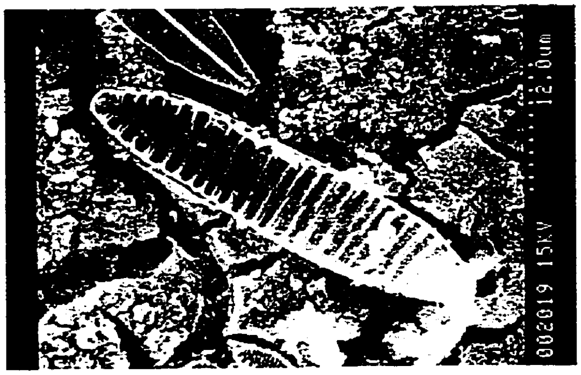
Rhoicosphenia abbreviata (AGARDH) LANGE-BERTALOT
Girdle view
Length: 20.0um



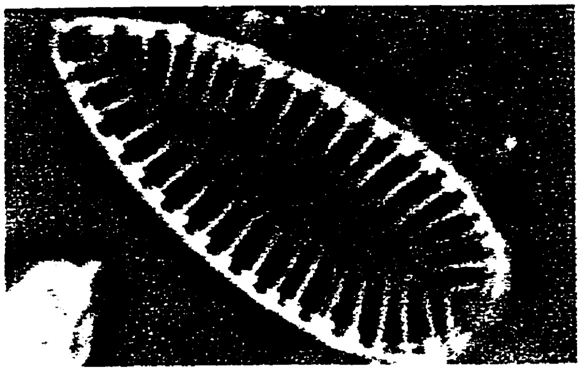
Rhoicosphenia abbreviata
Valve view
Length: 20.0um



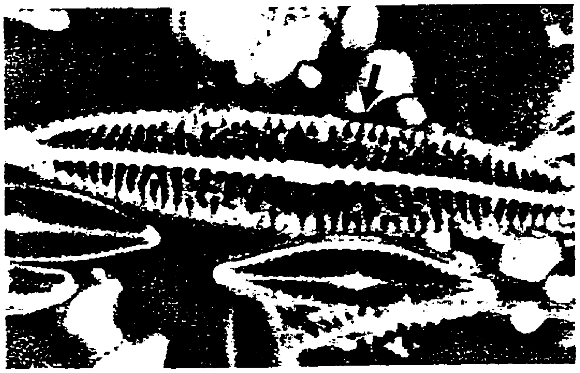
Surirella angustata KUTZING
Length: 38.0um



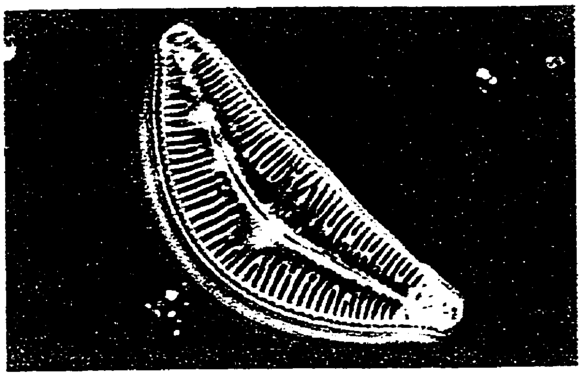
Surirella angustata KÜTZING



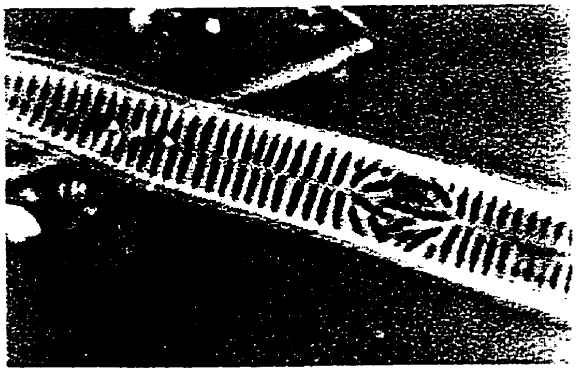
Surirella brebissoni KRAMMER & LANGE-BERTALOT
Length: 25.0um



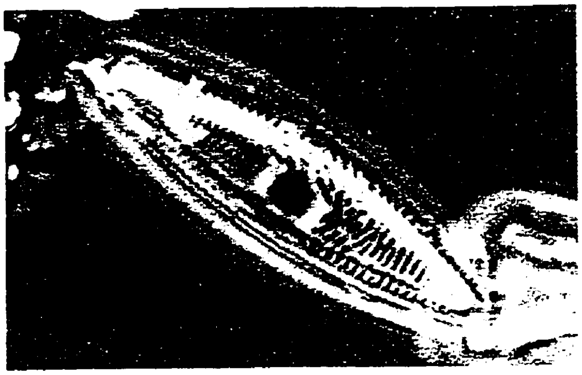
Deformed *Navicula tripunctata*
Length: 37.6um



Deformed *Cymbella sp.*
Length: 40.0um



Deformed *Fragilaria ulna* (NITZSCH) LANGE-BERTALOT



Deformed *Fragilaria capucina*
Length: 28.0um

Appendix 2
Raw epilithic diatom counts for Laurel Creek and Carroll Creek
May 1995 – February 1997
(site numbers refer to those shown in Fig1. Chapter 5)

		May-95						Jun-95						Jul-95	
		Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic4	Ic5
1	*Achnanthes clevei*														
2	*Achnanthes conspicua*												1		
3	*Achnanthes delicatula*														
4	*Achnanthes exigua*														
5	*Achnanthes hungarica*														
6	*Achnanthes laevis*														
7	*Achnanthes lanceolata*	15	1					5	4	1		1		6	11
8	*Achnanthes lauenbergiana*														
9	*Achnanthes marginulata*														
10	*Achnanthes minutissima*	17		2	41	3	2	156	83	58	63	117	74	6	26
11	*Achnanthes oblongella*														
12	*Achnanthes parvula*									3					
13	*Achnanthes semiaperta*														
14	*Achnanthes sp.1*														
15	*Achnanthes sp.2*														
16	*Achnanthes stolida*														
17	*Achnanthes subatomoides*														
18	*Achnanthes trinodis*														
19	*Amphora inariensis*														
20	*Amphora libyca*								1						1
21	*Amphora montana*														
22	*Amphora ovalis*														
23	*Amphora pediculus*	6		2	1			1	3	17	23		27		46
24	*Amphora sp. 1*														
25	*Caloneis amphisbaena*														
26	*Caloneis bacillum*														1
27	*Cocconeis pediculus*												1		
28	*Cocconeis placentula*			1					3				1	44	29
29	*Cyclotella distinguenda*						1				1				
30	*Cyclotella menenghiniana*	4	1		2					2	1			130	30
31	*Cyclotella stelligeroides*														
32	*Cyclotella striata*														
33	*Cymatopleura elliptica*														
34	*Cymbella affinis*														
35	*Cymbella caespitosa*														
36	*Cymbella prostrata*														
37	*Cymbella reichardtii*												3		
38	*Cymbella silesiaca*				1				1	3		2	7		
39	*Cymbella similis*														
40	*Cymbella sinuata*									1			3		1
41	*Cymbella sp. 1*														
42	*Diatoma mesodon*														
43	*Diatoma tenuis*											1			
44	*Diatoma vulgaris*				1							3			
45	*Diploneis oblongella*														
46	*Diploneis sp.1*														
47	*Eunotia bilunaris*														
49	*Fragilaria brevistriata*			3											

		May-95						Jun-95						Jul-95	
		Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic4	Ic5
50	*Fragilaria capucina*	6				1									
51	*Fragilaria construens*														
52	*Fragilaria exigua*													2	
53	*Fragilaria fasciculata*									1					
54	*Fragilaria leptostauron*														
55	*Fragilaria pinnata*														3
56	*Fragilaria pulchella*														
57	*Fragilaria tenera*	1													
58	*Fragilaria ulna*	3		1		4			1		1			1	
59	*Frustula vulgaris*														
60	*Gomphonema acuminatum*														
61	*Gomphonema aff. parvulum*	3			1			1	1	2			7		
62	*Gomphonema augustatum*														
63	*Gomphonema olivaceum*	4		1	6	8			1			10	1		1
64	*Gomphonema truncatum*														
65	*Gyrosigma attenuatum*														
67	*Melosira varians*														
68	*Meridion circulare*	11	7												
69	*Navicula accomoda*														
70	*Navicula aff. decussis*														
71	*Navicula aff. modica*														
72	*Navicula capitata v. capitata*			2	1										
73	*Navicula capitatoradiata*								1					1	1
74	*Navicula clementis*														
75	*Navicula cocconeiformis*			2	1										
76	*Navicula cryptocephala*									1			1		
77	*Navicula cryptotenella*	2		1	3			7	6	9	9	1	2	4	5
78	*Navicula decussis v. decussis*														
79	*Navicula digitulus*														
80	*Navicula eliginensis*									1					
81	*Navicula exigua v. exigua*														
83	*Navicula gregaria*	29	34	44	46	34	26	4	47	19	24	1	19		14
84	*Navicula halophila*														
85	*Navicula integra*	1		2											
86	*Navicula kriegeri*														
87	*Navicula laevissima*														
88	*Navicula lanceolata*	44	148	95	64	138	143	1	11	11	50	15	13		6
89	*Navicula menisculus*									1					
90	*Navicula minima*														
91	*Navicula miniscula*														
92	*Navicula modica*														
94	*Navicula pupula*														2
95	*Navicula pusilla*														
96	*Navicula pygmaea*														
97	*Navicula radiosa*							2							
98	*Navicula reichardtiana*				1			3	12	6	1	1		1	1
99	*Navicula rhyncocephala*														
100	*Navicula saprophila*	1	1	1	3			8	1	3	4		12		4

		May-95						Jun-95						Jul-95	
		Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic4	Ic5
101	*Navicula schroeteri*														
102	*Navicula seibigii*			2					1	2					
103	*Navicula seminulum*														
104	*Navicula sp.1*														
105	*Navicula sp.2*														
106	*Navicula sp.3*														
107	*Navicula sp.4*														
109	*Navicula subminiscula*														
110	*Navicula tripunctata*	2	2		1				1	1					
111	*Navicula trivialis*	1									2				1
112	*Navicula venetata*														
113	*Navicula ventralis*														
114	*Navicula viridula*														
115	*Nitzschia acicularis*			1	5	2	15			5	4				1
116	*Nitzschia amphibia*										1			2	4
117	*Nitzschia capitellata*	2		2	1		1						1		
118	*Nitzschia constricta*														
119	*Nitzschia dissipata v. media*	2	1	3	1					1					
120	*Nitzschia dissipata v.dissipata*	13	1	3	6	2	3	1	16	7	9	17	5		5
121	*Nitzschia fonticola*											3			
123	*Nitzschia frustulum*														
124	*Nitzschia gracilis*											2			
125	*Nitzschia heufleuriana*														
126	*Nitzschia incognita*														
127	*Nitzschia inconspicua*									18	1	17	12		
128	*Nitzschia linearis*	1						1		1					1
129	*Nitzschia microcephala*														
130	*Nitzschia palea*	1	1	10	3	2	4	5	3	15	1	2	8	2	6
131	*Nitzschia paleacea*														
132	*Nitzschia paleaformis*				1										
133	*Nitzschia pusilla*	5	2	14	6	3	5	5	3	6	3	3	1		
134	*Nitzschia recta*	2	1	1	1	1									
135	*Nitzschia sociabilis*									3	1				
136	*Nitzschia solita*										1				
137	*Nitzschia tubicola*														
138	*Pinnularia brebissonii*														
139	*Pinnularia sp.1*														
140	*Rhoicosphenia abbreviata*											4			
141	*Stauroneis anceps*														
142	*Stauroneis kreigerii*														
143	*Stauroneis smithii*														
144	*Surirella angustata*													1	
145	*Surirella brebissoni*	21		7	3	2				2			1		
146	*Surirella minuta*	3													

	Jul-95				Aug-95						Sep-95						May-96				
	Ic6	Ic7	Ic8	Ic9	Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic1	Ic2	Ic3	Ic4	Ic5
1																					
2					8	13	11	2													
3														4							
4																					
5																					
6																					
7		4			15	8				1	3	9			1		1			3	3
8																					
9																					
10	11	34	103	53	76	41	32	61	97	31	19	36	11	19	57	30		12	36	2	19
11																					
12																					
13																					
14																					
15																					
16																					
17																					
18																					
19																					
20	1										1										
21					4																
22																					
23	26	39	3	26	53	37	64	46	9	60	16	7	8	134	16	23	1		5		2
24																					
25																					
26	1			1																	
27	9						1	1		1	3		1		1						
28	11	3	13	16	23	57	3	1	13	3	85	51		1	29	7		1			1
29																					
30	7	9	23	24	2					1	4		3		6	1					
31	1																				
32																					
33																					
34													1								
35																					
36																					
37																					
38		1	2	2			1														
39																					
40	6	3		6	3	1	4			8				5	2	5					
41																					
42																					
43													1					1			
44													2								
45																					
46																					
47																	1				1
49																					

	Jul-95				Aug-95						Sep-95						May-96				
	lc6	lc7	lc8	lc9	lc4	lc5	lc6	lc7	lc8	lc9	lc4	lc5	lc6	lc7	lc8	lc9	lc1	lc2	lc3	lc4	lc5
50											3		2					1	3	1	
51	2			3								2	1								
52														1							
53																					
54																					
55											6			5		1					
56																					
57																		2			
58									1	1	7	1	2	1	2					5	
59										1											
60																					
61	4	10	19	11	1		1	24	12	19	14	1	3	2	40	45		1		1	
62																					
63										1	1							68	121	14	30
64											2		2								
65	1												1								
67																					
68											1						12	10	2	131	7
69		1																			
70																					
71																					
72	6	2		1							1	1	1								
73	20	32	8	25	4	1	1		1	1	4	10	14		1	1					
74																					
75																					
76		1			1	1				1											
77	4	8	3	8	1	1	1	4	1	1	3	5	2	2		10	23	4	3		4
78																					
79																					
80		1											1								
81	2												1								
83	11	3	4	4		10	3		1	2	2	50	16		1		2	11	8	8	5
84		2																			
85											1										
86																					
87	1	1																			
88	10	3		3						3	1	4	7	1		2	150	68	18	14	122
89					1	1															
90																1					
91																					
92					2																
94	2																				
95																					
96																					
97																					
98		1					1				9	8	1			2		1			
99																					
100	1	1		2	5	2		3	6	1				1	1	1		7		1	

	Jul-95				Aug-95						Sep-95						May-96				
	lc6	lc7	lc8	lc9	lc4	lc5	lc6	lc7	lc8	lc9	lc4	lc5	lc6	lc7	lc8	lc9	lc1	lc2	lc3	lc4	lc5
101	1						1		2	11			65	4	4	10					
102	1	1											2								
103																					
104																					
105																					
106																					
107																					
109							1														
110		1									1	4	1	2			3	6		1	2
111	3										1	1	1		1						
112							2														
113																					
114	3																	1			
115		1							1				7								
116	1			2		25	1	8	10	7	4	1	2	1	6	19					
117	2		3	3									4		2						
118																					
119										2			2								
120	1	2	1		1					1		1	1	3	1	22	3	4		2	4
121										1											
123																					
124	1												1				1				
125																					
126																					
127	13	6	4	2			66	49	34	36				7	16	15					
128																					
129									2												
130	22	26	7	5			3		6	2	4	6	23	6	12	4	1	1	3	1	
131									2												
132																					
133																					
134			2			2					2	2	2								
135																	1				
136	8	2	3	2			3	1	1	2			3	1	1	1			1		
137																					
138																					
139		1																			
140	5									2								1			
141																					
142											2										
143																					
144													3								
145	2	1	2	1					1				1				1			14	
146													1							2	

	May-96				Jul-96									Aug-96							
	Ic6	Ic7	Ic8	Ic9	Ic1	Ic2	Ic3	Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic1	Ic2	Ic3	Ic4	Ic5	Ic6	Ic7	Ic8
1						1															
2					3	1	13	20	10	30	7			1	2	5	20	5	24	8	
3																					
4																					
5																					
6																					
7	2				2	13	2	17	6	5	2		1	11	21	7	3	8	1	1	
8					1				9	7						4	6	1	2	3	
9						1															
10	7	2	2		44	134	43	108	50	29	62	47	13	35	109	33	46	39	24	15	24
11																					
12																					
13																					
14										2											
15								2													
16																					
17																					
18									1		1						2	1			
19							1														
20																					
21																					
22	2																				
23	4	5			23	4	82	28	56	98	76	8	22	55	2	52	68	28	81	99	15
24																					
25																					
26			1		2	1						1		1						2	
27							2			1								1	2	2	
28					3	14	28	2	11	1	1			4	29	64	13	57	5	9	11
29													1								
30	2									1			2			1		3	1	7	1
31																					
32																					
33																					
34																					
35																					
36	1																				
37	1									3	4								2		
38																		1			
39																					
40					1		2	2	1	2	7	1	17	1		2			6		19
41																					
42																					
43																					
44	1	1		1									2								
45																1			1		
46			1																		
47																					
49																					

	May-96				Jul-96									Aug-96							
	lc6	lc7	lc8	lc9	lc1	lc2	lc3	lc4	lc5	lc6	lc7	lc8	lc9	lc1	lc2	lc3	lc4	lc5	lc6	lc7	lc8
50	2				1										1				1	1	
51																					
52																					
53																					
54					1																
55								1							1		1	1			
56																					
57				2															1		
58				1				1					2								
59																					
60																					
61				1	2		2				1		1		1		1		1		
62																					
63	4	2	121	43				1										1			
64																					
65																					
67																					
68					2		1											1			
69																					
70																					
71																					
72																		3	1		
73										1	1					3			2	3	4
74										1											
75																					
76					1		1	1							2		1		2	1	
77	7	10		1	82	5	2	1	3			2	6	85	6	2	1	2		2	2
78																					
79																					
80	15		1												1					3	
81																					
83	7	7	6	7	8	9	3	3	21	3	3	1	13		9	7	4	12	2	3	
84																					
85		1																	1		
86																					
87																					
88	105	148	63	135	3		3	1		1	1		3	1	5			4			1
89	1				7									1							
90								1													
91													2								
92																					
94																					
95																					
96																					
97							2														
98			1			1		1	9						1	3	1				
99																					
100				2		12		8	17	2	3	14	21		3		1	4	5		5

	May-96				Jul-96									Aug-96							
	Ic6	Ic7	Ic8	Ic9	Ic1	Ic2	Ic3	Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic1	Ic2	Ic3	Ic4	Ic5	Ic6	Ic7	Ic8
101																			3		
102		3									1					2					
103																1	2	2	1	1	
104																				1	
105								1													
106																					
107																					
109																	1				
110					1	1	2		2					1		3	1	1			
111																					1
112									1												
113																					
114		3		2																	1
115											1		2						1	1	1
116					1		9		3	1	1		1			1	26	10	4		
117						2	1				2		1								
118																		4			
119		2																			
120			1	1	4	1						10	2	1							
121							1					1		1	1	1					
123																					
124																					1
125																					
126																					103
127								1		7	24	112	20			3			2		
128																					
129													1							2	
130	23	4		2						3	1	3	53	1	3	5	2	2	15	17	3
131																					
132																					
133	1	6								1								2	3		
134	1			1	3					1								2			
135	10		1	1	5								3							1	
136													7						6	11	3
137	2										1										
138																					
139																					
140		5																		5	5
141																					
142																					
143																					
144														1				1			
145	2	1	2										4		3			2		2	
146																		2			

	Aug-96	Sep-96									Nov-96					Jan-97					Feb-97	
	Ic9	Ic1	Ic2	Ic3	Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic2	Ic3	Ic6	Ic7	Ic9	Ic2	Ic3	Ic6	Ic7	Ic9	Ic2	Ic3
1			1																		2	
2		13		17	17	10	6					2	1			1	2	5	1		1	6
3			1									2									4	
4					1																	
5																	1					
6																						
7	1	16	6	12	38	3	4				2					20		2	1		45	
8		8		32	5	1											2	7				2
9		48																				
10	69		96	26	63	30	23	50	30	13	46	20	61	27	9	106	31	37	10	16	63	40
11																						
12																						
13																						
14																		1				
15																						
16																						
17																				1		
18		5		1		2																
19																						
20																1						
21																						
22				1																		
23	26	46	5	50	30	43	30	56	4	3		10		1		6	10	68	33	16	39	129
24								1														
25																						
26		2		1		1								2					1			1
27					2	2	2	1														1
28	4	5	22	23	23	35	2		2		1	2	1			11	2	4	1	1	13	1
29																						
30	1	1		1			1		1				1		2				1			
31						1							1									
32																						
33																						
34												1										
35																						
36						2							1							1		
37				1														7	1			
38													3		2		1	4				
39																						
40	4		1	1	1	1	1	1	1							2		1		1		2
41																						
42																						
43													1									
44														1	58					1		
45																					1	
46																						
47																						
49													1		1						2	

	Aug-96	Sep-96									Nov-96					Jan-97					Feb-97	
	lc9	lc1	lc2	lc3	lc4	lc5	lc6	lc7	lc8	lc9	lc2	lc3	lc6	lc7	lc9	lc2	lc3	lc6	lc7	lc9	lc2	lc3
50											1		5	1			1	2	1	1		
51					2	1																
52																						
53						1													1			
54																						
55		2			1	1														1		
56																			1			
57													43	14	17				1	1		2
58											1		9	3	16	1		1				
59										1											1	
60												1										
61	2		1						1	2	2	1	3	2	2	2	3		1			
62																						
63	1							1			56	84	14	2	19	5	122	3		1	1	2
64					1																	
65						1																
67																						
68		1	1		1	6					1					7	2					
69																						
70		1																				
71																						
72		1									1				1						1	
73	3		1	3	3	5		2	5	4		1	1	5	1							
74																						
75																						
76			2				1		1			1	1				1					
77	7	41	28	1		8		4	4	2			1	14	6		1	4	12	1	5	
78																						
79																						
80																		1				
81																						
83		5	15	2	6	13	1	1	3	1	14	39		7	4	7	5	11	6	9	5	5
84																						
85											1											
86																						
87																						
88			10	1		2		1	2	2	72	6	3	24	37	23	8	8	92	118	9	
89																						
90																			1			
91																						
92																						
94					1				1													
95																						
96																						
97		1																				
98						2						7		2		1	4	1				
99																						
100	1	1	5	3	1			1	1	1				1				2				

	Aug-96	Sep-96									Nov-96					Jan-97					Feb-97	
	Ic9	Ic1	Ic2	Ic3	Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic2	Ic3	Ic6	Ic7	Ic9	Ic2	Ic3	Ic6	Ic7	Ic9	Ic2	Ic3
101							1	27	43	55			1	2	1							
102					1	1				2										1		
103																						
104																						
105																						
106				12												2						5
107				1																		
109				1															1		1	
110			3	3		9			2		2	7		4	3		1	3	6	1		3
111		2								1												
112					1			3	7	2											1	
113																						
114																			4			
115																						
116	1			3	2	2	2						1			1		3				
117																						
118						2				3												
119						1				1		3	3	3				1				
120	10			2		4		1	7	3		4	27	32	16		1	5	12	6	6	
121														6								
123			2																			
124														1								
125																						
126													1									
127	59						123	44	48	89			1	5	2	1		5	1	8		
128						4										2						
129	1									2									1			
130	2	1				1	1	2	7	5		4	4	6	1		1	5	1			
131						1																
132																						
133									26	3			5					1				
134												3	1	2		1						
135							1		2				4	1	1			5		9		1
136							1			3				2				1	1			
137																						
138														1								
139																						
140	8			2		4		4		1		2		28	1		1	1	8	6		
141													1									
142																						
143																						
144									2													
145										1				1				1				
146																						

	Feb-97			May-95							Jun-95							Jul-95	
	lc6	lc7	lc9	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc3	cc4
1																			
2	1												2						
3											2								
4																			
5																			
6									1										
7	1			12			1				1		1	1	3				1
8	3																		
9																			
10	71	10	11	5	21	7	20	21	4	48	132	160	40	58	46	113	112	63	59
11																			
12																			
13																			
14																			
15																			
16																			
17																			
18																			
19																			
20																			
21																			
22																			
23	57	20	9	5	9	10	1	8		1	6	1	8	8	4	11	3	36	41
24																			
25						1													
26		1																	
27												2		1	2	1			
28				1		1	1					2				1		24	6
29				1															
30	1	1		1			2	1			1			2	1	2	1		4
31																			
32																			
33				1															
34																			
35																			
36		1																	
37	1								4	1								5	4
38	1		5		4	2	3	2	3	4		18	7	10	22	17	17	2	5
39																			
40	1	1											3		1		1	1	
41				1															
42																			
43					4	1	1	8									1		
44					1								1	1			1	1	
45																1			
46																			
47																			
49	1				1														

	Feb-97			May-95							Jun-95							Jul-95	
	lc6	lc7	lc9	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc3	cc4
50	1	2		8	2	3	3	4	6	2	5							1	
51																			
52																			
53																			
54																			
55													1						
56		1																	
57	2	1																	
58					28	15	12	11	5	2								1	
59		1		1															
60																			
61	1	1		16	2			1			2				1				
62											1								
63	1	2	5	4	47	63	73	76	118	82	2	1	1	3	2	4	7	8	
64																			2
65				1															
67																			
68				42	6	9	20	9	7	3								2	
69																			
70																			
71																			
72														2					
73				1					1		1	2	6		1	2	4	12	24
74																			
75																			
76			3								2					1		2	3
77	5	11	14	21	28	8	2	4	2	14	6	5	18	32	2	20	25	21	8
78																1			
79																			
80																			
81																			
83	5	10	23	8		8	3	5	2	7	2	1	9	4	4	2	4	2	
84																			
85																			
86													1						
87																			
88	5	119	50		1	43	7	1	1			1	4						
89			1																
90																			
91																			
92																			
94																			
95																			
96													1						
97											2								
98			8	5	1		7	6	2			3	16	37	21	2	4	4	5
99																			
100	4		2		1	1	1	3	3	4		1	13		26				

	Feb-97			May-95							Jun-95							Jul-95	
	lc6	lc7	lc9	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc3	cc4
101																			
102															1				
103																			
104																			
105																			
106																			
107																			
109	2																		
110	1	2	6	36	15	15	5	4	9	6	5		7	6	5	3	6	3	2
111					2														1
112																			
113																			
114																			
115															14				
116	1	1																	
117							2			1				1					
118			1																
119	1		2														2		
120	7	6	7	9	9	3	5	1	13	2			19	11	3	9	10	2	4
121	6		5																3
123																			
124					1		2						1	1		1			
125																			
126																			
127	5		14												1				
128				3						1	2			1					5
129																			
130	2	1	12	2		1	2	8		3	19	2	39	16	35	7		5	20
131																			
132																			
133			7	5	7	2	10	11	10	8	1		2	1	2				
134															2				
135	3		6	3		1				4						2		4	
136																			
137																			
138																			
139																			
140	9	8	9		2							1		2				1	2
141																			
142				1															
143																			
144				2			1				2								
145	1			5	8	6	16	16	9	7	6			2	1		2		1
146																			

	Jul-95				Aug-95							Sep-95							May-96
	cc5	cc6	cc7	cc8	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc2
1																			
2																			
3	1			3															
4																			
5																			
6																			
7	3				4		2	4	8		1	4	2		7	2			1
8															1				
9																			
10	91	48	80	97	66	74	14	108	25	47	97	61	25	38	59	85	20	34	90
11																			
12																			
13																			
14																			
15																			
16																			
17																			
18																			
19													1	1					
20							1						1	1					
21																			
22						1		1						1		1			
23	14	40	26	8	15	51	44	45	50	70	30	30	88	61	36	40	59	46	5
24																			
25																			
26						1	1		1										1
27	2	3	1	2	1	1		2	4							2		1	
28	2		3	2	10	23	4	3	6	2		7	6	3	5	12	1	3	
29			1																
30	13	8	1	4	5	4	13	6	4	1	2			9	5		4	1	
31																			
32													1						
33												1							
34						4	30		1	3	19		4	1			28	16	
35			3				1												
36																			
37			2										3	1					
38	2	11	13	11			2	4		2	4			2			2	3	1
39																			
40	1	5		2				2	15	2					5	8	1		
41																			
42																			
43																			
44							5			7	6			4			43	46	
45																			
46																			
47																			
49														1				4	

	Jul-95				Aug-95							Sep-95							May-96
	cc5	cc6	cc7	cc8	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc2
50	2				1			1	1				1	1					
51												1	2						2
52															1	1			
53					2							1	1						1
54																			
55													1	1	1				
56																			
57																			
58		1					1			7	7	3	1	2			2	6	
59																			
60																			
61	3	1							2	1				6	2	5	1		27
62																			
63	1			2			1	1		1	1		1		7	2			1
64						2	2		1								1		
65					1							2	1				2		
67																			
68						1						1	2						40
69																			
70																			
71															1				
72					1														
73	28	47	18	13	8	1	16	7	38	7	6	5	8	4	7	6	13	7	1
74																			
75																			
76				1	2							1	2		3		1		
77	15	13	30	31	30	4	11	9	2	2	7	15	5	7	5	5	11	11	6
78																			
79																			
80																			
81																			
83			3	2		1	2	1			1	2	2	8					1
84																			
85					1														
86																			
87																			
88							1							1			1		
89																			
90																			
91																			
92																			
94	1						3							1	1				
95																			
96																			
97					1							1							
98	5	8	1	6	2	3	5		3		1	2	3	3	2	6			5
99																			
100						4	3		34				2	2	5	3			2

	Jul-95				Aug-95							Sep-95							May-96
	cc5	cc6	cc7	cc8	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc2
101																			
102						1													
103																			
104																			
105																			
106																			
107																			
109																			
110	2	6	10	2	38	7	2	2		1	1	25	10	1		1	4	1	3
111							2							1					
112																			
113																			
114																			
115							1												
116																9			
117								2				1			1				
118																			
119					2					1	1		1		1				
120	1	1	1	1	3	2	7					5	11	10	2	1	1	1	10
121		1				7	4		1	1	1			5	1	3		1	
123																			
124																			
125							1					13							
126							1												
127																			
128					1	1						8							
129																			
130	13	7	7	12	3	5	20	2	4	45	15	4	11	20	37	7	5	19	
131															1				
132																			
133																			1
134												3	4	4	1				
135					1							3							1
136																			
137																			
138																			
139																			
140				1	2	2									3	1			
141																			
142																			
143																			
144												1							
145																			1
146																			

	May-96						Jun-96								Jul-96				
	cc3	cc4	cc5	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5
1																			
2							1			2	1				1			2	3
3													1						
4																			
5																			
6							5								10				
7							17	5	5	1	3	3			7	2	1	1	4
8							12		1									3	
9																			
10	1		7		1	1	108	79	89	45	56	17	42	32	156	38	66	31	59
11							1												
12																			
13																			
14																			
15																			
16															1				
17																			
18																2			
19																			
20																			
21																			
22																			
23		2	4		3	3	3	21	43	86	75	16	30	6		100	75	95	53
24																			
25																			
26					1	1		2				1				5	2		
27								1	1		3	2	2				1	1	3
28								1		1						3		4	
29																			
30											1								3
31																			
32																			
33																			
34											1								
35																			
36																			
37															2				
38		1	3	2	6	4		1	1	1	4	13	35	36	1	1	1	1	3
39														1					
40									1			1							2
41															1				
42																			
43	1						1												
44	1					1		1						1			2		
45																1			
46																			
47									1										
49																			

	May-96						Jun-96								Jul-96				
	cc3	cc4	cc5	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5
50	1				3	2		1		2		1	1	2	1	2			
51		3																	
52																			
53																			
54																			
55																			
56																			
57							8	1							2				
58	9	7	4	11	11	25										1			
59																			
60																			
61	1	1					6	4	1	2						1		1	2
62																			
63	52	99	127	159	110	81		1	5	1	1	5	6	8					
64																			
65					1														
67							5	3							2				
68	31	27	16	11	13	32	23	1				1	2	1	9	2			1
69																			
70																			
71																			
72																			
73			1					16	1	8	3	10	4	8		1	2	24	12
74																			
75																			
76				2			1	4										1	
77					12	6	1	6	23	21	14	11	36	66		28	12	9	10
78																			
79																			
80																			
81																			
83	5	6	1		3	5		4	3	5	5	14	1	1			6	1	5
84																			
85																			
86																			
87																			
88	85	33	19	8	6	3			4	4	6	4					2		2
89																1	3	2	
90																			
91																			
92																			
94																			
95																			
96																			
97								1											
98		1	2	2			1	8	1	3	2	38	5	6		5	4	4	5
99																			
100		2	1				1	5	6		1	6				1		2	3

	May-96						Jun-96								Jul-96				
	cc3	cc4	cc5	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5
101																			
102																			
103																			
104																			
105																			
106																			
107																			
109							1										2		
110	3	5	5	2	12	16		18	8	1	7	7	10	13		4	1	7	2
111											1						2		
112							2					1			1				
113		1																	
114	6		1	2		1				1							2		
115															1				
116								1	1									1	
117																		2	
118																			
119																			
120	1	7	1		14	6		3	3	9	11	40	19	12		1	7	3	8
121			1									1							
123																			
124												1							
125										1									
126							1								1				
127																			
128					1	1		7											1
129																			
130							1	2	2	3	4	2	4	1	4	1	4	4	8
131										1									
132																			
133	1	2						1						1				1	
134										1				1					1
135		3				3		1					1	2					
136																	2		
137																			
138																			
139																			
140							1					4	1	1			2		10
141																			
142																			
143																			
144			7																
145	2			1	3	9		1				1		1			1		
146										1	1								

	Jul-96			Aug-96								Sep-96							
	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5	cc6	cc7	cc8
1																			
2		1		11	1			4	1		1	18		2		1			
3																			
4																			
5																			
6				22			1					7							
7	1			28	2			1	2	1	9	18	8	1		1		1	
8				2		1						13			3				
9																			
10	30	53	89	93	75	44	42	61	93	60	58	116	86	71	28	89	41	63	26
11																			
12																			
13											5								
14																			
15																			
16												1							
17																			
18																			
19																			
20											1								
21											13								
22										1	1								
23	78	93	19	2	54	101	52	83	34	41	8	4	75	94	42	71	127	84	28
24																			
25																			
26	1	1	1		4		1		1	1						1		1	
27	5				1				3	1	2								
28	1			1	8	2		1	1	1	2		6	2		3	1	4	
29																			
30		1	2			2	4		4	1	1			2	1			4	
31																			
32																			
33																			
34							3			1					3			3	5
35																			
36																			
37												12							
38	11	6	2				2	1		5	5			1	1		1	3	2
39																			
40	2	1	2		1	1			2	1	1							2	
41				1															
42																			
43																			
44							4								1	1			11
45																			
46																			
47				2															
49																			

	Jul-96			Aug-96								Sep-96							
	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5	cc6	cc7	cc8
50					1						1							1	3
51				1															
52																			
53																			
54																			
55																			
56																			
57			1	1															
58				1	1						1							1	1
59					1														
60																			
61	3	3	1	1		1	1		1	2	3		3	1					
62																			
63		5	6			1			1	6	1						3	2	1
64				1			1												
65													1						
67				8			1												
68				3	2	2					1		2						
69																			
70																			
71																			
72											1				3				
73	11		8		5	8	14	4	9	16	19			1	13	2	2	4	3
74																			
75																			
76	1			2	2							2							
77	11	24	10	1	11	15	13	15	19	25	14	1	9	8	7	10	8	16	9
78																			
79				3															
80											1								
81																			
83					1	3	3		1	2	3		1	1	4	1			
84																			
85																			
86																			
87																			
88	3					2	1		1									1	
89				3				2								1	1		
90								1											
91																			
92																			
94								1											
95				1															
96																			
97				1															
98	11	3	8		5	2	2	5	6	5	13		3	4	6	5	3	2	
99												1							
100	1	1	1		1	4	1	1	2	2	1		1	2		3			

	Jul-96			Aug-96								Sep-96							
	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5	cc6	cc7	cc8
101											6								
102																			
103																			
104																			
105																			
106																			
107																			
109									2						2	1			
110	6	1	1		17	8	8	2	1	6	4	1	2	2	6		1	1	1
111					1							1			1				
112				1							2	3							
113																			
114							2				2				6	1			
115	1													1	15				1
116								2							1			1	
117		1																	
118																			
119																			
120	19		13		1	1	15	10	5	5			2	3	10	1	10	1	3
121		1	1			1	3		4	2			1		3	3			2
123																			
124																			
125															1				
126				2															
127							1				2								
128																			
129																			
130	1	2	34	3	1		22	5	4	15	12	1		3	41	4	2	3	102
131								1											
132																			
133					2		1												
134	1			4	1										1				
135											1					1			
136															1				2
137																			
138																			
139																			
140	2	3	1	1			1		3		5							1	
141																			
142																			
143												1							
144					1														
145						1	1							1				1	
146																			

	Nov-96					Jan-97					Feb-97		
	cc1	cc3	cc5	cc7	cc8	cc1	cc3	cc5	cc7	cc8	cc3	cc7	cc8
1													
2	12					4		1		1	1		
3									1				
4									1				
5													
6	23												
7	21						1	1				2	
8	6					3							
9													
10	94	19	1	4	69	22	18	49	14	17	6	61	36
11													
12													
13													
14													
15													
16	3												
17													
18													
19													
20													
21													
22			1										2
23	7		3	4	1	1	6	37	21	5	79	62	97
24													
25													
26	1							1				1	2
27								2			1	2	
28	1									2			1
29													
30			3					1					
31													
32													
33													
34		2		3	2								
35		1	1										
36													
37						160		1	1			1	
38	3	11	16	6	13	1	2		5	6	1	1	1
39													
40										1		3	2
41													
42						1							
43		18	4				2	3	1	6	1		
44		5	7	8	10								
45													
46													
47													
49													

	Nov-96					Jan-97					Feb-97		
	cc1	cc3	cc5	cc7	cc8	cc1	cc3	cc5	cc7	cc8	cc3	cc7	cc8
50		2							3		4		2
51													
52													
53													
54													
55													
56													
57							1					1	
58		20	5	1			8	5	3	2	2		3
59													
60													
61	3	1					1			1		2	1
62													
63	5	30	2	87	56	2	92	30	20	43	16	5	1
64													
65								1			4	1	1
67		2											
68							2				2		1
69													
70													
71													
72								1		1			
73			22	1	1			3	3		1	3	2
74													
75													
76	3		7	3									
77	1	6	6	3	5	1	1	7	7	9	20	16	13
78													
79						1							
80													
81													
83		4	31	3	1		21	22	43	17	8	10	2
84													
85													
86													
87													
88								3	1		4	2	
89								1		1		1	2
90													
91										1			
92													
94													
95													
96													
97													
98	3	3	24	10	8		5	5	5	24	2	6	6
99													
100							3	1	1	5		1	

	Nov-96					Jan-97					Feb-97		
	cc1	cc3	cc5	cc7	cc8	cc1	cc3	cc5	cc7	cc8	cc3	cc7	cc8
101													
102													
103													
104													
105													
106													
107													
109							3			1			
110		11	19	14	2	1	15	10	39	18	37	9	18
111			1										
112	1	1						1					
113													
114		1	1					1	1	2			
115			1										
116													
117													
118													
119									3				
120	6	52	7	11	15	3	17	5	12	29	8	6	5
121	1	7			1								
123													
124													
125													
126													
127								1					
128			4						8	1			
129													
130	3	4	19	39	12			1	2	2		1	
131													
132													
133	2		14	2	2								
134								1	1				
135				1	2				1	4	1	1	2
136													
137													
138													
139													
140								2		1	1	2	
141													
142													
143													
144	1												
145							2	3	3		1		
146			1										

Appendix 3
Water quality data for Laurel Creek and Carroll Creek
June 1995 – February 1997
For data collected from May – September, values represent monthly means of at least 2 samples
(site numbers refer to those shown in Fig1. Chapter 5)

		Jun-95						Jul-95					
		Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic4	Ic5	Ic6	Ic7	Ic8	Ic9
Conductivity (μS)	**COND**	538	540	627	661	732	824	541	538	671	951	1182	1259
pH	**pH**	7.4	7.5	7.4	7.4	7.6	7.5	7.0	7.4	7.2	7.4	8.2	7.9
Temperature (oC)	**TEMP**	20	19	23	23	22	22	17	17	22	23	22	22
Total phosphorus (μg/l)	**TP**	42.6	57.6	180.3	133.4	116.2	94.6	39.1	53.2	189.0	214.6	86.2	62.2
Soluble reactive phosphorus (μg/l)	**SRP**	18.8	29.5	2.7	2.3	5.1	2.6	10.4	31.2	2.8	15.0	6.8	7.0
Alkalinity (mg/l CaCO3)	**ALK**	242	244	168	179	190	198	250	241	206	199	211	216
Biological oxygen demand (mg O2/l)	**BOD5**	2.7	1.5	6.1	7.4	5.0	3.9	2.9	0.8	7.1	7.6	2.1	3.3
Total suspended solids (mg/l)	**TSS**	1.0	2.0	31.0	21.5	12.0	10.5	3.4	3.8	72.5	71.3	11.9	7.5
Total nitrogen (mg/l)	**TN**	6.01	5.83	3.96	1.99	2.24	1.80	< 1.00	1.60	1.69	2.91	2.45	1.99
Nitrate (mg/l)	**NO3**	1.36	1.56	0.74	0.60	0.68	0.66	0.33	0.70	0.60	0.71	1.18	1.10

	Aug-95						Sep-95						May-96	
	Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic1	Ic2
COND	599	621	498	545	702	706	570	558	807	1023	897	1403	521	464
pH	7.0	7.4	7.4	7.4	7.9	8.0	7.3	7.8	7.6	7.7	8.1	8.2	8.0	7.9
TEMP	18	18	23	23	23	22	17	17	19	19	19	19	13	12
TP	54.1	57.7	210.9	197.6	128.3	94.0	38.0	42.2	99.5	184.2	73.8	54.6	39.2	31.8
SRP	21.2	27.1	2.8	4.5	2.8	5.2	13.9	19.9	3.3	64.5	10.4	52.4	6.9	4.9
ALK	258	247	194	186	194	194	268	258	210	195	130	207	203	180
BOD5	3.3	2.4	7.4	7.0	6.6	4.9	2.1	1.5	3.7	7.8	6.3	3.6	3.0	2.3
TSS	3.5	5.9	55.1	51.6	26.4	16.5	4.3	3.9	34.4	11.3	5.1	2.9	12.1	12.0
TN	<1.00	1.51	1.36	2.56	1.63	1.12	<1.00	1.68	1.83	5.79	6.83	3.21	2.50	2.40
NO3	0.35	0.69	0.37	0.34	0.62	0.61	0.42	0.72	0.42	0.69	1.64	1.02	1.11	1.08

	May-96							Jul-96							
	Ic3	Ic4	Ic5	Ic6	Ic7	Ic8	Ic9	Ic1	Ic2	Ic3	Ic4	Ic5	Ic6	Ic7	Ic8
COND	506	541	547	567	616	808	814	594	532	573	552	568	564	742	992
pH	7.9	7.7	8.0	8.4	8.2	8.1	8.0	8.0	8.0	7.9	7.7	7.9	7.8	8.0	8.2
TEMP	12	12	11	16	14	13	13	16	16	16	18	16	21	20	19
TP	41.6	51.5	73.5	83.0	122.9	106.8	122.3	25.8	25.3	60.6	50.6	46.4	106.3	114.8	75.4
SRP	7.2	11.1	13.4	1.7	6.3	8.6	11.9	12.4	11.4	37.9	28.2	27.1	5.4	10.5	12.9
ALK	189	204	211	198	188	193	190	257	254	263	261	268	201	219	238
BOD5	2.7	2.8	3.1	6.0	4.0	4.1	3.8	0.6	0.9	1.2	1.2	1.0	3.9	3.9	2.9
TSS	18.7	10.3	36.7	41.2	84.7	84.1	136.1	2.4	4.7	2.0	2.8	4.4	50.3	66.2	28.4
TN	2.55	3.70	3.85	2.65	2.80	2.90	2.85	3.40	2.85	2.30	2.75	3.25	2.10	2.30	2.90
NO3	1.21	2.62	2.60	1.25	1.41	1.53	1.46	2.10	1.67	1.24	1.57	2.07	1.14	1.32	1.90

	Jul-96	Aug-96									Sep-96			
	lc9	lc1	lc2	lc3	lc4	lc5	lc6	lc7	lc8	lc9	lc1	lc2	lc3	lc4
COND	1013	642	581	607	542	535	590	745	1069	1083	577	510	551	571
pH	8.1	8.2	8.1	8.0	7.9	8.0	7.8	7.9	8.2	8.1	7.9	7.8	7.7	7.6
TEMP	18	16	17	17	19	18	22	22	20	19	15	17	15	18
TP	61.2	22.4	27.3	58.2	53.9	56.2	142.4	159.1	110.1	81.8	25.4	26.8	56.4	57.4
SRP	9.1	11.4	12.9	35.5	17.3	26.3	2.4	6.0	1.8	3.1	13.3	10.6	30.1	25.4
ALK	244	286	255	270	263	255	199	205	228	235	262	225	243	258
BOD5	2.1	0.8	0.4	0.4	1.1	0.8	4.4	4.4	3.3	2.5	0.3	0.5	0.7	1.1
TSS	14.8	3.2	3.6	2.0	10.6	8.7	54.8	64.2	28.5	11.0	8.1	6.2	7.9	4.3
TN	2.70	3.59	2.21	1.42	1.00	1.63	1.44	1.43	2.32	1.93	2.95	1.90	1.76	1.76
NO3	1.76	2.44	1.85	1.11	0.71	1.11	0.65	0.69	1.42	1.14	1.95	1.38	1.34	0.98

	Sep-96					Nov-96					Jan-97				
	lc5	lc6	lc7	lc8	lc9	lc2	lc3	lc6	lc7	lc9	lc2	lc3	lc6	lc7	lc9
COND	588	517	515	622	593	569	642	726	913	1145	497	540	566	764	943
pH	7.7	8.0	7.9	7.9	7.9	8.1	8.1	8.2	8.3	8.3	8.0	7.9	7.9	8.0	7.9
TEMP	16	19	18	18	17	4.0	3.1	2.5	2.5	3.0	-0.1	-0.1	-0.1	-0.2	-0.1
TP	59.9	146.4	119.4	111.1	105.5	18.00	20.43	80.36	59.64	39.19	26.86	36.93	56.86	70.43	69.81
SRP	26.7	14.9	12.1	14.1	17.6	4.57	10.57	21.21	12.36	4.86	7.64	18.64	16.29	13.64	11.79
ALK	269	192	180	172	160	245	269	280	285	292	199	212	204	210	221
BOD5	1.1	3.8	3.1	2.6	2.0	2.1	2.2	3.7	3.3	2.9	3.1	3.6	3.7	3.9	4.6
TSS	10.1	48.4	50.7	44.4	33.6	3.9	0.0	23.5	16.5	8.0	13.2	6.2	23.8	64.6	43.8
TN	1.76	1.80	1.95	2.15	2.17	1.8	2.0	2.6	2.1	2.4	1.4	2.0	2.5	2.4	2.4
NO3	0.98	0.86	1.05	1.30	1.25	1.4	1.6	1.6	1.7	1.9	1.3	2.1	2.4	2.4	2.5

	Feb-97					Jun-95							Jul-95		
	lc2	lc3	lc6	lc7	lc9	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc3	cc4	cc5
COND	549	582	945	762	1222	551	561	560	540	514	544	546	607	609	557
pH	7.9	7.8	7.7	7.7	7.6	7.1	7.4	7.3	7.5	7.7	7.8	7.9	7.6	7.4	7.8
TEMP	0.5	-0.1	0.2	-0.1	-0.1	13.9	18.3	18.5	20.1	20.2	19.6	19.4	18.1	18.6	21.3
TP	38.29	34.86	63.64	116.86	77.86	14.36	17.57	16.68	15.11	28.43	18.25	24.82	13.86	19.18	15.25
SRP	9.29	12.36	14.57	11.86	12.29	10.07	5.90	10.15	14.18	10.43	5.07	3.63	2.71	3.57	15.22
ALK	223	222	204	202	198	275	240	249	239	223	223	227	232	240	220
BOD5	3.2	4.2	4.5	5.3	4.5	1.8	2.2	2.6	3.2	2.8	2.4	2.5	2.1	2.7	3.0
TSS	24.4	8.7	31.6	291.1	69.4	5.5	3.0		5.5	7.0	2.0	0.5	4.2	1.9	5.0
TN	2.4	2.1	2.7	2.2	2.2	8.9	16.0	16.6	7.9	8.8	15.4	16.3	1.8	1.6	1.3
NO3	0.9	1.3	1.7	1.8	1.6	3.3	4.3	4.3	2.6	2.6	4.6	4.7	1.4	1.0	0.6

	Jul-95			Aug-95							Sep-95			
	cc6	cc7	cc8	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc2	cc3	cc4	cc5
COND	488	521	542	649	655	612	580	526	551	560	647	640	590	509
pH	7.6	8.0	8.0	7.9	7.5	7.5	7.8	8.3	8.4	8.4	7.9	7.8	8.2	8.2
TEMP	22.1	22.0	20.8	14.9	19.2	20.0	23.4	23.4	21.9	22.0	9.3	13.5	14.0	17.8
TP	22.68	23.86	38.61	24.36	20.00	20.82	19.89	7.65	6.72	10.72	15.29	13.43	21.43	52.86
SRP	7.78	1.18	1.82	10.21	5.03	10.64	49.64	42.54	6.11	3.11	7.29	1.71	2.36	22.71
ALK	207	205	212	299	261	264	249	231	230	225	303	245	248	218
BOD5	2.6	2.4	2.3	2.0	2.9	3.0	3.9	3.5	2.9	3.0	1.6	1.7	2.0	2.8
TSS	2.8	3.1	1.3	4.3	2.4	2.8	1.6	0.4	3.1	2.0	11.8	2.8	3.9	3.5
TN	<1.00	7.7	6.4	12.5	3.0	2.4	1.3	1.2	10.7	10.8	15.9	2.8	2.8	1.8
NO3	0.4	3.1	2.9	4.5	1.4	1.1	0.6	0.6	3.3	3.5	4.8	1.3	1.2	0.6

	Sep-95			May-96							Jun-96		
	cc6	cc7	cc8	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc1	cc2	cc3
COND	447	490	433	537	664	642	636	613	639	638	410	569	698
pH	8.7	8.2	8.3	7.8	7.9	8.0	8.0	8.1	8.0	7.9	7.3	7.7	8.0
TEMP	17.7	17.6	15.3	10.9	11.5	10.8	11.2	11.6	11.2	11.0	14.1	14.2	15.7
TP	18.57	13.79	12.05	26.43	61.39	62.89	65.46	64.82	64.71	63.26	9.00	43.71	115.29
SRP	6.14	3.00	2.21	9.89	22.50	25.71	27.50	35.00	26.86	24.43	3.57	21.86	44.86
ALK	193	214	230	228	242	240	237	230	235	240	207	262	291
BOD5	2.3	2.0	2.2	5.6	6.8	6.3	6.4	6.3	6.4	6.3	0.7	1.1	3.2
TSS	2.5	4.1	2.4	2.4	3.9	4.4	4.2	6.4	8.4	9.6	0.8	1.5	3.1
TN	1.7	3.1	12.1	4.4	7.1	7.6	7.6	7.9	7.9	7.8	3.3	4.2	6.5
NO3	0.4	1.3	3.8	3.3	6.2	6.4	6.5	6.6	6.9	6.6	0.8	2.5	5.6

	Jun-96					Jul-96							
	cc4	cc5	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5	cc6	cc7	cc8
COND	632	656	653	643	624	602	576	597	572	543	552	526	540
pH	7.9	8.0	7.9	7.6	7.7	7.7	8.2	8.1	8.0	8.2	8.2	8.3	8.1
TEMP	15.3	15.7	15.7	15.5	15.5	14.9	13.7	18.4	18.3	19.6	19.0	18.8	17.2
TP	90.07	88.07	93.29	123.43	82.57	12.07	19.64	21.86	34.04	45.86	31.89	19.25	18.21
SRP	41.71	40.00	47.71	46.29	24.29	5.71	11.21	4.57	11.14	14.25	6.61	2.25	2.54
ALK	278	273	273	266	260	313	295	263	260	244	248	220	226
BOD5	2.2	2.2	2.4	2.9	2.8	0.6	0.6	1.0	1.1	1.6	1.3	1.3	2.9
TSS	3.0	7.2	3.8	6.0	7.7	0.8	1.6	0.4	1.2	2.9	0.8	0.8	0.4
TN	7.2	6.4	6.7	6.3	5.9	3.9	5.4	4.4	4.0	3.6	3.1	5.1	5.5
NO3	6.2	5.7	6.0	5.7	5.0	1.9	3.4	2.5	2.4	2.0	1.8	3.4	3.6

	Aug-96								Sep-96					
	cc1	cc2	cc3	cc4	cc5	cc6	cc7	cc8	cc1	cc2	cc3	cc4	cc5	cc6
COND	644	567	513	517	490	453	539	561	565	592	616	610	581	577
pH	7.5	7.9	7.8	7.6	7.8	7.8	7.9	7.9	7.5	8.0	8.0	7.9	8.1	8.2
TEMP	17.8	15.1	21.4	20.9	22.7	21.1	19.1	18.9	16.1	14.2	18.6	17.8	20.3	19.6
TP	16.86	16.39	24.21	38.21	62.68	48.43	21.50	16.48	14.71	22.79	26.79	41.00	69.93	55.43
SRP	8.18	8.96	4.46	5.86	18.96	8.93	1.79	2.25	7.36	16.71	7.29	18.36	29.71	26.71
ALK	338	296	226	238	223	200	223	235	293	303	259	267	255	252
BOD5	1.2	0.4	0.8	1.2	1.7	1.5	1.0	0.8	0.9	0.7	1.5	1.4	2.2	1.8
TSS	1.9	3.1	1.7	4.5	4.1	3.5	2.4	3.2	0.8	0.0	2.4	3.2	3.9	4.1
TN	3.0	5.6	2.8	2.7	2.0	2.4	9.0	9.1	2.0	4.1	3.2	3.2	3.0	2.8
NO3	1.9	3.6	1.5	1.3	0.7	0.8	3.6	3.4	1.3	3.2	2.2	2.1	1.7	1.7

	Sep-96		Nov-96					Jan-97					Feb-97		
	cc7	cc8	cc1	cc3	cc5	cc7	cc8	cc1	cc3	cc5	cc7	cc8	cc3	cc7	cc8
COND	572	561	468	768	736	725	594	478	714	666	724	716	546	533	540
pH	8.1	8.1	7.8	8.3	8.4	8.7	8.2	7.6	8.1	8.2	8.4	8.2	8.1	8.4	8.2
TEMP	18.1	16.9	4.1	5.4	5.2	5.3	5.2	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1	-0.1
TP	24.57	20.29	5.36	17.07	20.07	15.29	16.48	6.50	38.43	49.29	47.86	45.76	83.71	102.00	95.57
SRP	6.57	4.14	2.17	7.54	8.92	6.72	7.27	2.71	23.79	35.86	34.14	33.64	52.43	65.14	62.36
ALK	239	237	236	333	323	313	312	197	290	282	281	283	222	213	214
BOD5	1.6	1.7	1.3	0.8	1.8	1.3	1.5	2.6	3.0	3.0	3.1	3.2	1.2	1.1	1.3
TSS	2.5	3.3	0.0	0.0	0.7	1.5	0.8	2.3	3.1	3.0	4.7	1.5	12.0	10.4	10.5
TN	4.9	4.8	1.8	5.7	6.5	6.1	7.1	7.2	7.6	8.2	9.1	8.7	7.2	7.4	6.4
NO3	3.4	3.5	0.9	4.3	4.1	4.9	5.0	6.8	6.9	7.2	8.2	8.1	4.9	5.5	5.9