Phytoplankton Activity in the Red and Assiniboine Rivers as They Flow Through the City of Winnipeg, Manitoba

By

Leslie G. Goodman

A thesis presented to the University of Manitoba in partial fulfillment of the requirements for a degree of Master of Science in the Faculty of Graduate Studies

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PHYTOPLANKTON ACTIVITY IN THE RED AND ASSINIBOINE RIVERS AS THEY FLOW THROUGH THE CITY OF WINNIPEG, MANITOBA

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MASTER OF SCIENCE

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Abstract

Phytoplankton activity in the Red and Assiniboine Rivers was examined during the ice-free period over two years (1994 and 1995) to evaluate the impact of physical and chemical factors (including) anthropogenic discharges on phytoplankton productivity, photosynthesis and standing crop. In total, approximately 60 kms of the Red and Assiniboine Rivers were sampled on a weekly basis for phytoplankton activity and this was related to the physico-chemical status in the Rivers by a series of multivariate approaches including principal component, canonical correlation and multiple discriminant analyses.

The spatio-temporal variability in parameters was examined and pronounced temporal fluctuations in parameters appeared to be highly correlated with River flow rate. Between Rivers and between upstream and downstream Red River locations, there were significant differences in primary productivity that were related to the availability of light within the water column (i.e., euphotic depth) and possibly to nutrient load.

The study clearly identified the restrictions of phytoplankton saturated production to the superficial layers of the water column. While light extinctions were significantly different between years of the study, there was an alteration in phytoplankton photosynthetic efficiency that is proposed to have sustained a conservative saturating depth for photosynthesis. The differences in turbidity between 1994 and 1995 in the Red River did not reduce saturated photosynthesis but rather compromised light-limited rates in 1994. However, in both years, the negative influence of turbidity was pronounced.

There were few periods during the study in which nutrient status was clearly observed to be a factor in modifying phytoplankton activity. However,

during late September and October, in 1995, there was a downward shift in the N/P ratio that coincided with the occurrence of the cyanobacteria Anabaena and Aphanizomenon. Photosynthetic parameters were shown to markedly deviate during this time as well.

This study was limited in its ability to determine the sole influence of nutrient load on phytoplankton productivity and photosynthesis. This was explained by the spatial gradient downstream of increasing light availability and nutrient load. Since it was clearly observed that euphotic depth and the underwater light environment were the principle factors to modify phytoplankton activity in the Red River, it was difficult to isolate the impact of nutrient load from euphotic depth downstream of the City of Winnipeg. Both parameters were significantly higher when compared with upstream locations.

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Chapter 1 Introduction

1.1 Features of Rivers

There are important physical features of rivers that may be integral to the biotic processes that occur within them. These features include generally short residence times, which vary in relation to channel morphometry, and turbulent mixing that prevents the water column from stratifying. Reynolds (1994) has described a river, not by the severity of the turbulence it experiences, but rather by the kinetic energy that it typically displays. The distinction between rivers and lakes is based on the fact that in the latter, it is wind energy that is the principle action to generate turbulence. In rivers, there is a continuous horizontal unidirectional movement of water that may vary in discharge rate but will always result in more or less turbulent eddies and never experience periods of stability as occur in lakes. As water is discharged downstream, attributes of the kinetic flow change with channel cross-section area. Turbulence in the form of eddies, riffles, runs and pools create erratic water movements and circulation patterns. Furthermore, there may be pronounced temporal changes in the discharge rate from the runoff of the surrounding watershed not to mention the resuspension of sediments from eroded river banks. Consequently, the entrained particulates, including phytoplankton, will be churned within the water column and likely be in continuous motion.

Another distinguishing feature of rivers as opposed to lakes is the typically higher concentrations of nutrients found in rivers throughout the year. The stratification that occurs in lakes during the summer months effectively seals off the deeper profiles of the lake and consequently traps nutrients from the superficial epilimnion (Wetzel 1983). In contrast, nutrient depletion is rarely observed in rivers since there are greater contributions from runoff from the surrounding watershed and the resuspension of sediments by turbulence (Meybeck 1982).

1.2 Algae and Rivers

The phytoplankton community in rivers must necessarily adapt to the variable river discharge and the degree of turbulent mixing (Reynolds 1994), not to mention the temporal cycles in water chemistry (Davis and Keller 1983) and the underwater light regime (i.e., Dokulil 1979 and 1994, Baker and Baker 1979 and Grobbelaar 1985). The successful phytoplankter will arguably be the one that is tolerant of physical limitations and able to rapidly assimilate available nutrients in order to maintain short generation times.

The phytoplankton community structure has also been related solely to flow driven changes in physical processes including discharge rate, temperature and light conditions. In the River Moselle, Descy (1993) considered the changes in phytoplankton community structure to be correlated to the severity in the changes in these factors. When there were large fluctuations in discharge, diversity was low and the assemblage was dominated by small centric Stephanodiscus spp. diatoms. Conversely, as these conditions improved, there was first an increase in the diversity, reflecting the intermediate range of river discharge, which was followed by a low diversity and dominance of Skeletonema spp. during low fluctuating conditions. Carvajal-Chitty (1993) found many similar responses in phytoplankton community structure in the Orinoco River in Venezuela. The pronounced shifts among Chlorophyceae, Bacillariophyceae and Cryptophyceae dominance was correlated with disturbance due to increases of water level and the suspended sediment.

River discharge may control phytoplankton growth through a dilution process. Enhanced retention times have been shown to result in higher phytoplankton abundance in systems that were constrained by temporal limitations, rather than nutrient concentrations (i.e., Gloss *et al.* 1980). Descy (1993) described the dilution rate as dependent on the reciprocal of the cross-section area and the rate of discharge. It has been observed that an increase in the standing crop of the phytoplankton population only occurred when their net growth rate exceeded the dilution rate.

An important feature to consider in the impact of hydrodynamic environments to phytoplankton processes is the resuspension of solids and the duration these particulates remain within the water column (Loehr 1987). Baker and Baker (1979), Grobbelaar (1985), Dokulil (1994) and Schmidt (1994) all attributed reduced phytoplankton photosynthesis and/or biomass to the suspended load in shallow lakes and rivers. Dokulil (1994) reported a negative log/log correlation between total suspended solids and chlorophyll. Furthermore, he reported that in the turbid lake, Neusiedler See, the depth to which maximum photosynthesis occurred was conservative between years at 20 cm.

1.3 Photosynthesis and Productivity in Turbid Systems

Arguably, the most influential consequence of the increased suspended load and elevated turbidity in rivers is the concomitant influence over the underwater light environment. Bindloss (1976), Baker and Baker (1979), Grobbelaar (1985), Cuker *et al.* (1990) and Lind *et al.* (1992), among others, have established a significant role for the high abiogenic "clay" turbidity in regulating the light available to phytoplankton production. As light penetrates the water column, it is attenuated through the processes of absorption and scattering by dissolved and particulate substances and the light which will be available for phytoplankton photosynthesis may only represent a small fraction of the incoming irradiance (Dokulil 1979, Wetzel 1983, Grobbelaar 1985, Oliver and Ganf 1988). When turbid conditions prevail, the depth to which irradiances penetrate will be severely compromised and will be evidence by shallow euphotic depth, secchi depth and greater light extinction (Talling 1971, Dokulil 1994 and Grobbelaar 1985).

While it has been clearly documented that phytoplankton standing crop may create a light-limitation in the water-column, i.e., self-shading (Talling 1971), the impact of abiogenic turbidity is less understood. However, conference symposia and publications have been forthcoming on this subject (i.e., volume 289 of Hydrobiologia). There is a growing body of evidence to show that abiogenic turbidity typical of shallow lakes, impoundments and rivers reduces the potential phytoplankton production by placing a limitation below that ordinarily observed by self-shading in otherwise nutrient rich conditions (Søballe and Kimmel 1987, Dokulil 1994). So severe is this limitation, that Jewson and Taylor (1978) have described a competitive response in phytoplankton for the light that is rapidly attenuated by abiogenic physical factors.

The importance of light-limitation on phytoplankton photosynthesis has been clearly established (Reynolds 1984 and 1994, Søballe and Kimmel 1987, Grobbelaar 1985, Dokulil 1994). Talling (1971) used the ratio of euphotic depth to mixing depth to describe the underwater light environment to which circulating phytoplankton were exposed. Since then researchers including Grobbelaar and Stegmann (1976), Grobbelaar (1985), Dokulil (1994) and Reynolds (1994), to name only a few, have referred to its utility in defining the photosynthetic and productivity processes of turbid shallow systems. Reynolds (1994) contrasted the photosynthetic processes and productivity of turbid lakes and rivers with those of deep clear lakes in which the entrained phytoplankton is in continuous vertical motion.

As cells are erratically relocated in the water column by turbulent motion, they are exposed to varying irradiances. In a clear water body, in which the light is principally attenuated only by water itself, the underwater light environment will conceivably penetrate to the circulation, or mixing, depth below. Therefore, the cells will be continuously exposed to a profile of light as they are transported vertically through the water column (Grobbelaar 1985, Reynolds 1994). However, as the suspended load, that is either abiogenic or biogenic, is increased in the water column, there is greater scattering and absorption of light. Consequently, light extinction results in shallower euphotic depths than the mixing or circulating depth. Cells that are entrained in the water column are exposed to less and less available light as they are transported to deeper depths. If the attenuation is so severe, there may be excessive portions of the water column that do not support net photosynthesis since light penetration beyond the compensation level is not encountered at these depths (Grobbelaar 1985, Reynolds *et al.* 1994).

The utility of the ratio of euphotic to mixing depth relates to the changes in euphotic depth due to turbidity (Grobbelaar 1985). As suspensions of particulates increase, there are concomitant increases in light extinction and reductions in the euphotic depth. A profile ensues between the euphotic depth and mixing depth in which subsaturating irradiances, or even darkness, prevail. If the circulation of the water column is over short intervals, then the exposure of communities to subsaturating irradiances will have less impact than if the circulation occurs over extended periods. Thus, Grobbelaar (1985 and 1989) and Reynolds (1994) have concluded that three factors are critical in determining photosynthesis in turbid systems: The circulation pattern of entrained cells, attenuation of light within the water column, and the relative mixing depth in the water column.

1.4 Natural and Anthropogenic Sources of Nutrients in Rivers

Since before the time of the first sewage collection system in the Indus valley and Middle East cities some 5000 years ago (Meybeck 1993), human activity have profoundly influenced the quality of surface waters. Our influence has accelerated since the 1950's with the mass production and application of N and P fertilizers, detergent polyphosphates, effluent from pulp and paper mills and textile and food industries, not to mention the enrichment by the fallout of atmospheric pollutants. Conservative estimates indicate that anthropogenic additions have resulted in a doubling of nutrient loading in river systems in the last few decades (Meybeck 1982 and 1993), and this is perhaps most pronounced in Europe. Furthermore, the transport of these nutrients to oceans only reduces these additions by less than 10 %, and the remainder is retained on the continental surface (Meybeck 1993). Concomitant with these enrichments has been changes in the biotic community. Nuisance phytoplankton blooms, including filamentous cyanobacteria and *Cladophora* have been observed to clog waterways and shorelines downstream of point discharges (Whitton 1975). There have also been substantial increases in heterotrophic bacterial processes on enhanced organic loads (Whotton 1994).

There are comparatively few forms of phosphates in natural bodies of water and over 90 % of phosphorus is bound to organics in cellular constituents (Wetzel 1983). Conversely, the sources of inorganic nitrogen are several-fold and include nitrate (NO_3^-), nitrite (NO_2^-) and ammonia (NH_4^+ and NH_3). In natural waters, that are not impacted by human activity, these nutrients are very nearly undetectable. For example, the concentrations of orthophosphates available to autotrophic organisms is typically between 1 to 24 $\mu g\ l^{-1}$ with the most commonly encountered value around 8 $\mu g\ l^{-1}$ (Meybeck 1982). Furthermore, there are relatively low concentrations of allochthonous organics in natural rivers since these are rapidly mineralized by decomposition and assimilated by autotrophic organisms.

There have been great strides to quantify natural concentrations in pristine rivers in order to generate a database for comparative work with human disturbed systems. For example, Meybeck (1993) has described the global concentrations in unpolluted waters as the most common natural concentration (MCNC). This value represents the median concentration on a distribution curve from major rivers around the world. In Table 1.1, the nutrient concentrations of unpolluted rivers, including their minimum, maximum and MCNC are compared to the Seine and the Mississippi Rivers of France and Unites States, both of which have been exploited by human activity.

Table 1.1 Statistical distribution of N and P (mg l^{-1}) in unpolluted world Rivers, the Seine and Mississippi Rivers that are affected by multiple human activity (from Meybeck 1993).

	Unpolluted Rivers			Seine	Mississippi
Species	Minimum	Maximum	MCNC		
Dissolved Inorganic Carbon (DIC)	2.3	31.0	6.0	55.0	23.2
Dissolved Organic Carbon (DOC)	2.5	8.5	4.2	3.65	3.5
Particulate Organic Carbon (POC)			3.0	13.5	
Ammonia (NH_4^+-N)	0.005	0.04	0.015	1.0	0.13
Nitrate (NO_3^--N)	0.05	0.2	0.10	4.3	1.1
Soluble Organic Nitrogen (SON)	0.05	1.0	0.26	0.5	0.13
Soluble Reactive Phosphorus (SRP)	0.002	0.025	0.01	0.4	0.3

The disparity between Rivers in regards to nutrient enrichment was pronounced in 1993, the year of the report. In particular, the concentrations of NH_4^+ and SRP were found to be higher in the Seine and Mississippi Rivers when compared unpolluted rivers and this enrichment was most pronounced in the Seine River. This was evidenced, for example, in concentrations of NH_4^+, NO_3^- and SON (Table 1.1).

In Manitoba, surface water quality, including local discharge regulations, are regulated by the government through a series of objectives outlined in, for example Williamson (1988). To meet these standards, the City of Winnipeg water pollution control efforts have incurred over $200 million in renovations to treatment plant processes over the past 20 years (Ross 1996).

Davis and Keller (1983) examined the seasonal cycles in the transport of dissolved and suspended material. In temperate rivers, there are seasonal changes in the chemical concentrations of rivers that at times, appear poorly correlated to precipitation. In the winter precipitation is accumulated as snow and is not a contributing factor to river discharge. While the high discharge rates that result from snowmelt appear uncorrelated to recent precipitation events, the runoff from the surrounding watershed significantly enhances the allochthonous nutrient load. Lastly, there is a transition into summer and autumn conditions with significant evapotranspiration losses. The varying contribution of water from rain, snowmelt and groundwater during the course of the year were proposed by Davis and Keller (1983) to be a factor that defines the chemical concentrations found in streamwater and river water.

Meybeck (1993) compared the influence of river discharge on nutrient concentrations in pristine and anthropogenically impacted rivers. As shown in Figure 1.1, these relationships were profound for concentrations of NO_3^- and SRP. In particular, the discharge in pristine rivers was poorly correlated with either NO_3^- or SRP concentration in the river water. The slight increase that is observed for NO_3^- was contributed by the runoff from the surrounding basin. Conversely, there are more pronounced correlations between river discharge and nutrient concentrations in regions more heavily exploited by human activity. In agricultural watersheds, the enhanced concentrations of NO_3^- and SRP observed in river water during high discharge result from the runoff of fertilizers and manure from saturated fields. Lastly, point sources of industrial or wastewater treatment plants are characterized by dilution patterns with increase discharge.

1.5 Nutrients and Biotic Processes

Quantifying the cycling of nutrients in disturbed areas is complicated by the biochemical reactions that result in transformations of organic and inorganic pools of carbon, nitrogen and phosphorus. This is most pronounced in nitrogen cycling in which ammonification of organic nitrogen, nitrification, denitrification and nitrogen fixation can dramatically alter the concentrations of the various nitrogen forms (Wetzel 1983). Jana (1994) provides a review of the processes of ammonification of organic nitrogen by heterotrophic bacteria in aquatic environments.

There are both ionized (NH_4^+) and unionized (NH_3-N) species of ammonia dissolved in water that exist in equilibrium defined by temperature and pH (Trussell 1972). When the unionized form reaches particularly high concentrations, it may become toxic to fish populations (Richardson 1991, Mommsen and Walsh 1992, Wajsbrot *et al.* 1993). There are inconsistencies in the reported thresholds of critical concentrations that may be species-

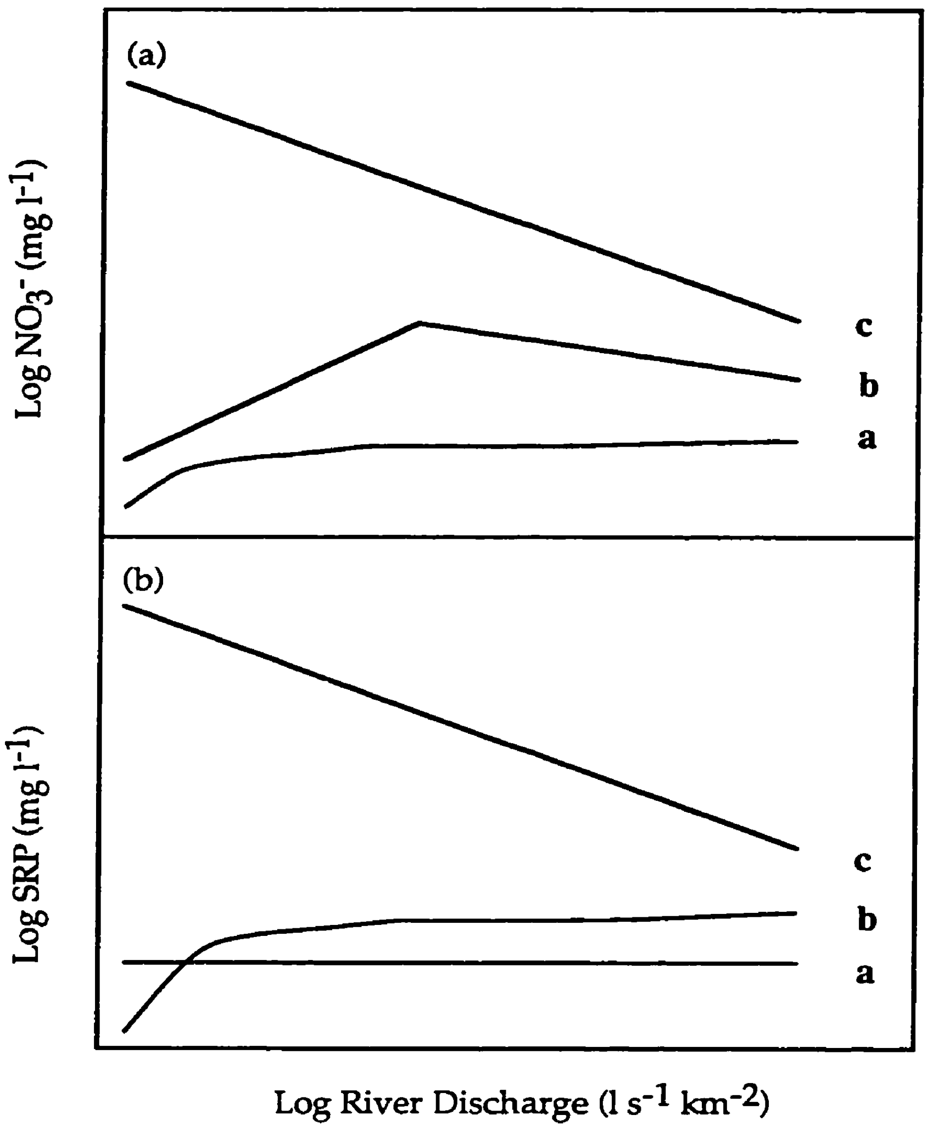


Figure 1.1 Behavior of (a) nitrate and (b) soluble reactive phosphorus to River discharge in:

- **a** prisitne streams;
- **b** agricultural watershed with drainage systems; and
- **c** systems receiving domestic waste water inputs.

specific. While Richardson (1991) has found that toxicity at 15 °C and pH 8 was approximately 1.60 mg NH_3-N l^{-1}, Wajsbrot *et al.* (1993) reported the maximum acceptable toxic concentration for growth at 0.3 and 0.5 mg NH_3-N l^{-1}. Furthermore, Szal *et al.* (1991) have reported greater toxicity in chlorinated effluent because of the interactive effects of residual chlorine, ammonia and reduced dissolved oxygen concentrations. Further complicating the issue of toxicity is the influence of intermittent exposure to ammonia that may be more important in defining toxicity than continuous exposure (Handy 1994).

Further transformations of the ammonia pool involve the nitrification of ammonia to nitrate, in which organic and inorganic nitrogen species are oxidized to nitrate. While the process reduces the concentration of ammonia in solution, the oxygen demand during the reaction may reduce oxygen concentrations dissolved in the water. Although the process may continue at low oxygen tensions, Wetzel (1983) has described an inhibition of nitrification in waters containing high concentrations of dissolved humic organic matter such as tannins.

Through the actions of denitrification and N_2 fixation, there may be export and/or import of nitrogen that does not strictly lead to its recycling within the system. In particular, denitrification occurs by facultative anaerobic bacteria and involves the biochemical reduction of oxidized nitrogen species, i.e., NO_3^- and NO_2^-, with concomitant oxidation of organic matter (Wetzel 1983). In so doing, the combined nitrogen concentration may be significantly reduced and the N_2 gas formed may represent a net export to the atmosphere. Conversely, some cyanobacteria may fix atmospheric/dissolved N_2 gas directly by way of nitrogenase and thereby import nitrogen into the system. Such a process is considered to have significant ramifications in the dominance of heterocystous cyanobacteria blooms during periods in which the N/P ratio is low (Schindler 1977, Hecky *et al.* 1993).

The assimilation of nitrogen compounds by autotrophic phytoplankton has been well studied in the laboratory setting (i.e., Hattori 1960, Syrett and Morris 1963, Healey 1977). And paralleling the numerous transformations of nitrogen by heterotrophic bacteria, there are seemingly varied sources of nitrogen available to algae as evidenced by the utilization of ammonia, nitrate and nitrite as well as organic sources such as urea, amino acids and purines (Healey 1973 and 1977, Neilson and Larsson 1980). However, whatever the source, there is consensus that it is first converted to NH_4^+-N before incorporation into cellular organic compounds (Syrett 1981). Consequently ammonia has generally been considered the more energy-efficient source of nitrogen for plants. Furthermore, the suppression of nitrate assimilation, via the inactivation of nitrate reductase, has been linked to the availability of ammonia (Syrett and Morris 1963, Eppley *et al.* 1969). However, while higher growth rates have been reported in algae grown on sources of ammonia, toxicity may occur at high concentrations (Toetz *et al.* 1977, Toetz and Cole 1980).

The forms of phosphorus that are available to autotrophs are more restricted. Generally, the only inorganic form that is assimilated by algae is orthophosphate, although there have been reports of utilization of polyphosphates and organic phosphorus compounds by the action of alkaline phosphatase (Healey 1973, Nalewajko and Lean 1980, Pick 1987).

Phytoplankton cells growing a nutrient-unlimited environment would normally show a C:N:P atomic ratio of approximately 106:16:1, typically referred to as the Redfield ratio (Redfield *et al.* 1963). While studies have adjusted the range in these ratios which suggest sufficiency, large departures are considered to represent nutrient limitation. Indicators of nutrient deficiency typically include ratios of compositional atomic nitrogen, phosphorus, carbon, silicon and units of biomass (chlorophyll *a*, dry weight).

The rather ubiquitous response to sufficiency/deficiency in numerous algae have permitted the semi-quantification of physiological deficiency (Healey 1975, Healey and Hendzel 1980). The general response to a deficiency in nutrient is a decrease in the cell quota of the limiting nutrient. The effects of both phosphorus and nitrogen limitation have been extensively studied in the marine diatom Thalassiosira (Eppley and Renger 1974, McCarthy and Goldman 1979). Nitrogen limitation causes a decrease in growth rate expressed as generation time and photosynthetic rate. The cell quotas for nitrogen, phosphorus, and chlorophyll *a* decline at a faster rate than that of carbon, bringing about an increase in the ratio of carbon to the other cell components when deficiency occurs (Healey 1973 and 1975, and Healey and Hendzel 1980). Phosphorus deficiency also increases the generation time, but while the cell quota for phosphorus drops, nitrogen remains constant and the carbon per cell increases.

The utility of atomic ratios in ecological applications has been indispensable in surface water management as reviewed by Hecky and Kilham (1988). Perhaps the importance of these ratios, and in particular the N/P ratio, is exemplified in the occurrence of heterocystous cyanobacteria in phosphorus enriched systems which result in a depressed N/P ratio (Schindler 1977). Although both the absolute concentrations and ratio of N and P vary depending on the source, an average N/P ratio for North American sewage is 4:1 to 5:1, which contrasts with the Redfield natural ratio of 16:1 to 30: 1 in natural inputs (Schindler *et al.* 1973). Concomitant with the change in the N/P nutrient ratio is the shift in the phytoplankton of sewage enriched receiving waters from a state of phosphorus deficiency to one of nitrogen limitation. The occurrence of the cyanobacterium Anabaena correlated with nitrogen limitation has been well documented (Schindler 1977, Hecky *et al.* 1993). Furthermore, Flett *et al.* (1980) has shown that it is not the concentration of soluble inorganic nitrogen (SIN) in the water column, per se, that influences phytoplankton composition. By altering the concentration of SIN, it appeared that there was little consequence on the dominance of heterocystous cyanobacteria, as their occurrence was noted at both high and low SIN concentrations. Rather, these researcher reported that it was the ratio of SIN to inorganic phosphorus that was the determining factor in the occurrence of a bloom. The importance of this ratio has also been used in efforts to determine causes of nuisance blooms of Cladophora in anthropogenically enriched streams (Lohman *et al.* 1992).

1.6 The Relation Between Light and Nutrients in Rivers

While the importance of nutrient status in defining sufficiency and deficiency has been clearly identified, there is an increasing acknowledgment of the restrictions of nutrients as sole predictors of phytoplankton activity in rivers and impoundments (Søballe and Kimmel 1987, Reynolds 1994, Dokulil 1994). In these systems, the residence time and turbidity are reported to reduce population dynamics below its potential (Bindloss 1976, Søballe and Kimmel 1987). For example, Kimmel *et al.* (1990) found that phytoplankton production was lower than would be predicted by elemental concentrations of N or P. Bindloss (1976) reported that although the Loch Leven had a high phytoplankton production potential, it was not realized because the resuspension of sediments significantly increased light attenuation.

Furthermore, the cycling of nutrients has been reported to shift from biogenic to physical control as residence time decreased (Meyer and Likens 1979).

Several researchers have reported differences in the relationships of total phosphorus concentrations with phytoplankton activity. Søballe and Kimmel (1987) and Dokulil (1994) found that phytoplankton standing crop were significantly lower, by about 2 to 3 times, than counts in lakes with comparable phosphorus concentrations. Phytoplankton abundance in systems of short residence times was found to often depend more on variation in physical characteristics (i.e., temperature, turbidity and flow variation) than on actual nutrient concentration (Hynes 1970, Swanson and Bachmann 1976, Round 1981, Søballe and Bachmann 1984, Søballe and Threlkeld 1985).

Models that related phytoplankton abundance and productivity strictly to nutrient concentration may neglect the influence of physical factors. In short-residence systems, such as rivers and impoundments, abiotic factors that may be unrelated to nutrient availability have clearly been shown to be important determinants of phytoplankton biomass (Dokulil 1994, Grobbelaar 1985, Søballe and Kimmel 1987, Loehr 1987). As a result of the dissimilarities in the magnitude of discharge between rivers and lakes, the relative importance of physical and biotic processes would necessarily differ and the river phytoplankton community composition and dynamism should be more closely tied to turbulence and light availability (i.e., Descy 1993, Dokulil 1994, Reynolds 1994).

1.7 The Utility of Algae in River Assessments

Algae are being increasingly exploited in biomonitoring in both Europe and the United States (i.e., Whitton 1975, Lhotsky and Marvan 1991, Coste *et* *al.* 1991, Dokulil 1991). Arguably, it makes more sense to monitor the response of the biological communities in conjunction with changes in the physico-chemical status than the latter alone. Organisms have a integrated response to their dynamic environment which may be readily measured. However, as pointed out by Whitton and Kelly (1995), even though photosynthetic algae are important components of most rivers, their actual use for monitoring purposes seldom matches their importance.

The advantages of using algae to monitor water quality are several fold. They form an important component of the system that can neither be removed nor ignored in ecological modeling, they are present before and after pollution incidents and their nutrient and community composition tend to reflect that of the surface water. However, as pointed out by Cox (1991), the validity of correlations between measured environmental variables and species abundance or standing crop without demonstrable causal relationships is questionable.

1.8 Objectives

The objectives of this study were to assess the activity of the phytoplankton community in the Red River and to determine the influence of Assiniboine discharge, and anthropogenic activity, including point source discharges and urban runoff, on these processes. To this end, the thesis has been organized into sections as follows:

(1) Chapter 2 provides a description of the study area including the physical geography and anthropogenic activity.

(2) Chapter 3 presents a summary of the methods, including field techniques, laboratory procedures and statistical approaches used in the collection and analysis of data.

(3) Chapter 4 provides a detailed description of the temporal and spatial variability observed in physical, chemical and phytoplankton parameters.

(4) Chapter 5 evaluates the underwater light environment as a potentially limiting factor to phytoplankton activity.

(5) Chapter 6, through a multivariate approach, identified the factors that were most influential to phytoplankton photosynthesis and productivity in the years of the study.

1.9 Definitions

The following includes definitions and terms encountered throughout the thesis:

(a) *Physical Parameters*: measures of flow rate, precipitation, *in situ* water temperature, ambient photosynthetically active radiation (PAR), light extinction and euphotic depth. Light extinction and euphotic depth were measurements of the available light within the water column and were, themselves, negatively correlated.

(b) *Chemical Parameters*: measurements of nutrient concentrations ($mg\ l^{-1}$) including carbon, nitrogen and phosphorus as follows:

- DO = *in situ* dissolved oxygen
- TN = total nitrogen (including all forms)

- SON = soluble organic nitrogen
- SIN = soluble inorganic nitrogen (including NH_4^+/NH_3-N + TON)
- NH_4^+/NH_3-N (mg l^{-1}) = total ammonia nitrogen (including ionized and un-ionized forms)
- TON = total oxidized nitrogen, or NO_3^-/NO_2^--N
- PN = particulate nitrogen, determined in 1994 only
- TP = total phosphorus
- DP = total dissolved phosphorus
- PP = particulate phosphorus
- SRP = soluble reactive phosphorus
- SOP = soluble organic phosphorus
- TOC = total organic carbon, determined in 1995 only
- SOC = soluble organic carbon
- PC = particulate carbon, determined in 1994 only

(c) *Phytoplankton Parameters*: measurements of phytoplankton activity, including standing crop, photosynthesis and primary production.

- Estimated Daily Productivity: measures of *in situ* primary production dependent on measures of *in vitro* photosynthesis and the availability of light within the water column.
- Standing crop or biomass (µg Chl *a*): estimated by the concentration of chlorophyll *a* extracted from filtered water samples.
- Parameters of Photosynthesis: measures of photosynthesis under light-limitation (alpha) and saturation (P_{max}) that result in a curvilinear relationship (i.e., the P vs. I curve).
- alpha (µg C l^{-1} h^{-1} µmole^{-1} m^{-2} s^{-1}): is the increasing slope of the P vs. I curve representative of light-dependent carbon uptake . With increasing

irradiance, more carbon is fixed in a linear relationship. Chlorophyll-normalized values of alpha are referred to as SPalpha (µg C h^{-1} $\mu mole^{-1}$ m^{-2} s^{-1} µg Chl *a*).

- P_{max} (µg C l^{-1} h^{-1}): the plateau of the P vs. I curve, representative of saturated carbon uptake. Once the threshold irradiance is exceeded, the relationship between carbon uptake and exposure irradiance become uncorrelated. Chlorophyll-normalized values of P_{max} are referred to as SP_{max} (µg C h^{-1} µg Chl a^{-1}).
- I_k (µmoles m^{-2} s^{-1}): the threshold irradiance that saturates photosynthesis. This is a derived value from the intercept of alpha and P_{max}.

Chapter 2 Study Site Description

2.1 Geography

The area considered in this study encompassed approximately 60 km of the Red and Assiniboine Rivers. The Red River is formed in the United States by the confluence of the Otter Tail and Bois de Sioux Rivers at Wahpeton, North Dakota (Water Resources Division 1953). From there, the River travels 880 km north, through Fargo/Moorhead, Grand Forks, Emerson and Winnipeg until it empties into Lake Winnipeg. Along this course, it is joined by the Assiniboine River within the limits of the City of Winnipeg.

The watershed of these two Rivers is vast in comparison with the study area. As shown in Figure 2.1, these Rivers drain large portions of Manitoba, southeastern Saskatchewan, North Dakota and northwestern Minnesota. The Red River basin extends roughly 160 km in the east/west direction to Winnipeg and has several major confluences (Water Resources Division 1953). These include the Sheyenne, Red Lake, Pembina and Roseau Rivers.

Continental glaciers shaped the basin into a landscape of very flat lake plains with gently rolling uplands, lakes and wetlands along the basin margins (Stoner *et al.* 1993). Although the basin only drops 0.1 m km^{-1} (McLaurin and Wedel 1981), a total area of 287,500 km^2 is drained by the River at Lockport (C.E.C. 1992).

The Assiniboine River basin drains southeastern Saskatchewan, northwest North Dakota and southern Manitoba. It travels south upon entering Manitoba, through the Manitoba Escarpment where it joins with the Qu' Appelle River. It then flows east to its confluence, first with the Souris River and finally with the Red. Of the water flowing through the City of

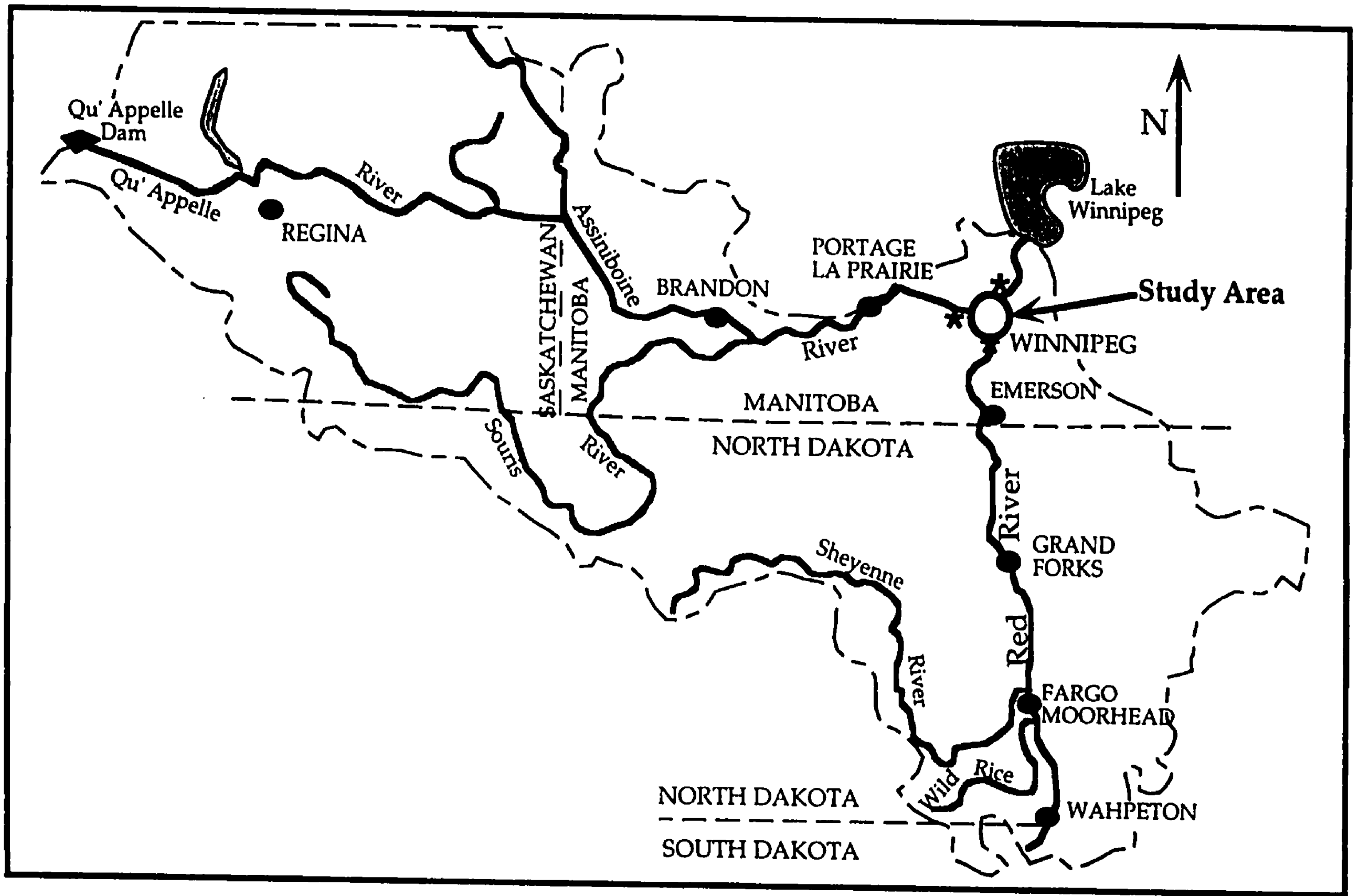


Figure 2.1 The watersheds of the Red and Assiniboine Rivers (from Wardrop et al. 1991).
* indicate the locations of the three Environment Canada hydrometric stations.

Winnipeg north of the confluence, approximately 31% is derived from the Assiniboine River and 69 % from the Red River. The combined origins of flow are 45% from Manitoba, 46% from the United States, and 9% from Saskatchewan (C.E.C. 1992).

Within the confines of the study are numerous smaller tributaries that may impact water quality in both the Red and Assiniboine Rivers. These include the LaSalle, and Seine Rivers as well as Grassmere, Parkdale, Bunn's and Cook's Creeks along the Red River, and the Sturgeon and Omand's Creeks along the Assiniboine.

2.2 Geology and Soil

The Red River watershed is underlain with a bedrock composed of Ordovician limestone and dolomite known as the Red River formation (Geological Survey of Canada 1987). Over this bedrock are significant deposits of glacial drift (rock flour, clay, sand, gravel and boulders) that vary in thickness from 9 to 15 meters (Water Resources Division 1953). Geologically, these deposits resulted from the alluvium emptied into Lake Agassiz by the former Assiniboine River system which, at the time of glacial retreat, drained the entire prairie region. Highly plastic clays have deposited over this till and have given rise to the meanders in the Red River (McLaurin and Wedel 1981). This winding nature is found along much of the Red River, from its origins in North Dakota, and through Manitoba to the north-end of Winnipeg. Thereafter, the River follows a relatively direct north-easterly course beyond Lockport (Ross and Hemphill 1991).

2.3 Climate

The climate of the Red River basin is described as continental subhumid (Stoner *et al.* 1993). The local climate in Winnipeg is best described by its extremes in conditions including wide ranges in temperatures and precipitation with the season (Ross and Hemphill 1991). The long-term monthly mean precipitation and temperatures in Winnipeg are found in Figure 2.2. April through October are attributed with daily means that are above freezing and are highest during July (Figure 2.2b). This period is also attributed with higher recorded amounts of precipitation in contrast with winter months, but there is typically a minimum of 17.5 mm of precipitation during each month. Highest precipitation is commonly found in June (Figure 2.2a).

Recorded precipitation varied considerably on a weekly basis during 1994 and 1995, the years of this study (Figure 2.3). In 1994, major events were observed in late June and early July. In 1995, major precipitation events occurred in August.

Although not shown, the *in situ* water temperatures are well above freezing by early May and remain consistently high during July and August. In September, temperatures are comparable to June but by October, they have fallen well below the recorded values in May.

2.4 Hydrology

Within the United States, 75 % of the Red River annual flow is received from the eastern tributaries as a result of regional patterns of precipitation, evapotranspiration, soils and topography (Stoner *et al.* 1993).

In Canada, the annual mean discharge rates (1964 to 1990) in the Red River are 146 $m^3 s^{-1}$ at St. Agathe, upstream of the City of Winnipeg (Water

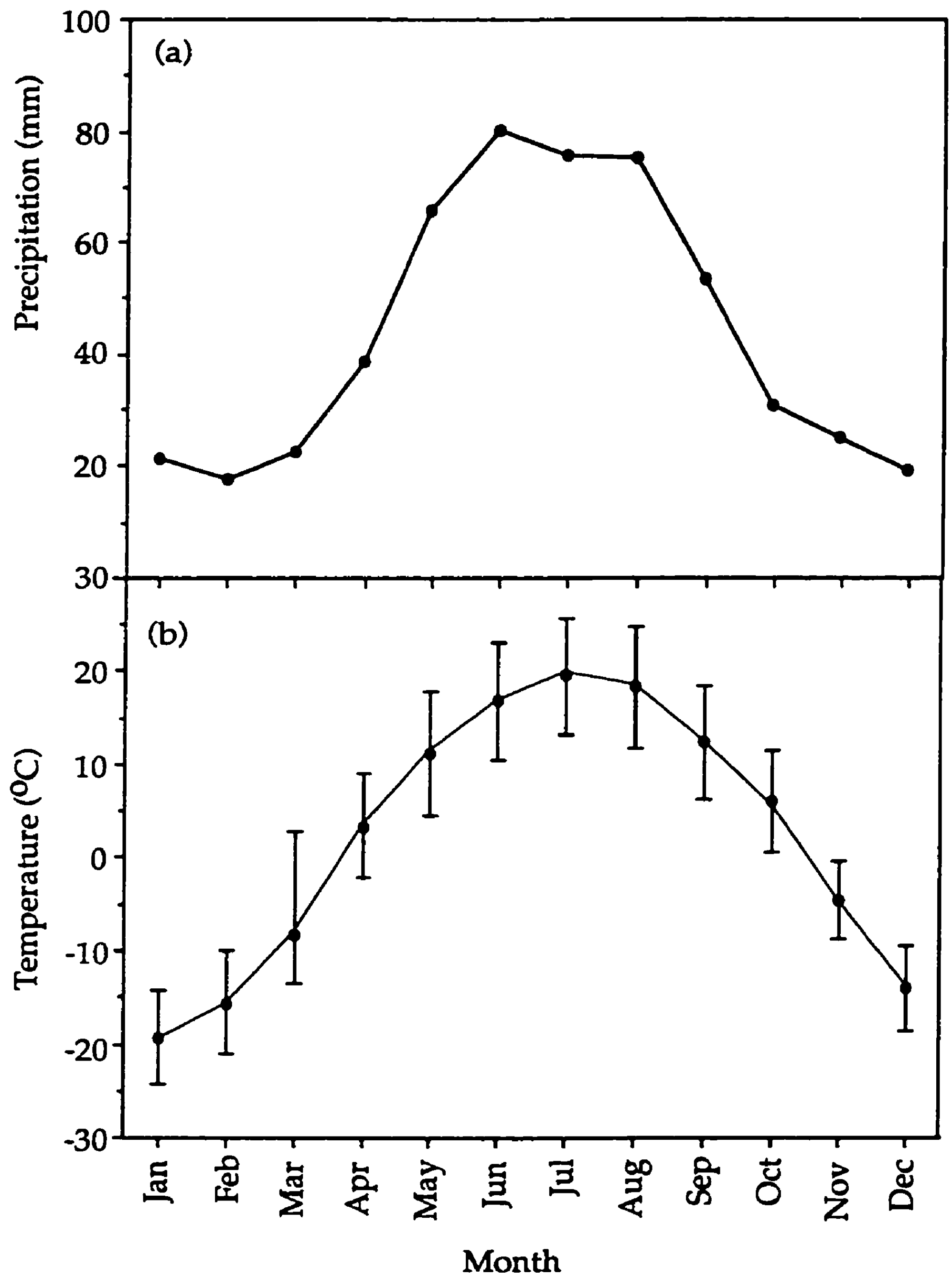


Figure 2.2 The average monthly (a) precipitation and (b) temperature $\pm$ maximum and minimum between 1961 and 1990 (Environment Canada, AES 1992).

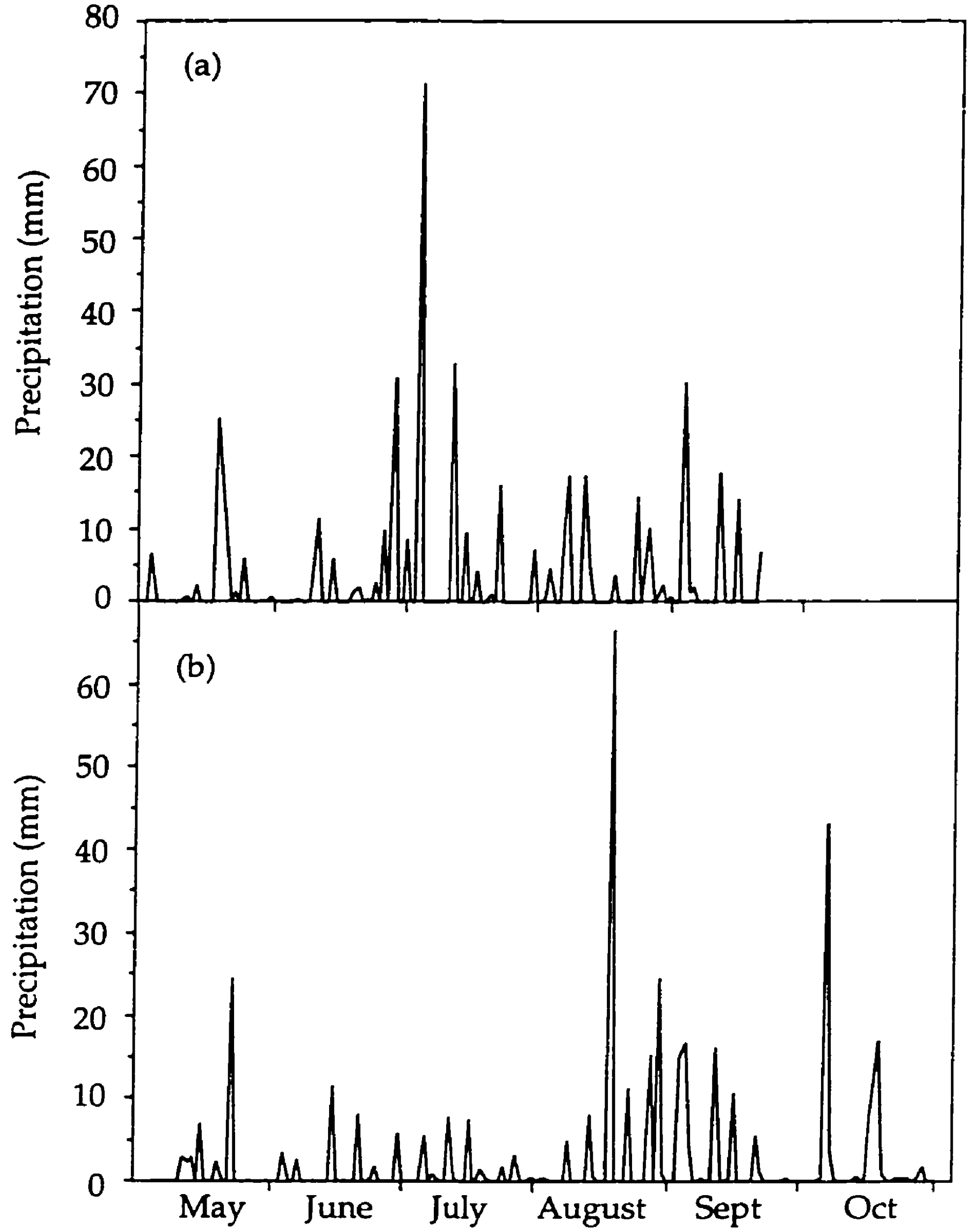


Figure 2.3 Total daily precipitation in (a) 1994 and (b) 1995 over the sampling period (May - September/October). Data from City of Winnipeg Telemetry studies (1994 and 1995) and Environment Canada Winnipeg International Airport (Environment Canada AES 1994 and 1995).

Survey of Canada 1992). Flows at Lockport, which include the contribution from the Assiniboine River, are higher at 206 $m^3 s^{-1}$, but these rates are extremely variable from year to year. Rates are dominated by spring runoff events that, in combination with higher spring precipitation, are often responsible for major flooding along the Rivers (Ross and Hemphill 1991, Stoner *et al.* 1993).

The long-term mean ± maximum/minimum discharge rates are found in Figure 2.4. Lowest discharges at Lockport occur during the month of February but increase during March and April. Thereafter, these rates taper off into the summer and fall months. The discharge rates in the Red and Assiniboine Rivers during 1994 and 1995 are found in Figure 2.5. As expected, these rates increased during March and April of both years. However, this rate increase was more pronounced in 1995. Moreover, these rates remained elevated through May and June in 1995, a feature that was most pronounced in the Assiniboine River.

There were several months in both 1994 and 1995 in which discharges approached the maximum recorded long-term rate (Figure 2.4). In addition, the discharges in both Rivers rarely decreased below the long term mean and never approached the long-term minimum.

2.5 River Morphometry

Water flows and levels are regulated along both drainage basins which influence the hydraulic properties of the Red and Assiniboine Rivers. On the Assiniboine River system, are the Shellmouth Dam and the Portage Diversion. The Qu' Appelle River has five smaller control structures in Saskatchewan that regulate water flow into the Assiniboine. On the Red River, both the Winnipeg Floodway and the St. Andrews Locks are the major

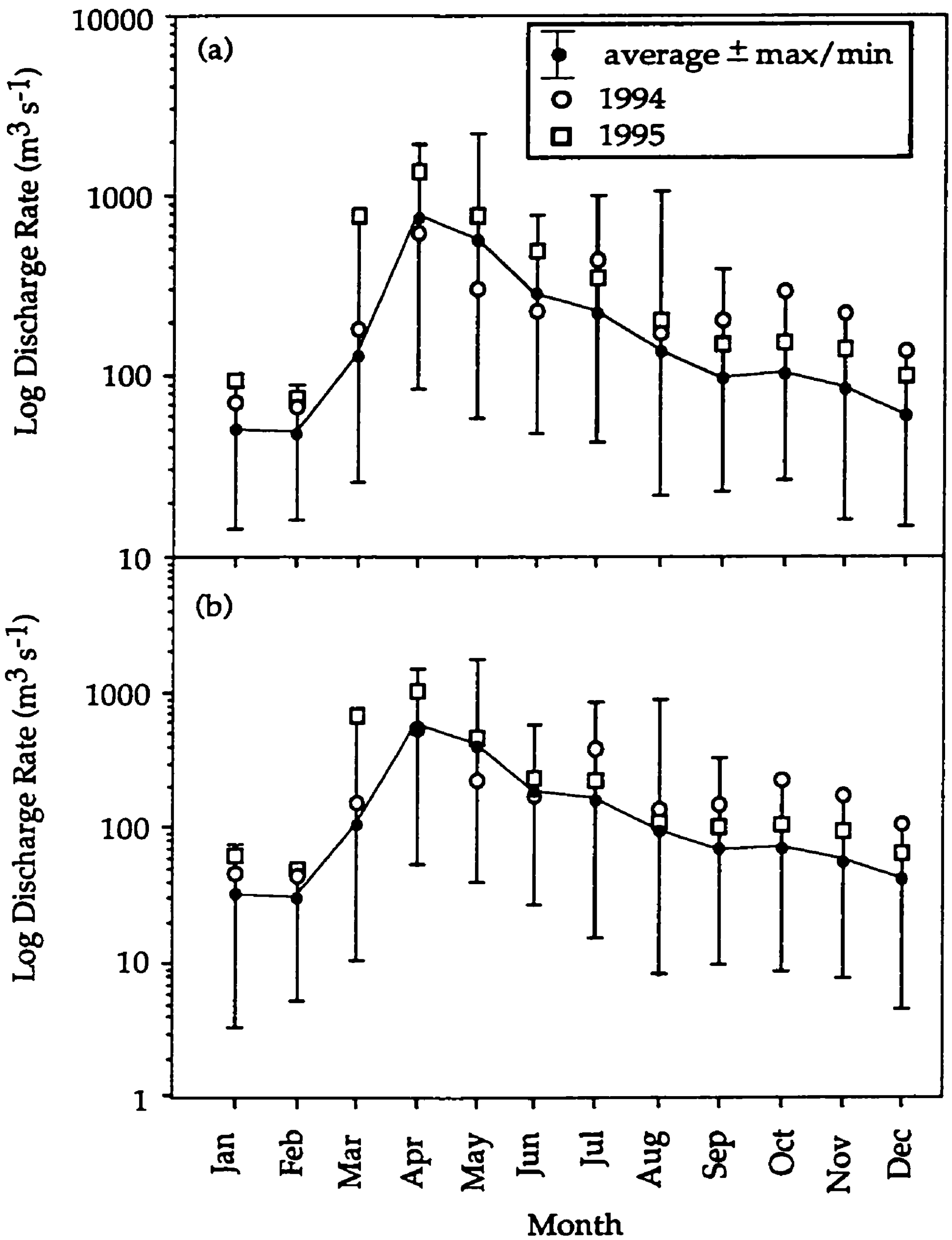


Figure 2.4 Long-term, 1994 and 1995 monthly River discharges monitored at (a) Lockport and (b) St. Agathe (Water Survey of Canada 1992, 1994 and 1995).

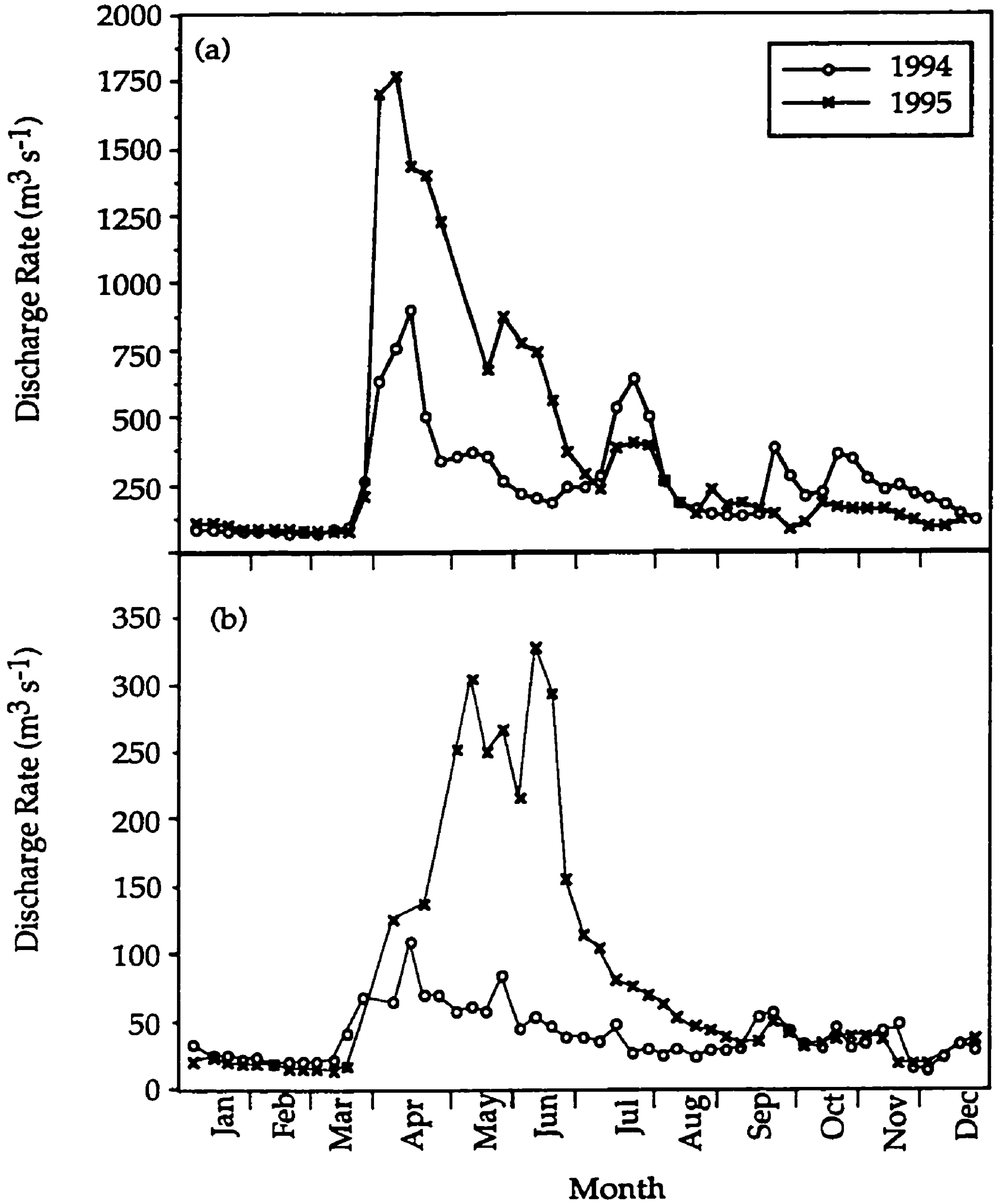


Figure 2.5 Weekly River discharge rates at (a) Lockport and (b) Headingley during 1994 and 1995 (Water Survey of Canada 1994 and 1995).

hydraulic structures in Manitoba. In addition, there are five major reservoirs located on tributaries of the Red River in the United States which include the Red Rock Reservoir on the Red Rock River; Orwell on the Ottertail River; Baldhill on the Sheyenne River; Homme Dam on the Park River and Lake Traverse. There are also numerous control structures found on the smaller tributaries of the Red, as for example the LaSalle River .

Within the City of Winnipeg and the boundaries of this study, the most important of these structures is the Lockport Dam on the Red River (Ross and Hemphill 1991). It effectively raises the River water level during the open water season, thereby increasing the channel width and cross-section area downstream of the Assiniboine confluence (Table 2.1).

2.6 Regional Uses

Williamson (1988) has outlined the Manitoba Surface Water Quality Objectives (MSWQO) and it is not surprising that land-use practices are paramount. These practices, which include the exploitation for hydroelectric stations, agriculture and forestry, may alter concentrations of pesticides, bacterial contaminants and sediment loads in the Rivers. In the United States, the Red River basin is heavily exploited for agriculture. In 1990, productive cropland covered 66 % of the land area (Stoner *et al.* 1993). Additional activity include sugar-beet refining, and potato processing.

More important to this study, is the recognition that surface water quality may be compromised through the disposal of industrial and municipal effluents. There are numerous cities and towns along the banks of the Red and Assiniboine Rivers and their tributaries that discharge varying

Table 2.1 Distances, GPS coordinates, channel widths and channel cross-section areas of sampling locations in the Red River. Distances were determined using a planimeter and map from the Surveys and Mapping Branch, Dept. of Energy, Mines and Resources (1980). No morphometric information was available for locations along the Assiniboine River.

Sampling Station	Distance of Sampling Station from R1 (km)	GPS Coordinates	Channel Width (m)	Cross-Section Area (m^2)
R1	0	49° 45' 06" N 97° 08' 16" W	139	455.7
R2	9	49° 47' 02" N 97° 08' 04" W	123	413.4
R3	16	49° 47' 52" N 97° 07' 09" W	117	548.6
R4	22	49° 52' 33" N 97° 07' 36" W	127	477.8
R5	31	49° 53' 23" N 97° 07' 32" W	153	477.7
R5.1	34.5	49° 55' 15" N 97° 07' 04" W	146	605.9
R6	38	49° 57' 00" N 97° 05' 54" W	150	878.7
R7	47	49° 57' 50" N 97° 04' 04" W	163	681.5
R8	55	49° 59' 57" N 97° 02' 54" W	210	717.1
R9	57	50° 03' 53" N 96° 58' 36" W	198	957.8
R10	63	50° 04' 47" N 96° 56' 21" W	298	1473.0

levels of treated sewage into the Rivers. These centers include: Fargo-Moorhead, Grand Forks, Souris, Brandon, Portage la Prairie, Selkirk and Winnipeg.

2.7 City of Winnipeg Wastewater Discharge Practices

Wastewater discharges to the Red and Assiniboine Rivers are derived from either point-source, or dry weather discharges, and urban stormwater runoff and combined sewer overflow, or wet weather events. Dry weather sources are defined as year round discharges from treatment facilities that are independent of major storm events or snow melt. In Winnipeg, these originate from three wastewater treatment facilities (WPCCs) (Figure 2.6). Two of these WPCCs are located along the Red River. The largest is located near the northern limit of the City, the NEWPCC, and services an area of approximately 16,200 ha, or roughly 70 % of the sewered-area of the City. The smaller facility, the SEWPCC, is located near the southern limit of the City along the Red River and services an area of approximately 7,700 ha or 20%. The third treatment facility, the WEWPCC, is also located near the western limit of the City of Winnipeg on the Assiniboine River and services 3,900 ha or 10 % (Permut *et al.* 1980). Information about WPCC loadings in the Red River is available in, for example, Wardrop *et al.* (1991).

All City of Winnipeg treatment facilities have been equipped with primary and secondary technologies that include oxygen-activated secondary treatment at both the NEWPCC and SEWPCC. Furthermore, sludge digestion and dewatering (of primary sludge and waste activated sludge) are performed at the NEWPCC (Ross 1996).

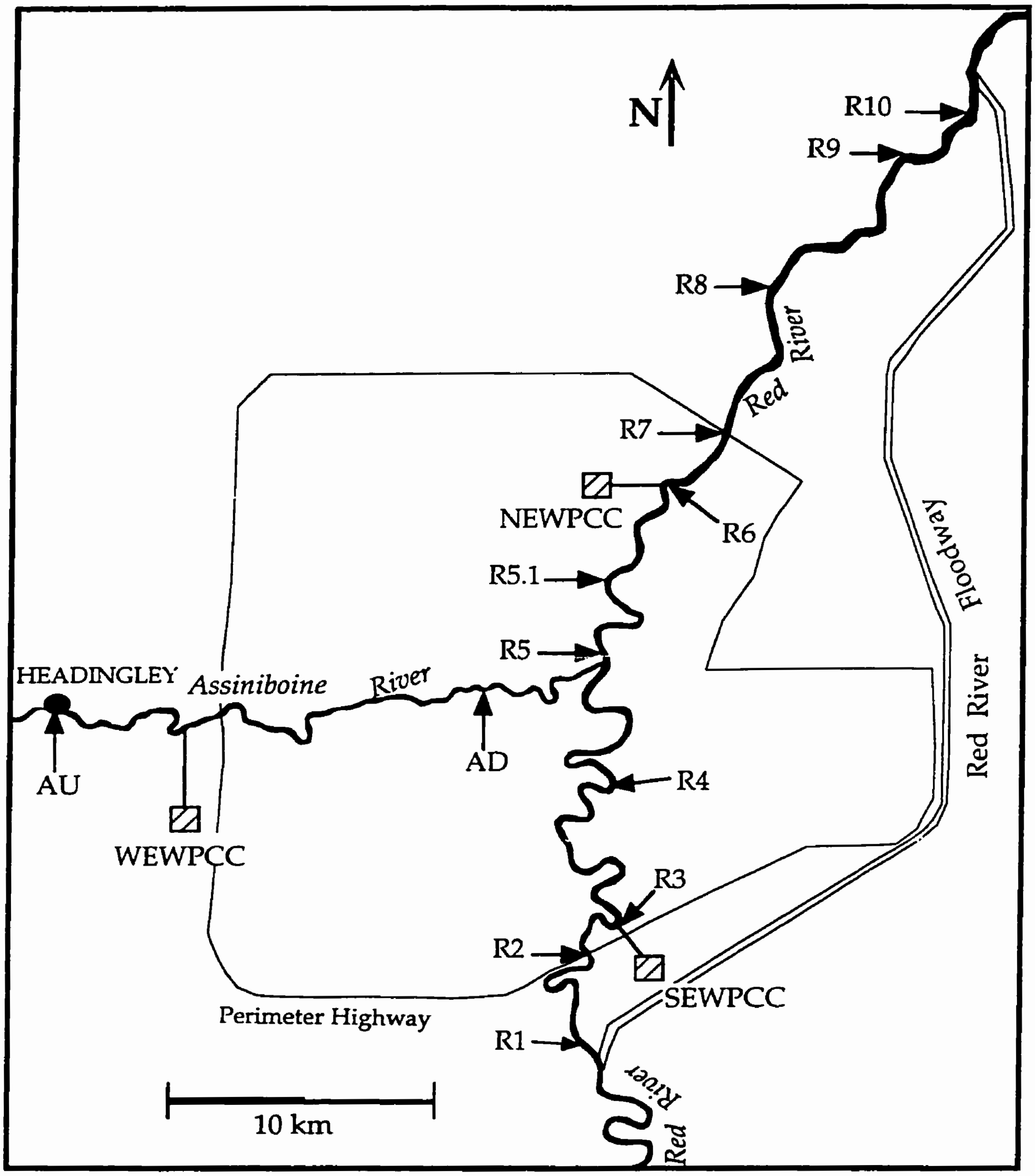


Figure 2.6 Locations of the thirteen sampling stations along the Red (R) and Assiniboine (A) Rivers in relation to the three water pollution control centers within the City of Winnipeg and the Assiniboine confluence. SEWPCC, NEWPCC and WEWPCC represent the South, North and West End Pollution Control Centers.

There are a few smaller dry weather discharge sources that have been identified other than the City of Winnipeg. In 1991, there were nine sources identified within confines of the study area between the NEWPCC and Lockport. Four were identified between Headingley and the Assiniboine confluence (Wardrop *et al.* 1991). However, based on their discharges, these were overwhelmingly outranked by the three WPCC's.

As the quality of treated effluent has increased, attention has shifted to the issue of discharges that originate from stormwater runoff and combined sewer overflows. These are episodic wet weather events, in which the volume of discharge overwhelms the carrying capacity of interceptors (Wardrop *et al.* 1991). The standard design for WPCC's in Winnipeg calls for secondary treatment of peak wet weather flows of up to 2.75 x average dry weather flow (Ross 1996). Approximately thirty to fifty times a year, however, the carrying capacity of interceptors is overwhelmed and overflows occur. In 1992, these events were associated with increases in fecal coliform densities (C.E.C. 1992).

Hvitved-Jacobsen (1986) provides an overview of the impacts of urban runoff on receiving waters and identifies three factors, namely the short and long term depletion of oxygen, inoculum of bacteria and pathogens, and the increase in phosphorus load as critical factors. Furthermore, stormwater and combined sewer runoff enhance scouring and resuspension at discharge sites which significantly increase the concentrations of total suspended solids in Rivers.

2.8 Site Selection

The boundaries of this study were set by the south Floodway Control structure and the Lockport Dam to the north of the City. Along the

Assiniboine River, the western boundary was established at Headingley (Figure 2.6). In total, there were eleven sampling locations chosen along the Red and two along the Assiniboine Rivers. Their locations were chosen to monitor changes in chemical and phytoplankton parameters through the City of Winnipeg as well as downstream of the NEWPCC.

Red River sampling locations were identified by an R and a number. R1 to R4 were stations located upstream of the Assiniboine River confluence, with R1 located downstream of the Floodway Structure but upstream of the LaSalle confluence (Figure 2.6). R3 was positioned adjacent to the SEWPCC. R5 and R5.1 were located downstream of the Assiniboine confluence and R6 adjacent to the NEWPCC. Lastly, R7 to R10 were located at increasing distance downstream of the NEWPCC to the Lockport Dam. The GPS coordinates and the approximate distance of these sampling station from R1 are found in Table 2.1.

Along the Assiniboine River, the two stations were identified with an A followed by either a U, to reflect its location upstream of the WEWPCC, or a D, to reflect its location downstream of the point source. AU was located in Headingley, adjacent to the Beaudry Park boat launch. AD was positioned within the City of Winnipeg at Clifton Street, some distance downstream of the WEWPCC (Figure 2.6). Site selection along the Assiniboine River was restricted due to accessibility of the River. In fact, AD was the farthest upstream along the Assiniboine that was considered to be reliably accessible throughout the sampling year.

Chapter 3 Materials and Methods

3.1 Introduction

This chapter describes the methods employed in the collection and determination of physical, chemical and phytoplankton parameters. A brief explanation is also provided outlining the statistical techniques that were employed in subsequent chapters.

3.2 Field/Sampling Methods

Stations were sampled weekly from the beginning of May to mid-October in 1994 and from late July to mid-October in 1995. The delay in 1995 was because of uncharacteristically high River discharge in both May and June that prevented navigation by boat. As well, in both years the sampling effort was suspended for a period in July (from the 18th to 31st in 1994; the 23rd to 30th in 1995). Thus, while there were 23 possible weeks of sampling in each year, only weeks 8 through 10 (late June to mid-July), and weeks 13 through 23 (August through mid-October) were sampled in both years. There was no information available for weeks 11 and 12 (in July) in 1994 and weeks 1 to 7 (in May and June) and week 12 (in July) in 1995.

To ensure that discrete water samples were taken from each location, the geographic sampling order was from the furthest downstream station (R10). Sampling continued upstream to the confluence of the Red and Assiniboine Rivers (R5). On the second day, the Assiniboine stations (AU and AD) as well as the locations upstream of the confluence (from R4 to R1) were sampled. The AU station was sampled at dawn on the second day using a canoe because of the restricted access by motor boat. These sampling locations are shown in Figure 2.6.

In situ measurements of dissolved oxygen and water temperature were made using a YSI (Model 50) probe and stirrer, while pH was measured using a Horiba U-10 Water Quality Checker™. All measurements were made at a depth of 0.5 m. The light profile, using 0.1 m increments, was determined at each station using a submersible LI-COR Spherical Quantum Sensor™ and LI-COR LI 1000™ datalogger. Concomitant above-water measurements were made using the LI-COR Flat Quantum Sensor™. Water samples were collected from a depth of 0.5 m using a horizontal 4L van Dorn sampler while the boat drifted with the River current. These samples were stored in 1L polyethylene containers at 4°C in coolers until transported to the laboratory. The Laboratory Services Division of the City of Winnipeg Waterworks, Waste and Disposal Department obtained samples for chemical analyses. Water samples were also collected for determination of *in vitro* primary productivity, soluble reactive phosphorus and biomass at the University of Manitoba.

3.3 Laboratory Methods and Calculations

Physical Parameters

Mean Daily Ambient Photosynthetically Active Radiation (PAR)

Measurements of PAR were made in both 1994 and 1995 from May through October. Hourly integrations of incident PAR were measured using a LI-COR quantum sensor with a datalogger that was mounted at the meteorological station of the Department of Plant Science, University of Manitoba. Because integrated PAR values were also applied to the estimation of *in situ* primary production, values were reduced by 10 % to account for scatter and reflection of light before it penetrated the water (Hutchinson 1975).

Hourly values were totaled over the 24 hour period to determine daily PAR values. For each sampling week (i.e., over the previous seven day period), these daily PAR values were averaged to obtain values of mean daily ambient PAR.

Total Weekly Precipitation

Precipitation information, from May to August in both 1994 and 1995, was acquired from the City of Winnipeg yearly telemetry rain stations. As shown in Figure 3.1, only those sites nearest to the sampling stations were used. For those weeks when telemetric measurements were not available, precipitation data from Environment Canada monthly meteorological summaries were used. This information was applied to weeks 21, 22 and 23 (end of September, October) in 1994 and to weeks 18 through 23 (September and October) in 1995. These measurements were taken at the Winnipeg International Airport (Environment Canada AES 1994, 1995). At each sampling location, the quantity of precipitation, recorded over the previous seven day period, was totaled for each sampling week.

River Flow Rates

Site-specific flow rates along the Red River were derived from cross-section areas and weekly River discharge rates as follows:

$$\text{Flow rate (m s}^{-1}\text{)} = \frac{\text{River Discharge (m}^3\text{ s}^{-1}\text{)}}{\text{Cross-section Area (m}^2\text{)}}$$

Weekly River discharges were provided by the Water Survey of Canada (1994 and 1995). Along the Red River, measurements at St. Agathe were employed for locations upstream of the Assiniboine confluence (Sites R1 through R4) while Lockport values were used for locations downstream (Sites R5 through R10). Along the Assiniboine River, discharge rates

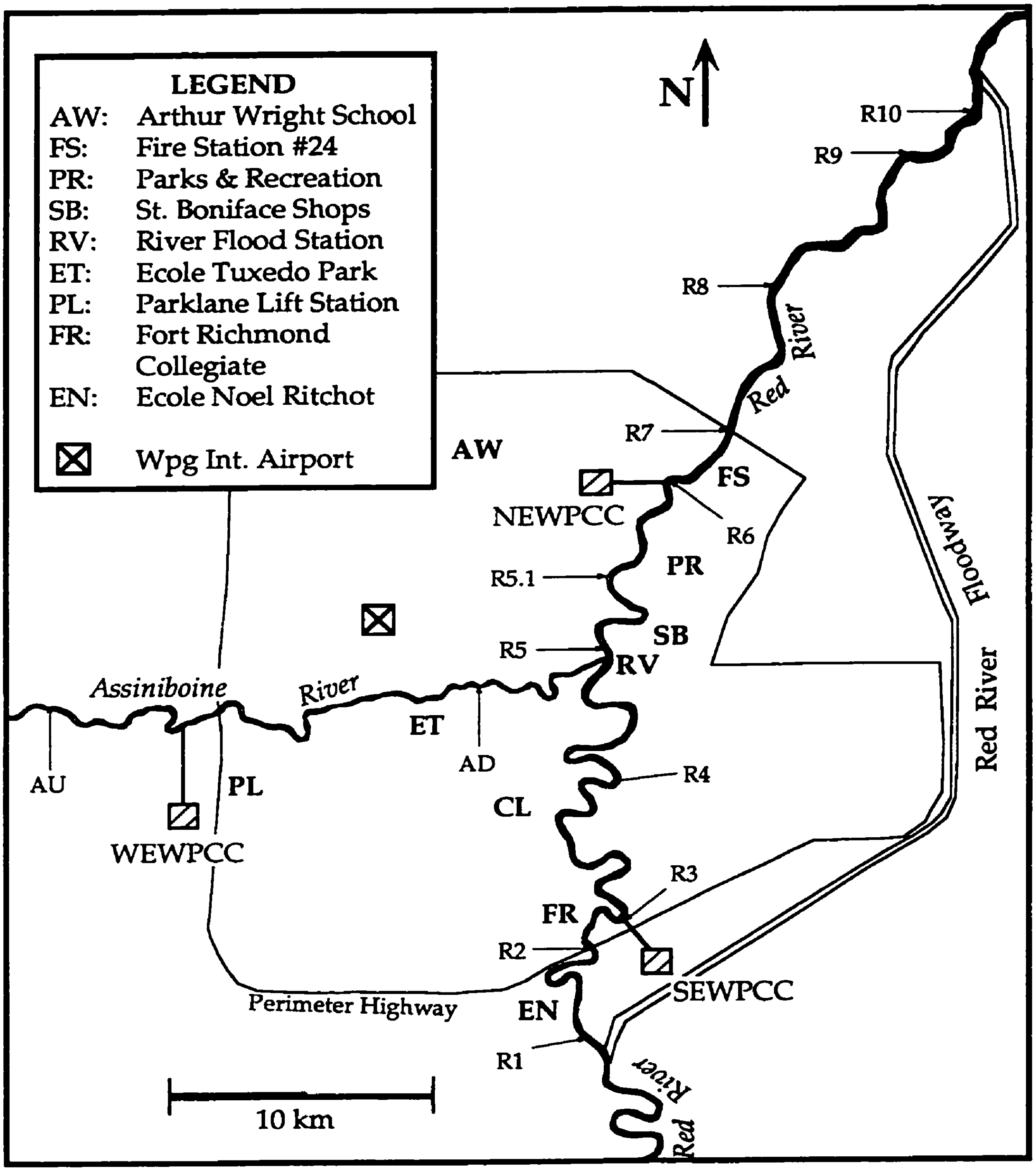


Figure 3.1 Locations of the telemetry stations in the City of Winnipeg used to gather precipitation information in 1994 and 1995. Superimposed are the locations of the sampling stations along both the Red and Assiniboine Rivers. When information from these telemetry stations was unavailable, recorded precipitation at the Winnipeg Interational Airport was used (Environment Canada, AES 1994 and 1995).

recorded at the Headingley station, immediately west of the City of Winnipeg, were used.

Cross-section area was determined from the width of the River, provided by the Survey Services Branch of the City of Winnipeg, Water and Waste Department. Both the River depth and channel profile were determined by a Lowrance X-15 Computer Scanner. The sonar profile was scanned into a computer and the software package, NIH Image 1.59 was used to calculated the cross-section area from defined horizontal (channel width) and vertical (channel depth) scales provided. The channel widths and depths and cross-section areas for stations along the Red River are found in Table 2.1. These parameters were not determined for stations along the Assiniboine River and consequently, the flow rates at the two stations along the Assiniboine River could not be determined.

Euphotic Depth and Mean Light Extinction per 0.1 m

At each sampling station, weekly measurements were made of both the depth of the euphotic zone and the extinction of light within the water column. Simultaneous measurements of PAR, at the surface and within the water column, were made at 0.1 m increments until light extinction was complete (i.e., < 1 µmoles m^{-2} s^{-1}). The depth of the euphotic zone (m) was defined as the total number of increments the probe was submersed x 1/10.

To determine light extinction within the water column, it was necessary to convert irradiance values (I) to percentages as follows:

$$\% I = \frac{I_{depth}}{I_{surface}} \times 100 \quad (3)$$

where I (µmoles m^{-2} s^{-1}) is the irradiance available at surface or at depth.

Light extinction (%) at each 0.1 m depth interval of the euphotic zone was calculated by the following relationship (Wetzel 1983):

$$\text{Light Extinction (\%)} = \frac{(\%\, I - \%\, I_{0.1})}{\%\, I} \times 100 \qquad (4)$$

where % I is the percentage of light available at a given depth and % $I_{0.1}$ is the percentage of light available 0.1 m below.

A mean value of light extinction per 0.1 m was then calculated over the entire water column, excluding both surface and final measurements.

Chemical Parameters

Sample Handling, Preservation and Storage

The majority of water chemistry was conducted by the Laboratory Services Division of the City of Winnipeg. Samples were mixed to resuspend settled particulates and split for each chemical determination. Samples that were to be measured for total Kjeldahl nitrogen (TKN), total ammonia nitrogen (NH_4^+/NH_3-N), total oxidized nitrogen, or TON (NO_3^-/NO_2^--N) and total phosphorus (TP) were preserved with 4% $HgCl_2$ and refrigerated at 4 °C until subsequent analysis. Samples that were analyzed for total dissolved phosphorus (DP), soluble Kjeldahl nitrogen (SKN) and soluble organic carbon (SOC) were passed through Sartorius 0.45 µm pore-size cellulose acetate filters under vacuum pressure. Filtrates that were to be analyzed for DP and SKN were preserved with 4% $HgCl_2$ and stored at 4 °C, and those sample filtrates that were to be analyzed for SOC were frozen. A flow chart highlighting the handling, preservation and storage methods used by the City of Winnipeg is found in Figure 3.2.

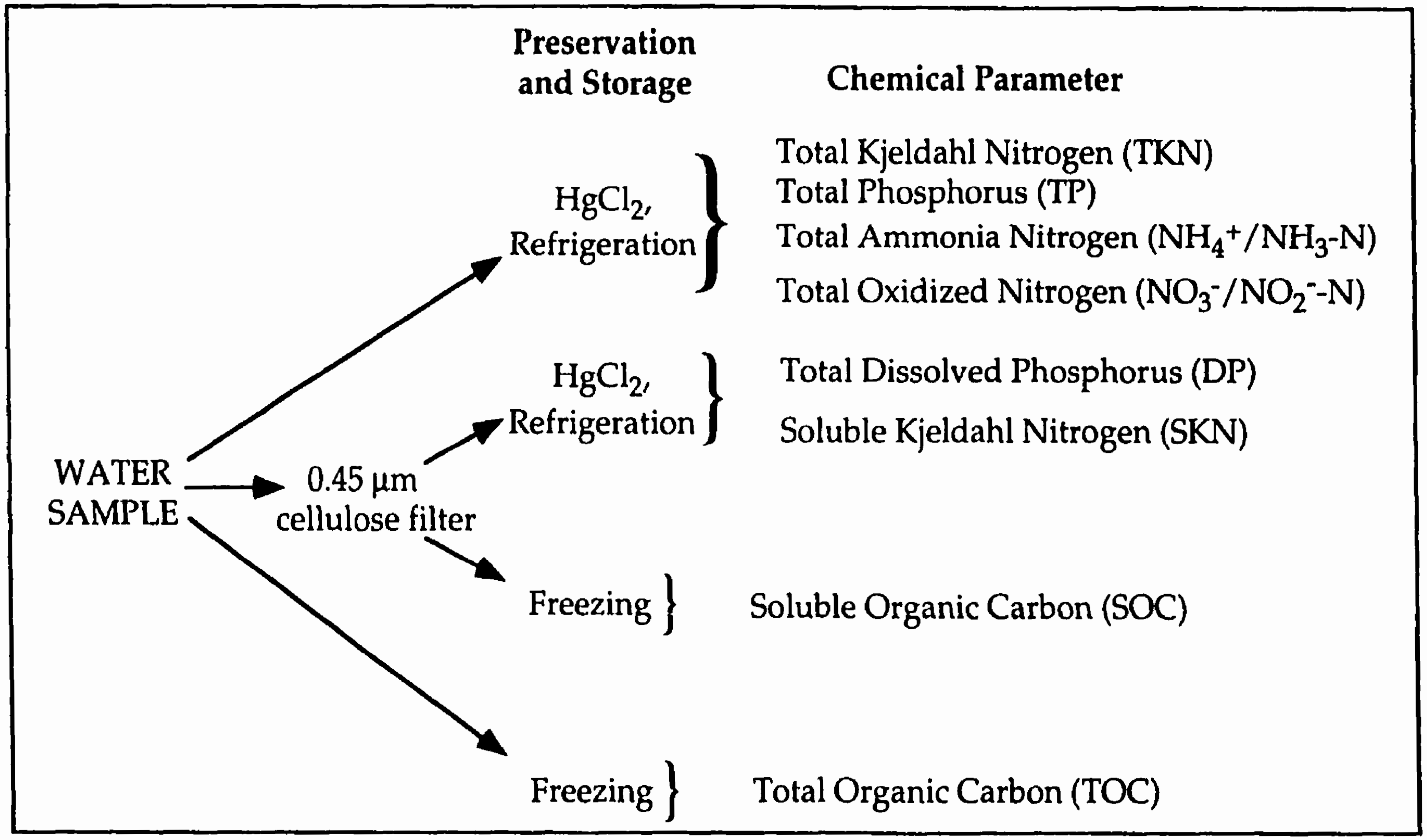


Figure 3.2: The handling, storage and preservation methods employed by the Laboratory Services Division of the City of Winnipeg Waterworks, Waste and Disposal Department. Dependent on the chemical parameter, samples were either preserved directly or initially passed through cellulose acetate filters. Preservation was ensured by the addition of mercuric chloride. Samples were either refrigerated at 4 °C or frozen. City of Winnipeg Waterworks, Waste and Disposal (Ross and Hemphill 1996).

In 1994, samples were also collected for determination of particulate carbon (PC) and nitrogen (PN). Whatman GF/C glass fiber filters were combusted at 450 °C for 4 hours, and stored in a glass lidded container. On each sampling occasion, 250 ml of water sample was passed through a pre-combusted filter and frozen until analyzed in late October 1994. The Elemental Analyzer used to determine both PC and PN was not available in 1995. However, total organic carbon (TOC) was measured in 1995 and water samples were frozen directly without preservation or filtration.

Soluble reactive phosphorus (SRP) concentrations were determined directly without preservation or storage at the University of Manitoba. Samples were initially passed through Whatman GF/C glass fiber filters to remove particulates. All glassware for this procedure was soaked in 7% HNO_3 for 2 or more days before use.

Chemistry Determinations

Particulate Carbon (PC) and Nitrogen (PN)

In 1994, PC and nitrogen PN were determined by the Freshwater Institute of Fisheries and Oceans, Canada according to Stainton *et al.* (1977). Filters that had been stored in the freezer were thawed and dried at low temperatures. These dried filters were then punched into pre-ignited nickel sleeves and placed into the sample wheel of the Elemental Analyzer (Model 240-XA). The samples, and a series of standards, were then combusted in an oxygen/helium atmosphere at 950 °C. The combustion gases were oxidized to CO_2, H_2O and N_2, through a series of specialized packings including heated copper. The mixture was then passed through a series of high precision thermal conductivity detectors to sequentially remove H_2O and CO_2 respectively. The difference between signals from each pair of detectors was proportional to the amount of H and C present in each sample. The only gas remaining, N_2, was measured against the pure He carrier gas.

Total Organic Carbon (TOC) and Soluble Organic Carbon (SOC)

TOC in 1995, and SOC, in both 1994 and 1995, were determined using a Dohrmann DC-180 high temperature carbon analyzer with infrared CO_2 detector at a temperature of 900 °C, following the combustion-infrared method (5310 B) (APHA 1992).

Nitrogen

Total and Soluble Kjeldahl Nitrogen (TKN and SKN)

TKN was determined using a macro-Kjeldahl method (4500-N_{org} B) (APHA 1992). Water samples were first digested with mercuric sulfate, sulfuric acid and potassium sulfate in a Bran and Luébbe BD-40 Heating Unit™ over a period of three hours to convert organic nitrogen to ammonia. Digested samples were then analyzed for ammonia-N in the Technicon AutoAnalyzer II™ following the automated phenate method (4500 NH_3 H) (APHA 1992). Determination of SKN followed this procedure with the exception that samples were first filtered.

Total Ammonia-N (NH_4^+/NH_3-N)

Determination of NH_4^+/NH_3-N followed the automated phenate method (4500-NH_3 H) (APHA 1992). Water samples were introduced into a Technicon AutoAnalyzer II™ and reacted with hypochlorite and phenol solutions. Sodium potassium tartrate solutions substituted for the EDTA required. The ammonia in solution formed a blue-green indophenol complex that was measured spectrophotometrically.

Soluble organic nitrogen (SON) was derived from these measurements as follows:

$$SON = SKN_{\text{(Soluble Organic N + } NH_4^+/NH_3\text{-N)}} - NH_4^+/NH_3\text{-N}$$

Note that in this derivation of SON, it was assumed that the NH_4^+/NH_3-Nadsorbed on particulate matter was negligible.

<u>Total Oxidized Nitrogen or TON (NO_3^-/NO_2^--N)</u>

TON followed the automated cadmium reduction method utilizing a Technicon AutoAnalyzer II™ (4500-NO_3 F) (APHA 1992). Nitrate (NO_3^-) present in the water samples was first reduced to nitrite (NO_2^-) in the presence of copper-cadmium granules. The total NO_2^--N was then complexed with sulfanilamide and N-(1-naphthyl)-ethylenediamine dihydrochloride to form a reddish-purple azo complex which could be measured spectrophotometrically.

TKN, NH_4^+/NH_3-N and TON measurements were used to derive Total Nitrogen (TN) and soluble inorganic nitrogen (SIN) as follows:

$$TN = TKN_{\text{(Total Organic N + } NH_4^+/NH_3\text{-N)}} + TON$$

$$SIN = NH_4^+/NH_3\text{-N} + TON$$

<u>Phosphorus</u>

There were three forms of phosphorus determined in this study. These forms included soluble reactive phosphorus (SRP), that responded to colorimetric tests directly without preliminary digestion; and total dissolved phosphorus (DP) and total phosphorus (TP) that required preliminary oxidative digestion to convert both condensed and organically bound phosphates to soluble reactive phosphorus (APHA 1992).

To determine both TP and DP, water samples were first digested to convert all phosphorus to reactive phosphate. The reactive phosphorus in solution was then determined by the automated ascorbic acid method (4500-P F) (APHA 1992) using a Technicon AutoAnalyzer II™. In this method, ammonium molybdate and potassium antimonyl tartrate reacted with orthophosphate to form a phosphomolybdic acid. Ascorbic acid, when added, reduced the phosphomolybdic acid to intensely colored molydenum blue which was then measured spectrophotometrically.

The SRP component was determined manually following the methods outlined in Stainton *et al.* (1977). Similar to ascorbic acid method, the molydenum blue in the sample was determined spectrophotometrically at 885 nm, and related to the concentration of SRP using a standard curve.

Particulate organic phosphorus (PP) and soluble organic phosphorus (SOP) were derived from the measurements of TP, DP and SRP as follows:

$$PP = TP_{\text{(Particulate Organic P + Soluble Organic-P + SRP)}} - DP_{\text{(Soluble Organic-P + SRP)}}$$

$$SOP = DP_{\text{(Soluble Organic-P + SRP)}} - SRP$$

Phytoplankton Parameters

Phytoplankton parameters were assessed in terms of standing crop, or biomass, photosynthetic parameters (i.e., photosynthesis at subsaturating and saturating irradiances) including the parameters alpha, P_{max} and I_k. Daily estimates of productivity were derived from these P vs I relationships.

Biomass (Chlorophyll *a*)

The biomass of phytoplankton in the Rivers was estimated from concentrations of chlorophyll *a* following the methods outlined in Marker

(1980). These values were not corrected for phaeophytin since spurious results were often observed.

For determinations, three x 250 ml samples were filtered onto Whatman GF/C papers. The filters were shaken in 8 to 10 ml of 90 % methanol and the pigments were extracted over a 24 hour period in the dark at 4 °C. The extracts were filtered through GF/A filters and chlorophyll *a* concentrations were determined spectrophotometrically at both 665 and 750 nm.

Photosynthesis-Irradiance Incubations

A photosynthesis-irradiance (P vs I) relationship was derived for each sampling station on each sampling occasion by *in vitro* incubations (Robinson *et al.* 1997). Eighteen sub-samples of 25 ml were dispensed into glass screw-top culture tubes (three of which were blackened with paint and bound with black plastic tape to exclude all light). Samples were inoculated with a standardized amount of $NaH^{14}CO_3$ and placed in a water-filled incubator, which maintained temperatures similar to that of the River, for two hours. The incubator was front lit by a high pressure sodium vapor lamp (Sylvania Lumalux LU-70), thereby creating a light gradient ranging from ca. 20 - 2000 µmoles m^{-2} s^{-1} PAR. Because of the severity observed in the *in situ* attenuation of light, at least half of the tubes were placed at subsaturating irradiances within the tank (9 out of 15 tubes were incubated at <200 µmole m^{-2} s^{-1} PAR). The irradiance to which each sample was exposed in the incubator was determined by a LI-COR underwater spherical quantum sensor. Test tubes were inverted several times during the incubation to maintain both the suspension of cells and an accurate incubation irradiance. Subsequently, samples were filtered simultaneously onto GF/A filters, fumed over concentrated HCl for 1-5 minutes to remove residual inorganic ^{14}C and placed into scintillation vials containing 5 ml ReadySafe® (Beckman Scientific) scintillation cocktail. Determination of specific radioactivity (dpm) was conducted in a Beckman LS3801 liquid scintillation counter, using "H-number" quenching correction.

The *in vitro* productivity was estimated from dpm according to the following relationship:

$$\mu g\ C\ l^{-1}\ h^{-1} = \frac{dpm_S \times C \times 1.05}{dpm_T \times T} \qquad (1)$$

where dpm_S is the specific radioactivity of each sample corrected for any dark "uptake"; C is the DIC of River water ($\mu g\ C\ l^{-1}$) as determined from alkalinity (APHA 1992), pH and temperature; 1.05 is an isotope discrimination factor; dpm_T is the specific radioactivity of added ^{14}C; T is the incubation duration (h).

Using non-linear regression (Systat 1986), alpha and P_{max} were estimated according to the relationship described by Platt and Jassby (1976):

$$P_s = P_{max} \times (1 - e^{\frac{-alpha \times I}{Pmax}} \times e^{\frac{-beta \times I}{Pmax}}) \qquad (2)$$

where P_{max} is the maximum observed rate of Ps; alpha is the slope of light-limited photosynthesis (i.e. photosynthetic efficiency) and I is the incubation irradiance.

Although beta, a measure of photo-inhibition, was included in the equation, it was never observed in incubated samples. Therefore, it was assigned a value of 0 in equation (2).

I_k, the irradiance after which photosynthesis became saturated, was derived from the intersect of P_{max} and alpha.

Chlorophyll normalized values of P_{max} (SP_{max}) and alpha (SPalpha) were also determined as measures of physiological performance.

Estimated *in situ* Productivity

In situ productivity was estimated for each sampling station using the following parameters:

(i) *in vitro* derived parameters of photosynthesis (alpha and P_{max})

(ii) hourly integrations of incident PAR, reduced by 10 % to account for reflection, that were measured at the meteorological station at the University of Manitoba

(iii) euphotic depth; and

(iv) mean light extinction within 0.1 m of water.

The hourly integrations of PAR were reduced by the mean light extinction in each successive 0.1 m of the euphotic zone to obtain values of *in situ* PAR. At each 0.1 m interval of the euphotic depth, these *in situ* PAR values were used in equation (2) with P_{max} and alpha to estimate *in situ* productivity. These estimates were multiplied by 100 to obtain values within a square meter, and were totaled over the entire euphotic depth to obtain the hourly euphotic column productivity measurements. Hourly values were summed over the day and the units were adjusted to mg C fixed m^{-2} day^{-1}.

3.4 Statistical Methods

Log Transformation

Following Mead (1988), datasets were log transformed prior to regression analyses and parametric tests of Analysis of Variance, Principal Component analysis and Canonical correlation analysis. The exploratory statistical software packages, DataDesk 4.0 ® (1988) and Syn-Tax 5.02 (Podani 1995), were used for these statistical analyses, unless otherwise stated.

Tukey Box-Plots

Modified Tukey boxplots (Figure 3.3) were utilized in all cases to characterize the variability of chemical and physical factors within the Red and Assiniboine Rivers.

These boxplots include five basic components (DataDesk 1988; Moore and McCabe 1989):

- the median value (50th percentile) of the dataset, as shown by the horizontal bar within the box;
- the 25th and the 75th percentiles that demark the ends of the box. The length of the box represents the interquartile range (IQR);
- the 1.5 IQR (1.5 x IQR), as shown by "hinges" that extend from the top and bottom of the box;
- suspected outliers that are above either 1.5 or 3 interquartile deviations of the main body of the data, are plotted as circles or stars, respectively; and
- the 95% confidence interval (C.I.), to aid in comparison of medians, is indicated as the shaded area. In particular, if two gray boxes fail to overlap, the corresponding medians are considered discernibly different at approximately the 5% significance level (DataDesk 1988).

Analysis of Variance (ANOVA)

One-way ANOVA

One-way ANOVAs were performed on several datasets to evaluate the significance of spatio-temporal physicochemical heterogeneity in the Red and Assiniboine Rivers. One-way ANOVA is a statistical method for comparing

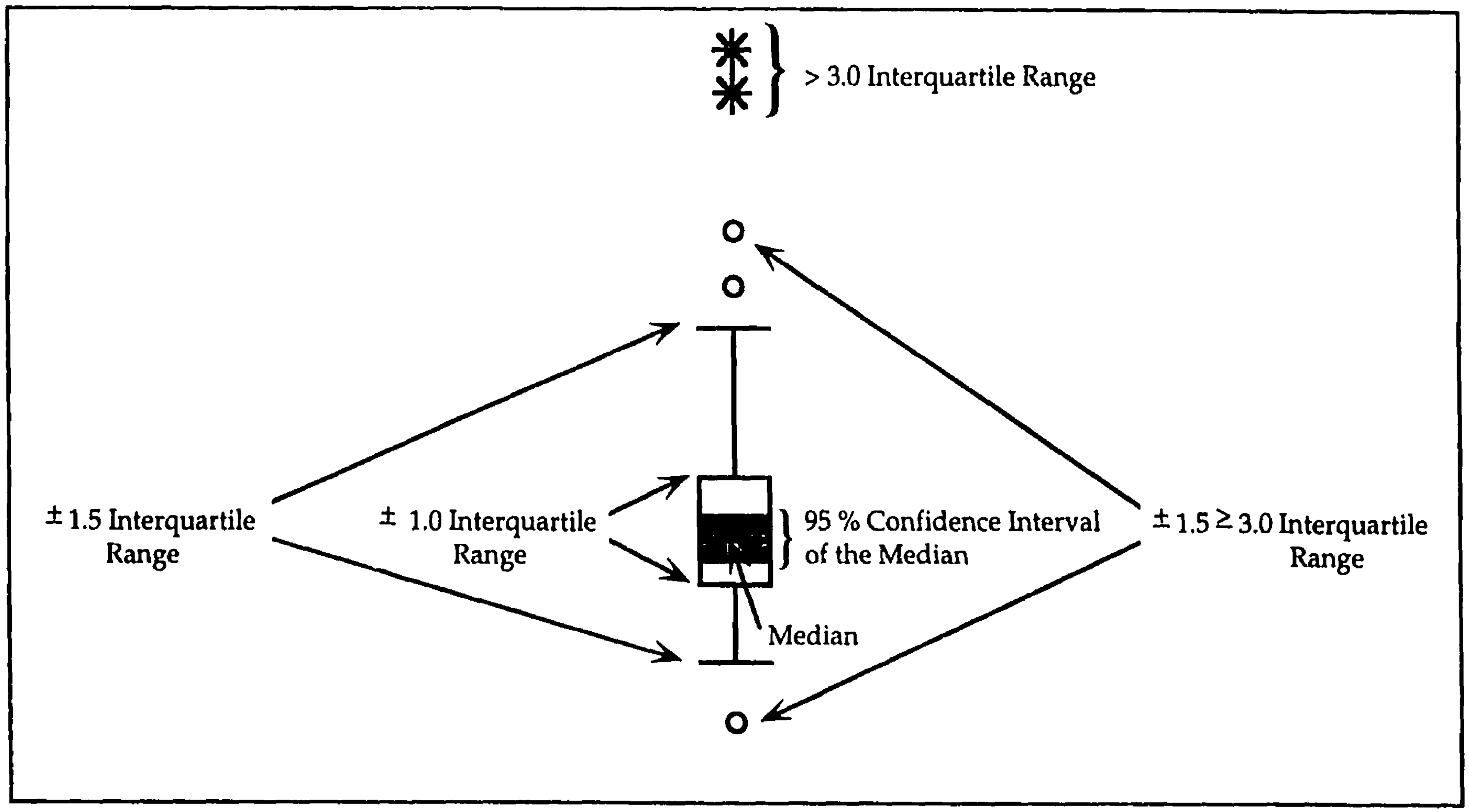


Figure 3.3 Diagram of Tukey Boxplot with explanation. The rectangular box represents ± interquartile range, with the median indicated by the horizontal line, and the shaded area representing the 95% confidence interval of the median. T's extend from the box to the nearest point within ± 1.5 interquartile range. Circles and stars represent outliers within and beyond ± 3.0 interquartile range, respectively (from Emerson & Strenio 1983).

several "population" means whereby the F-statistic tests the null hypothesis $\mu_1 = \mu_2 = \ldots = \mu_p$ against the alternative that *at least one mean* is not equal to the others (DataDesk 1988). Larger F-values suggest that the means differ more than expected on the basis of the underlying sample-to sample variability within groups and support rejection of the null hypothesis. Conversely smaller values suggest that the means are not discernibly different (Zar 1974, Moore and McCabe 1989).

In this study, the null hypothesis was rejected when $p \leq 0.05$ and the groups were said to significantly differ. When $0.05 < p \leq 0.10$, the groups were said to be nearly significantly different.

Multiple comparisons were not performed in this study since the approach is not based upon random effects as are found in this study (Neter *et al.* 1990). Alternatively, when significant differences were detected from ANOVA, the 95 % confidence intervals from the boxplots were used to determine the precise relationship.

Two-way ANOVA

In many instances, two-way ANOVAs were performed. Similar to the one-way, two-way ANOVA tests the null hypothesis that means of several populations differ significantly. However, the two-way ANOVA introduces more parameters since three null hypotheses can be tested: the main effect of the first parameter on the response, the main effect of the second parameter, and the interaction between the two parameters. This is important since parameters might influence the response, both individually and jointly, through some interaction (Neter *et al.* 1990). In this study, when significant interactions between parameters occurred (i.e., $p \leq 0.005$ for the interaction), one-way ANOVAs were performed.

Principal Component Analysis (PCA)

In many instances in this study, when the goal was to compare multivariate data sets, PCAs were performed using the statistical package DataDesk 4.0 (1988). This statistical approach provides a method to graphically and mathematically express multi-dimensional relationships within a new set of fewer orthogonal (perpendicular) axes. When multivariate datasets are examined in this way, each variable that is included in analysis adds another axis or dimension to the relationship. For example, there are two axes, both x and y, when two variables are compared; three axes, x y and z, with three variables etc. The objective of PCA is to reduce the dimensions required to describe variability within the multivariate dataset by redistributing the variance to the first few axes. This redistribution is accomplished by finding a rigid rotation of the original multiple axes while not influencing the relative point positions. Indeed, often the variability tapers off dramatically after the second or third axis of a multivariate dataset, and the subsequent axes have been shown to often represent spurious information (Gauch 1982).

Whereas in standard axes, the x and y axes intercept at coordinates (0,0), the first principal axis of the PCA passes through the center of the point cloud and the (0,0) coordinates represent the means of each data variable (DataDesk 1988). The first axis points in the direction of greatest variability in the cloud of points and therefore is considered to be the line through the means along which the variance of the projection is greatest. Subsequent axes must be perpendicular to the former, and therefore higher axes are fully determined (DataDesk 1988).

In this study, it was typically only the first axis that was used and the "success" of the PCA redistribution of variance was quoted as a percent. The

PCA axis I was used in subsequent traditional regressions as the x, or independent axis. It was often regressed, for example, against phytoplankton parameters to evaluate the correlation between physico-chemical parameters and a measure of phytoplankton activity.

Canonical Correspondence Analysis (CCA)

CCA examines the relationship between two series (thus 'canonical') of data collected on the same individuals. CCA extracts successive linearly uncorrelated ordination axes thereby maximizing the correlation between the two sets of variables (ter Braak 1987). In ecological applications, the second variable set generally consists of environmental measures. The ordination diagram displays the positions of both the individuals and environmental variables, as well as vectors indicating the direction and 'strength' of the environmental correlates. Essentially, the resultant ordination is a biplot of individuals in which the relationship is 'constrained' (i.e., dependent) by the environmental information.

In this study, several CCAs were calculated using weekly measures of chemical or phytoplankton parameters as one data set and the physical variables of flow rate and light availability as constraining environment variables. All canonical analyses were undertaken using the program Syn-Tax 5.02 (Podani 1995). Figure 3.4 provides an example of the CCA output and interpretation.

Multiple Discriminant Analysis (MDA)

MDAs were performed in several instances using Syn-Tax 5.02 (Podani 1995). The objective of multiple discriminant analysis is to find axes (or linear composites) along which two or more groups are maximally separated (Green 1979). To distinguish between two groups using one variable simply

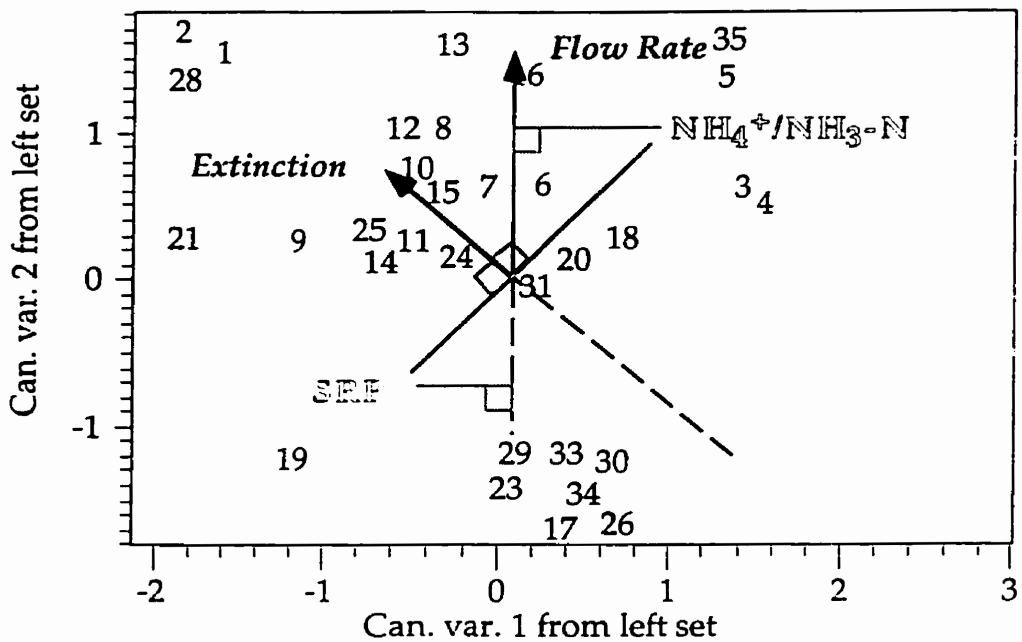


Figure 3.4 An example of the CCA scatterplot used in this study. Arrows, or vectors, point in the direction of the increasing environmental parameter (as shown here for extinction and flow rate). Environmental parameters have been italicized in all CCA scatterplots. The left-hand set of parameters, or "individuals", are represented by the numbers found scattered within the plot. The highest ranking of these individuals are found nearest that parameter. In this study, each parameter has been outlined for easy identification (in this example these include SRP and NH_4^+/NH_3-N). To determine the influence of flow rate and/or extinction on SRP and NH_4^+/NH_3-N, right angles are visualized from the vector to the parameter. If this is associated near the head of the vector, there is a strong positive correlation. In this example, NH_4^+/NH_3-N is considered to have a very strong positive correlation to flow rate. A negative correlation is found when the parameter is segregated in the opposite direction to the vector. In this example, SRP has a strong negative correlation to flow rate. If the right angle intercepts the center, or centroid, of the vectors, the response is considered to be average, or is considered to have no significant correlation with that environmental parameter. In the above example, both SRP and NH_4^+/NH_3-N were found to exhibit this condition. This was evident by the right angle to the centroid.

requires a single axis. However, when two or more groups are to be distinguished using numerous variables greater complexity results, increasing the difficulty in making discriminations. Similar to the PCA, MDA provides a tool to reduce the dimensionality and to summarize relationships. However, MDA differs from PCA as it strives to find the best linear fit that maximally distinguishes between several groups among several variables by yielding linear composites in which *the between group variance is maximized relative to the variance within groups.* In fact, the MDA points to those variables that are most useful in discriminating amongst the groups.

Scaling of the discriminant weights is accomplished by "spherizing" the average within-groups variation (i.e., providing an average within-group variance of unity displayed as the 95% confidence ellipses) (Green 1979). This step is important to hypothesis testing. The question whether group centroids significantly differ is visualized by the proximity of these ellipses to one another. When ellipses overlap, the groups do not differ significantly. Conversely, when these ellipses are discrete from each other, there are significant differences between the groups.

Chapter 4 Spatio-Temporal Variability in Physical, Chemical and Phytoplankton Parameters in the Red and Assiniboine Rivers

4.1 Introduction

The objectives of this chapter were to identify the spatial and temporal variability that occurred in physical, chemical and phytoplankton parameters. First, the underlying temporal variability in the datasets were described by their episodic features. Secondly, the division of the Red River into groups based on the proximity to the Assiniboine confluence and/or NEWPCC, was evaluated.

When the datasets were structured into seasonal episodes and River groups, variability was quantified within each year and between years of the study. The spatial differences between Red River groups and between Red and Assiniboine Rivers was examined as well.

4.2 Data Structures

Seasonal Episodes

Both 1994 and 1995 datasets were divided into episodes following Davis and Keller (1983) and Meybeck (1993) who attributed the fluctuations in dissolved loads in Rivers to annual and/or cyclical events. I used the parameters including mean daily ambient PAR, *in situ* water temperature, total weekly precipitation and River discharge rate to create these divisions since they appeared to exhibit episodic features (Figure 4.1). For example:

- mean daily ambient PAR was significantly higher at the beginning of the sampling year when compared with conditions at the end of the year;
- *in situ* water temperatures were much lower at both the beginning

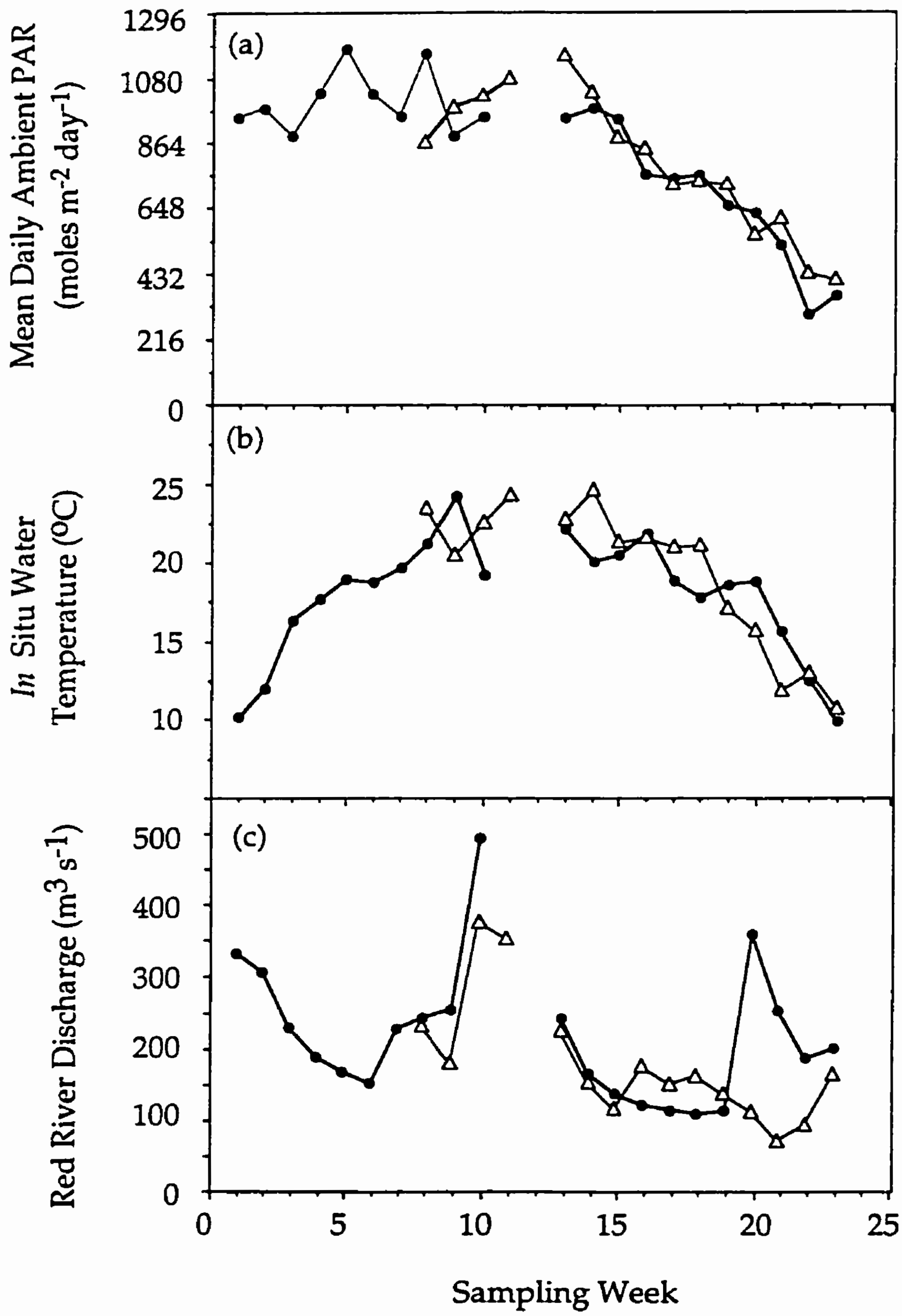


Figure 4.1 The weekly means of (a) daily ambient PAR, (b) *in situ* water temperature and (c) Red River discharge rate during sampling in 1994 (—●—) and 1995 (—△—).

and end of the sampling year when compared with mid-season values;

- Red River discharge rate appeared to fluctuate cyclically. Rates were higher in weeks 8 through 10 in both years, and in weeks 1 to 3, and 21 to 23 in 1994. Conversely, low discharge periods were found in weeks 4 through 7 in 1994, and weeks 14 through 19 in both 1994 and 1995.

The divisions I used to create the seasonal episodes are defined in Table 4.1.

Table 4.1 The seasonal episodes and corresponding sampling weeks in 1994 and 1995.

Episode	1994	1995
1	Weeks 1 to 3	No Sampling Due to High Flows
2	Weeks 4 to 7	No Sampling Due to High Flows
3	Weeks 8 to 10	Weeks 8 to 11
Sampling Interrupted Due to River Flows in 1994		
4	Weeks 13 to 20	Weeks 13 to 20
5	Weeks 21 to 23	Weeks 21 to 23

Both PCA and MDA were employed to validate these divisions. PCAs were performed on three series of log transformed parameters. The physical parameters included mean daily ambient PAR, total weekly precipitation, Red River discharge rate and *in situ* water temperature. Light extinction was correlated with River discharge rate and therefore removed from the analysis. The chemical dataset included SOC, TN and TP. The third series comprised phytoplankton biomass (Chl *a*), parameters of the P vs. I curve (i.e., alpha, P_{max} and I_k) and estimated daily productivity. The first two axes of PCA were subjected to MDA to obtain the 95 % confidence ellipses for each seasonal episode so that the relative significance of these divisions could be evaluated.

The individual data points were removed from the MDA ordination for presentation.

Physical Parameters

The PCA performed on the 1994 and 1995 datasets ascribed 74.4 % and 82.5 % of the total variance to axes I and II and the MDAs exhibited significant separation of seasonal episodes (Figures 4.2 and 4.3). In 1994, episodes 3 and 5 were situated at either extremes along the first axis of the PCA and MDA, with seasonal episode 1 situated between these (Figure 4.2). Seasonal episodes 2 and 4 separated from the other episodes but were themselves closely associated. In 1995, all seasonal episodes differed significantly with a sequential distribution of the episodes along the first axis (Figure 4.3).

The PCAs of 1994 showed that seasonal episodes 1 and 5 represented periods of low water temperatures and ambient PAR (Figure 4.2). The intermediate seasonal episodes were found to exhibit high ambient PAR and water temperatures, and episode 3 represented the period of greatest ambient PAR. Similarly, the PCA performed on the 1995 dataset showed a clear separation of seasonal episode 5 from the others (Figure 4.3). Although there was less contrast between seasonal episodes 3 and 4, episode 3 was heavily weighted by ambient PAR and *in situ* water temperature, while episode 4 represented a period of fluctuating precipitation.

Chemical Parameters

The ordinations clearly separated seasonal episodes in both the PCAs and MDAs (Figures 4.4 and 4.5). In 1994, 84.7 % of the variance was distributed along axes I and II of the PCA, and it decreased slightly to 82.1 % in 1995. The ellipses of the MDAs were all discrete, showing that there were

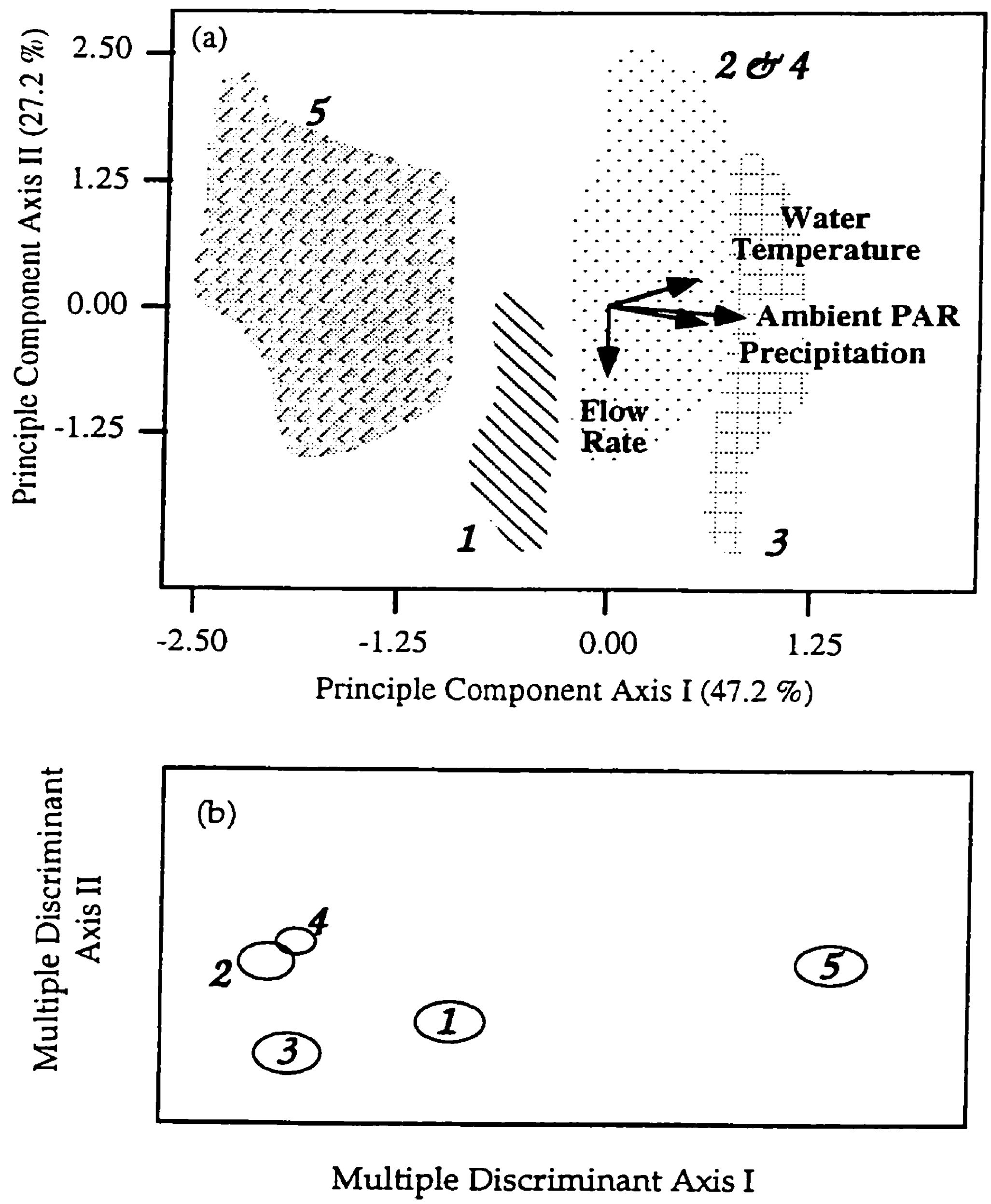


Figure 4.2 Ordinations of (a) Principle Components and (b) Multiple Discriminant Analyses performed on daily ambient PAR, *in situ* water temperature, Red River flow rate and total weekly precipitation. Individual data points have been grouped in the PCA and numbered 1 to 5 to indicate the seasonal episodes in 1994.

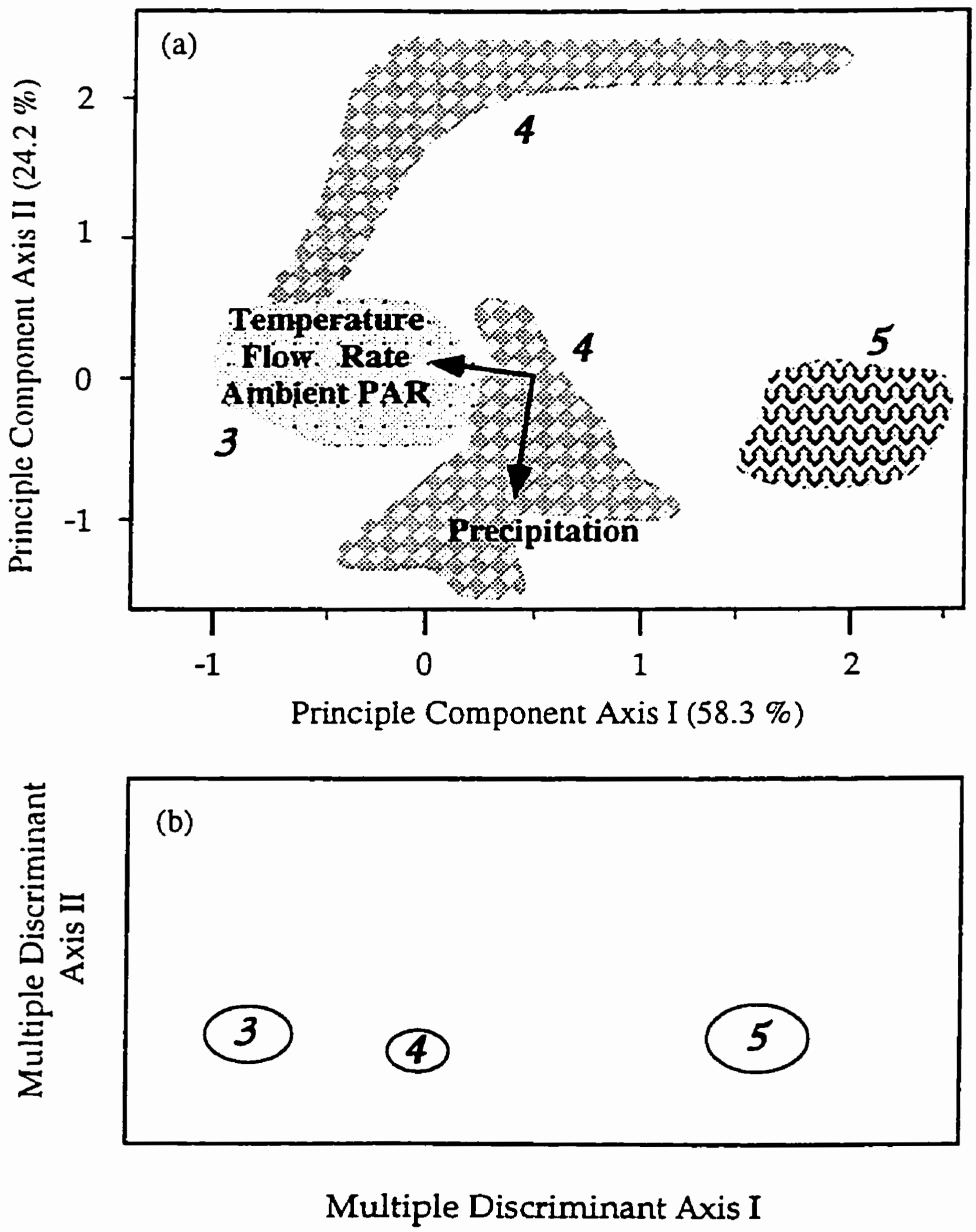


Figure 4.3 Ordinations of (a) Principle Components and (b) Multiple Discriminant Analyses performed on daily ambient PAR, *in situ* water temperature, Red River flow rate and total weekly precipitation. Individual data points have been grouped in the PCA and numbered 3 to 5 to indicate the seasonal episodes in 1995.

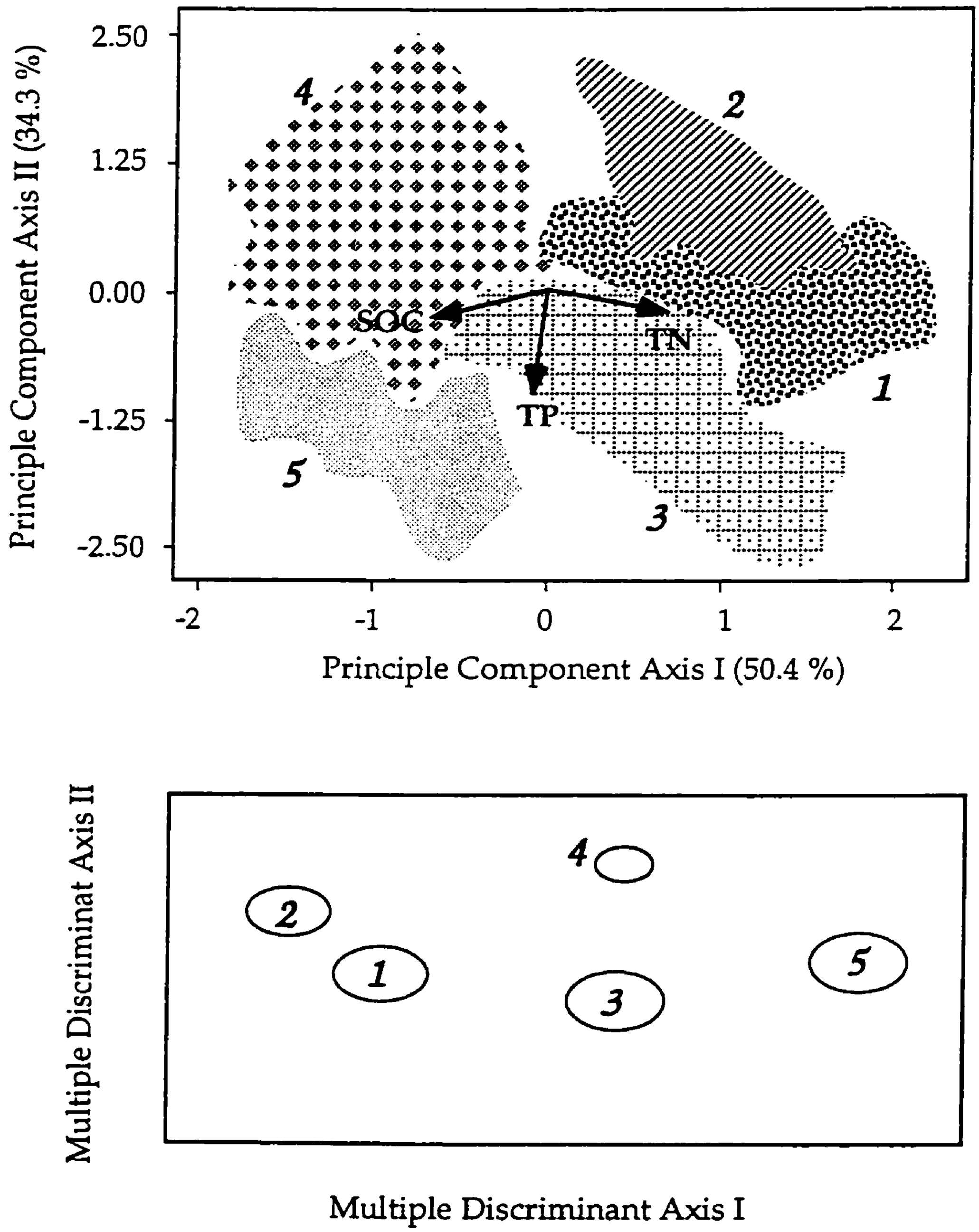


Figure 4.4 Ordinations of (a) Principle Components and (b) Multiple Discriminant Analyses performed on TN, TP and SOC. Individual data points have been grouped in the PCA and numbered 1 to 5 to indicate the seasonal episodes in 1994.

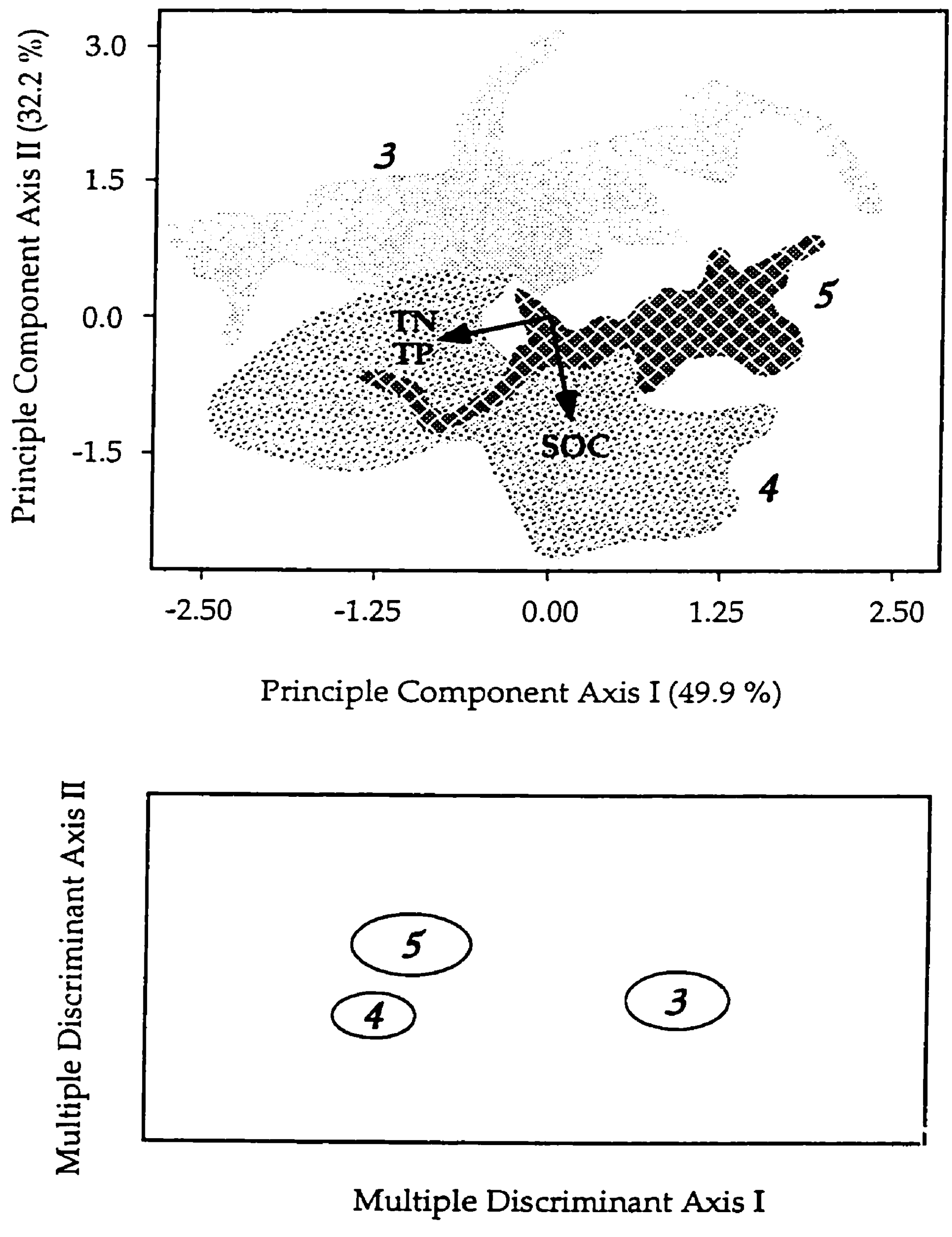


Figure 4.5 Ordinations of (a) Principle Components and (b) Multiple Discriminant Analyses performed on TN, TP and SOC. Individual data points have been grouped in the PCA and numbered 3 to 5 to indicate the seasonal episodes in 1995.

significant differences in chemical status between seasonal episodes in both years.

In the 1994 dataset, seasonal episodes 4 and 5 were attributed with a high concentration of SOC but low TN (Figure 4.4). In contrast, the first three seasonal episodes of 1994 were found to exhibit the reverse relationships. There were further separations of the dataset by TP along the second axis. This was evidenced by the separation of seasonal episodes 4 from 5, and 3 from episodes 1 and 2. TP concentrations were highest in episodes 3 and 5, and lowest in 2 and 4. These concentrations appeared to be intermediate in episode 1.

There were seasonal divisions observed in chemical parameters in the PCAs performed on the 1995 dataset. These divisions were based on the SOC concentrations (Figure 4.5). In particular seasonal episode 3 was shown to be a period of low SOC in contrast to episode 4 while intermediate concentrations typified seasonal episode 5. Each seasonal episode displayed varying concentrations of TN and TP.

Phytoplankton Parameters

There were episodic features found in the phytoplankton parameters. As found in the chemical datasets, the PCA redistribution maintained a large proportion of the variance along the first two axes. In 1994, this amounted to 94.5% and 93.9 % in 1995 (Figures 4.6 and 4.7). The MDAs identified several episodes that were significantly different. However the MDA failed to separate episodes 2 and 4, in 1994 and episodes 3 and 4, in 1995. Seasonal episode 5 was segregated from the other episodes in both years.

As shown in the PCA, seasonal episodes 1, 2 and 4 in 1994, represented periods of high biomass, P_{max}, alpha and estimated daily productivity (Figure

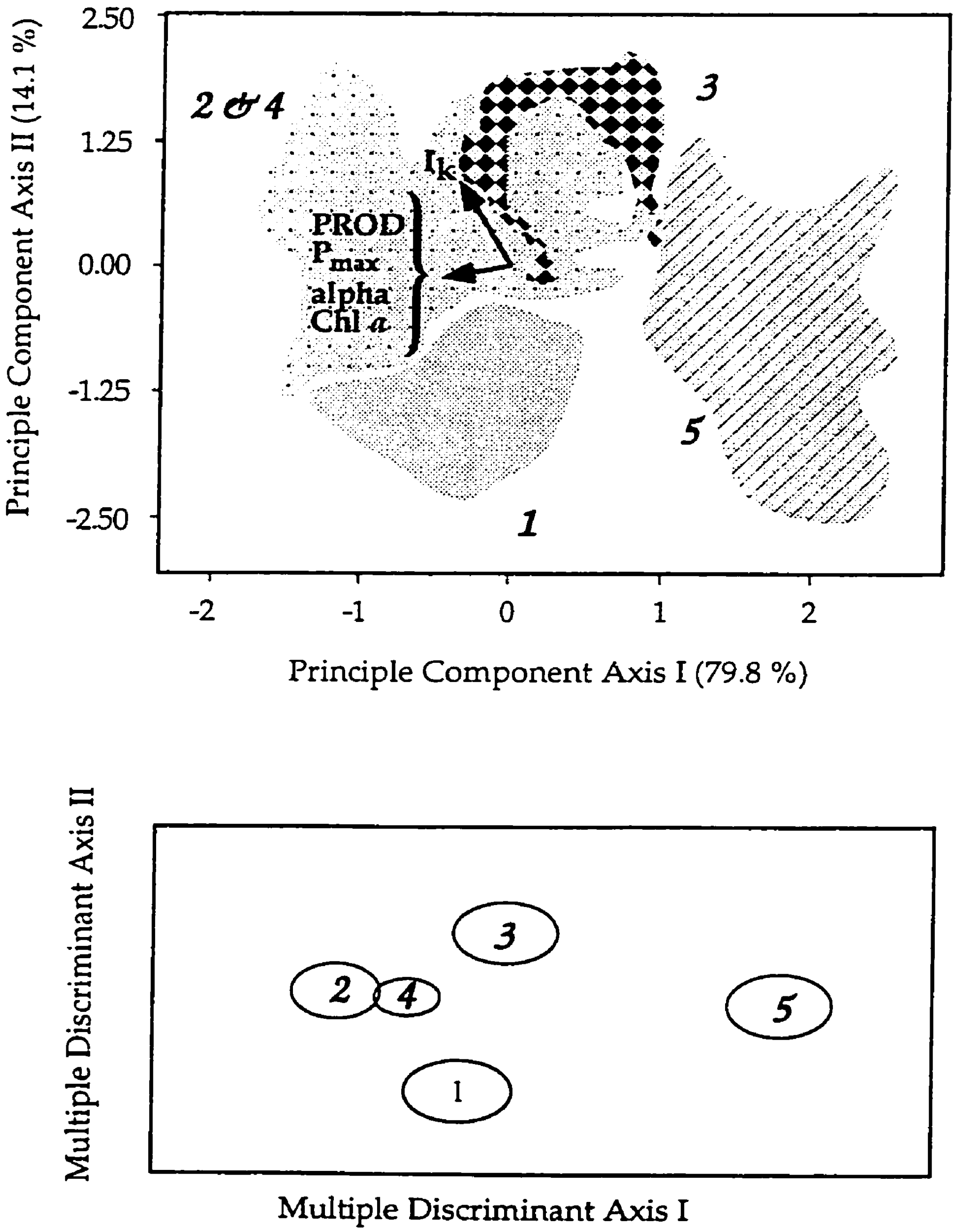


Figure 4.6 Ordinations of (a) Principle Components and (b) Multiple Discriminant Analyses performed on biomass (Chl *a*), P_{max}, alpha, I_k and estimated daily productivity. Individual data points have been grouped in the PCA and numbered 1 to 5 to indicate the seasonal episodes in 1994.

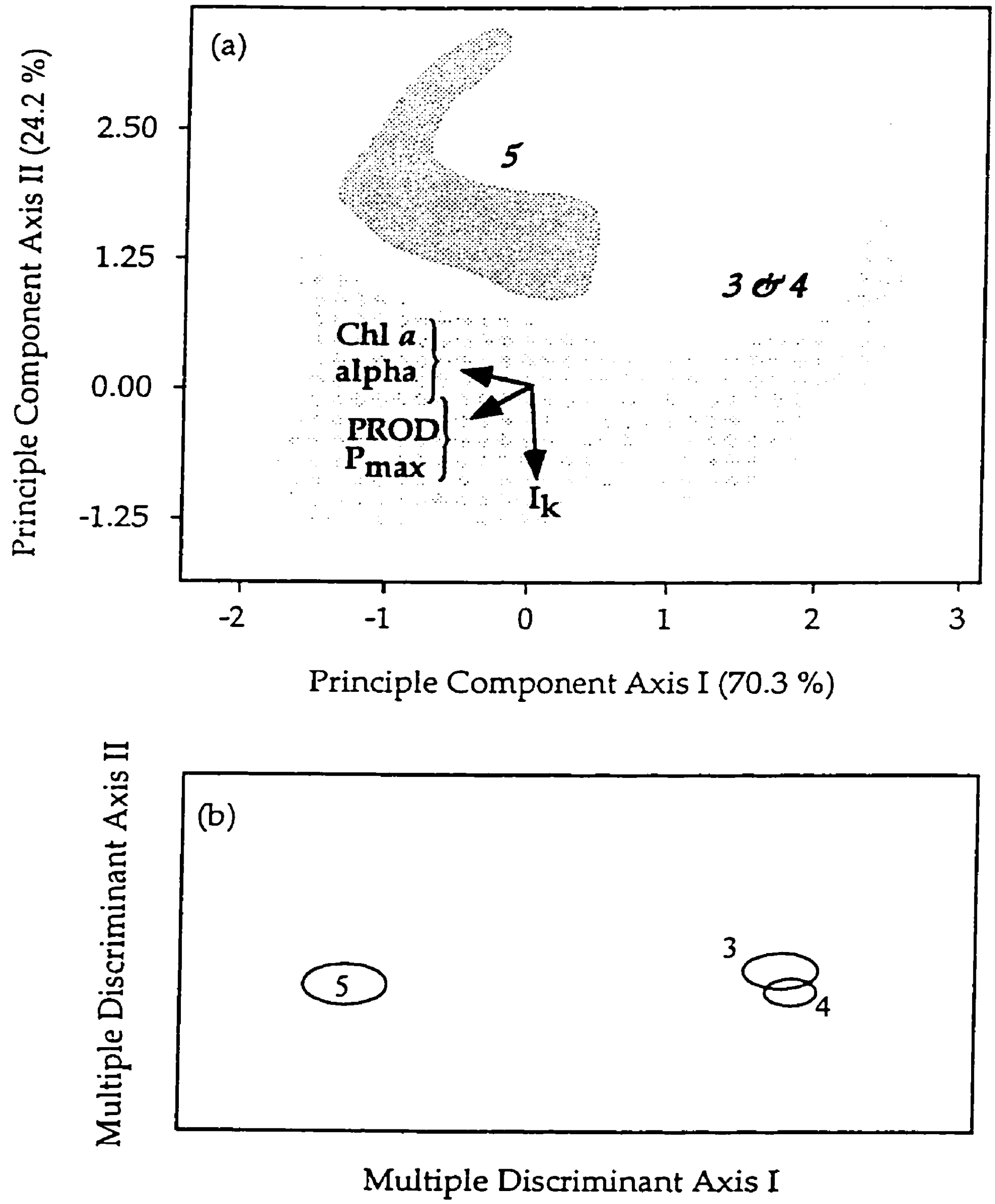


Figure 4.7 Ordinations of (a) Principal Components and (b) Multiple Discriminant Analyses performed on biomass (Chl *a*), P_{max}, alpha, I_k and estimated daily productivity. Individual data points have been grouped in the PCA and numbered 3 to 5 to indicate the seasonal episodes in 1995.

4.6). Episodes 2 and 4 displayed high values of I_k, but episode 1 did not. Episodes 3 and 5 displayed markedly lower biomass and photosynthesis.

In 1995 there appeared to be an increase in phytoplankton activity from episode 3 into episodes 4 and 5. Low measures of biomass, alpha, P_{max} and estimated daily productivity characterized episode 3. Conversely, high values were attributed with both episodes 4 and 5. There was a noticeable decline in I_k observed between episodes 4 and 5 (Figure 4.7).

River Sections

The sampling locations along the Red River were sectioned into three groups based on their association to either the Assiniboine River confluence or proximity to the point source discharge at the NEWPCC. Group 1 included sites R7 to R10 that were downstream of the NEWPCC. The "inter-city" section, referred to as group 2, comprised sites R5, R5.1 and R6 that were situated between the Assiniboine River confluence and the NEWPCC. Lastly, group 3 incorporated the "upstream" sites R1 to R4, that were located upstream of the Assiniboine River confluence. These River sections are shown in relation to both WPCC's and the Assiniboine confluence in Figure 4.8. Individual sampling locations are also shown.

Along the Assiniboine River, the Upstream (AU) and Downstream (AD) sampling stations were grouped together as the Assiniboine group (Figure 4.8).

One-way ANOVAs were performed to quantify the "within group" (or "intra-group") variability in physical, chemical and phytoplankton parameters in each of the seasonal episodes in 1994 and 1995. Results are presented in Tables 4.2 to 4.7, located at the end of the chapter. When significant variability between locations was detected by ANOVA (i.e., $p \leq$

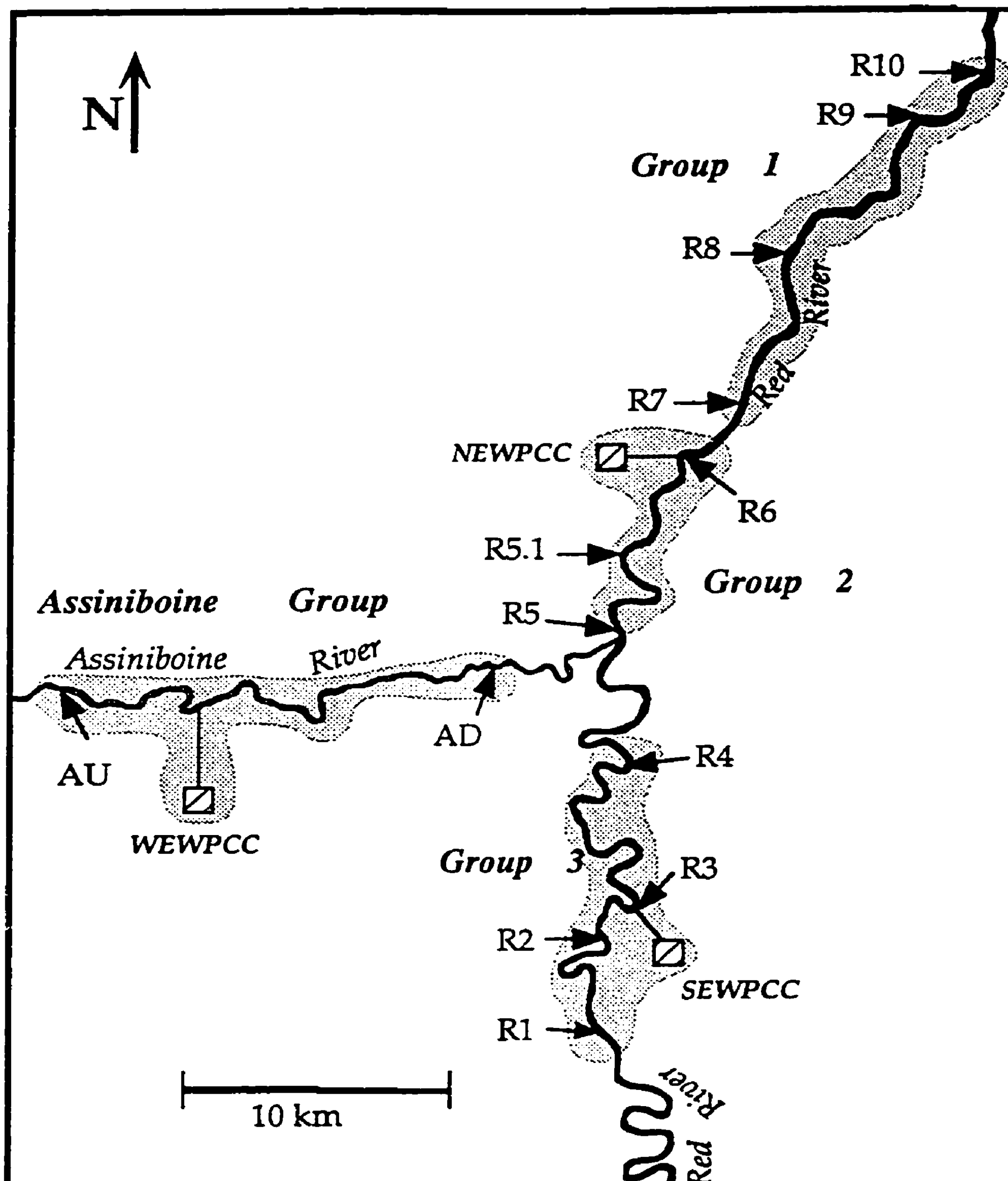


Figure 4.8 The river sections along the Red and Assiniboine Rivers in relation to the thirteen sampling stations. River groups have been shaded. Included are the three water pollution control centers within the City of Winnipeg. SEWPCC, NEWPCC and WEWPCC represent the South, North and West End Water Pollution Control Centers.

0.05), line-plots of means and standard deviations were created to display these differences. Along the Red River, the distance from R1 was used to plot these sampling stations. The distances of the sampling stations from R1 are presented in Table 2.1.

Intra-Group Variability in Physical Parameters

No intra-group variability was observed in measures of total weekly precipitation ($p \geq 0.893$) or *in situ* water temperature ($p \geq 0.836$). However, Red River flow rates were different throughout 1994 and 1995 (Tables 4.2, 4.3, 4.5 and 4.6). Flow rates declined from R7 to R10 in group 1 (Figure 4.9) and from R5 to R6 in group 2 (Figure 4.10). There were two exceptional periods during this study, and in particular seasonal episode 3 in 1994 and episode 5 in 1995, when flow rate among these locations were equivalent ($p > 0.10$).

In contrast with groups 1 and 2, River flow rate did not differ significantly in locations R1 to R4 in group 3 during any seasonal episode in either 1994 or 1995 ($p \geq 0.224$).

Flow rate in the Assiniboine River was not determined since cross-section information was not available.

There were no instances of intra-group variability in light extinction in either groups 2 or 3, and few in group 1. These were restricted to episodes 1 and 2 in 1994 ($p = 0.029$ and 0.012, respectively) and episode 5 in 1995 ($p = 0.017$). Similar differences were found in the depth of the euphotic zone in both episodes 1 and 2 in 1994 ($p = 0.007$ and 0.012, respectively). However, there were no significant differences found in the depth of the euphotic zone in 1995 ($p \geq 0.239$). During those periods of significant variability, R10 displayed lower light extinctions and consequently, greater euphotic depths (Figures 4.11 and 12).

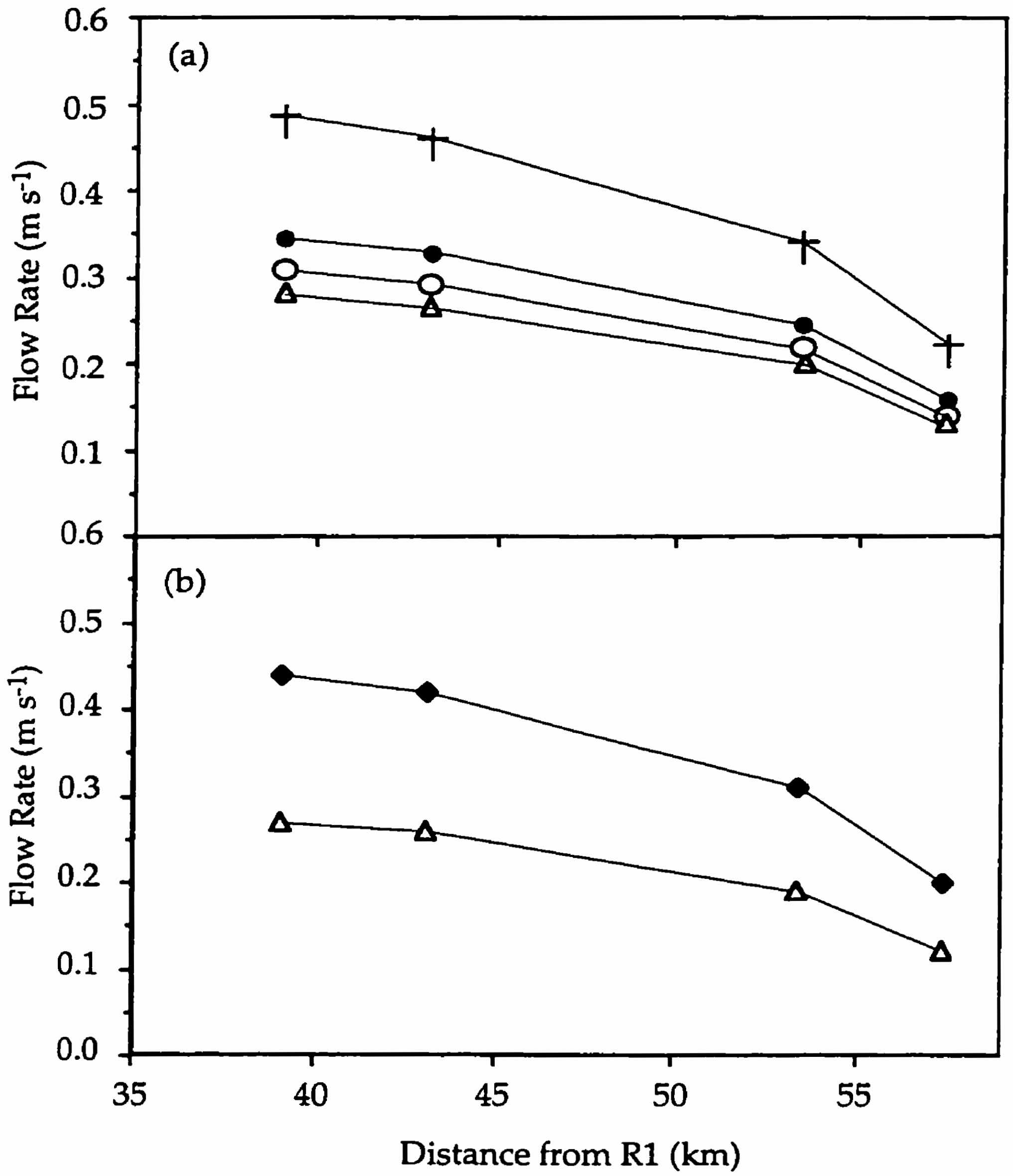


Figure 4.9 Mean Red River flow rate observed within group 1 in each seasonal episode in (a) 1994 and (b) 1995. Locations are represented as their distance from R1 (Table 2.1). Significant differences were found in seasonal episodes 1 (┼), 2 (○), 4 (▲) and 5 (●) in 1994 and episodes 3 (◆) and 4 (▲) in 1995. Error bars have been removed for clarity.

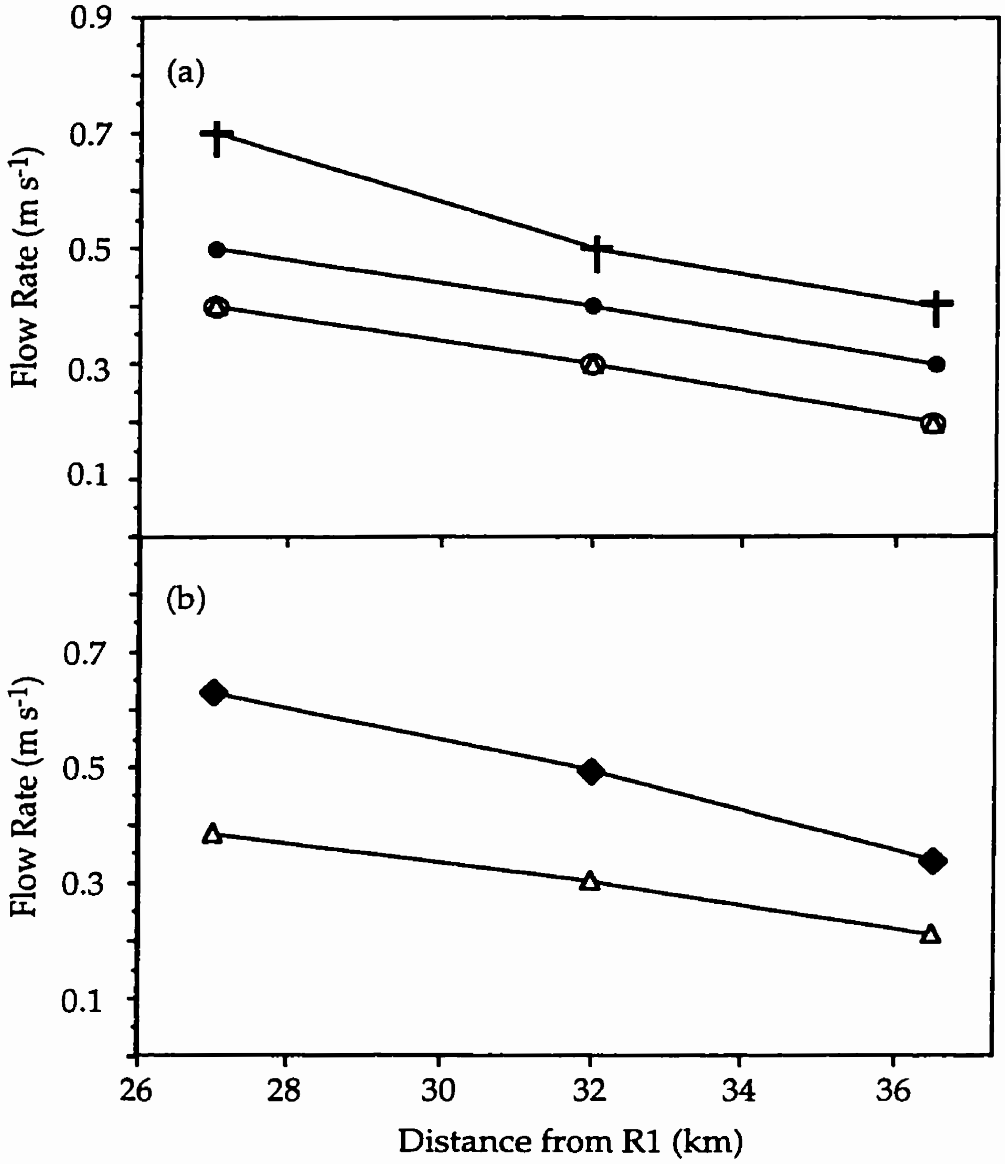


Figure 4.10 Mean flow rates in group 2 locations during (a) 1994 and (b) 1995. Locations are represented as their distance from R1. Significant differences were found in seasonal episodes 1 (+), 2 (O), 4 (▲) and 5 (●) in 1994 and episodes 3 (◆) and 4 (▲) in 1995. Error bars have been removed for clarity.

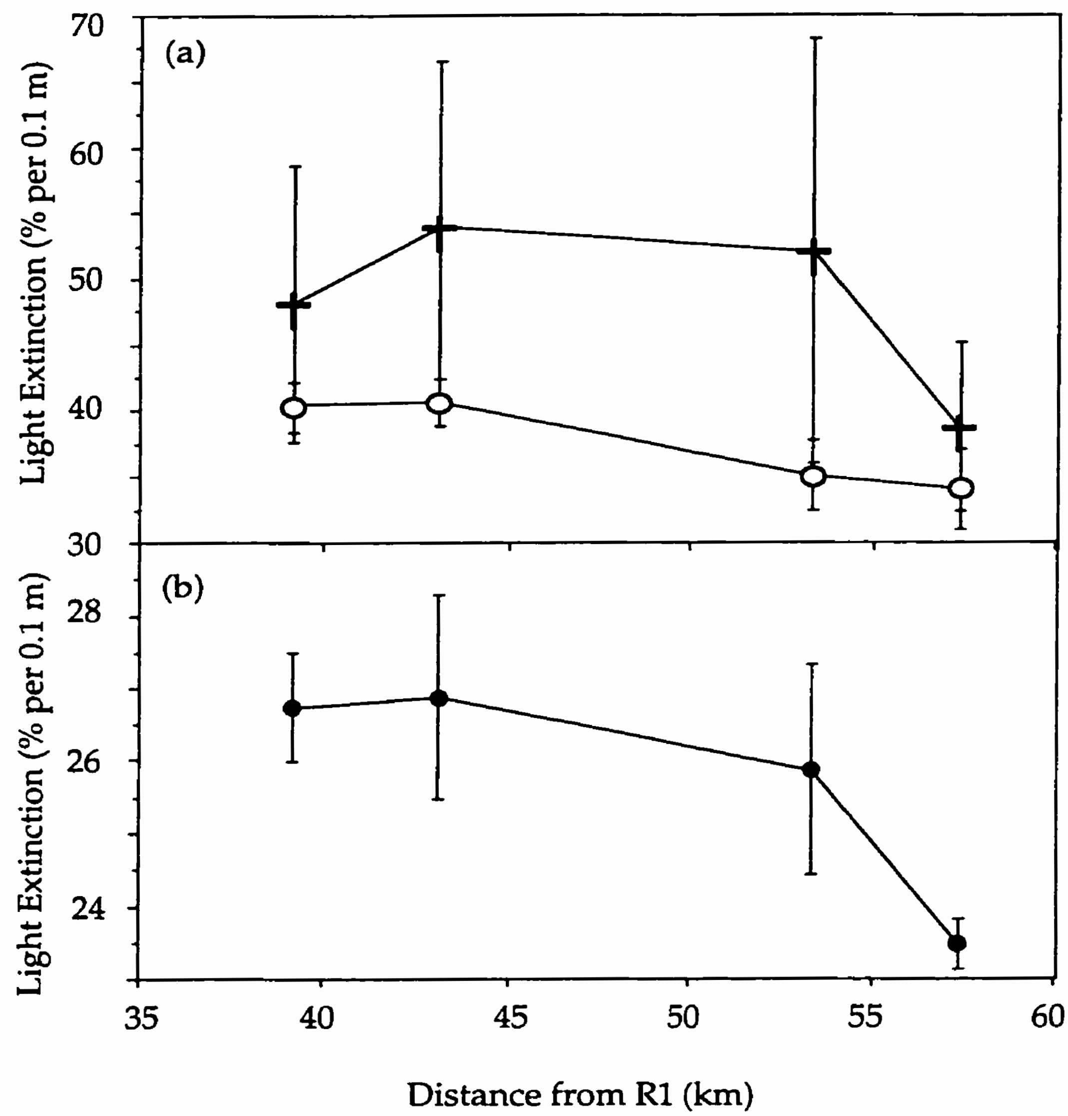


Figure 4.11 Mean light extinction observed in group 1 locations during (a) 1994 and (b) 1995. Locations are represented as their distance from R1. Significant differences were found in seasonal episodes 1 (+) and 2 (O) in 1994 and episode 5 (●) in 1995.

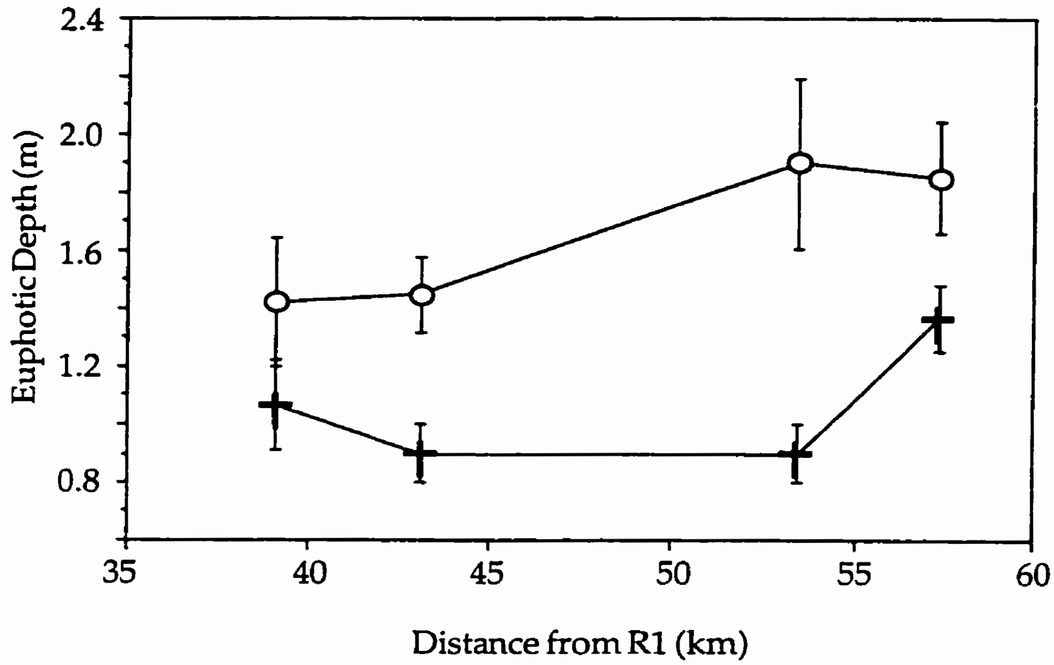


Figure 4.12 Mean euphotic depth observed in group 1 locations during 1994. Locations are represented as their distance from R1. Significant differences were found in seasonal episodes 1 (+) and 2 (O).

Comparisons were not made of euphotic depth or light extinction between Assiniboine locations because the upstream locations was consistently sampled before sunrise.

Intra-Group Variability in Chemical Parameters

In 1994, variability among locations in group 1 was restricted to episodes 1 and 2 (Table 4.2). Concentrations of PN ($p \leq 0.052$) and PC ($p \leq 0.035$) were significantly lower in R10 during seasonal episodes 1 and 2 (Figure 4.13), as well as PP ($p = 0.065$) in episode 1 and NH_4^+/NH_3-N ($p = 0.029$) in episode 2 (Figure 4.14).

In 1995, the variability within group 1 was restricted to the concentration of SOC ($p = 0.035$) during episode 5. Concentrations were found to decline from R7 to R9 but were elevated again at R10 (Figure 4.15).

There were only a few instances of intra-group variability in chemical parameters in group 2 in 1994 and 1995. In 1994, concentrations of TN ($p = 0.098$) were much lower at site R5.1 than either R5 or R6 in episode 1 (Figure 4.16). In seasonal episode 2, pH ($p = 0.030$) and PN ($p = 0.020$) were found to increase from site R5 to R6 (Figure 4.17), while NH_4^+/NH_3-N ($p = 0.005$) was found to decrease (Figure 4.18). In 1995, the only factor to exhibit a difference among locations was SIN ($p = 0.035$) in seasonal episode 5 and it was found to decrease in concentration from R5 to R6 (Figure 4.19).

NH_4^+/NH_3-N was the only chemical parameter found to exhibit variability among locations in group 3 (Figure 4.20). Significant differences were found during seasonal episodes 1 ($p = 0.045$), 2 ($p = 0.001$), 4 ($p = 0.000$) and 5 ($p = 0.007$) in 1994, and all episodes in 1995 ($p \leq 0.028$). Concentrations were significantly higher downstream of the SEWPCC, at location R4.

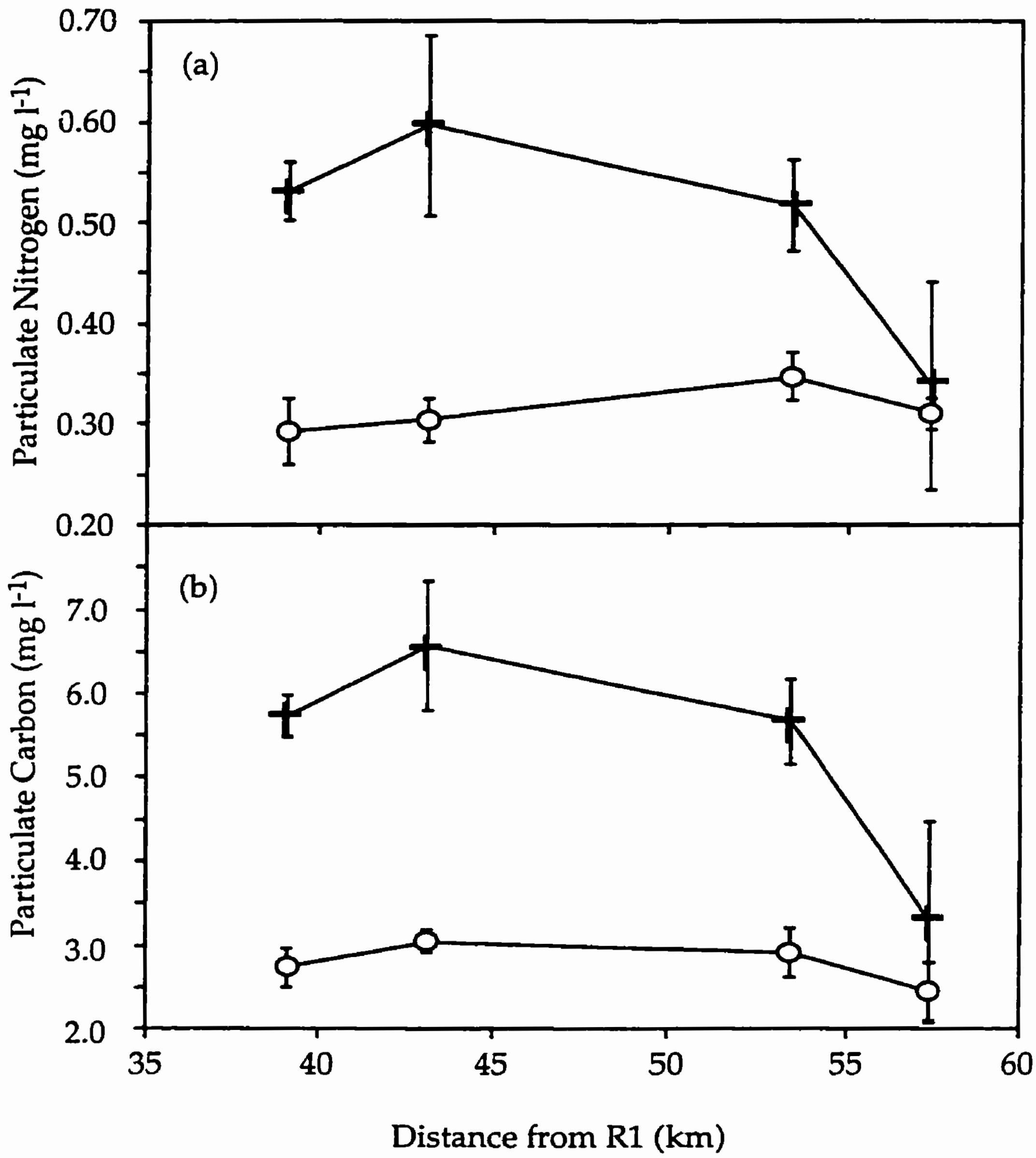


Figure 4.13 Mean (a) particulate nitrogen (mg l^{-1}) and (b) particulate carbon (mg l^{-1}) in group 1 locations during 1994. Locations are represented as their distance from R1. Significant differences were found in seasonal episodes 1 (+) and 2 (O) in 1994.

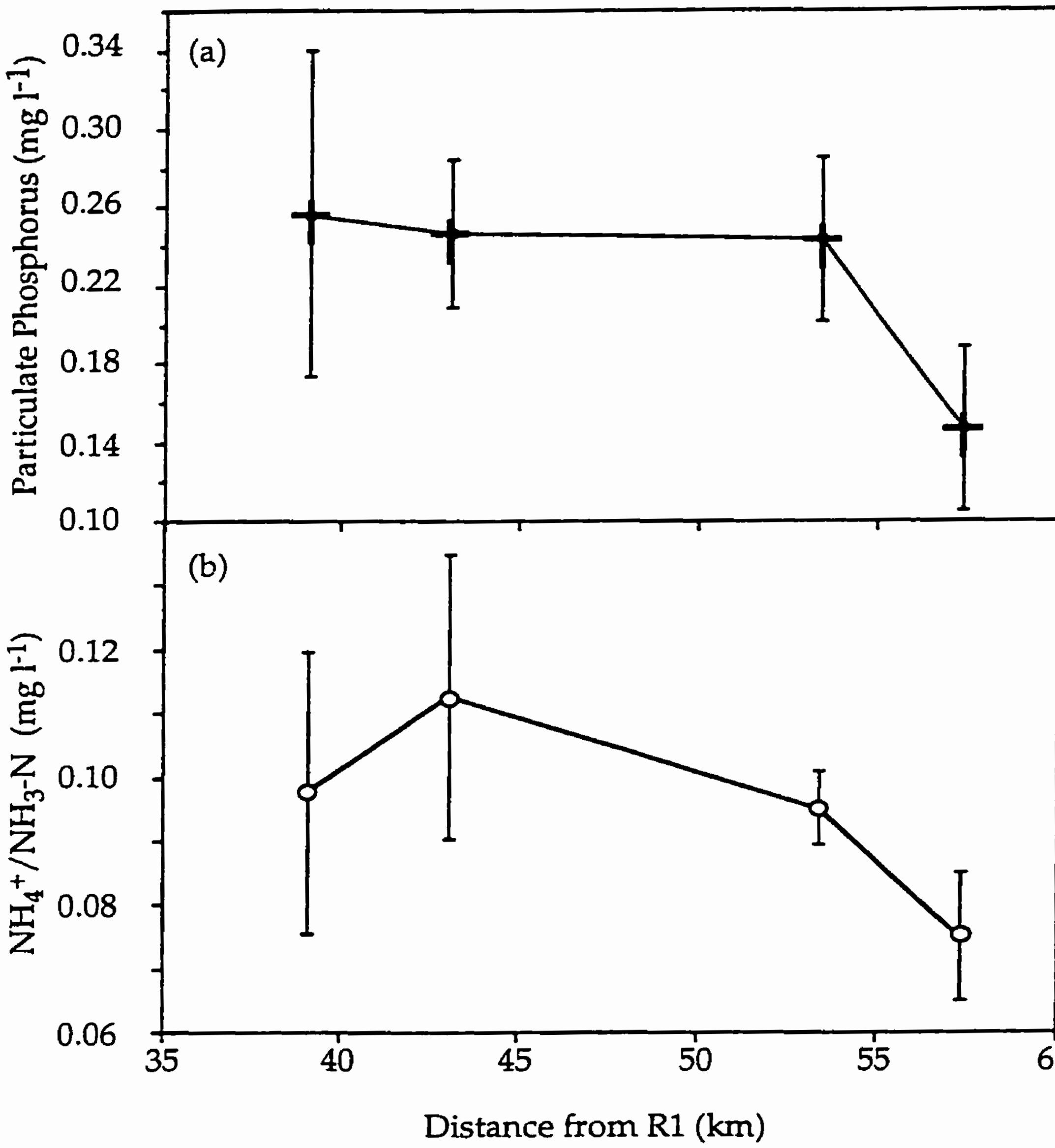


Figure 4.14 Mean concentrations of (a) particulate phosphorus and (b) total ammonia (NH_4^+/NH_3-N) in group 1 locations during 1994. Locations are represented as their distance from R1. Significant differences were found in seasonal episodes 1 (+) and 2 (o).

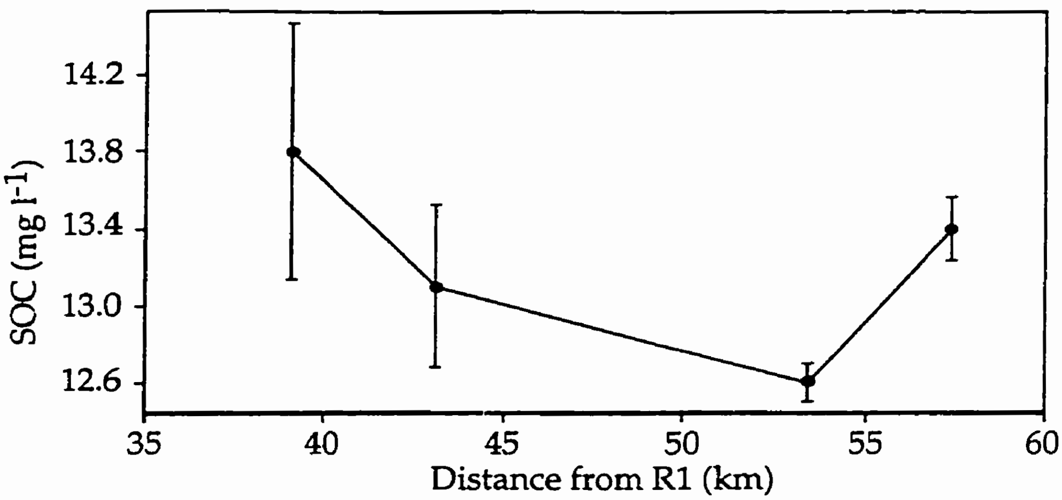


Figure 4.15 Mean concentration of soluble organic carbon (SOC) (mg l^{-1}) found in group 1 locations during seasonal episode 5 in 1995. Locations are represented as their distance from R1.

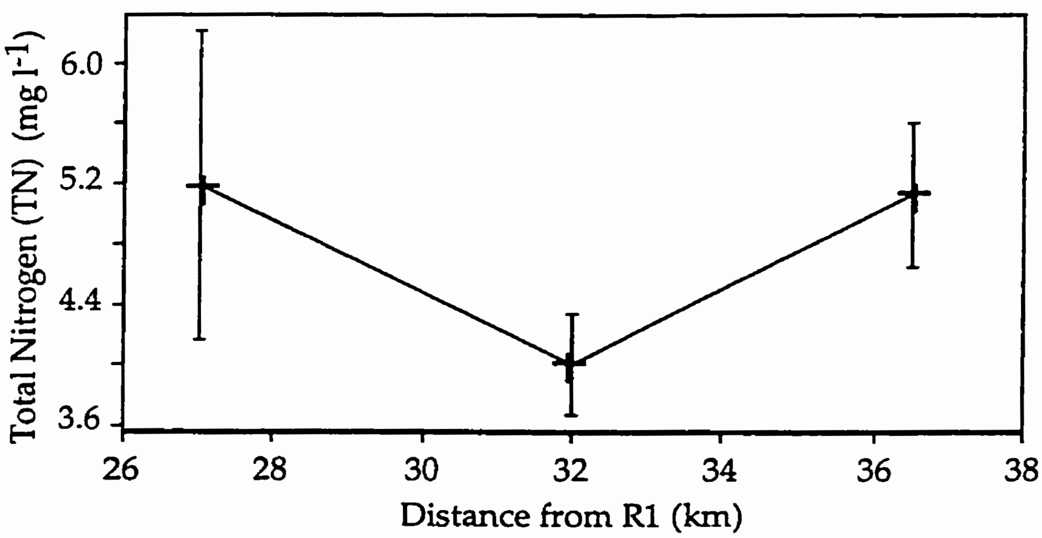


Figure 4.16 Mean concentration of total nitrogen (mg l^{-1}) observed in locations R5, R5.1 and R6 during seasonal episode 1 in 1994. Locations are represented as their distance from R1.

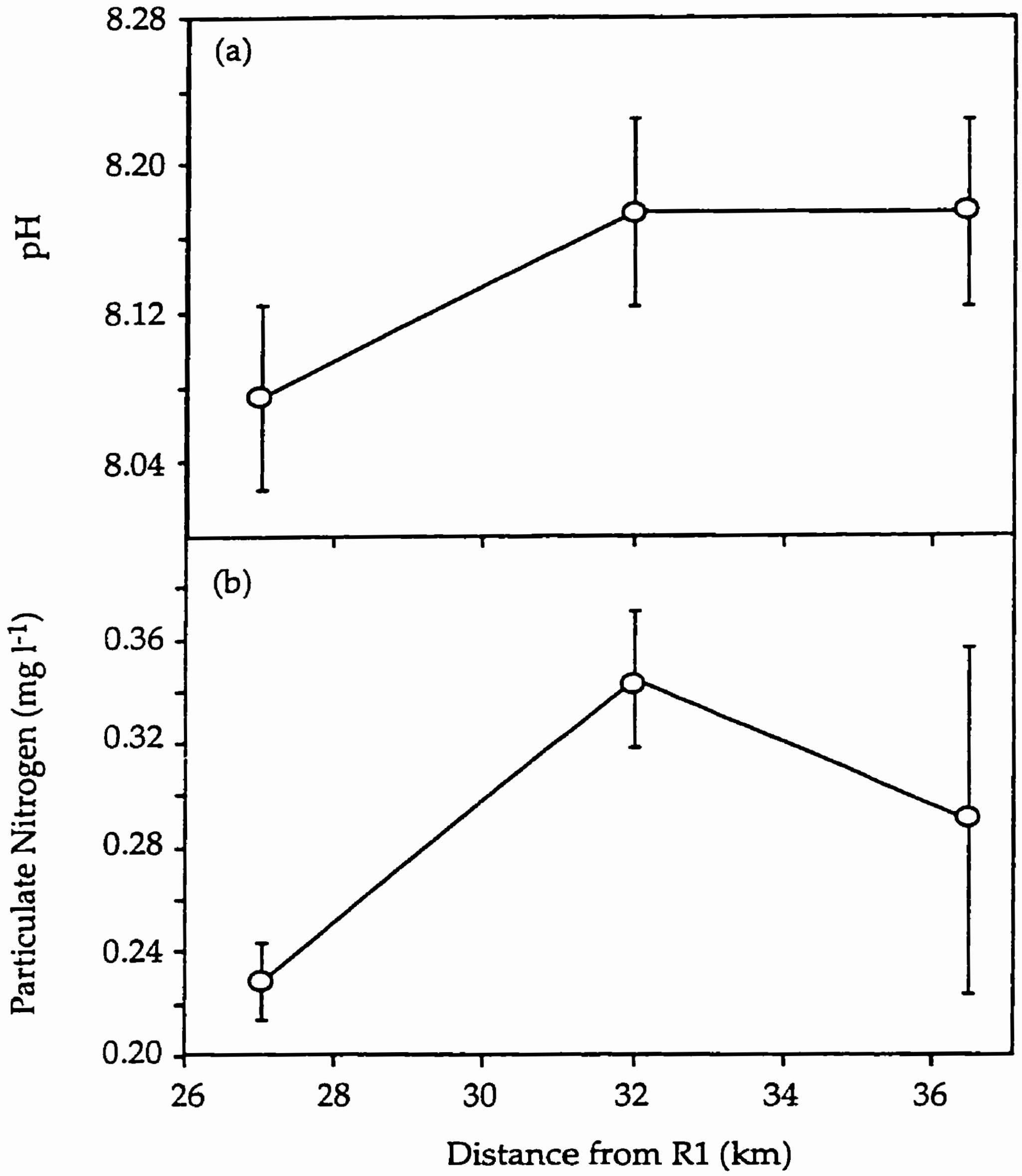


Figure 4.17 Mean (a) pH and (b) particulate nitrogen concentration in group 2 locations during seasonal episode 2 in 1994. Locations are represented as their distance from R1.

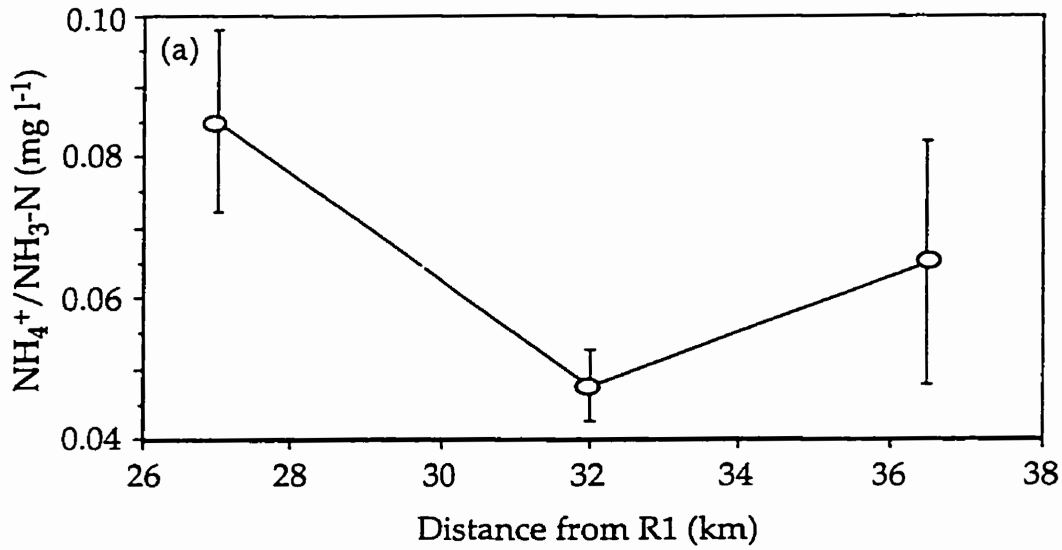


Figure 4.18 Mean concentration of total ammonia (NH_4^+/NH_3-N) in group 2 locations during seasonal episode 2 in 1994. Locations are represented by their distance from R1.

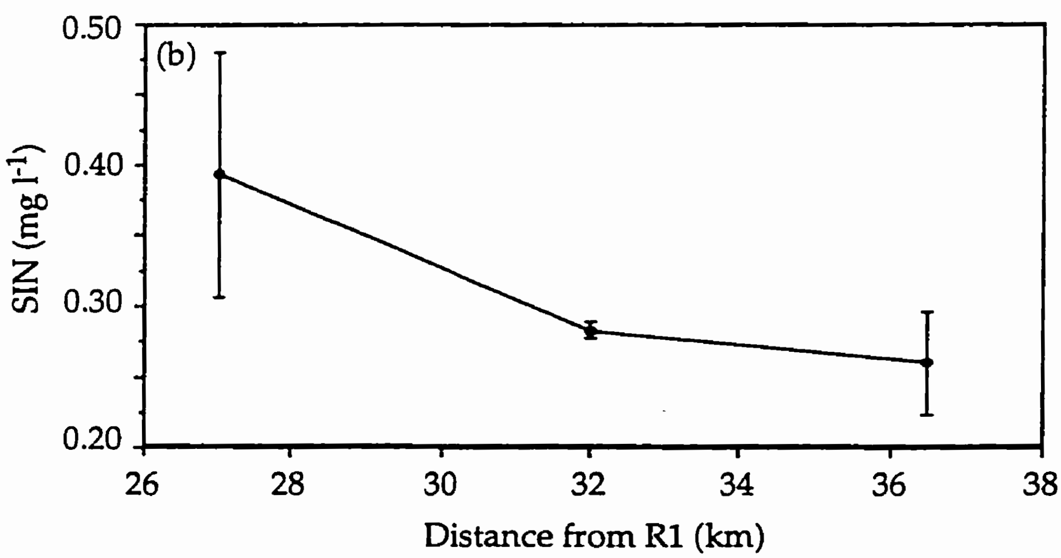


Figure 4.19 Mean concentration of soluble inorganic nitrogen (SIN) in group 2 locations during seasonal episode 5 in 1995. Locations are represented by their distance from R1.

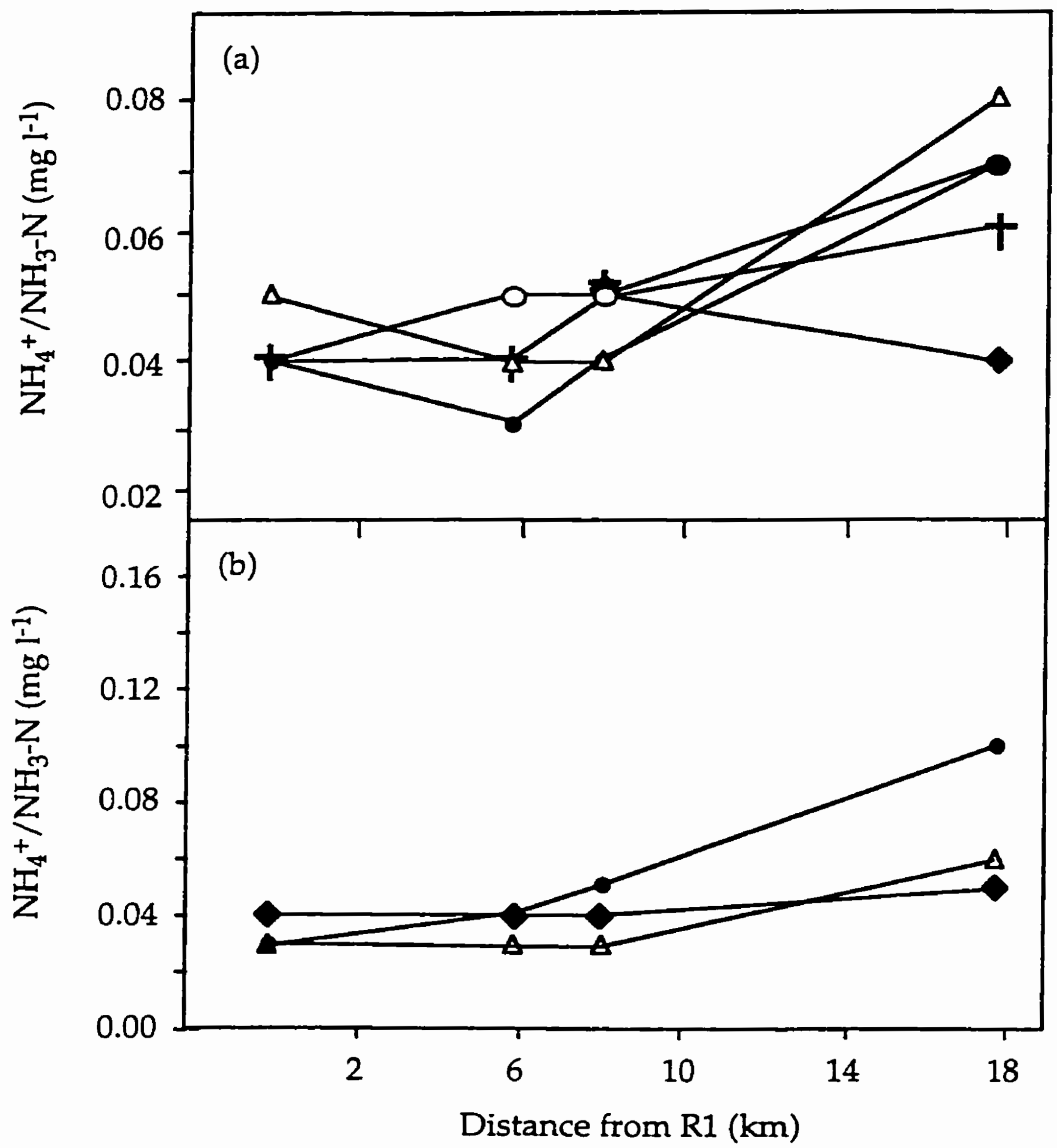


Figure 4.20 Mean concentrations of total ammonia nitrogen (NH_4^+/NH_3-N) in group 3 locations during (a) 1994 and (b) 1995. Significant differences were found in seasonal episodes 1 (+), 2 (○), 3 (◆), 4 (△) and 5 (●) in 1994 and episodes 3 (◆), 4 (△) and 5 (●) in 1995. Locations are represented by their distance from R1. Error bars have been removed for clarity.

In a similar approach, the variability in chemical parameters was examined between the upstream (AU) and downstream (AD) Assiniboine locations. Results from one-way ANOVAs are presented in Tables 4.8 and 4.9 at the end of the Chapter.

In 1994, AD was found to exhibit significantly (or near significantly) higher concentrations of the following chemical parameters: PN ($p = 0.006$) and SOC ($p = 0.093$) in seasonal episode 2 (Figure 4.21); SRP in episodes 3 ($p = 0.087$), 4 ($p = 0.009$) and 5 ($p = 0.019$) (Figure 4.22); NH_4^+/NH_3-N in episodes 4 ($p = 0.095$) and 5 ($p = 0.009$) as well as DP in episode 4 ($p = 0.071$) (Figure 4.23). Conversely, AU had near significantly higher pH ($p = 0.089$) in episode 3 (Figure 4.23) and higher concentrations of SOC ($p = 0.046$) in episode 5 (Figure 4.24).

In 1995, differences between Assiniboine locations were found in the following chemical parameters: SRP in episodes 3 ($p = 0.074$) and 4 ($p = 0.059$) as well as SOP in episode 3 ($p = 0.063$) (Figure 4.24); TN in episode 4 ($p = 0.009$) and DP in episodes 4 ($p = 0.038$) and 5 ($p = 0.031$) (Figure 4.25a); and SIN and NH_4^+/NH_3-N in episode 5 ($p = 0.060$, 0.053, respectively) (Figure 4.25b). With the notable exception of SOP in seasonal episode 3, chemical concentrations were typically higher at AD.

Intra-Group Variability in Phytoplankton Parameters

In 1994, variability among locations in group 1 was restricted to seasonal episode 2 when estimated daily primary productivity ($p = 0.009$) and I_k ($p = 0.051$) were significantly higher at R9 and R10 than at either R7 or R8 (Figure 4.26). In 1995, variability was found in seasonal episode 3 when I_k ($p = 0.080$) was significantly higher at R7.

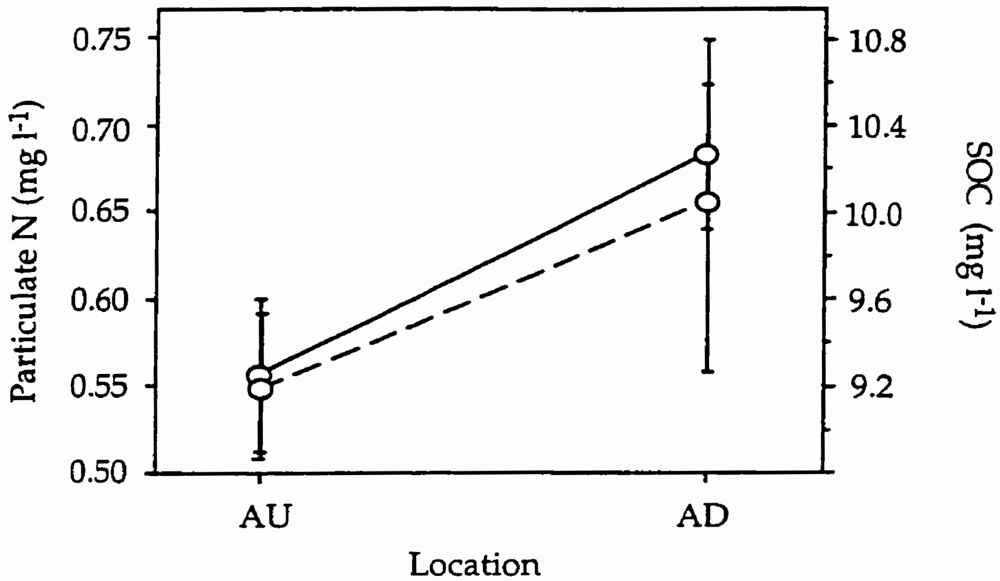


Figure 4.21 Mean concentrations of (a) particulate nitrogen (——) and (b) soluble organic carbon (SOC) (— — ·) in Assiniboine locations during seasonal episode 2 in 1994. Refer to text for description of locations.

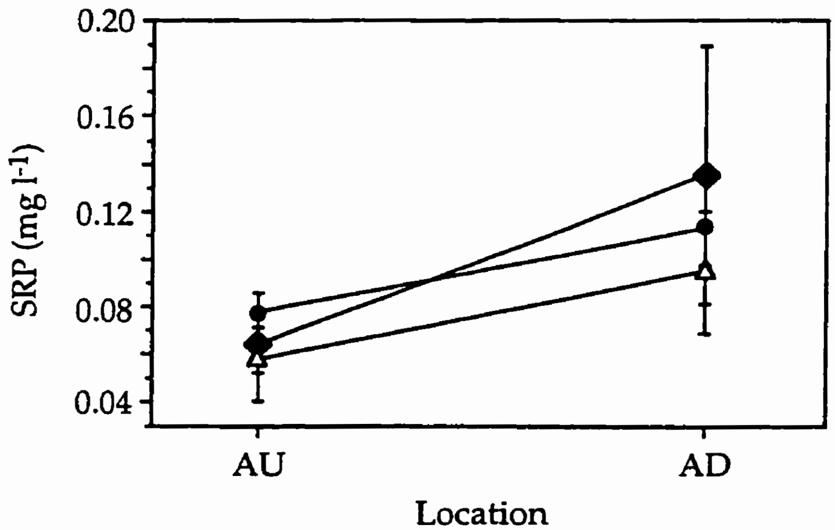


Figure 4.22 Mean concentration of soluble reactive phosphorus (SRP) in Assiniboine locations during seasonal episodes 3 (◆), 4 (Δ) and 5 (●) in 1994. Refer to text for description of locations.

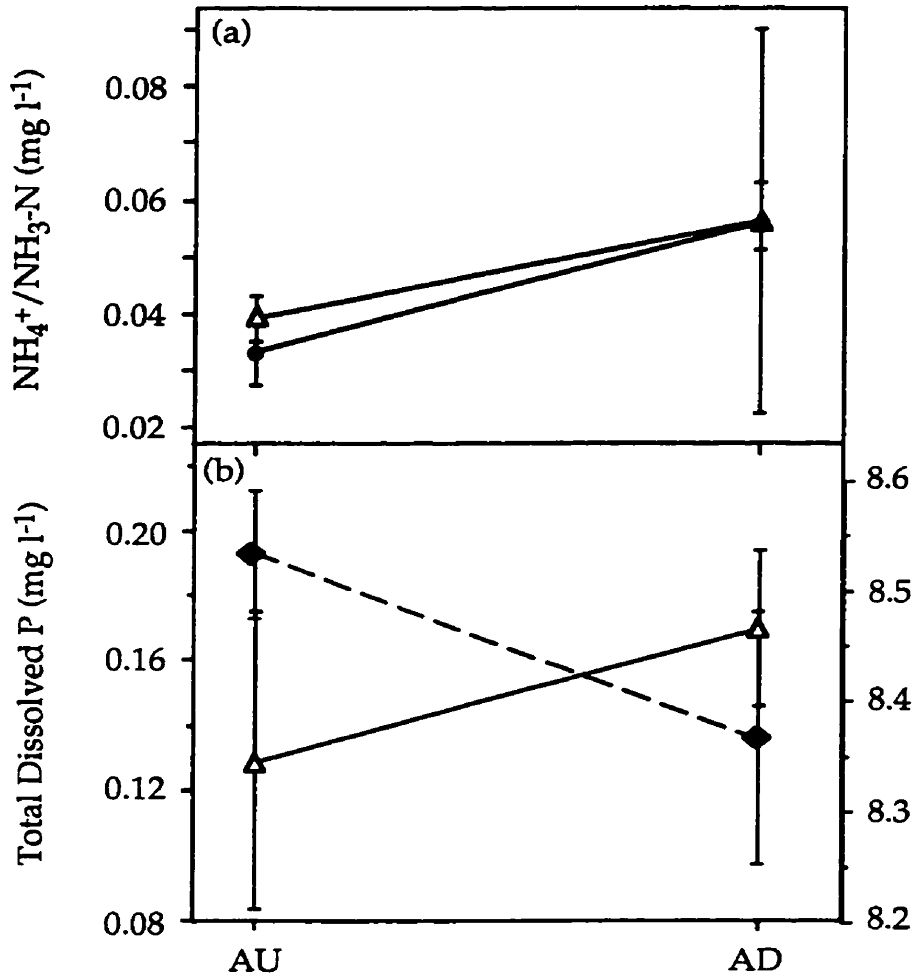


Figure 4.23 Mean concentrations of (a) total ammonia N (NH_4^+/NH_3-N) and (b) total dissolved phosphorus (——) and pH (— — ·) in the Assiniboine locations in 1994. Significant differences were found during seasonal episodes 3 (◆), 4 (▲) and 5 (●). Refer to text for description of Assiniboine locations.

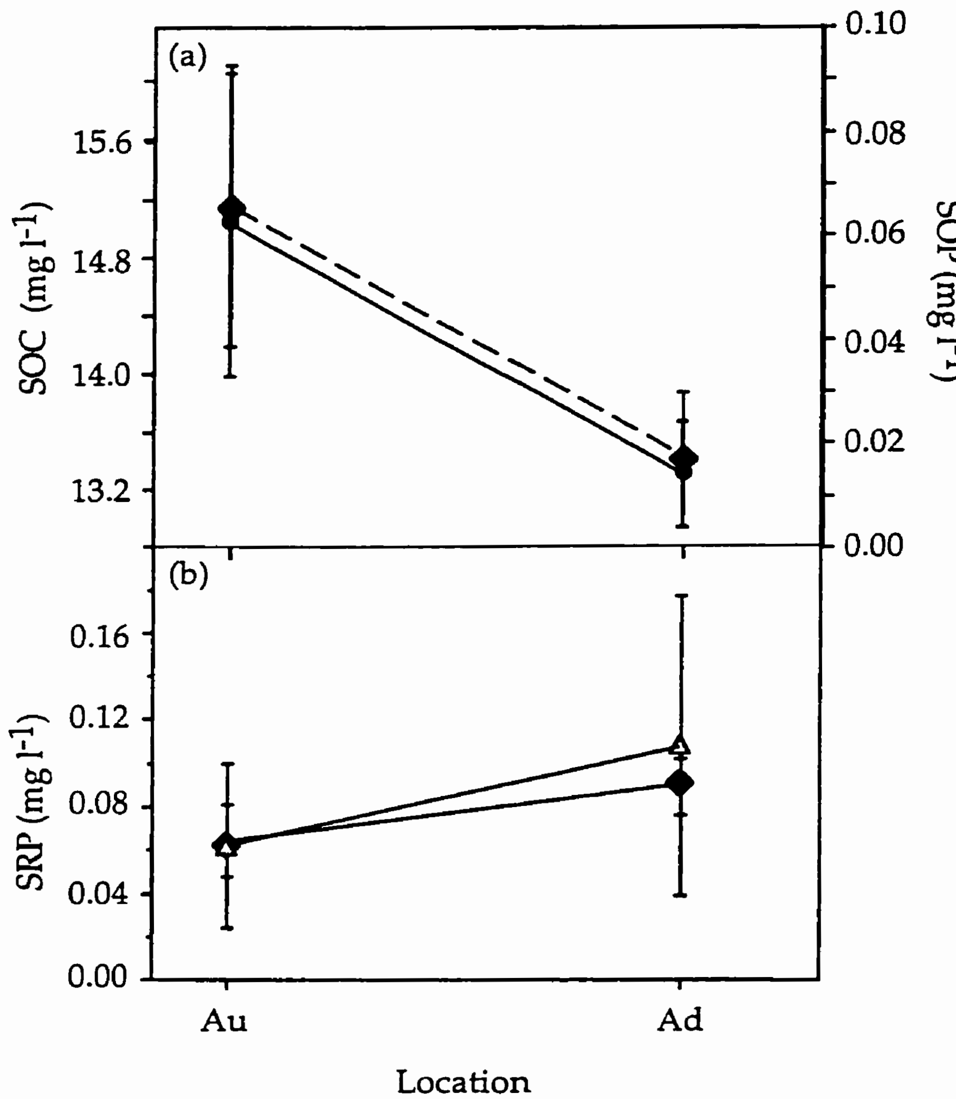


Figure 4.24 Mean concentrations of (a) soluble organic carbon (SOC) (———) and soluble organic phosphorus (SOP) (— — -) and (b) soluble reactive phosphorus (SRP) in Assiniboine locations. Significant differences in SOC were found during seasonal episode 5 (●) in 1994; in SOP and/or SRP during episodes 3 (◆) and 4 (▲) in 1995. Refer to text for description of locations in the Assiniboine River.

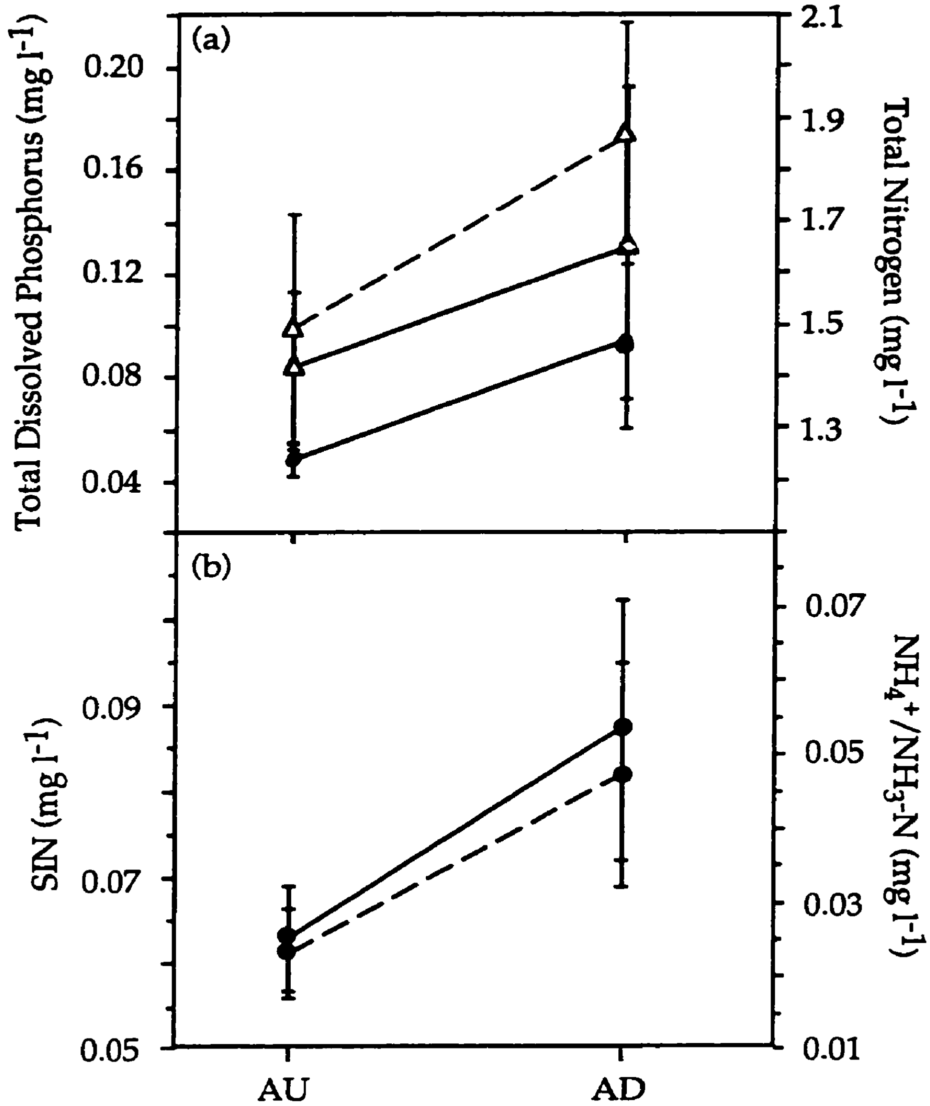


Figure 4.25 Mean concentrations of (a) total dissolved phosphorus (——) and total nitrogen (— — ·) and (b) soluble inorganic nitrogen (SIN) (——) and total ammonia N (NH_4^+/NH_3-N) (— — ·) in Assiniboine locations. Significant differences were found in seasonal episodes 4 (Δ) and/or 5 (o) in 1995.

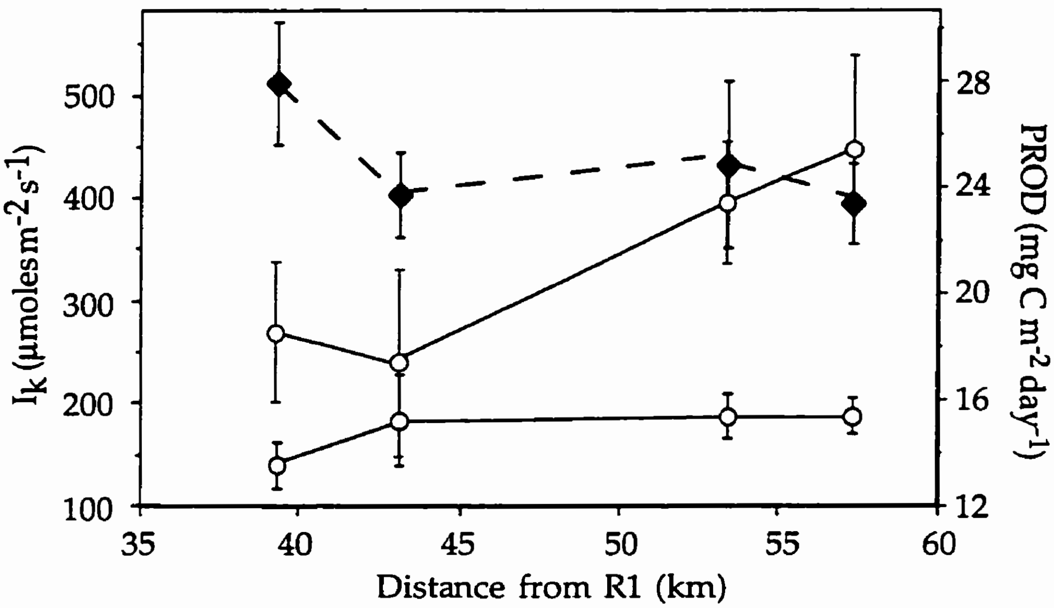


Figure 4.26 Mean measurements of I_k and estimated daily phytoplankton productivity (PROD) in Group 1 locations. Significant differences in I_k were found during seasonal episodes 2 in 1994 (—○—) and 3 in 1995 (— ◆ -). Differences in estimated daily productivity were found during episode 2 in 1994 (—○—).

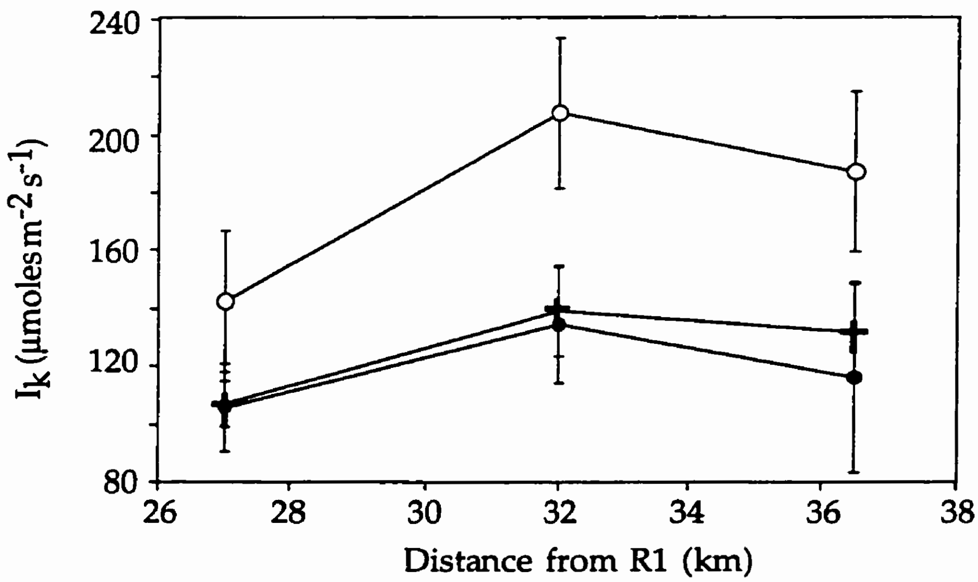


Figure 4.27 Mean measurements of I_k in Group 2 locations in 1994. Significant differences were observed during seasonal episodes 1 (✝), 2 (○) and 5 (•).

Within group 2 in 1994, variability between locations occurred during episodes 1, 2 and 5 (Table 4.3). While only I_k (p = 0.059) was significantly lower in episode 1, all phytoplankton parameters were significantly lower at R5 in episode 2 (Figures 4.27 to 4.29). Moreover, there was a progressive increase in parameters downstream of R5. Lastly, in seasonal episode 5, significantly lower activity was noted at R5 in all parameters with the exception of chlorophyll *a* (Figures 4.27 to 4.29).

In 1995, variability among locations in group 2 was restricted to alpha, P_{max} and I_k during seasonal episode 5 (Figure 4.30).

In group 3, intra-group variability was found in alpha (p = 0.064) during seasonal episode 2 in 1994. Alpha was similar at R1 and R4, but significantly higher than found in samples taken from R3 (Figure 4.31). Phytoplankton activity at location R2 were intermediate.

Significant differences in phytoplankton parameters in AU and AD were found in seasonal episodes 2 and 4 in 1994 (Table 4.8). In episode 2, both biomass (p = 0.037) and I_k (p = 0.002) were shown to be significantly higher at AD than at AU (Figure 4.32) as was estimated daily productivity in episode 4 (p = 0.077) (Figure 4.33). There were no significant differences detected in phytoplankton parameters between Assiniboine locations in 1995 (Table 4.9).

4.3 Temporal Variability Between Seasonal Episodes in 1994 and 1995

To quantify the differences between seasonal episodes in each year along the Red River, two-way analysis of variance was performed for all physical, chemical and phytoplankton parameters. The first factor was seasonal episode (1, 2, 3, 4 or 5), the other, River section (Group 1, 2 or 3).

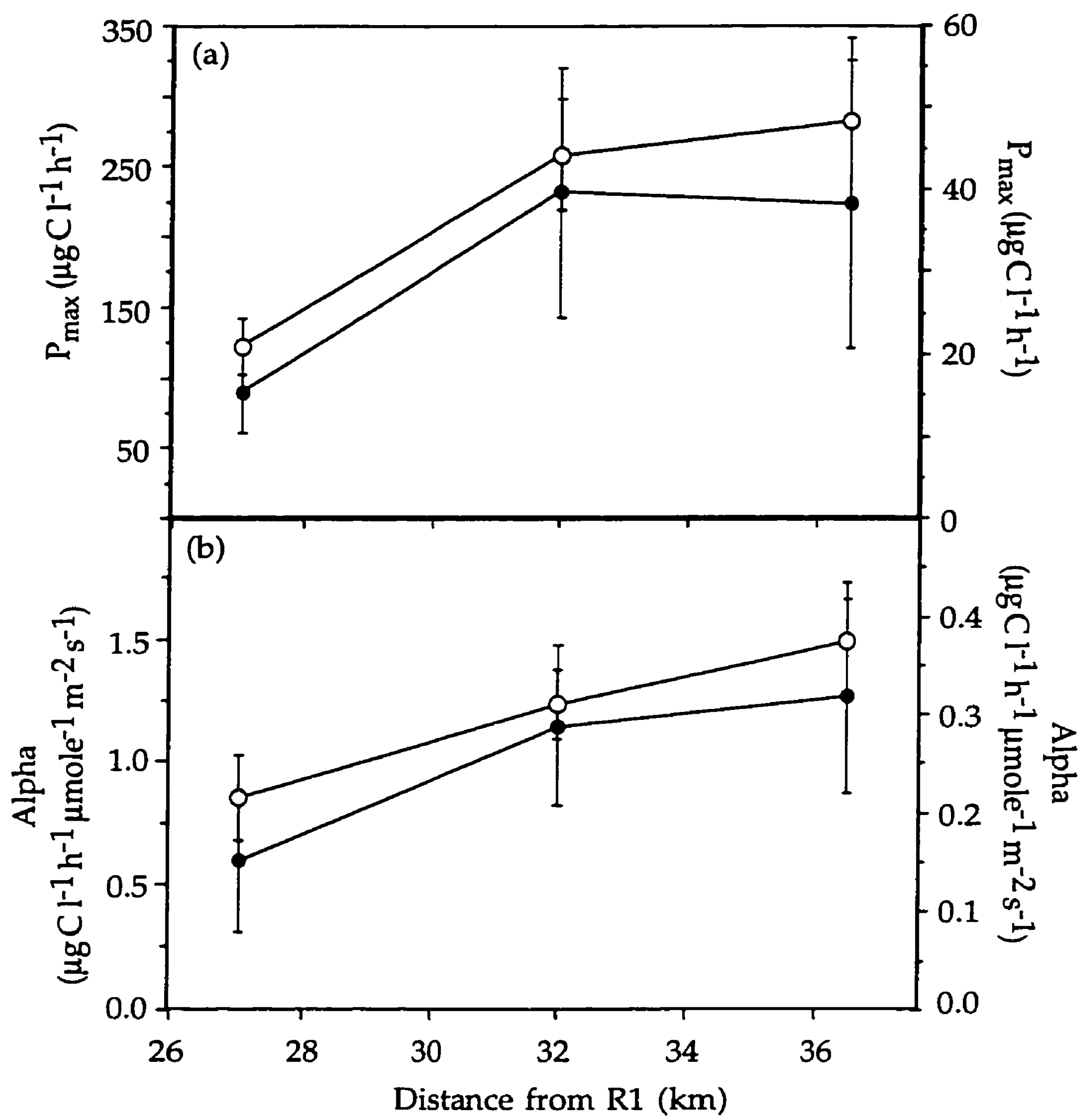


Figure 4.28 Mean measurements of P_{max} and alpha in group 2 locations in 1994. Significant differences were found during seasonal episodes 2 (○) and 5 (●).

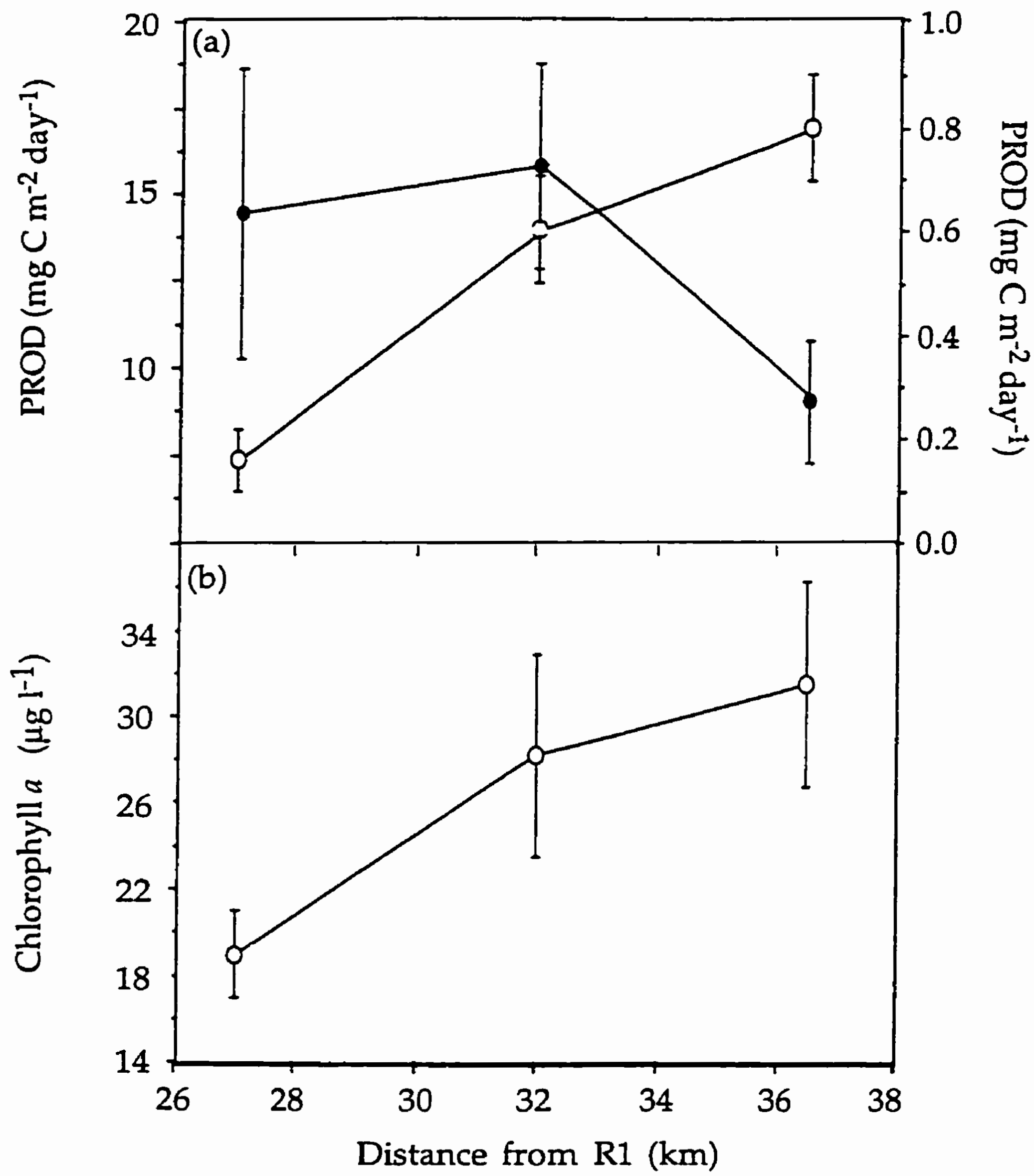


Figure 4.29 Mean (a) estimated daily phytoplankton productivity (PROD) and (b) chlorophyll a in group 2 locations. Significant differences were found during seasonal episodes 2 (o) and 5 (•) in 1994.

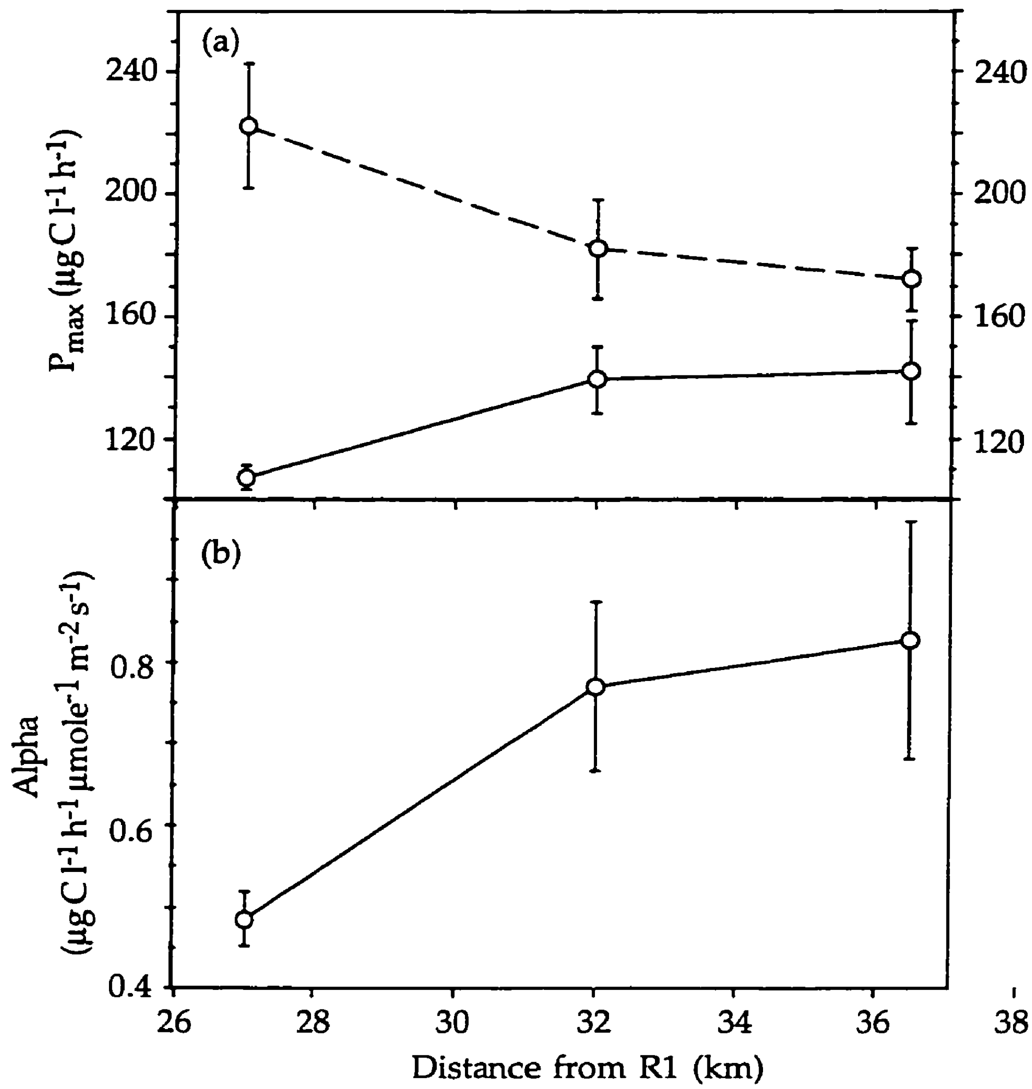


Figure 4.30 Mean (a) P_{max} (———) and I_k (— —) and (b) alpha in group 2 locations during seasonal episode 2 in 1994.

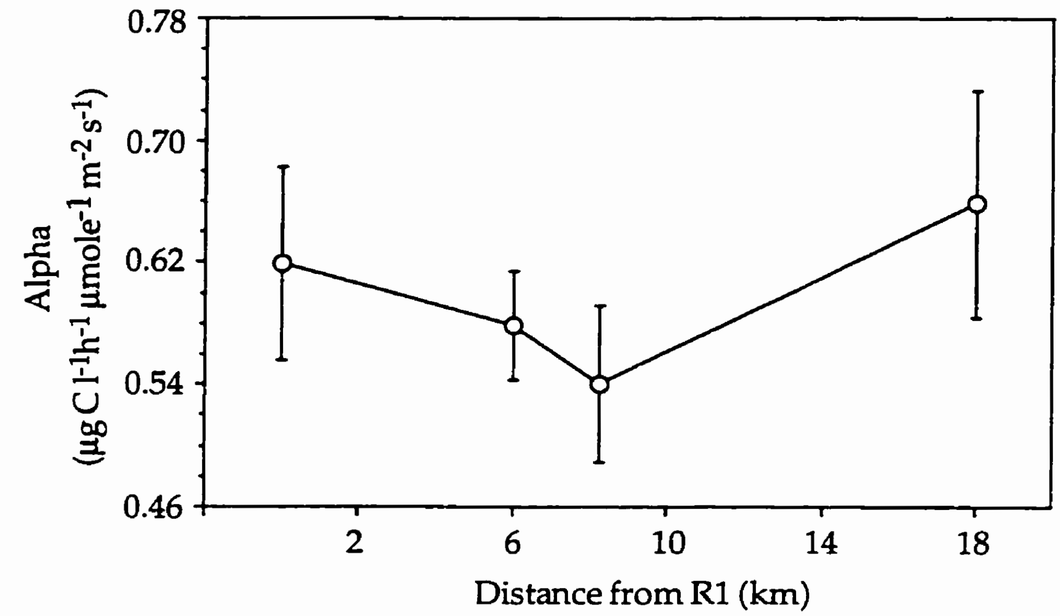


Figure 4.31 Mean measurements of alpha in group 3 locations during seasonal episode 2 in 1994.

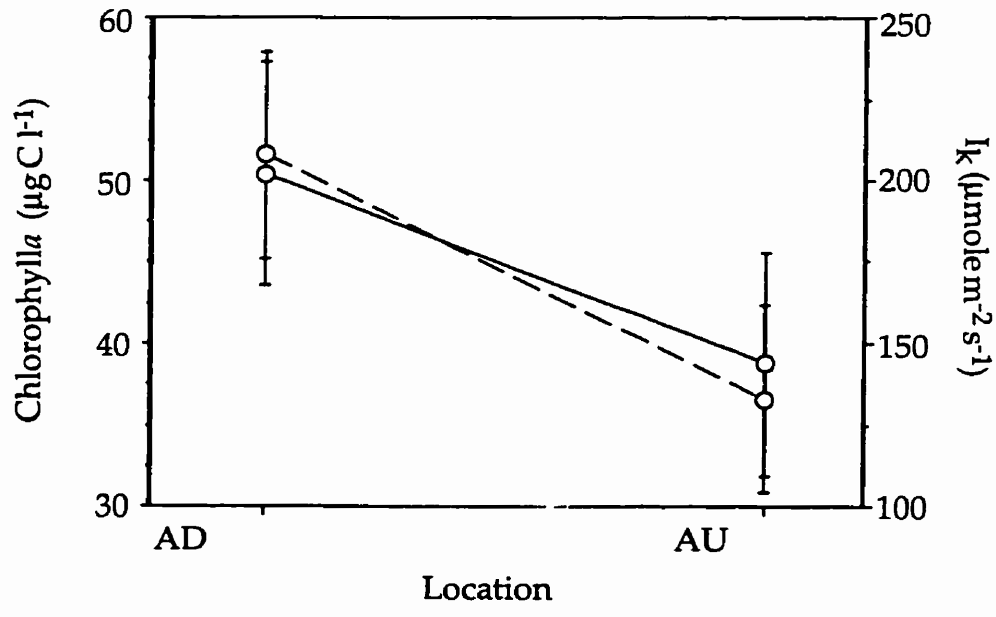


Figure 4.32 Mean chlorophyll *a* concentrations (—+— and I_k (— — ·) in Assiniboine locations in seasonal episode 2 in 1994. Refer to text for a description of Assiniboine locations.

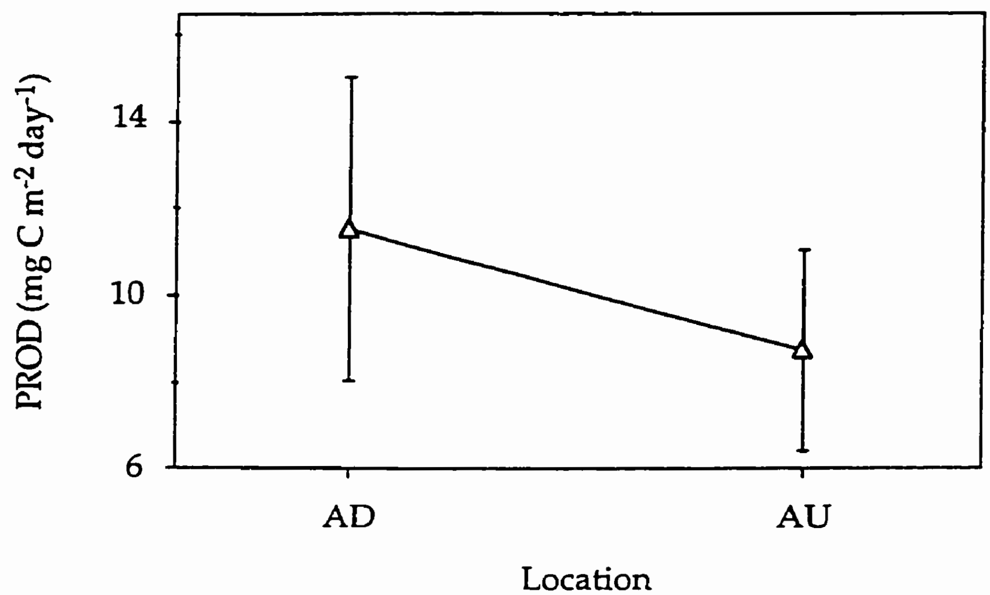


Figure 4.33 Mean estimated phytoplankton primary productivity (PROD) in Assiniboine locations in seasonal episode 4 in 1994. Refer to the text for a description of Assiniboine locations.

One-way ANOVAs were chosen for the analysis of these parameters in the Assiniboine River.

These ANOVAs were calculated for five physical, sixteen chemical and five phytoplankton parameters. The physical parameters included total weekly precipitation, Red River flow rate, *in situ* water temperature, euphotic depth and light extinction. The chemical parameters included the following: DO, pH, TN, SON, SIN, NH_4^+/NH_3-N, TON, PN, TP, DP, PP, SRP, SOP, PC, TOC and SOC. The phytoplankton parameters included biomass (Chl *a*), P_{max}, alpha, I_k and estimated daily phytoplankton primary productivity.

ANOVA results are presented in Tables 4.10 and 4.11 at the end of the chapter. To summarize significant differences between seasonal episodes, three dimensional line plots of episode means were constructed for all River sections along the Red River and the upstream and downstream locations along the Assiniboine River. These three dimensional line plots are found at the end of the chapter in Figures 4.34 to 4.80.

Variability in Physical Parameters Between Seasonal Episodes

Total Weekly Precipitation

Total weekly precipitation differed significantly between seasonal episodes in 1994 in both the Red ($p = 0.000$) and the Assiniboine ($p = 0.000$) Rivers. Highest amounts were recorded in episode 1 followed by episode 3 (Figures 4.34). No episodic differences were detected in either the Red ($p = 0.398$) or the Assiniboine ($p = 0.982$) Rivers in 1995.

Flow Rate

Flows rate in the Red River was significantly different between seasonal episodes in both 1994 ($p = 0.000$) and 1995 ($p = 0.000$), with the highest rate associated with episode 3 in both years (Figure 4.35). In 1994, River flow initially declined from seasonal episode 1 to 2, but increased in episode 3. Rates declined in episode 4, but in episode 5, increased once again. In contrast, River flow steadily declined from seasonal episode 3 to 5 in 1995.

Although flow rate was not determined in the Assiniboine River, the discharge rate at Headingley was found to differ significantly between seasonal episodes, both in 1994 ($p = 0.000$) and 1995 ($p = 0.000$). It steadily declined in each sampling year (Figure 4.36).

In Situ Water Temperature

In situ water temperatures, in both the Red and Assiniboine Rivers, were significantly different between seasonal episodes in both 1994 and 1995 ($p = 0.000$). Highest temperatures were found during seasonal episode 3, in both 1994 and 1995 (Figure 4.37).

Mean Daily Ambient PAR

Mean daily ambient PAR was significantly different between seasonal episodes in both 1994 ($p = 0.000$) and 1995 ($p = 0.000$). Maximal values were found in seasonal episode 3, during weeks 8 to 10, and lows in episodes 1 and 5, at both the beginning and end of the sampling year (Figure 4.1a).

Euphotic Depth

There were significant seasonal differences found in the depth of the euphotic zone in the Red River in 1994 ($p = 0.000$) and in both the Red and Assiniboine Rivers in 1995 ($p = 0.000$ and 0.003, respectively) (Figures 4.38 and 4.39). In 1994, episodes 2 and 4 represented periods of high euphotic depths. In 1995, the euphotic depth steadily increased from episode 3 to 5 within the Red River and between episodes 3 and 4 in the Assiniboine River.

Light Extinction

In both the Red and Assiniboine Rivers, there were significant seasonal differences found in the extinction of light during 1994 ($p \leq 0.016$) and 1995 ($p = 0.000$). High extinctions were noted in episodes 1, 3 and 5 in 1994 (Figures 4.40 and 4.41). In contrast, there was a steady decline throughout the sampling year in 1995 (Figures 4.40b and 4.41b).

Variability in Chemical Parameters Between Seasonal Episodes

Dissolved Oxygen (DO)

Concentrations of DO, in both the Red and Assiniboine Rivers, was found to exhibit significant episodic variability in both 1994 ($p = 0.000$) and 1995 ($p = 0.000$) (Tables 4.10 and 4.11). In 1994, DO concentrations declined from seasonal episode 1 to 3 and thereafter increased once again into episode 5. In 1995, DO concentrations were depressed throughout episodes 3 and 4 but dramatically increased in episode 5 (Figures 4.42 and 4.43).

pH

There were significant seasonal differences in pH values detected in 1994 in both the Red ($p = 0.000$) and Assiniboine ($p = 0.004$) Rivers. In the Red River, pH first declined from seasonal episodes 1 to 3 in 1994, increased in seasonal episode 4 but dramatically declined in episode 5 (Figure 4.44). In contrast, pH in the Assiniboine River increased from seasonal episodes 1 to 4, but dramatically declined in seasonal episode 5 (Figure 4.45).

Whereas the pH of Red River water in 1995 was lowest during seasonal episode 4 (Figure 4.44), this was found during episode 3 in the Assiniboine River (Figure 4.45).

Nitrogen

Total Nitrogen (TN)

In 1994, there were significant reductions in TN concentrations from seasonal episode 1 to 4 within both the Red and Assiniboine Rivers ($p = 0.000$) (Figure 4.46 and 4.47). Concentrations increased slightly from episode 4 into episode 5.

Among groups 1 and 2 in the Red and within the Assiniboine, there were no significant differences in TN concentration between seasonal episodes in 1995 ($p = 0.242$ and 0.654, respectively). However, within group 3, TN concentration was lowest during episode 5 ($p = 0.026$) (Figure 4.46).

Soluble Organic Nitrogen (SON)

In 1994, SON concentrations in both the Red and Assiniboine Rivers, were shown to exhibit an overall decline in concentration ($p = 0.000$) (Figure 4.48 and 4.49). However, SON concentrations did not differ significantly between episodes in 1995 ($p = 0.983$ and 0.288, respectively).

Soluble Inorganic Nitrogen (SIN), Total Oxidized Nitrogen (TON) and Total Ammonia-N (NH_4^+/NH_3-N)

Most inorganic nitrogen parameters varied significantly between seasonal episodes in both the Red and Assiniboine Rivers. Soluble inorganic nitrogen (SIN), total oxidized nitrogen (TON) and (NH_4^+/NH_3-N) exhibited significant differences in both 1994 and 1995 (Tables 4.10 and 4.11).

In 1994, both SIN and TON increased from episode 1 to 3 in the Red River, declined in episode 4 and increased again in episode 5 (Figures 4.50 and 4.51). Concentrations of NH_4^+/NH_3-N were significantly lower during episode 3 in 1994 in groups 1 and 2. However, the seasonal differences in NH_4^+/NH_3-N concentrations were not observed in group 3 (Figure 4.52).

In 1995, SIN and TON concentrations declined from seasonal episodes 3 to 5 (Figures 4.50 and 4.51). This was in contrast with the increase in concentrations of NH_4^+/NH_3-N from episode 3 to 5 (Figure 4.52).

Similar trends in concentrations of SIN and TON were found in the Assiniboine River in both 1994 and 1995 (Figures 4.53 and 4.54). In 1994, SIN and TON concentrations increased from episode 1 to 3, declined in episode 4 and increased again in episode 5. In 1995, there was a decline from seasonal episode 3 to 5.

During 1994, concentrations of NH_4^+/NH_3-N increased from seasonal episode 1 to 4 within the Assiniboine River (Figure 4.55). While NH_4^+/NH_3-N concentrations were shown to increase within groups 1 and 2 in the Red during 1995 (Figure 4.52), concentrations declined significantly from episode 3 to 4 in the Assiniboine River (Figure 4.55). Furthermore, concentrations increased at AD from episode 4 to 5, but decreased during at AU.

Particulate Nitrogen (PN)

Significant seasonal differences were found in the concentrations of particulate nitrogen (PN) within the Red River ($p = 0.000$) during 1994. Concentrations fluctuated from highs in seasonal episodes 1, 3 and 5 to lows in episodes 2 and 4 (Figure 4.56). This variability was not observed within the Assiniboine ($p = 0.265$).

Phosphorus

Total Phosphorus (TP) and Total Dissolved Phosphorus (DP)

There were significant episodic differences in phosphorus loads found in the Red River during both 1994 ($p = 0.000$) and 1995 ($p = 0.000$). In the Assiniboine River, there were only "nearly" significant differences found in 1994 ($p = 0.069$) and none in 1995 ($p = 0.302$).

In 1994, TP concentrations fluctuated in both Rivers from highs in episodes 3 and 5 to lows in episodes 2 and 4 (Figures 4.57 and 4.58). In 1995, concentrations in the Red River were dramatically lower in episode 5 than in early periods.

In both the Red and Assiniboine Rivers, concentrations of DP were found to differ significantly between episodes in 1994 (p = 0.000 and 0.004, respectively) and 1995 (p = 0.000 and 0.024, respectively). While DP concentrations increased overall within the Red River in 1994 (Figure 4.59a), they declined between episodes 3 and 5 within the Assiniboine River (Figure 4.60a). In 1995, concentrations generally declined from episode 3 to 5 in both the Red and Assiniboine Rivers with only a small increase noted during episode 4 (Figures 4.59b and 4.60b).

<u>Particulate Phosphorus (PP)</u>

PP concentrations exhibited significant variability between seasonal episodes in the Red River (p = 0.000) in 1994, fluctuating from highs during episodes 1, 3 and 5 and lows during episodes 2 and 4 (Figure 4.61a). However, no significant differences were observed in 1995 (p = 0.586).

While there were no significant differences detected in 1994 (p = 0.398) PP concentrations in the Assiniboine River were found to increase throughout the 1995 sampling year (p = 0.030) (Figure 4.62b).

<u>Soluble Reactive Phosphorus (SRP)</u>

Within both the Red and Assiniboine Rivers, concentrations of SRP were found to exhibit significant seasonal differences during 1994 (p = 0.000 and 0.004, respectively) (Figures 4.63a and 4.64a). However, in 1995 only "nearly" significantly differences were observed in the Red River (p = 0.054)

(Figure 4.63b) and none were found in the Assiniboine River ($p = 0.105$) (Figure 4.64b).

Within the Red River in 1994, concentrations were found to gradually increase during the sampling year with a slight decrease noted in episode 4 (Figure 4.63a). In 1995, SRP concentrations in groups 2 and 3 declined from episodes 1 to 5. However, concentrations dramatically increased in episode 5 within group 1 (Figure 4.63b).

In 1994, SRP concentrations within the Assiniboine River fluctuated from highs during episodes 1, 3 and 5 to lows in episodes 2 and 4 (Figure 4.64a).

Soluble Organic Phosphorus (SOP)

Whereas SOP concentrations were found to differ significantly in the Red River during both 1994 ($p = 0.038$) and 1995 ($p = 0.000$) (Figure 4.65), there were only "nearly" significant differences observed in the Assiniboine River in 1994 ($p = 0.091$) and none in 1995 ($p = 0.853$) (Figure 4.66).

The differences observed within the Red River in 1994 were resultant of the highs that occurred during episodes 3 and, in the case of groups 1 and 2, 5 (Figure 4.65). Within the Assiniboine in 1994, and the Red River in 1995, SOP concentrations declined overall from the beginning to the end of the sampling year (Figure 4.65 and 4.66).

Carbon

Particulate Carbon (PC)

PC exhibited significant variability between seasonal episodes in 1994 in the Red River ($p = 0.000$) (Figure 4.67a). Episodes 3 and 5 were periods when PC concentrations were significantly higher than during episodes 2 or 4.

There was much less variability in PC concentrations in the Assiniboine River in 1994 ($p = 0.097$). Concentrations increased only slightly from episodes 1 to 3, and thereafter decreased into episode 5 (Figure 4.67b). No equivalent data were available for 1995.

Total Organic Carbon (TOC)

In both the Red and Assiniboine Rivers, concentrations of TOC increased significantly during the sampling year in 1995 ($p = 0.000$). However, there was a slight decrease noted between episodes 4 and 5 in both Rivers (Figure 4.68).

Soluble Organic Carbon (SOC)

SOC was found to differ significantly between seasonal episodes in both years in both Rivers ($p = 0.000$). Overall, concentrations of SOC appeared to increase by the end of the sampling period (Figures 4.69a and 4.70a). Similar to TOC, SOC concentrations in 1995 were found to level off between episodes 4 and 5 in both Rivers (Figures 4.69b and 4.70b).

Phytoplankton Parameters

In general, there were differences in phytoplankton parameters between seasonal episodes in both the Red and Assiniboine Rivers in 1994 ($p = 0.000$ and $p \leq 0.091$, respectively) and 1995 ($p \leq 0.038$ and $p \leq 0.013$, respectively) (Figures 4.71 to 4.79). The notable exception was phytoplankton biomass. Between seasonal episodes 2 and 4, in 1994, there were no observed differences in groups 1 and 2 in the Red nor between locations in the Assiniboine River (Figure 4.75 and 4.80).

In 1994, measures of phytoplankton activity (i.e., P_{max}, alpha and I_k) and estimated daily productivity in the Red River were found to be highest in seasonal episode 2 in groups 1 and 2, and in seasonal episode 1 in group 3 (Figures 4. 71a to 4.74a). Intermediate values were typically found during episode 4. Activity among the three River groups was depressed during episode 3 in 1994, and lowest in episode 5. While phytoplankton biomass was found to be highest during seasonal episode 1 in groups 2 and 3, it was greatest in episode 2 within group 1 (Figure 4.75).

In the Assiniboine River in 1994, phytoplankton activity and estimated daily productivity first increased from episode 1 to 3 but thereafter declined into episode 5 (Figures 4.76a to 4.79a). There were no significant differences observed in biomass measured during 1994 in the Assiniboine ($p = 0.458$).

In 1995, there was an increase in most phytoplankton parameters noted during the sampling year in both Rivers (Figures 4.71b to 4.80b). The exception was I_k, which increased from episode 3 to 4, but thereafter dramatically declined (Figure 4.73b and 4.78b).

4.4 Temporal Variability Between Years in Comparable Seasonal Episodes

Two-way analysis of variance was performed to quantify the differences within the Red River between the two years of this study. The first factor was sampling year (1994 or 1995), the other River section (Group 1, 2 or 3). One-way ANOVA was chosen for the Assiniboine River.

These ANOVAs were calculated for the five physical, sixteen chemical and five phytoplankton parameters described above. ANOVA results are presented in Tables 4.12 and 4.13 at the end of the chapter. The three dimensional line plots of seasonal episode means were used to display these yearly differences among the three groups in the Red River and the upstream and downstream locations along the Assiniboine River (Figures 4.34 to 4.80). These are located at the end of the chapter.

Variability in Physical Parameters Between Years of the Study

Total Weekly Precipitation

In the Red River, total weekly recorded precipitation differed between years in episodes 3 and 5 ($p = 0.042$ and 0.000, respectively). In particular amounts were higher in 1994 during episode 3 but this was reversed in episode 5 (Figure 4.34). These yearly differences were also observed in the Assiniboine River.

Red River Flow Rates and Assiniboine River Discharge Rates

1994 Red River flow rates exceeded those of 1995 during seasonal episodes 3 and 5 ($p = 0.029$ and 0.000, respectively). Flow rates were most similar during episode 4 ($p = 0.450$) (Figure 4.35).

Discharge rates in the Assiniboine River were higher during the 1995 sampling period. Furthermore, rates in episode 3 were significantly higher than had been recorded in 1994. There was a dramatic decline observed from episode 3 to 4, but this rate continued to exceed the previous year ($p = 0.065$). By episode 5, however, equivalent discharge rates were observed between years ($p = 0.948$) (Figure 4.36).

In Situ Water Temperature

In situ water temperatures differed significantly between years in episode 4 in the Red ($p = 0.033$) and episode 3 ($p = 0.027$) in the Assiniboine River. In both instances, temperatures were significantly higher in 1995 (Figure 4.37).

Euphotic Depth

In the Red River, the euphotic depths were found to be significantly higher in 1995 ($p \leq 0.007$) (Figure 4.38). Significantly greater euphotic depths were found in 1995 in the Assiniboine River during episodes 4 ($p = 0.078$) and 5 ($p = 0.087$) (Figure 4.39).

Light Extinction

Light extinction, in the Red River, was significantly higher in 1994 during all three episodes ($p \leq 0.047$). Higher light extinctions were also observed in 1994 during episodes 4 and 5 in the Assiniboine River ($p = 0.018$ and 0.001, respectively) (Figures 4.40 and 4.41).

Variability in Chemical Parameters Between Years of the Study

Dissolved Oxygen (DO)

In the Red River, DO concentrations were found to be higher in 1994 during episode 4 ($p = 0.000$), but higher in 1995 in episodes 3 and 5 ($p = 0.000$) (Figure 4.42). Within the Assiniboine River, DO concentrations were significantly higher in 1994 in seasonal episode 5 ($p = 0.012$) (Figure 4.43).

pH

Red River pH values were consistently higher in 1995 ($p = 0.000$) (Figure 4.44). Conversely, during episodes 4 and 5 in the Assiniboine River, the pH was found to be higher in 1994 ($p = 0.000$) (Figure 4.45).

Nitrogen

Total Nitrogen (TN)

In both Rivers, TN concentrations were significantly higher in 1994 during seasonal episode 3 ($p \leq 0.002$) (Figures 4.46 and 4.47).

Soluble Organic Nitrogen (SON)

Concentrations of SON were found to differ significantly between years in both the Red and Assiniboine Rivers ($p \leq 0.046$ and 0.025, respectively). While concentrations in both Rivers were higher in 1994 in episode 3, they were lower during both episodes 4 and 5 (Figures 4.48 and 49).

Soluble Inorganic Nitrogen (SIN), Total Oxidized Nitrogen (TON) and Total Ammonia-N (NH_4^+/NH_3-N)

Within the Red River, there were significantly higher concentrations of SIN ($p = 0.000$) and TON ($p = 0.000$) during episode 5 in 1994 when compared to 1995 (Figures 4.50 and 51). Conversely, the concentrations of NH_4^+/NH_3-N during 1995 exceeded those measured in 1994 during episodes 4 and 5 ($p = 0.000$ and 0.004, respectively) (Figure 4.52).

During episode 4 in the Assiniboine River, SIN ($p = 0.000$), TON ($p = 0.001$) and NH_4^+/NH_3-N ($p = 0.002$) were higher in 1994 (Figures 4.53, 4.54 and 4.55). In episode 5, only SIN ($p = 0.004$) and TON ($p = 0.001$) were found to be significantly higher in 1994.

Phosphorus

Total Phosphorus (TP) and Total Dissolved Phosphorus (DP)

During this study, both TP and DP concentrations were significantly higher in 1994 in both the Red and Assiniboine Rivers ($p \leq 0.035$ and 0.035, respectively) (Figures 4.57 to 4.60).

Particulate Phosphorus (PP)

In the Red River, 1994 concentrations of PP exceeded those measured in 1995 during both episodes 3 and 5 ($p = 0.000$) (Figure 4.61). However, in the Assiniboine River, only episode 3 was attributed with this difference ($p = 0.031$) (Figure 4.62).

Soluble Reactive Phosphorus (SRP)

While SRP was significantly higher in 1994 during all seasonal episodes in the Red River ($p \leq 0.004$), 1994 concentrations were only significantly higher in seasonal episode 5 in Assiniboine River ($p = 0.022$) (Figures 4.63 and 4.64).

Soluble Organic Phosphorus (SOP)

In the Red River, there were no significant yearly differences in SOP concentrations in either episode 3 or 4 ($p \geq 0.151$). However, in episode 5, 1994 concentrations greatly exceeding those of 1995 ($p = 0.001$) (Figure 4.65). In the Assiniboine River, significantly higher concentrations were found in 1994 during episode 4 ($p = 0.025$) (Figure 4.66).

Carbon

Soluble Organic Carbon (SOC)

Concentrations of SOC were higher in 1994 during seasonal episode 3 ($p = 0.003$) in the Red River, and episode 5 in both the Red and Assiniboine Rivers ($p \leq 0.010$) (Figures 4.69 and 4.70).

Variability in Phytoplankton Parameters Between Years of the Study

Measures of Phytoplankton Activity (alpha, P_{max} and I_k)

In the Red River, P_{max} was significantly higher in 1995 in both episodes 3 and 5 ($p \leq 0.049$) (Figure 4.71). In contrast, P_{max} during episode 3 in the Assiniboine River was significantly higher in 1994 ($p = 0.012$) (Figure 4.76).

Alpha exhibited yearly differences in all comparable seasonal episodes in the Red River ($p = 0.000$). While alpha was higher in 1994 in episodes 3 and 4, it was higher in 1995 in episode 5 (Figure 4.72). In the Assiniboine

River, alpha was significantly higher in 1994 in episodes 3 and 4 ($p = 0.000$) (Figure 4.77).

Lastly, measurements of I_k indicated that the threshold irradiance that saturated photosynthesis was significantly higher in 1995 in all seasonal episodes in the Red River ($p = 0.000$) (Figure 4.73). In the Assiniboine River, these differences were found in episodes 3 and 4 ($p = 0.000$) (Figure 4.78).

Estimated Daily Productivity

In the Red River, there were significant yearly differences in estimated daily productivity all seasonal episodes ($p \leq 0.050$) (Table 4.12). While productivity values were higher in 1994 in episode 4, they were lower than 1995 during episodes 3 and 5 (Figure 4.74).

In the Assiniboine River, significant differences were only observed during episode 3 ($p = 0.000$) when productivity was significantly higher during 1994 (Figure 4.79).

Biomass (Chlorophyll *a*)

Phytoplankton biomass was significantly higher in 1995 during episodes 3 and 5 ($p \leq 0.006$) in the Red River and in 1994 in episode 3 in the Assiniboine River ($p = 0.016$) (Figures 4.75 and 4.80).

4.5 Spatial Variability Within the Red River Between Groups 1, 2 and 3

To quantify the spatial heterogeneity along the Red River, one-way analysis of variance was performed using River section (Group 1, 2 or 3) from each seasonal episode in both 1994 and 1995. The differences between Assiniboine locations were previously described in the first section of this chapter.

ANOVAs were calculated for the five physical, sixteen chemical and five phytoplankton parameters and results are presented in Tables 4.14 and 4.15 at the end of the chapter. The three dimensional line plots were used to display spatial variability in Red River sections are found among Figures 4.34 to 4.75 at the end of the chapter.

Spatial Variability in Physical Parameters

Total Weekly Precipitation

Analysis of variance showed that the precipitation information collected did not vary significantly between the three groups along the Red River in either 1994 ($p = p \geq 0.837$) or 1995 ($p \geq 0.188$) (Figure 4.34).

Red River Flow Rates

Red River flow rates were significantly lower in group 1 during all seasonal episodes in 1994 ($p \leq 0.018$) (Figure 4.35a). In 1995, flow rates were lower in group 1 during seasonal episode 4 ($p = 0.001$), and were nearly significantly lower in seasonal episode 3 ($p = 0.108$) and episode 5 ($p = 0.081$) (Figure 4.35b).

In Situ Water Temperature

There were no significant differences detected in the *in situ* water temperatures between Red River groups during this study ($p \leq 0.463$) (Figure 4.37).

Euphotic Depth and Mean Light Extinction

Significantly higher euphotic depths were associated with group 1 during seasonal episodes 2 ($p = 0.009$) and 4 ($p = 0.099$) in 1994, and 3 ($p = 0.026$) and 4 ($p = 0.000$) in 1995 (Figure 4.38).

There were significantly lower light extinctions noted within group 1 during seasonal episodes 2 ($p = 0.000$) and 3 ($p = 0.081$) in 1994 and episodes 3 ($p = 0.082$) and 4 ($p = 0.000$) in 1995. Moreover, during episodes 2 and 4, there was a sequential change in measures of extinction. Highest values were observed within group 3 and lowest in group 1 (Figure 4.40).

Spatial Variability in Chemical Parameters

Dissolved Oxygen (DO)

In contrast with group 1, DO concentrations were significantly higher within group 3 during seasonal episode 5 in both 1994 ($p = 0.005$) and 1995 ($p = 0.006$). During episode 4 in 1995, "nearly" significantly higher DO concentrations were found in group 2 ($p = 0.097$) (Figure 4.42).

pH

During seasonal episodes 4 and 5 in 1994 ($p = 0.001$ and 0.004, respectively), and in episode 5 in 1995 ($p = 0.015$) the pH within group 1 was significantly lower than either group 2 or 3 (Figure 4.44).

Nitrogen

Total Nitrogen (TN)

TN did not differ significantly between groups in the Red River in 1994 ($p \geq 0.119$) or 1995 ($p \geq 0.151$) (Figure 4.46).

Soluble Organic Nitrogen (SON)

SON concentrations were significantly higher in group 1 in the Red River during seasonal episodes 3 and 4 in 1994 ($p = 0.044$ and 0.020, respectively) and 4 in 1995 ($p = 0.008$) (Figure 4.48).

Soluble Inorganic Nitrogen (SIN), Total Oxidized Nitrogen (TON) and Total Ammonia Nitrogen (NH_4^+/NH_3-N)

In 1994, SIN was found to be significantly higher in concentration in group 1 during seasonal episodes 1 ($p = 0.000$), and 4 ($p = 0.000$) and nearly in seasonal episode 5 ($p = 0.071$) (Figure 4.50a). In 1995, the only period of higher concentrations was during episode 5 ($p = 0.000$). Again, highest concentrations were associated with group 1 (Figure 4.50b).

In 1994, TON concentrations were higher in group 1 during seasonal episodes 1 ($p = 0.003$) and 4 ($p = 0.096$) in 1994 (Figure 4.51a). Conversely, in episode 3 in 1995, TON concentrations were higher in group 3 ($p = 0.101$) (Figure 4.51b).

Concentrations of NH_4^+/NH_3-N were found to differ significantly between groups in the Red River in both 1994 ($p \leq 0.035$) and 1995 ($p = 0.000$). Concentrations were always highest downstream of the City in group 1, intermediate within the "inter-city" in group 2 and lowest in the upstream group 3 (Figure 4.52). Moreover, concentrations were significantly altered downstream of WPCC's as evidenced at sampling locations R4, R7 and/or R8 that were located downstream of the SEWPCC and NEWPCC, respectively (Figure 4.81 located at the end of the chapter).

Particulate Nitrogen (PN)

PN concentrations were highest in group 1 during seasonal episode 4 ($p = 0.000$) in 1994 (Figure 4.56a). PN data was not available in 1995.

Phosphorus

Total Phosphorus (TP) and Total Dissolved Phosphorus (DP)

TP concentrations were significantly different between Red River groups during seasonal episodes 1 ($p = 0.027$) and 4 ($p = 0.012$) in 1994 and episodes 4 ($p = 0.056$) and 5 ($p = 0.002$) in 1995. In seasonal episode 1, equivalent concentrations were found between groups 1 and 2, but these were significantly higher than in group 3 (Figure 4.57). Conversely, equivalent concentrations were found between groups 2 and 3 in the remaining periods, but these were significantly lower than found within group 1.

Significant differences in DP were restricted to seasonal episode 5 in both 1994 ($p = 0.103$) and 1995 ($p = 0.000$). Concentrations were significantly higher in the group 1, and equivalent between groups 2 and 3 (Figure 4.59).

Particulate Phosphorus (PP)

PP concentrations were not significantly different along the Red River in 1994. In 1995, concentrations in group 1 were significantly higher during seasonal episode 4 ($p = 0.012$) (Figure 4.61b).

Soluble Reactive Phosphorus (SRP)

In 1994, SRP concentrations differ significantly between groups in seasonal episodes 1 ($p = 0.022$) and 4 ($p = 0.000$) and in episodes 4 ($p = 0.002$) and 5 ($p = 0.001$) in 1995 (Figure 4.63b). Highest concentrations were found in group 1 downstream of the NEWPCC (Figure 4.63a). Moreover, in 1995, the concentrations of SRP were found to increase throughout the year within group 1.

Soluble Organic Phosphorus (SOP)

Concentrations of SOP were higher in Red River group 2 during seasonal episodes 1 ($p = 0.082$) and 4 ($p = 0.043$) in 1994 (Figure 4.65). No spatial variability was observed in 1995 ($p \geq 0.206$).

Carbon

Particulate Carbon (PC)

Significantly higher concentrations of PC were found within group 3 in the Red River during seasonal episodes 2 ($p = 0.019$) and 3 ($p = 0.029$) in 1994 (Figure 4.66a).

Total Organic Carbon (TOC)

TOC, measured in 1995, was not found to exhibit significant spatial variability in the Red River ($p \geq 0.320$).

Soluble Organic Carbon (SOC)

Group 3 was found to exhibit higher SOC concentrations during seasonal episode 5 ($p = 0.058$) in 1994 (Figure 4.69a). No other periods were found to exhibit spatial differences in concentrations.

Spatial Variability in Phytoplankton Parameters

Photosynthetic Parameters (alpha, P_{max} and I_k)

P_{max} was found to differ between Red River groups throughout 1994 ($p \leq 0.096$) and 1995 ($p = 0.000$). P_{max} values were highest in group 1 and lowest in group 3 (Figure 4.71). Group 2 values were typically equivalent to group 1. However, in seasonal episodes 3 and 5 in 1994, they were equivalent to group 3.

Alpha was consistently found to differ between Red River groups during 1994 ($p \leq 0.047$) and 1995 ($p = 0.000$). While in 1994, alpha in group 1 was higher than both 2 and 3 (Figure 4.72a), groups 1 and 2 were equivalent in 1995 (Figure 4.72b).

I_k differed significantly between groups among most seasonal episodes in both 1994 ($p \leq 0.043$) and 1995 ($p \leq 0.055$). The notable exception was found during seasonal episode 1 in 1994 when no significant differences could be detected ($p = 0.801$). Otherwise, groups 1 and 2 were equivalent in I_k, but were significantly higher than group 3 (Figure 4.73).

Estimated Daily Productivity

Estimated daily productivity was found to differ significantly between groups in both 1994 ($p \leq 0.011$) and 1995 ($p = 0.000$). Groups 1 and 2 were equivalent throughout much of the sampling year. However, these groups displayed significantly higher estimates of productivity than group 3 (Figure 4.74). Exceptions were found during seasonal episodes 2 in 1994 and 5 in 1995 when group 1 estimated phytoplankton daily productivity exceeded measurements from group 2 (Figure 4.74).

Biomass (Chlorophyll *a*)

Biomass was found to differ significantly between River groups in most seasonal episodes in 1994 ($p \leq 0.002$) and 1995 ($p \leq 0.016$). Similar to I_k, the notable exception was found in seasonal episode 1 in 1994 ($p = 0.941$). During periods of significant spatial heterogeneity, there was less biomass found in group 3 than in either groups 1 or 2 (Figure 4.75).

4.6 Variability Between the Red and Assiniboine Rivers

To quantify the spatial heterogeneity between the Red and Assiniboine Rivers, one-way analyses of variance were performed using River sections (Group 1, 2, 3 or As) from each seasonal episode in both 1994 and 1995.

ANOVAs were calculated for the same five physical, sixteen chemical and five phytoplankton parameters previously described. ANOVA results are found in Tables 4.16 and 4.17 at the end of the chapter. The three dimensional line plots previously were used to describe these differences between Rivers and these are located at the end of the chapter.

Spatial Variability in Physical Parameters

Total Weekly Precipitation

Significant differences between Rivers were found in seasonal episodes 4 ($p = 0.000$), in 1994 (Figure 4.34), and 3 ($p = 0.057$) in 1995. Compared to the Red River, weekly precipitation in the Assiniboine River was significantly higher during episode 4. However, the reverse was found during episode 3 (not shown).

In Situ Water Temperature

For the most-part, water temperatures were equivalent between Rivers. The only exception occurred during episode 4 ($p = 0.094$), in 1994 when lower temperatures were found in the Assiniboine River (not shown).

Euphotic Depth and Mean Light Extinction

There were significant differences in the euphotic depths between Rivers. This was noted in seasonal episodes 2 ($p = 0.000$) and 4 ($p = 0.001$) in 1994 (Figures 4.38a and 4.39a) and episodes 3 ($p = 0.000$) and 5 ($p = 0.000$) in 1995 (Figures 4.38b and 4.39b). These differences were also observed in light extinction during seasonal episodes 2 ($p = 0.000$), 3 ($p = 0.073$) and 4 ($p = 0.001$) in 1994 and all episodes in 1995 ($p \leq 0.019$) (Figures 4.40 and 4.41).

The water column in the Assiniboine River was characterized by shallower euphotic depths and significantly higher light extinctions than found in the Red River (Figures 4.38 to 4.41) with the exception that during episode 3 in 1994, comparable extinctions were found between groups 1, 2 and the Assiniboine but these were significantly lower than group 3 (Figures 4.40a and 4.41a). In episodes 3 and 4 in 1995, comparable extinctions were found between groups 3 and the Assiniboine but were significantly higher than the groups 1 and 2 that were downstream of the confluence (Figures 4.40b and 4.41b).

Spatial Variability in Chemical Parameters

Dissolved Oxygen (DO)

DO concentrations were higher in the Assiniboine River in episode 5 in 1994 ($p = 0.000$) (Figure 4.42a and 4.43a). DO concentrations were comparable between Rivers in 1995.

pH

The Assiniboine River was found to be more alkaline than the Red throughout the study ($p \leq 0.062$) (Figures 4.44 and 4.45).

Nitrogen

Total Nitrogen (TN)

TN differed between Rivers throughout the study. In seasonal episodes 1 ($p = 0.098$), 2 ($p = 0.103$) and 3 ($p = 0.066$) in 1994 and 4 ($p =0.000$) in 1995, Red River concentrations exceeded those in the Assiniboine River (Figures 4.46 and 4.47). However, in episode 3 ($p = 0.027$) in 1995, TN concentrations were equivalent in groups 1, 2 and the Assiniboine but were significantly higher in group 3 (Figure 4.46b and 4.47b).

Soluble Organic Nitrogen (SON)

SON concentrations between Rivers were similar upstream of the NEWPCC among the Assiniboine locations and groups 2 and 3. However, group 1 concentrations were significantly higher during seasonal episodes 3 (p

= 0.076) and 4 (p = 0.024) in 1994 (Figures 4.48a and 4.49a). Conversely, in episode 4 in 1995, groups 1, 3 and the Assiniboine locations were equivalent but were significantly higher than group 2 (p = 0.008) (Figures 4.48b and 4.49b).

Soluble Inorganic Nitrogen (SIN), Total Oxidized Nitrogen (TON) and Total Ammonia Nitrogen (NH_4^+/NH_3-N)

SIN, TON and NH_4^+/NH_3-N concentrations were consistently lower in the Assiniboine River in both years ($p \leq 0.000$, 0.002 and 0.000, respectively) (Figures 4.50 to 4.55). However, there were comparable concentrations of NH_4^+/NH_3-N between As and group 3 during seasonal episode 3, in 1995 and episode 5, in both 1994 and 1995 (Figures 4.52 and 4.55).

Particulate Nitrogen (PN)

PN concentrations were significantly higher in the Assiniboine during seasonal episodes 2 (p = 0.000), 3 (p = 0.076), 4 (p = 0.000) and 5 (p = 0.102) in 1994 (Figure 4.56).

Phosphorus

Total Phosphorus (TP) and Total Dissolved Phosphorus (DP)

In seasonal episode 2 (p = 0.001), in 1994, and episode 5 (p = 0.001), in 1995, TP concentrations were comparable in the Assiniboine River and Red River group 1, but these were significantly higher than groups 2 or 3 (Figures 4.57 and 4.58). This sharply contrasted with episodes 1 (p = 0.051) and 5 (p = 0.043) in 1994 and episode 4 (p = 0.018) in 1995 when concentrations were significantly lower in the Assiniboine River. Lastly, in episode 4, in 1994, there were comparable concentrations of TP in the Assiniboine and Groups 2 and 3 in the Red River. Concentrations were, however, significantly lower than found within group 1 (Figure 4.57 and 4.58).

DP concentrations were significantly lower in the Assiniboine River, in both 1994 and 1995, during episodes 3 ($p = 0.095$ and 0.067, respectively), 4 ($p = 0.000$ in both years) and 5 ($p = 0.000$ in both years) (Figures 4.59 and 4.60).

Particulate Phosphorus (PP)

In seasonal episode 4 in 1994 ($p = 0.043$) and 1995 ($p = 0.002$), concentrations of PP were found to differ significantly between groups in the Red and the Assiniboine Rivers. While in 1994, concentrations of PP were comparable between groups 1, 3 and the Assiniboine (Figures 4.61a and 4.62a), they were significantly higher in the Assiniboine River during 1995 (Figures 4.61 b and 4.62b).

Soluble Reactive Phosphorus (SRP)

Between the two Rivers, there were consistently higher concentrations of SRP in the Red during 1994 ($p \leq 0.032$) and 1995 ($p = 0.000$) (Figures 4.63 and 4.64).

Soluble Organic Phosphorus (SOP)

Red River SOP concentrations were significantly higher than those in the Assiniboine River during seasonal episodes 3 and 4 in 1995 ($p = 0.009$ and 0.000, respectively) (Figures 4.65b and 4.66b). In seasonal episode 4 ($p = 0.054$) in 1994, concentrations in the Assiniboine River was comparable to both groups 2 and 3 but were significantly lower than found in group 1 (Figures 4.65a and 4.66a).

Carbon

Particulate Carbon (PC)

PC concentrations, in 1994, were significantly higher in the Assiniboine River during seasonal episodes 2 and 4 ($p = 0.000$ and 0.000, respectively)

(Figure 4.67). However, in episode 3 ($p = 0.031$), concentrations were equivalent between the Assiniboine and group 3. There were no comparable PC data available in 1995.

Total Organic Carbon (TOC)

There were significantly higher TOC concentrations found in the Red River during episode 5 ($p = 0.005$) in 1995 (Figure 4.68).

Soluble Organic Carbon (SOC)

Between the two Rivers, there were several seasonal episodes in 1994 in which concentrations of SOC were significantly higher in the Red. These included seasonal episodes 2 ($p = 0.004$), 4 ($p = 0.015$) and 5 ($p = 0.043$) in 1994 (Figures 4.69a and 4.70a) . No differences were found between Rivers in 1995 ($p \geq 0.253$).

Spatial Variability in Phytoplankton Parameters

Photosynthetic Parameters (alpha, P_{max} and I_k)

P_{max} measurements were significantly higher in the Assiniboine during seasonal episodes 3 ($p = 0.000$), 4 ($p = 0.000$) and 5 ($p = 0.000$) in 1994 and episode 4 ($p = 0.000$) in 1995 (Figures 4.71 and 4.76).

For the most-part, alpha measurements in the Assiniboine River were higher than any group in the Red River as well. However, during seasonal episodes 1 and 2 in 1994 and episode 3 in 1995, measurements were comparable between the Assiniboine and Red River group 1 (Figures 4.72 and 4.77).

I_k values in the Assiniboine River were comparable to the Red River throughout much of 1994. In episode 5, however, measurements in the Assiniboine were significantly higher than groups 1 and 3 in the Red River

(Figures 4.73a and 4.78a). In 1995, I_k in the Assiniboine was higher than in group 3 during episode 3, lower than groups 1 and 2 in episode 4 and significantly lower than the Red River during episode 5 (Figures 4.73b and 4.78b).

Estimated Daily Productivity

Estimated daily productivity in the Assiniboine was higher than any group in the Red River during seasonal episodes 3 and 5 in 1994 (Figures 4.74a and 4.79a), and episode 4 in 1995 (Figures 4.74b and 4.79b). During seasonal episodes 2 and 4 in 1994 and episode 3 in 1995, comparable estimates were found between groups 2, 3 and As. However these estimates were significantly lower than found in group 1.

Biomass (Chlorophyll *a*)

Throughout much of the sampling year in 1994 ($p = 0.000$) and during all of 1995 ($p \leq 0.001$), there were significant differences in biomass between the two Rivers in this study (Figures 4.75 and 4.80). The only episode in which significant differences were not observed were during episode 1 ($p = 0.959$). Otherwise, the biomass determined in the Assiniboine River was typically higher than the Red River. In episode 5 in 1995, biomass measurements in group 1 of the Red River were comparable to those in the Assiniboine River (Figures 4.75 and 4.80).

4.7 The Impact of the Assiniboine River on the Red River Downstream of their Confluence

Paired t-tests, using locations R4 and R5, were performed to identify any impact of the Assiniboine River on the Red River downstream of their confluence. This approach was based on the premise that any change between these locations was resultant of the status of the Assiniboine River that discharged between these sites.

Factors that were analyzed in paired t-tests included two physical (*in situ* water temperature and euphotic depth), sixteen chemical and five phytoplankton parameters that were employed in previous analyses.

Results of the t-tests are found in Table 4.18. When significant differences were detected, boxplots were created using R4, R5 and the Assiniboine downstream (AD) locations. These are found in Figures 4.82 and 4.83 at the end of the chapter.

There were few significant differences found between R4 and R5 in terms of their chemical status. The only parameters that were different included total ammonia-N ($p = 0.039$) and soluble organic Carbon ($p = 0.025$). Both were found to be significantly lower in concentrations at R5 in the Red and AD in the Assiniboine River (Figure 4.82).

In terms of the phytoplankton dynamics, significant differences were observed in all parameters between sites R4 and R5 ($p \leq 0.043$). Measurements were always significantly higher at R5 in the Red and at AD in the Assiniboine River (Figures 4.83). However, on a chlorophyll normalized basis, SP_{max} remained significantly different between R4 and R5 ($p = 0.041$). Higher SP_{max} was observed at both R5 and AD in contrast with R4 (Figure 4.83).

4.8 Summary

1. There were pronounced cyclical features found in the physical, chemical, and phytoplankton parameters. These features were employed to subdivide the 1994 and 1995 datasets into seasonal episodes as defined in Table 4.1.

2. In 1994, seasonal episodes 1, 3 and 5 differed significantly from episodes 2 and 4 in physical, chemical and phytoplankton parameters. Episodes 2 and 4 were equivalent in physical and phytoplankton parameters but were significantly different in chemical concentrations.

3. In 1995, episodes were significantly different in physical and chemical parameters. However, phytoplankton parameters did not differ between episodes 3 and 4.

4. There were discernible sections in the Red River. Group 3 was upstream of the Assiniboine confluence and included sites R1 to R4. The only parameter that differed significantly was the concentration of NH_4^+/NH_3-N.

5. Group 2 included the inter-city locations between the Assiniboine confluence and the NEWPCC (i.e., R5, R5.1 and R6). Parameters including flow, pH and nitrogen concentrations (i.e., TN, PN, SIN and NH_4^+/NH_3-N) were observed to differ in locations in a few episodes. Phytoplankton parameters differed during episodes 1, 2 and 5 in 1994.

6. Group 1 included locations downstream of the NEWPCC. There were lower flow rates observed at R10 as well as more light available.

Chemical parameters, including PN, PC, PP, SOC and NH_4^+/NH_3-N were reported, on occasion, to differ in locations as well. There were few reports of differences in phytoplankton activity in these locations.

7. There were differences in chemical parameters between upstream and downstream locations in the Assiniboine River. Typically, concentrations were higher at the downstream location.

8. Differences in phytoplankton parameters in Assiniboine locations were restricted to episodes 2 and 4 in 1994. Higher activity was observed at location AD.

9. There were pronounced differences in physical, chemical and phytoplankton parameters between seasonal episodes in each year. These differences were quantified by ANOVA and are presented in Tables 4.10 and 4.11.

10. In 1994, many parameters oscillated between episodes. In particular, highs in nutrient concentrations were observed in episodes 1, 3 and 5 and lows in episodes 2 and 4. Lows were also observed in measures of available light during episodes 1, 3 and 5.

11. In 1995, there were less fluctuations observed. Rather, parameters exhibited more of a sequential decline/incline from seasonal episode 3 to 5 without the crests and troughs identified in 1994.

12. Temperature displayed an inverted "U", first increasing to a crest in episode 3 and thereafter declining. Dissolved oxygen was inverse to temperature.

13. There were many parameters that differed significantly between years as presented in Tables 4.12 and 4.13. In general, seasonal episodes 3 and 5 exhibited pronounced yearly differences while episode 4 was most similar. With few exceptions, chemical concentrations were higher in 1994. The notable exception was NH_4^+/NH_3-N concentrations that were higher in 1995 during episodes 4 and 5.

14. Phytoplankton parameters displayed pronounced yearly differences. P_{max} and I_k were higher in 1995, while alpha was higher in 1994.

15. Estimated daily productivity was significantly higher in 1994 during episode 4. Otherwise, higher production estimates were observed in 1995.

16. The results from the analysis of spatial heterogeneity between sections in the Red River are presented in Tables 4.14 and 4.15. Generally speaking, both light availability and nutrient concentrations were higher in group 1 locations. Flow rate was also low in group 1 when contrasted with group 3. However, particulate carbon concentrations were often higher in group 3 locations.

17. Phytoplankton parameters were consistently higher among group 1 locations when compared with activity in group 3.

18. Results from the analysis of differences between Assiniboine and Red Rivers are presented in Tables 4.16, 4.17 and 4.18. There were few parameters that differed between R4 and R5 so as to represent an impact of Assiniboine discharge downstream of the confluence. The two chemical parameters found to display significant differences were

NH_4^+/NH_3-N and SOC. Both were significantly lower in concentration at AD and R5. Chlorophyll normalized P_{max} was the only phytoplankton parameter to exhibit significant differences. It was higher at AD and R5 compared to R4.

Table 4.2 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the intra-group differences between locations R7 to R10 in Group 1 during the five seasonal episodes in 1994.

Parameter	Episode 1	Episode 2	Episode 3	Episode 4	Episode 5
Physical Parameters					
Precipitation	1.000	1.000	1.000	1.000	1.000
River Flow Rate	0.003	0.000	0.186	0.002	0.001
In Situ Water Temperature	0.999	0.836	0.989	0.999	1.000
Light Extinction	0.029	0.012	0.533	0.601	0.566
Euphotic Depth	0.007	0.012	0.804	0.916	0.387
Chemical Parameters					
Dissolved Oxygen	0.969	0.673	0.998	0.626	0.147
pH	0.940	0.637	0.971	0.479	0.387
(a) Nitrogen					
TN	0.611	0.942	0.855	0.979	0.937
SON	0.332	1.000	0.612	0.940	0.783
SIN	0.267	0.963	0.508	0.250	0.950
NH_4^+/NH_3-N	0.353	0.029	0.510	0.320	0.461
TON	0.595	0.804	0.571	0.566	0.979
PN	0.024	0.052	0.856	0.866	0.306
(b) Phosphorus					
TP	0.190	0.602	0.860	0.333	0.577
DP	0.907	0.938	0.800	0.305	0.407
PP	0.065	0.697	0.980	0.912	0.285
SRP	1.000	0.962	0.965	0.421	0.981
SOP	0.903	0.847	0.828	0.539	0.797
(c) Carbon					
PC	0.015	0.035	0.904	0.751	0.988
SOC	0.792	0.722	0.983	0.966	0.309
Phytoplankton Parameters					
Estimated Daily Productivity	0.138	0.009	0.732	0.639	0.244
Chl *a*	0.885	0.160	0.220	0.997	0.990
P_{max}	0.559	0.420	0.643	0.647	0.799
alpha	0.114	0.413	0.429	0.721	0.604
I_k	0.108	0.051	0.641	0.402	0.860

Table 4.3 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the intra-group differences between locations R5, R5.1 and R6 in Group 2 during the five seasonal episodes in 1994.

Parameter	Episode 1	Episode 2	Episode 3	Episode 4	Episode 5
Physical Parameters					
Precipitation	1.000	0.893	1.000	1.000	1.000
River Flow Rate	0.016	0.000	0.287	0.019	0.010
In Situ Water Temperature	0.990	0.982	0.998	0.978	0.998
Light Extinction	0.700	0.226	0.875	0.990	0.364
Euphotic Depth	0.526	0.916	0.906	0.998	0.692
Chemical Parameters					
Dissolved Oxygen	0.975	0.974	0.844	0.933	0.991
pH	0.959	0.030	0.958	0.693	0.821
(a) Nitrogen					
TN	0.098	0.901	0.773	0.870	0.965
SON	0.897	0.977	0.690	0.890	0.849
SIN	0.634	0.310	0.944	0.800	0.958
NH_4^+/NH_3-N	0.907	0.005	0.916	0.966	0.699
TON	0.699	0.399	0.929	0.816	0.975
PN	0.992	0.020	0.881	0.070	0.927
(b) Phosphorus					
TP	0.131	0.894	0.961	0.555	0.862
DP	0.732	0.777	0.884	0.526	0.187
PP	0.344	0.412	0.891	0.973	0.642
SRP	0.819	0.688	0.515	0.469	0.954
SOP	0.360	0.755	0.969	0.564	0.419
(c) Carbon					
PC	1.000	0.375	0.912	0.429	0.988
SOC	0.975	0.547	0.897	0.710	0.935
Phytoplankton Parameters					
Estimated Daily Productivity	0.586	0.000	0.563	0.618	0.063
Chl *a*	0.963	0.003	0.759	0.383	0.146
P_{max}	0.590	0.000	0.151	0.381	0.084
alpha	0.875	0.003	0.207	0.334	0.082
I_k	0.059	0.020	0.474	0.774	0.401

Table 4.4 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the intra-group differences between locations R4 to R1 in Group 3 during the five seasonal episodes in 1994.

Parameter	Episode 1	Episode 2	Episode 3	Episode 4	Episode 5
Physical Parameters					
Precipitation	0.993	0.973	1.000	1.000	1.000
River Flow Rate	0.536	0.551	0.804	0.722	0.224
In Situ Water Temperature	1.000	0.991	0.999	1.000	1.000
Light Extinction	0.314	0.427	0.972	0.414	0.364
Euphotic Depth	0.696	0.374	0.959	0.550	0.617
Chemical Parameters					
Dissolved Oxygen	1.000	0.990	0.978	0.998	0.995
pH	0.942	0.781	0.818	0.987	0.835
(a) Nitrogen					
TN	0.440	0.872	0.760	0.993	0.956
SON	0.992	0.648	0.565	0.492	0.746
SIN	0.833	0.916	0.966	0.885	0.934
NH_4^+/NH_3-N	0.045	0.001	0.773	0.000	0.007
TON	0.904	0.965	0.956	0.995	0.979
PN	0.611	0.414	0.461	0.346	0.754
(b) Phosphorus					
TP	0.763	0.592	0.954	0.697	0.362
DP	0.735	0.326	0.986	0.578	0.930
PP	0.764	0.321	0.894	0.415	0.516
SRP	0.900	0.869	0.999	0.388	0.993
SOP	0.706	0.953	0.976	0.633	0.319
(c) Carbon					
PC	0.255	0.401	0.841	0.397	0.761
SOC	0.995	0.930	0.995	0.579	0.895
Phytoplankton Parameters					
Estimated Daily Productivity	0.965	0.733	0.999	0.780	0.905
Chl *a*	0.982	0.911	0.628	0.957	0.275
P_{max}	0.994	0.933	0.999	0.979	0.994
alpha	0.999	0.064	0.948	0.984	0.982
I_k	0.804	0.456	0.471	0.989	0.929

Table 4.5 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the intra-group differences between locations R7 to R10 in Group 1 during the three seasonal episodes in 1995.

Parameter	Episode 3	Episode 4	Episode 5
Physical Parameters			
Precipitation	1.000	1.000	1.000
River Flow Rate	0.006	0.000	0.179
In Situ Water Temperature	0.996	0.997	0.987
Light Extinction	0.851	0.744	0.017
Euphotic Depth	0.851	0.932	0.926
Chemical Parameters			
Dissolved Oxygen	0.930	0.925	0.890
pH	0.845	0.825	0.666
(a) Nitrogen			
TN	0.707	0.625	0.961
SON	0.702	0.800	0.647
SIN	0.994	0.966	0.108
NH_4^+/NH_3-N	0.578	0.984	0.375
TON	0.997	0.966	0.254
PN			
(b) Phosphorus			
TP	0.279	0.542	0.341
DP	0.633	0.784	0.206
PP	0.617	0.213	0.599
SRP	0.883	0.801	0.831
SOP	0.554	0.579	0.753
(c) Carbon			
TOC	0.889	0.977	0.884
SOC	0.220	0.875	0.035
Phytoplankton Parameters			
Estimated Daily Productivity	0.912	0.908	0.522
Chl *a*	0.968	0.993	0.853
P_{max}	0.993	0.916	0.858
alpha	0.857	0.929	0.836
I_k	0.080	0.833	0.675

Table 4.6 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the intra-group differences between locations R5, R5.1 and R6 in Group 2 during the three seasonal episodes in 1995.

Parameter	Episode 3	Episode 4	Episode 5
Physical Parameters			
Precipitation	0.987	1.000	1.000
River Flow Rate	0.030	0.000	0.280
In Situ Water Temperature	0.992	0.997	0.950
Light Extinction	0.770	0.974	0.876
Euphotic Depth	0.824	0.833	0.986
Chemical Parameters			
Dissolved Oxygen	0.982	0.925	0.766
pH	0.854	0.825	0.821
(a) Nitrogen			
TN	0.628	0.625	0.438
SON	0.945	0.800	0.913
SIN	0.837	0.966	0.035
NH_4^+/NH_3-N	0.461	0.984	0.374
TON	0.845	0.966	0.211
PN			
(b) Phosphorus			
TP	0.532	0.542	0.551
DP	0.525	0.784	0.442
PP	0.909	0.213	0.209
SRP	0.863	0.801	0.566
SOP	0.375	0.579	0.791
(c) Carbon			
TOC	0.725	0.798	0.680
SOC	0.946	0.875	0.358
Phytoplankton Parameters			
Estimated Daily Productivity	0.726	0.568	0.116
Chl *a*	0.576	0.618	0.279
P_{max}	0.762	0.464	0.011
alpha	0.619	0.441	0.006
I_k	0.422	0.971	0.020

Table 4.7 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the intra-group differences between locations R1 to R4 in Group 3 during the three seasonal episodes in 1995.

Parameter	Episode 3	Episode 4	Episode 5
Physical Parameters			
Precipitation	0.474	0.931	1.000
River Flow Rate	0.920	0.273	0.832
In Situ Water Temperature	1.000	1.000	0.980
Light Extinction	0.966	0.980	0.971
Euphotic Depth	0.926	0.986	0.968
Chemical Parameters			0.994
Dissolved Oxygen	0.985	0.909	0.821
pH	0.872	0.801	0.977
(a) Nitrogen			
TN	0.455	0.820	0.677
SON	0.964	0.149	0.698
SIN	0.988	0.952	0.406
NH_4^+/NH_3-N	0.025	0.000	0.028
TON	0.996	0.983	0.833
(b) Phosphorus			
TP	0.651	0.813	0.383
DP	0.624	0.631	0.297
PP	0.566	0.955	0.782
SRP	0.984	0.787	0.254
SOP	0.244	0.360	0.082
(c) Carbon			
TOC	0.894	0.865	0.635
SOC	0.816	0.916	0.775
Phytoplankton Parameters			
Estimated Daily Productivity	0.978	0.984	0.948
Chl *a*	0.678	0.998	0.999
P_{max}	0.995	0.976	0.626
alpha	0.936	0.985	0.865
I_k	0.796	0.420	0.580

Table 4.8 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the differences between upstream and downstream locations in the Assiniboine River during the five seasonal episodes in 1994.

Parameter	Episode 1	Episode 2	Episode 3	Episode 4	Episode 5
Physical Parameters					
Precipitation	1.000	1.000	1.000	1.000	1.000
River Flow Rate					
In Situ Water Temperature	0.325	0.852	0.651	0.812	0.879
Chemical Parameters					
Dissolved Oxygen	0.923	0.576	0.424	0.163	0.496
pH	0.374	0.360	0.089	0.204	0.646
(a) Nitrogen					
TN	0.895	0.792	0.985	0.272	0.583
SON	0.352	0.757	0.662	0.833	0.534
SIN	0.257	0.356	0.696	0.213	0.688
NH_4^+/NH_3-N		0.356	0.891	0.095	0.009
TON	0.283	0.550	0.663	0.313	0.843
PN	0.723	0.006	0.928	0.460	0.396
(b) Phosphorus					
TP	0.288	0.221	0.464	0.506	0.796
DP	0.345	0.977	0.781	0.071	0.506
PP	0.576	0.474	0.613	0.921	0.903
SRP	0.369	0.187	0.087	0.009	0.019
SOP	0.928	0.591	0.289	0.746	0.726
(c) Carbon					
PC	0.731	0.480	0.630	0.469	0.978
SOC	0.336	0.093	0.622	0.926	0.046
Phytoplankton Parameters					
Estimated Daily Productivity	0.751	0.794	0.656	0.077	0.971
Chl *a*	0.767	0.037	0.450	0.877	0.957
P_{max}	0.978	0.656	0.798	0.287	0.996
alpha	0.806	0.705	0.568	0.834	0.862
I_k	0.403	0.002	0.840	0.252	0.682

Table 4.9 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the differences between upstream and downstream locations in the Assiniboine River during the three season episodes in 1995.

Parameter	Episode 3	Episode 4	Episode 5
Physical Parameters			
Precipitation	1.000	1.000	1.000
River Flow Rate			
In Situ Water Temperature	0.953	0.840	0.890
Chemical Parameters			
Dissolved Oxygen	0.435	0.473	0.205
pH	0.673	0.568	0.676
(a) Nitrogen			
TN	0.741	0.009	0.977
SON	0.521	0.109	0.942
SIN	0.599	0.226	0.060
NH_4^+/NH_3-N	0.106	0.199	0.053
TON	0.765	0.377	
PN			
(b) Phosphorus			
TP	0.434	0.240	0.608
DP	0.373	0.038	0.031
PP	0.511	0.466	0.441
SRP	0.074	0.059	0.133
SOP	0.063	0.391	0.670
(c) Carbon			
TOC			
SOC	0.658	0.711	0.492
Phytoplankton Parameters			
Estimated Daily Productivity	0.615	0.763	0.804
Chl *a*	0.810	0.782	0.936
P_{max}	0.672	0.383	0.783
alpha	0.913	0.727	0.461
I_k	0.268	0.141	0.925

Table 4.10 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the differences between seasonal episodes in the Red River in (a) 1994 and (b) 1995.

Parameter	(a). 1994	(b). 1995
Physical Parameters		
Precipitation	0.000	0.398
River Flow Rate	0.000	0.000
In Situ Water Temperature	0.000	0.000
Euphotic Depth	0.000	0.000
Light Extinction	0.000	0.000
Chemical Parameters		
Dissolved Oxygen	0.000	0.000*
pH	0.000	0.001
(a) Nitrogen		
TN	0.000	0.242**
SON	0.000	0.983
SIN	0.000*	0.000*
NH_4^+/NH_3-N	0.002	0.000*
TON	0.000*	0.000
PN	0.000*	N/A
(b) Phosphorus		
TP	0.000	0.000
DP	0.000	0.000
PP	0.000	0.586
SRP	0.000*	0.054*
SOP	0.038	0.000
(c) Carbon		
PC	0.000	N/A
TOC	N/A	0.000*
SOC	0.000	0.000
Phytoplankton Parameters		
Estimated Daily Productivity	0.000*	0.001
Chl *a*	0.000	0.000
P_{max}	0.000*	0.038
alpha	0.000*	0.000
I_k	0.000*	0.000*

* one-way ANOVAs were performed because interaction between seasonal episode and group occurred.

** one way ANOVA using only group 3 p = 0.026.

Table 4.11 Probability (p) values obtained from one-way Analysis of Variance. ANOVAs were performed to quantify the differences between seasonal episodes within the Assiniboine River in (a) 1994 and (b) 1995.

Parameter	(a). 1994	(b). 1995
Physical Parameters		
Precipitation	0.000	0.982
River Discharge	0.000	0.000
In Situ Water Temperature	0.000	0.000
Euphotic Depth	0.139	0.003
Light Extinction	0.016	0.000
Chemical Parameters		
Dissolved Oxygen	0.000	0.000
pH	0.004	0.130
(a) Nitrogen		
TN	0.000	0.654
SON	0.000	0.288
SIN	0.002	0.000
NH_4^+/NH_3-N	0.040	0.080
TON	0.001	0.000
PN	0.265	N/A
(b) Phosphorus		
TP	0.069	0.302
DP	0.044	0.024
PP	0.398	0.030
SRP	0.004	0.105
SOP	0.091	0.853
(c) Carbon		
PC	0.097	N/A
TOC	N/A	0.000
SOC	0.000	0.000
Phytoplankton Parameters		
Estimated Daily Productivity	0.002	0.000
Chl *a*	0.458	0.013
P_{max}	0.008	0.000
alpha	0.031	0.000
I_k	0.091	0.000

Table 4.12 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the differences between years in seasonal episodes 3, 4 and 5 within the Red River.

Parameter	Episode 3	Episode 4	Episode 5
Physical Parameters			
Precipitation	0.042	0.030	0.000
River Flow Rate	0.029	0.450	0.000
In Situ Water Temperature	0.144	0.033	0.144
Euphotic Depth	0.000*	0.057*	0.008*
Light Extinction	0.001*	0.047*	0.000*
Chemical Parameters			
Dissolved Oxygen	0.000	0.000	0.000
pH	0.000	0.000	0.000
(a) Nitrogen			
TN	0.000	0.108	0.238
SON	0.006	0.000	0.025
SIN	0.771*	0.660	0.000
NH_4^+/NH_3-N	0.385	0.000	0.004*
TON	0.760*	0.803	0.000
(b) Phosphorus			
TP	0.000	0.035*	0.000*
DP	0.000	0.006	0.000*
PP	0.000	0.210*	0.000
SRP	0.000	0.004*	0.000*
SOP	0.577	0.151*	0.001
(c) Carbon			
SOC	0.003	0.316	0.000*
Phytoplankton Parameters			
Estimated Productivity	0.034*	0.050*	0.000*
Chl *a*	0.006*	0.833*	0.000*
P_{max}	0.049*	0.374*	0.000*
alpha	0.000*	0.000*	0.000*
I_k	0.000*	0.000*	0.000*

* one-way ANOVAs were performed because interactions between year and group occurred.

Table 4.13 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the differences between years in seasonal episodes 3, 4 and 5 within the Assiniboine River.

Parameter	Episode 3	Episode 4	Episode 5
Physical Parameters			
Precipitation	0.000	0.065	0.094
River Discharge Rate	0.000	0.003	0.948
In Situ Water Temperature	0.027	0.556	0.753
Euphotic Depth	0.817	0.078	0.087
Light Extinction	0.861	0.018	0.001
Chemical Parameters			
Dissolved Oxygen	0.470	0.154	0.012
pH	0.002	0.032	0.179
(a) Nitrogen			
TN	0.002	0.212	0.798
SON	0.010	0.041	0.046
SIN	0.144	0.000	0.004
NH_4^+/NH_3-N	0.731	0.002	0.219
TON	0.107	0.001	0.001
(b) Phosphorus			
TP	0.000	0.005	0.035
DP	0.002	0.021	0.013
PP	0.031	0.207	0.404
SRP	0.355	0.959	0.022
SOP	0.350	0.025	0.873
(c) Carbon			
SOC	0.309	0.541	0.010
Phytoplankton Parameters			
Estimated Daily Productivity	0.000	0.796	0.157
Chl *a*	0.016	0.722	0.207
P_{max}	0.012	0.124	0.834
alpha	0.000	0.000	0.666
I_k	0.000	0.000	0.823

Table 4.14 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the differences between Red River groups during the five seasonal episodes in 1994.

Parameter	Episode 1	Episode 2	Episode 3	Episode 4	Episode 5
Physical Parameters					
Precipitation	0.971	0.837	0.880	0.991	1.000
River Flow Rate	0.018	0.003	0.016	0.008	0.001
In Situ Water Temperature	0.984	0.624	0.929	0.463	0.982
Light Extinction	0.173	0.001	0.081	0.121	0.514
Euphotic Depth	0.342	0.009	0.405	0.099	0.765
Chemical Parameters					
Dissolved Oxygen	0.771	0.342	0.322	0.185	0.005
pH	0.238	0.135	0.153	0.001	0.004
(a) Nitrogen					
TN	0.770	0.666	0.386	0.119	0.383
SON	0.986	0.630	0.044	0.020	0.500
SIN	0.000	0.965	0.837	0.000	0.071
NH_4^+/NH_3-N	0.035	0.000	0.000	0.000	0.000
TON	0.003	0.590	0.987	0.096	0.262
PN	0.218	0.239	0.163	0.000	0.182
(b) Phosphorus					
TP	0.027	0.633	0.594	0.012	0.877
DP	0.167	0.716	0.914	0.844	0.103
PP	0.496	0.930	0.437	0.191	0.667
SRP	0.022	0.769	0.416	0.000	0.751
SOP	0.082	0.655	0.978	0.043	0.363
(c) Carbon					
PC	0.565	0.019	0.029	0.781	0.073
SOC	0.980	0.633	0.767	0.342	0.058
Phytoplankton Parameters					
Estimated Daily Productivity	0.011	0.000	0.006	0.000	0.012
Chl *a*	0.927	0.000	0.006	0.001	0.001
P_{max}	0.096	0.000	0.000	0.000	0.001
alpha	0.047	0.000	0.000	0.000	0.005
I_k	0.801	0.011	0.055	0.000	0.001

Table 4.15 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the differences between Red River groups during seasonal episodes 3, 4 and 5 in 1995.

Parameter	Episode 3	Episode 4	Episode 5
Physical Parameters			
Precipitation	0.188	0.998	1.000
River Flow Rate	0.108	0.001	0.081
In Situ Water Temperature	0.670	0.988	0.819
Euphotic Depth	0.026	0.000	0.667
Light Extinction	0.082	0.000	0.672
Chemical Parameters			
Dissolved Oxygen	0.685	0.097	0.006
pH	0.143	0.436	0.015
(a) Nitrogen			
TN	0.302	0.877	0.151
SON	0.287	0.008	0.810
SIN	0.161	0.258	0.000
NH_4^+/NH_3-N	0.000	0.000	0.000
TON	0.101	0.447	0.180
(b) Phosphorus			
TP	0.785	0.145	0.002
DP	0.863	0.182	0.000
PP	0.954	0.012	0.465
SRP	0.749	0.002	0.001
SOP	0.840	0.403	0.206
(c) Carbon			
TOC	0.368	0.987	0.320
SOC	0.962	0.956	0.914
Phytoplankton Parameters			
Estimated Daily Productivity	0.000	0.000	0.000
Chl *a*	0.000	0.000	0.031
P_{max}	0.000	0.000	0.000
alpha	0.000	0.000	0.000
I_k	0.003	0.008	0.043

Table 4.16 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the differences between Red and Assiniboine Rivers during the five seasonal episodes in 1994.

Parameter	Episode 1	Episode 2	Episode 3	Episode 4	Episode 5
Physical Parameters					
Precipitation	0.685	0.537	0.135		
In Situ Water Temperature	0.989	0.112	0.351	0.094	0.323
Light Extinction	0.261	0.000	0.073	0.001	0.624
Euphotic Depth	0.499	0.000	0.525	0.000	0.938
Chemical Parameters					
Dissolved Oxygen	0.895	0.165	0.282	0.222	0.000
pH	0.062	0.000	0.000	0.000	0.000
(a) Nitrogen					
TN	0.098	0.103	0.066	0.115	0.256
SON	0.995	0.615	0.076	0.024	0.000
SIN	0.000	0.000	0.000	0.000	0.000
NH_4^+/NH_3-N	0.002	0.000	0.000	0.000	0.000
TON	0.000	0.000	0.000	0.000	0.000
PN	0.351	0.000	0.076	0.001	0.102
(b) Phosphorus				0.000	
TP	0.051	0.006	0.504	0.038	0.043
DP	0.280	0.724	0.095	0.000	0.000
PP	0.620	0.129	0.594	0.056	0.822
SRP	0.032	0.000	0.000	0.000	0.000
SOP	0.160	0.481	0.929	0.054	0.229
(c) Carbon					
PC	0.611	0.000	0.031	0.000	0.112
SOC	0.988	0.004	0.392	0.015	0.043
Phytoplankton Parameters					
Estimated Daily Productivity	0.095	0.000	0.000	0.000	0.000
Chl *a*	0.921	0.000	0.000	0.000	0.000
P_{max}	0.140	0.000	0.000	0.000	0.000
alpha	0.042	0.000	0.000	0.000	0.000
I_k	0.588	0.097	0.098	0.000	0.001

Table 4.17 Probability (p) values obtained from Analysis of Variance. ANOVAs were performed to quantify the differences between Red and Assiniboine Rivers during seasonal episodes 3, 4 and 5 in 1995.

Parameter	Episode 3	Episode 4	Episode 5
Physical Parameters			
Precipitation	0.057	0.996	1.000
In Situ Water Temperature	0.722	0.599	0.231
Euphotic Depth	0.001	0.000	0.000
Light Extinction	0.019	0.000	0.000
Chemical Parameters			
Dissolved Oxygen	0.519	0.062	0.015
pH	0.001	0.000	0.002
(a) Nitrogen			
TN	0.027	0.000	0.224
SON	0.324	0.020	0.897
SIN	0.000	0.000	0.000
NH_4^+/NH_3-N	0.000	0.000	0.000
TON	0.000	0.000	0.000
(b) Phosphorus			
TP	0.335	0.018	0.001
DP	0.067	0.000	0.000
PP	0.842	0.002	0.000
SRP	0.000	0.000	0.000
SOP	0.074	0.003	0.397
(c) Carbon			
SOC	0.924	0.591	0.253
Phytoplankton Parameters			
Estimated Daily Productivity	0.000	0.000	0.002
Chl *a*	0.000	0.000	0.000
P_{max}	0.000	0.000	0.000
alpha	0.000	0.000	0.000
I_k	0.001	0.002	0.000

Table 4.18 Probability (p) values obtained from Paired T-Test. Paired t-tests were performed to quantify the differences between locations R4 and R5 along the Red River and in so doing, evaluate the impact of the Assiniboine River discharge.

Parameter	p Value
Physical Parameters	
In Situ Water Temperature	0.907
Euphotic Depth	0.195
Chemical Parameters	
Dissolved Oxygen	0.120
pH	0.580
(a) Nitrogen	
TN	0.784
SON	0.210
SIN	0.614
NH_4^+/NH_3-N	0.039
TON	0.820
PN	0.207
(b) Phosphorus	
TP	0.876
DP	0.754
PP	0.635
SRP	0.501
SOP	0.697
(c) Carbon	
TOC	0.527
PC	0.415
SOC	0.025
Phytoplankton Parameters	
Estimated Daily Productivity	0.012
Chl *a*	0.024
P_{max}	0.001
alpha	0.043
I_k	0.000
Chlorophyll normalized	
Estimated Productivity	0.219
P_{max}	0.041
alpha	0.868

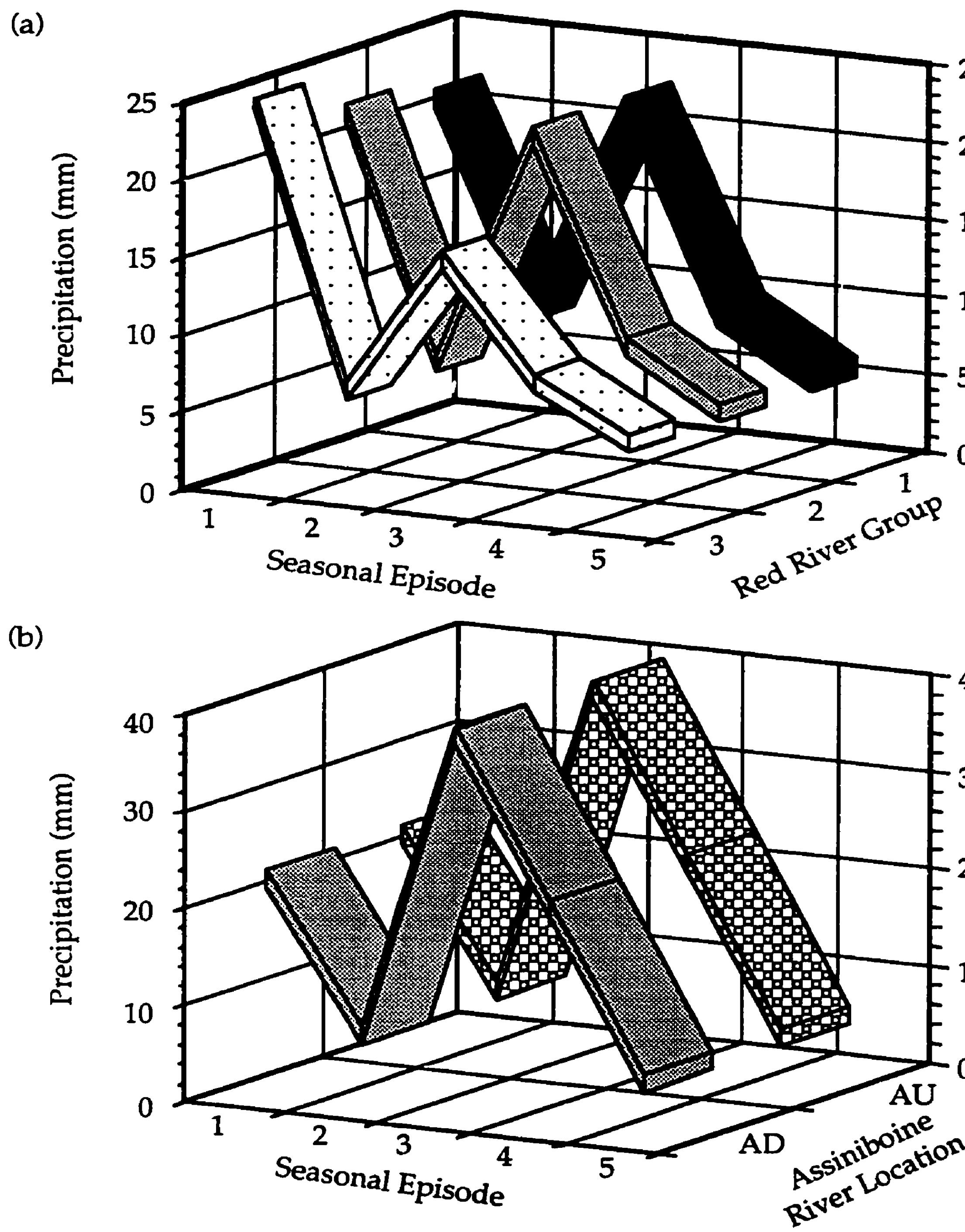
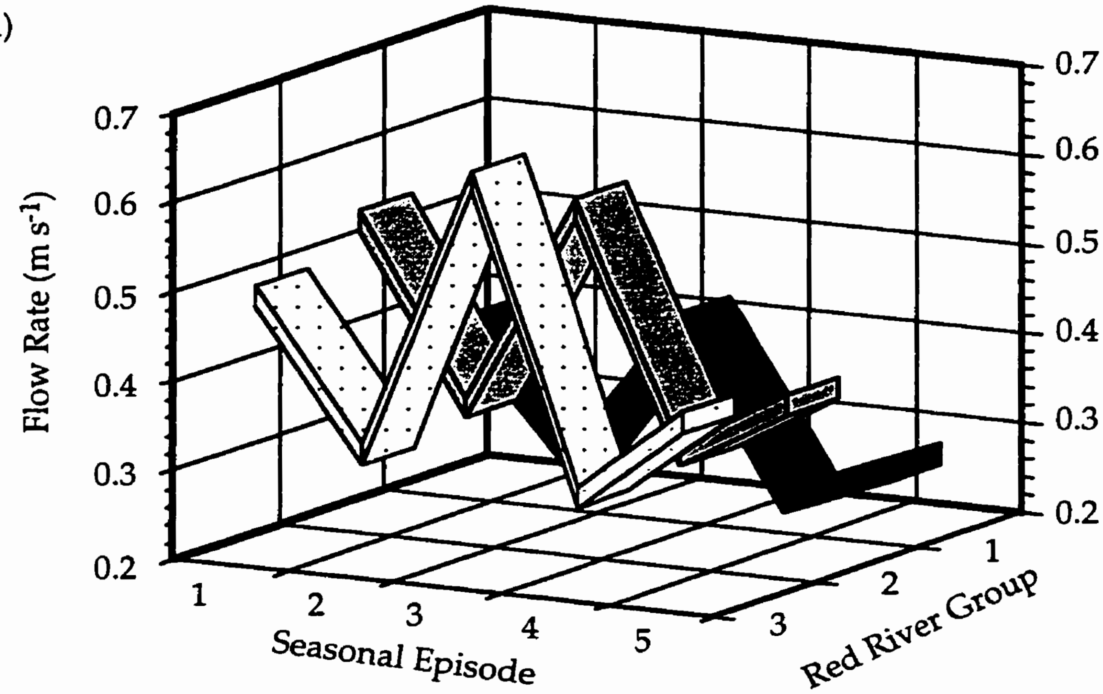


Figure 4.34 Three dimensional line plots of the average precipitation observed in each seasonal episode in the (a) Red and (b) Assiniboine Rivers in 1994. Refer to the text for a description of the Red River groups and Assiniboine locations.

(a)



(b)

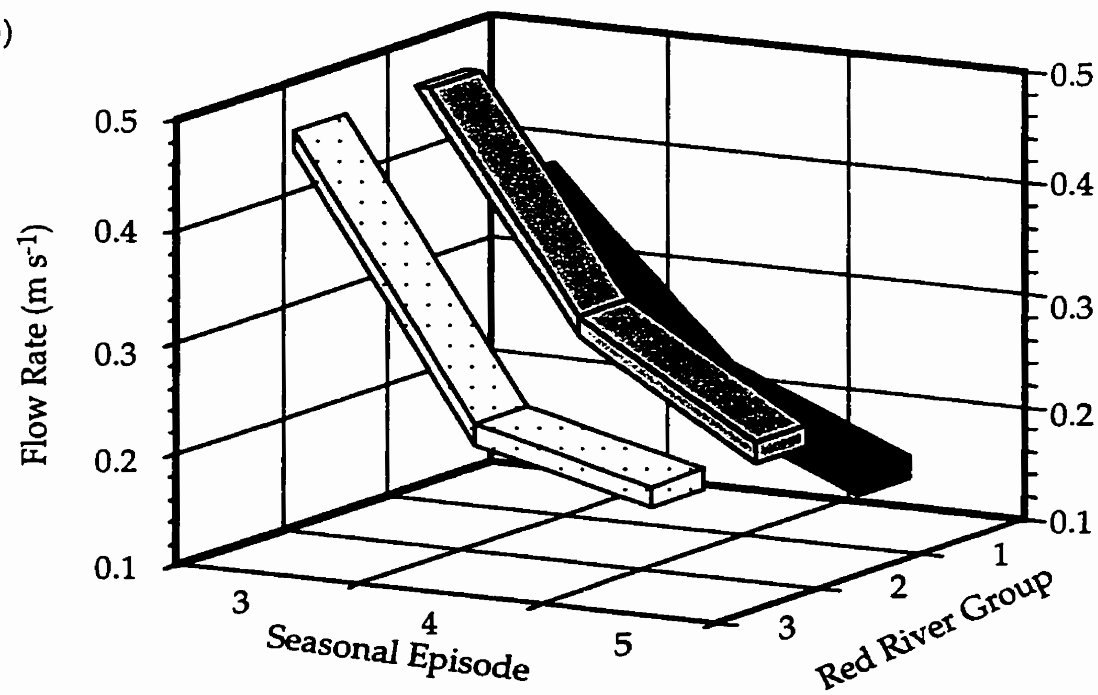


Figure 4.35 Three dimensional line plots of the average flow rate in each seasonal episode in each of the three groups in the Red River in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

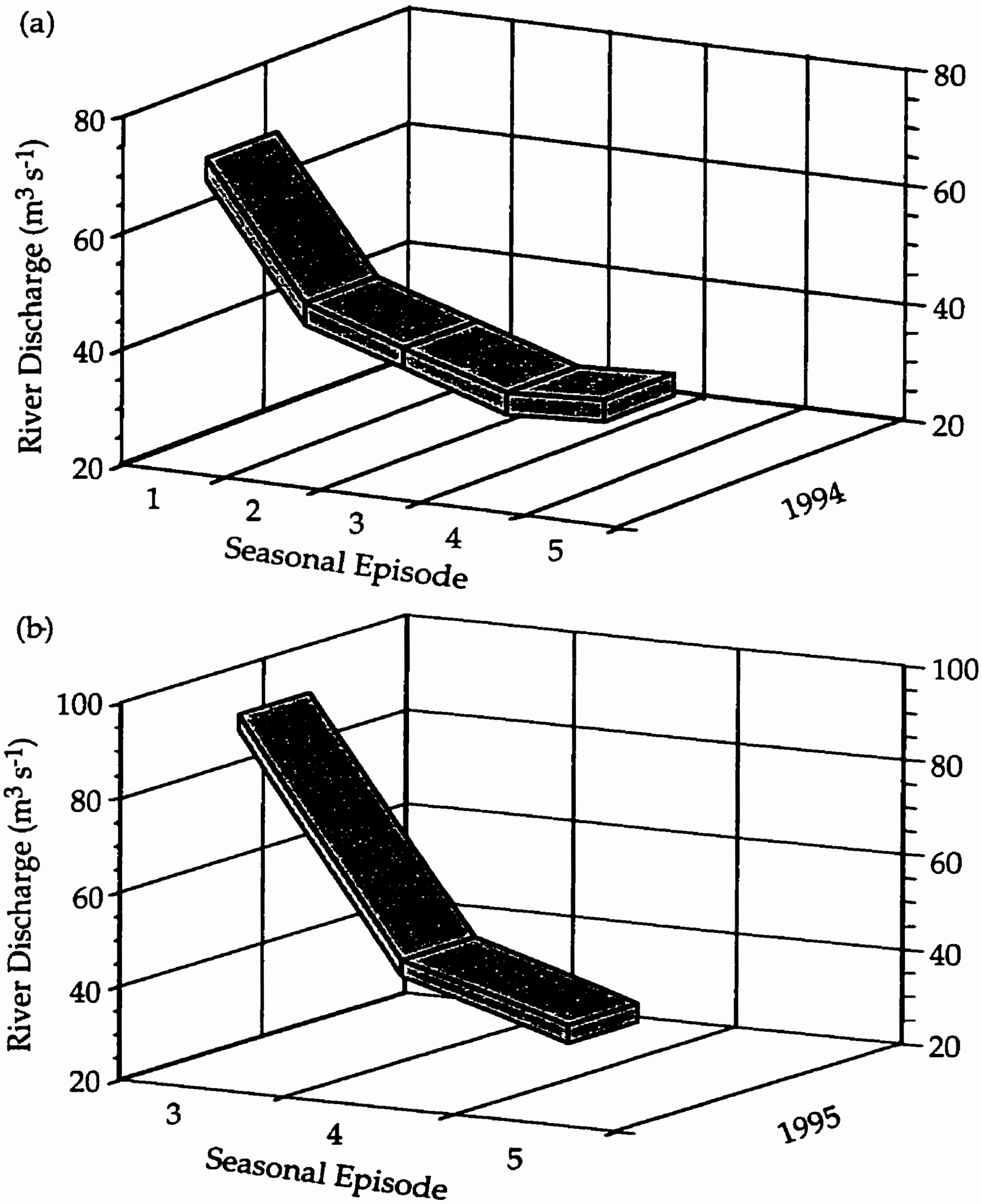
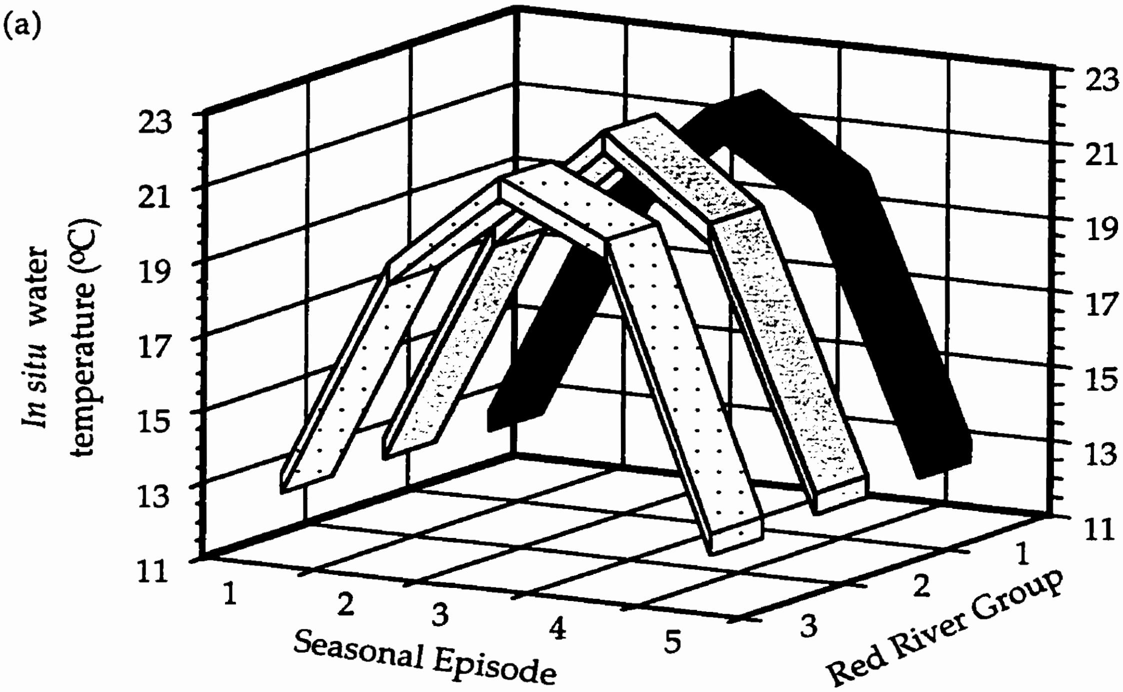


Figure 4.36 Three dimensional line plots of the average River discharge (at Headingley) in each seasonal episode in the Assiniboine River in (a) 1994 and (b) 1995.

(a)



(b)

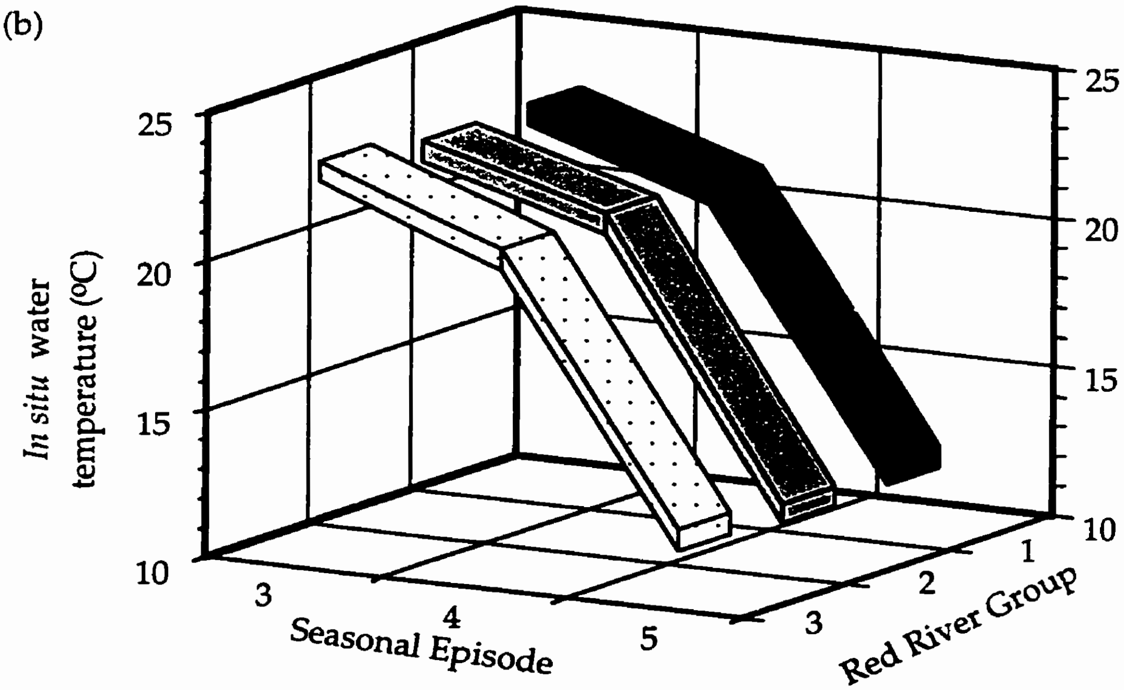


Figure 4.37 Three dimensional line plots of the average *in situ* water temperature for each seasonal episode in each of the three groups in the Red River in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

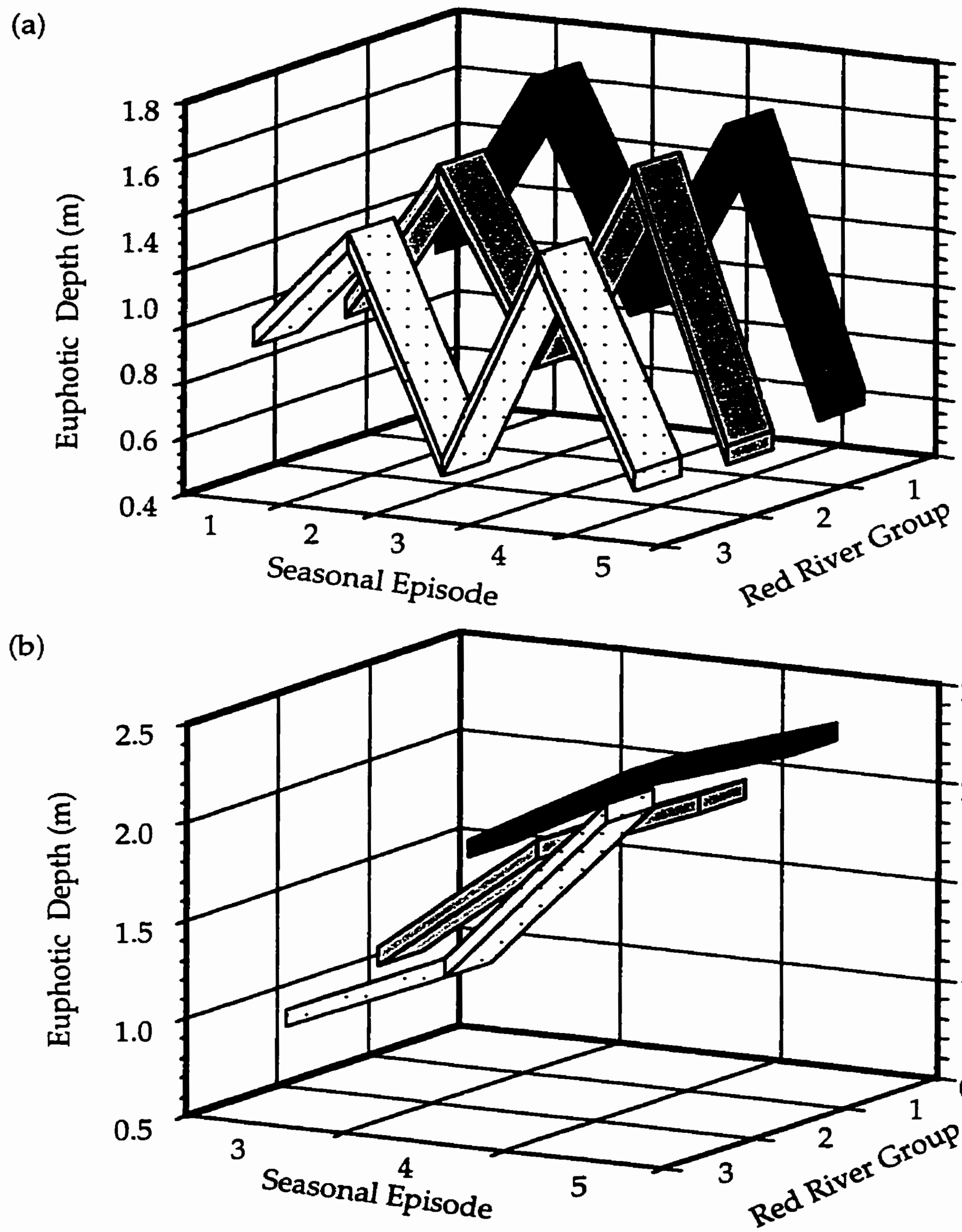


Figure 4.38 Three dimensional line plots of the average euphotic depth for each seasonal episode in each of the three groups along the Red River in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

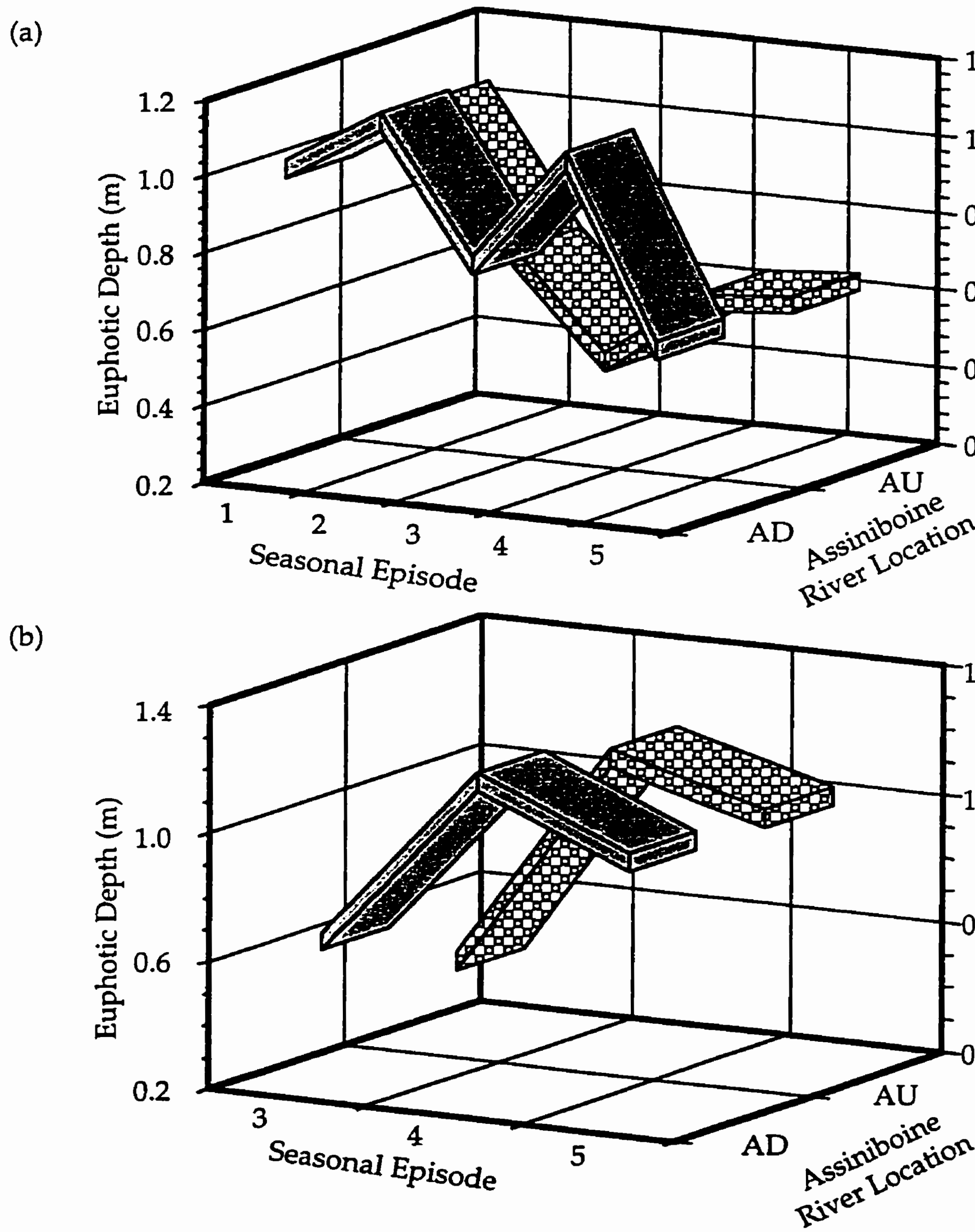


Figure 4.39 Three dimensional line plots of the average euphotic depth in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

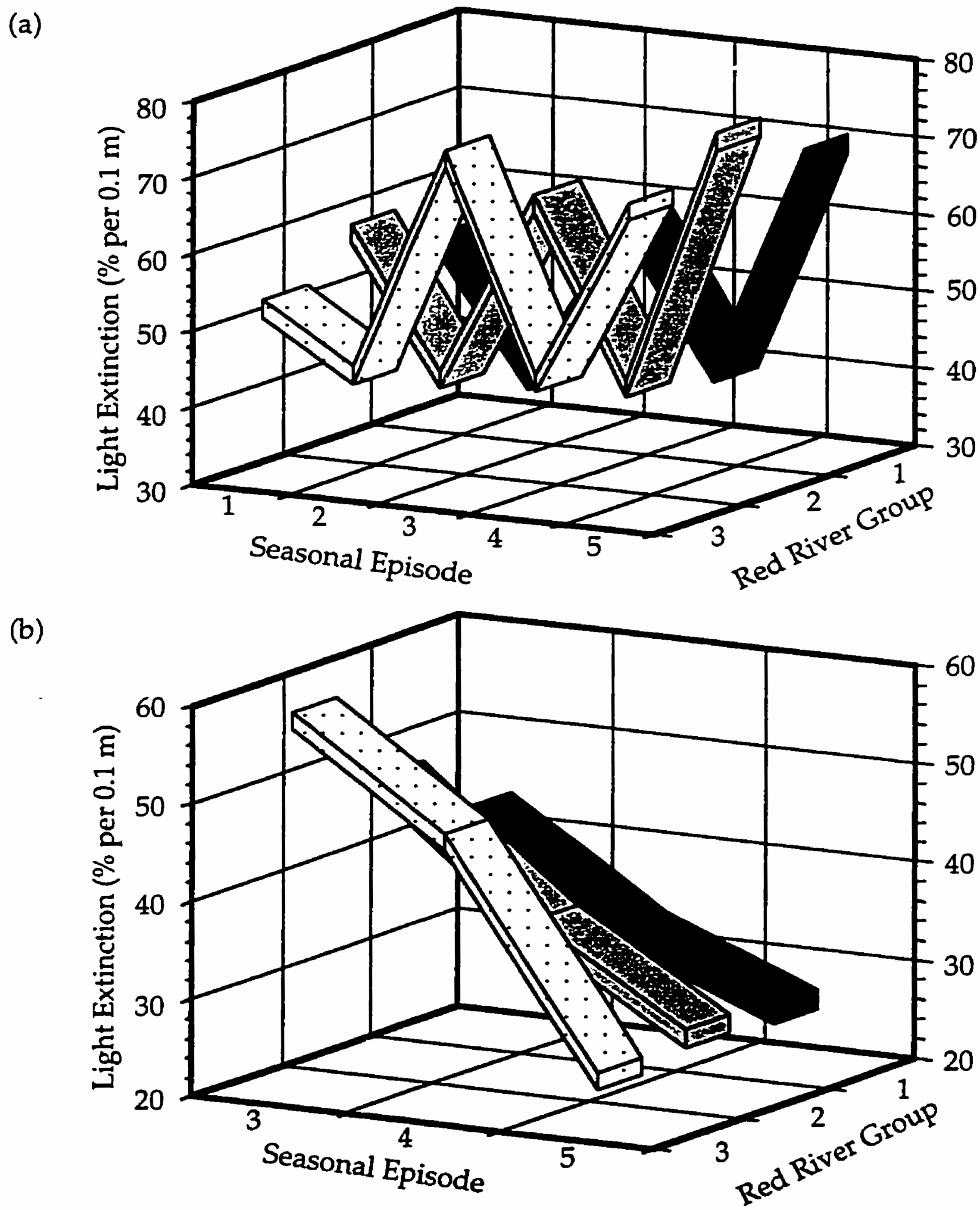
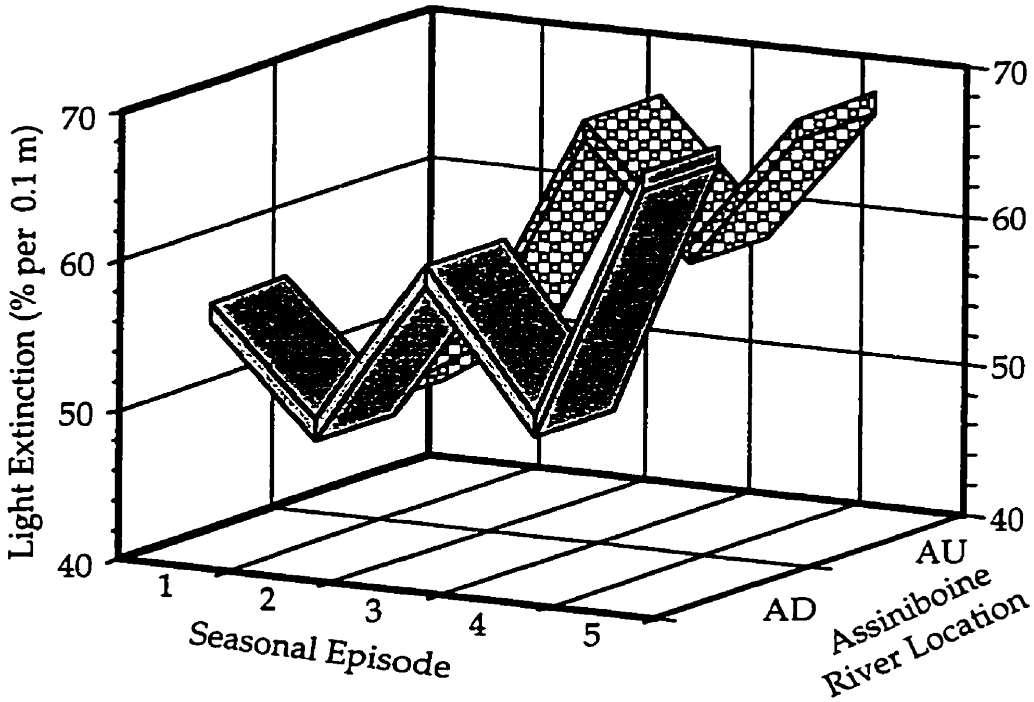


Figure 4.40 Three dimensional line plots of the average measured light extinction in each seasonal episode in the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

(a)



(b)

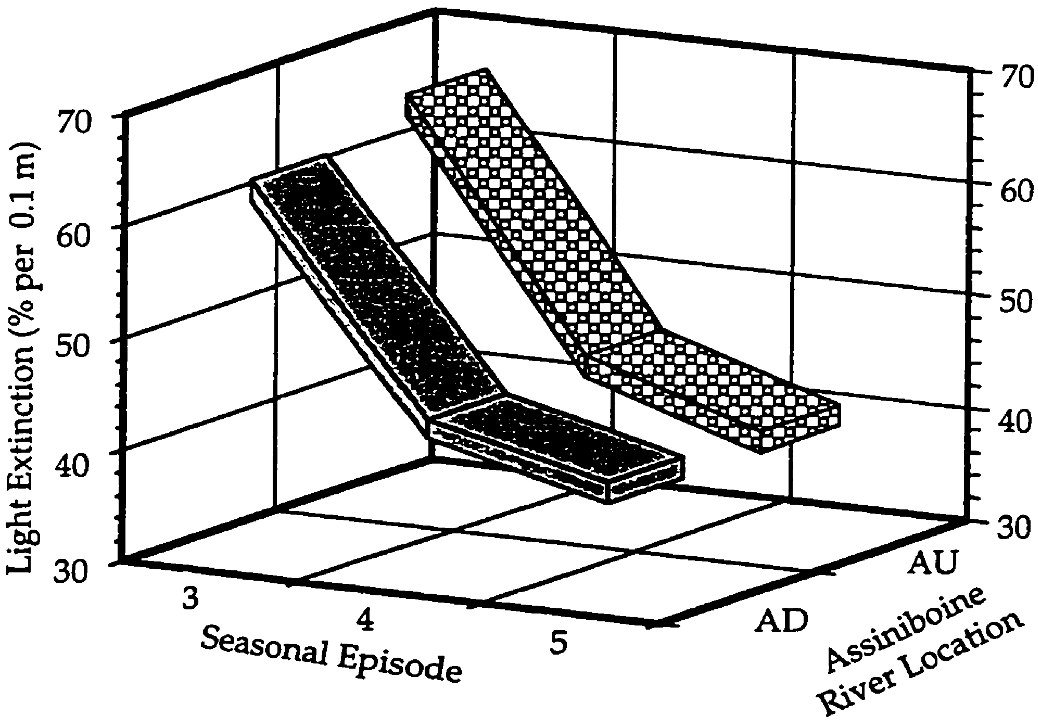


Figure 4.41 Three dimensional line plots of the average measured light extinction in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

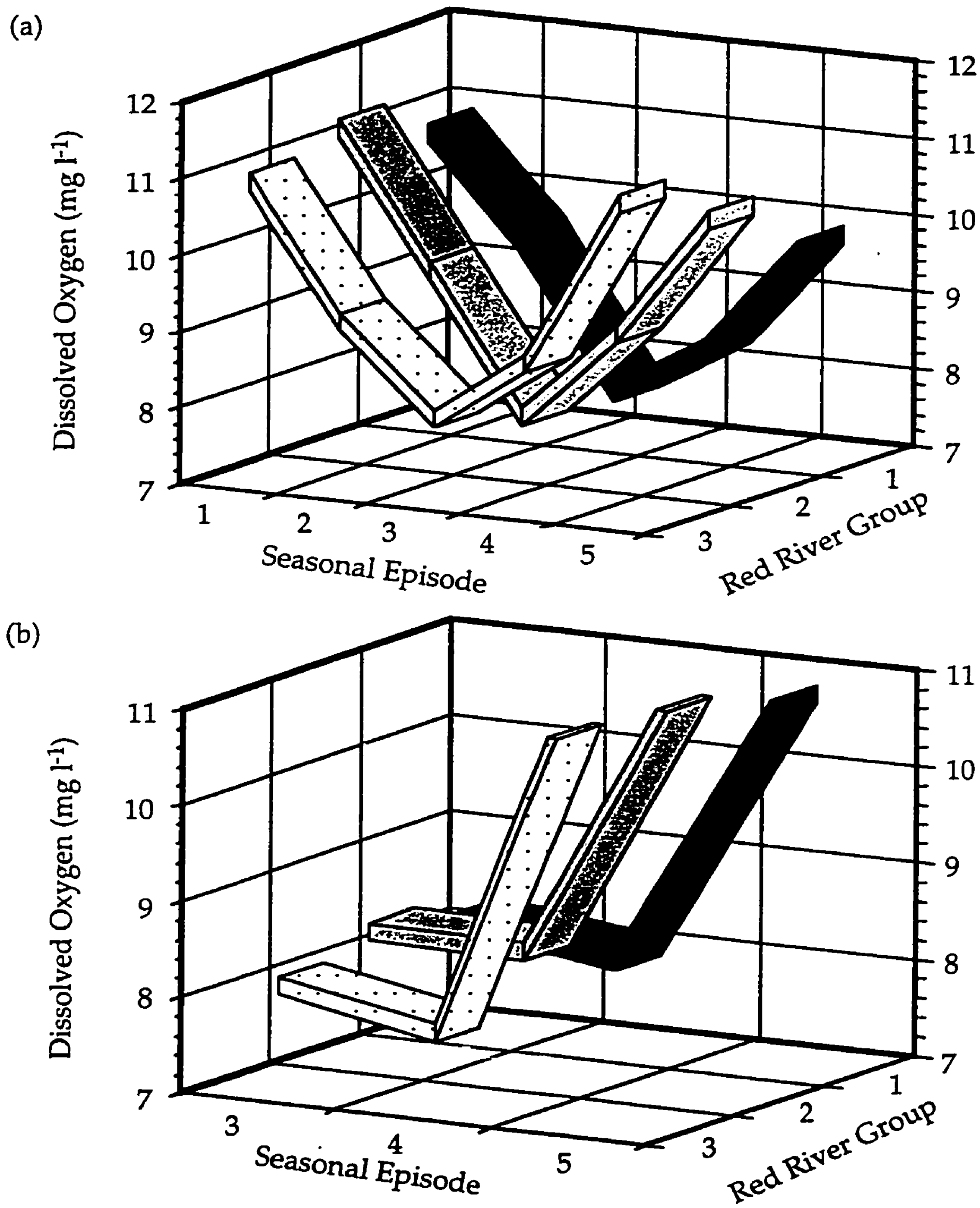


Figure 4.42 Three dimensional line plots of the the average dissolved oxygen concentration in each seasonal episode for the three groups in the Red River in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

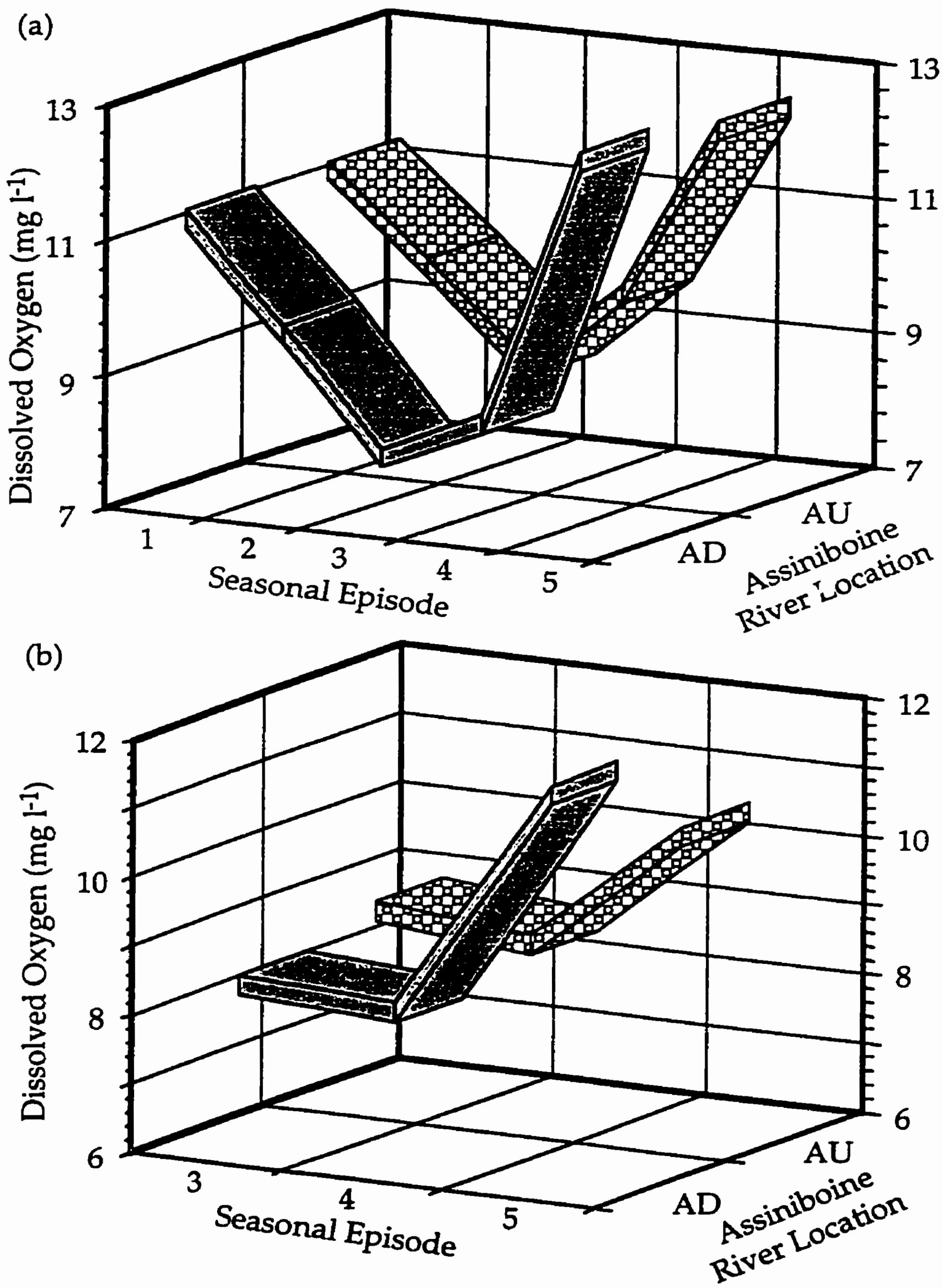


Figure 4.43 Three dimensional line plots of the average dissolved oxygen concentration in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

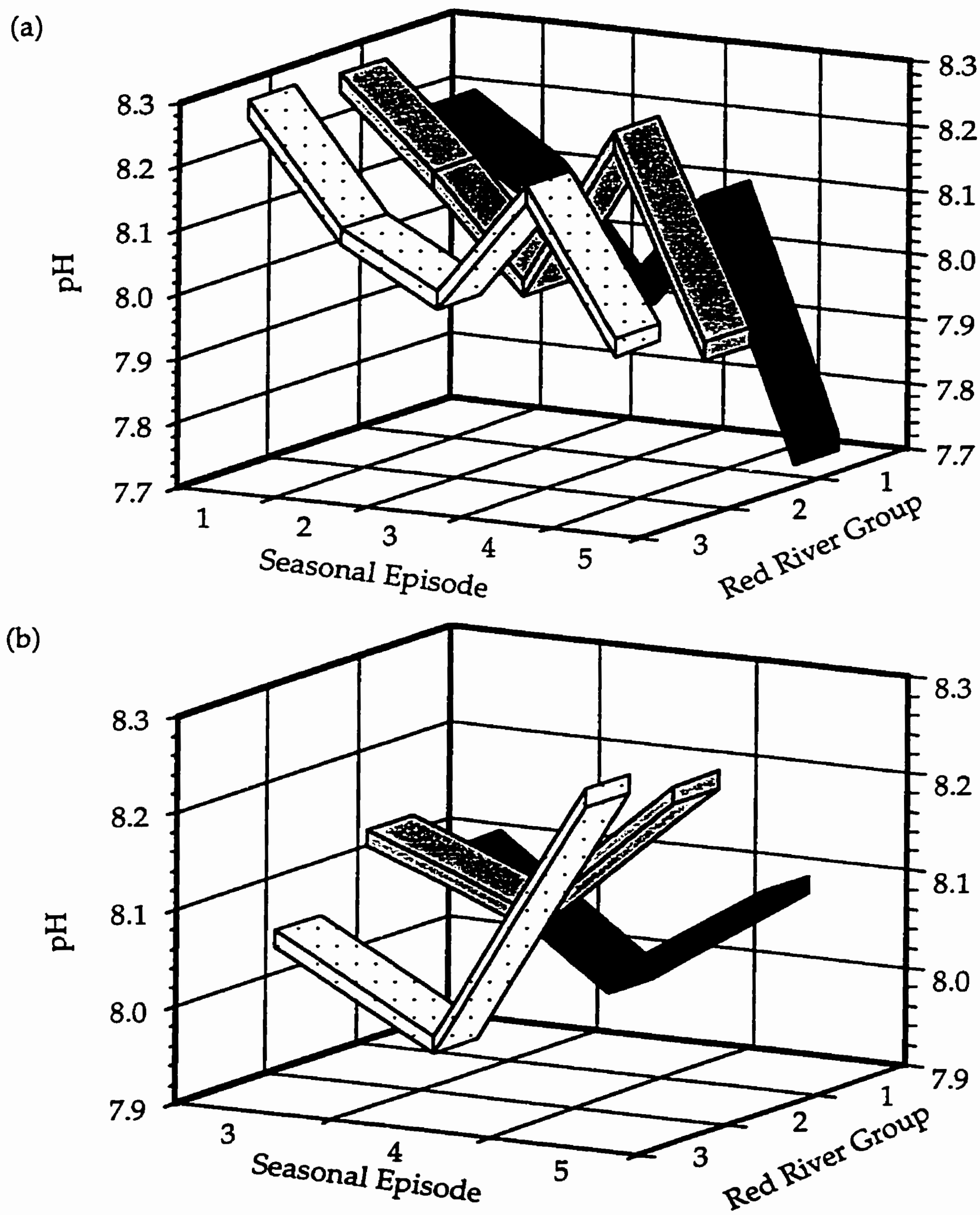


Figure 4.44 Three dimensional lin plots of the average pH for each seasonal episode in each of the three groups in the Red River in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

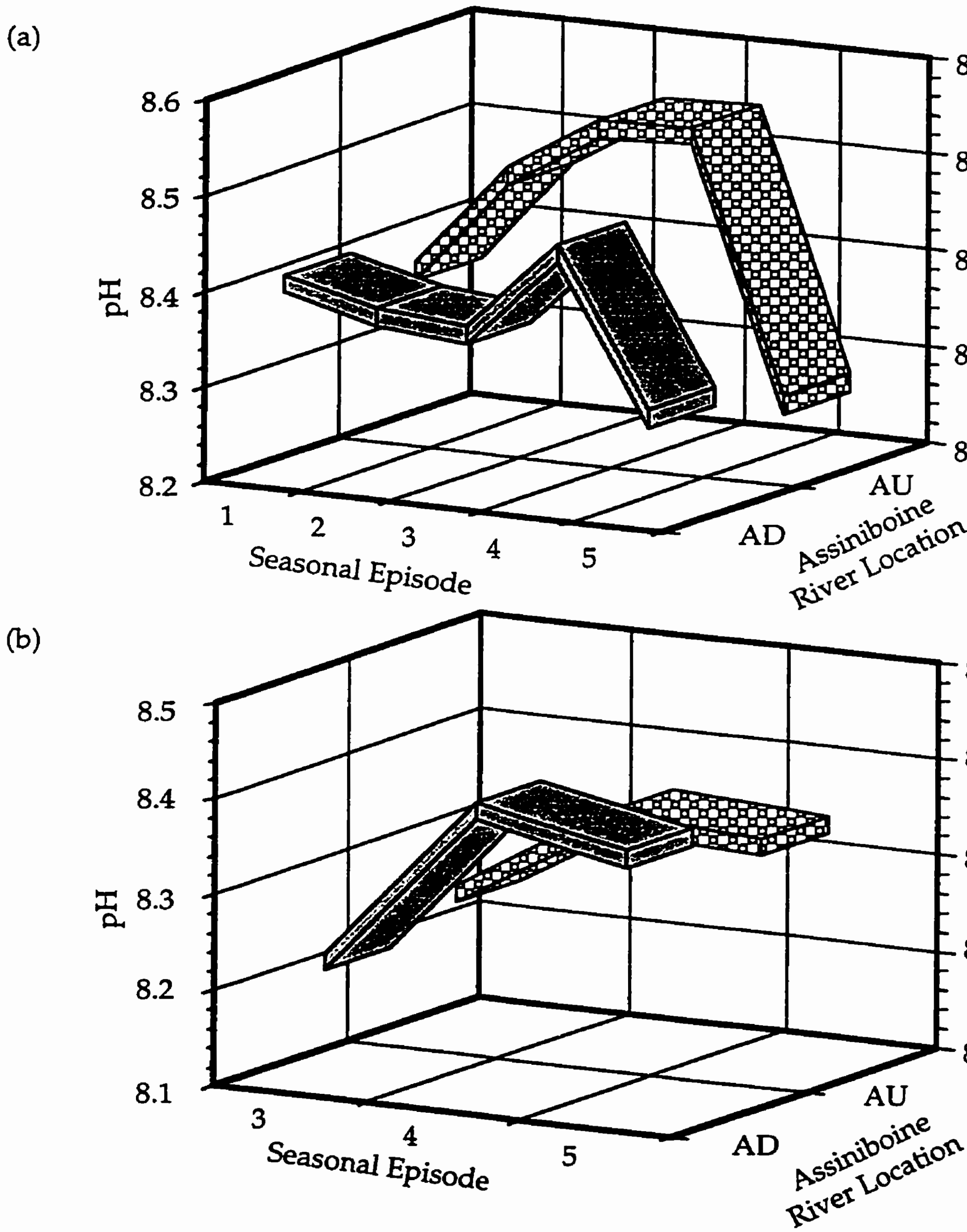


Figure 4.45 Three dimensional line plots of the average pH measurements in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

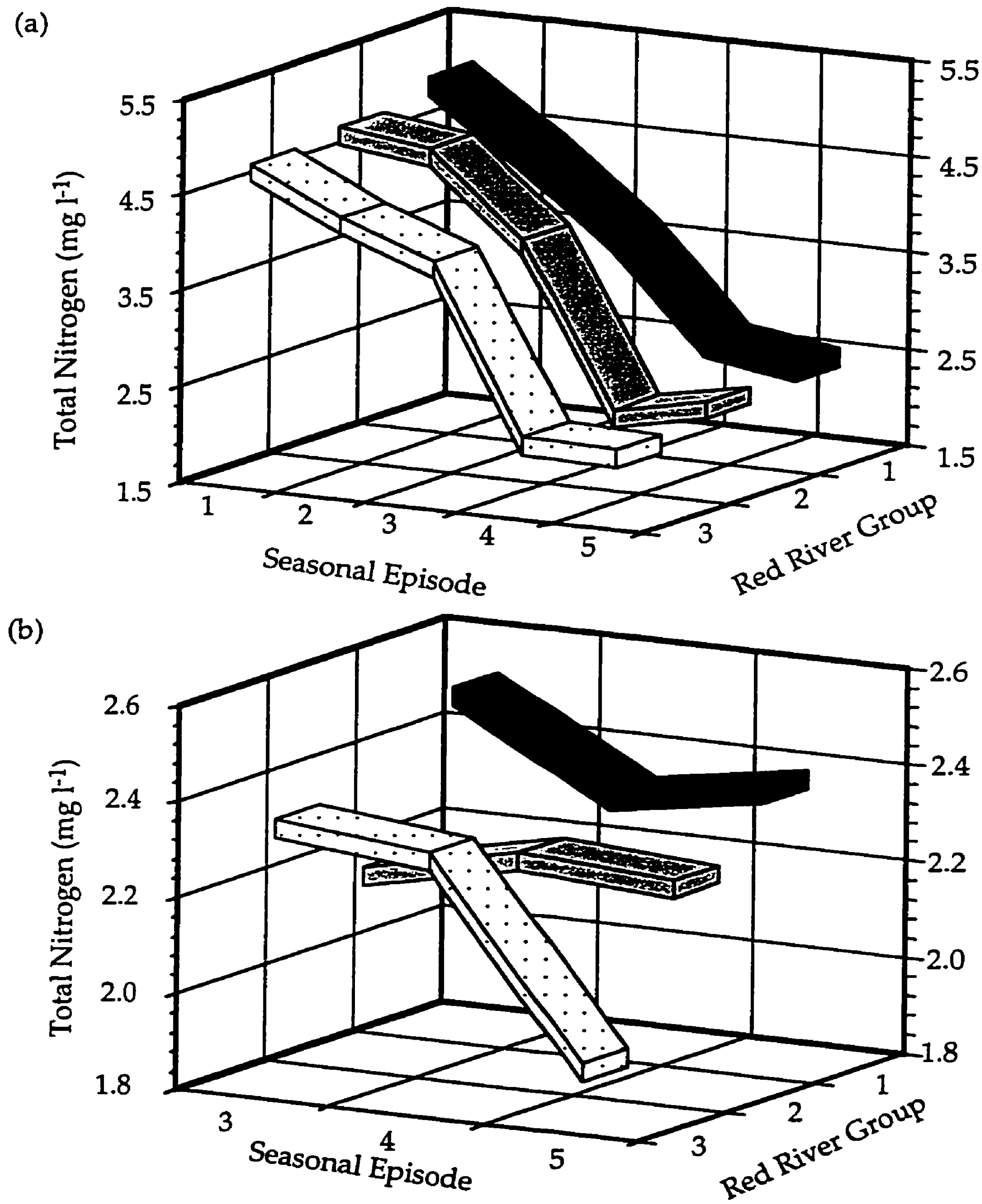


Figure 4.46 Three dimensional line plots of the average total nitrogen concentration in each seasonal episode in each of the three groups in the Red River in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

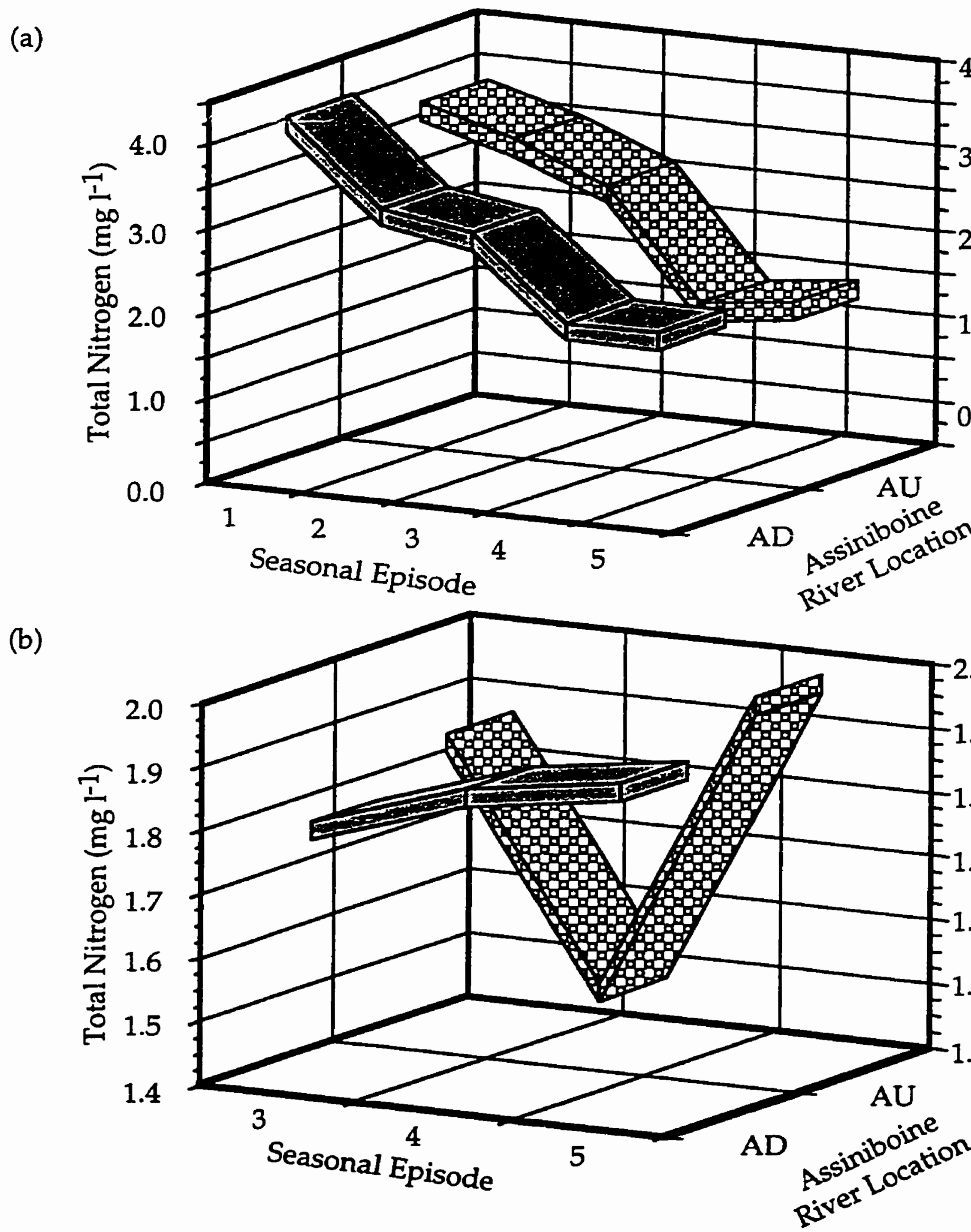
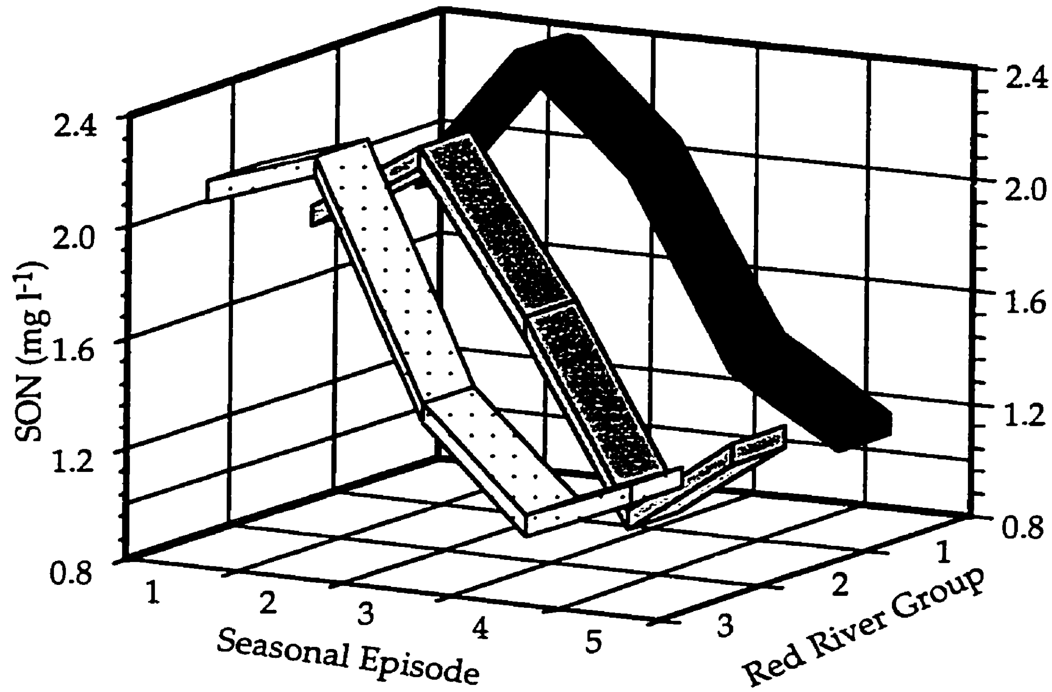


Figure 4.47 Three dimensional line plots of the average total nitrogen (TN) concentration in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

(a)



(b)

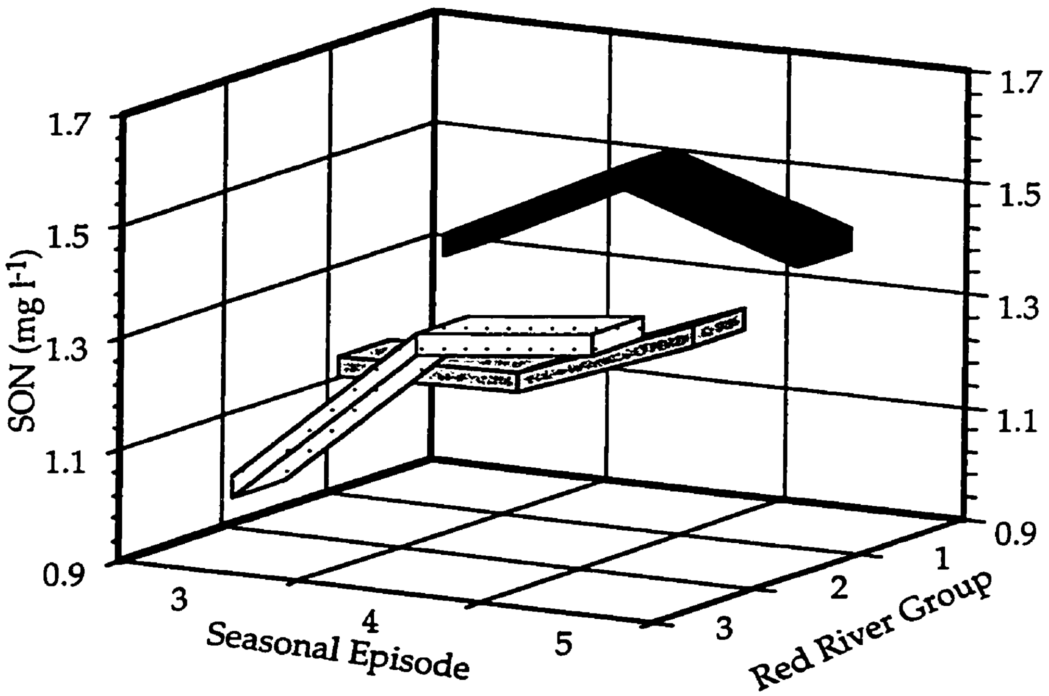


Figure 4.48 Three dimensional line plots of the average soluble organic nitrogen (SON) concentration found in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

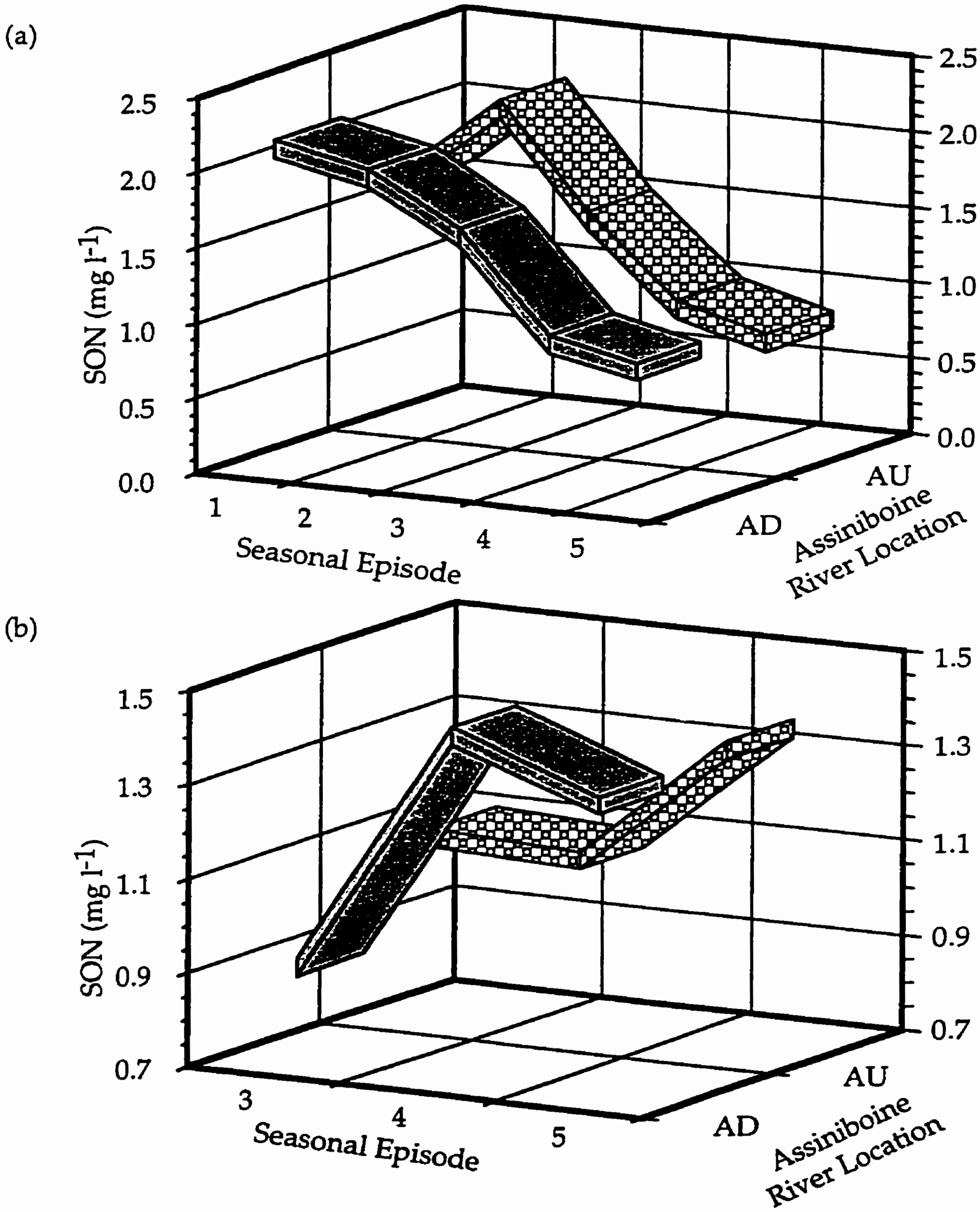
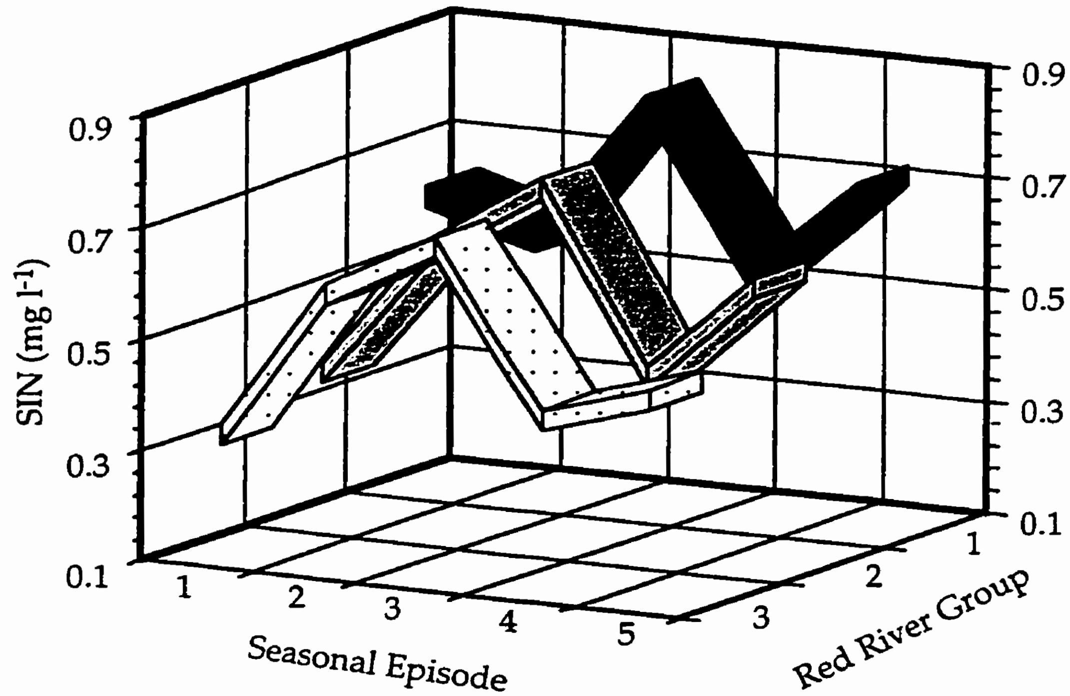


Figure 4.49 Three dimensional line plots of the average soluble organic nitrogen (SON) concentration in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

(a)



(b)

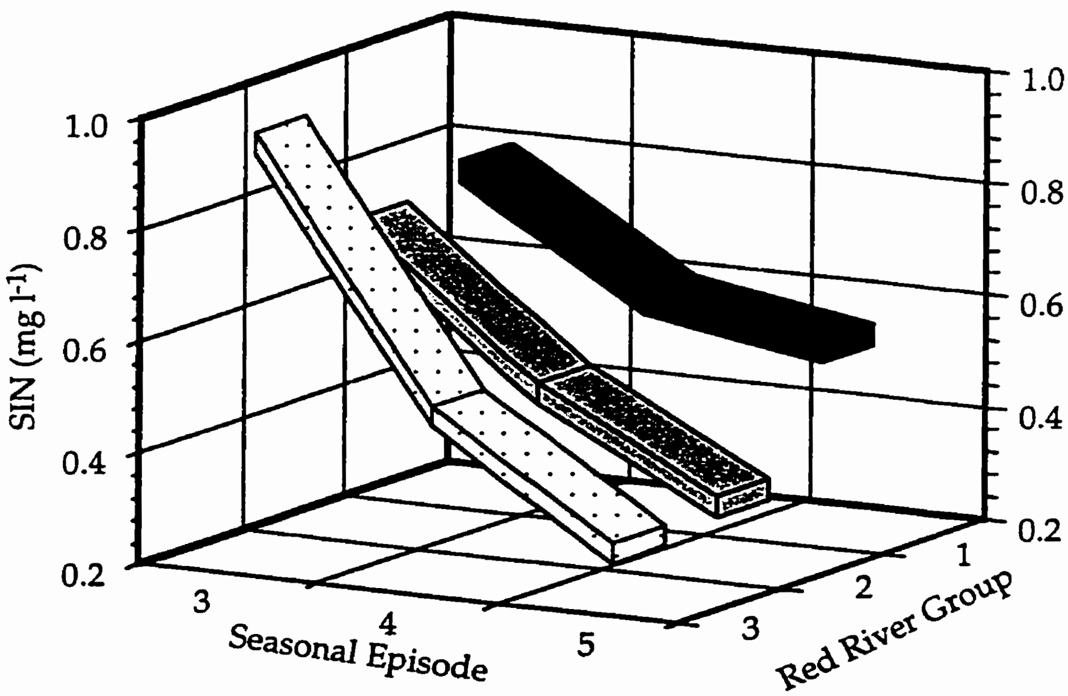


Figure 4.50 Three dimensional line plots of the average soluble inorganic nitrogen (SIN) concentration found in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

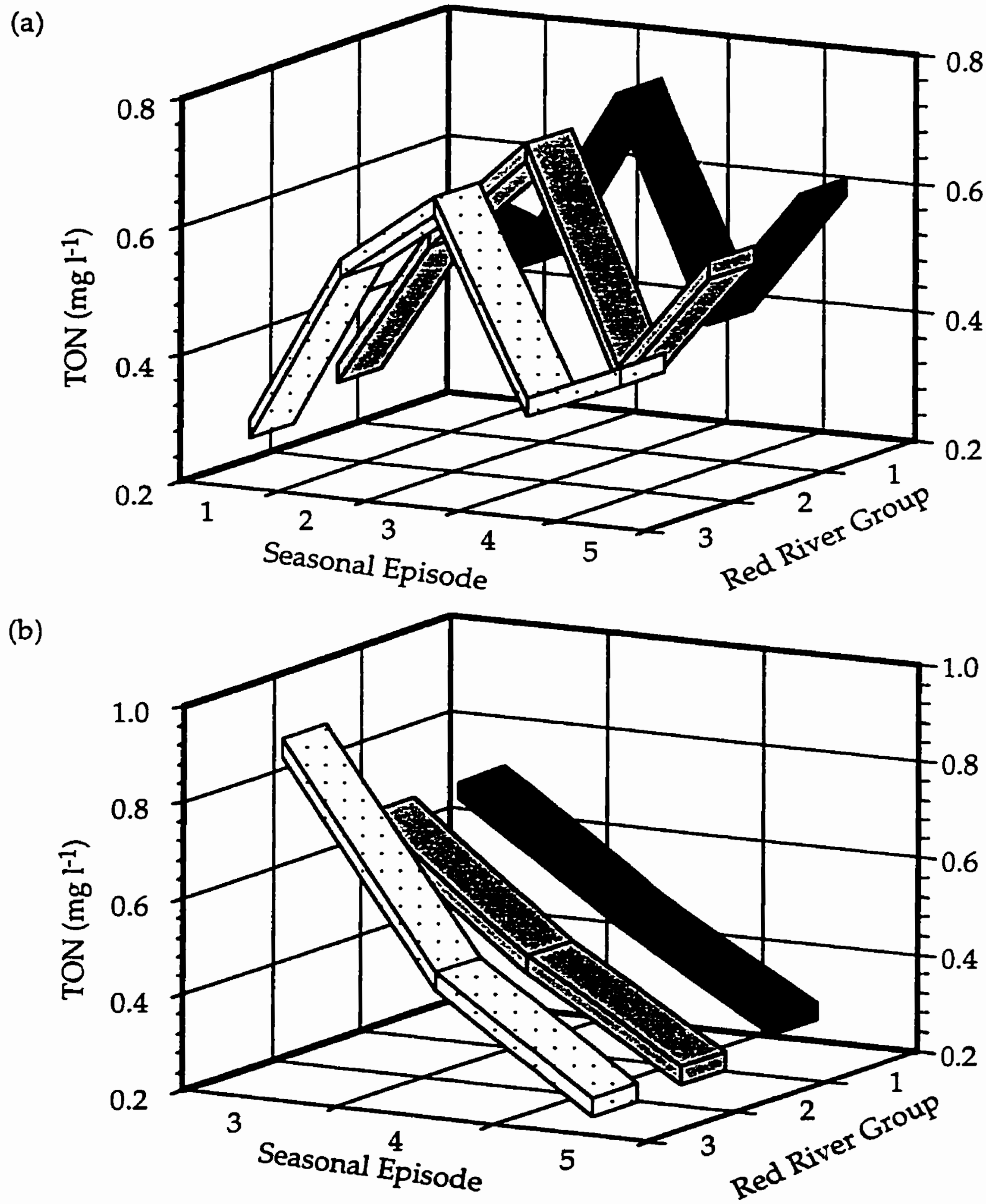
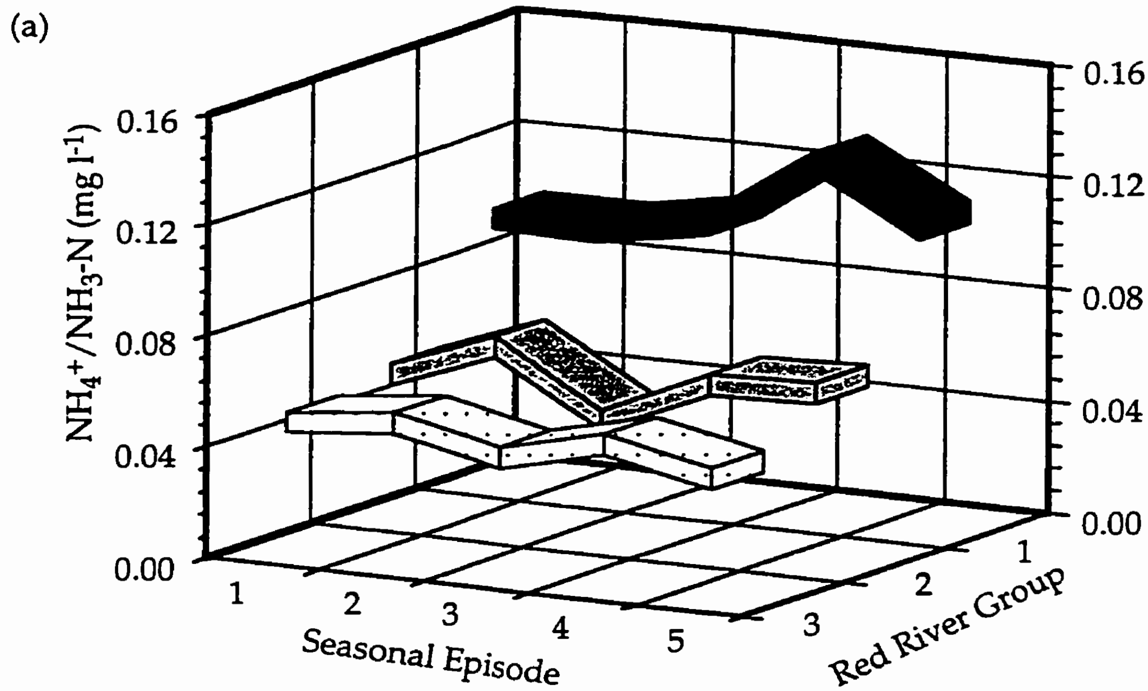


Figure 4.51 Three dimensional line plots of the average total oxidized nitrogen (TON) concentration found in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.



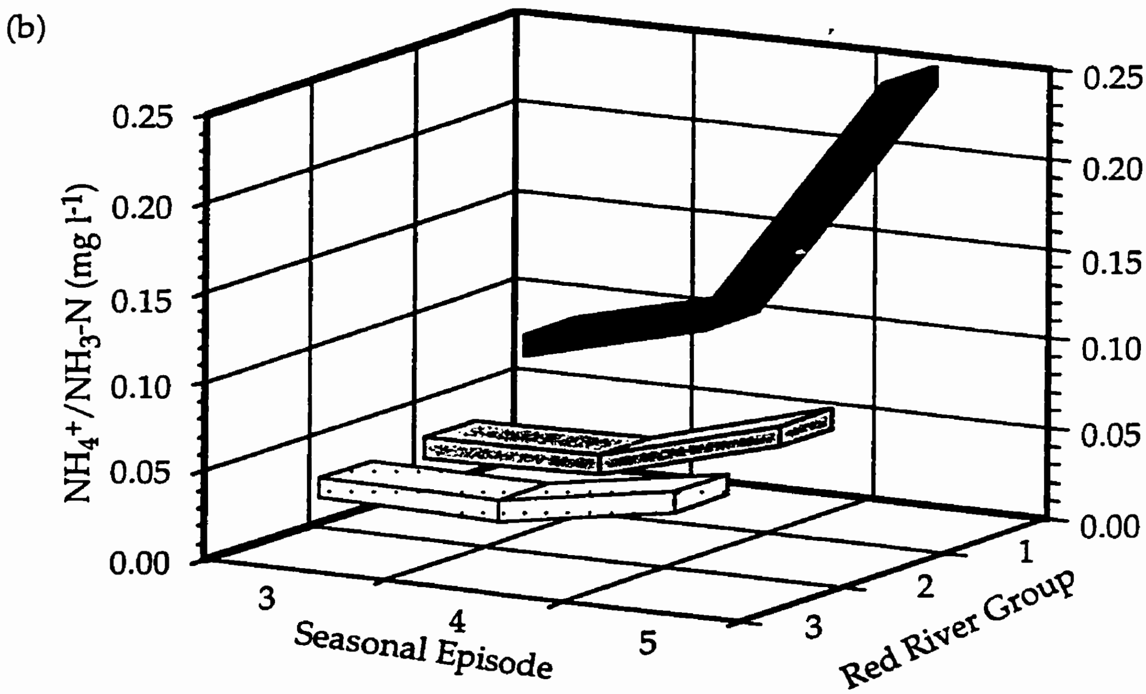
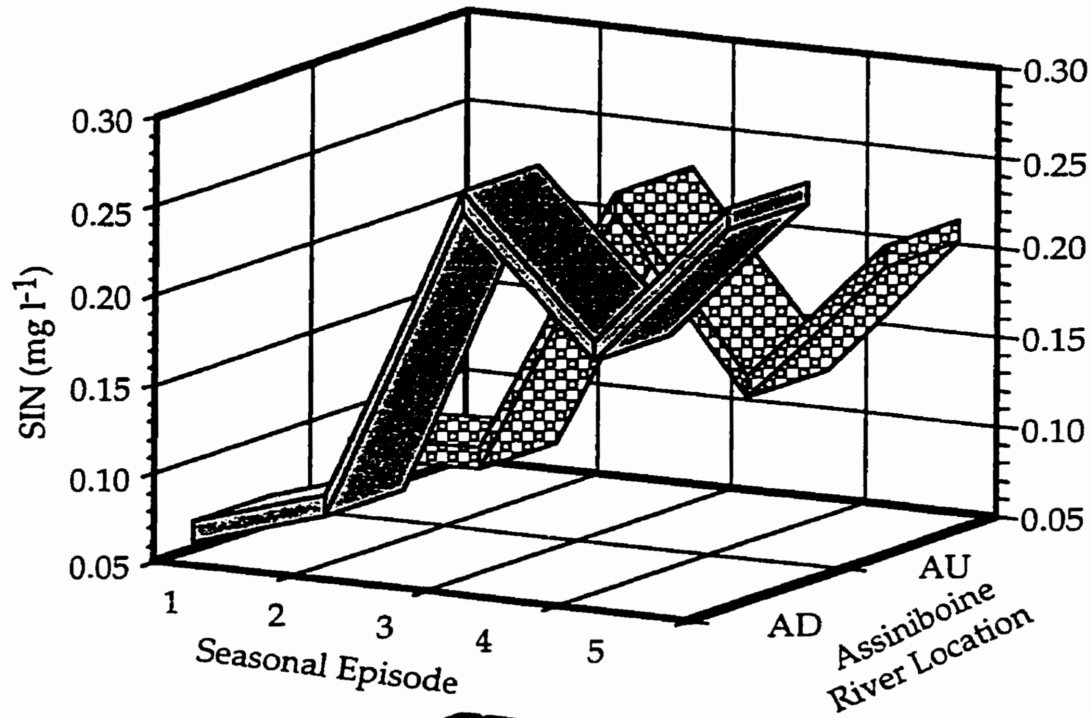


Figure 4.52 Three dimensional line plots of the average total ammonia nitrogen (NH_4^+/NH_3-N) concentration found in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

(a)



(b)

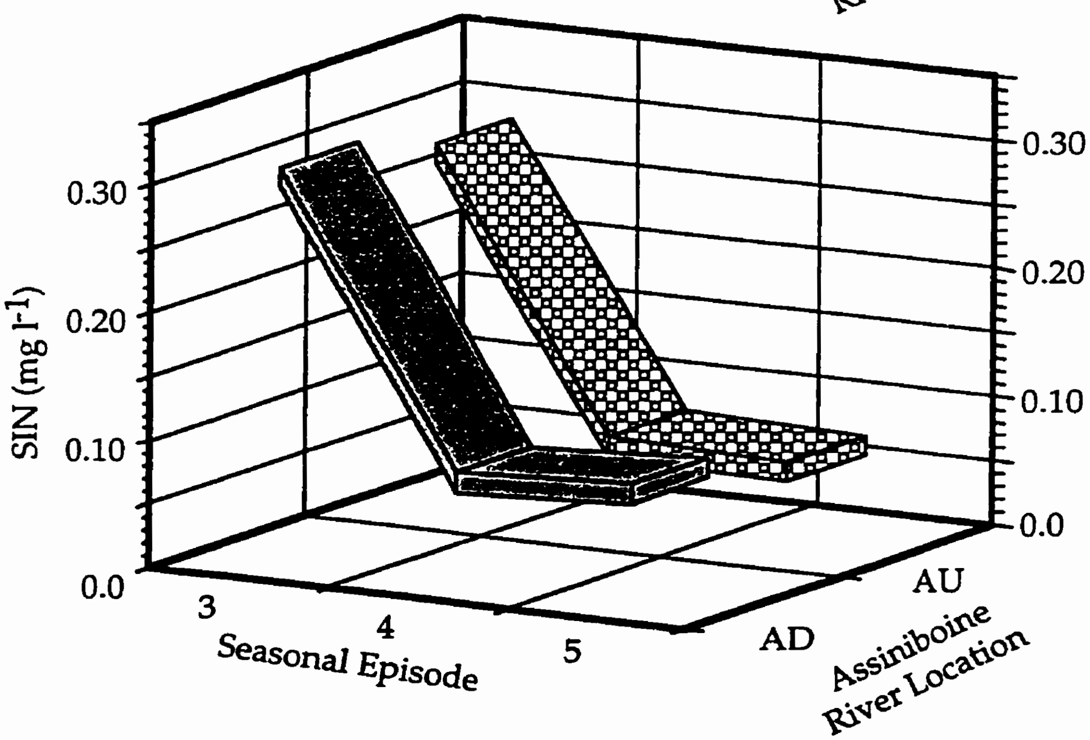
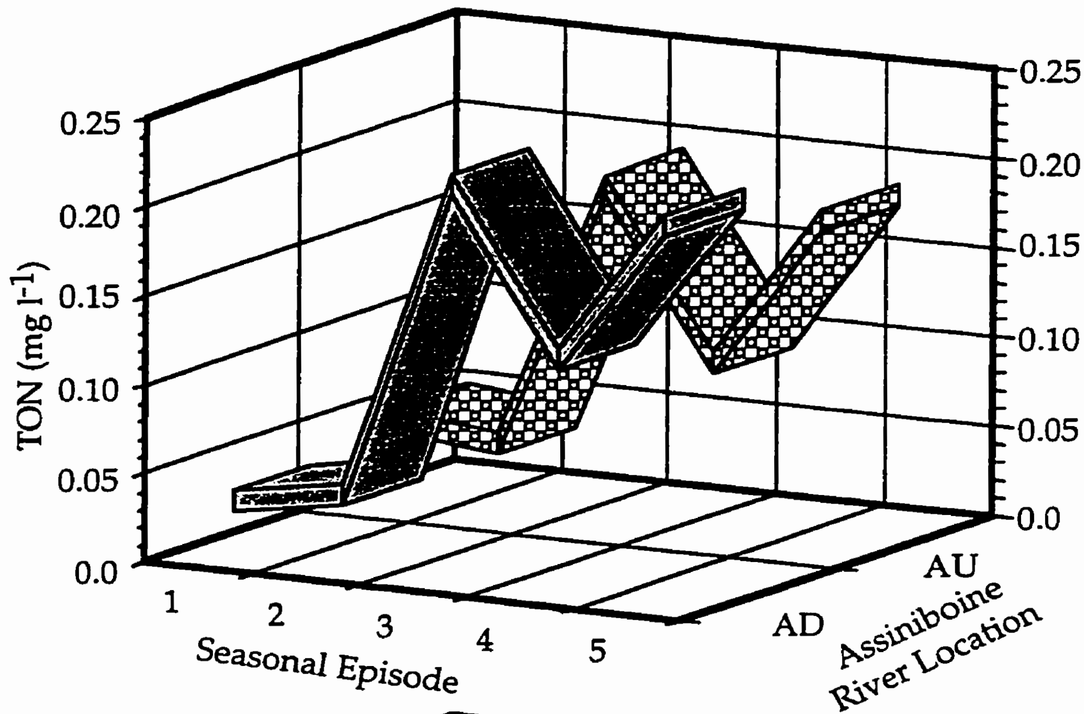


Figure 4.53 Three dimensional line plots of the average soluble inorganic nitrogen (SIN) concentration in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

(a)



(b)

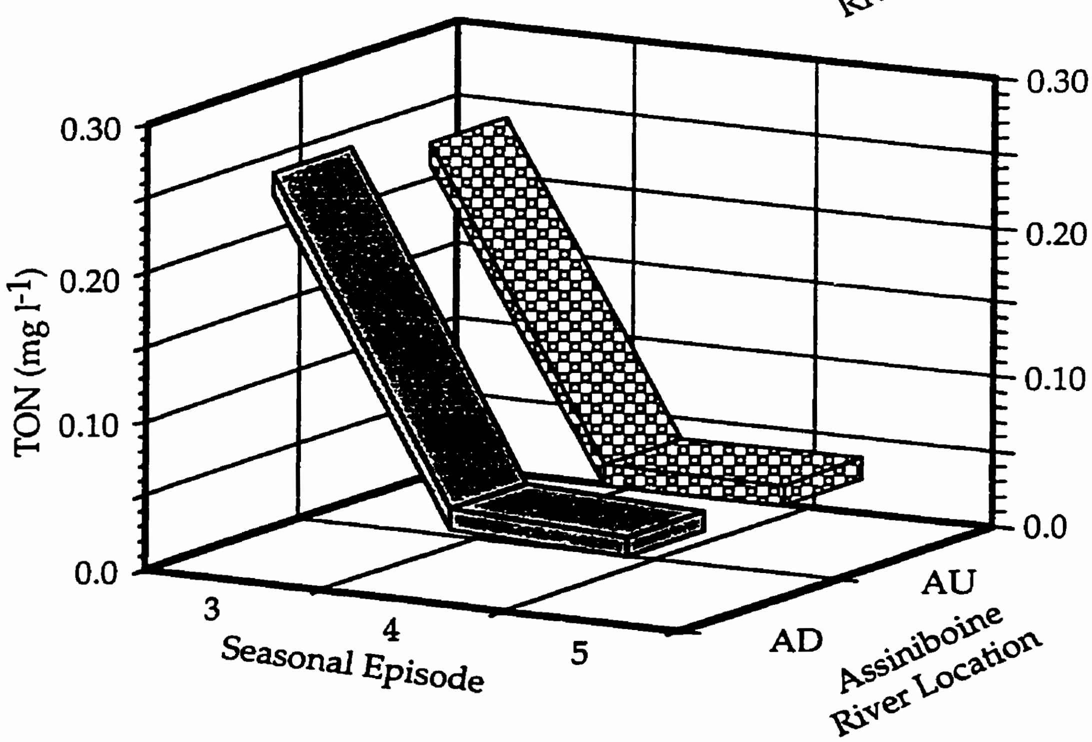


Figure 4.54 Three dimensional line plots of the average total oxidized nitrogen (TON) concentration in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

(a)

(b)

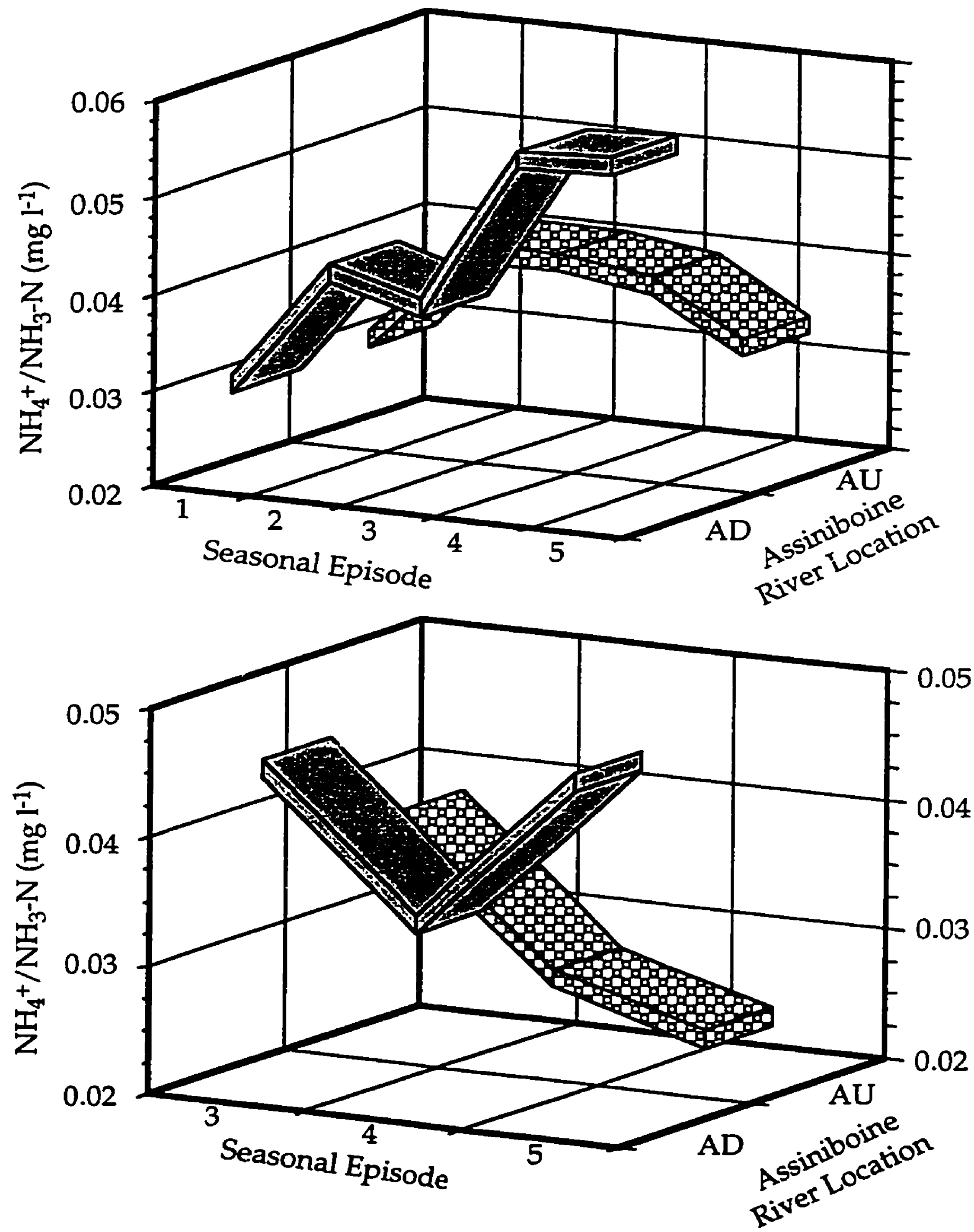


Figure 4.55 Three dimensional lin plots of the average total ammonia nitrogen (NH_4^+/NH_3-N) concentration in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

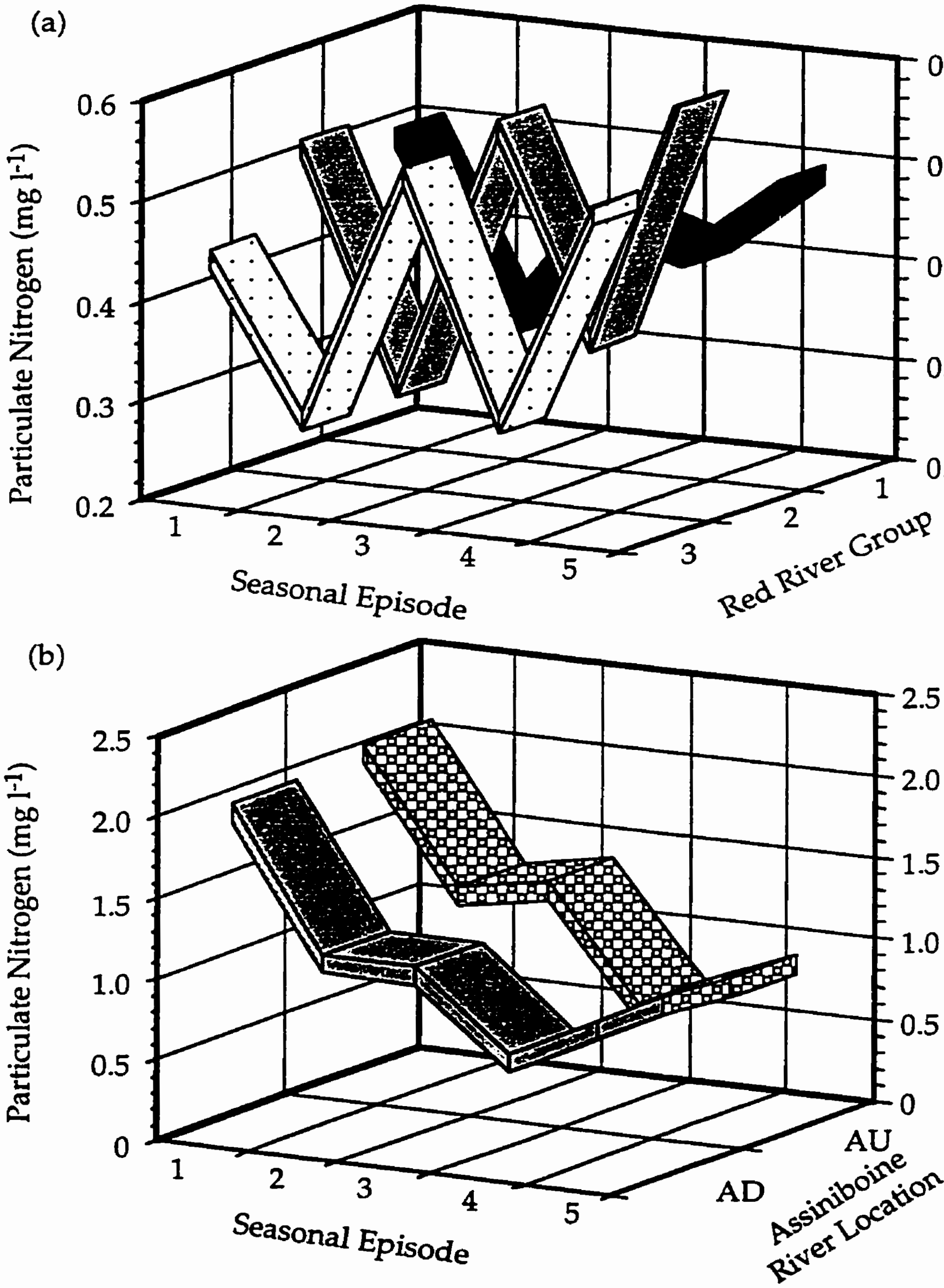


Figure 4.56 Three dimensional line plots of the average particulate nitrogen concentration found in each seasonal episode in 1994 in (a) the three Red River groups and (b) the Assiniboine locations. Refer to the text for a description of the Red River groups and Assiniboine locations.

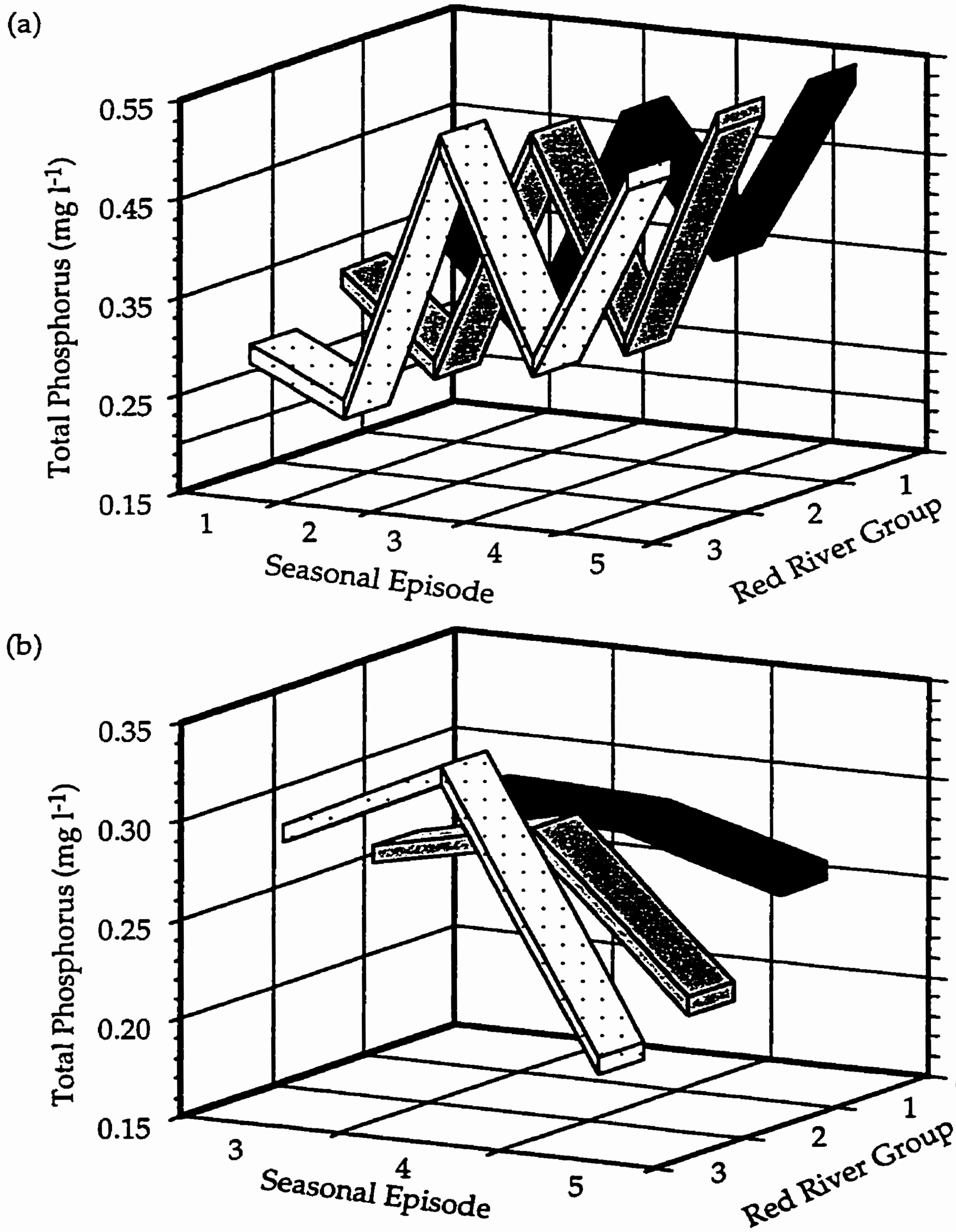


Figure 4.57 Three dimensional line plots of the average total phosphorus concentration found in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

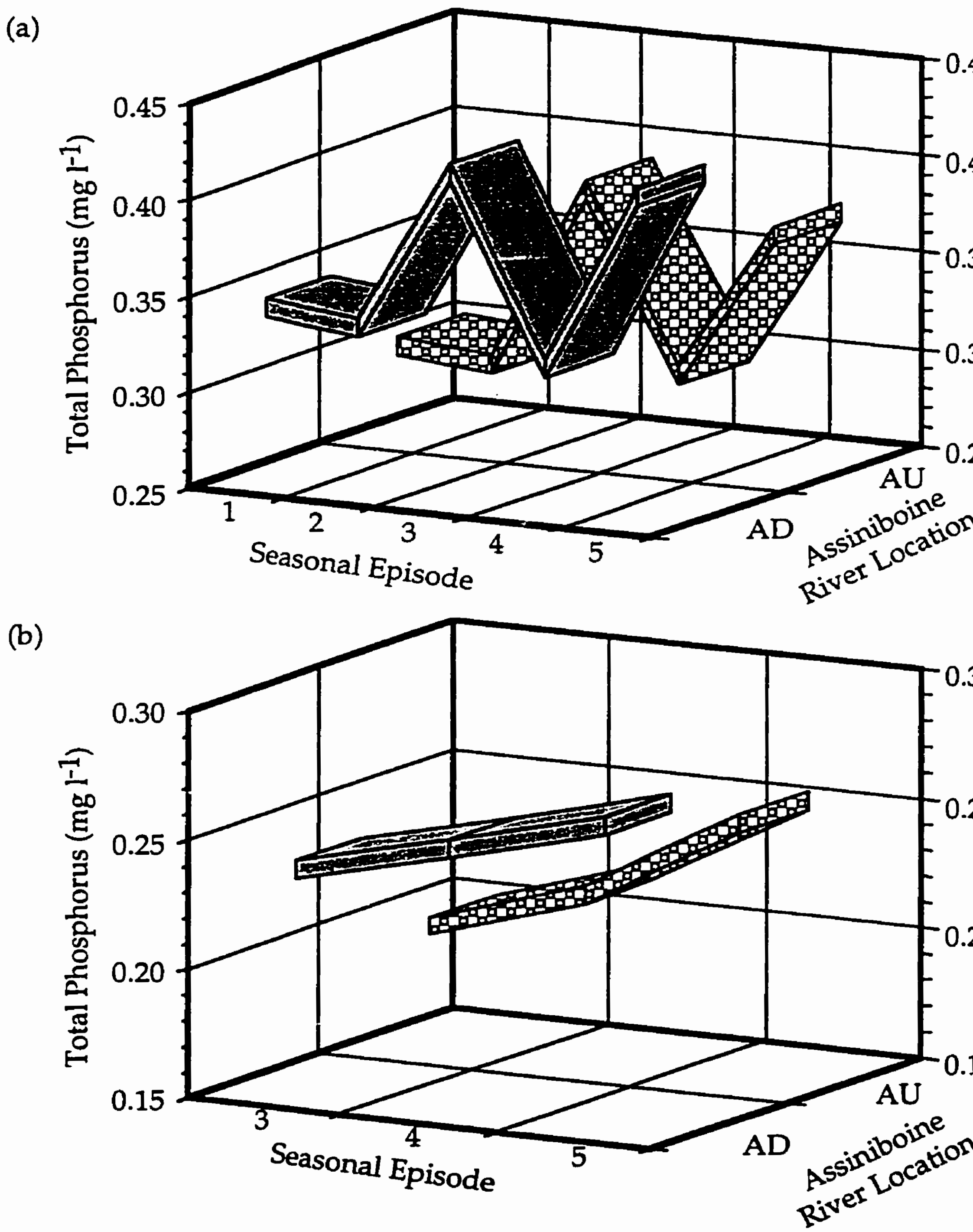


Figure 4.58 Three dimensional line plots of the average total phosphorus concentrations in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

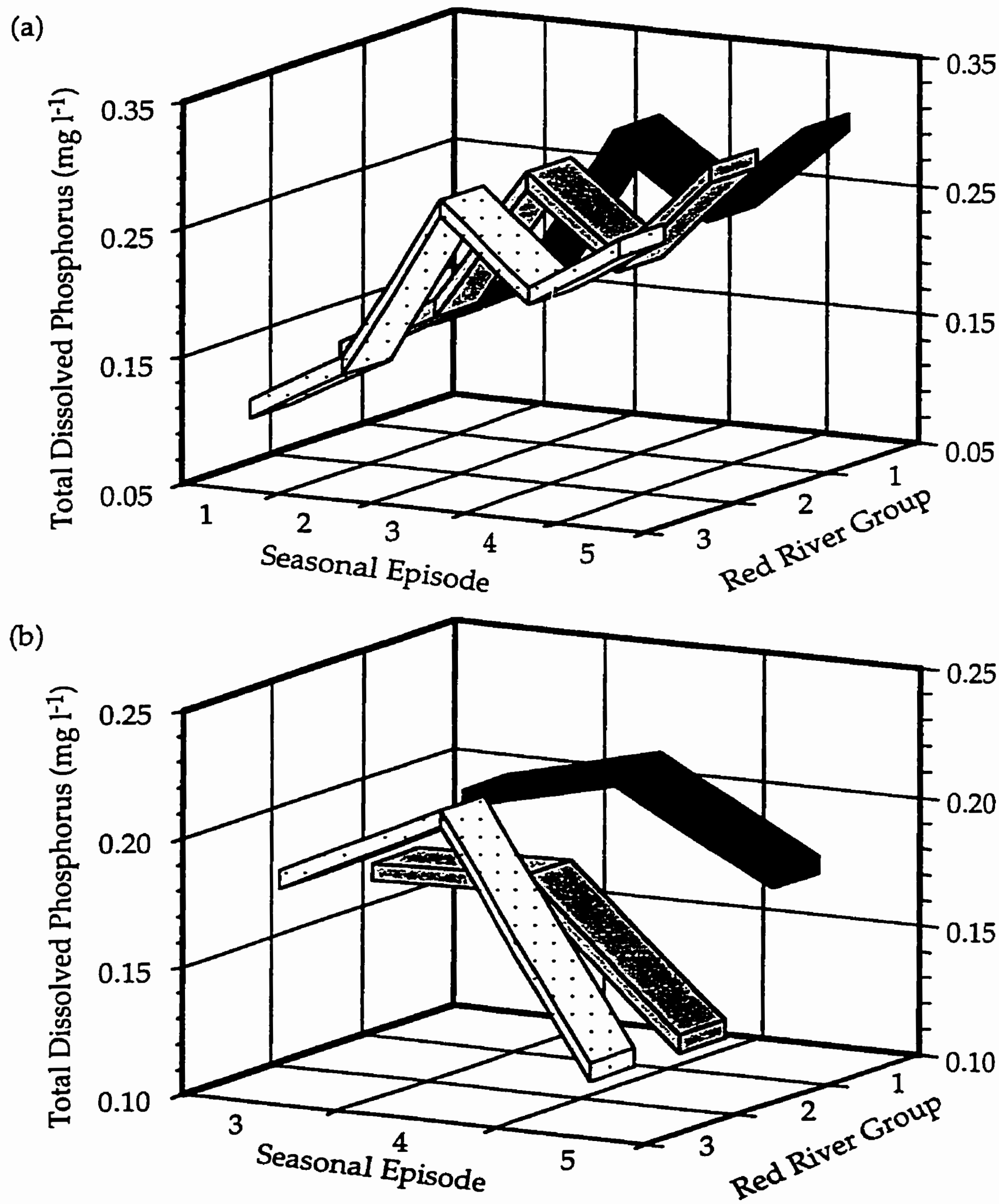


Figure 4.59 Three dimensional line plots of the average total dissolved phosphorus concentration found in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

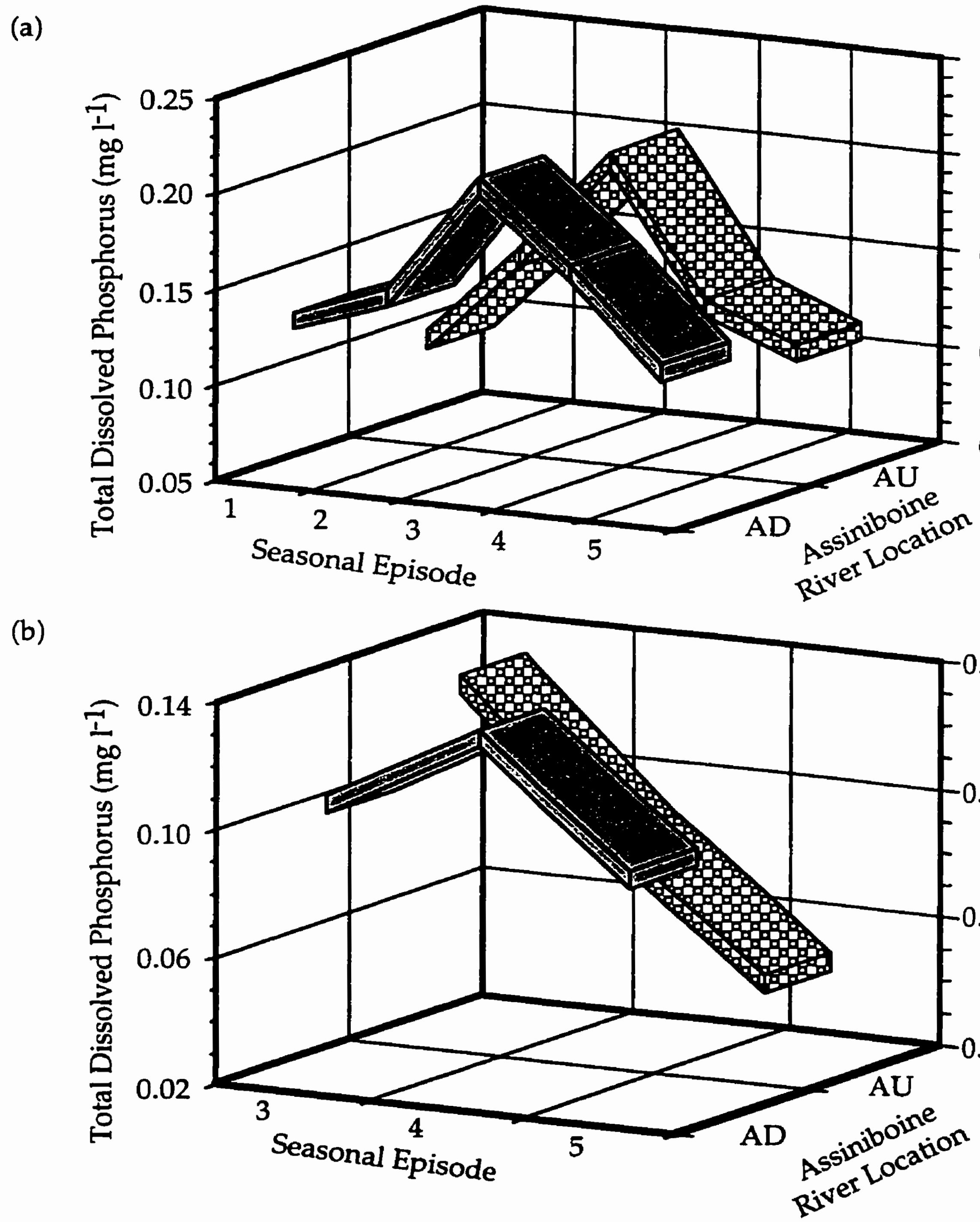
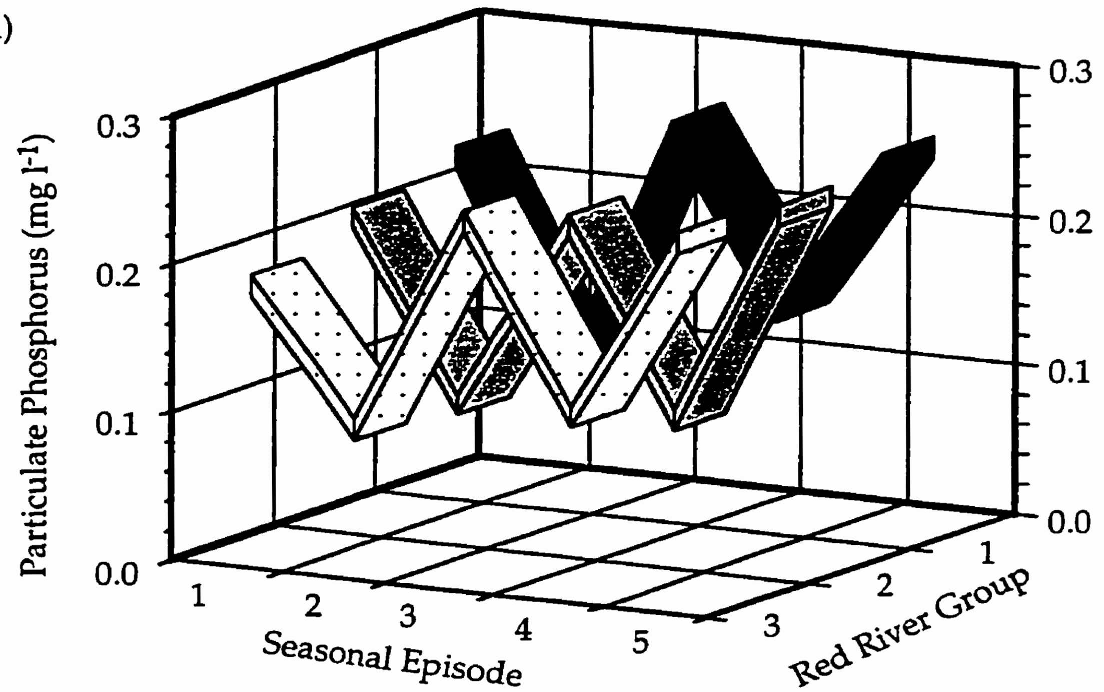


Figure 4.60 Three dimensional line plots of the average total dissolved phosphorus concentration in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

(a)



(b)

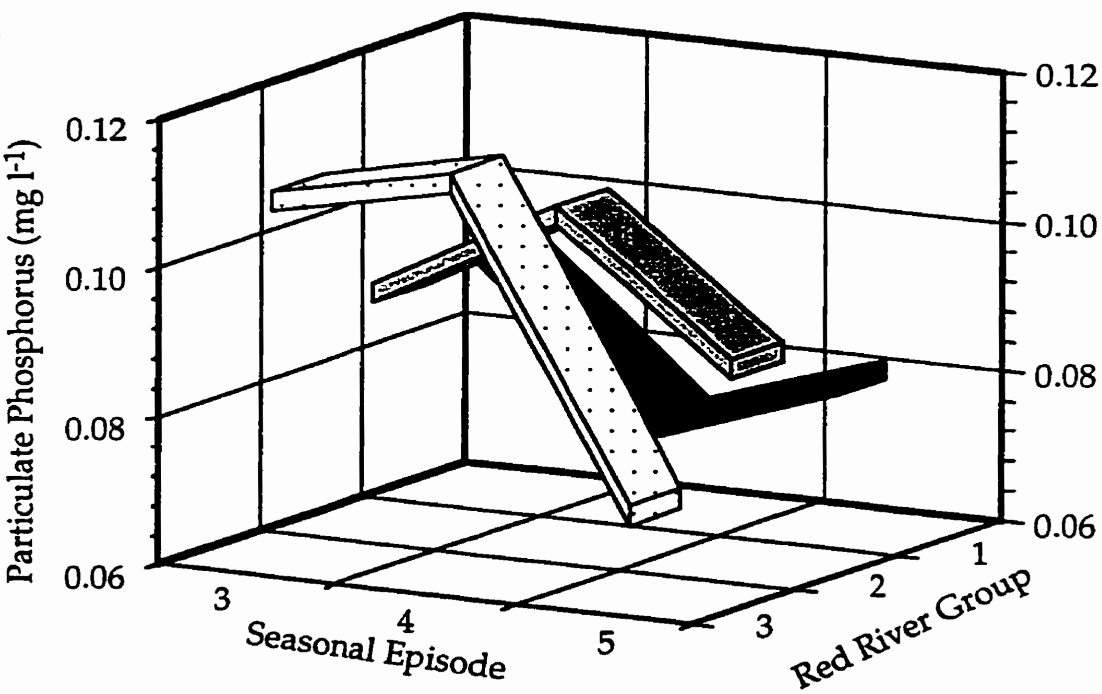


Figure 4.61 Three dimensional line plots of the average particulate phosphorus concentration found in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

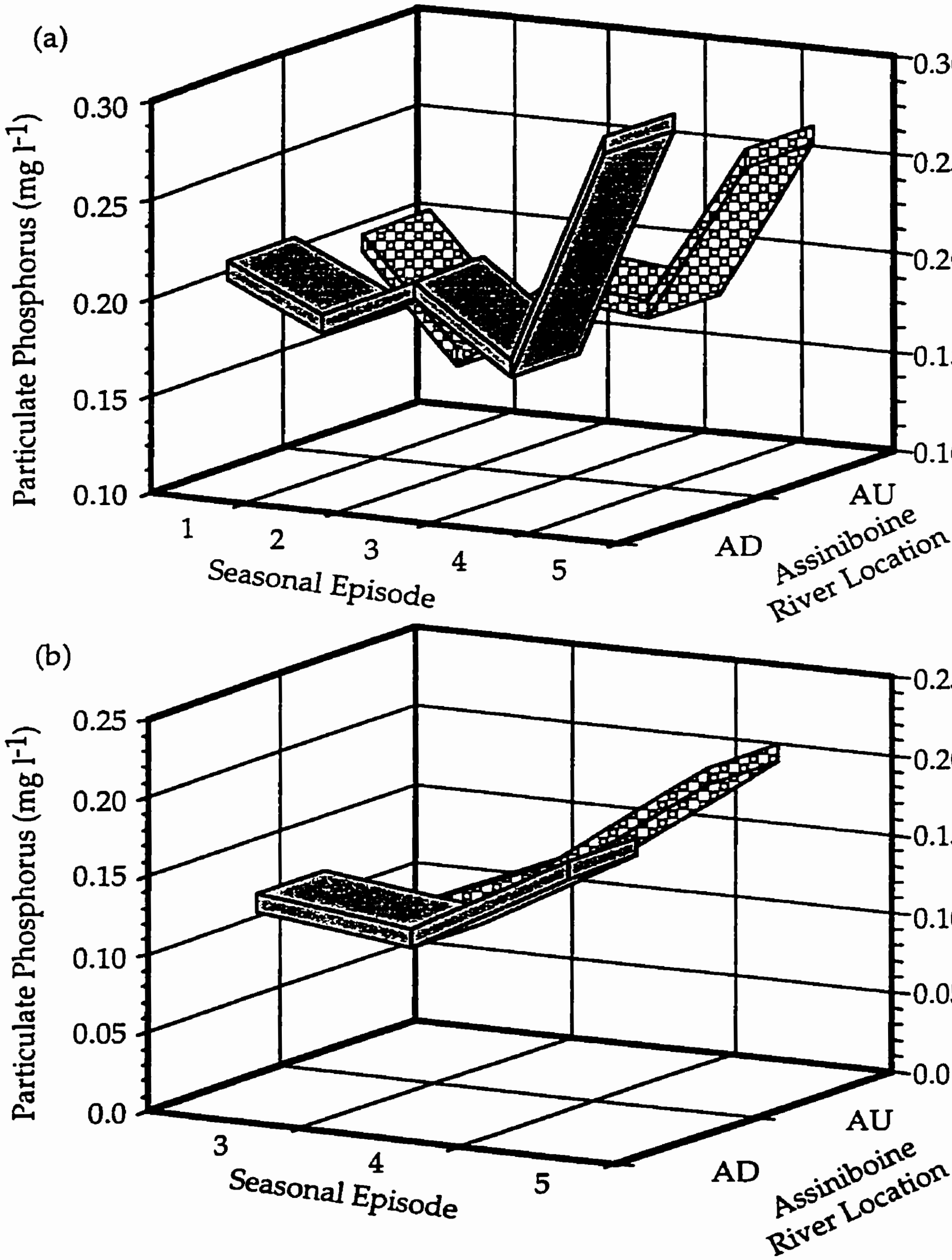
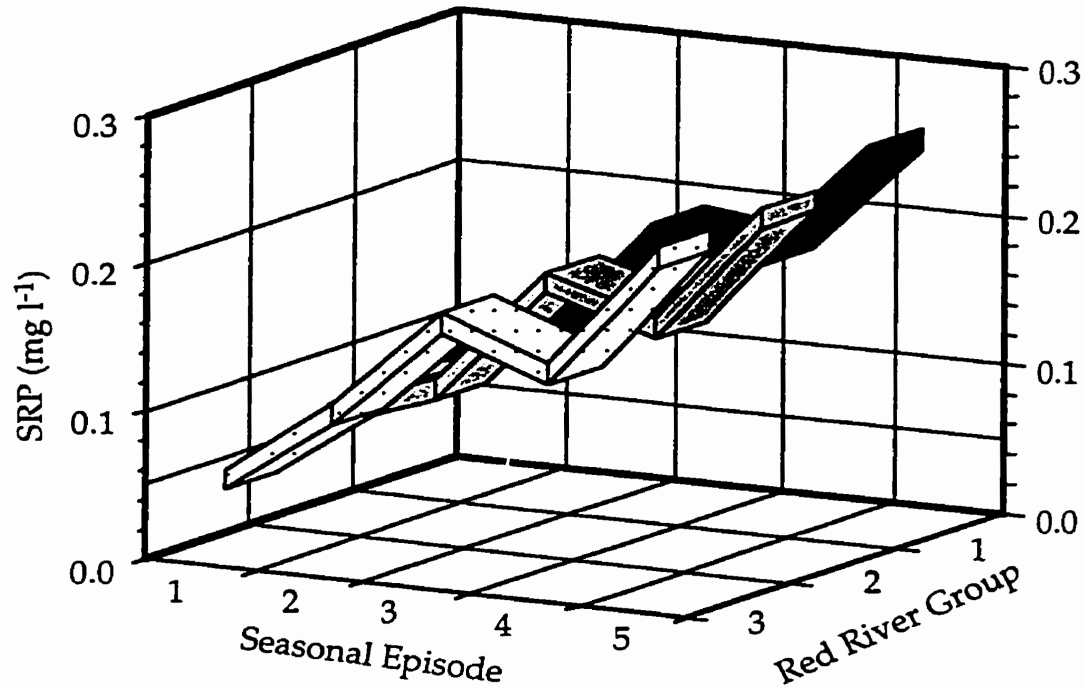


Figure 4.62 Three dimensional line plots of the average particulate phosphorus concentration in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

(a)



(b)

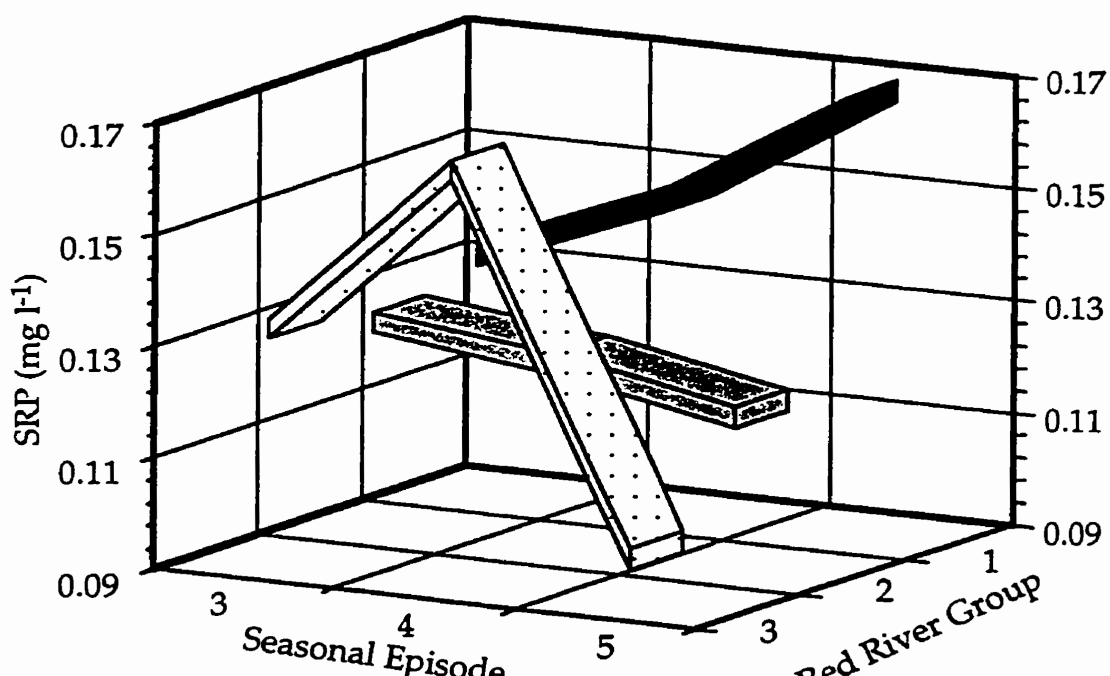


Figure 4.63 Three dimensional line plots of the average soluble reactive phosphorus (SRP) concentration found in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

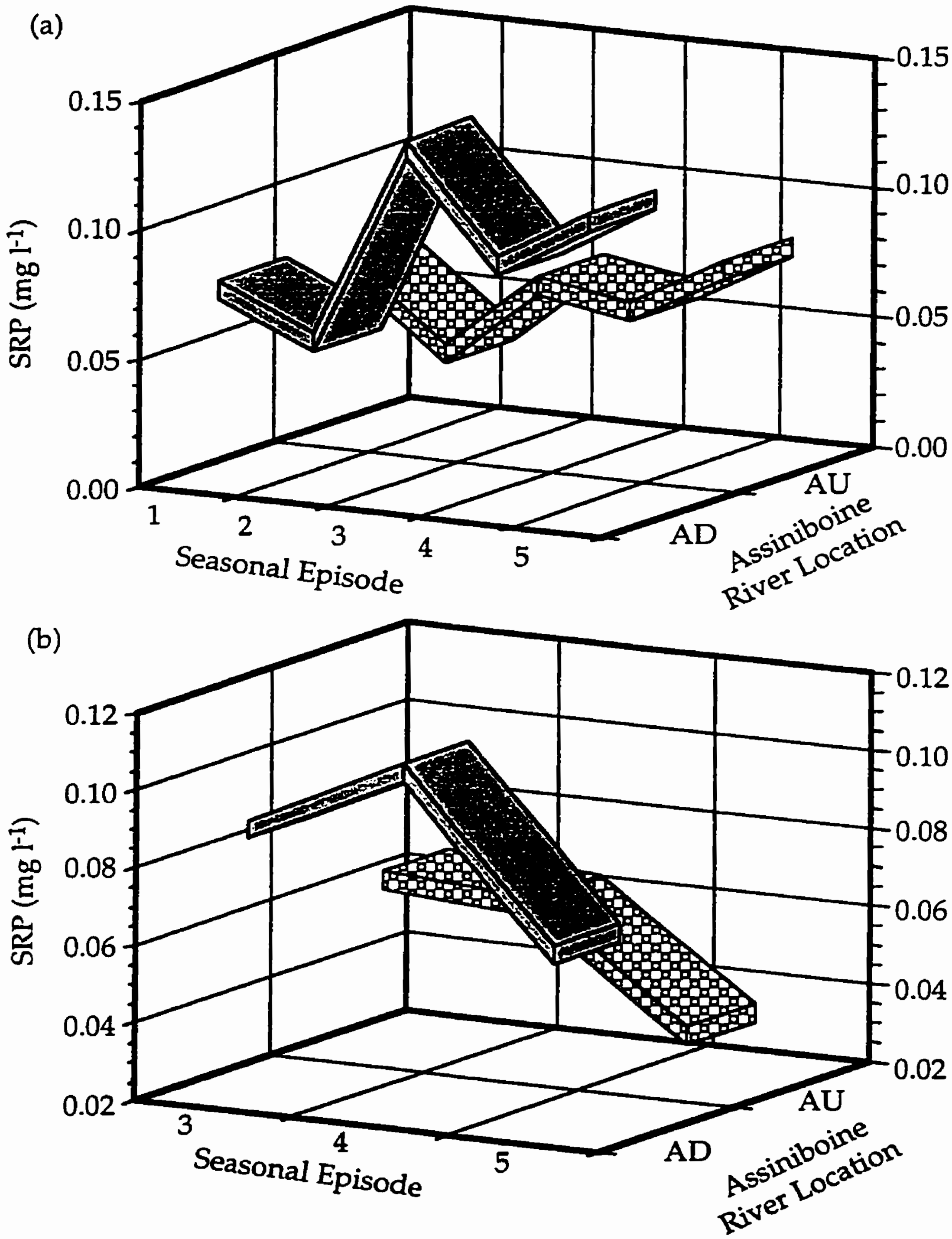
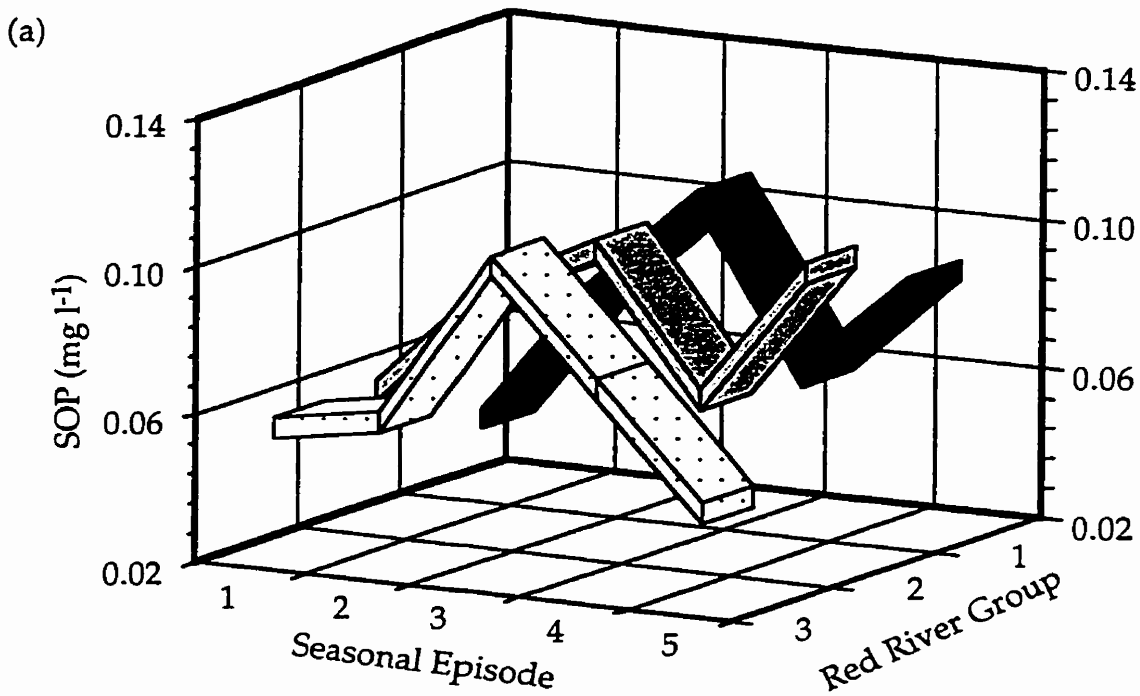


Figure 4.64 Three dimensional line plots of the average soluble reactive phosphorus (SRP) in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.



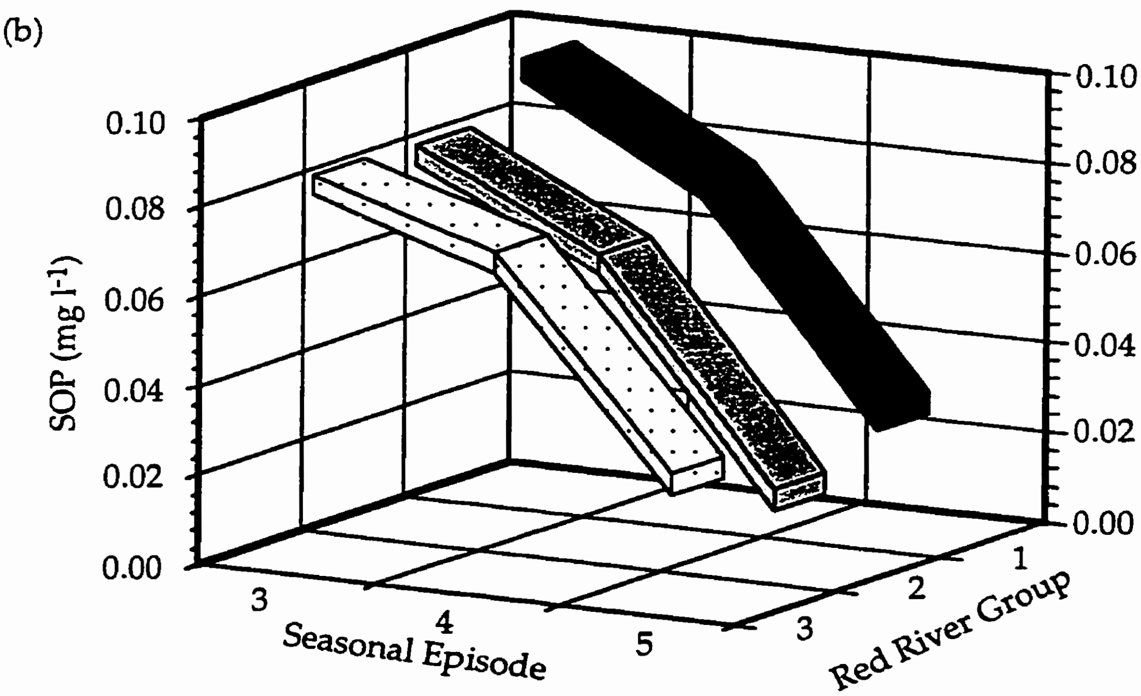


Figure 4.65 Three dimensional line plots of the average soluble organic phosphorus (SOP) concentration found in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

(a)

(b)

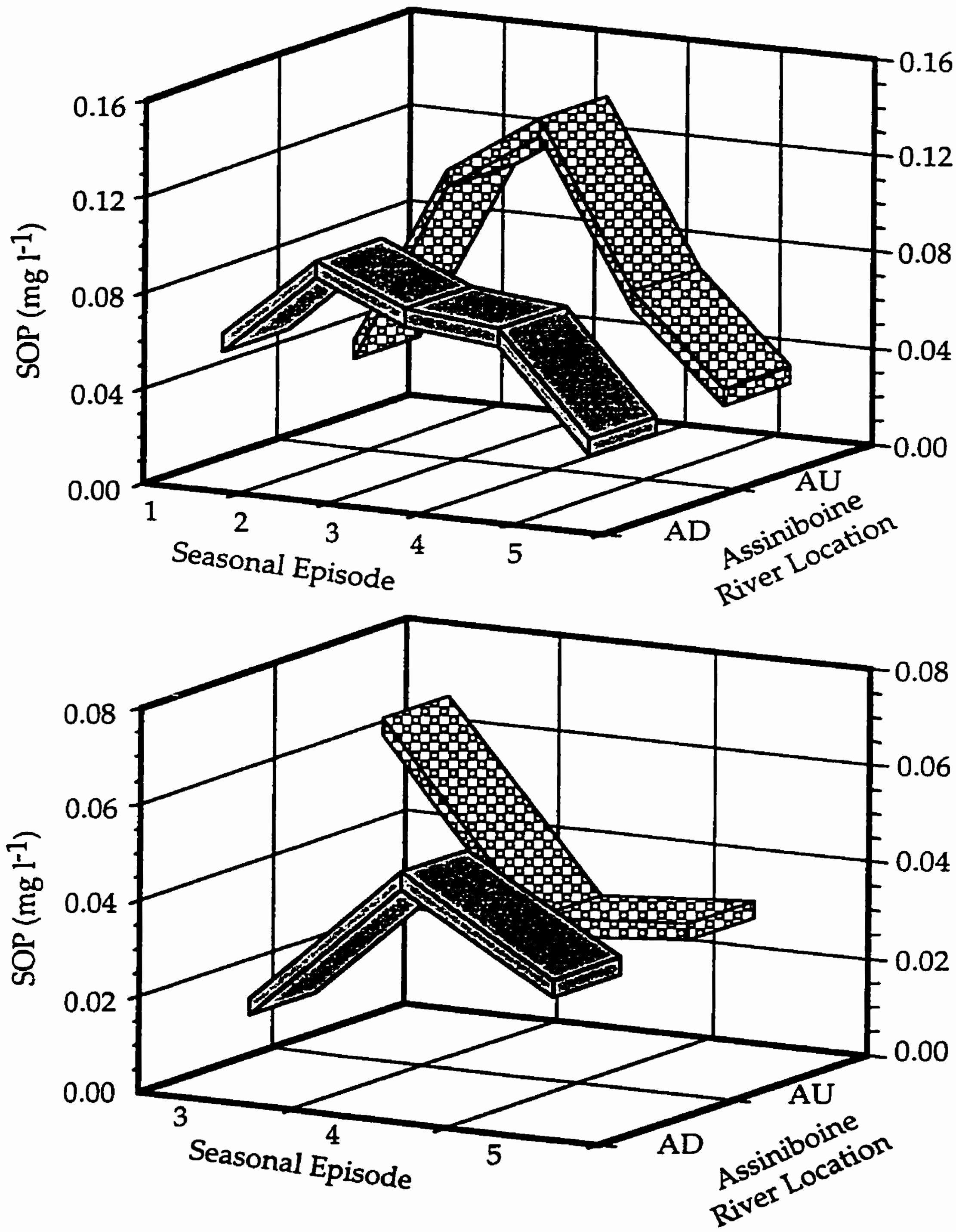


Figure 4.66 Three dimensional line plots of the average soluble organic phosphorus (SOP) in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

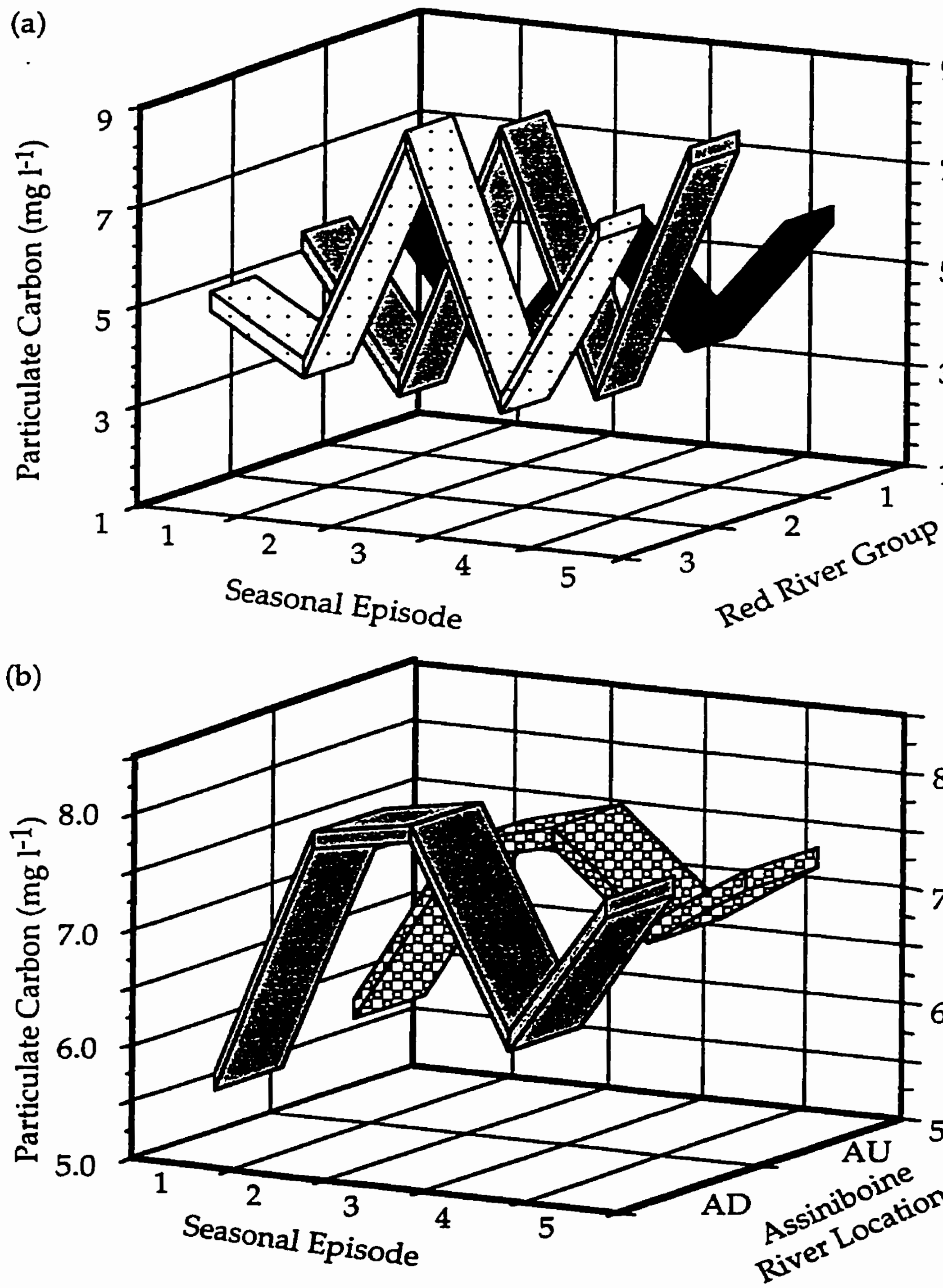


Figure 4.67 Three dimensional line plots of the average particulate carbon concentration found in each seasonal episode in 1994.
(a) In each of the three Red River groups and (b) in the Assiniboine locations. Refer to the text for a description of the Red River groups and Assiniboine locations.

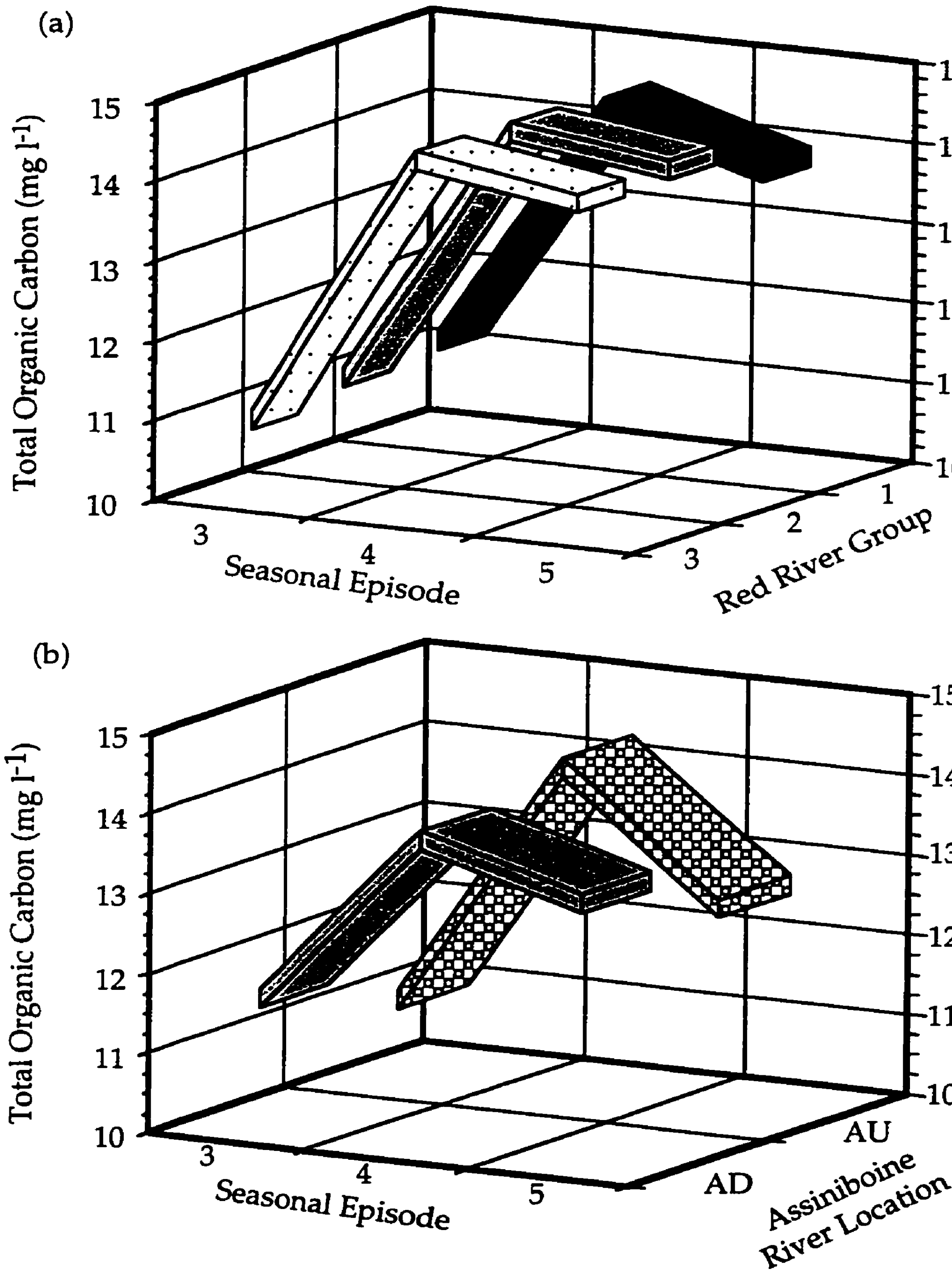
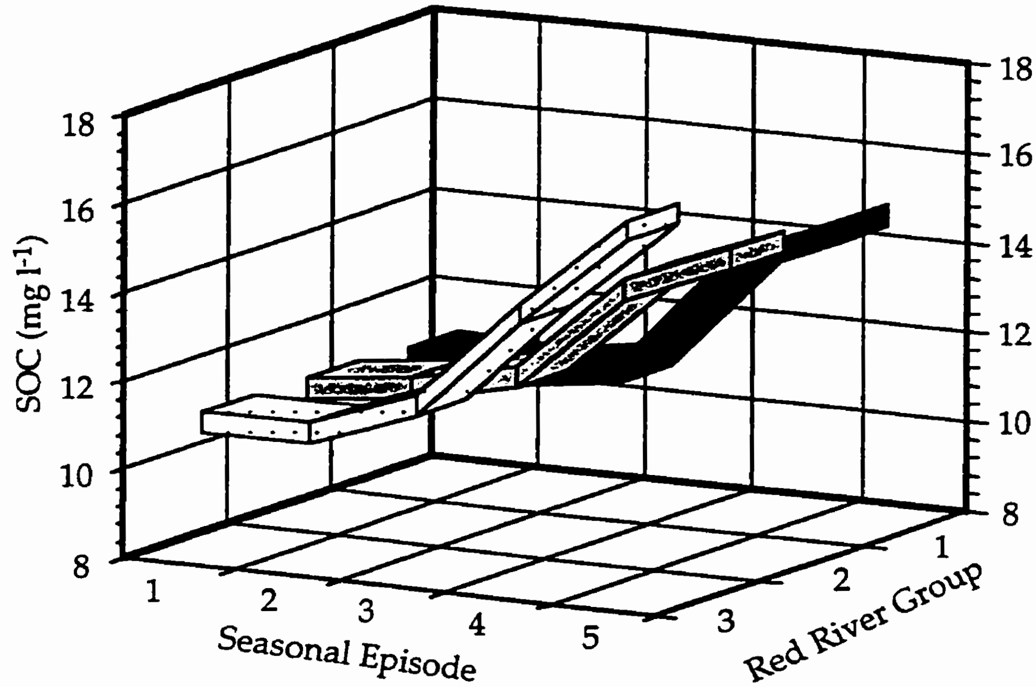


Figure 4.68 Three dimensional line plots of the average total organic carbon (TOC) concentration found in each seasonal episode in 1994 in (a) the three Red River groups and (b) the Assiniboine River locations. Refer to the text for a description of Red River groups and Assiniboine River locations.

(a)



(b)

Figure 4.69 Three dimensional line plots of the average soluble organic carbon (SOC) concentration found in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

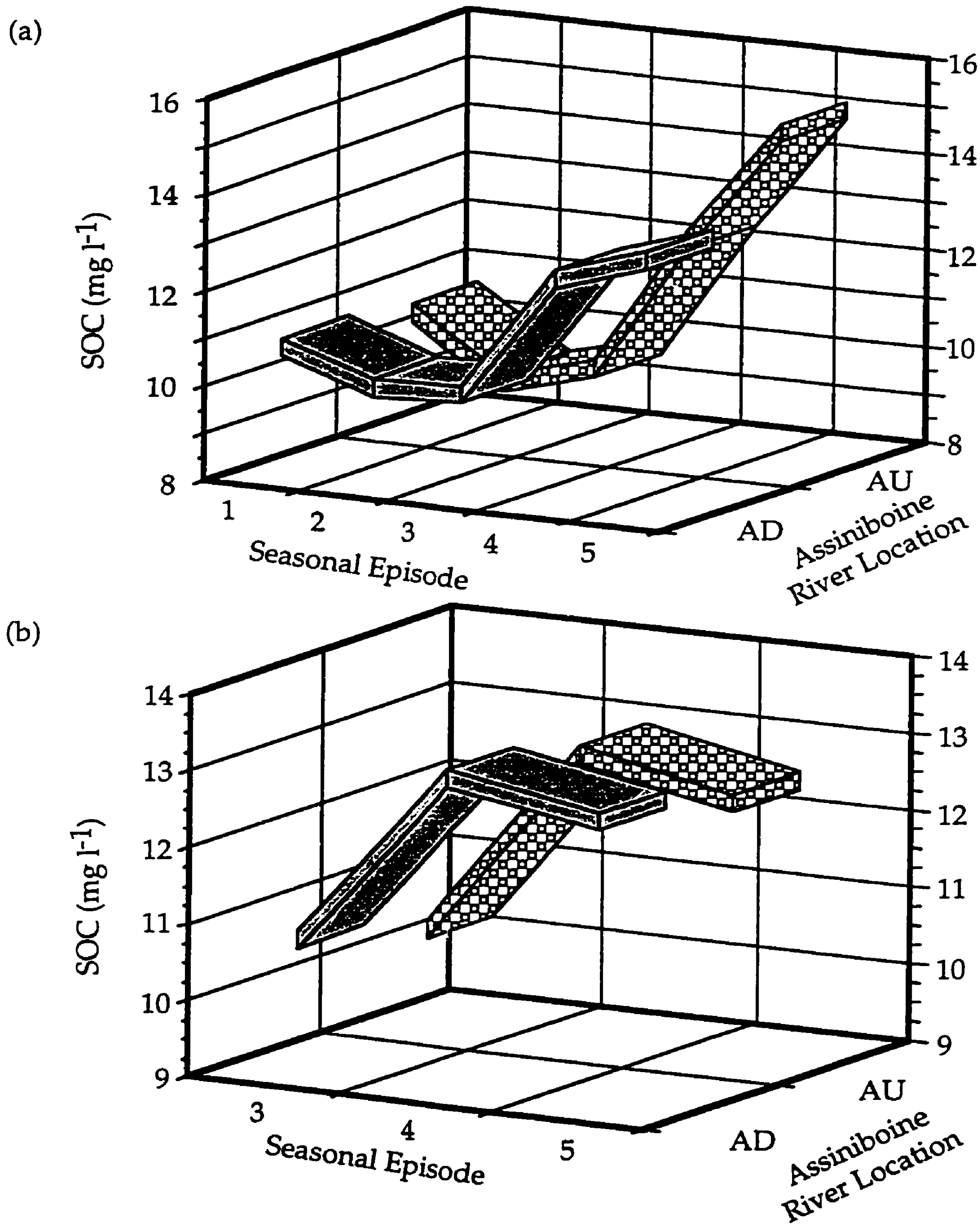


Figure 4.70 Three dimensional line plots of the average soluble organic carbon (SOC) concentration in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

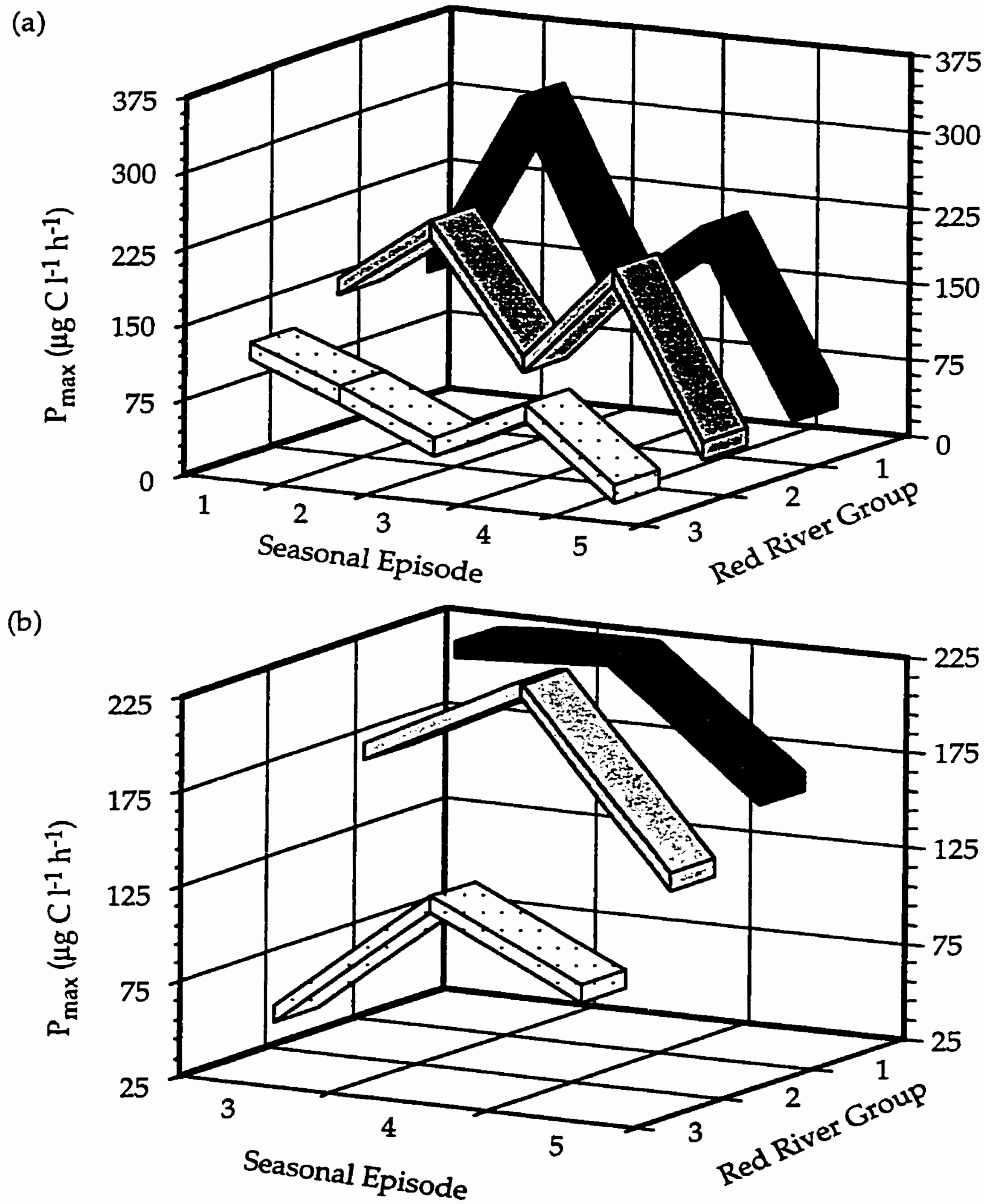


Figure 4.71 Three dimensional line plots of the average P_{max} measurement found in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

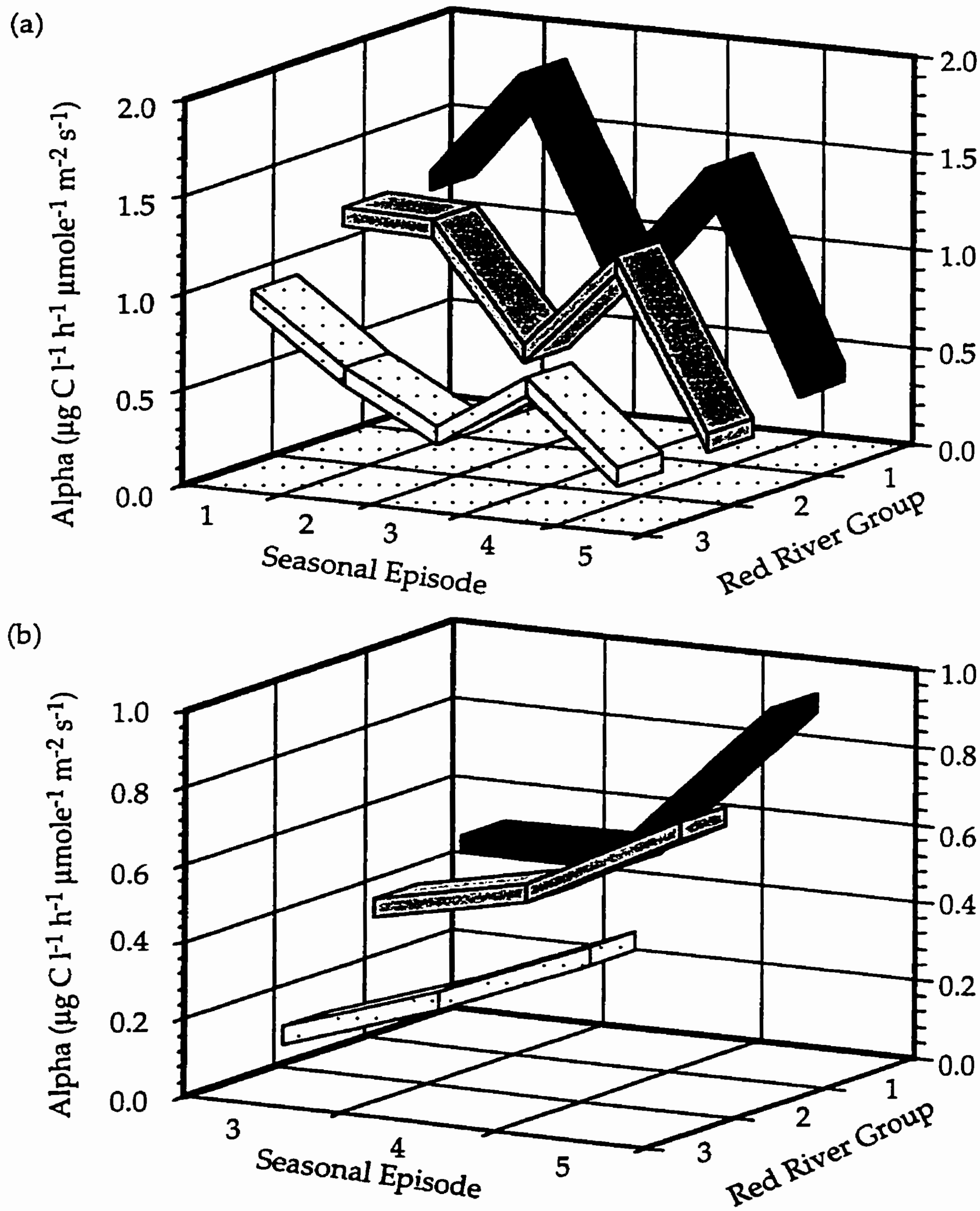


Figure 4.72 Three dimensional line plots of the average alpha measurment observed in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

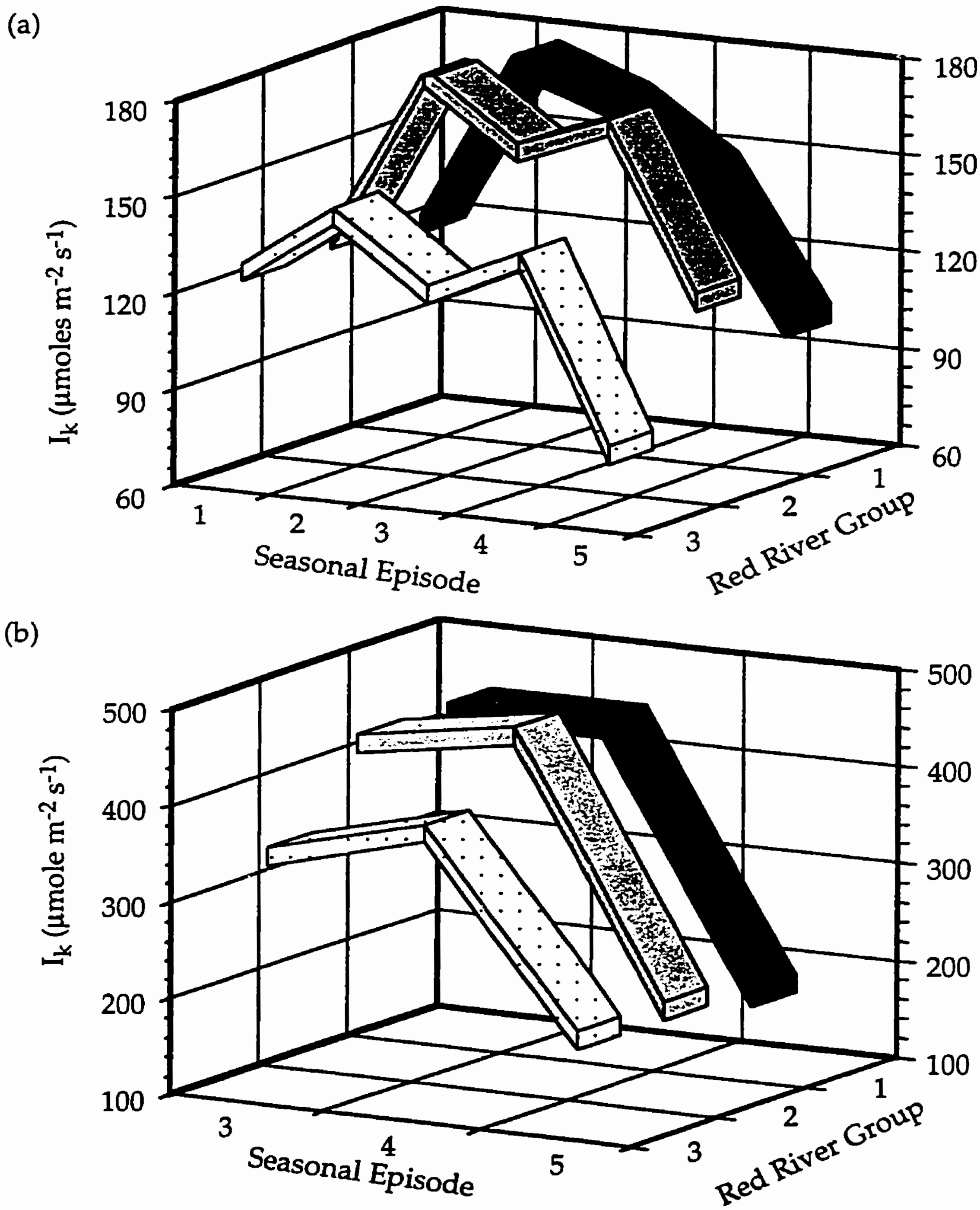


Figure 4.73 Three dimensional line plots of the average I_k irradiance encountered in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

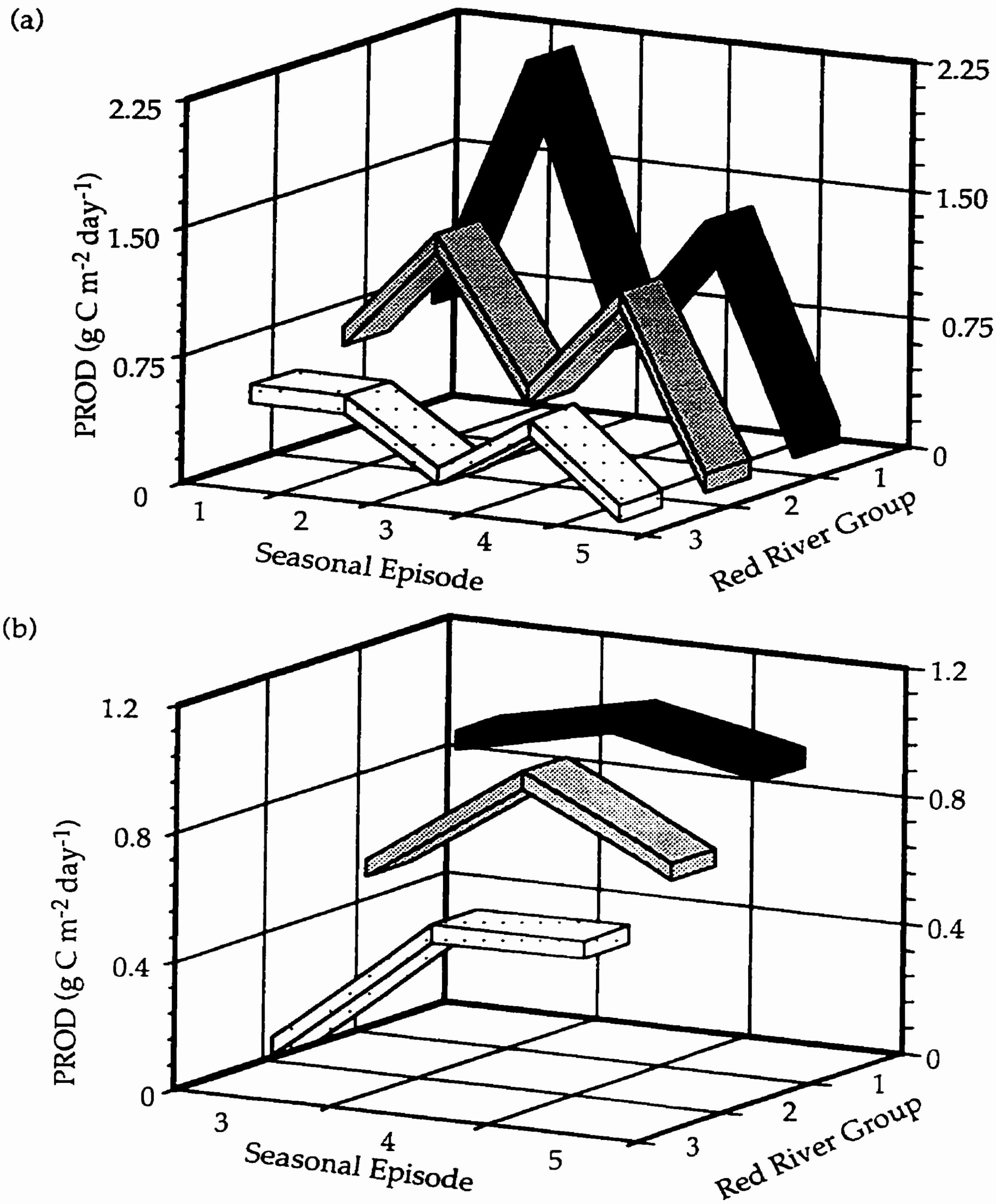
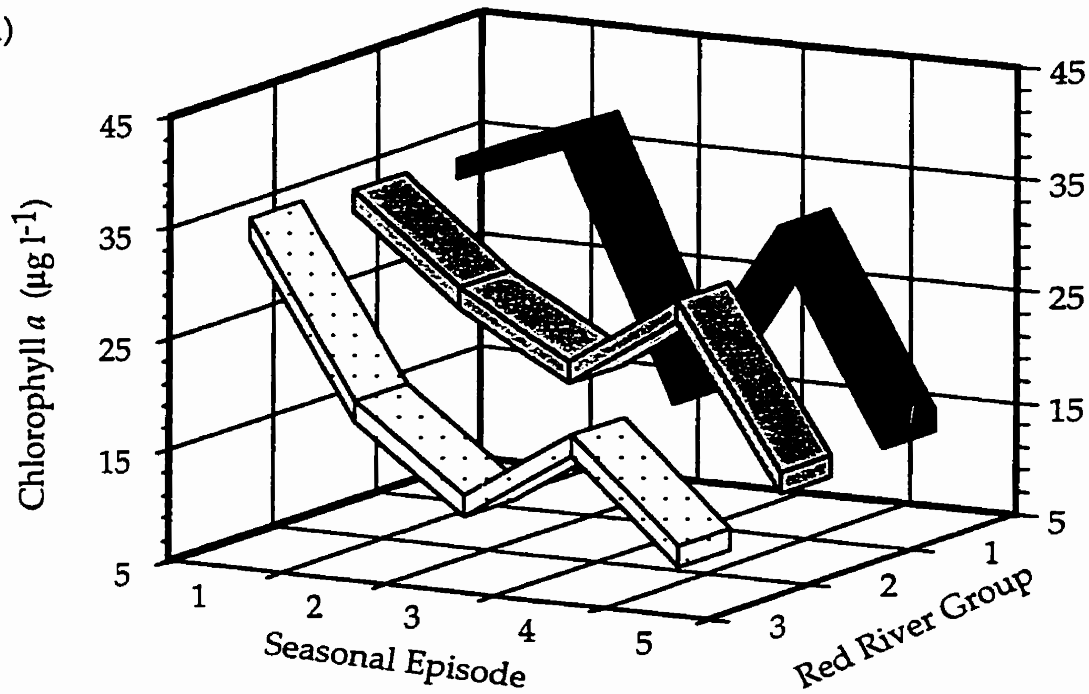


Figure 4.74 Three dimensional line plots of the average estimated daily phytoplankton productivity (PROD) measured in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

(a)



(b)

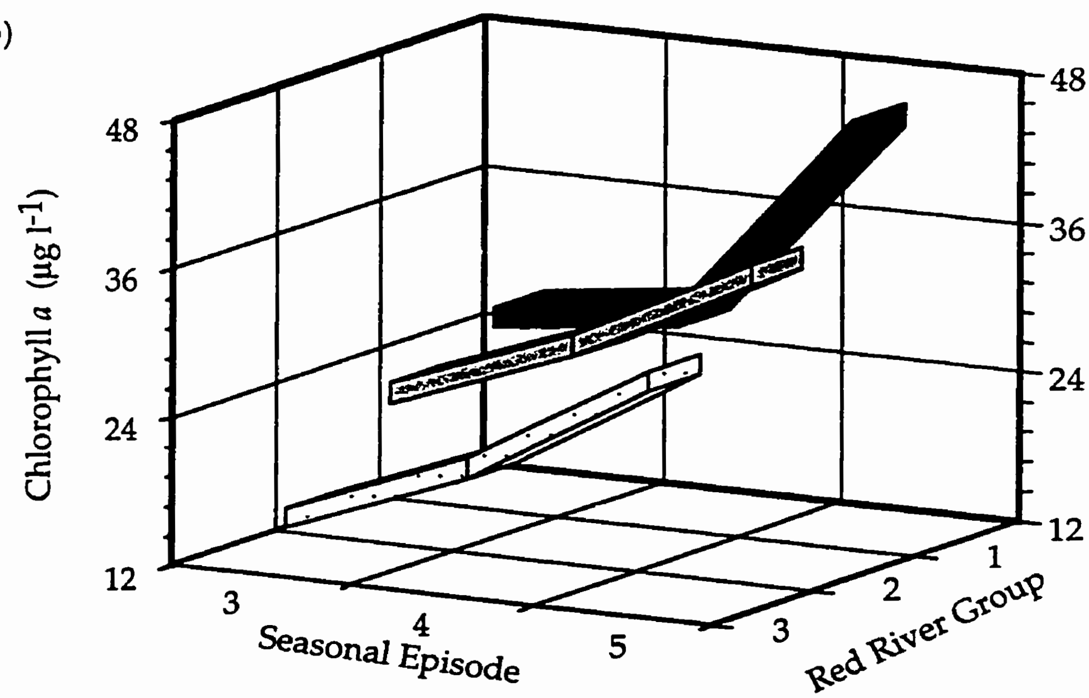


Figure 4.75 Three dimensional line plots of the average phytoplankton chlorophyll *a* concentration found in each seasonal episode in each of the three Red River groups in (a) 1994 and (b) 1995. Refer to the text for a description of the Red River groups.

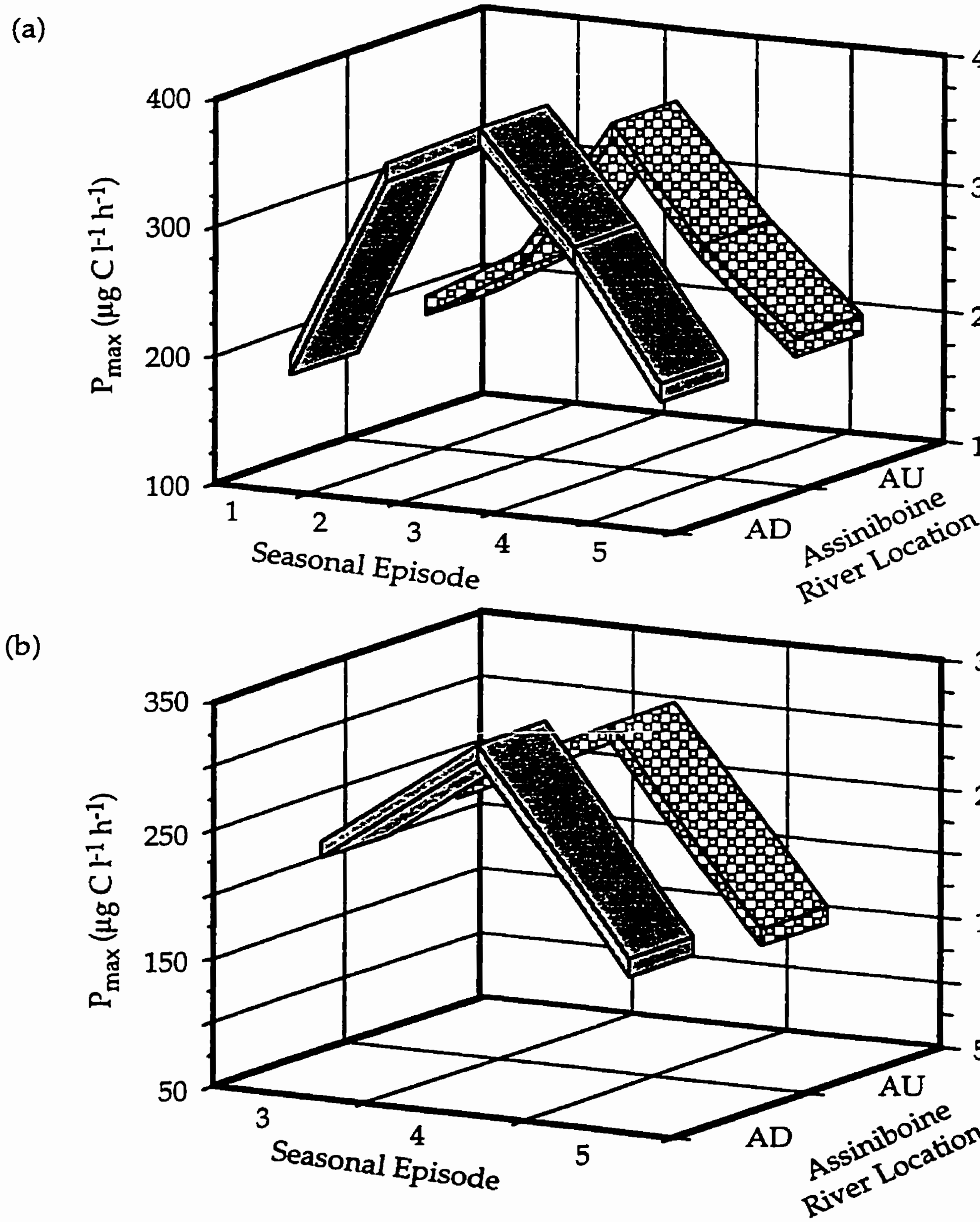


Figure 4.76 Three dimensional line plots of the average P_{max} measurement found in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

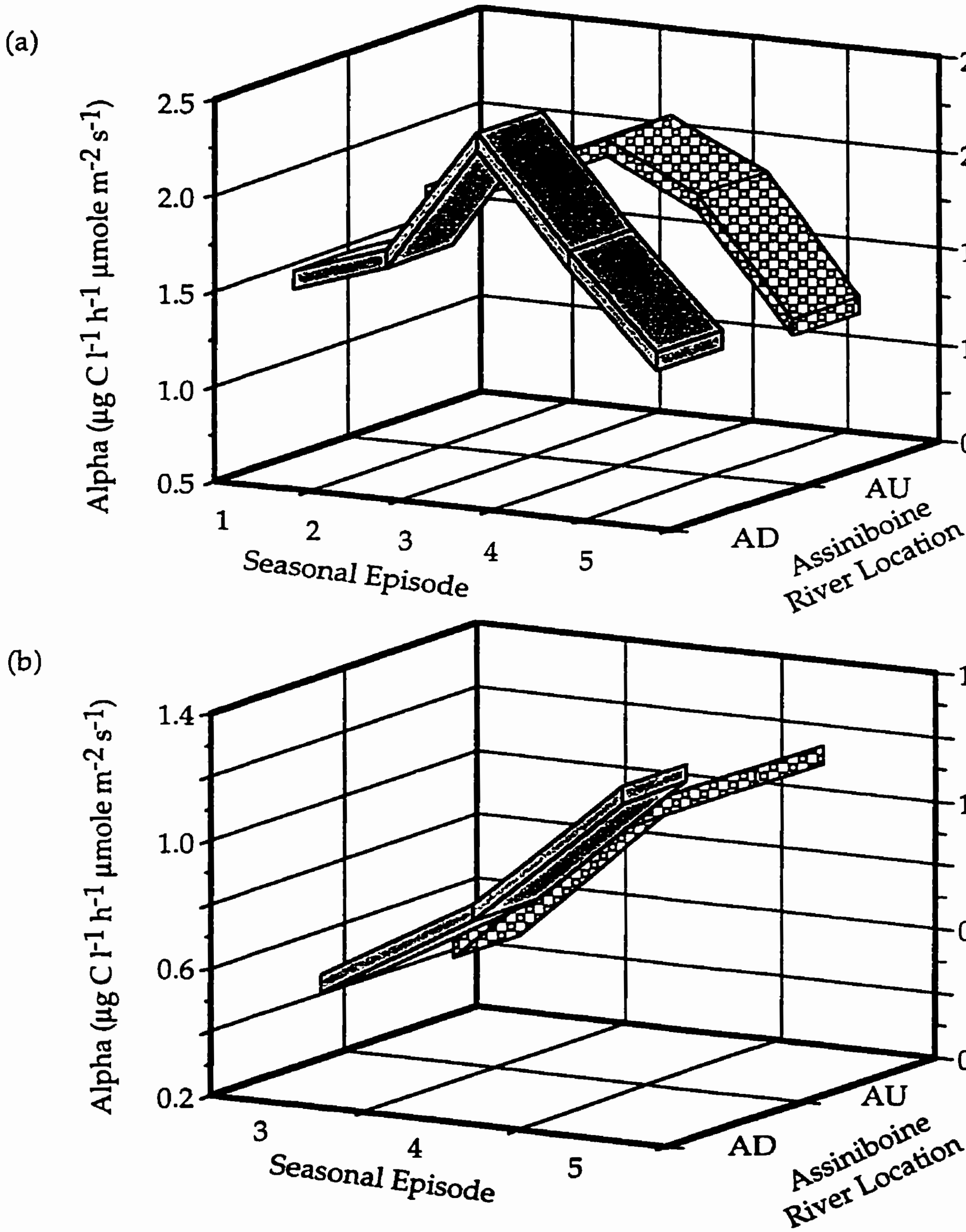


Figure 4.77 Three dimensional line plots of the average alpha measurement observed in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

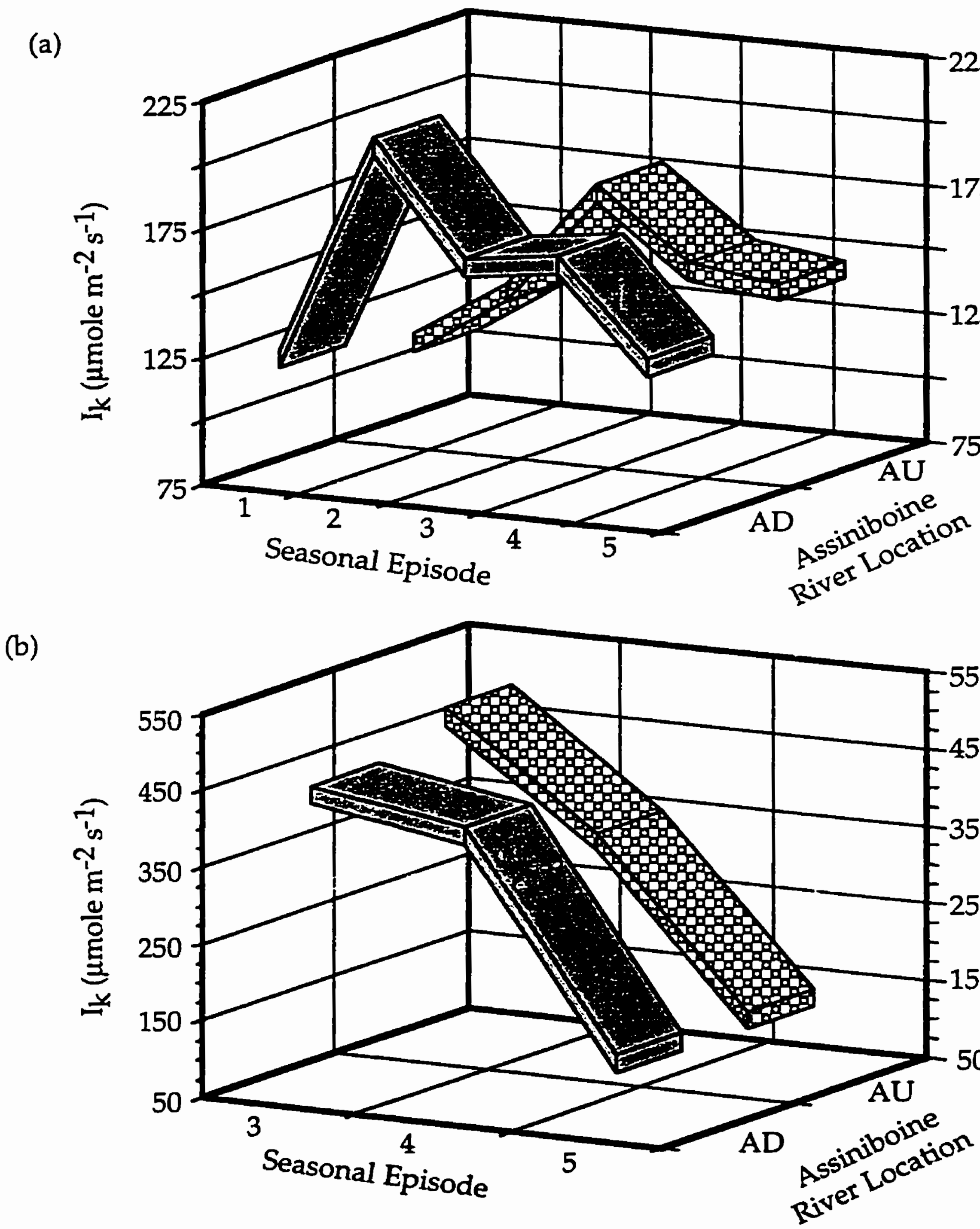
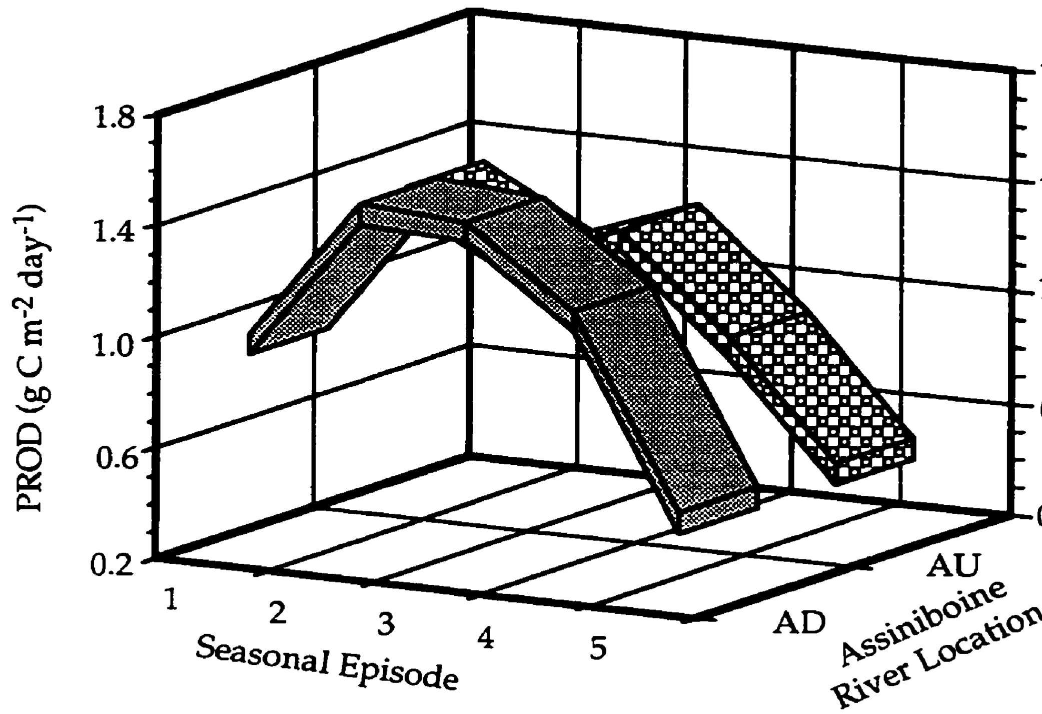


Figure 4.78 Three dimensional line plots of the average I_k irradiance encountered in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

(a)



(b)

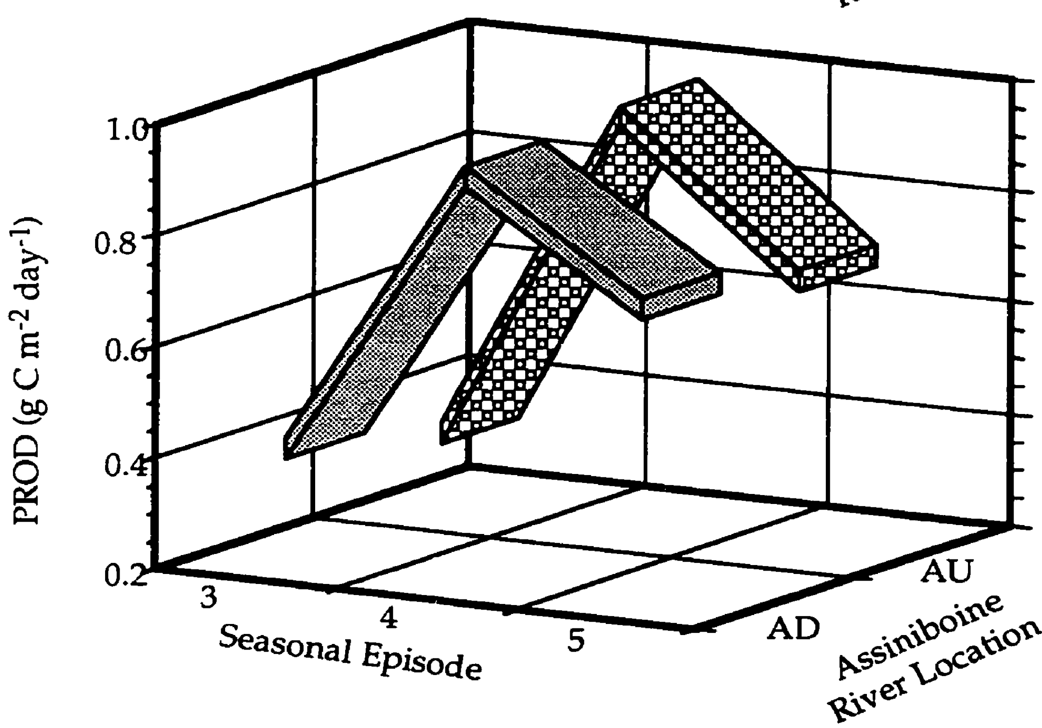


Figure 4.79 Three dimensional line plots of the average estimated daily phytoplankton productivity (PROD) in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

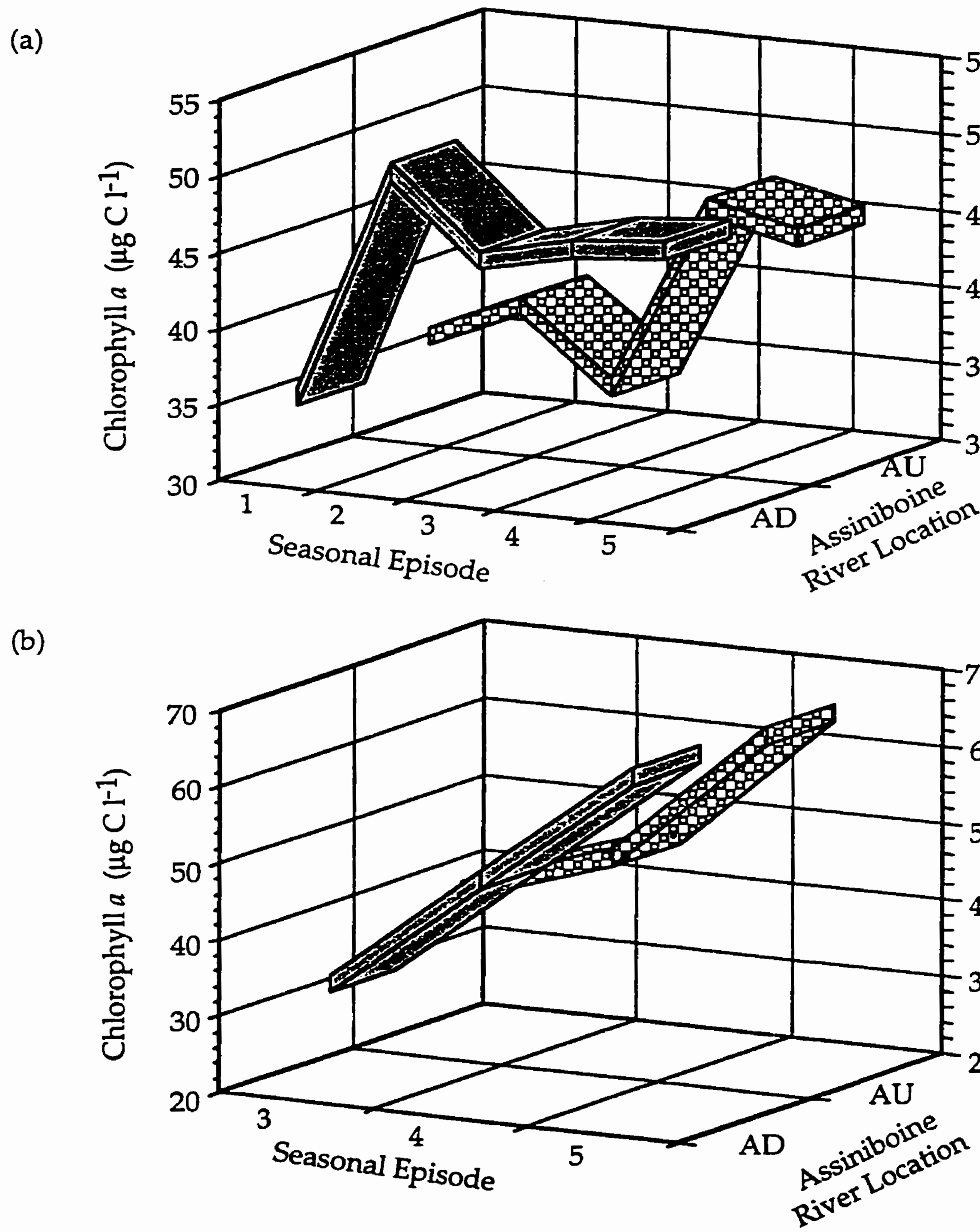


Figure 4.80 Three dimensional line plots of the average phytoplankton chlorophyll *a* concentration in each seasonal episode in the two Assiniboine locations in (a) 1994 and (b) 1995. Refer to the text for a description of the Assiniboine River locations.

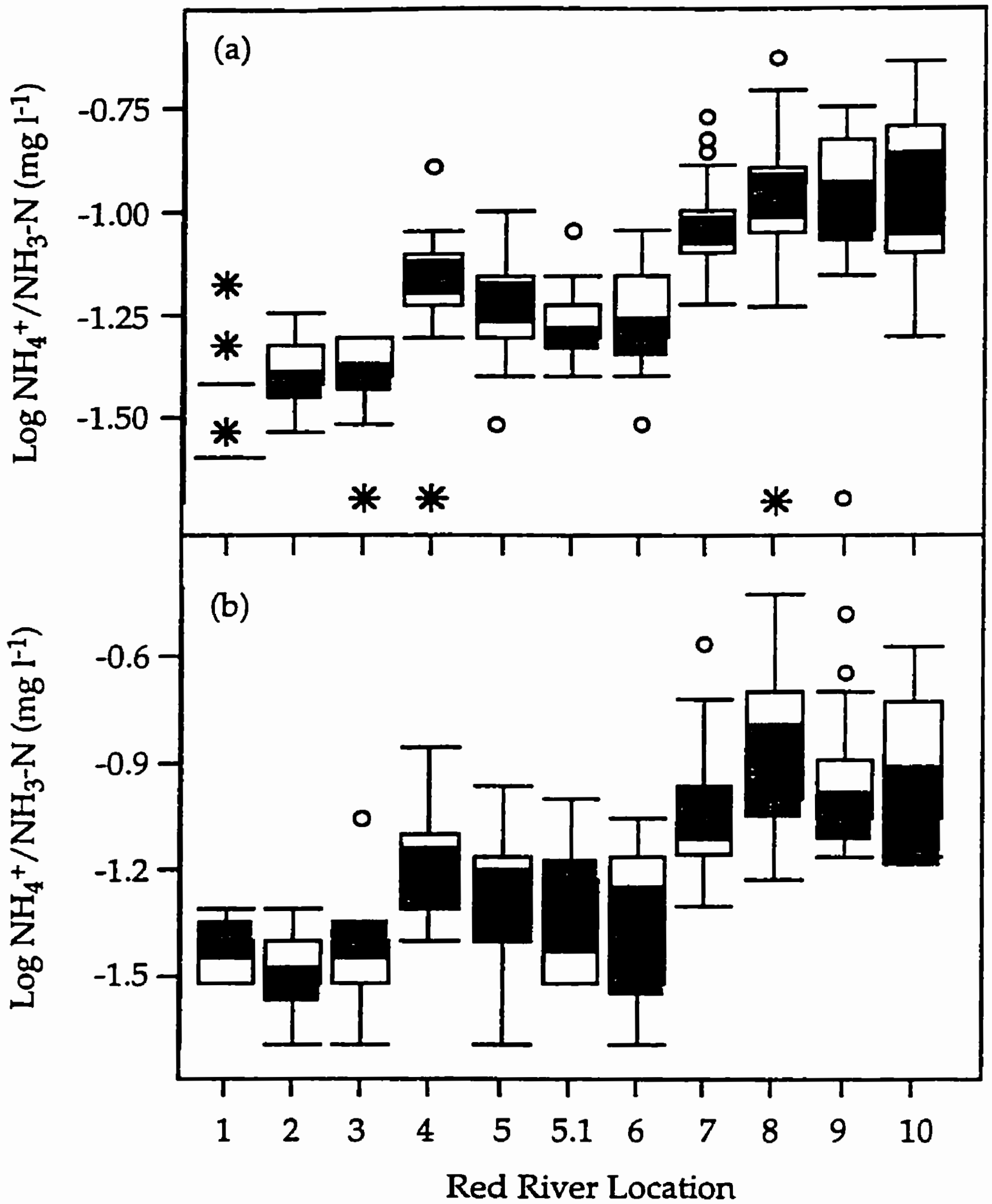


Figure 4.81 Boxplots and 95 % confidence intervals for concentrations of NH_4^+/NH_3-N in the Red River during (a) 1994 and (b) 1995. Locations 1 to 4 correspond to Red River group 3; 5 to 6 to Red River group 2 and 7 to 10 Red River group 1.

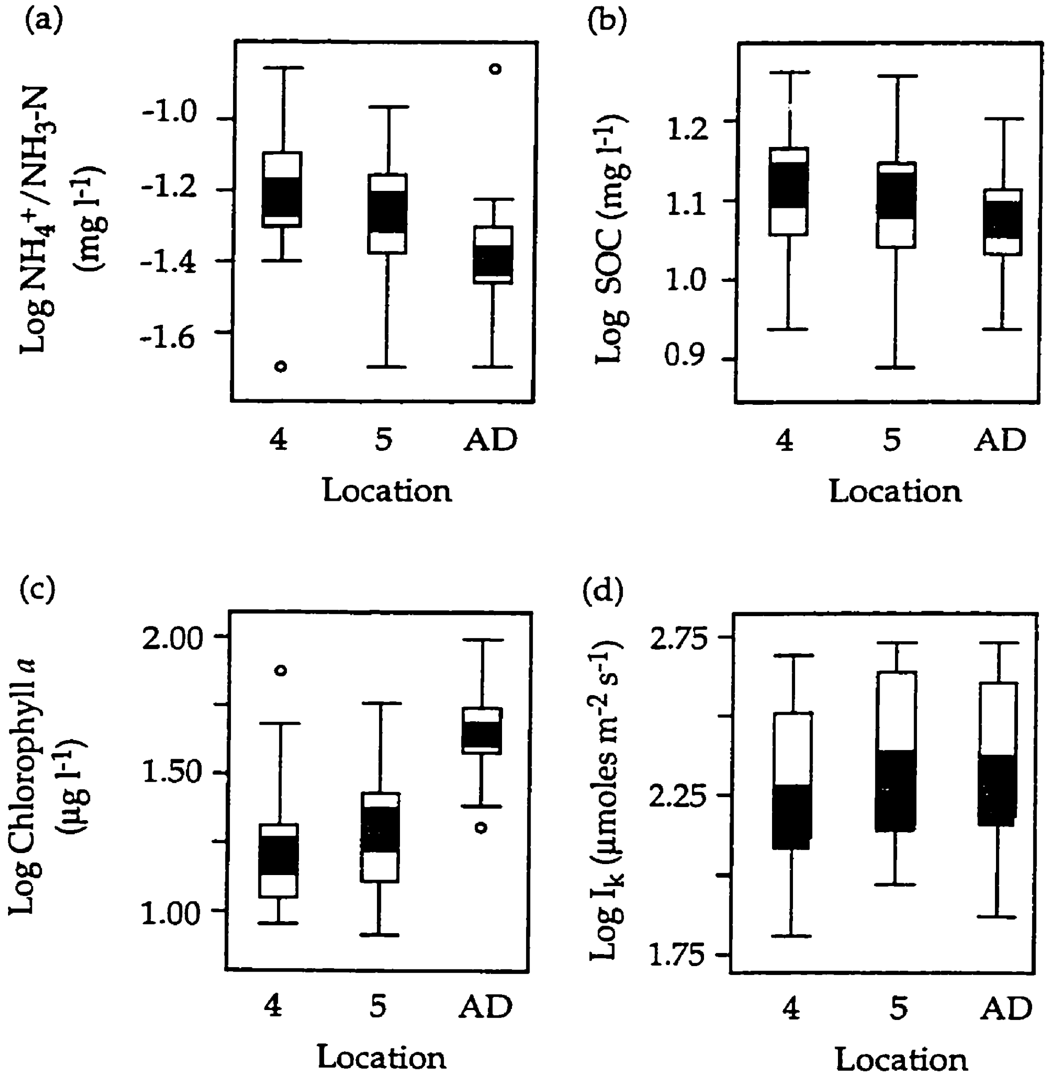


Figure 4.82 Boxplots of (a) NH_4^+/NH_3-N, (b) SOC, (c) chlorophyll *a* and (d) I_k that were found to differ significantly between locations R4 and R5 in paired t-tests. Location AD, from the Assiniboine River, has also been included for comparison.

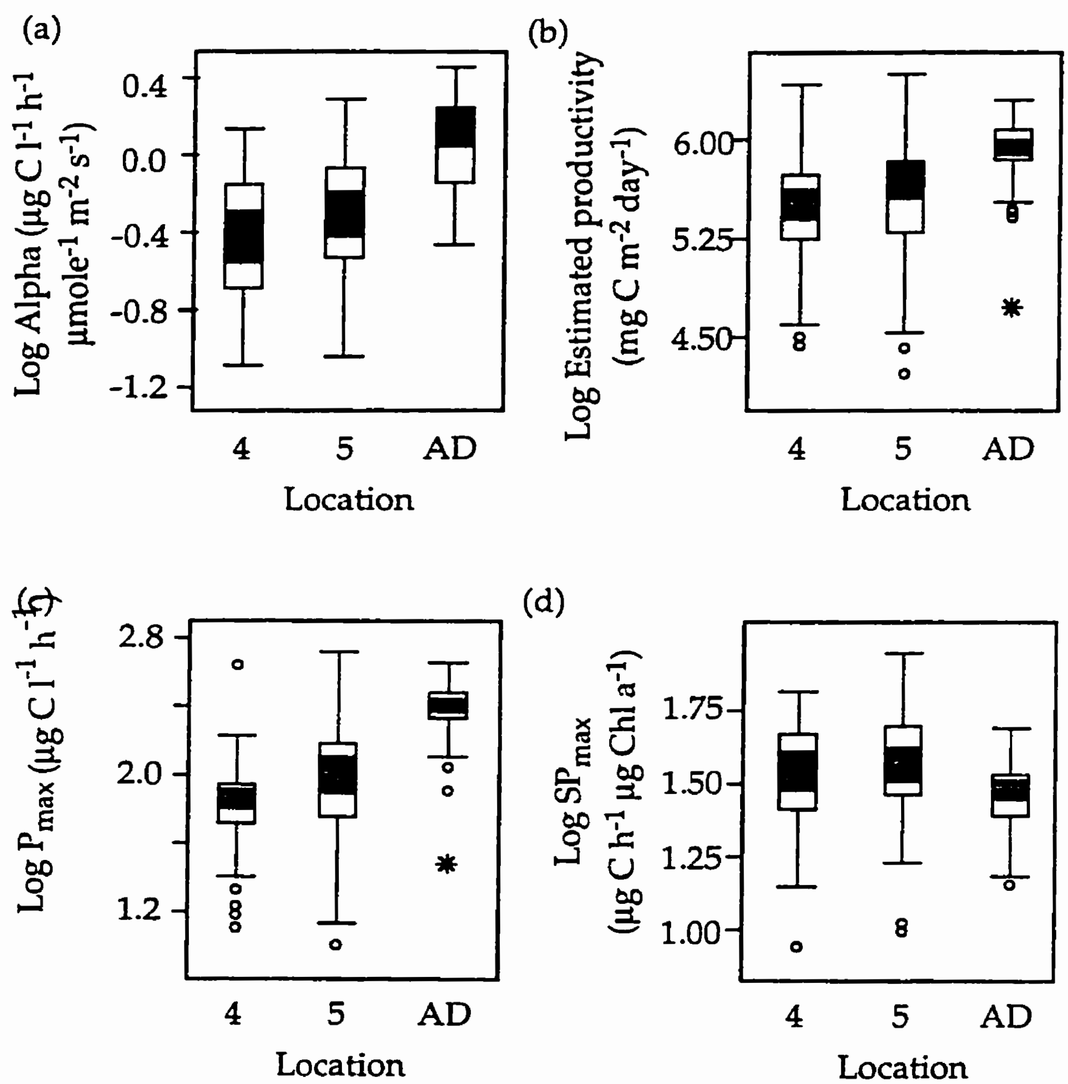


Figure 4.83 Boxplots of (a) alpha, (b) estimated daily productivity, (c) P_{max} and (d) SP_{max} that were found to differ significantly between locations R4 and R5 in paired t-tests. Location AD, from the Assiniboine River, has also been included for comparison.

Chapter 5 The Influence of the Light Environment on Phytoplankton Photosynthesis and Productivity

5.1 Introduction

Commonly used in the assessment of photosynthesis and productivity is the photosynthesis-irradiance, or P. vs. I, relationship. It is typically derived from *in vitro* measurements of carbon assimilated, or oxygen evolved, along an irradiance gradient. The carbon fixed during the incubation experiment is plotted against the corresponding exposure irradiance to obtain a curvilinear relationship with two characteristic regions (Figure 5.1). These include the light-limited slope termed alpha, in which photosynthesis increases linearly with irradiance. Light-saturated photosynthesis, or P_{max}, is that portion of the curve in which photosynthesis is uncoupled from further increases in irradiance (Geider and Osborne 1992). I_k is a derived parameter from the intercept of P_{max} and alpha and represents the threshold irradiance that saturates photosynthesis.

The physiological processes that define both P_{max} and alpha have been reviewed by many (i.e., Falkowski 1981, Prezelin 1981, Richardson *et al.* 1983, Geider and Osborne 1992). Indeed, the abrupt transition from light-limited to saturated regions of the P-I curve is considered a switch in control of photosynthesis from the photosynthetic unit (PSU) in the light reactions to the dynamics of carboxylation of Rubisco and Calvin cycle enzyme activity in the dark reactions.

There are predictable alterations observed in the P vs. I curve in response to the pre-history of light availability (i.e., Prezelin and Sweeney 1978, Falkowski and LaRoche 1991, Prezelin 1981, and Sukenik *et al.* 1987). For example, the prolonged exposure to light-limiting irradiances is

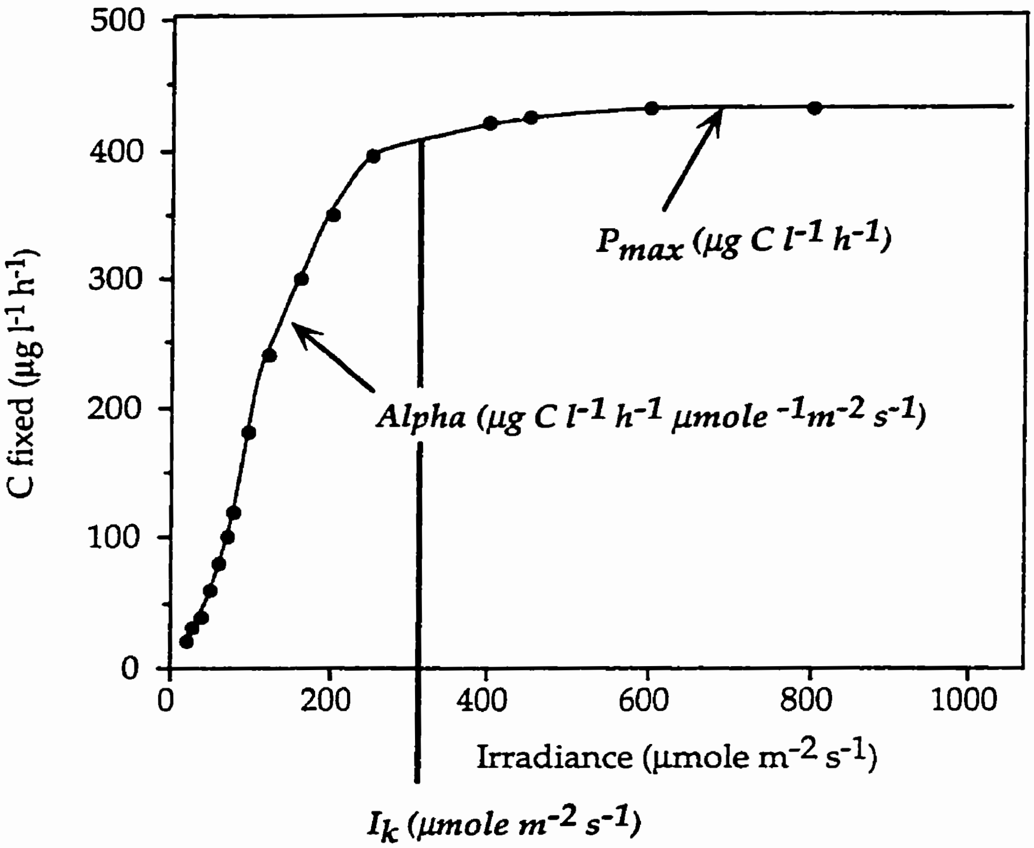


Figure 5.1 Model of the photosynthesis vs. irradiance relationship. The slope of the curve represents light-limited photosynthesis, commonly referred to as alpha. Saturated photosynthesis occurs in the plateau, or light-uncoupled portion of the curve. This is commonly referred to as P_{max}. I_k is the threshold irradiance that marks this change in photosynthesis and is derived from the intercept of P_{max} and alpha.

correlated with an overall increase in alpha that is considered to be the result of an increase in the PSU size or activity. However, when normalized to chlorophyll *a*, these differences are not typically observed since they are cancelled out by the proportional increase in pigment concentration (Falkowski 1981, Geider and Osborne 1992, Prezelin 1981). The notable exception is found in cells that predominantly increase accessory pigments in response to low light conditions. In this instance, alpha may appear slightly higher because of the under-estimation of photosynthetic pigments (Richardson *et al.* 1983).

The objectives of this chapter included the following:

1). Determination of the factors that influenced and modified the light environment in 1994 and 1995.

2). Contrast the importance of these light-modifying factors along a spatial gradient from locations in group 3 to group 1.

3). Quantification of the influence of the light environment, in 1994 and 1995, on photosynthetic activity and estimated productivity.

5.2 Results

The Nature of the Light Environment in 1994 and 1995

There were significant differences observed in parameters that defined the light environment between years of the study as well as between River sections (Table 5.1). Profiles of the light environment for both 1994 and 1995 are shown in Figure 5.2. These profiles are based on means for each year, as presented in Table 5.1, and a commonly encountered surface irradiance of 1000 µmoles m^{-2} s^{-1}. In both years, there was a rapid attenuation of light with

Table 5.1 Summary statistics for light parameters in the Red River and groups 1 and 3 in 1994 and 1995.

	1994	1995
Light Extinction (% per 0.1 m)		
Red River		
Mean ± SD	54 ± 19	37 ± 15
Max	97	98
Min	26	18
Group 1		
Mean ± SD	50 ± 19	31 ± 8
Max	97	63
Min	28	21
Group 3		
Mean ± SD	58 ± 18	44 ± 21
Max	88	98
Min	28	18
Euphotic Depth (m)		
Red River		
Mean ± SD	1.0 ± 0.6	1.6 ± 0.6
Max	2.1	3.0
Min	0.2	0.2
Group 1		
Mean ± SD	1.2 ± 0.58	2.0 ± 0.5
Max	2.1	3.0
Min	0.2	0.2
Group 3		
Mean ± SD	1.0 ± 0.5	1.5 ± 0.7
Max	2.1	3.0
Min	0.3	0.2

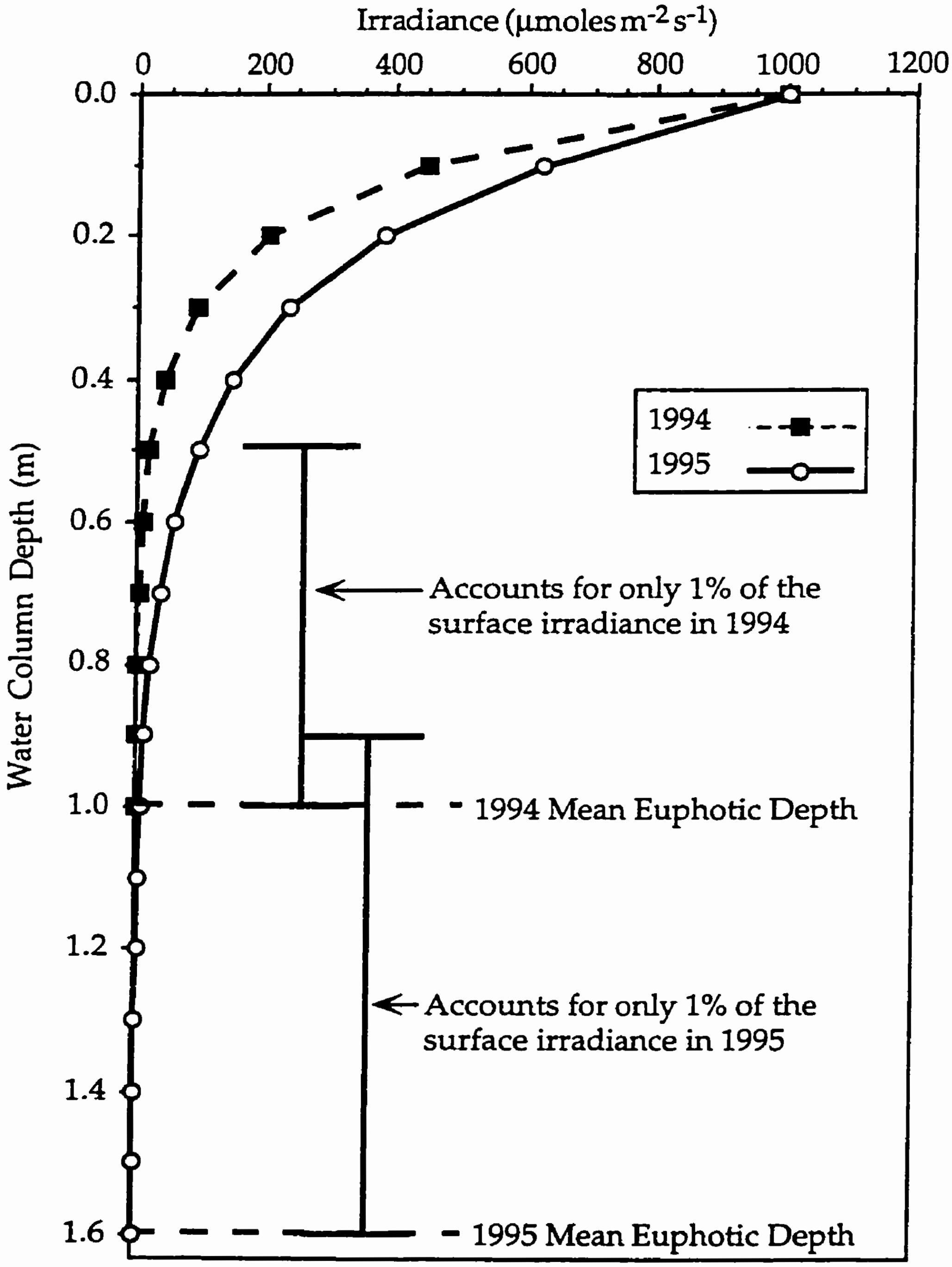


Figure 5.2 Profiles of the light environment found in the Red River water column during 1994 and 1995.

over 80 % of the light extinguished by 0.2 and 0.4 m in 1994 and 1995, respectively. While in 1994, only 1 % of the total surface irradiance was available below 0.5 m, this was found deeper in the water column, below 0.9 m, in 1995. Based on these findings, it appeared that there was more light available within the water column in 1995 in contrast with 1994.

Regression analyses were performed to identify the parameters that were correlated with these changes in the light environment. Factors that were considered included concentrations of PC and PN and flow rate, as these were shown to fluctuate in a similar fashion to the light environment (refer to Chapter 4). Overall, precipitation was not shown to be an important factor defining the light environment and was therefore excluded from the analysis.

There were strong correlations between the concentrations of PC, and to a lesser extent of PN, with light extinction and euphotic depth in 1994, for which data was available (Figure 5.3). Indeed, these measures seemed to be appropriate surrogates for suspended particulate matter in the water column. It was found that overall, PC explained 72.4 % of the variation in extinction observed in the Red River while PN explained 33.7 % (Figure 5.3). In the case of euphotic depth, 75.2 % of the variability was explained by PC, and 41.2 % by PN (Figure 5.4).

When each group was examined separately, it was found that the relationship between particulates and the underwater light environment differed spatially. In particular, it was shown that the concentration of PC explained more of the variability in light extinction and euphotic depth upstream in group 3 when compared with the downstream group 1. For example, the correlation between PC concentration and light extinction in group 3 was 89.4 %, while only 46.9 % in group 1 (Figure 5.3).

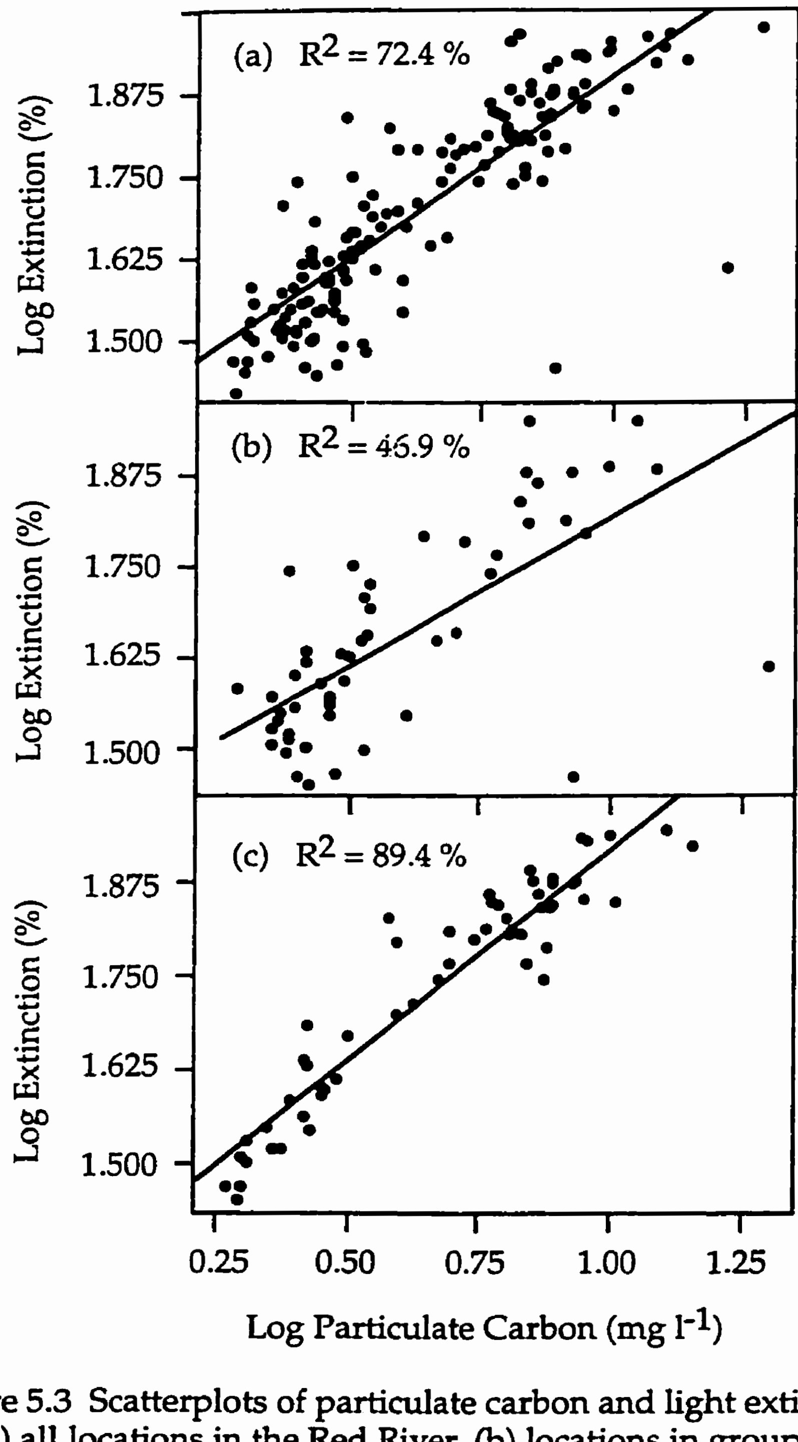


Figure 5.3 Scatterplots of particulate carbon and light extinction for (a) all locations in the Red River, (b) locations in group 1 and (c) locations in group 3 in 1994. Similar scatterplots for particulate nitrogen exhibited correlations of (a) 33.7 %, (b) 18.4 % and (c) 55.3 %.

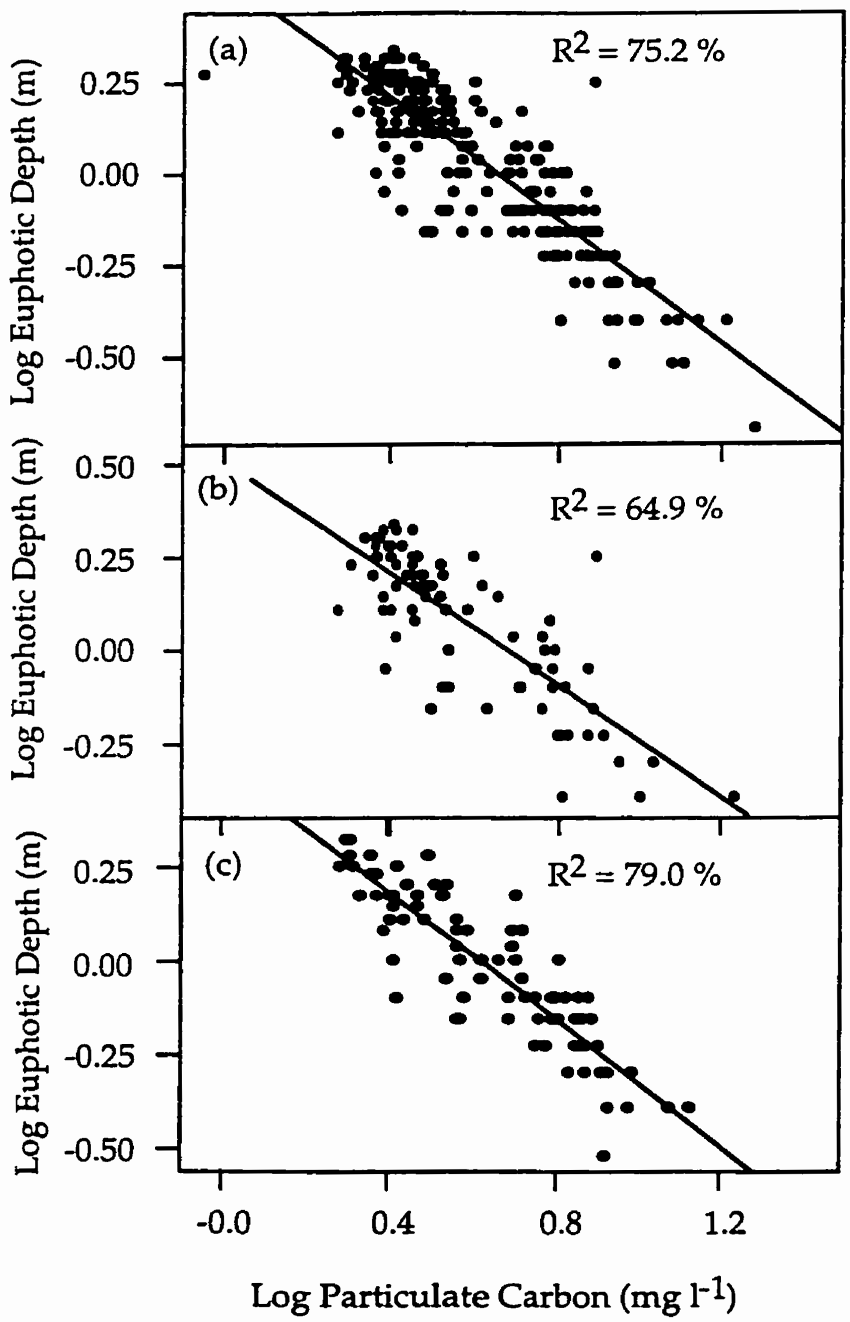


Figure 5.4 Scatterplots of particulate carbon and euphotic depth in 1994 for (a) all locations in the Red River, (b) locations in group 1 and (c) locations in group 3 in 1994. Similar scatterplots of particualte nitrogen exhibited correlations of (a) 41.2 %, (b) 27.6 % and (c) 61.4 %.

Red River flow rate was also found to influence the extinction of light and euphotic depth in the water column (Figures 5.5 and 5.6). However, of the variability in light parameters observed, only approximately 30 % was explained solely by River flow rate. As was found with PC, however, the correlation was much higher in group 3 ($R^2 \approx 50$ %) as compared with group 1 ($R^2 \approx 19$ %).

Upon further examination it was found that flow rate was correlated with PC and PN (Figure 5.7). Even though flow rate and PC concentration were poorly correlated overall, (i.e., R^2 = 23.2% for PC and 7.5 % for PN), it was found that flow rate accounted for a significant portion of the variability in concentrations of particulates among sampling locations in group 3 (R^2 = 57.4 % for PC; 40.0 % for PN). There were only "nearly" significant correlations observed in group 1 ($p \geq 0.08$).

The overall impact of flow rate and particulate concentration on parameters that defined the light environment was evaluated by PCA using the 1994 dataset. A multiple parameter axis of physical factors was derived in PCA and included flow rate, PC and PN. The first axis from the PCA was regressed against euphotic depth and light extinction. The correlations of this *physical* PCA axis to light extinction and euphotic depth were 62.5 % and 65.8 %, respectively (Figure 5.8). On a group basis, however, these correlations ranged from approximate 45 % for group 1 to 75 % for group 3.

Phytoplankton Parameters in Relation to the Light Environment

The 1994 and 1995 P vs. I relationships are presented in Figure 5.9. These curves are based on means for each year from Table 5.2 and exclude weeks 1 to 7 in 1994 and week 11 in 1995, for which comparable data between 1994 and 1995 were not available.

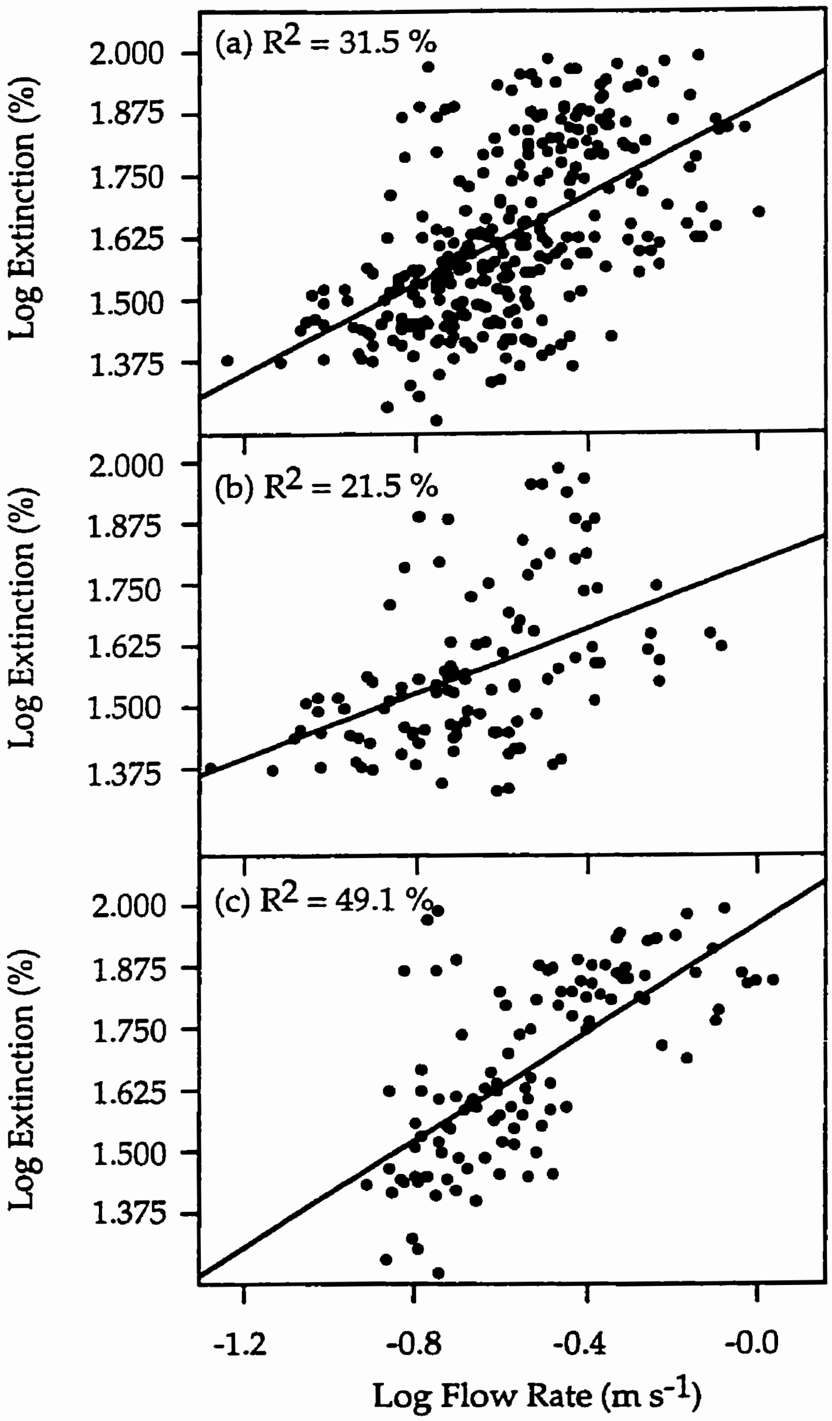


Figure 5.5 Scatterplots of flow rate and light extinction in both 1994 and 1995 for (a) all locations in the Red River, (b) all locations in group 1 and (c) all locations in group 3.

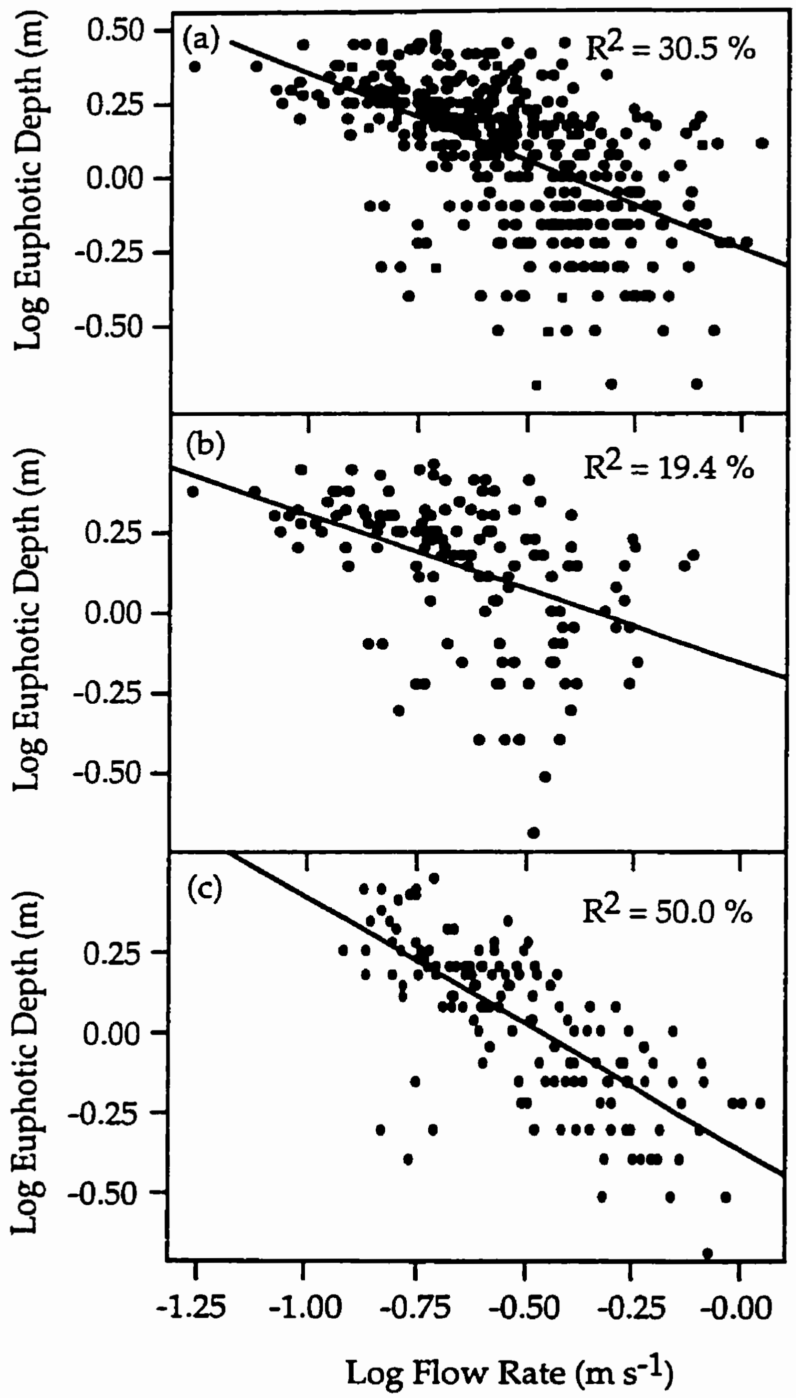


Figure 5.6 Scatterplots of flow rate and euphotic depth in both 1994 and 1995 for (a) all locations in the Red River, (b) locations in group 1 and (c) locations in group 3.

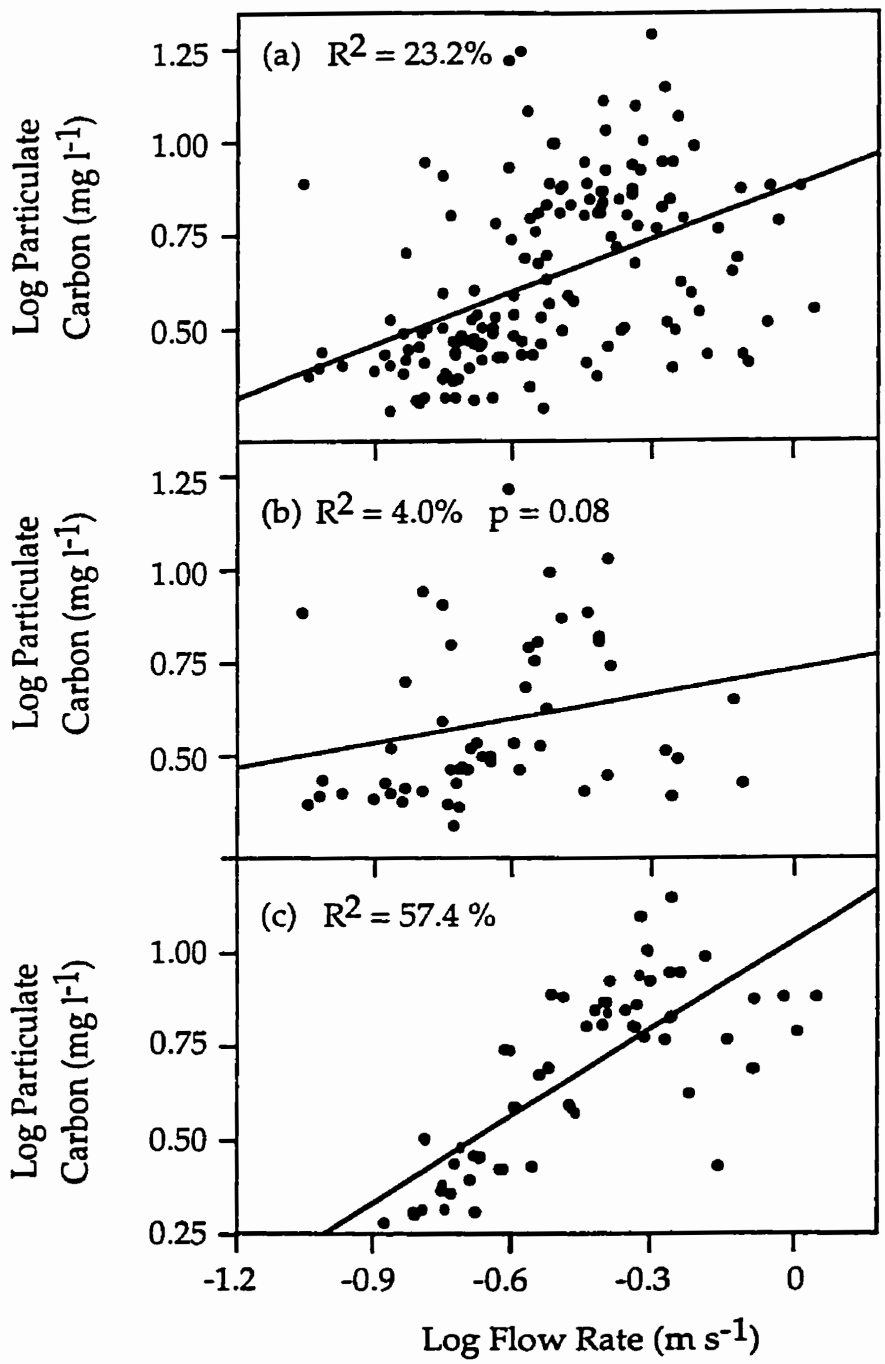


Figure 5.7 Scatterplots of flow rate and particulate carbon for (a) all Red River locations, (b) locations in group 1 and (c) locations in group 3 in 1994. Similar scatterplots for particulate nitrogen exhibited correlations of (a) 33.7 %, (b) 18.7 % and (c) 55.3 %.

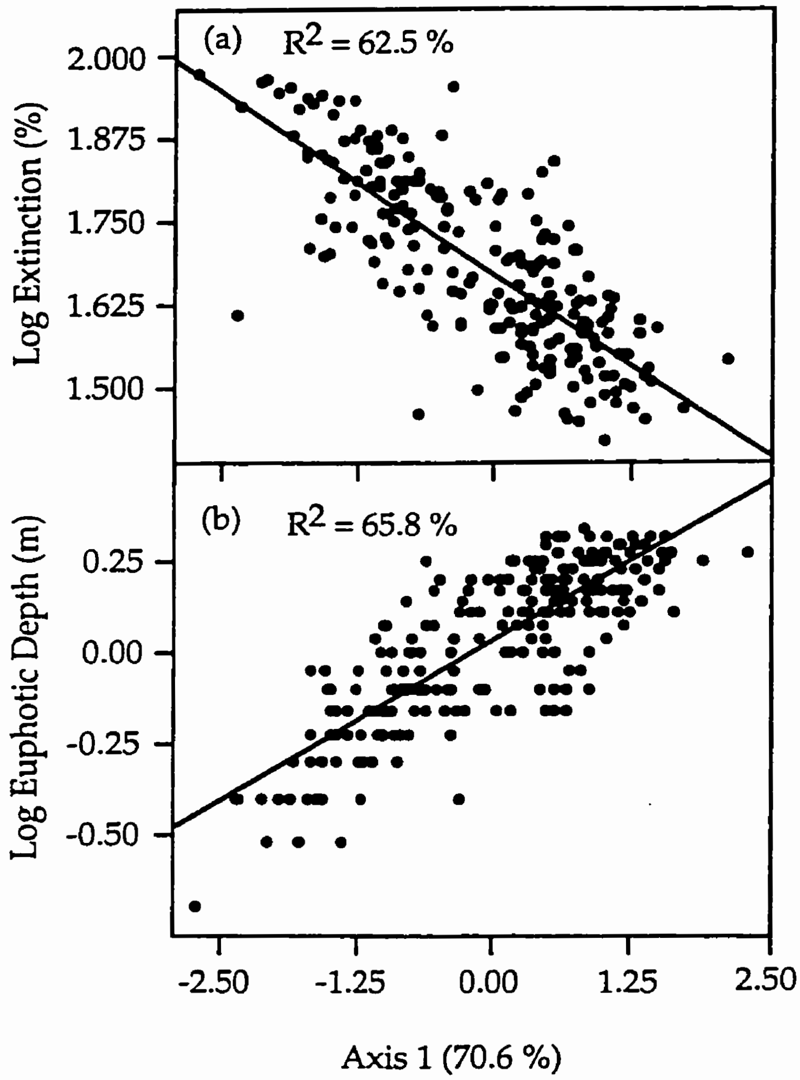


Figure 5.8 Scatterplots of PCA axis I (comprising flow rate, particulate carbon and particulate nitrogen) with (a) light extinction and (b) euphotic depth in 1994. Axis I maintained 70.6 % of the total variability in flow rate, PC and PN.

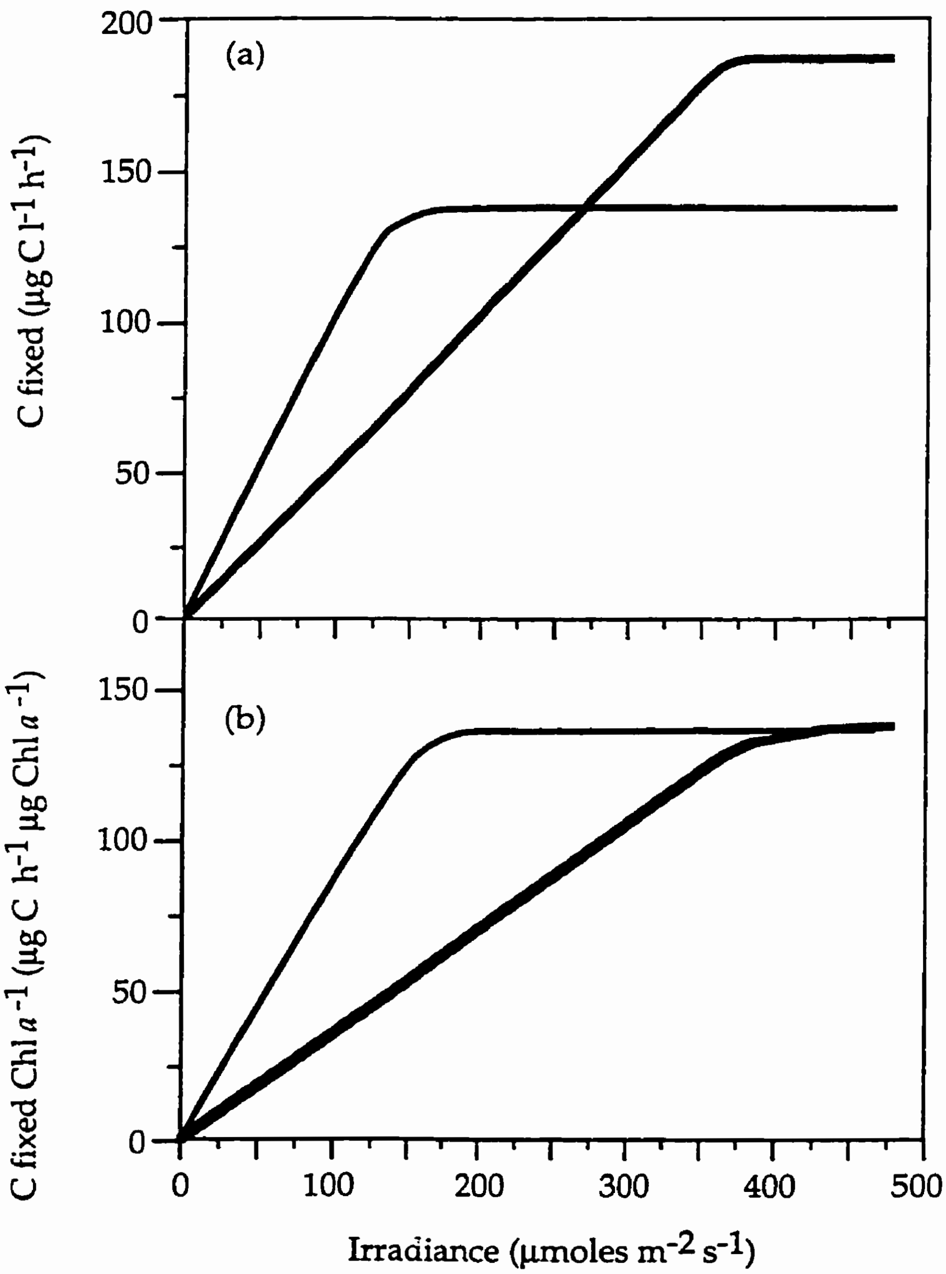


Figure 5.9 (a) Profiles of photosynthetic parameters vs. irradiances (i.e., P vs I curves) for 1994 (——) and 1995 (——) (b) The same profiles as based on chlorophyll normalized values. Profiles are based on summary statistics found in Table 5.2.

Table 5.2 Statistical means for phytoplankton parameters in 1994 and 1995 for the Red River. Excluded from these means are weeks 1 through 7 in 1994 and week 11 in 1995.

	1994	1995
Biomass (μg Chl *a* l^{-1})	24.00	31.30
P_{max} (μg C l^{-1} h^{-1})	141.60	187.30
Alpha (μg C l^{-1} h^{-1} $\mu mole^{-1}$ m^{-2} s^{-1})	0.94	0.54
I_k ($\mu mole$ m^{-2} s^{-1})	141.00	367.00
SP_{max} (μg C h^{-1} μg Chl *a* $^{-1}$)	5.98	5.90
SPalpha (μg C h^{-1} $\mu mole^{-1}$ m^{-2} s^{-1} μg Chl a^{-1})	0.04	0.02

It was found that significant yearly differences existed between all photosynthetic parameters (Figure 5.9). In particular, the higher alpha observed in 1994 suggested that a greater amount of carbon was fixed at lower irradiances when contrasted with 1995. Consequently, photosynthesis was found to be saturated at a lower irradiance in 1994, as evidenced by the lower I_k value. While SPalpha was shown to differ significantly between 1994 and 1995, when normalized for chlorophyll *a*, SP_{max} was not (Table 5.2). Therefore, the rate of carbon uptake at saturating irradiances was considered to be equivalent between years.

Yearly differences in photosynthetic parameters was also shown by auto-correlation (Figure 5.10). Furthermore, the relationship between P_{max} and alpha was shown to retain a high degree of correlation within each year. The notable exception was found during seasonal episode 5, in 1995, in which values of alpha appeared to deviate from the point cloud for the year. Alpha, during this period, exhibited greater similarity to conditions in 1994.

A profile of the *in situ* estimated productivity in the Red River is presented in Figure 5.11. It is based on the mean light profile and I_k for each year (Tables 5.1 and 5.2). I_k defined the boundary between saturated and light-

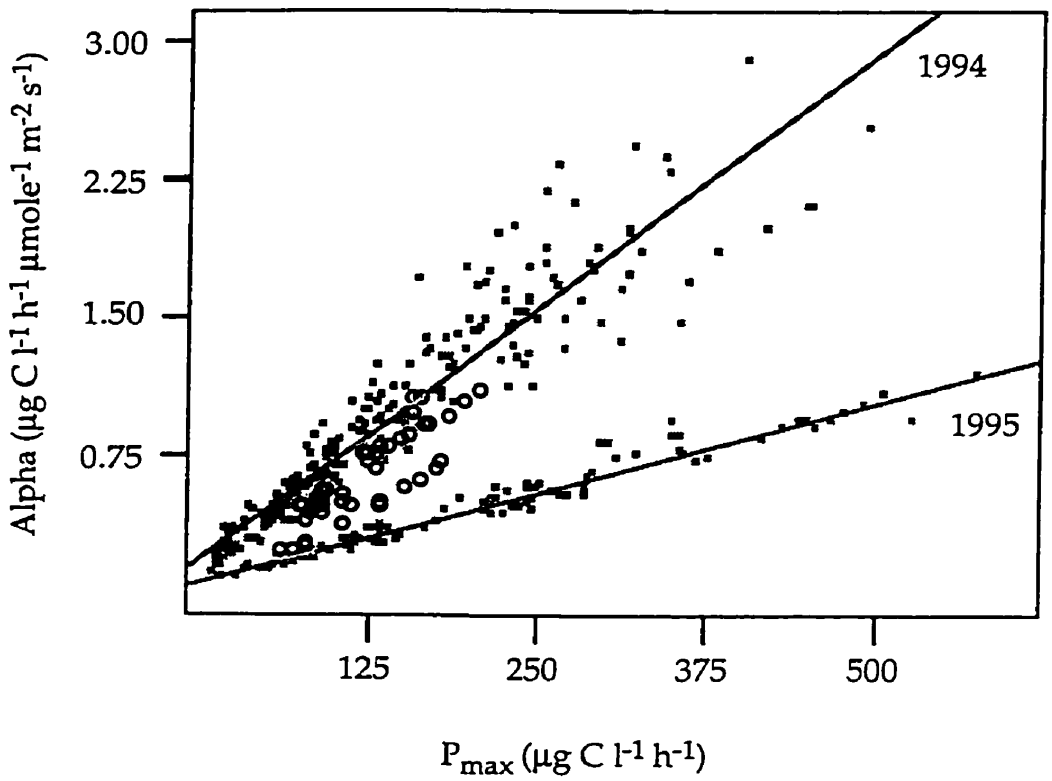


Figure 5.10 Autocorrelation of Red River P_{max} and alpha in 1994 and 1995. o represent measurements in seasonal episode 5 in 1995.

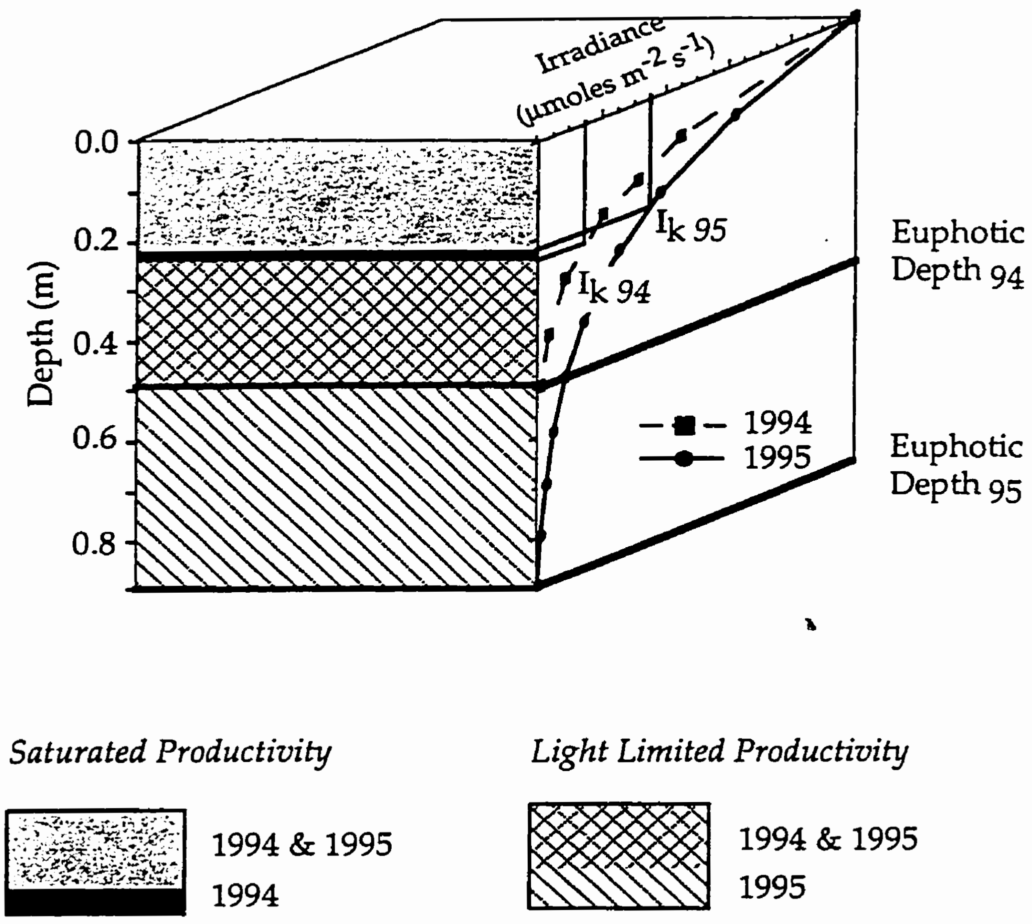


Figure 5.11 Profiles of productivity found at subsaturating and saturating irradiances in 1994 and 1995. Results are based on the light profile found in Figure 5.1 and statistics presented in Table 5.3. Euphotic depths have been adjusted to reflect the depth to which only 1% of surface irradiance is available.

limited productivity. In 1995, this boundary occurred at an average irradiance of 367 µmoles m^{-2} s^{-1} but was significantly lower, at 141 µmoles m^{-2} s^{-1}, in 1994. When this was considered in addition to the light profile for each year, it appeared that the depth to which I_k irradiances penetrated was equivalent between years (Figure 5.11). Furthermore, the quantity of saturated productivity, represented by the area above the light profile, was found to be equivalent between years (Table 5.3). In contrast, the amount of estimated productivity that occurred at light-limiting irradiances was considerably larger in 1995. The net outcome was that total estimated daily productivity was higher in 1995. The notable exception was found in seasonal episode 4, when total estimated productivity was higher in 1994. While light-limited productivity during this episode was equivalent between years ($p = 0.462$), there was greater saturated productivity found in 1994 ($p = 0.000$).

Table 5.3: Mean ± standard deviation and ANOVAs (year * parameter) for production estimates in the Red River during 1994 and 1995. Excluded are weeks 1 to 7 in 1994 and week 11 in 1995.

	1994	1995	P Value
Estimated Daily (Total) Productivity (mg C m^{-2} day^{-1})	635 ± 661	770 ± 714	0.000
Light-saturated	404 ± 418	372 ± 372	0.375
Light-limited	231 ± 248	397 ± 354	0.000
Light saturated/Total Production	0.65 ± 0.06	0.47 ± 0.13	0.000
Light limited/Total Production	0.35 ± 0.06	0.53 ± 0.13	0.000
Light saturated/limited	1.96 ± 0.57	0.99 ± 0.51	0.000

As shown in Table 5.3 and Figure 5.12, the contribution of saturated productivity to the total estimate was considerably higher in 1994 when contrasted with 1995. Only 47 % of the total daily estimated productivity in 1995 was achieved under light-saturation. This contrasted with 65 % in 1994.

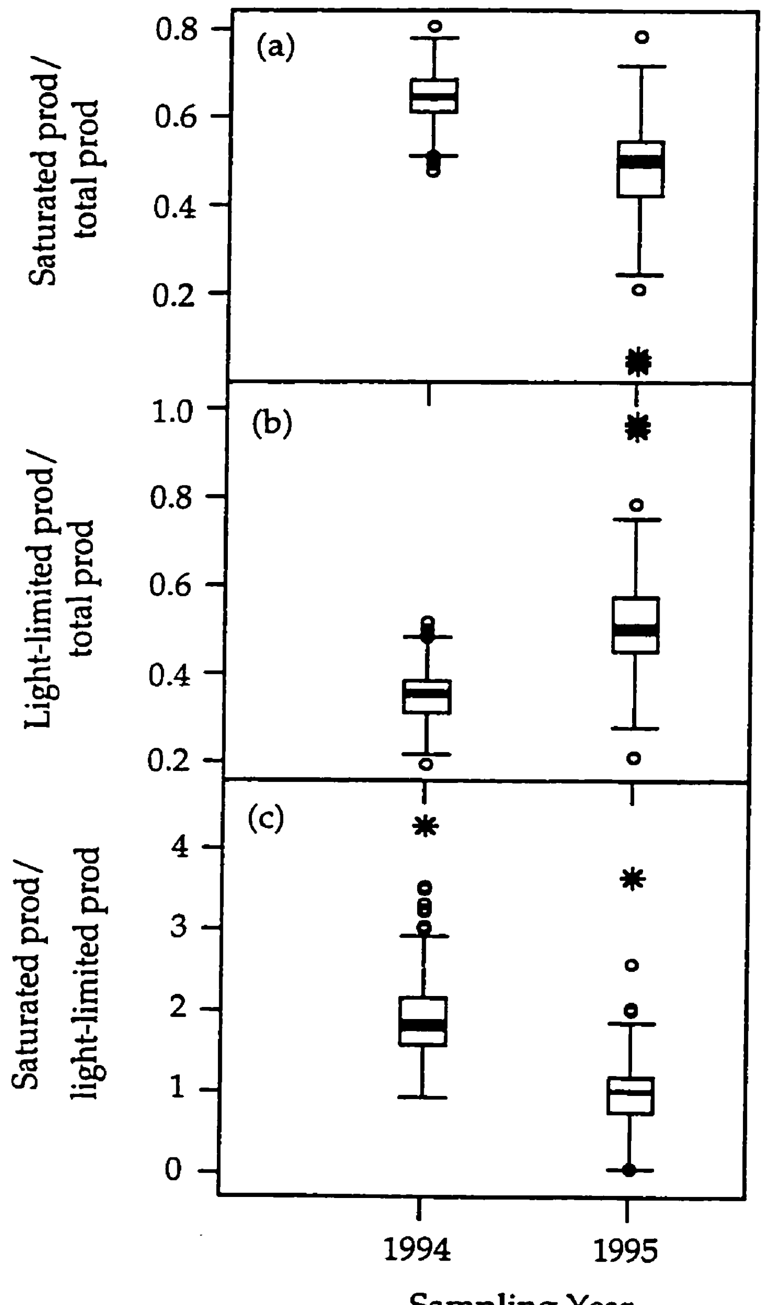


Figure 5.12 Boxplots of yearly comparisons in ratios of productivity. Comparisons were made between (a) saturated to total daily estimated production (total prod), (b) light-limited to total prod and (c) saturated to light-limited production estimates.

The overall impact was that the saturated to light-limited ratio of production was considerably higher in 1994.

There were significant shifts noted in the ratios of light-saturated to limited production estimates between seasonal episodes in both 1994 and 1995 (Figure 5.13). For group 3, these differences were noted between each episode. While in 1994, ratios were found to be lower during episodes 2 and 4 ($p = 0.001$), they were shown to increase from episode 3 to 5 ($p = 0.028$) in 1995. In contrast, ratios differed only between episodes 4 and 5 in 1995 for locations in group 1 ($p = 0.003$).

Comparisons between groups 1 and 3 revealed that chlorophyll-normalized parameters of photosynthesis differed significantly between groups (Figure 5.14). Consistently, photosynthetic parameters were significantly lower among locations in group 3 when compared with group 1 ($p = 0.000$ in all cases).

There were relationships observed between flow rate and PC concentration with production ratios for locations in group 3 (Figure 5.15). Both flow rate and PC concentration were found to positively influence the ratio of saturated to light-limited productivity ($R^2 = 23.6$ %). As flow rate and PC concentration increased, the contribution of light-saturated productivity to the total estimate was found to increase as well. These relationships between flow rate and/or PC concentration and productivity were not significant in group 1.

5.3 Discussion

The Light Environment

It was found that parameters such as flow rate and particulate carbon represented effective measures of, and perhaps determinants of, the degree of

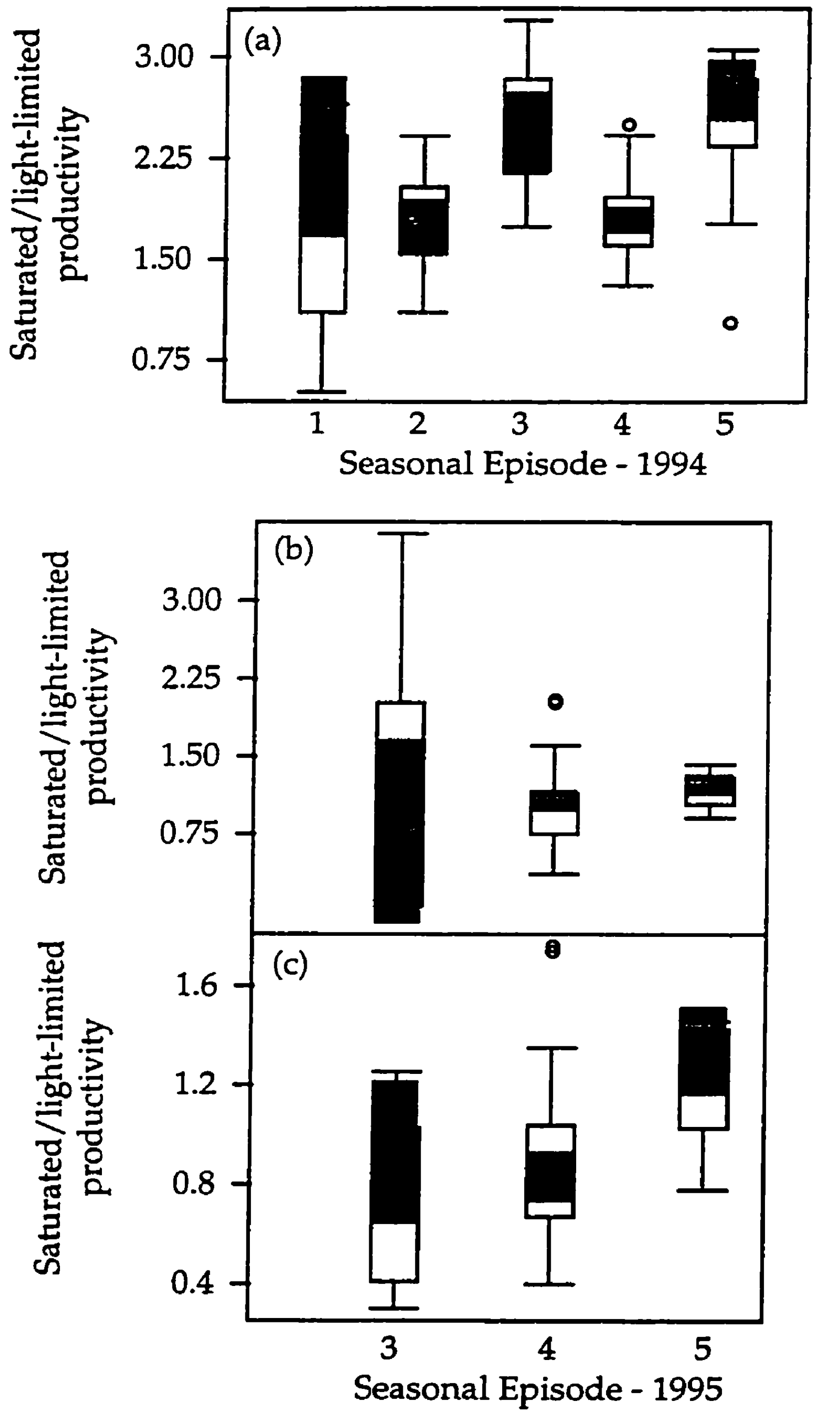


Figure 5.13 Boxplots displaying the relationship of saturated to light-limited productivity in Group 3 in (a) 1994 and (b) 1995 and (c) Group 1 in 1995. One way ANOVA (seasonal episode * product -ivity) results were p = 0.001, 0.028 and 0.003, respectively.

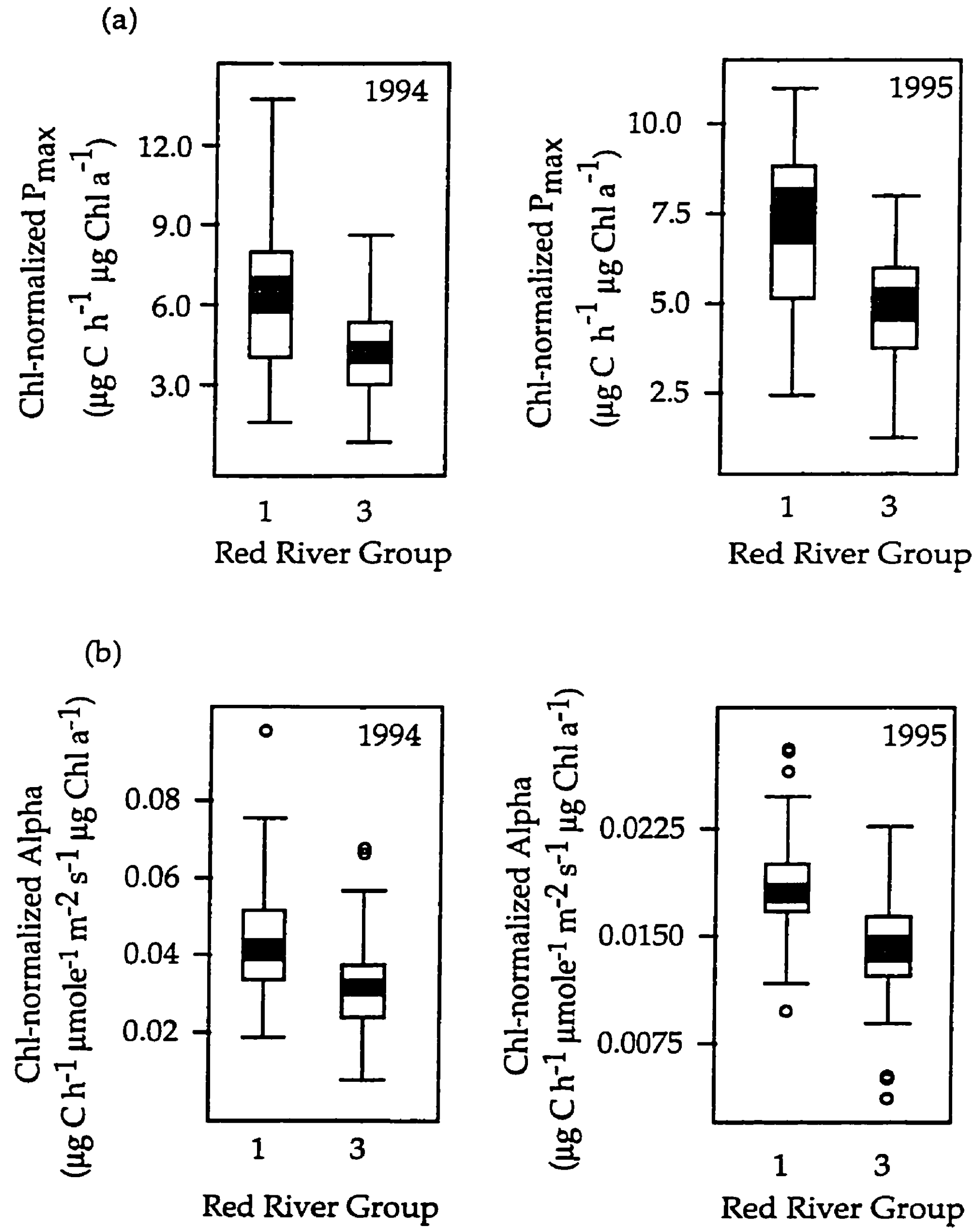


Figure 5.14 Boxplots for Red River groups 1 and 3 during 1994 and 1995. (a) Chlorophyll-normalized P_{max} and (b) chlorophyll-normalized alpha. ANOVAs showed that significant differences were always observed between groups 1 and 3 during the study ($p = 0.000$).

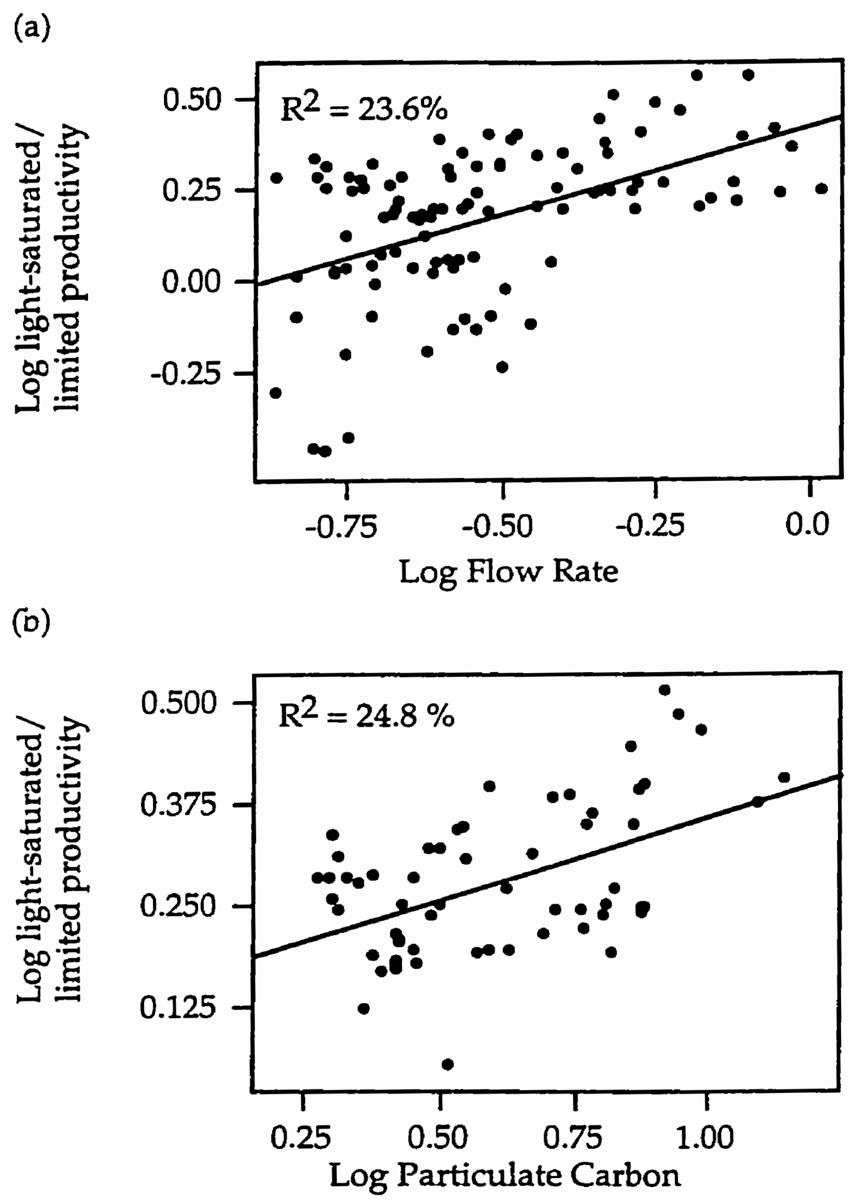


Figure 5.15 Scatterplots of (a) 1994/95 flow rates and (b) 1994 particulate carbon concentrations with the ratio of saturated to light-limited productivity in group 3 in the Red River. Seasonal episodes 1 and 5 have been removed since these were shown to be potentially influenced by seasonal factors such as ambient light and water temperature (Figures 4.6 and 4.7).

light extinction and the depth of the euphotic zone in the Red River (Figure 5.8). During those periods of high flow rate and/or elevated concentrations of PC and PN, the light environment in the Red River was characterized by shallow euphotic depth and high light extinction. Conversely, when flow rate declined and/or the concentration of PC in water column dropped, there was an overall increase in the depth of the euphotic zone and concomitant reduction in the extinction of light. Although PC and PN determinations were not performed in 1995, it has been shown that particulate phosphorus concentration was significantly lower when compared with 1994 (Figure 4.61). When considered in addition to the overall lower flow rate encountered during 1995, these factors may provide insight into the marked difference observed in the light environment between the two years of the study (Table 5.1).

It was important to recognize, however, that the degree to which flow rate and PC and PN concentration influenced the light environment was not constant in the River but rather displayed a spatial gradient between groups 3 and 1. This was evidenced by the stronger correlations observed for locations in group 3 (Figures 5.3 to 5.7). For example, over 89.0 % of the variability that was observed in the light extinction could be explained by the concentration of PC in group 3, but this was reduced to 46.9 % in group 1 (Figure 5.3).

Based on these findings, it was likely that additional factors were responsible for modifying the light environment in group 1. Perhaps the greatest evidence for this is found in the disparity in the relationship between flow rate and concentration of PC. Either through runoff or scouring of the River banks and bed, the concentration of PC within the water column in group 3 was increased during higher flow periods and thus contributed to the reduced light environment (Figures 5.3, 5.4 and 5.7). In contrast, there was no significant relationship observed between flow rate and concentration of PC in group 1 (Figure 5.7). In group 1, the influence of flow rate on the light environment (Figures 5.5 and 5.6) was shown to be independent of the relationship between PC/PN and the light environment (Figures 5.3 and 5.4).

This spatial disparity between groups 1 and 3 may be related to both the morphometric features of the Red River for each group and possibly the exposure to anthropogenic activities within the City of Winnipeg. Due to the significant differences in cross-section areas between River groups, group 3 locations experienced higher flow rates when compared with group 1 (Figure 4.35). In addition, the concentrations of PC and PN were found to decline between these groups (Figures 4.56 and 4.67). However, along this spatial gradient was greater urban activity that may have negatively influenced the attenuation of light in group 1. The net result may have been to reduce the importance of flow rate in defining the light environment among locations in group 1. Still, the concentration of PC was significantly lower in group 1 when compared to group 3 and this was most-likely the factor that resulted in a spatial gradient in the availability of light within the water column (Figures 4.35, 4.38, 4.40, 5.3 and 5.4).

Phytoplankton Parameters in Relation to the Light Environment

Photosynthetic parameters were found to differ markedly between years of this study (Figures 5.9 and 5.10). Reflected in a higher alpha, incubation experiments indicated that phytoplankton populations in 1994 were more efficient in photosynthetic activity when exposed to light-limiting conditions when compared with 1995. Furthermore, populations had lower irradiance requirements to saturate photosynthesis as evidenced by lower I_k values. These differences remained significant in values of SPalpha (Table

5.2). However, there were no significant differences in rates of saturated photosynthesis, as evidenced in equivalent values of SP_{max}.

When these photosynthetic relationships were superimposed on the light profile for each year, two significant trends were observed. First, while light extinction was significantly higher in 1994, there was an equivalent amount of saturated production estimated between years (Table 5.3 and Figure 5.11). This was reflected by a similar depth to which I_k irradiances penetrated into the water column. The lower I_k in 1994 resulted in an greater range of the light profile capable of supporting saturated photosynthesis. Consequently, although light extinction was much greater in 1994, saturated production could be found at equivalent depths in the water column when compared to 1995.

Secondly, there were significantly higher estimates of light-limited production in 1995. This was due, in part, to the onset of light-limited photosynthesis at a higher irradiance but also to the reduced attenuation of light within the water column. This contributed to an 80 % increase in the euphotic depth from 1994. In contrast, the light profile in 1994 was severely truncated by higher extinctions and consequently was related to less production at light-limiting irradiances (Figure 5.11).

The net result was that of the total estimate, significantly greater contributions from saturated production occurred in 1994 when contrasted with 1995 (Figure 5.12). While in 1995, only 48 % of the total estimate was derived from saturated photosynthesis, this increased to 65 % in 1994. In fact, the higher total estimate found in 1995 was shown to be the result of significantly greater contributions of light-limited production (Table 5.3). This pronounced difference in daily production was clearly shown in the ratio of saturated to light-limited productivity. While contributions were nearly equivalent between saturated and light-limited production in 1995, contributions of saturated production far exceeded light-limited estimates in 1994 (Table 5.3).

This relationship between saturated to light-limited production deviated from expectations based solely on the light environment. It was hypothesized that the greater light extinction would be correlated with an increase in the contribution from light-limited productivity in 1994, as evidence by a higher alpha. The depth to which I_k irradiances penetrated in the water column was postulated to be more shallow due to light extinction and consequently, the increased photosynthetic efficiency would enhance the production that occurred below saturating, or I_k, irradiances. However, this was not the case. It was found that the increased photosynthetic efficiency observed in 1994 enhanced the range of irradiances for which saturated photosynthesis could be supported (Figure 5.9). Furthermore, this adjustment was shown to compromise the contributions from light-limited activity when compared with 1995 (Figure 5.12). The net result was that daily productivity in 1994 was predominantly supported by saturating rates and the impact of the reduced light environment was dampened and restricted to only a small region of the light profile (Table 5.3 and Figure 5.11).

Curiously, the depth to which I_k irradiances penetrated was found to be relatively conservative between years ($p = 0.391$), even though the light profile could have potentially supported saturated production to greater depths in 1995 (Figure 5.2). In this interpretation, it has been assumed that there is a continuous mixing of the phytoplankton population within the water column and that the population was exposed to the entire light profile (Reynolds 1994). Thus, it is speculated that the changes observed in photosynthetic efficiency may have conserved the depth to which saturated production occurred (Dokulil 1994). This would optimize production during turbid periods and possibly minimize photo-oxidation during clear periods. In so doing, the contribution from saturated productivity would be guaranteed.

It was found that factors including flow rate and PC were correlated with the ratio of saturated to light-limited production (Figure 5.15). High flow rate and PC concentration were shown to reduce the contribution from light-limited production. However, these relationships were restricted to group 3 and were not prevalent, for the most-part, among locations in group 1. These differences between groups 1 and 3 may have been related to the spatial disparity in the factors that control the light environment as previously described. The episodic shifts in flow and particulates would have strongly influenced the light environment in group 3. However, these episodic shifts would have been dampened among locations in group 1, and this may have offset the influences of flow rate and PC on the ratio of saturated to light-limited production.

The significant shift in the saturated to light-limited ratio in group 1 during seasonal episode 5, in 1995, was likely the result of changes in alpha and P_{max} and not correlated to changes in flow rate and/or PC concentration (Figure 5.10). Upon closer examination, the changes observed in photosynthetic parameters and biomass coincided with the occurrence of heterocystous cyanobacteria, that included Anabaena spp. and Aphanizomenon spp.

There were significant differences observed in parameters of photosynthesis between River groups 3 and 1 (Figure 5.13). Locations in group 3 were shown to display significantly lower parameters when contrasted with group 1. Whether these differences can be attributed to the gradient observed in light responses is difficult to quantify as there were dramatic differences observed between River sections in other factors such as nutrient status (see Chapter 4).

Lastly, the fact that SPalpha remained significantly different between years suggests that there may have been either a shift in taxonomic composition and/or a significant production of accessory pigments in 1994 (Richardson *et al.* 1983). The latter has been shown to enhance the activity of the light harvesting complex and thereby increase photosynthetic efficiency. Unfortunately, the higher concentrations of accessory pigments would not have been detected in the chlorophyll determinations performed.

5.4 Summary

1. There was a significantly higher euphotic depth and lower degree of light extinction in 1995 when compared with 1994. In 1994, the higher extinction resulted in severe truncation of the light profile.

2. There were significant relationships between both River flow rate and/or PC concentration with the light available in the water column. Both flow rate and PC concentration were correlated with a reduction in the availability of light in group 3. However, this relationship was only significant for PC in group 1.

3. There was a spatial disparity between River groups. In particular, correlations between flow and the light environment and PC concentration and the light environment were stronger in group 3 when contrasted with group 1. Changes in flow rate contributed to the fluctuations observed in PC concentration in group 3. Conversely, there was no significant relationship observed in group 1.

4. It is proposed that this spatial disparity in flow related changes in PC concentration is related to the River morphometry and possibly a greater urban influence on group 1 conditions. Further study is required in order to quantify this relationship.

5. There were significant differences observed in phytoplankton parameters between years of the study and between River groups 3 and 1. A higher estimate of daily production was found in 1995 and this was highest in group 1.

6. Of the total estimate, there was a greater contribution from saturated productivity in 1994 when compared with 1995. This was a result of a

higher photosynthetic efficiency and consequently, a reduction in the I_k irradiance. Furthermore, the ratio of saturated to light-limited production was significantly higher in 1994 than in 1995.

7. The trends observed in the ratio of saturated to light-limited productivity deviated from the expected as based solely on the light profile. The higher extinction and shallower euphotic depth, typical of 1994, were hypothesized to have reduced the rate of saturated photosynthesis. The higher photosynthetic efficiency observed in 1994 was hypothesized to have enhance productivity below I_k irradiances. Instead, the phytoplankton response was found to influence to range of irradiances that supported saturated rates of productivity.

8. Consequently, production estimates in 1994 were higher than expected. And although light extinction was significantly higher in 1994, the saturated production estimate was equivalent between years. The difference in the total estimate between 1994 and 1995 was due to the production under light-limitation.

9. It is suggested that the differences observed in photosynthetic parameters reflects a conservative strategy to optimize the depth to which I_k irradiances penetrate. In so doing, light-saturated production estimates are not impacted by turbidity and high extinctions.

10. The marked differences observed spatially between River groups 3 and 1 in production ratios is speculated to be correlated with the vulnerability of each River section to physical factors. In group 3, the saturated to light-limited production ratio was found to be correlated with flow rate and PC concentration. This was not observed in group 1.

11. The dramatic shift observed in alpha and P_{max} during seasonal episode 5, in 1995, may be a contributing factor to the observed change in the saturated to light-limited production ratio.

Chapter 6 Physical and Chemical Limitations to Phytoplankton Activity in the Red River

6.1 Introduction

The assessment of River community dynamics is a particularly interesting issue since running waters are becoming increasingly affected by anthropogenic discharges. Close to home, the Clean Environment Commission Hearings as recently as 1992 called for the greater understanding of biological activities in the receiving waters of the Red and Assiniboine Rivers. These Rivers are exploited by several municipalities for effluent discharge. Yet little information has been gathered on the influence of these activities on resident biological communities.

It cannot be disputed that any assessment of phytoplankton dynamics in Rivers impacted by anthropogenic inputs must consider the influence of chemicals such as nitrogen, phosphorus and/or carbon (Schindler 1977, Tilman *et al.* 1982). However, attention must also be focused on physical factors, including residence time/flow rate (i.e., Søballe and Kimmel 1987), turbidity (Jewson and Taylor 1978, Grobbelaar 1989, Cuker *et al.* 1990, Dokulil 1994, Reynolds 1994) and temperature (Baker and Baker 1979).

Compounding the complexities in Rivers are the pronounced seasonal variabilities in physical elements in temperate regions. In the Red and Assiniboine Rivers, the catchment area receives significant amounts of snow during the winter that greatly enhance River discharge during spring runoff. Indeed, these flows sharply contrast with the lows that are experienced both in late summer and mid-winter (Figure 2.5). These seasonal fluctuations are also evident in incident light intensities and water temperatures (Figure 4.1).

In addition to the seasonal cycles, there may be cross-correlations between chemical status in Rivers and physical factors such as flow rate that cycle annually (Davis and Keller 1983). Runoff from agricultural fields may increase nutrients, pesticides and particulates in Rivers during spring run-off or rain storms. Urban runoff due to precipitation may be uncorrelated with River discharge and consequently, the increases observed in nutrient concentrations may appear negatively correlated to flow rate. Lastly, in urban regions that are impacted by pollution discharge, higher flow rates may significantly modify and even reduce concentrations of chemicals downstream of point sources (Meybeck 1993) (Figure 1.1).

Early attempts to quantify the impact of pollution in waterways aimed at the identification of indicator species (i.e., Sladecek 1973). This approach, however, has met with limited success since community alterations do not typically involve profound compositional changes (Cairns 1972, del Giorgio *et al.* 1991). This limitation has been offset considerably with the development of multivariate techniques that correlate community structure with environmental conditions. del Giorgio *et al.* (1991), for example, used PCA to show that along a pollution gradient, there was an alteration in community distribution that favored more tolerant species. Varis (1991) employed canonical correlation analysis techniques to identify environmental conditions that favored the occurrence of cyanobacteria in Finnish lakes. This researcher found that of the chemical factors, N/P ratios and P concentrations strongly influenced community structure. Fangstrom and Willen (1987) employed detrended CCA to ordinate species along lake types, from acid humic to acid impoverished, and subarctic.

Multivariate approaches will be integral in ecological modeling of Rivers. The appreciation of physico-chemical factors that influence the structural and functional community dynamics can only be ascertained when all parameters are considered jointly. As pointed out by Varis (1991), a characteristic of water quality studies is the large number of variables involved. Indeed, when you consider all of the physical and chemical factors that are relevant to water quality studies, as well as the dynamics of the biotic communities, the utility of traditional univariate and bivariate statistical analysis appears very limiting. Conclusions that may be derived from such conventional applications will be simplistic and unappreciative of the dynamic environment of these communities.

Unfortunately there have been few studies which apply multivariate techniques to the functional or physiological dynamism of phytoplankton communities along pollution gradients. Indeed, Allen and Koonce (1973) argued that in ecological studies of phytoplankton, it may be more important to analyze aspects of growth and physiology rather than standing crop alone. Baker and Baker (1979), Grobbelaar (1989) and Dokulil (1994), for example, point to the utility of photosynthetic processes to fulfill this end. Thus, the goals of this chapter were to quantify relationships between phytoplankton activity, as measured by alpha, P_{max}, (the defining characteristics of photosynthetic response to light), Chl *a* (an estimate of phytoplankton biomass) and daily estimated productivity with physico-chemical factors in the Red River using multivariate techniques. To this end, the following objectives have been identified:

1). Definition of the temporal variability in physical and chemical parameters in the Red River including the quantification of seasonal variation in nutrients as a function of physical factors (Davis and Keller 1983, Meybeck 1993).

2). Quantification of spatial heterogeneity between Red River groups.

3). Evaluation of the importance of physico-chemical factors in modifying phytoplankton performance and in so doing, identify the critical factors that modify phytoplankton activity in Red River groups.

4). Quantification of the (dis)similarities in phytoplankton activity between Red and Assiniboine Rivers and the impact of Assiniboine discharge on phytoplankton processes downstream of it's confluence with the Red.

6.2 Results

Cross"-Correlations Between Physical and Chemical Parameters

As previously described in Chapter 4, there were significant seasonal features in the physical, chemical and phytoplankton parameters in both 1994 and 1995 (Figures 4.2 to 4.7). Perhaps the most profound observations were the fluctuations in nutrients and phytoplankton parameters that coincided with flow rate changes. Those seasonal episodes associated with low flow rates had a tendency to display markedly lower concentrations of particulates and totals of carbon, nitrogen and phosphorus. Furthermore the cycling patterns differed between seasonal episodes in each year. While in 1994, there were crests and troughs in these physical, chemical and phytoplankton parameters, they appeared to gradually decrease or increase with less pronounced fluctuations between episodes in 1995. These episodic features were so pronounced that this feature became the basis for analysis of variance that defined the temporal variability in physical and chemical parameters in Chapter 4.

As pointed out by Davis and Keller (1983), it is necessary to consider annual and/or cyclical patterns when quantifying the impact of dissolved loads. In this study, there were often significant correlations between physical and chemical factors when regressions were performed but these relationships could not be distinguished as solely impacting on phytoplankton processes. In order to establish nutrient relations with phytoplankton activity, it was considered important to quantify the variability in chemistry and phytoplankton activity that may have been correlated to changes in physical factors.

To examine these relationships, a series of CCAs were performed. Weekly measures of chemical and phytoplankton parameters comprised the first dataset while the physical variables including flow rate and light extinction represented the constraining environmental dataset. Precipitation was excluded since it was previously shown to be poorly correlated with other physical, chemical or phytoplankton parameters (not shown). Group 1, including locations 7 to 10, was chosen in this analysis as it consisted of sites that were downstream of the NEWPCC that would be most substantially impacted by anthropogenic activity. These relationships were contrasted with locations 1 to 3 from group 3 that were either upstream or adjacent to the SEWPCC. Site 4 was excluded since it was previously shown to differ significantly in concentrations of NH_4^+/NH_3-N (Figure 4.20 and Tables 4.4 and 4.7). The CCAs were performed on Red River group means for the following datasets: phytoplankton activity including biomass (ie., chlorophyll *a*), alpha, P_{max} and daily estimated productivity; TN and TP; PN, PP and PC; NH_4^+/NH_3-N and SRP; and ratios of $(NH_4^+/NH_3\text{-N})$/SRP, TON/SRP and SIN/SRP. Results are presented in Figures 6.1 to 6.6.

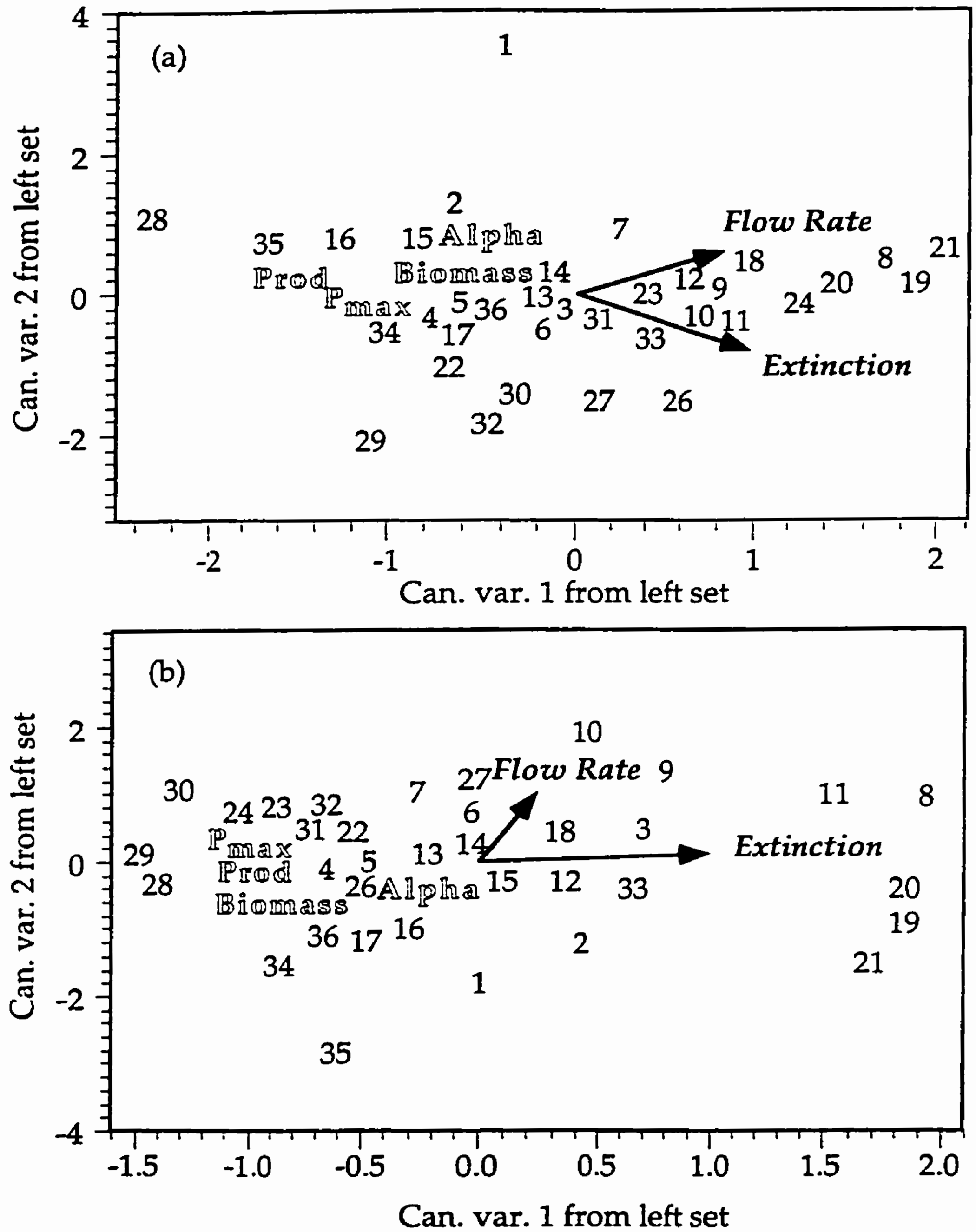
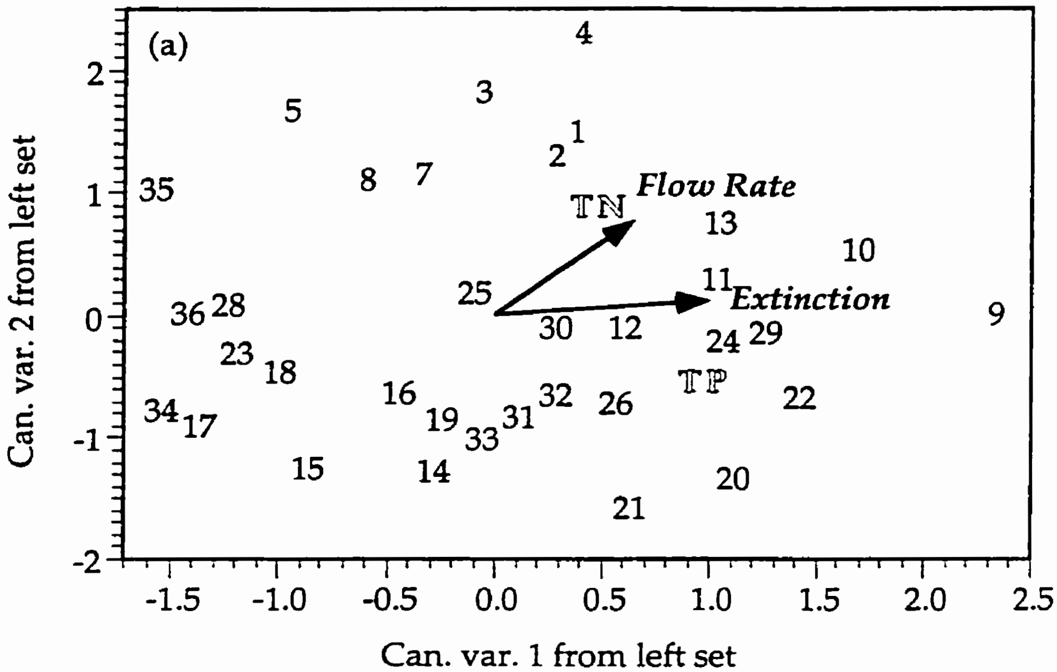


Figure 6.1 Canonical correlation analysis results for the relationship between light extinction and flow rate with biological activity (biomass, P_{max}, alpha and productivity) in (a) group 3 and (b) group 1 for all sampling weeks in 1994 and 1995. Numbers represent individual sampling weeks as found in Appendix A.6.1.



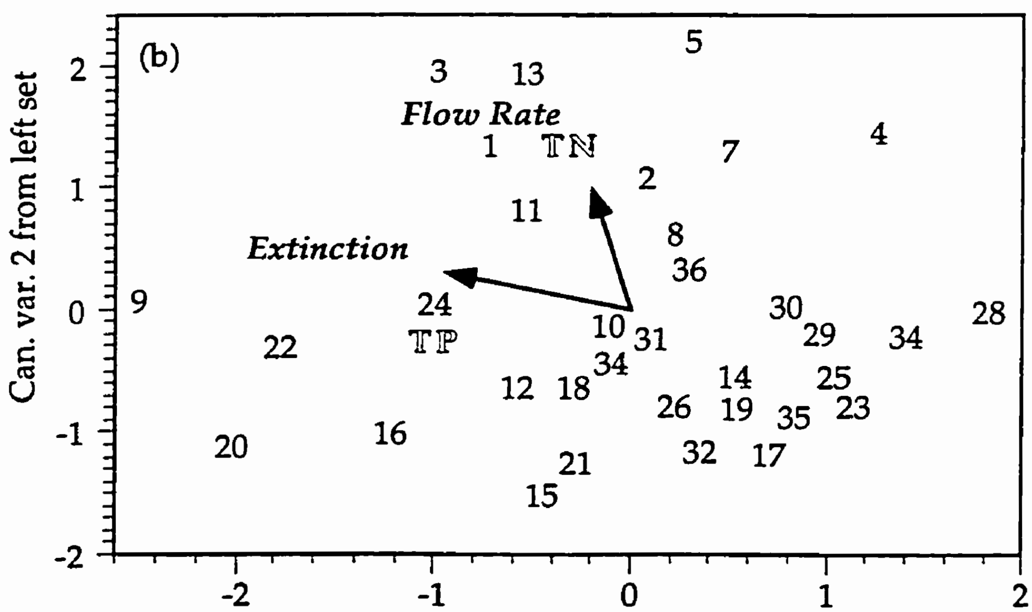


Figure 6.2 Canonical correlation analysis results for the relationship between light extinction and flow rate with total nitrogen (TN) and total phosphorus (TP) in (a) group 3 (locations 1 to 3) and (b) group 1 for all sampling weeks in 1994 and 1995. Numbers represent individual sampling weeks as found in Appendix A.6.1.

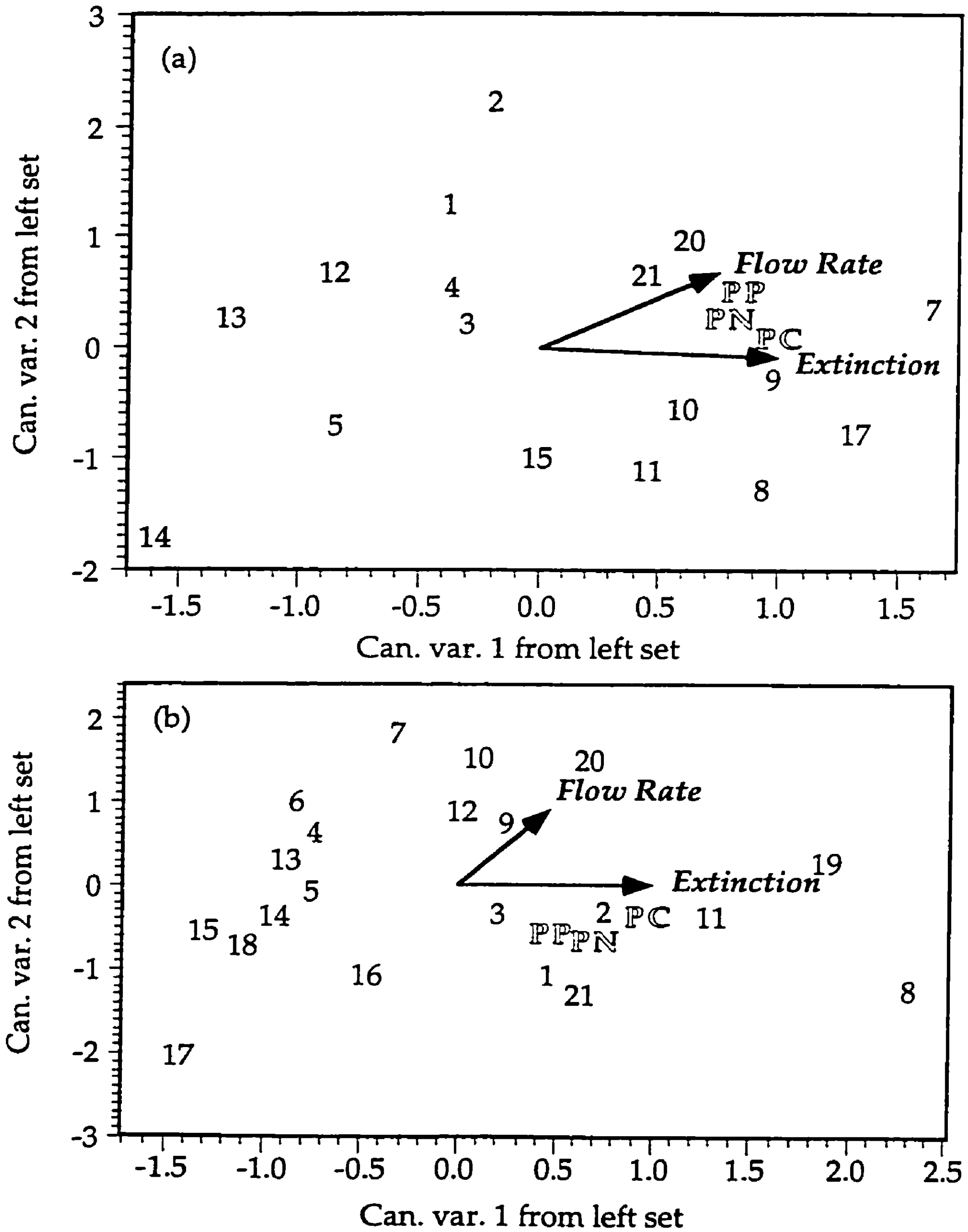


Figure 6.3 Canonical correlations analysis results for the relationship between light extinction and flow rate with particulate nitrogen (PN), phosphorus (PP) and carbon (PC) in (a) group 3 (locations 1 to 3) and (b) group 1 for all sampling weeks in 1994. Numbers represent individual sampling weeks as indicated in Appendix A.6.1.

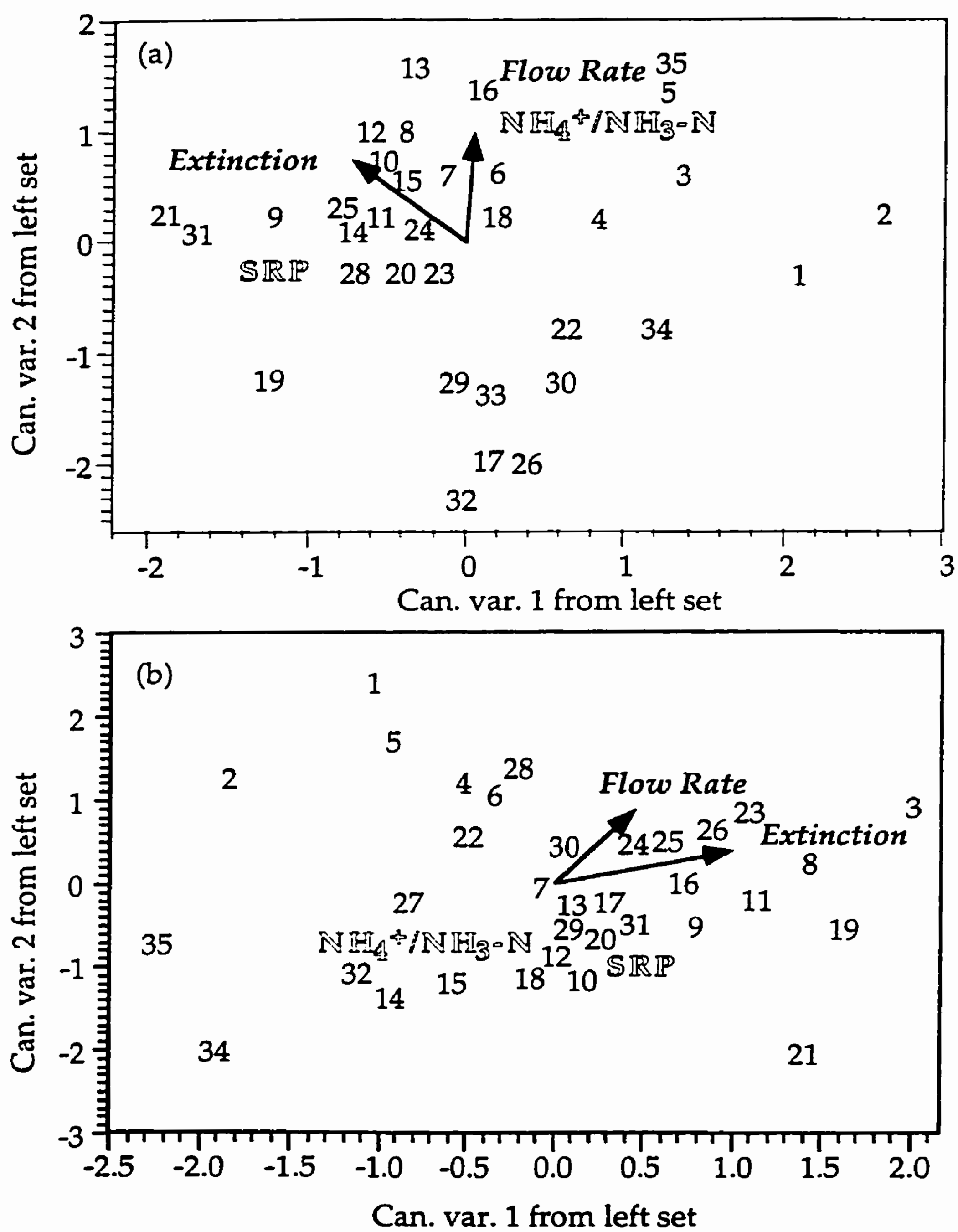


Figure 6.4 Canonical correlation analysis results for the relationship between light extinction and flow rate with ammonia-N (NH_4^+/NH_3-N) and phosphorus (SRP) in (a) group 3 (locations 1 to 3) and (b) group 1 for all sampling weeks in 1994 and 1995. Numbers represent individual sampling weeks as found in Appendix A.6.1.

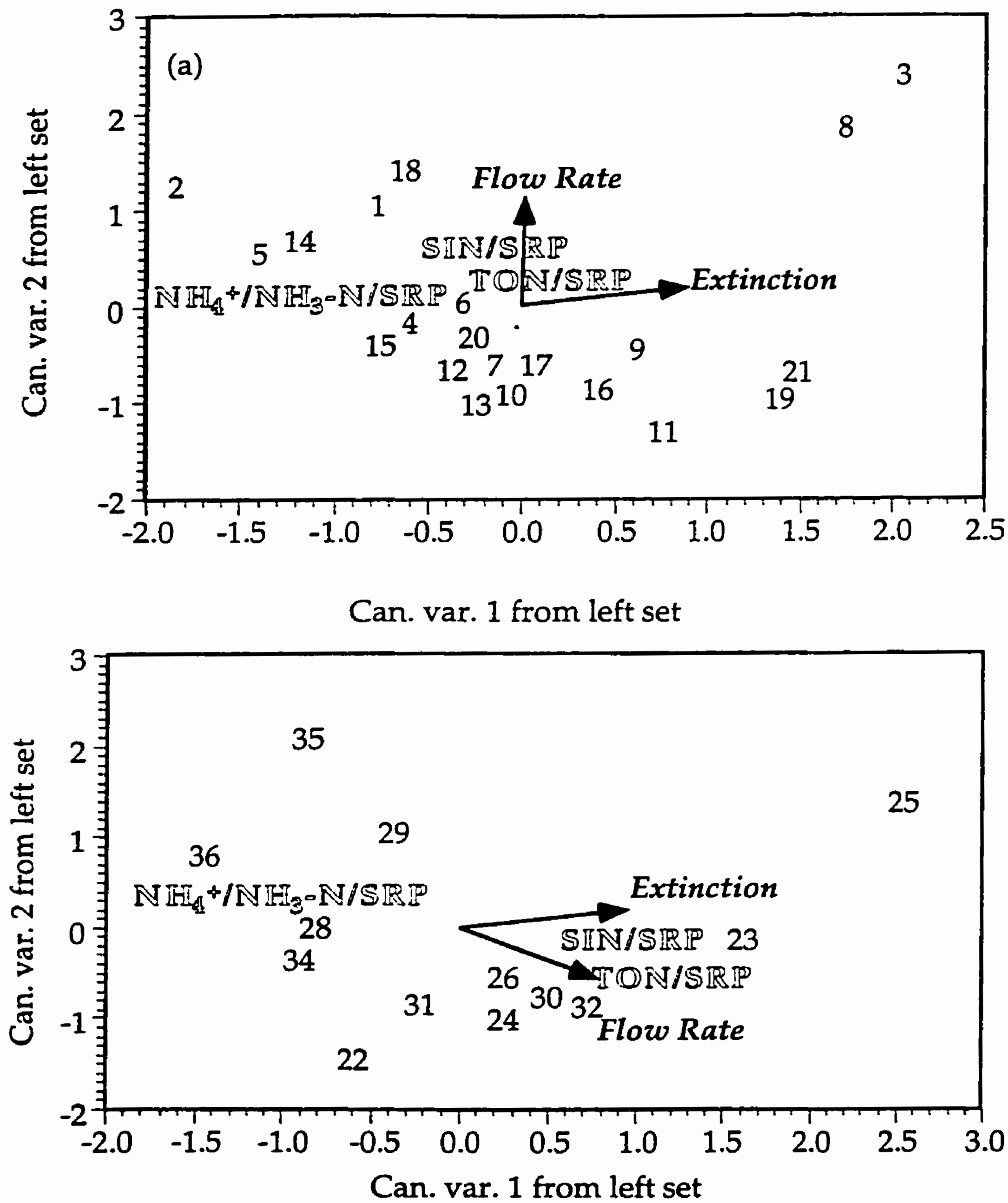
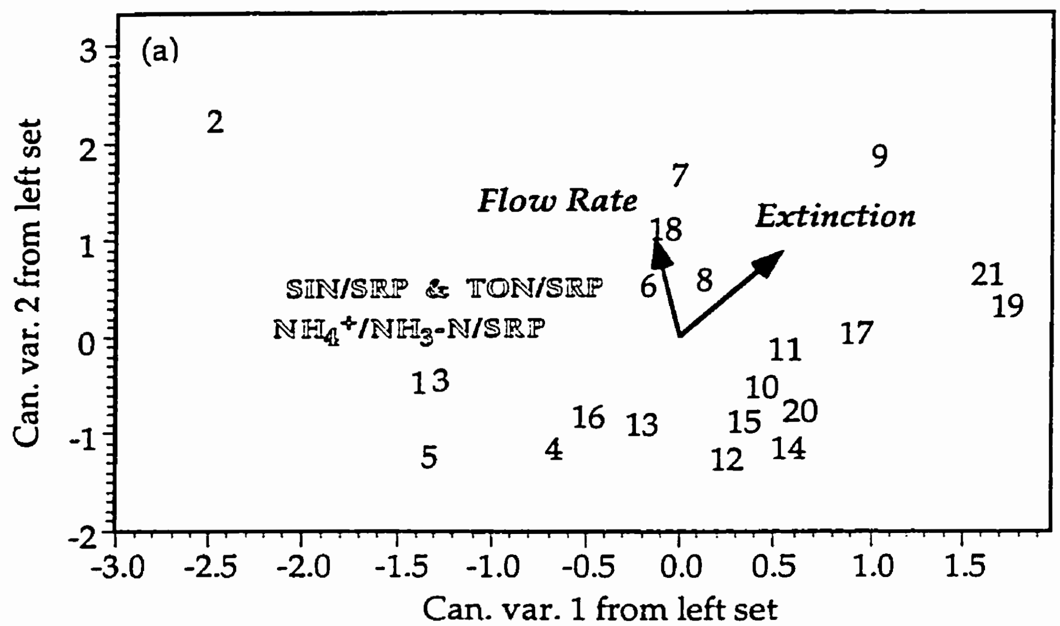


Figure 6.5 Canonical correlation analysis results for the relationship between light extinction and flow rate with N/P ratios in group 1 in (a) 1994 and (b) 1995. Numbers represent individual sampling weeks as found in Appendix A.6.1.



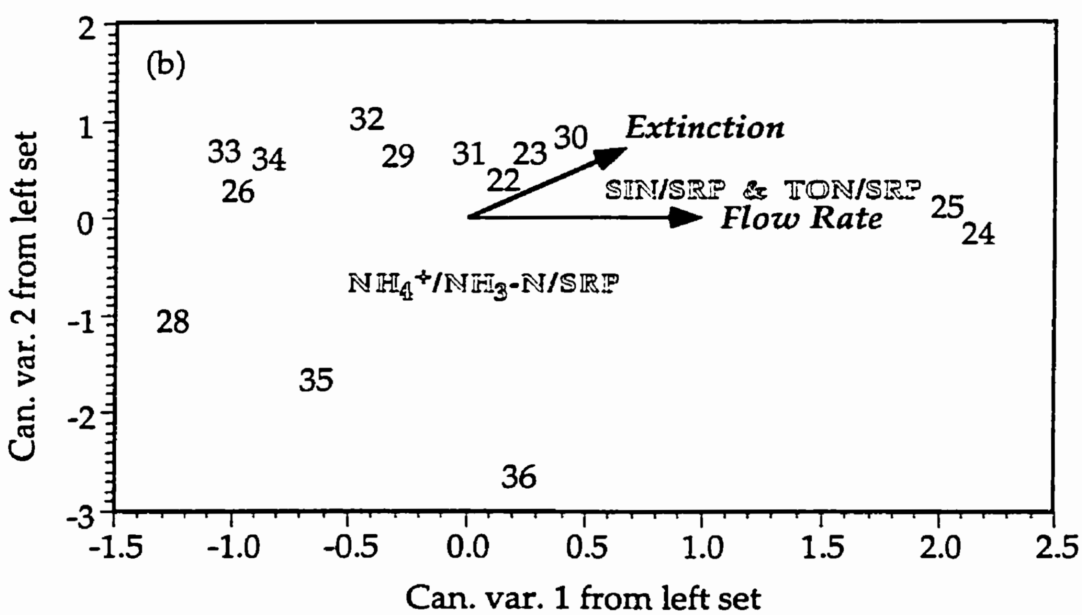


Figure 6.6 Canonical correlation analysis results for the relationship between light extinction and flow rate with N/P ratios in group 3 in (a) 1994 and (b) 1995. Numbers represent individual sampling weeks as found in Appendix A.6.1.

In each CCA, there were positive correlations observed between flow rate and light extinction. Higher flow rates were typically associated with reductions in available light, as evidenced by higher measures of light extinction. However, these were not direct relationships as evidenced by the angle shared between vectors. Furthermore, flow rate appeared to be better correlated with light extinction in group 3 when contrasted with group 1.

Results from the examination of phytoplankton response to flow rate and light extinction are presented in Figure 6.1. Typically, phytoplankton activity was significantly reduced by high flow rate and/or light extinction. In group 1, this relationship to flow rate was, however, less significant. There were times when phytoplankton activity in the group was poorly correlated to flow rate directly (i.e., $p \geq 0.05$). However, the strong negative response to light extinction remained. It appeared that, regardless of the River section phytoplankton activity was markedly influenced by light extinction. This was clearly evidenced by the segregation of biomass, alpha, P_{max} and daily estimated productivity from light extinction.

There were also pronounced correlations between physical and chemical parameters. This was observed, for example, in measures of TN and TP as well as PC, PN and PP (Figures 6.2 and 6.3). Typically, higher concentrations of totals and particulates were observed during higher flow and/or higher light extinction periods.

As first described in Chapter 5, there were striking differences in the relationship of flow rate to concentrations of particulates between groups 1 and 3 (Figure 6.3). Concentrations were highly correlated with both flow rate and light extinction in group 3 while only light extinction in group 1. Higher flow rates may have increased the particulate load in the water column in group 3, thereby increasing the extinction of light. In contrast, the particulateconcentrations in group 1 locations were uncorrelated to flow rate and concentrations were significantly lower when contrasted with group 3.

The relationships between physical factors and soluble inorganic nutrients is shown in Figure 6.4. It was found that the concentrations of SRP were higher during periods of higher light extinction. There were no significant relationships observed with flow rate ($p \geq 0.05$). Flow rate was shown, however, to have a profound influence on the concentration of NH_4^+/NH_3-N in group 1. Higher flow rates were found to dilute concentrations in the water column downstream of the NEWPCC. In contrast, there were no clear correlations for locations in group 3. Often, as evidenced in Figure 6.4, concentrations were increased by higher rates of flow, presumably because of activities occurring upstream of the study area.

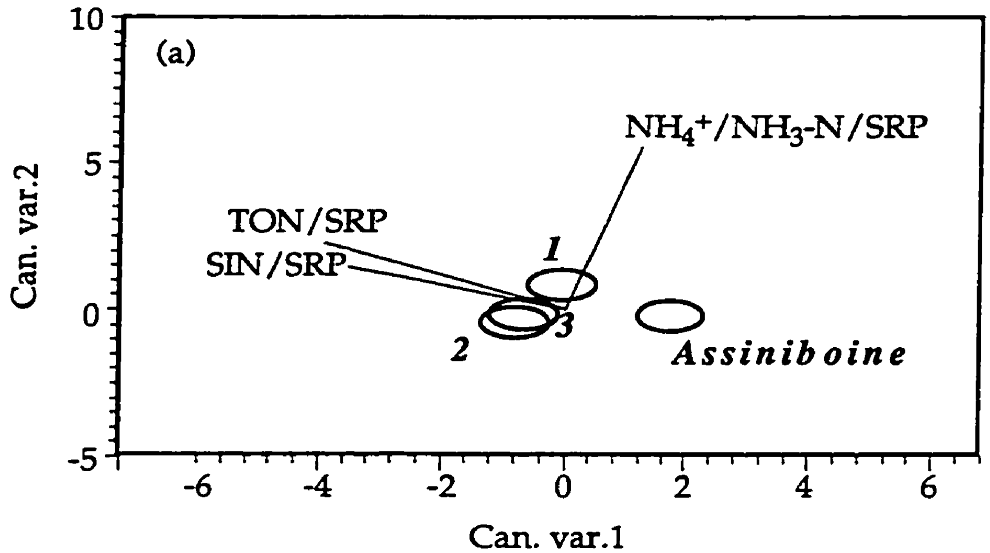
When ratios of (NH_4^+/NH_3-N)/SRP were ordinated by CCA, it was found that ratios were typically higher during lower flow and/or lower light extinction periods in group 1 in both 1994 and 1995 (Figure 6.6). These relationships were, however, poorly correlated among locations in group 3 (Figure 6.6). Furthermore, there were no significant relationships observed in the ratios of SIN/SRP and TON/SRP in both groups 1 and 3 to flow rate or light extinction in 1994 (Figures 6.5 and 6.6). In sharp contrast, higher ratios of SIN/SRP and TON/SRP were correlated with higher flow rates and light extinction in 1995 (Figure 6.5). It appeared that (NH_4^+/NH_3-N)/SRP ratios were not always parallel to ratios of SIN/SRP and TON/SRP.

These findings confirmed the occurrence of "cross"-correlations between physical and chemical factors. Consequently, individual factors could not be considered solely without their relationship to other parameters. Generally speaking, there appeared to be greater nutrients available within the water column during higher flow periods but were shown to dramatically reduce the availability of light. The notable exception appeared in concentrations of NH_4^+/NH_3-N which were higher in concentrations during lower flow, lower light extinction periods.

Spatial Heterogeneity in Phytoplankton Parameters in the Red River

Along the length of the Red River, there was significant spatial heterogeneity observed in phytoplankton activity (Figures 4.71 to 4.75 and 5.14). While anthropogenic activity was a possibly factor that modified this activity, the influence of the Assiniboine River discharge, downstream of the confluence, had to be considered as well. In order to establish the factors responsible for these spatial differences in phytoplankton activity in the Red River, MDAs were performed using ratios of SIN/SRP, TON/SRP and (NH_4^+/NH_3-N)/SRP as well as euphotic depth and chlorophyll-normalized photosynthetic parameters (i.e., SP_{max} and SPalpha). All Red River groups were used as well as the Assiniboine downstream location. Results are presented in Figures 6.7 and 6.8.

Although there were significantly lower ratios of SIN/SRP and TON/SRP observed in the Assiniboine River, there were no significant modifications observed in the chemical status downstream of the confluence in the Red River group 2 (Figure 6.7). Indeed, the SIN/SRP and TON/SRP ratios were indistinguishable among Red River groups. The (NH_4^+/NH_3-N)/SRP ratios were not found to be important in defining the differences between the Red and Assiniboine Rivers. Significantly higher ratios were, however, observed in group 1 in the Red when compared with groups 2 and 3. These findings were consistent between years of the study.



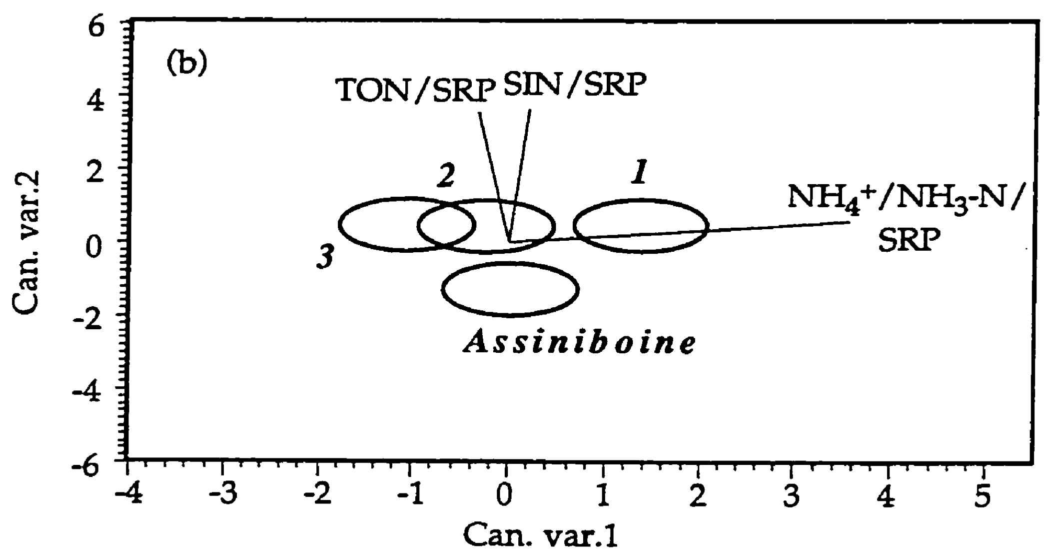


Figure 6.7 Multiple discriminant analysis of the N/P ratios found between Red River groups 1, 2 and 3 and the Assiniboine downstream location in (a) 1994 and (b) 1995. 95 % confidence intervals are indicated by the spheres. Individual sampling weeks have been removed for clarity.

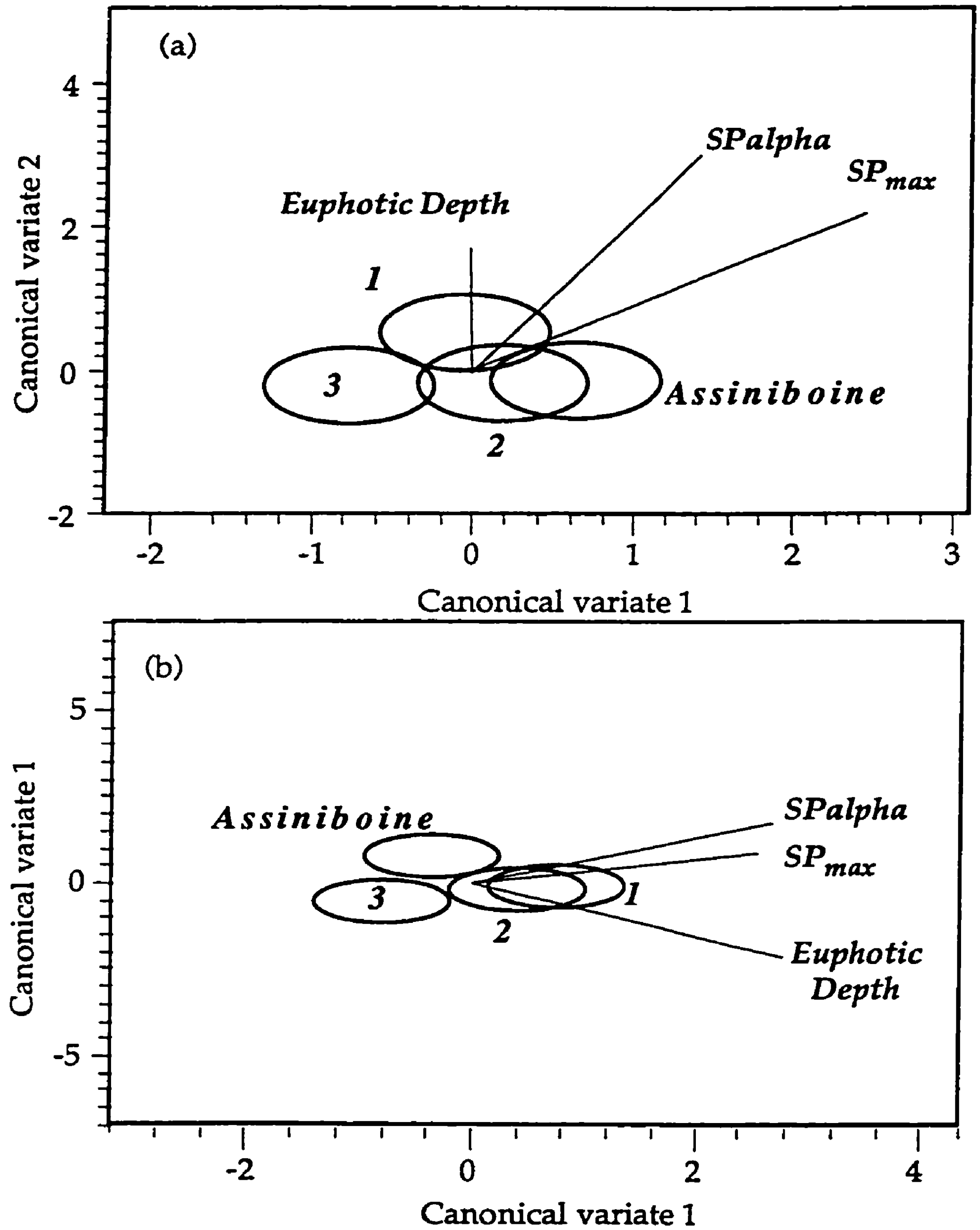


Figure 6.8 Multiple discriminant analysis of the biological parameters found between Red River groups 1, 2 and 3 and the Assiniboine downstream location in (a) 1994 and (b) 1995. 95 % confidence intervals are indicated by spheres. Individual sampling weeks have been removed for clarity.

The MDAs of photosynthetic parameters for 1994 and 1995 are found in Figure 6.8. There were no significant differences observed between the Assiniboine River and groups 1 and 2 in 1994. There were, however, significantly higher measures of SP_{max} in the Assiniboine River and group 1 of the Red River when contrasted with group 3. There were also differences found in the euphotic depths between Rivers and groups in the Red River.

In 1995, there was greater disparity between the Assiniboine and Red Rivers and between the Red River groups 1 and 3. The separations between Rivers was shown to be resultant of significantly higher euphotic depths, and to a lesser extent, phytoplankton activity in the Red River. These factors also separated groups in the Red River. Activity was highest in group 1 (Figure 6.8).

Factors That Modified Phytoplankton Activity During 1994 and 1995

While it was shown that there were many factors which fluctuated in concert with flow rate (refer to chapter 4), flow rate itself appeared to be poorly correlated with phytoplankton parameters in regression analysis (not shown). In order to quantify the factors that were influential on phytoplankton activity during 1994 and 1995, a series of CCAs were performed among locations in groups 1 and 3. This was based on the premise that phytoplankton response to anthropogenic activity would be most quantifiable if River groups were substantially isolated. Since group 2 did not consistently separate from either group 1 and/or 3 (Figures 6.7 and 6.8), it was excluded from this approach. Phytoplankton parameters including biomass, P_{max}, alpha and daily estimated productivity were ordinated in CCA with euphotic depth and N/P ratios representing the constraining environmental variables (Figure 3.4). These environmental parameters were chosen as they were consistently correlated with phytoplankton activity. Neglected from this approach were the total, particulate and organic sources of carbon, nitrogen and phosphorus since these were either cross-correlated with light availability (Figures 6.2 and 6.3), or were not significantly correlated with phytoplankton activity in simple regression analyses (i.e., $p \geq 0.05$). The results from the CCA ordinations are presented in Figures 6.9 and 6.10.

In both 1994 and 1995, the euphotic depth was clearly identified as the primary factor responsible in defining phytoplankton activity in both groups 1 and 3 (Figures 6.9 and 6.10). This was evidenced by the length of the vector in the CCA scatterplot and also in follow-up regression analyses. In 1994, 58.1 % of the variability in phytoplankton parameters was explained solely by euphotic depth (Figure 6.11). This was reduced to 43.7 % in 1995. The importance of euphotic depth was also evidenced by the placement of phytoplankton activity in the CCA nearest the axis weighted by euphotic depth.

In 1994, euphotic depth and phytoplankton activity were both shown to be greatest during episodes 2 and 4, intermediate in episode 1 and very low during episodes 3 and 5 (Figures 6.9 and 6.10). In 1995, episode 3 was characterized by lower euphotic depths and phytoplankton parameters than in either episodes 4 or 5. Episode 4 was intermediate in terms of both euphotic depth and phytoplankton activity. Week 15 was an exception in which extremely high euphotic depth and consequently high phytoplankton activity was observed (Figures 6.9 and 6.10). Lastly, there were both high euphotic depth and phytoplankton activity observed during episode 5.

The second series of axes created in the CCA were the N/P ratios. In 1994, these vectors were much shorter than in 1995, highlighting their secondary role in defining the phytoplankton relationships. Indeed, when

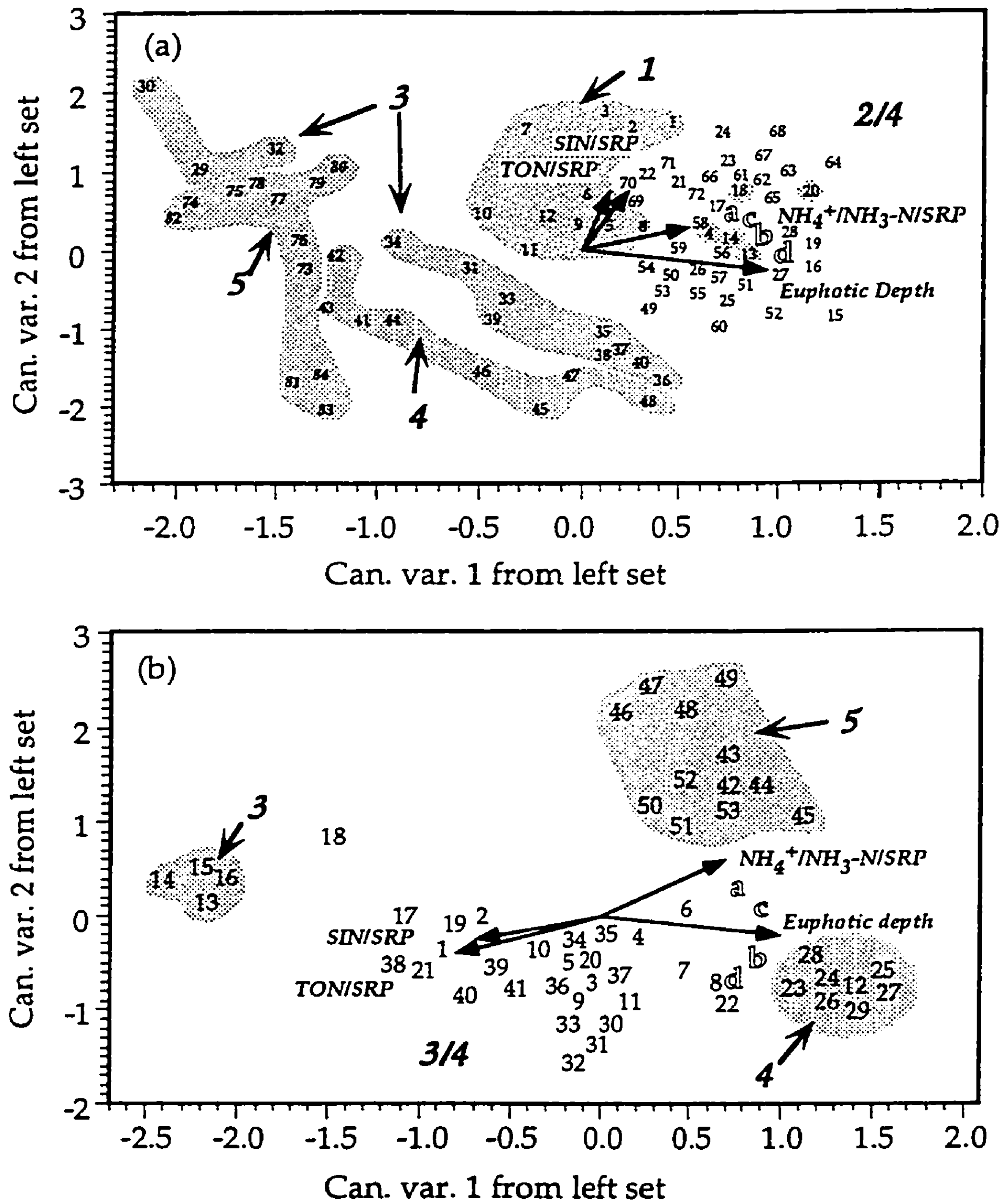


Figure 6.9 Canonical correlation analysis results for the relationships between biological activities and euphotic depth and N/P ratios as environmental variables in (a) 1994 and (b) 1995 for locations in group 1. Seasonal episodes as indicated by numbers 1 to 5. Key to individual sampling weeks is presented in Appendices A.6.2 and A.6.3.
(a = Chlorophyll a; b = P_{max}; c = alpha and d = daily estimated productivity).

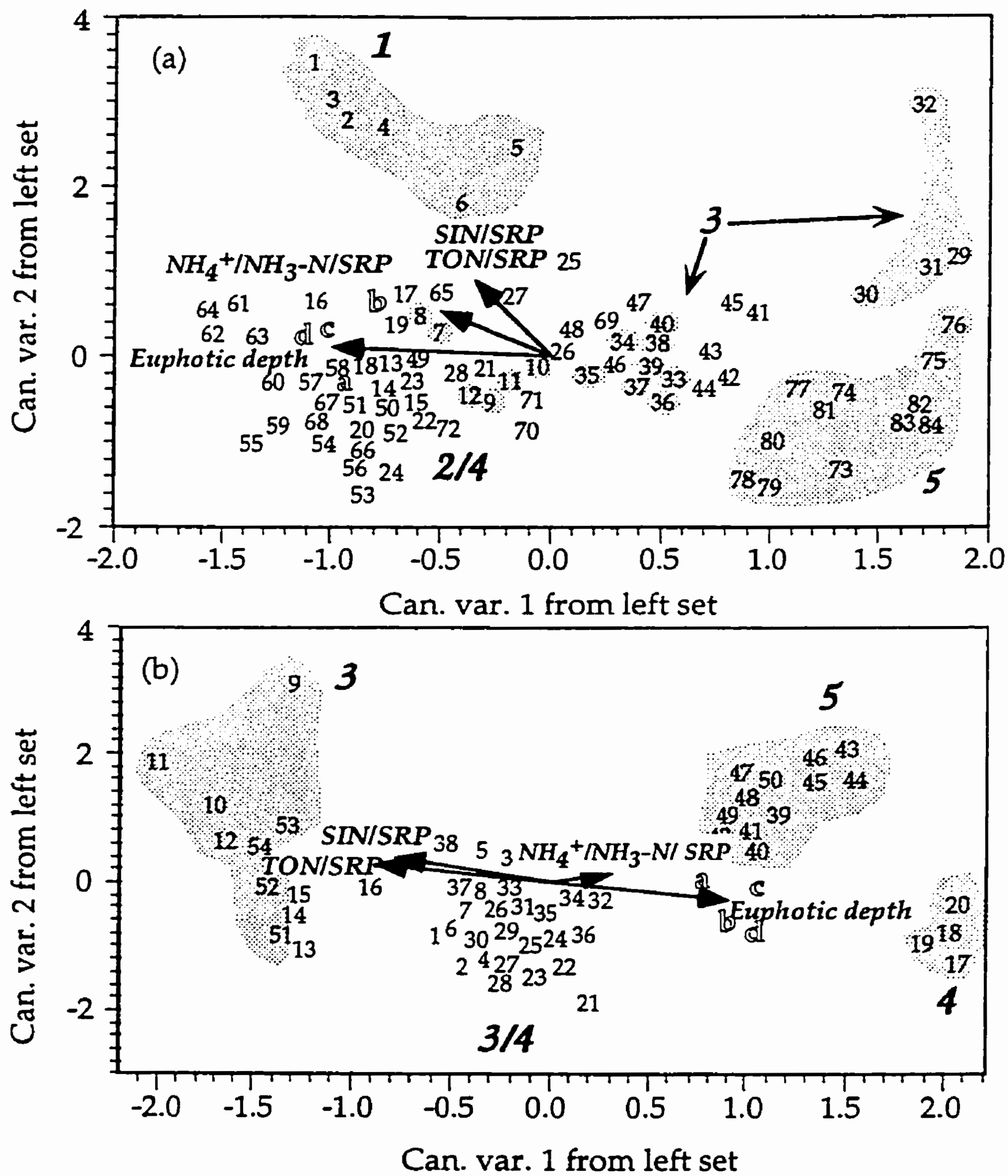


Figure 6.10 Canonical correlation analysis results for the relationships between biological activities and euphotic depth and N/P ratios as environmental variables in (a) 1994 and (b) 1995 for locations in group 3. Seasonal episodes as indicated by numbers 1 to 5. Key to individual sampling weeks is presented in Appendices A.6.2 and A.6.4.
(a = Chlorophyll a; b = P_{max}; c = alpha and d = daily estimated productivity).

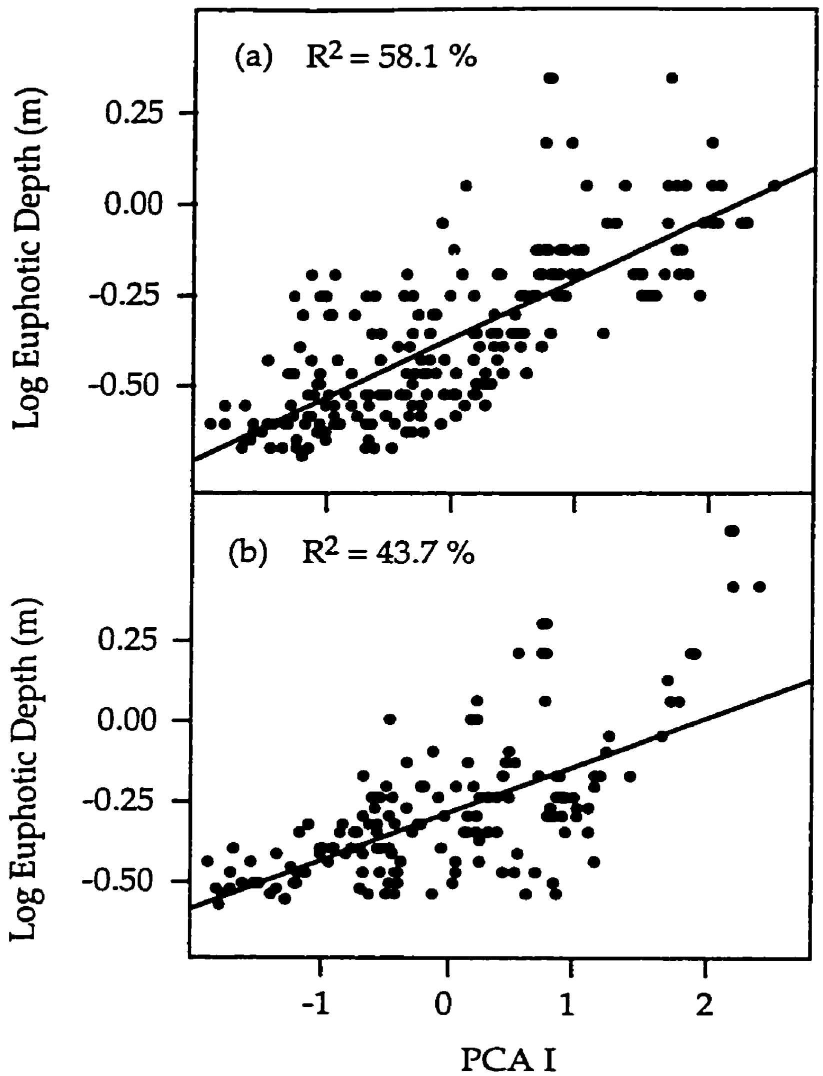


Figure 6.11 Scatterplot of principal component axis I (comprising Chl a, P_{max}, alpha and productivity) with euphotic depth in (a) 1994 and (b) 1995 in the Red River. PCA I maintained 91.5 % and 87.7 % of the variability in biological parameters in 1994 and 1995, respectively.

the 1994 regressions were compared, it was found that euphotic depth explained an equivalent proportion of the variability in phytoplankton activity as did a physico-chemical multivariate axis that included both euphotic depth and N/P ratios (Figures 6.11 and 6.12). Conversely, correlations were much higher when ratios of TON/SRP and SIN/SRP were included in the regression analysis in 1995, thereby suggesting a greater role in defining phytoplankton activity.

In 1994, all N/P ratios in the CCAs were related with euphotic depths, indicating that higher N/P ratios were typically observed during periods of deeper euphotic depths (Figure 6.9). Lower N/P ratios were only observed during periods when euphotic depths were extremely shallow, as were observed during episodes 3, 4 and 5 (Figure 6.9). In 1995, the opposite relationship was found. In particular, TON/SRP and SIN/SRP ratios were negatively correlated with euphotic depths. High euphotic depths were now shown to be related to low N/P ratios. These high euphotic depth and low N/P events were clearly observed during week 15 and seasonal episode 5 in 1995. Correlated with this condition was heightened phytoplankton activity. During seasonal episode 5 in 1995 there was also a significantly higher ratio of (NH_4^+/NH_3-N)/SRP observed. This condition was clearly unique to episode 5 and not observed during any other period in 1995 (Figure 6.9).

Coinciding with the shift in N/P ratio during episode 5 in 1995 were dramatic alterations in the behavior of alpha and P_{max}. As clearly observed in Figure 5.10, there was a "tight" relationship between P_{max} and alpha for most of 1995. The notable exception, as shown in Figure 6.13, was found in week 20 and episode 5 when SP_{max} and SPalpha differed significantly from most observations in 1995.

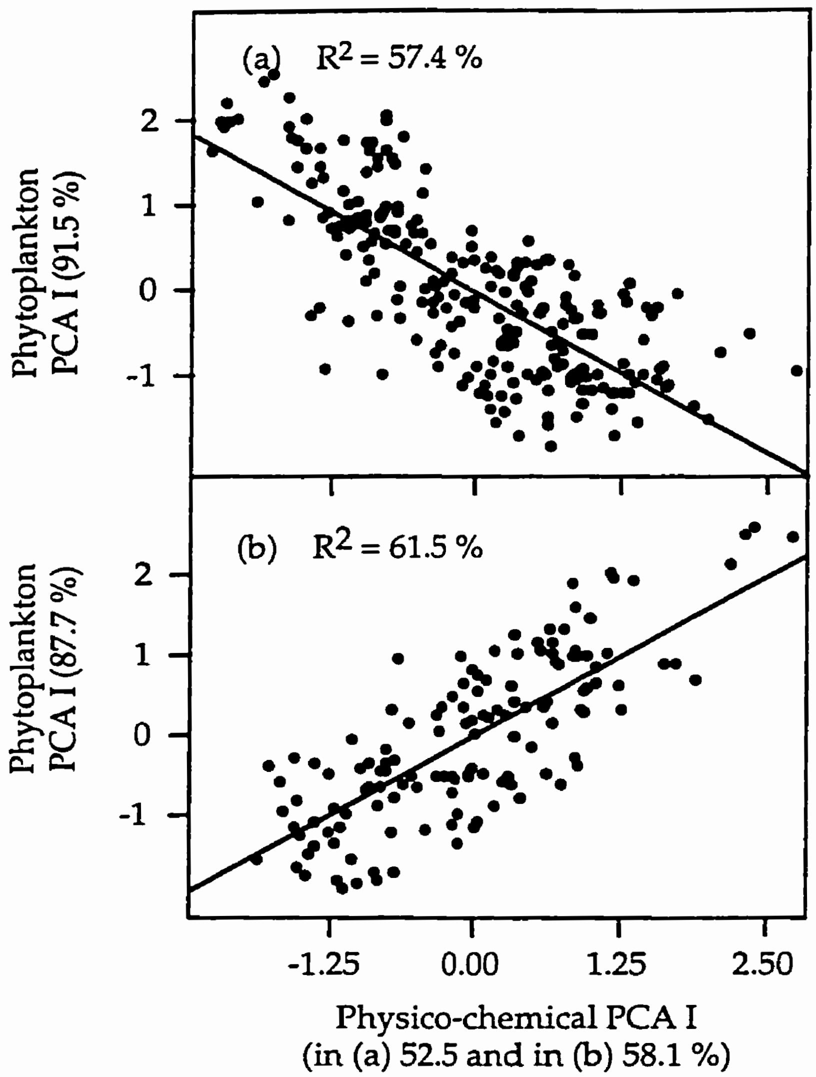


Figure 6.12 Scatterplot of the physico-chemical axis I (comprising euphotic depth and N/P ratios) with phytoplankton axis I (comprising Chl a, P_{max}, alpha and productivity) in (a) 1994 and (b) 1995 in the Red River.

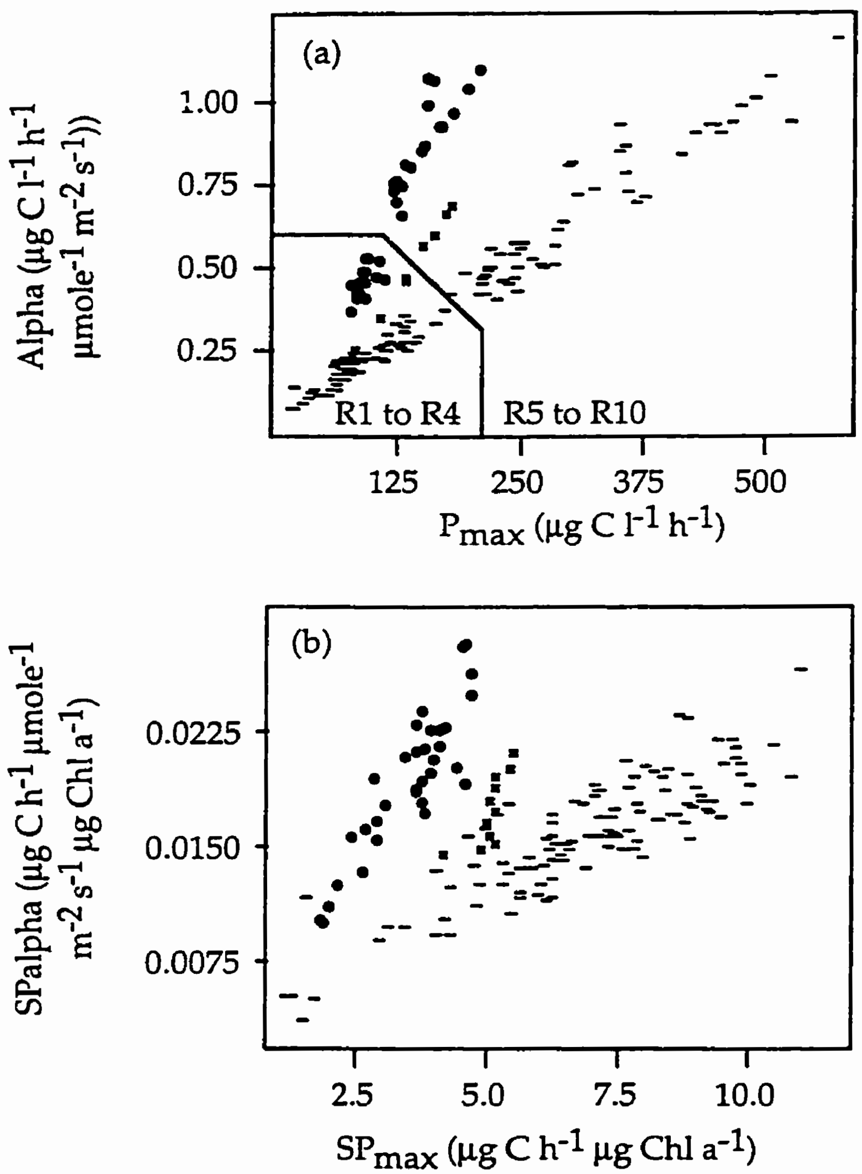


Figure 6.13 Scatterplot of autocorrelations between photosynthetic parameters. (a) P_{max} and alpha and (b) SP_{max} and SPalpha during episodes 3 and 4 (-) and episode 5 (•) in 1995. Week 20 of episode 4 was also markedly different from other weeks in episode 4 (▪).

When CCAs from group 1 were contrasted with those of group 3, there were few inconsistencies observed. For the most part, the relationships were similar between groups (Figures 6.9 and 6.10). In particular the downward shift in the N/P ratio that was observed in group 1 during seasonal episode 5 in 1995 was also observed in group 3. These conservative responses between River sections were related to the constancy in SIN/SRP and TON/SRP ratios. By analysis of variance, it was found that spatial differences in these parameters were restricted to seasonal episode 5 in 1994 and episode 3 in 1995 ($p = 0.000$ in both instances). During episode 5, the ratios were found to be significantly higher in group 1 but higher in group 3 during episode 3 (Figures 6.14 and 6.15).

6.3 Discussion

Phytoplankton in the Red River was shown to exhibit pronounced seasonal fluctuations that were based on the cycling in physical and chemical parameters. Although factors such as water temperature have been shown to strongly influence photosynthesis (Davison 1991, Baker and Baker 1979), in this study it was flow rate and/or the light environment that imposed the greatest limitation on phytoplankton activity (i.e., Grobbelaar 1989, Dokulil 1994 and Reynolds 1994). As Grobbelaar (1985) and others have pointed out, there are significant increases in abiogenic suspended loads during high flows that dramatically increase turbidity and the attenuation of light within the water column. In this study, the impact of higher concentrations of PC, PN and PP on the extinction of light were clearly evident (Figure 6.3). Søballe and Kimmel (1987) have reported that biogenic factors such as TP and TN may not be highly correlated with phytoplankton activity in turbid systems. In this study, increases in TP and TN were correlated with increased light extinction

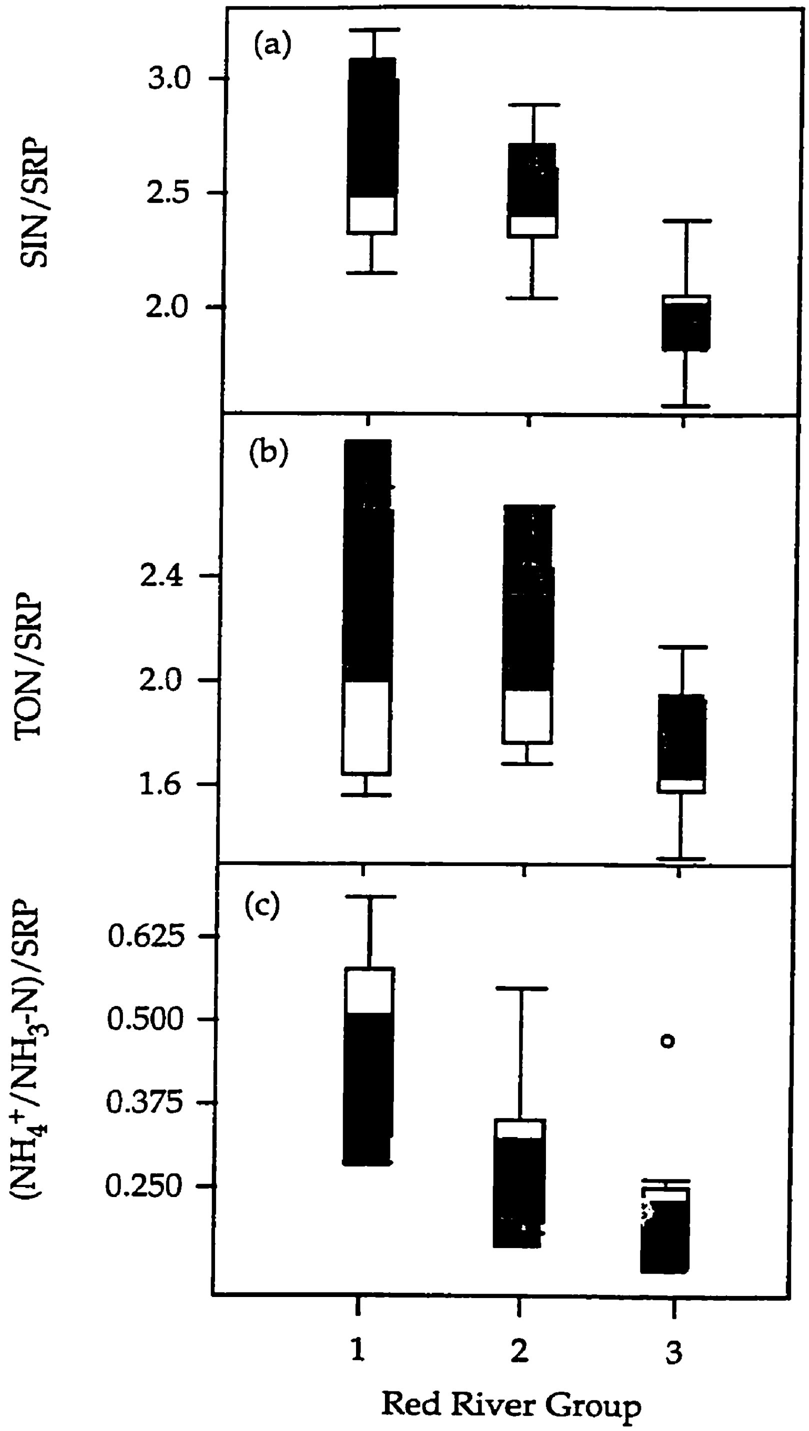


Figure 6.14 Boxplots of N/P ratios in the Red River during seasonal episode 5 in 1994 during which significant differences ($p = 0.000$) were observed between groups.

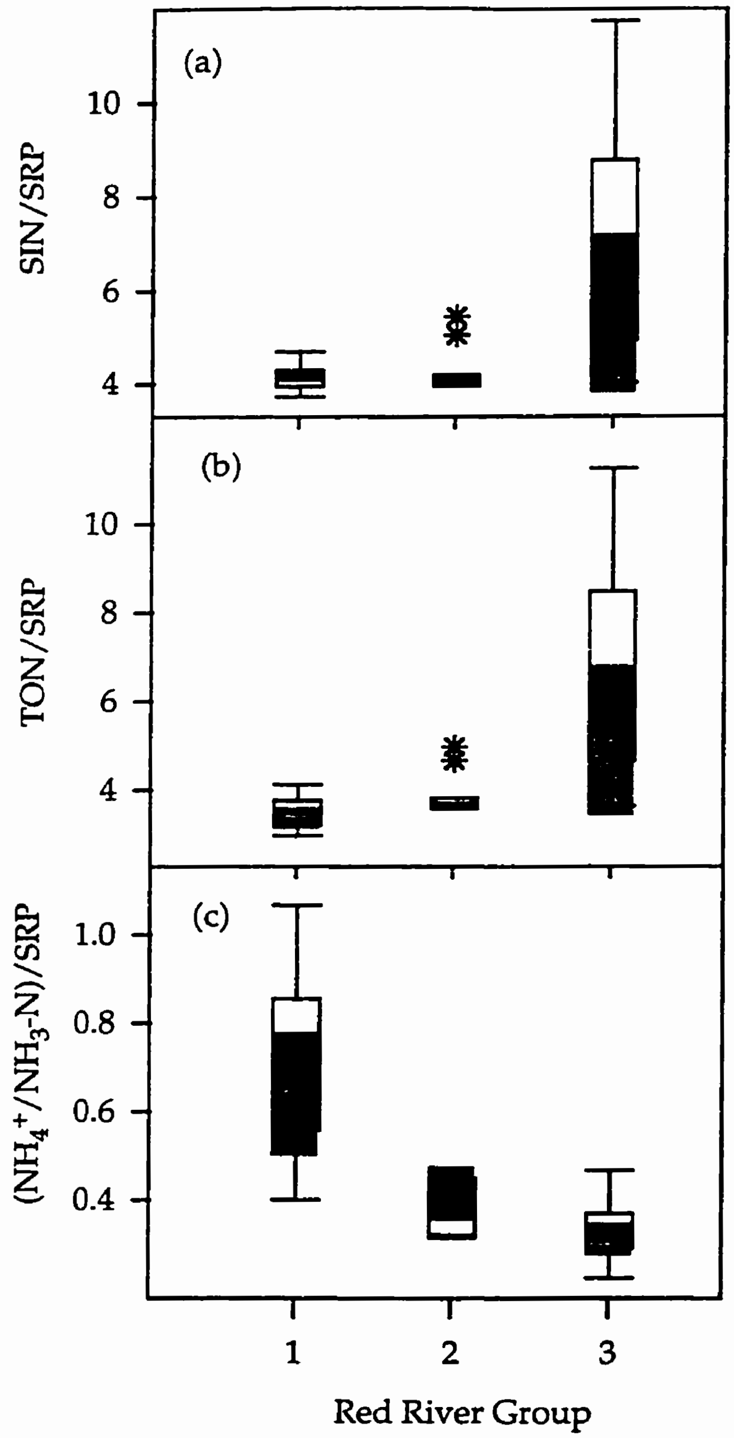


Figure 6.15 Boxplots of N/P ratios in the Red River during seasonal episode 3 in 1995 during which signfiicant differences (p = 0.000) were observed between groups.

(Figure 6.2) and consequently with pronounced reductions in phytoplankton photosynthesis (Figure 6.1).

Perhaps the greatest evidence for the overwhelming influence of light on phytoplankton activity in the Red River was observed in the disparity of responses during episode 5 in 1994 and 1995 (Figures 6.9 and 6.10). In particular, phytoplankton activity during 1994 were measurably lower than had been found in previous episodes and was correlated with significant reductions in the light environment. In contrast, episode 5, in 1995, was characterized by deep euphotic depths, low light extinctions and high phytoplankton activity. Furthermore, phytoplankton activity was profoundly influenced by the low N/P ratio, as evidenced in both changes in alpha and P_{max} (Figure 6.13) that coincided with the occurrence of the cyanobacteria Anabaena and Aphanizomenon spp. While this low N/P ratio was observed during the same episode in 1994, it was inconsequential in defining phytoplankton activity because it's importance was offset by the poor light environment. Consequently, phytoplankton activity during episode 5 in 1994 were significantly reduced when contrasted with 1995.

There were other periods in this study found to exhibit these light driven responses in the phytoplankton community. During episode 3 in 1994, there were significantly lower SIN/SRP ratios observed in group 1 than in any other period during the year. However, the significant reduction in available light suppressed any biogenic response to chemical changes. As well, there was unusually low phytoplankton productivity in weeks 11 and 13 in 1995. In simple regressions of physico-chemical factors with phytoplankton parameters, these weeks appeared as strong outliers. However, both events were shown by CCA to be resultant of a pronounced reduction in the light environment. While the phytoplankton activity observed in week 13 was considerably lower that most weeks in episode 4, there was significantly higher activity observed in week 15. Again, it was correlated with dramatic changes in the light environment (Figures 6.9 and 6.10). Indeed, the contrast between weeks 13 and 15 in 1995 provides an appreciation of the oscillating nature in phytoplankton activity in the Red River in response to the dynamic light environment.

The importance of physical and chemical factors in modifying phytoplankton activity is therefore best viewed along a gradient of River discharge (Søballe and Kimmel 1987). During high flow periods, the light environment is the principle factor that determines phytoplankton performance. Although the environment may be nutrient sufficient, phytoplankton biomass is limited by the rapid attenuation of light by non-phytoplankton turbidity (Grobbelaar 1985, Lind *et al.* 1992). Consequently, the relationships between chemical status and phytoplankton activity are offset and ambiguous. In 1994, only poorly correlated nutrient relationships were observed. The most highly correlated relationships with phytoplankton activity were those to physical factors rather than a combined physico-chemical axis (Figures 6.11 and 6.12).

Reynolds *et al.* (1994) described few situations in which chemical factors defined biotic activity in turbid systems. In this study, chemical status did become a factor in defining phytoplankton dynamics after the light environment and physical constraints were removed. This was clearly shown when the low N/P ratio, observed during episode 5 in 1995, became a dominant factor correlated with heightened phytoplankton activity and the occurrence of cyanobacteria (Figures 6.9, 6.10 and 6.13). Jacobsen (1994) found that after the physical factors were lessened, chemical status became a dominant influence on the assembly and succession of the phytoplankton community.

Phytoplankton responses to low N/P ratios are clearly documented (i.e., Schindler 1977, Healey and Hendzel 1980 and Hecky *et al.* 1993). As pointed out by Flett and co-workers (1980), the correlation of bloom formation is stronger with the low SIN/SRP ratio and not the concentration of NH_4^+-N itself. As shown in this study, the higher NH_4^+/NH_3-N concentration that was concurrently observed with changes in phytoplankton activity and the occurrence of cyanobacteria was not critical in modifying phytoplankton responses. Rather, it was the overall SIN/SRP ratio that evoked these changes (Figures 6.9 and 6.10).

In this study, there was significantly greater phytoplankton activity observed in group 1 when contrasted with group 3. Biomass, alpha, P_{max} and daily estimated productivity were all significantly higher in locations R7 to R10 when contrasted with locations R1 to R4 (Figures 4.71 to 4.75). However, as clearly shown in this study, the dynamism in phytoplankton did not differ markedly between groups. In particular, the CCAs showed that phytoplankton performance was conserved between upstream and downstream sections and that the light environment retained it's over-riding influence on phytoplankton activity downstream of the NEWPCC (Figures 6.9 and 6.10). Furthermore, during periods when chemical status was a defining factor (i.e., episode 5 in 1995), phytoplankton responses were similar in both groups 1 and 3. This was evidenced in comparable shifts in alpha and P_{max} (Figure 6.13) as well as substantially heightened phytoplankton activity (Figure 6.9 and 6.10). It appeared that while group 1 locations received effluent and urban runoff from the City of Winnipeg, phytoplankton activity was not profoundly different from that in group 3.

The factor likely responsible for the conservative phytoplankton response was the SIN/SRP ratio. Even though NH_4^+/NH_3-N concentrations were shown to increase dramatically through the City of Winnipeg, it did not appear to influence the SIN/SRP ratio. Spatial differences in the SIN/SRP ratio were restricted to few periods and in particular, seasonal episode 5 in 1994 and seasonal episode 3 in 1995 (Figures 6.14 and 6.15).

The Assiniboine River had little influence on the chemical status of the Red River. As was shown previously, the discharge at the confluence was found to result in a dilution of NH_4^+/NH_3-N concentrations between R4 and R5 (Figure 4.82). Furthermore, the differences in SIN/SRP and TON/SRP had negligible influences on group 2 chemical status (Figure 6.8). Indeed, both group 3 and 2 were equivalent.

In contrast, the Assiniboine River was shown to exhibit differences in phytoplankton activity from that in group 3 in 1994, and all Red River groups in 1995. This separation was manifested as higher SP_{max} when contrasted to group 3 and in 1995, by euphotic depth.

Although the influence of the Assiniboine discharge on phytoplankton dynamics downstream of the confluence can not be dismissed, it is proposed to have only a minor role in defining spatial heterogeneity, if it has a role at all. While there were significant differences found between groups 3 and 2 that were potentially the result of Assiniboine discharge, these were restricted to 1995 (Figure 6.8) Furthermore, these differences were correlated with euphotic depth which has been clearly shown to be the most critical factor defining phytoplankton activity. Thus, it is difficult to quantify the differences between groups 2 and 3 based solely on the discharge from the Assiniboine River when these differences may have been related to the light environment.

Rather, it is proposed that the greater phytoplankton activity observed downstream of the Assiniboine confluence and the City of Winnipeg is primarily resultant of the morphometric features of the Red River and secondarily, the enrichment by anthropogenic discharges. Furthermore, this is proposed to have influenced only the standing crop of the phytoplankton community. As has been described in Chapters 2 and 4, there are reductions in flow rate, enhancement of light availability and nutrients downstream of group 3 and it is therefore difficult to discount the influence of one parameter for another. However, as has been clearly established in this study, the foremost factor that determined phytoplankton activity was the availability of light. Because of the Lockport Dam, there are both greater euphotic depths and lower light extinctions found in locations in groups 1 and 2 (Figures 4.38 and 4.40) that would permit greater phytoplankton photosynthesis.

It does not appear that the higher NH_4^+/NH_3-N concentrations inhibited phytoplankton activity downstream of the SEWPCC or the NEWPCC. In fact, there is no evidence that NH_4^+/NH_3-N influenced phytoplankton activity either positively or negatively. Indeed, there appeared to be spurious relationships between (NH_4^+/NH_3-N)/SRP ratios and phytoplankton activity in seasonal episode 5 in 1995. Rather, the occurrence of heterocystous cyanobacteria was correlated with a downward shift in SIN/SRP ratios (Flett et al. 1980).

The high NH_4^+/NH_3-N concentrations that coincided with enhanced phytoplankton activity during this study can not be quantified because of the "cross"-correlation between light availability and NH_4^+/NH_3-N concentrations. In particular, higher phytoplankton activity was observed in conjunction with enhanced light availability and higher NH_4^+/NH_3-N concentration (Figure 6.4). Therefore, the influence of NH_4^+/NH_3-N on phytoplankton activity could not be isolated from the influence of enhanced light availability on phytoplankton activity. The latter was clearly shown in this study to markedly influence phytoplankton response.

6.4 Summary

1. There were significant seasonal cycles observed in phytoplankton activity that were correlated with changes in physical and chemical parameters. During high flow periods, there were typically low light environments and low phytoplankton activity observed.

2. The light environment was shown to be significantly altered by flow rate and/or PC, PN and PP concentrations. Strong correlations existed in group 3 between flow rate and light extinction with concentrations of TN and TP and PN, PP and PC. In group 1, correlations were observed between particulates and light availability only.

3. Although nutrient concentrations were typically higher in concentration during higher flow periods, there was a pronounced reduction in light environment. Consequently, phytoplankton activity was poorly correlated with high nutrient levels.

4. The factor that overwhelmingly determined phytoplankton activity in this study was the availability of light within the water column. This influence was so strong that it suppressed chemical influences on phytoplankton activity during light-limiting periods (Grobbelaar 1985, Lind *et al.* 1992).

5. The influence of light availability on phytoplankton production was highlighted by the oscillations in phytoplankton activity within each seasonal episode. Examples of these oscillating responses were clearly observed during episode 4 in 1995.

6. The influence of chemical factors on phytoplankton activity were restricted to a few seasonal episodes in 1995. The most pronounced

influence was observed during episode 5 when lower N/P ratios were correlated with pronounced changes in alpha and P_{max}. The occurrence of cyanobacteria, Anabaena and Aphanizomenon spp. during this period was also noted.

7. There was a constancy of phytoplankton responses found between River sections that was, in this study, unaltered by City of Winnipeg activity. It appeared that the low ratios of N/P observed late in 1995 were equivalent among locations in groups 3 and 1.

8. The consistency in phytoplankton responses is proposed to be the result of a relatively stable SIN/SRP ratio between locations along the Red River. Few periods were found during this study in which these N/P ratios differed significantly.

9. This study was not able to distinguish any influences of NH_4^+/NH_3-N on phytoplankton activity from the significant "cross"-correlations it shared with flow rate and light availability. There were two reasons for this. Firstly, elevated River flow rate was shown to dilute NH_4^+/NH_3-N concentration. However, correlated with this action was a significant reduction in the light environment that had a profound influence on phytoplankton activity. Secondly, there was a gradient between locations of reduced flow rate, greater euphotic depth, and reduced light extinction that coincided with a higher concentration of NH_4^+/NH_3-N from anthropogenic activity. Thus, a higher NH_4^+/NH_3-N concentration was always observed in conjunction with more available light. Consequently, the influence NH_4^+/NH_3-N on phytoplankton performances could not be isolated from the issue of light availability.

10. There did not appear to be any negative influences of NH_4^+/NH_3-N concentrations on phytoplankton activity. Indeed phytoplankton activity was significantly higher among locations downstream of the NEWPCC in conjunction with higher concentrations of NH_4^+/NH_3-N. Furthermore, ratios of (NH_4^+/NH_3-N)/SRP were spurious in defining phytoplankton activity as was evidenced during seasonal episode 5, in 1995.

11. Although there were significant differences observed in phytoplankton activity and SIN/SRP ratios between the Assiniboine and Red Rivers, there appeared to be little impact of these differences upon activity downstream of the confluence. SIN/SRP ratios did not differ significantly between groups 2 and 3 and the phytoplankton responses in group 2 were comparable to group 3 and/or 1.

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Appendix

Table A.6.1 Key to the numbering of sampling weeks employed in canonical correlation analysis in Figures 6.1 to 6.6. Means of locations within each group were used.

Canonical Correlate Number	Corresponding Sampling Week	Year
1	1	1994
2	2	1994
3	3	1994
4	4	1994
5	5	1994
6	6	1994
7	7	1994
8	8	1994
9	9	1994
10	10	1994
11	13	1994
12	14	1994
13	15	1994
14	16	1994
15	17	1994
16	18	1994
17	19	1994
18	20	1994
19	21	1994
20	22	1994
21	23	1994
22	8	1995
23	9	1995
24	10	1995
25	11	1995
26	13	1995
27	14	1995
28	15	1995
29	16	1995
30	17	1995
31	18	1995
32	19	1995
33	20	1995
34	21	1995
35	22	1995
36	23	1995

Table A.6.2 Key to the numbering of sampling weeks employed in canonical correlation analsyis in Figures 6.9a and 6.10a.

CCA Number	Year	Seasonal Episode	Week	GROUP 1 Locations	GROUP 3 Locations
1	1994	1	1	7	1
2	1994	1	1	8	2
3	1994	1	1	9	3
4	1994	1	1	10	4
5	1994	1	2	7	1
6	1994	1	2	8	2
7	1994	1	2	9	3
8	1994	1	2	10	4
9	1994	1	3	7	1
10	1994	1	3	8	2
11	1994	1	3	9	3
12	1994	1	3	10	4
13	1994	2	4	7	1
14	1994	2	4	8	2
15	1994	2	4	9	3
16	1994	2	4	10	4
17	1994	2	5	7	1
18	1994	2	5	8	2
19	1994	2	5	9	3
20	1994	2	5	10	4
21	1994	2	6	7	1
22	1994	2	6	8	2
23	1994	2	6	9	3
24	1994	2	6	10	4
25	1994	2	7	7	1
26	1994	2	7	8	2
27	1994	2	7	9	3
28	1994	2	7	10	4
29	1994	3	8	7	1
30	1994	3	8	8	2
31	1994	3	8	9	3
32	1994	3	8	10	4
33	1994	3	9	7	1
34	1994	3	9	8	2
35	1994	3	9	9	3
36	1994	3	9	10	4
37	1994	3	10	7	1
38	1994	3	10	8	2
39	1994	3	10	9	3
40	1994	3	10	10	4
41	1994	4	13	7	1

CCA Number	Year	Seasonal Episode	Week	GROUP 1 Locations	GROUP 3 Locations
42	1994	4	13	8	2
43	1994	4	13	9	3
44	1994	4	13	10	4
45	1994	4	14	7	1
46	1994	4	14	8	2
47	1994	4	14	9	3
48	1994	4	14	10	4
49	1994	4	15	7	1
50	1994	4	15	8	2
51	1994	4	15	9	3
52	1994	4	15	10	4
53	1994	4	16	7	1
54	1994	4	16	8	2
55	1994	4	16	9	3
56	1994	4	16	10	4
57	1994	4	17	7	1
58	1994	4	17	8	2
59	1994	4	17	9	3
60	1994	4	17	10	4
61	1994	4	18	7	1
62	1994	4	18	8	2
63	1994	4	18	9	3
64	1994	4	18	10	4
65	1994	4	19	7	1
66	1994	4	19	8	2
67	1994	4	19	9	3
68	1994	4	19	10	4
69	1994	4	20	7	1
70	1994	4	20	8	2
71	1994	4	20	9	3
72	1994	4	20	10	4
73	1994	5	21	7	1
74	1994	5	21	8	2
75	1994	5	21	9	3
76	1994	5	21	10	4
77	1994	5	22	7	1
78	1994	5	22	8	2
79	1994	5	22	9	3
80	1994	5	22	10	4
81	1994	5	23	7	1
82	1994	5	23	8	2
83	1994	5	23	9	3
84	1994	5	23	10	4

Table A.6.3 Key to the numbering of sampling weeks employed in canonical correlation analysis in Figure 6.9b.

CCA Number	Year	Seasonal Episode	Week	Group 1 Locations
1	1995	3	8	7
2	1995	3	8	8
3	1995	3	8	9
4	1995	3	8	10
5	1995	3	9	7
6	1995	3	9	8
7	1995	3	9	9
8	1995	3	9	10
9	1995	3	10	7
10	1995	3	10	8
11	1995	3	10	9
12	1995	3	10	10
13	1995	3	11	7
14	1995	3	11	8
15	1995	3	11	9
16	1995	3	11	10
17	1995	4	13	7
18	1995	4	13	8
19	1995	4	13	9
20	1995	4	13	10
21	1995	4	14	7
22	1995	4	15	7
23	1995	4	15	8
24	1995	4	15	9
25	1995	4	15	10
26	1995	4	16	7
27	1995	4	16	8
28	1995	4	16	9
29	1995	4	16	10
30	1995	4	17	7
31	1995	4	17	8
32	1995	4	17	9
33	1995	4	17	10
34	1995	4	18	7
35	1995	4	18	8
36	1995	4	18	9
37	1995	4	18	10
38	1995	4	19	7
39	1995	4	19	8
40	1995	4	19	9
41	1995	4	19	10

CCA Number	Year	Seasonal Episode	Week	Group 1 Locations
42	1995	4	21	7
43	1995	4	21	8
44	1995	4	21	9
45	1995	5	21	10
46	1995	5	22	7
47	1995	5	22	8
48	1995	5	22	9
49	1995	5	22	10
50	1995	5	23	7
51	1995	5	23	8
52	1995	5	23	9
53	1995	5	23	10

Table A.6.4 Key to the numbering of sampling weeks employed in canoncial correlation analysis in Figure 6.10b.

CCA Number	Year	Seasonal Episode	Week	Group 3 Locations
1	1995	3	8	1
2	1995	3	8	2
3	1995	3	8	3
4	1995	3	8	4
5	1995	3	9	1
6	1995	3	9	2
7	1995	3	9	3
8	1995	3	9	4
9	1995	3	10	1
10	1995	3	10	2
11	1995	3	10	3
12	1995	3	10	4
13	1995	4	13	1
14	1995	4	13	2
15	1995	4	13	3
16	1995	4	13	4
17	1995	4	15	1
18	1995	4	15	2
19	1995	4	15	3
20	1995	4	15	4
21	1995	4	16	1
22	1995	4	16	2
23	1995	4	16	3
24	1995	4	16	4
25	1995	4	17	1
26	1995	4	17	2
27	1995	4	17	3
28	1995	4	17	4
29	1995	4	18	1
30	1995	4	18	2
31	1995	4	18	3
32	1995	4	18	4
33	1995	4	19	1
34	1995	4	19	2
35	1995	4	19	3
36	1995	4	19	4
37	1995	4	20	1
38	1995	4	20	2
39	1995	5	21	1
40	1995	5	21	2

CCA Number	Year	Seasonal Episode	Week	Group 3 Locations
41	1995	5	21	3
42	1995	5	21	4
43	1995	5	22	1
44	1995	5	22	2
45	1995	5	22	3
46	1995	5	22	4
47	1995	5	23	1
48	1995	5	23	2
49	1995	5	23	3
50	1995	5	23	4
51	1995	3	11	1
52	1995	3	11	2
53	1995	3	11	3
54	1995	3	11	4