Impact of urbanization on the water quality, fish habitat, and fish community of a Lake Ontario coastal marsh, Frenchman's Bay

Report prepared for the City of Pickering
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SUMMARY

We conducted a two-year (2001-3) study to assess the impacts of urbanization on the water quality and fish habitat of Frenchman's Bay, which is located in a highly urbanized watershed of Lake Ontario, Canada. During summer (end of May to mid-September) 2002, continuous monitoring devices were installed in two main tributaries, Amberlea Creek (below Hwy 401) and Pine Creek (above Hwy 401), and in two stations of the bay to measure a suite of physico-chemical parameters. Because of the low water levels, the monitoring was discontinued in the marsh, but was maintained in Amberlea and Pine Creeks from September 2002 to end of March 2003. We also carried out a parallel biweekly sampling program for nutrient and suspended solids at an open-water station during the summer of 2002 and one winter sampling trip in January 2003. Our investigation of the aquatic food-web included a survey of the aquatic plant community during the summer of 2001 and 2002, and a wetland-fish community survey that included nine sampling occasions between August 2001 and November 2002.

The negative impact of runoff from Hwy 401 on the water quality of Amberlea Creek was clear: elevated levels of suspended solids and dissolved nutrients in summer, and elevated water turbidity and conductivity during winter could be linked directly to the onset of precipitation events. By comparison, water quality of the Pine Creek station, which is located well above the highway, did not exhibit the same degree of degradation, although we suspect that similarly degraded conditions would be found in Pine Creek downstream of Hwy 401. The heavier than normal rainstorms in July 2002 gave an excellent opportunity to observe the effects of storm events on creeks, while drier and hotter than normal weather in August allowed us a glimpse into how the marsh may behave if similar conditions anticipated by global climate change models are realized. We suggest that the marsh will become less hospitable to fish in such a scenario because

water levels will be lower, water will stay warmer through the night, and become poorly oxygenated.

Composite maps of physico-chemical conditions in Frenchman's Bay, supplemented by information from a biweekly monitoring program revealed significant site-to-site differences in water quality. The three long-term sites we monitored during the summer of 2002 had very distinct characteristics. The Open station was deep (about 3.0 m), had warm surface water, lower conductivity, high DO content and low chlorophyll and turbidity. This description is consistent with the lower nutrient and suspended solids data reported for this station in a previous year. By comparison, the North station was shallow and warm, and seemed to be the most polluted of the three sites, with high conductivity, high chlorophyll and turbidity, and relatively low oxygen content. Like the North station, the South station was also shallow and warm, but was well-oxygented and had lower conductivity, chlorophyll and turbidity levels.

There are a number of indicators of ecosystem health that can be used to assess the quality of fish habitat in a coastal wetland such as Frenchman's Bay. In this study, we use a number of recently developed indicators based on physico-chemical and biological information (Chow-Fraser, unpub. data, McMaster University). A Wetland Water Quality Index (WQI) has been developed that is based on the findings from Crosbie and Chow-Fraser (1999) and Lougheed et al. (2001) in which water- and sediment-quality of wetlands located along all of the Canadian Great Lakes have been related to altered land uses in their watershed. In addition, we use information on macrophyte diversity as discussed in Lougheed et al. (2001), the Wetland Zooplankton Index (WZI) developed by Lougheed and Chow-Fraser (2002), and the periphyton index developed by McNair and Chow-Fraser (2003), and an unpublished index based on the biomass of zoobnethos to assess the ecological status of Frenchman's Bay. All of the bioindicators point to Frenchman's Bay as being moderately degraded, although in better condition than other urban coastal marshes along the Lake Ontario shoreline. That may explain why it still attracts a surprisingly large number of spawning and nursery fish throughout the spring and summer.

Continuous water-quality monitoring should be continued for at least one more year in the creeks to supplement information in the current survey. We also recommend that the daily water samples taken in 2002 be processed and analyzed for nutrients and heavy metals (cadmium, copper, lead and zinc) to assess the degree and type of pollution from highway runoff. Water quality and the fish community in the marsh have already been well characterized in this study, although the fish community in the creeks will require further investigation. To improve habitat for the existing fish community, consideration should be given to enhancing and amalgamating the “islands” of emergent vegetation that currently exist in the north end of the lagoon. Since water quality in the north show obvious signs of pollution from the creeks, it would be desirable to redirect the highway runoff through a retention pond to remove the sediment and pollutants before the water is allowed to flow into the bay.

INTRODUCTION

The ecology of wetlands in largely urban settings can be influenced by stressors that are unique to these systems, including recreational impacts (boating, angling), altered hydrologic regimes related to increased hardened surfaces in the watershed (Eyles et al. 2003), and nutrient and sediment enrichment from effluents of sewage-treatment facilities, storm sewers and culverts that drain major transportation corridors (Chow-Fraser et al. 1996; Chow-Fraser 1999; Ehrenfeld 2000). These urbanization impacts are prevalent in Southern Ontario, where metropolitan areas such as Toronto and Hamilton have expanded rapidly over the past 3 decades, and have severely altered ecosystem functions of associated drowned river-mouth marshes and protected lagoons (Environment Canada 2001).

Proper study of these ecosystems will require knowledge about ecological interactions within the marsh, as well as factors external to the marsh, such as changes in seasonal patterns of stream flow, physicochemical characteristics of source streams, and the type and amounts of pollutants that enter water courses from surface runoff. This is especially important considering that the combined effect of climate change and predicted land-use alteration in settled areas of the Great Lakes basin will likely increase surface runoff from the current 17% (calculated for 1994-2003) to 21% (calculated for 2090 to 2099) (Barlage et al. 2002). We also need to include more studies that document long-term changes in wetland response to landscape alteration (e.g. Cootes Paradise Marsh in Hamilton, Chow-Fraser et al. 1998).

In this report, we assess the impact of urbanization on current conditions of an urban lagoon and its watershed, and relate these to long-term changes in water quality, fish habitat, and the fish community over the past four decades. We used a number of recently available technologies to continuously monitor the water quality of both stream and wetland habitat over a

10-month period during 2002-3. We also conducted an intensive sampling program from August 2001 to March 2003 to document the current status of Frenchman's Bay with respect to its biological, physico-chemical and hydrologic environment. These results will reveal impaired ecological functions and form the basis for developing appropriate remedial actions.

Description of study site

The Frenchman's Bay watershed has a population of about 50,000 people and extends over 20 km^2. More than 80% of the watershed is urbanized making it one of the most densely urbanized in Canada (Eyles et al. 2003). The watershed is situated between Petticoat Creek to the west and Duffins Creek to the east (Figure 1). The northern limit is abruptly defined by a steep bluff, which is the shoreline of Glacial Lake Iroquois. The semi-enclosed coastal lagoon is drained by four main tributaries: Amberlea (301 hectares, 13.5 % of watershed), Dunbarton (212 ha, 9.5%), Pine (677 ha, 30%) and Krosno (784 ha, 35%) Creeks (Eyles et al. 2003; Figure 2). Smaller tributaries on the north, west and east margins of Frenchman's Bay have been extensively engineered by pipes and culverts to form storm-water 'sewersheds' (260 ha, 12%) that empty directly into the Bay.

Currently, Frenchman's Bay covers an area of 85 ha, of which approximately 47 ha is open water (Env. Canada 2001). The Bay is relatively shallow by lake standards, with a maximum depth of 3.5 m during mid-summer. However, water levels associated with coastal wetlands are closely tied to seasonal variation in Lake Ontario elevations, with maxima occurring in May and minima occurring in December (see Figure 3a). Accordingly, a drop of 30-40 cm from May to September is not unusual and this result in a substantial shrinkage of aquatic habitat in the wetland perimeter over the growing season. Although much of the lagoon is separated from Lake Ontario by a barrier beach (900 m long x 50 m wide x 2 m high), it is kept connected to the lake by a dredged entrance that allows boats to access marinas within the Bay.

A primary source of contaminants to the watercourse is highway runoff from Hwy 401, a major transportation corridor located immediately upstream of Frenchman's Bay (Figure 1). During the winter, large volumes of de-icing salt are applied after every snowfall. In addition to greatly increasing water conductivity, run-off from the highway can contain elevated levels of heavy metals such as cadmium, copper, lead and zinc (Marsalek and Ng 1989). Analysis of sediment cores retrieved from Frenchman's Bay reveal elevated levels only in the upper portion of the core that date back to the 1960s (Eyles et al. 2003). Currently, many parameters such as Total Keldahl Nitrogen (TKN), phosphorus, cyanide, oil and grease and total organic carbon exceed Ontario Ministry of Environment Provincial Sediment Quality Guidelines.

By groundwater flow modelling, Eyles et al. (2003) have shown that the lagoon is fed by groundwater from a large inland well beyond the boundaries of the surface watershed. This large area is presently undeveloped but as urban areas expand northward in the watershed, contaminated groundwater may move across surface watershed boundaries into Frenchman's Bay and Lake Ontario. The watershed is underlain by several layers of glacial sediment formed as a result of glacial advance and retreat of the Laurentide Ice Sheet between 70,000 and 12,000 years ago. These sediments cover a gently sloping bedrock surface composed of Whitby Formation shales of Late Ordovician age (approximately 440 million years; Eyles, et al., 2002; Ministry of Northern Development and Mines, Bedrock Geology of Ontario, Map 2544).

Eyles et al. (2003) used a wide range of geophysical techniques to determine the nature of bottom sediments and the distribution of contaminated sediment in the lagoon. From core analyses, they concluded that the bay is no older than 3,000 years, and that the first signs of human impact from the watershed can be attributed to indigenous peoples about 1000 years ago. The bay was relatively pristine for the next 800 years, as indicated by large amounts of laminated marl (fine sediment enriched in $CaCO_3$), which is typical of protected lagoons with clear water and extensive areas of submergent aquatic vegetation such as *Chara* that secrete $CaCO_3$ to form the chalky deposit. The marl deposition was abruptly replaced by a layer of black-coloured, foul-smelling mud rich in wood debris, partially decomposed organic matter and pollen of grass and weeds, which has been referred to in other studies as the "European Settlement Layer', which indicate the onset of European settlement and widespread forest clearances and subsequent soil erosion after 1840 (Weninger and McAndrews 1989).

METHODS

Precipitation, stream flow and water level data

Daily total rainfall (mm) and snowfall (cm) from the end of May 2002 to end of March 2003 for Frenchman's Bay were obtained from the Ontario Climate Centre of the Atmospheric Environment Service of Environment Canada (B. Smith, Environment Canada, Downsview, ON). Canadian Climate Normals 1971-2000 for Frenchman's Bay (43° 49'N; 79° 05' W) were retrieved from the Environment Canada website (http://www.msc.ec.gc.ca/climate). Mean monthly Lake Ontario elevations recorded at Cobourg, ON (Station 13590, 1985 IGLD) which is the most appropriate station to approximate conditions in Frenchman's Bay, were obtained for the period 1992 to 2001 from the Canadian Hydrographic Service of Environment Canada (CCIW, Burlington, ON), as were monthly water level data for Lake Ontario averaged from data collected at all water-level gauges over the same period.

Physico-chemical characteristics

Temporal variation

During the summer of 2002 (May to September), we used YSIä multi-parameter probes (Models QS and XL) to obtain hourly measurements of four physico-chemical characteristics of water in Amberlea and Pine Creeks, respectively (Figure 2). Parameters monitored by these YSIä dataloggers included pH, temperature, dissolved oxygen (DO) and specific conductance at both sites. The station for Amberlea Creek was located downstream of a large culvert that collected runoff from Hwy 401, whereas that for Pine Creek was located well above the highway and was presumably unaffected by highway runoff. All sensors in the probes were calibrated in the laboratory immediately before initial deployment, and thereafter, DO sensors were maintained and calibrated monthly in the field. The probe at the Amberlea Creek site was discontinued in early July due to equipment failure. In September, we re-established a YSIä 6600 mutli-parameter probe in Amberlea Creek and the YSIä XL in Pine Creek. Both probes monitored hourly changes in temperature, pH, conductivity and DO but in addition, the 6600 collected information on chlorophyll and turbidity levels in Amberlea Creek through the winter. For the summer months, two YSIä 6600 probes were also deployed in the North and South stations. The North station (indicated by "North" in Figure 2) was close to the confluence of Amberlea and Dunbarton Creeks in an area that had supported large emergent stands of marsh vegetation during the 1960s and 1970s (Figure 4); the other was located at the southwestern end of the marsh in an open-water area near a relatively intact cattail bed (indicated by "South" in Figure 2). All sensors in these probes were calibrated in the laboratory immediately before initial deployment, and thereafter, appropriate pre-calibrated replacement probes were hot-swapped with *in-situ* probes on a monthly basis. During January 2003, we visited Frenchman's Bay when it was completely frozen over. We drilled a hole through the ice at the "Open" station and collected measurements with the YSIä 6600.

Spatial variation

On August 20, 2002, we took georeferenced measurements of pH, temperature, DO, conductivity, turbidity and chlorophyll along 8 transects of Frenchman's Bay (Figure 5). This was accomplished by attaching a YSIä 650 display (equipped with a Garmin GPS unit) to a 6600 multi-probe and towing it along the side of a canoe (at about 30 cm below the water surface) to collect data at regular intervals. All the transect data were collected within a 6-hour period. We used ESRIä ArcGIS to transfer the data into a Geographic Information System and then interpolated them to raster using the inverse distance option.

Nutrient, chlorophyll, and suspended solids

Field collections

From the end of June to early September 2002, we collected daily water samples from Amberlea Creek using an ISCOä integrative sampler to determine changes in concentrations of total suspended solids (TSS) and total phosphorus (TP) from weekly composite samples. The sampler collected 250 mL of water from the Amberlea site every 6 hours for a daily total of 1L of water. Every 10-14 days, contents from filled ISCO bottles were poured into acid-washed Nalgene containers. On arrival back to the lab (usually within 4-5 hours of collection), bottles were sorted, and equal aliquots from each day were pooled to form a weekly composite sample, which were destined for TSS and TP analyses. At approximately monthly intervals, samples were collected with a van Dorn bottle in Amberlea and Pine Creek stations, and at the North and South sites; the open-water site (indicated as "Open" in Figure 2), was sampled more frequently at biweekly intervals. Water destined for nutrient and suspended solids analyses were stored in acid-washed Nalgene bottles; samples destined for chlorophyll analysis were stored in brown opaque Nalgene bottles that were not acid-washed. All water-chemistry samples were kept in the dark at 5 °C during transport back to the laboratory. During the winter sampling trip in January 2003, we also used a van Dorn sampler to collect water for nutrient and suspended solids analyses.

Laboratory processing and analysis

Samples for chlorophyll-a content of phytoplankton were first filtered through 0.45-µm GF/C filters, then stored frozen in tin foil until analysis. At the time of analysis, frozen filters were unwrapped and placed in 10 mL of 90% reagent-grade acetone for 24-48 h (American Public Health Association 1992). Samples were centrifuged, and chlorophyll-a content was determined by measuring absorbance with a Milton Roy 301 spectrophotometer before and after acidification (to account for phaeophytin pigments). Chlorophyll samples reported in this study were all measured in triplicate. Following digestion in potassium persulfate in an autoclave, samples for TP were measured in triplicate according to the molybdenum blue method of Murphy and Riley (1962). Total Kjeldahl nitrogen (TKN), total nitrate nitrogen (TNN) and total-ammonia nitrogen (TAN) were measured with Hach protocols and reagents (Hach Company 1989) using a Hach DR2000 spectrophotometer (Hach, Loveland, Colorado, U.S.A.). Total nitrogen (TN) was calculated by addition of TKN and TNN.

Water samples for total suspended solids (TSS) determination were filtered through pre-weighed GF/C filters and frozen until processing. Filters were first dried at 100 °C for 1 h, dried in a dessicator with calcium sulphate for another hour, and then weighed to determine TSS. Loss on ignition was determined after combustion at 550 °C for 20 min followed by drying in the dessicator for an hour. Weight of the combusted filter was assumed to be total inorganic suspended solids, whereas difference in the weight of the filter before and after combustion was total organic suspended solids.

Periphyton biomass

McNair and Chow-Fraser (2003) found that periphytic chlorophyll-a biomass was a good indicator of human-induced water-quality degradation, and recommended that both benthic and planktonic algal biomass be routinely monitored as part of an effective wetland management program. We followed the methods outlined in Goldsborough et al. (1986) to sample the biomass of periphyton with artificial substrata (clear acrylic rods, 0.6 cm diameter, 90 cm long) (McNair and Chow-Fraser 2003). Each rod was pre-scored at 5-cm intervals (to allow subsamples from various depths to be easily taken), then cleaned with alcohol to remove oils deposited through handling. Rods were inserted vertically into the sediment in five blocks of four rods each (rods approximately 1 m apart, arranged in a line) during the latter part of May 2001, two blocks at the North site and three blocks at the South site. Normally, we would place rods within or close to submergent beds, but because submsersed aquatic vegetation was very scarce at both stations (especially at the North site), blocks of rods were placed in an area close to where fish surveys were routinely conducted, whether or not there were any macrophytes. Rods were placed at water depths ranging from 40 - 70 cm, and at least 3 m from emergent vegetation to prevent shading effects. Samples were collected after approximately four weeks of colonization in late June. We used cutting pliers to collect a 5-cm sample from each rod at a depth of 10-15 cm. Samples were wrapped in foil, stored on ice in the field, then frozen until they were analyzed for chlorophyll-a content back in the lab. Periphyton biomass was estimated as µg CHLa $\bullet cm^{-1} \bullet d^{-1}$.

Emergent and submergent vascular plants

For this study, no attempt was made to conduct a complete taxonomic survey of the vascular plant community in Frenchman's Bay. The submergent macrophyte community was surveyed within each periphyton block using a 0.75 m x 0.75 m floating PVC quadrat. Percentage cover of submergents within the quadrat was estimated one time by direct observation at the surface. All submersed species present in the quadrat and within the periphyton blocks (approximately 1 m x 5 m) were noted. Plants were identified to species where possible, and always to genus using Voss (1972) and Newmaster et al (1997). Several *Potamogeton* species with slender leaves that were not identified to species because of absence of flowering or fruiting structures were grouped into *Potamogeton spp*. The dominant species of emergent plants were identified and noted from several canoe surveys during 2001 and 2002.

Benthic and planktonic invertebrates

Sampling for zoobenthos (combination of zooplankton and benthos) was carried out during the summers of 2001 and 2002 with funnel traps. Each trap consists of 3 inverted funnels (mouth diameter of each being 19 cm, covering a total surface area of 0.028 m^2) placed on top of sediment to capture invertebrates that reside at the water-sediment interface. The funnels were kept in place by a Plexiglas board, and marked with rope and floats for easy retrieval. Tubing connected a 620 mL square bottle to each funnel. Two sets of funnels (n = 6 bottles) were deployed for 24 h at the South station during August in 2001 and during June in 2002. After the incubation period, the square bottles were disconnected from the funnel apparatus and emptied into a 64-µm sieve to collect all invertebrates. The contents were then backwashed into glass storage bottles with deionized water to which was added an equal amount of 8% sugar-formalin to make a final concentration of 4% formalin. In 2001, we also used a 5-L Schindler-Patalas trap to collect triplicate samples of zooplankton from the South station, close to where the funnel traps were deployed. Contents were filtered through 64-µm mesh and backwashed into glass storage bottles with deionized water and preserved in formalin as above. Samples were kept for up to 6 months before they were sorted and processed.

To avoid handling formalin, zoobenthos samples were first transferred into 70% ethanol solution. We used a dissecting scope to sort invertebrates from debris that were entangled with animals in the sample, and to identify all animals to family. Four bottles from each year were processed in this way. The samples were then rinsed with deionized water and dried in a 60°C oven for 24 hours. The dry weight of the zoobenthos was measured with an Ohaus microbalance

(± 0.01 mg) and expressed as g•m^{-2} .   All zooplankton from each bottle were identified to genus and to species whenever possible.

Fish community

Two pairs of large fyke nets (13-mm and 4-mm bar mesh, 5-m length, 1.1-m x 1.4-m front opening) and one set of small nets (4-mm bar mesh, 2.1-m length, 0.5-m x 1.0-m front opening) were set at the North and South stations in Frenchman's Bay.   The nets were set parallel to shore with openings facing each other, connected with a 10-m lead and 3-m wings that were oriented at 45º angle from the front opening.   The large nets were set at the 1-m depth contour while the small net was set at 0.5-m depth contour.   Fish that were present in the nets after approximately 24 hours were removed and identified with the aid of Scott and Crossman (1998). Unknown species (especially small fish) were anesthetized, labeled, and then kept frozen until they could be identified at a later date. Their lengths were measured and later used with length-weight regressions to generate biomass estimates.   When certain species were too abundant to process individually, they were grouped into size classes (small and large) and a suitable subset was measured and the average lengths were applied to the sub-groups.

To the extent possible, wetland fishing should occur in areas that best represent the distribution of habitat and variations in conditions.   Criteria include appropriate depth, and proximity to emergent vegetation and the likelihood of submergent vegetation being present at some point during the summer, even though little or no submergent plants may be observable at the time of sampling.   The South station was deemed to be suitable habitat because of the existence of a relatively large *Typha* bed along the shore and evidence of some submergent plants in previous surveys.   The North station was located in the middle of the largest existing stand of cattails, although historically, the stand had been much larger (see Figure 2).   Contours at the south station were generally too deep for us to deploy the small nets.   At the North site, depths were suitable for deployment of both large and small nets. In both cases, nets were oriented parallel to the *Typha* beds. As is the case for most Great Lakes coastal wetlands, water levels generally retreat predictably through the summer (Figure 3), so that nets have to be moved further from shore but still set parallel to the vegetation. The fish community was surveyed with fyke nets during August and November in 2001, and then approximately monthly from April to November in 2002.

<u>Use of ecological indicators to assess Great Lakes coastal wetlands</u>

There are a number of indicators of ecosystem health that can be used to assess the quality of fish habitat in a coastal wetland such as Frenchman's Bay. In this study, we use a number of recently developed indicators based on physico-chemical and biological information (Chow-Fraser, unpub. data, McMaster University). A Wetland Water Quality Index (WQI) is being developed that is based on the findings from Crosbie and Chow-Fraser (1999) and Lougheed et al. (2001) in which water- and sediment-quality of wetlands located along all of the Canadian Great Lakes have been related to altered land uses in their watershed. In addition, we will use information on macrophyte diversity as discussed in Lougheed et al. (2001), the Wetland Zooplankton Index (WZI) developed by Lougheed and Chow-Fraser (2002), and the periphyton index developed by McNair and Chow-Fraser (2003), and an unpublished index based on the biomass of zoobenthos to assess the ecological status of Frenchman's Bay.

Since the Wetland WQI has not yet been published, we will briefly describe its development and intended use here. Data from ninety-three coastal wetlands, sampled during the summers of 1998, 2000, 2001and 2002, were included in the development of this index. These 93 wetlands are located throughout the US and Canadian shoreline of all five Great Lakes, although wetlands of Lake Huron (particularly Georgian Bay) are underrepresented. Over 40 of these wetlands were visited at least twice over the 4 years, for a total of 128 wetland-years. All wetlands were sampled for a comprehensive list of water-quality parameters, including primary nutrient concentrations (phosphorus and nitrogen), water clarity (turbidity, light extinction coefficients, chlorophyll and total suspended solids), and physical parameters (temperature, pH, conductivity and dissolved oxygen concentration).

A Principal Component Analysis (PCA) was used to first ordinate the dataset. Ordination is a commonly used exploratory technique to identify the most important variables among a large number of variables. Jongman et al. (1995) describes it as an extension of fitting straight lines and planes (or axis) through many variables by least-squares regression. The first axis is one that describes the greatest amount of variation in the entire dataset, while the next axis is inserted at right angles to the first axis at a plane that describes most of the remaining variation; all subsequent axes are inserted at right angles to the preceding and so on for as many axes as there are variables. Of the 21 water and sediment-quality variables, only 12 emerged as being important and were included in the final analysis. This first axis, which accounted for 44% of the variation, separated wetlands along an obvious degradation gradient: wetlands that were highly disturbed, characterized by high water turbidity, nutrient concentration and conductivity, were located at the extreme right of the axis, whereas undisturbed wetlands , characterized by clear, nutrient-poor, low-conductivity water were located to the extreme left of the axis. The second axis, which accounted for 11.5% of the variation, was significantly correlated with temperature and pH, which reflected in part the large geographic range (all five Great Lakes are represented) and the diversity in bedrock geology and latitude. The third axis was significantly correlated with nitrogen, which reflected inputs from agricultural runoff and sewage effluent in degraded wetlands. Since the first seven axes accounted for 90% of all variation in the dataset, we generated an index by multiplying scores for the first seven axes by their standardized eigenvalues and summing them. In this index, a low negative WQI score indicates a very pristine wetland, while a high positive score indicates highly degraded wetlands. Chow-Fraser (unpub. data) has found that WQI scores tended to range from –3 to +3 for the 128 wetland-years.

The biomass of zoobenthos in a wetland can indicate the quality of a Great Lakes coastal wetland (Chow-Fraser, unpub. data) because in a degraded wetland, benthivores and planktivores tend to dominate in the absence of piscivores (Chow-Fraser 1998). Hence, in degraded systems, most of the benthic invertebrates at the water-sediment interface are removed, whereas in undisturbed systems, there is an abundance of insects and other invertebrates. Based on this conceptual framework, we have proposed to use the biomass of zoobenthos in wetlands to rapidly indicate the suitability of wetland habitat for piscivores (Chow-Fraser et al., unpub. manuscript).

Statistical methods

Statistical analyses were performed using SAS JMP software version 4.0.4 for the Macintosh or PC (SAS Institute Inc., Cary, North Carolina). When warranted, data were $\log_{10}$-transformed to normalize the data prior to conducting regression and correlation analyses. Data used in the Principal Components Analysis were first standardized to a mean of zero and a standard deviation of one. Analysis of variance was used to determine significant differences among means, and when appropriate, Tukey-Kramer test was used to determine significant differences among pairs of means. To compare changes in the fish community over the season, we used paired t-tests. “SE” refers to the standard error of the mean whenever it appears in this report.

RESULTS and DISCUSSION

Our results will be divided into four main sections. The first will focus on temporal and spatial changes in physico-chemical conditions and water quality of the two main tributaries, Amberlea and Pine Creeks, as well as three sites in Frenchman's Bay during the summer of 2002. The second will document temporal changes in the physico-chemical conditions of Amberlea Creek over the fall and winter of 2002-3, as well as nutrient chemistry of the bay in January 2003. The third will focus on the current status of fish habitat, including the quality of the wetland, based on indices developed for periphyton, aquatic macrophytes, benthic and planktonic invertebrates in coastal Great Lakes wetlands. This section will also include an exploration of temporal and spatial variation in the fish community from August 2001 to November 2002. The final section will relate the current ecological status of Frenchman's Bay to historical conditions of the aquatic foodweb.

I) Summer conditions

Physico-chemical conditions

Specific conductance values measured in Amberlea Creek were generally higher than those in Pine Creek throughout the year (Figure 6). For example, between May 27 to July 2, a mean of 1.86 mS/cm $\pm$ 0.019 SE was obtained for Amberlea Creek, compared with 1.27 mS/cm $\pm$ 0.011 SE obtained for Pine Creek. This difference was anticipated since the Pine Creek site was located above Hwy 401, whereas the Amberlea Creek site was located downstream of the highway (see Figure 2), and is expected to have contributions of salts and other roadway runoff. By comparison, mean values for the north (0.480 mS/cm $\pm$ 0.002 SE) and south (0.383 mS/cm + 0.001 SE) stations within the marsh were much lower over the same time period.

To examine the response of the creeks and the marsh to rain events in more detail, we graphed hourly changes in water chemistry over four intervals, which are indicated as Episodes "A', "B", "C", and "D" above the first panel in Figure 6. By zooming into these shorter intervals, it was easy to see how rainfall drastically diluted out conductivity in the creeks during rainstorms. For example, in response to the 5.8 and 7.0 mm of rain that fell on May 30 and June 4, conductance values in Amberlea and Pine Creeks (Figure 7a and b, respectively) plummeted. Similar drops in conductivity related to rainfall events are shown in Episode B and C (Figure 8 and 9, respectively). By contrast, we could not detect a similar dilution effect on data for the two marsh sites (panels c and d in Figures 7, 8, 9 and 10); however, the pattern was much more erratic for the North station compared with the flat-line appearance of the South station, suggesting that the North station had been more affected by rainstorms than the South.

Diurnal temperature fluctuations were very similar from creek to creek (panels a and b in Figures 7 and 8) and from site to site within the marsh (panels c and d in Figures 7, 8, 9 and 10); however, comparison of marsh versus creek water revealed some interesting differences. At the marsh sites, temperature fluctuations did not exhibit a repeatable pattern, and there were smaller differences between daily minima and maxima. In contrast, differences between daily minima and maxima were much greater at the creek sites, and the diurnal fluctuations exhibited a repeatable pattern. Changes in daytime temperatures for Pine Creek were similar to those for the marsh sites, but changes in nighttime temperatures diverged; whereas the creek cooled down predictably through the night, the marsh tended to remain relatively warm. We calculated monthly means for the hourly data obtained from Pine Creek and the two marsh stations (Figure 11). The North station was always significantly warmer than the South station, and both were significantly warmer than Pine Creek water (ANOVA; $P<0.0001$), especially during June and July.

Due to equipment failure, we could not obtain continuous measurements for Amberlea Creek throughout the entire summer, but we were able to monitor the creek during June, and this afforded us a closer look at changes in the DO levels of the creek during Episodes A and B (Figures 7b and 8b, respectively). During June, we noted that DO levels were consistently close to saturation, and we do not expect this to change much during the summer since flow from the culvert tends to keep the water well aerated. This contrasts the situation in Pine Creek, where for about a two-week period in Episode A (Figure 7a) and again for a week in the latter part of Episode B (Figure 8a), conditions were actually anoxic. By comparison, for about 10 days during Episode C, oxygen concentrations exhibited a unique diurnal pattern in which maxima corresponded with mid-day primary production rates (when temperatures tended to be highest) and minima corresponded with nighttime respiration rates (when temperatures tended to be coolest) (Figure 9a). It is curious, however, that DO levels for remainder of the time were so erratic. Oxygen concentrations at the North station were generally lower than those at the South station during this same time (Panels c and d in Figures 7, 8). There were some striking differences between North and South stations during the latter part of July (Episode C; Figure 9b and c). After two of the heaviest rainstorms of the summer delivered 32.2 and 26.0 mm over two consecutive days (see top panel of Figure 9), DO concentrations at the North station dropped to anoxic levels on at least 5 occasions, whereas levels at the South station were maintained above 6 mg/L.

Nutrients and suspended solids

To examine the impact of urbanization on the level of pollutants in streams, we monitored changes in concentrations of TSS and TP in weekly composite samples of water collected from Amberlea Creek four times daily in equal amounts. Both TSS and TP concentrations were initially high during the spring runoff in early May, but dropped to relatively low levels by the end of May (Figure 12a). Thereafter, the peaks in TSS levels tended to coincide with precipitation events (Figure 12b), although there was a peak occurring in mid-August (julian day 223; Figure 12a) that did not match with a rainfall event. TP concentrations also varied in a similar manner through the season, with increased values coinciding with rain events, although TP and precipitation amounts were not significantly correlated. Correlations between rain events and these weekly mean values were very weak, and this reinforces the need to have hourly probe data to track precipitation events.

Elevated TP concentrations measured in early May at Amberlea Creek (Figure 13a) were also evident at the North station (Figure 13b), and likely reflect contributions from spring runoff. By comparison, TP concentrations for both the South and Open stations were initially low, but continued to increase through the season (Figure 13b). By the end of summer, values associated with the South station were significantly higher than those measured at the North station, even though at springtime, the reverse had been true. When all the data for the creek and marsh sites were compared together (ANOVA, Tukey-Kramer test), there were no significant differences among seasonal means for the North, South, Amberlea and Pine Creek sites, but all of these were significantly higher than that for the Open station (Figure 14a). Since SRP values for Amberlea were very high (about 60 µg/L; Figure 14b), most of the TP that enters into Amberlea Creek and that eventually discharges into Frenchman's Bay is in a form that is readily available for algal growth (Figure 14b).

We also compared site-to-site variation in TNN data (Figure 13c). Mean concentrations corresponding to both Amberlea and Pine Creeks were significantly higher than those for the three marsh sites (ANOVA, Tukey-Kramer test $P<0.05$; Figure 14c), indicating that nitrate may be one of the more important pollutants from creek water. Mean TN concentrations exhibited a similar pattern, suggesting that Pine and Amberlea Creeks contributed nitrogen in both inorganic and organic forms to Frenchman's Bay (Figure 14d). Because of the large seasonal variations in TSS concentrations at both creek and marsh sites (Figure 13d), we found that only the North site had significantly different means from all other sites (P<0.01; Figure 14f). It is noteworthy that except for the South site, where minerals (i.e. inorganic) contributed to approximately 25% of the total suspended solids, all of the stations had percentages ranging between 40 and 50% (Figure 14h). This means that the organic fraction (i.e. algae, protozoans and detritus) constituted a very large fraction of the suspended particles in both the creek and marsh water.

As demonstrated earlier, the concentration of suspended solids in a wetland can vary substantially in time and space (Figure 13d). To properly characterize these variations, we must take continuous measurements over days and months during the summer. Most sampling programs, however, cannot allocate sufficient time and effort to achieve this level of rigour, and that is why the advent of multi-parameter probes with turbidity and chlorophyll sensors that are capable of long-term datalogging, have greatly advanced our ability to track temporal and spatial changes. To fully describe the spatial and temporal complexity of the light environment in Frenchman's Bay , we installed a YSI ä 6600 probe at each of the North and South stations to monitor hourly changes in turbidity and chlorophyll from late-May to mid-September (Figure 15).

We first calculated daily means for the turbidity and chlorophyll data collected by the multi-parameter probes (thin and thick solids lines in Figure 15 a and b, respectively). As a check on the accuracy of these sensors, we compared sensor data to corresponding discrete samples of TSS and chlorophyll collected at the North and South stations (circles and squares in Figure 15 a and b) that were processed using conventional bench-top methods. We found a highly significant positive correlation between data types for chlorophyll (n= 14; r=+0.8953; P<0.0001), but no significant correlations between turbidity and TSS (n=13; r=0.413; P=0.1603). The departure between turbidity and TSS is probably a reflection of the high hourly variation in turbidity that were recorded by the probes (Figures 16 to 19), and that was not captured by processing a single discrete sample. When data were matched by the hour of sampling, the correlation became highly significant ($n=13$; $r=0.936$; $P<0.0001$). On the other hand, hourly variation in CHL tended to be low, and that is why a grab sample sufficiently represented the overall conditions of the day.

It is clear that when hourly data are available, a different picture emerges with regards to the pattern of seasonal maxima and minima. Nevertheless, differences between seasonal means generated from hourly data were not numerically very different from those generated from grab samples (Table 1). The magnitude of the turbidity maxima did not correlate well with the magnitude of rainfall (Figure 15 a). For instance, there were no clear spikes in turbidity at the time when the most severe rainstorm occurred (Episode C), although turbidities were clearly elevated for this period. Seasonal maxima in turbidity actually occurred during mid- to late-June for both the North and South stations (Figure 16 and 17), and as we will show later, were probably related to bioturbation by benthivorous fish in addition to rain-related erosion from the watershed (Figure 15).

Compared with the South station, diurnal chlorophyll variation associated with the North Station became more and more dramatic as the summer progressed, so much so that by mid-August, values ranged five-fold over the course of a day (Figures 16, 17, 18 and 19). This pattern occurred during a drought when the weather had been hot (approaching 30°C during the daytime; (Figure 10a), and when nutrients had been in good supply(Figure 13b and 13c). This may explain why the DO concentrations also exhibited high diurnal fluctuations (see Figure 10a), high concentrations presumably due to very high daytime photosynthetic rates, and the low concentrations (< 6 mg/L) presumably due to associated high nighttime algal respiration rates.

Spatial variation

A study involving 8 canoe transects (see Figure 4 for location of transects) was conducted in August to characterize the spatial variation in temperature, conductivity, DO, pH, chlorophyll and turbidity in Frenchman's Bay (Figure 20). Water at the southwestern and northeastern ends were the warmest, while water entering from Amberlea Creek was the coldest (several degrees warmer than that entering from Pine Creek) and appeared to flow through the marsh to the harbour entrance at the southeastern end (Figure 20a). Areas with warmer water were quite shallow (less than 1 m deep) and tended to coincide with existing emergent beds near the North and South stations (see Figure 2). Areas of higher water conductivity at the northeastern portion of the bay were clearly associated with stream inflows from Amberlea, Dunbarton and Pine Creeks. Conductivities were reduced by 25% by the time water reached the harbour entrance. Water close to the entrance also had higher oxygen content, and this was also true for water at the southwestern end and at the deep station (Figure 20b). By comparison, the northern perimeter had about a third lower DO concentrations (Figure 20c). The pattern of pH distribution was very similar to that for DO and reflects the contribution of lower pH water from the creek at the northern end of the bay (Figure 20d). There was an obvious northwest-to-southeast gradient for chlorophyll and turbidity (Figure 20 e and f), which may reflect dilution from Lake Ontario water, and higher algal production in the shallow, vegetated near-shore areas in the northeast and southwest.

It is clear from these composite maps that the three marsh stations in this study had fairly distinct characteristics. The Open station was deep (about 3.0 m), with warm surface water, lower conductivity, high DO content and low chlorophyll and turbidity. This description is consistent with the lower nutrient and suspended solids data reported for this station (Figures 13 and 14). By contrast, the North station was shallow and warm, and seemed to be the most polluted of the three sites, with high conductivity, high chlorophyll and turbidity, and relatively low oxygen content. Like the North station, the South station was also shallow and warm, but was well-oxygented and had lower conductivity, chlorophyll and turbidity levels.

2) <u>Winter conditions</u>

Compared to summer conditions, there was a more dramatic difference between Pine and Amberlea creeks during the winter months (Figure 6b and c). Whereas in the summer precipitation tended to dilute conductivity, precipitation in winter greatly elevated conductivity because of the application of de-icing salts, as evidenced by the close timing between onset of snowfall and spikes in conductivity (Figure 6a and c). For both creeks, there appeared to be a base value of 0.25 mS/cm above which conductivities increased in accordance with snowfall events.

We examined hourly changes within the creeks in more detail in five winter episodes (Episodes E, F, G, H, and I: Figures 21 to 25 inclusive). Over the course of the winter months (October to February), conductivity values ranged from < 1 to >30 mS/cm, and this made it difficult to use the same scale if we wanted to have optimum detail in each graph. Therefore, we plotted the data using different scale, but included a reference line of 2.5 mS/cm in each graph. Temperatures in the creek at the beginning of October were still above 10°C, but had dropped to 6°C or so by the end of the month (Episode E; Figure 21). Since precipitation was primarily rainfall, conductance values were still relatively low, and exhibited the characteristic dilution pattern witnessed during summer after rainstorms. DO levels were consistently high, at or above 10 mg/L. Water turbidity appeared to respond somewhat to rain events, although the response was variable and dampened compared to those observed in the Frenchman's Bay stations (Figures 16, 17 and 18). Nevertheless, the patterns observed in the later episodes during the subsequent four months (Figures 22 to 25) showed a more pronounced response. There was also some evidence that the precipitation (either rainfall or snowfall) dislodged periphytic algae from rocks and sediment surfaces that caused periodic chlorophyll peaks tocoincide with precipitation events (Figures 21 to 23). We speculate that this reflects scouring rather than elevated growth of algae because of the sub-optimal growth conditions (cold temperature and low light availability) during the winter months.

The first major snowfall occurred in mid-November (Figure 22), and within 12 hours, we saw elevated conductance values in Amberlea Creek that remained close to 10 mS/cm over a 24-hour period before returning to base levels of 2.5 mS/cm. The next substantial snowfall did not occur until mid December (20 cm on December 16th; Figure 23), but in the interim, even though there had only been a trace of snow (<1 cm) on December 12th, de-icing salts must have been added to the highway because we saw elevated conductivity during this time. For most of December, DO levels in both Amberlea and Pine Creeks were at or near saturation, but following a major snowfall on December 25th, temperatures cooled to 1°C, and lower DO conditions prevailed in Amberlea Creek until the new year. Figure 24 (Episode H) shows the greater effect on specific conductivity in Amberlea Creek compared with Pine Creek following each snowfall event; maxima in Amberlea Creek approached or exceeded 20 mS/cm (Figure 24a) whereas they seldom exceeded 15 mS/cm in Pine Creek (Figure 24c). The other obvious difference between Amberlea and Pine involved diurnal fluctuations in DO, which were more consistently dramatic for Pine Creek. By the end of February, DO levels in Amberlea dropped to 6 mg/L, probably because addition of salts (conductivity above 30 mS/cm) forced oxygen out of solution (Figure 25a).

We visited Frenchman's Bay on January 25, 2003 to monitor water-quality conditions at the Open station. The TP was 16.22 µg/L, which is somewhat lower than the mean of 20.92 µg/L during the summer. Both chlorophyll and TNN values were similar to summer means (7.40

vs 6.84 µg/L CHL, and 0.30 vs 0.25 mg/L TNN). Conductivity measured at the Open station at this time was 0.320 mS/cm, which is bracketed by values ranging between 0.30 and 0.45 mS/cm during the summer. Overall, winter levels of nutrients and chlorophyll at the Open station were very similar to those observed in the summer.

3) Fish habitat and fish community

Wetland Water Quality Index (WQI)

Appropriate data collected at the South station (August 2001) and at the Open station in July 2002 were used to calculate Wetland WQI scores (see description in Methods) for Frenchman's Bay. Chow-Fraser (unpub. data) found that most WQI scores fell between –3 to +3 and proposed to assign wetlands to one of 6 qualitative categories based on WQI scores:

WQI Score	Category
-3 to -2	Exceptional
-2 to -1	Excellent
-1 to 0	Good
0 to +1	Moderately degraded
+1 to +2	Very degraded
+2 to +3	Highly degraded

The two calculated WQI scores for Frenchman's Bay were quite different: 0.639 for the South station and -0.095 for the Open station. These differences may relate to year-to-year variation, or may be due to different physico-chemical characteristics associated with the two different stations (Figures 13, 14 and 20). According to the preceding chart, the South station during 2001 was probably moderately degraded whereas the Open station in 2002 was relatively good quality.

Aquatic vegetation

An areal photo taken of the marsh during 1999 (Env. Canada 2001) indicates there are currently 47 ha of emergent vegetation remaining from the historical high of 68 ha during 1960 (Williams and Lyon 1997). When other stressors (e.g. eutrophication, sedimentation or introduction of exotic invaders) are kept at bay, year-to-year variation in the areal extent of emergent vegetation in a coastal marsh tends to be limited by water level of the Great Lake in question. This has been substantiated by highly significant correlations between water levels in the Great Lakes and the percent emergent vegetation of the various wetlands studied (Williams and Lyon 1997; Chow-Fraser et al. 1998). Williams and Lyon (1997) reported data for Frenchman's Bay in their study, and in Figure 26, we have plotted their data along with an observation for 1999, which had been a year with comparatively low water levels in the recent decade (74.57 m above sea level; Figure 3b). Despite this low lake elevation, the corresponding extent of emergent vegetation in Frenchman's Bay was lower than expected based on previous low-level episodes in the 1960s. This comparison suggests that other factors besides water level are currently controlling the growth of emergent vegetation in Frenchman's Bay.

Table 2 lists all the common aquatic vegetation encountered in our survey of Frenchman's Bay during 2001-2. We noted 5 dominant emergent taxa, including the invasive exotic species, purple loosestrife (*Lythrum salicaria*), which were well established among the cattail beds along the shore. There were so few individuals of submergent taxa throughout the marsh that it would have been futile to determine any areal extent. Of those that we encountered, we identified 5 different taxa: 2 species of pondweed (curly pondweed which is exotic to the Great Lakes), waterweed, common bladderwort as well as Eurasian milfoil, which is another invasive species from Europe that has become established in Great Lakes wetlands. From the floating-leaved category, we encountered fragrant water lily, European frog-bit and star duckweed.

Periphyton biomass as indicator

We found a highly significant positive relationship (r^2=0.50; $P<0.0001$) between periphyton biomass and corresponding WQI scores for 24 of the wetlands reported in McNair and Chow-Fraser, which includes Frenchman's Bay ("FB" in Figure 27) and 5 other Lake Ontario coastal wetlands (see legend for names corresponding to wetland codes). The dotted line in Figure 27 operationally separates "disturbed" wetlands (to the right) from "undisturbed" wetlands (to the left). Accordingly, Darlington wetland ("DA") is identified as being moderately degraded, and this fits with our general impression of the wetland through our fish survey (Chow-Fraser, unpub. data), while Cootes Paradise Marsh ("CP"), a degraded urban wetland that is being restored as part of the Hamilton Harbour Remedial Action Plan (Chow-Fraser et al. 1998; Chow-Fraser 1998, 1999), was correctly classified as being very degraded. We were pleased to see that the WQI correctly identified Presqu'ile Provincial Park as a good-quality wetland. Within Frenchman's Bay, the periphyton biomass was significantly higher at the North site (49.25 $\mu g \bullet cm^{-2} \bullet d^{-1}$) than at the South site (25.17 $\mu g \bullet cm^{-2} \bullet d^{-1}$) (t-test; P=0.001).

Wetland Zooplankton Index

The current zooplankton in Frenchman's Bay consist mostly of small-bodied taxa such as rotifers and small cladocera (*Bosmina* and *Ceriodaphnia*; Table 3). We identified plankton from samples collected at both the Open and South stations, near where the fish had been surveyed during August 2001. We followed the procedure outlined by Lougheed and Chow-Fraser (2002) to calculate the Wetland Zooplankton Index (WZI) for Frenchman's Bay and obtained a value of 2.71. WZI scores vary between 1 and 5, where the lowest quality is 1 and the highest is 5. The value of 2.71 is therefore slightly below the mid-point, suggesting that Frenchman's Bay is slightly degraded. Relative to other urban-impacted coastal such as nearby Humber River, and Cootes Paradise located at the west end of Lake Ontario, the lagoon is of higher quality (Table 4). However, it is quite a bit lower quality than wetlands to the east such as Presqu'ile Provincial Park and Napanee River, which are considered to be high-quality wetlands based on water-quality criteria (Chow-Fraser, unpub. data).

There is a highly significant negative relationship between WZI and WQI scores for 35 coastal marshes that represented both the Upper (closed squares) and Lower (open squares) Great Lakes (r^2=0.59; P<0.0001; Figure 28). Consistent with the other bioindicator we have already used (i.e. periphyton), the location of Frenchman's Bay ("FB") in this figure clearly confirms that at least portions of the marsh are in a degraded state.

Biomass of zoobenthos

Data for sixteen coastal wetlands sampled in Lakes Erie and Ontario during 2000 to 2002 were pooled to examine the relationship between WQI values (indicating the overall quality of the wetland) and the biomass of zoobenthos. Consistent with our hypothesis of how wetlands function, we found a significant negative relationship between zoobenthos biomass and WQI values (n=15; r^2=0.35; P=0.021; Figure 29a), indicating that as wetland quality deteriorates, the biomass of zoobenthos decreases. This reduction in zoobenthos is significantly related to a decline in the piscivore biomass in these wetlands (n=15; r^2=0.50; P=0.0033; Figure 29b). In fact, when both WQI and piscivore biomass were entered into a multiple regression analysis, we found that zoobenthos biomass could be predicted from both variables as follows (Figure 29a and b, respectively):

$$\textbf{Zoobenthos biomass} = \underset{(\pm\,0.142)}{-0.33}\ \textbf{WQI} + \underset{(\pm\,0.000041)}{0.001409}\ \textbf{Piscivore biomass} + 0.5127276$$

(r^2= 0.66 P=0.0016 n=15). The biomass of zoobenthos in any wetland is therefore a reflection of both the abundance of piscivores in the system as well as the ambient water quality. In the case of Frenchman's Bay, the WQI indicates that the marsh is moderately degraded, and the zoobenthos biomass indicates that there are impaired ecosystem functions since the piscivore community is lower than expected.

Fish community

We surveyed the fish community in Frenchman's Bay on 9 occasions between 2001 and 2002 (Table 5). Although the total number of species varied from a low of 9 on April 26,2002 to 17 on Aug 7, 2002, the numbers were very stable during the May, June, August and September surveys (16 and 17). Brown bullhead, emerald shiner, and yellow perch were very common and were represented in almost every survey, including those in the early spring and late fall when species totals tended to be lower. The rare taxa (appearing in only one or two surveys) included the shiners (blacknose, sand, mimic), rock bass, white perch, white bass and rainbow smelt. Some fish tended to be caught only as adults when they migrated into the marsh to spawn during the spring or fall (alewife, white sucker, and northern pike).

Since fish had been sampled from both the North and South stations on every occasion, and we knew there were significant differences between stations with respect to environmental conditions (see Figures 13, 14 and 20), we wanted to determine if there were any species-specific preferences for a particular station. We found 16 species that differed significantly between stations for either abundance, biomass or both (Paired T-tests; Table 7). A group of 8 species occurred in greater numbers and/or biomass at the South station, and these included northern pike, yellow perch, alewife, largemouth bass and pumpkinseed (Figures 30 to 31). Another group of 8 were more abundant at the North compared to the South station, and these included brown bullhead, gizzard shad, bowfin and common carp (Figure 32 and 33). When all the fish were pooled, we found that the South station had significantly greater numbers of fish ($P<0.001$; Figure 34a), whereas the North station had significantly higher biomass ($P<0.001$; Figure 34b). This indicates that a greater number of small-sized individuals were caught at the South station, while fewer large-sized fish were caught at the North station. In most instances, both biomass and abundance data yielded similar seasonal trends (Figures 30-33); however, for gizzard shad, 5 large spawning individuals accounted for a relatively high biomass during early spring, whereas the many juveniles present during summer accounted for very little biomass, and thus gave rise to different seasonal patterns (Figure 32).

4) <u>Current ecological status in relation to historical conditions</u>

Marsh hydrology

Like other coastal marshes of Lake Ontario, the water level in Frenchman's Bay can be predicted from elevation of Lake Ontario, which exhibit long-term naturally occurring cyclical fluctuations (Figure 3b). Some researchers argue that the operation of the St. Lawrence Seaway in 1960 has significantly affected this natural cycle, and therefore we follow the custom of accounting for this disruption by calculating long-term averages for data from 1918 to 1960 and from 1960 forward (see Figure 3a). We have also calculated a mean for data recorded in Cobourg, ON, because the Lake Ontario average account for overall lake levels throughout the lake, whereas the water-level gauge at Cobourg would reflect more regional conditions for Frenchman's Bay .

Mean monthly levels corresponding to data collected prior to 1960 are significantly lower than those for the subsequent 4 decades, even though in both cases, the peak occurred in June (74.97 and 75.11m above sea level, respectively; Figure 3a). The corresponding monthly data for

Cobourg (available only from 1992 to 2001) show that on average, water levels in May and June were identical at 75.12 m, which is 10 cm higher than that for the post-1960 data. Three important conclusions can be drawn from this comparison. First, mean monthly water levels from 1960-1999 have been significantly higher than those corresponding to 1918-1960. Secondly, mean monthly water levels in Frenchman's Bay during winter and spring have been higher than corresponding mean data calculated for both 9960-1999 and 1918-1960. Thirdly, water levels have been peaking earlier in the year during the past decade, since the peak in monthly maxima has occurred in May rather than in June, and the trend for mean data no longer show a peak in June. Although these long-term changes may seem subtle, they can seriously affect the growth of emergent plants, and cause cascading effects that could ultimately jeopardize the spawning success of wetland-dependent fish.

Another important factor that determines water levels in Frenchman's Bay is the type and amount of precipitation that enters the watershed. We compared precipitation patterns for 2002-3 with the 1971-2000 climate normals, and discovered that the past year has been unusual in several respects (Figure 35). First, the amount of rain that fell in July was greater than normal; however, the quantity that fell during the remainder of the year was much lower than expected, especially in August and in December (Figure 35a). Secondly, more than twice the normal amount of snow fell in November, but the very dry December more than compensated for this increase (Figure 35b). Even though the winter of 2003 was colder and snowier than normal (total snowfall of 124.5 cm compared with 95 cm normally), the total precipitation was less than expected because of reduced total rainfall from October to March (only 132 compared with 236.6 mm).

Interannual changes in precipitation can also lead to year-to-year variation in creek flow, which can ultimately affect the water levels in Frenchman's Bay. Because none of the streams in our watershed has a long-term flow record, we obtained data for nearby Duffins Creek, which had been monitored for at least the past decade at two locations. One location is in East Duffins Creek (Station 02HC019 in Figure 1), which is very far from Hwy 401, while the other is located in lower Duffins Creek in the Town of Ajax, immediately above Hwy 401 (Station 02HC049 in Figure 1). There was very good correspondence between mean annual water levels of Lake Ontario (measured at Cobourg, ON) and mean annual flow rates measured at lower Duffins Creek, although there were too few data points to produce a significant correlation ($P=0.06$; Figure 36). The significantly higher flow rates in lower Duffins Creek compared with the upper East tributary, confirms that paved surfaces in cities can greatly increase flow rates of urban creeks.

Water quality

We can broadly compare current water-quality conditions in Frenchman's Bay with those documented in three other studies dating back to the mid-1970s (Table 8). Since only one study reported a range of temperatures from 7 to 22ºC, it is difficult to draw much from this comparison, except to point out that our range appears to have shifted upwards several degrees because our range is now 11 to 27ºC. The range in pH for this study seems to agree with those reported in the three previous studies, and we do not think pH has changed over this time. The study conducted in the mid 1970s indicated DO levels ranged from 8-12 with a mean of 10.2 mg/L, while the one conducted a decade later reported a mean of 9.1 mg/L with an expanded range that included some lower DO values. Continous hourly monitoring of the North station in this study certainly confirm that the marsh can undergo periods of anoxia at night; therefore, without more information in terms of the time of sampling, we cannot conclude that current conditions have worsened. Regardless of how it compares with historic conditions, however, the seasonal mean of 5.7 mg/L at the North station is sufficiently low that we should consider it a probable impediment to certain fish species during mid-to-late summer. On the other hand, a mean of 9.22 mg/L for the South station is very similar to historic values (9.1 and 10.2 mg/L) and do not point to any deterioration.

Mean Secchi depth transparency reported by McNab and Hester in 1974-5 was 78 cm, which compares favourably with our mean value of 65 cm at the Open station. On the other hand, the mean of 22 cm reported by Stephenson for the mid 1980s suggest that water clarity has actually improved recently, and this is consistent with the higher TSS value of 43 mg/L reported for the late 1970s, compared with current means ranging from 11.8 to 28.3 for all three stations in this study. Phosphorus levels have probably increased in the marsh over the 30 years; Lemay and Mulamootil reported a mean of 10 µg/L (range of <1-26 µg/L) for total P in 1977 whereas we report means that range from 21.7 to 77.8 µg/L for the three stations. On the other hand, total nitrate levels appeared to have declined from a mean of 1.01 mg/L in 1977 to means ranging from 0.19 to 0.50 mg/L in 2001 and 2002.

Aquatic plants

The 1939 aerial photo shows a very large contiguous stand of emergent vegetation at the north and another smaller stand at the southwest perimeter of Frenchman's Bay; in addition, Hydro Marsh, which is located at the southeast corner, at the mouth of Krosno Creek (see Figure 1) was intact (Plate 1a). A substantial portion of Hydro Marsh was lost during construction of the Pickering Nuclear Generating Station (Nelson et al. 1991), and the 1993 aerial photo indicates that very little of the marsh has survived (Plate 1b). A portion of the north shore was filled in for a project that was later abandoned, while the creation of a park on the west side of the Bay further claimed more of the wetland habitat (Nelson et al. 1991). During the 1950s, further infilling and drainage occurred as a result of the construction of Highway 401 across the top of the Bay.

The infilling that took place in the past, and the continued dredging that takes place currently have incrementally affected both the areal extent and diversity of the aquatic plant community in Frenchman's Bay.   During the 2001-2 surveys, we only found 6 of the 11 common submergent taxa, 3 of the 7 floating taxa, and 5 of the 7 emergent taxa that had been noted in reports prepared in the 1970s and 1980s (Table 2).   The submergent taxa (e.g. *Potamogeton richardsonii*) and some of the floating species that begin under water (e.g. *Potamogeton natans*) would have been particularly vulnerable to decreased water transparency (Lougheed et al. 2001) that accompanied increased nutrient and sediment loading from urbanization. Part of the reduction in areal extent of emergent plants may be attributed to increased water levels after the 1960s (Figure 26; Williams and Lyon 1997), but the added disturbance from urban development along the shoreline and increased sedimentation has probably contributed to its inability to rebound once water levels retreated.   Since large intact stands are better at coping with bioturbation associated with carp spawning and feeding (Lougheed et al. 1998; Chow-Fraser 1999) than are small islands of vegetation that currently exist, we should try to restore the integrity of the large contiguous stand that characterized the northern portion of the Bay (see Figure 4).

Human disturbance has likely contributed to the success of invasive purple loosestrife (*Lythrum salicaria*), which now colonizes large areas of the marsh, visually dominating the shoreline when it flowers in mid-summer. It is unlikely that native emergent species will be able to displace the *Lythrum* without some effort being made to reduce the area it currently dominates.

Fish community

The list of fish in Table 5 can be broadly separated into four groups.   **Group A** contains 14 species that were mentioned in at least 4 of the past studies, and that were also well represented in our surveys.   **Group B** contains 19 species that had been considered rare by previous authors or that had only been mentioned in one or two studies, and which we now catch only on occasion or not all.   Hence, we consider historic distributions of the 33 species in

Groups A and B to be very similar to present distributions. **Group C** were 13 taxa that had been commonly mentioned in previous studies but which we did not catch or only rarely encountered. **Group D** included 5 species that were rare or that had not been reported before, but which we now find to be common. We consider the current distribution of species in Groups C and D to have departed from historic trends.

We will first deal with departures in Group C. The reduced occurrence of rockbass, white perch, white bass, freshwater drum, channel catfish, round whitefish, and rainbow smelt in our surveys may be an indication that these species have actually declined in abundance, and we suggest that further investigations be carried out to verify their status and link their disappearance to habitat changes in the bay. As for the apparent reduction in bluegills, we suggest that this may be an artifact of differences in taxonomic identification. Juvenile sunfish are often difficult to identify in the field, and in most cases, we lumped them into a category called "immature sunfish. We are not certain whether some of these would have been keyed to bluegill or to pumpkinseed, but we are sure that we did not catch any adult bluegills in our fykenets over the past two summers.

The fact that we caught white crappie but no black crappie suggest to us that the black crappie reported in previous studies may have been incorrectly identified, because we are fairly certain of our identification. If both had been correctly identified, then there is one other explanation. Scott and Crossman (1998) indicate that black crappie likes vegetated, clear-water systems and is less turbidity tolerant than white crappie. If there has in fact been a replacement of black crappie by white crappie, then this would be further evidence that the marsh is progressing towards a more degraded state in recent years.

Species such as the American eel and smallmouth bass may have escaped our notice because they tend to inhabit deeper areas of the marsh that we cannot adequately sample with fyke nets. In this study, we focused on the wetland-associated taxa and did not spend time to sample fish that may migrate into creeks to spawn during spring and fall. Had we done that, we may have found some of the salmonids mentioned in previous studies. This possibility is being investigated in the coming field season and we should have information to address this deficiency by the end of this field season.

The fish in Group D are those that we now find commonly but that had only been encountered on rare occasions in the past. Johnny darter and three-spine stickleback are members of this group that we commonly catch in fyke nets here and elsewhere in Lake Ontario wetlands; however, they are difficult to catch with electrofishing boat, and the discrepancy noted here may simply reflect use of different gear types between studies. There are two reasons why tadpole madtom may have been missed in previous surveys. First, they are small and are probably difficult to catch by electrofishing boat, and secondly, they can be easily misidentified as brown bullhead.

Overall, at least 75% of our survey information is consistent with those reported in published documents, indicating that the fish community has maintained its general structure over the past 25 years. The apparent decline and/or disappearance of 7 to 10 of the species in Group C, however, signals that some species may have been affected by the increased urbanization and their status should be clarified with further field evaluation.

Earlier, we established that there were significant differences in the distributions of fish sampled from the North and South stations (Figures 30 to 34; Table 7). The Toronto Region Conservation Authority had surveyed the fish community in Frenchman’s Bay since 1991. In most years, they surveyed the communities at the northern and southern portion of the marsh during July or August with an electrofishing boat. Even though they sampled at other times and at other areas of the marsh (East and West), we excluded these from consideration here to enable proper comparison of long-term trends. We then used their data to validate our observations. Paired T-tests of abundance and biomass data yielded results that were almost in total agreement with our findings. Fish were more abundant at the South station but biomass was significantly higher at the North station (Table 7). Pumpkinseed, yellow perch, white sucker, alewife and northern pike (Figures 37 and 38) favoured the South station, whereas brown bullhead, bowfin, crappie, and common carp (Figures 39 and 40) favoured the North station.

The only discrepancies between TRCA data and ours concern the largemouth bass and white sucker. According to their data, largemouth bass has been absent since the late 1990s, and were more pronounced at the North station during the early 1990s (Figure 40). In our recent surveys, however, we found them as juveniles in relatively large numbers at the South station (Figure 31). The fyke nets that we use are very efficient at catching juvenile fish that frequent the marsh in July and August. It is quite possible that the electrofishing boat in recent years have missed the smaller fish during the July surveys since their October survey in 1999 revealed that several adult largemouth bass were caught at the South station. As for white sucker, electrofishing boat may be better at catching these fish during July since we no longer found them at either stations after spring using fyke nets. Hence, difference in gear bias may again explain the apparent discrepancies. We are now comparing the effects of different gear types on results of fish surveys in 10 coastal wetlands of the lower Great Lakes (Chow-Fraser et al., unpub. data), and the conclusions from that study may further explain possible biases or inconsistencies in the two databases.

GENERAL DISCUSSION

The marsh ecosystem in Frenchman's Bay is currently showing many signs of degradation, as demonstrated by the suite of bioindicators used in this study, including one based on water-quality, periphyton biomass, zooplankton community, and zoobenthos biomass. Compared to conditions that existed in the 1960s and 1970s, both the submergent and emergent vegetation have been greatly reduced in diversity and areal extent. Like many other marshes in southern Ontario, decline of the submergent component is linked to deteriorating water quality resulting from increased loading of nutrients and sediments from the watershed (Crosbie and Chow-Fraser 1999; Lougheed et al. 2001). Our monitoring program clearly demonstrates the negative impact of runoff from Hwy 401 on the water quality of Amberlea Creek: elevated levels of suspended solids and dissolved nutrients in summer, and elevated water turbidity and conductivity during winter could be linked directly to the onset of precipitation events. By comparison, water quality of the Pine Creek station, which is located well above the highway, do not exhibit the same degree of degradation; however, we suspect that water quality of the creek below the highway is as degraded as that of lower Amberlea Creek, and we propose to monitor Pine Creek this summer below and above the highway to verify this hypothesis.

The loss of emergent vegetation over the past three decades can be attributed to sustained high water levels in Lake Ontario. Interannual fluctuations in water level occur naturally in the Great Lakes, and is a primary mechanism that maintains biodiversity in these coastal wetlands (Keddy and Reznicek 1986), since alternating periods of high and low water prevent aggressive species from monopolizing the marsh. In undeveloped watersheds, the emergent vegetation can retreat upland to the wet meadows during years of high water level, and once water levels drop, the seed bank within the wet meadows helps to rejuvenate the marsh. However, when urban areas encroach on the floodplain, the wet meadows containing the seed bank are irreversibly destroyed. Without recruitment, the pre-existing plant community becomes vulnerable to displacement by exotic invasive species such as the purple loosestrife. The lack of a sufficient buffer around urban wetlands is therefore a major impediment to maintaining healthy marsh communities along the Great Lakes shoreline.

The site-to-site variation in the abundance of fish in Frenchman's Bay is not unusual for coastal wetlands (Lougheed and Chow-Fraser 2001). Normally, the more suitable fish habitat are found in areas that are protected from wind and wave resuspension, where aquatic vegetation can flourish. Within vegetated areas, the associated water is usually cooler, less turbid and better oxygenated throughout the day and night as compared to areas without vegetation, and this is important for wetland-dependent fish such as northern pike and largemouth bass. The submergent plants also provide substrate for egg attachment, protection from predators for larvae and juveniles, and habitat for invertebrates on which both adults and juveniles feed. In Frenchman's Bay, even though the Open station has relatively good water quality, it cannot provide suitable habitat for most of the wetland taxa because it does not support emergent or submergent vegetation. The marsh in the southwestern end of the lagoon is home to a surprisingly large number of fish species during the summer and fall; even the remnant marsh located at the northern end provides habitat for a large number of fish, although these species tend to be those that are known to be more tolerant of degraded conditions.

In addition to nutrients and sediment, runoff from Hwy 401 is expected to contribute amounts of heavy metals to the marsh (Marsalek and Ng 1989). Samples of water have been collected daily over the summer in 2002 and these can be selectively analyzed for cadmium, copper, lead and zinc to determine their distribution pattern in relation to storm events. This information will complement our current understanding of the extent of pollution from runoff to natural ecosystems in heavily urbanized watersheds such as the Frenchman's Bay catchment.

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Table 1. Comparison of means generated from hourly probe data, and those generated from discrete samples. Numbers in bracket indicate the sample size for each mean.

	Probe data		Discrete data	
Station	**Turbidity**	**Chlorophyll**	**TSS**	**Chlorophyll**
North	**24.48** (2735)	**22.97** (2735)	**31.76** (13)	**19.83** (13)
South	**7.51** (2711)	**16.23** (2711)	**10.35** (14)	**13.65** (14)

Table 2 . List of common aquatic vegetation found in Frenchman's Bay compiled from historic (Nelson et al. 1991, Tarandus Assoc. Ltd. 1995) and recent (2001-2) surveys conducted as part of this study.

Scientific Name	Common Name	Type	Historic	Recent	Exotic
Decodon verticillatus	Swamp loosestrife	Emergent	X	X	
Lythrum salicaria	Purple loosestrife	Emergent	X	X	X
Sagittaria cuneata	Arrowhead (Wapato)	Emergent	X		
Sagittaria latifolia	Arrowhead (Duck Potato)	Emergent	X		
Typha angustifolia	Narrow-leaved cattail	Emergent	X	X	
Typha latifolia	Broad-leaved cattail	Emergent	X	X	
Typha X *glauca*	Hybrid Cattail	Emergent	X	X	
Polygonum amphibium	Water smartweed	Emergent	X		
Zannichellia palustris	Horned pondweed	Submergent	X		
Elodea Canadensis	Common waterweed	Submergent	X	X	
Ceratophyllum Canadensis	Coontail	Submergent	X		
Vallisneria americana	Tapegrass	Submergent	X		
Potamogeton berchtoldii	Pondweed	Submergent	X		
Potamogeton crispus	Curly-leaved pondweed	Submergent	X	X	X
Potamogeton pectinatus	Sago pondweed	Submergent	X	X	
Potamogeton richardsonii	Pondweed	Submergent	X		
Potamogeton sp.	Slender pondweed	Submergent	X	X	
Utricularia vulgaris	Common bladderwort	Submergent	X	X	
Myriophyllum spicatum	Eurasian milfoil	Submergent	X	X	X
Hydrocharis morsus-ranae	European frog-bit	Floating	X	X	X
Lemna minor	Common duckweed	Floating	X		
Lemna trisulca	Star duckweed	Floating	X	X	
Nuphar advena	Spatterdock	Floating	X		
Nuphar variegata	Yellow water lily	Floating	X		
Nymphaea odorata	Fragrant water lily	Floating	X	X	
Potamogeton natans	Floating pondweed	Floating	X		

Table 3. List of zooplankton found at the Open and South stations in Frenchman's Bay during August 2001. Optimum and Tolerance scores are those used to calculate the Wetland Zooplankton Index (Lougheed and Chow-Fraser 2002).

Taxon	Optimum Score	Tolerance Score
Brachionus longirostris	1	1
Filinia sp.	1	1
Hexarthra sp.	1	1
Keratella cochlearis	3	1
Polyarthra	3	1
Macrothrix	1	1
Ceriodaphnia reticulata	4	2
Scapheloberis	4	2
Diaphanasoma brachyurum	5	2
Moina micrura	1	2
Bosmina longirostris	2	1

Table 4. Comparison of Wetland Zooplankton Index (WZI) scores for Lake Ontario wetlands sampled by Lougheed and Chow-Fraser (2002). Wetlands are sorted by ascending WZI scores.

Year of sampling	Wetland name	Type of stressor	WZI score
1998	Humber River	Carp, agricultural, urban	1.99
1998	Bronte Creek	Carp, agricultural, urban	2.02
1998	Grindstone Creek	Carp, agricultural, urban	2.07
1998	Ottawa Second Marsh	Carp, agricultural, urban	2.15
1998	Martindale Pond	Carp, urban	2.16
1994	Cootes Paradise Marsh (before restoration)	Carp, agricultural, urban	2.46
2001	**Frenchman's Bay** (This study)	Carp, urban	**2.71**
1998	Cootes Paradise Marsh (after restoration)	Agricultural, urban	2.76
1998	Wellers Bay	Low agricultural	3.30
1998	Blessington Bay	Low agricultural	3.33
1998	Presqu'il Provincial Park		3.47
1998	Sawguin Creek	Low agricultural	3.57
1998	West Lake	Low agricultural	3.72
1998	Hay Bay Marsh	Low agricultural	3.86
1998	Napanee River		4.05

Table 5. Fish species found in historic and recent (2001-2002) surveys in Frenchman's Bay surveys. "X" indicates that the species was present in either the "north" or "south" stations in the bay. Numbers in the "Historic" column refer to documents in **Table 6**.

Species	Historic	08/01/01	11/03/01	04/12/02	04/26/02	05/22/02	06/18/02	08/07/02	09/24/02	11/01/02	Group
alewife	1,3,6,10,12	X	--	--	--	--	X	X	X	X	A
bowfin	2,3,4,7,8,9,10,11,12,13	X	--	X	X	--	X	X	--	--	A
brown bullhead	2,3,5,6,7,8,10,11,12,13	X	X	X	X	X	X	X	X	X	A
white sucker	2,3,5,7,8,9,10,11,12,13	--	X	X	X	X	--	--	--	--	A
common carp	2,3,4,5,6,7,8,9,10,11,12	X	X	X	X	X	X	X	X	--	A
gizzard shad	3,6,7,9,10,11,12	--	X	X	--	--	--	X	X	--	A
northern pike	1,2,3,6,7,8,9,10,11,12,13	X	X	X	X	--	X	--	--	--	A
pumpkinseed	2,3,4,6,7,8,9,10,11,12,13	X	X	X	--	--	X	X	X	X	A
largemouth bass	2,3,4,8,9,10,11,12,13	X	X	--	--	--	--	X	X	X	A
emerald shiner	2,3,8,10,12	--	X	X	X	X	X	--	X	X	A
yellow perch	2,3,7,8,9,10,11,12,13	X	X	X	X	X	X	X	X	X	A
bluntnose minnow	3,8,10,12	--	X		X	X	X	X	X	X	A
fathead minnow	2,3,8,12	--	--	--	--	X	X	X	X	X	A
spottail shiner	2,3,8,12	X	--	--	--	X	X	X	X	--	A
golden shiner	2,8,10	X	--	--	--	--	X	--	--	X	B
brassy minnow	--	--	--	--	--	--	--	--	--	X	B
blacknose shiner	--	--	--	--	--	X	--	--	--	--	B
sand shiner	---	--	--	--	--	X	--	--	--	--	B
mimic shiner	---	--	--	--	--	--	--	--	X	--	B
trout-perch	---	--	--	--	--	X	--	--	--	--	B
Coho salmon	8,11,13	--	--	--	--	--	--	--	--	--	B
creek chub	2,3,8,12	--	--	--	--	--	--	--	--	--	B
common shiner	2,8 rare	--	--	--	--	--	--	--	--	--	B
spotfin shiner	2,8 rare	--	--	--	--	--	--	--	--	--	B

Goldfish	2,8 rare	--	--	--	--	--	--	--	--	--	B
Banded Killifish	8 rare	--	--	--	--	--	--	--	--	--	B
brook silverside	3,12 rare	--	--	--	--	--	--	--	--	--	B
burbot	7 rare	--	--	--	--	--	--	--	--	--	B
brown trout	7,10 rare	--	--	--	--	--	--	--	--	--	B
lake trout	7 rare	--	--	--	--	--	--	--	--	--	B
walleye	11 rare	--	--	--	--	--	--	--	--	--	B
Central mudminnow	3 rare	--	--	--	--	--	--	--	--	--	B
logperch	7 rare	--	--	--	--	--	X	--	--	--	B
rockbass	2,4,7,8,9,11,13	--	--	--	--	--	--	X	--	--	C
bluegill	2,4,8,9,11,13	X	--	--	--	--	--	--	--	--	C
white perch	2,3,4,8,9,11,12,13	--	--	--	--	X	--	--	--	--	C
white bass	2,7,8,9,10,11,12,13	--	--	--	--	--	--	X	--	--	C
rainbow smelt	2,5,7,8,11,12,13	--	--	X	--	X	--	--	--	--	C
black crappie	2,3,7,8,9,10,11,12,13	--	--	--	--	--	--	--	--	--	C
rainbow trout	7,8,9,10,11,13	--	--	--	--	--	--	--	--	--	C
American eel	2,7,8,11,13	--	--	--	--	--	--	--	--	--	C
freshwater drum	2,8,9,11,13	--	--	--	--	--	--	--	--	--	C
channel catfish	2,4,9,11,13	--	--	--	--	--	--	--	--	--	C
smallmouth bass	2,7,8,9,11,13	--	--	--	--	--	--	--	--	--	C
Chinook salmon	2,4,8,9,11,13	--	--	--	--	--	--	--	--	--	C
round whitefish	2,8,9,11,13	--	--	--	--	--	--	--	--	--	C
johnny darter	2,8 rare	--	X	X	--	X	X	X	X	X	D
3-spine stickleback	2,8 rare	--	--	--	X	X	X	--	--	--	D
tadpole madtom	2,8 rare	--	--	--	--	--	X	X	X	X	D
white crappie	---	X	--	--	--	--	--	X	X	X	D
Immature sunfish	---	--	X	--	--	X	--	X	X	--	D
Total # species		**12**	**12**	**11**	**09**	**16**	**16**	**17**	**16**	**13**	**51**

Table 6. List of unpublished or published documents used to construct **Table 5**.

Document #	Citation
1	Gartner Lee Limited. 1987, 1988. *Biological Overview of Frenchman's Bay*. Town of Pickering, Prepared by Sandbury Building Corporation.
2	Metropolitan Toronto and Region Conservation Authority. 1975. *A Review of Interests in the Frenchman Bay Area –Town of Pickering.* MTRCA, Toronto, ON.
3	Stephenson, T.D. 1988. *Fish utilization of Toronto Area Coastal Waters.* M.Sc. Thesis. University of Toronto, Department of Zoology/Institute for Environmental Studies, Toronto, ON.
4	Wainio, A.A. 1976. *Fish and Wildlife Values of Freshman's Bay.* OMNR files, Maple District, ON.
5	Casselman, J.M. 1973. *Differentiation of northern pike and white sucker eggs from Liverpool Creek, 1973.* Unpub. Manuscript, OMNR files, Maple District, ON.
6	B.A.R. Environmental. 1987. *Survey of critical fish habitat within International Joint Commission Designated Areas of Concern, August-November, 1986.* Report prepared for OMNR, Toronto, ON.
7	Limnos Ltd. 1987. *Fishing in Frenchman's Bay and Lake Ontario.* Report on fishing activities conducted under a Scientific Collectors' Permit.
8	MacNab, I.D., and Hester, R.A. 1976a. *Operation Doorstep Angling—Metropolitan Toronto Fishery Project Summary,* OMNR and MTRCA..
9	MacNab, I.D., and Hester, R.A. 1976b. *Operation Doorstep Angling—Metropolitan Toronto Fishery Project Report, Vol. 3—Database,* OMNR and MTRCA, Toronto, ON.
10	Ontario Ministry of Natural Resources. 1986. *Field Collection Records (Fish) for Frenchman's Bay: September and November 1986.* Unpub. file, Maple District, ON.
11	Ontario Ministry of Natural Resources. Unpublished documents. Toronto, ON.
12	Steedman, R.J., Stephenson, T.D., and Regier, H.A. 1987. Aquatic Ecosystems of the Toronto Area. In: *Toronto Area Waters: Current Status and Prospects for Rehabilitation.* Background papers for a one-day symposium, May 21, 1987, Toronto, ON, p. 1-21.
13	Metropolitan Toronto and Region Conservation Authority. 1976. *Toronto Angler's Guide.* MTRCA, Toronto, ON.

Table 7. Summary of P-values associated with paired t-tests to determine significant differences between fish abundances and biomass data corresponding to North and South stations in Frenchman's Bay. Data were all log-transformed prior to analyses. Bolded numbers indicate that differences are significant ($P \leq 0.10$). "Yes" indicates that data received from TRCA (Toronto Region Conservation Authority) are consistent with findings in this study, whereas "No" indicates that there was evidence to the contrary (Figures 39 to 41).

Type	Species	Abundance	Biomass	TRCA data
South > North	Northern pike	**0.091**	0.472	**Yes**
	Yellow perch	**0.0436**	**0.016**	**Yes**
	Bluntnose minnow	**0.001**	**0.002**	
	Johnny darter	**0.0001**	**0.0001**	
	Alewife	0.3607	**0.0189**	**Yes**
	Fathead minnow	**0.058**	**0.0001**	
	Pumpkinseed	**0.074**	0.1027	**Yes**
	Largemouth bass	**0.06**	**<0.001**	**No**
	All taxa	**<0.001**	**----**	**Yes**
North > South	Brown bullhead	0.1035	**0.0367**	**Yes**
	Gizzard shad	**<0.001**	**<0.001**	
	White sucker	**0.07**	**0.001**	**No**
	Golden shiner	0.1016	**0.001**	
	Bowfin	**0.0003**	**0.0001**	**Yes**
	White crappie	**0.0042**	**0.0001**	**Yes***
	Common carp	**0.03**	**0.046**	**Yes**
	3-spine stickleback	**0.095**	**0.0002**	
	All taxa	**----**	**<0.001**	**Yes**

* Assumes that White crappie had been incorrectly keyed to Black crappie

Table 8. Comparison of current and historic water-quality conditions in Frenchman's Bay, ON.

Parameter		McNab & Hester (1974-75)	Lemay & Mulamootil (1977)	Stephenson (1985-86)	2001	2002		
					South	North	South	Open
Temperature (°C)								
	Range	---	7-22.0	---	25.0-25.7	11.5-26.8	11.9-27.22	---
	Mean				---	**19.24**	**21.49**	
	n				2	110	113	
pH								
	Range	7.5-8.8	7.2-7.8	7.0-8.9	8.5-8.7	7.3-8.7	7.8-8.9	---
	Mean	**8.0**	**7.5**	**7.8**	---	**8.12**	**8.50**	
	n				2	110	113	
Conductivity (mS/cm)								
	Range	---	---	---	0.39-0.42	0.36-1.82	0.23-0.50	0.33-0.43
	Mean				---	**1.12**	**0.36**	**0.38**
	n				2	110	113	10
Dissolve Oxygen (mg/L)								
	Range	8-12	---	3.5-15.9	8.8-8.9	0.1-12.5	5.3-13.7	---
	Mean	**10.2**		**9.1**	---	**5.7**	**9.22**	
	n				2	110	113	
Secchi disk (cm)								
	Range		45-bottom	5-60	60-85	----	---	50-90
	Mean	78		**22**	---			**65**
	n				2			10
Turbidity (NTU)								
	Range				8.73-12.57	0.48-146.3	0.59-74.45	---
	Mean				---	**24.49**	**7.51**	
	n				2	110	113	
Total SS (mg/L)								
	Range	---	0-148	---	8.73-12.57	13.1-83.7	4.6-16.3	6.37-20.10
	Mean		**43**		**---**	**28.3**	**11.8**	**13.37**
	n				2	10	9	10
Total phosphorus (µg/L)								
	Range	---	<1-26	---	66.1-70.8	41-125	33-157	11-37
	Mean		**10**		---	**77.0**	**77.8**	**21.7**
	n				2	10	9	10
Total Nitrate N (mg/L)								
	Range	----	<0.01-7.0	---	0.1-0.2	0.30-1.50	0.07-0.57	0.10-0.53
	Mean		**1.01**		---	**0.50**	**0.19**	**0.26**
	n				2	10	9	10
Total Ammonia-N (mg/L)								
	Range	---	---	---	0.03-0.14	---	---	0.03-0.13
	Mean				---			**0.07**
	n				2			6

LIST OF FIGURES

Figure 11. Monthly mean temperature collected on an hourly basis at the North, South and Pine Creek stations during 2002.

Figure 12. a) Changes in concentrations of total suspended solids (TSS) and total phosphorus (TP) corresponding to composite water samples collected 4 times daily and pooled weekly at Amberlea Creek station from late-May to mid-September, 2002. b) Changes in rainfall amount during the same period.

Figure 13. Seasonal changes in a) total phosphorus concentration for samples collected in Amberlea Creek, b) total phosphorus concentration for samples collected at the North, South and Open marsh stations, c) total nitrate-N concentration for samples collected at all study sites and d) total suspended solids concentration for samples collected at all study sites during summer 2002.

Figure 14. Mean water quality parameters for all study sites. Bars are 1 S.E. of the mean. P-values < 0.05 indicate significant differences among sites as determined by ANOVA. Bars that share the same letter indicate that their means are statistically homogeneous as indicated by the Tukey-Kramer test. TP= total phosphorus; SRP = soluble reactive phosphorus; TNN= total nitrate-Nitrogen; TN = total nitrogen; CHL = chlorophyll-a; TSS= total suspended solids; TISS=total inorganic suspended solids; % minerals calculated by dividing TISS by TSS and multiplying by 100.

Figure 15. a) Comparison of seasonal changes in continuous measurements of water turbidity (solid line) and discrete samples of total suspended solids (TSS) (open circles and closed squares) corresponding to the North and South stations. Amount of rainfall during this period is superimposed on these data (note inverted axis).
b) Comparison of seasonal changes in continuous (solid line) and discrete (open circle and closed square) measurements of chlorophyll (CHL) corresponding to the North and South stations. Amount of rainfall during this period is superimposed on these data (note inverted axis).

Figure 16. Hourly changes in turbidity and chlorophyll for a) North and b) South marsh stations from May 30 to June 19, 2002 (Episode A).

Figure 17. Hourly changes in turbidity and chlorophyll for a) North and b) South marsh stations from June 20 to July 4, 2002 (Episode B).

Figure 18. Hourly changes in turbidity and chlorophyll for a) North and b) South marsh stations from July 9 to July 29, 2002 (Episode C).

Figure 19. Hourly changes in turbidity and chlorophyll for a) North and b) South marsh stations from August 2 to August 24, 2002 (Episode D).

Figure 20. GIS-rendered map showing changes in various physico-chemical characteristics of the water in Frenchman's Bay, collected August 20,2002 with a YSIä 6600 probe.

Figure 1

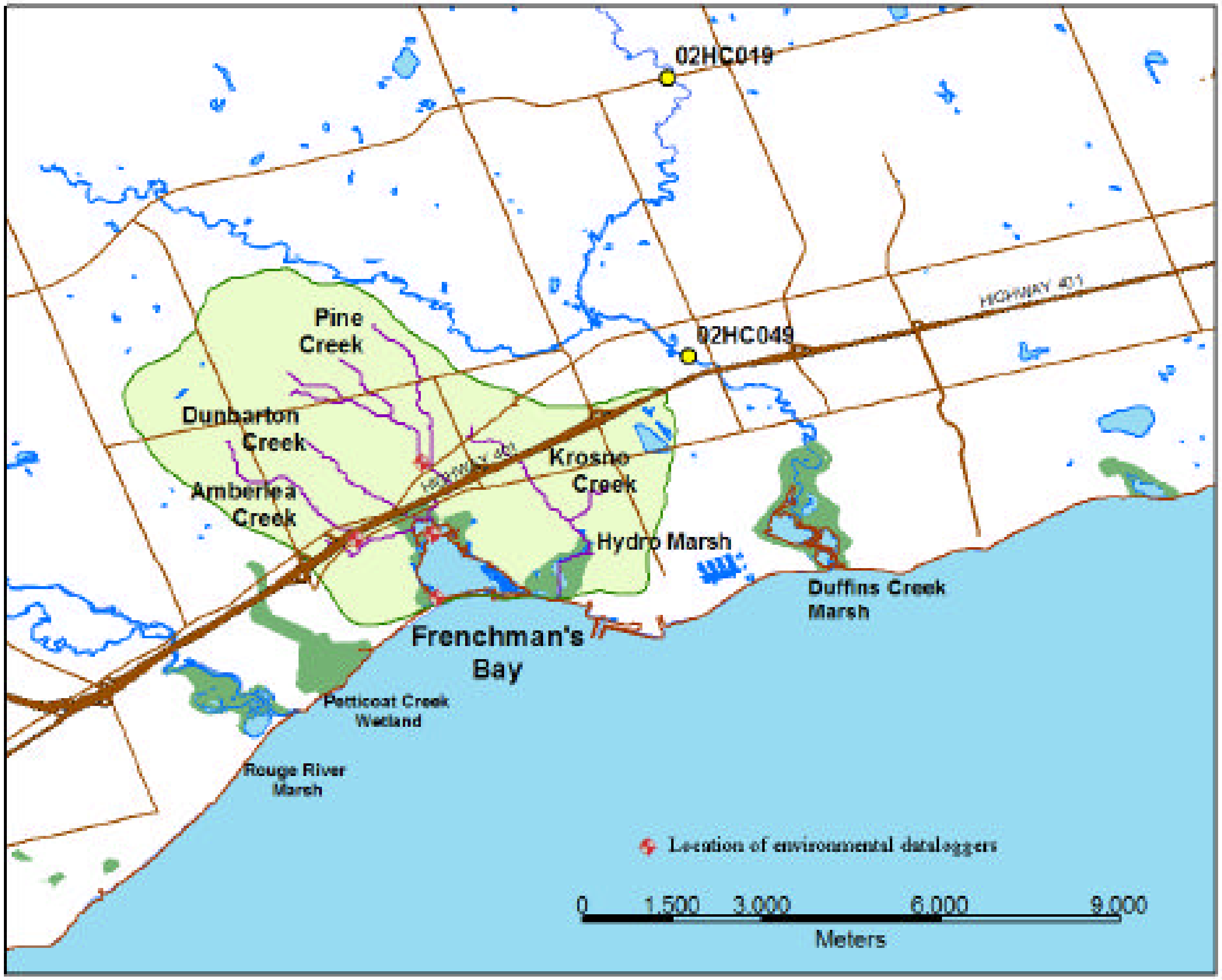
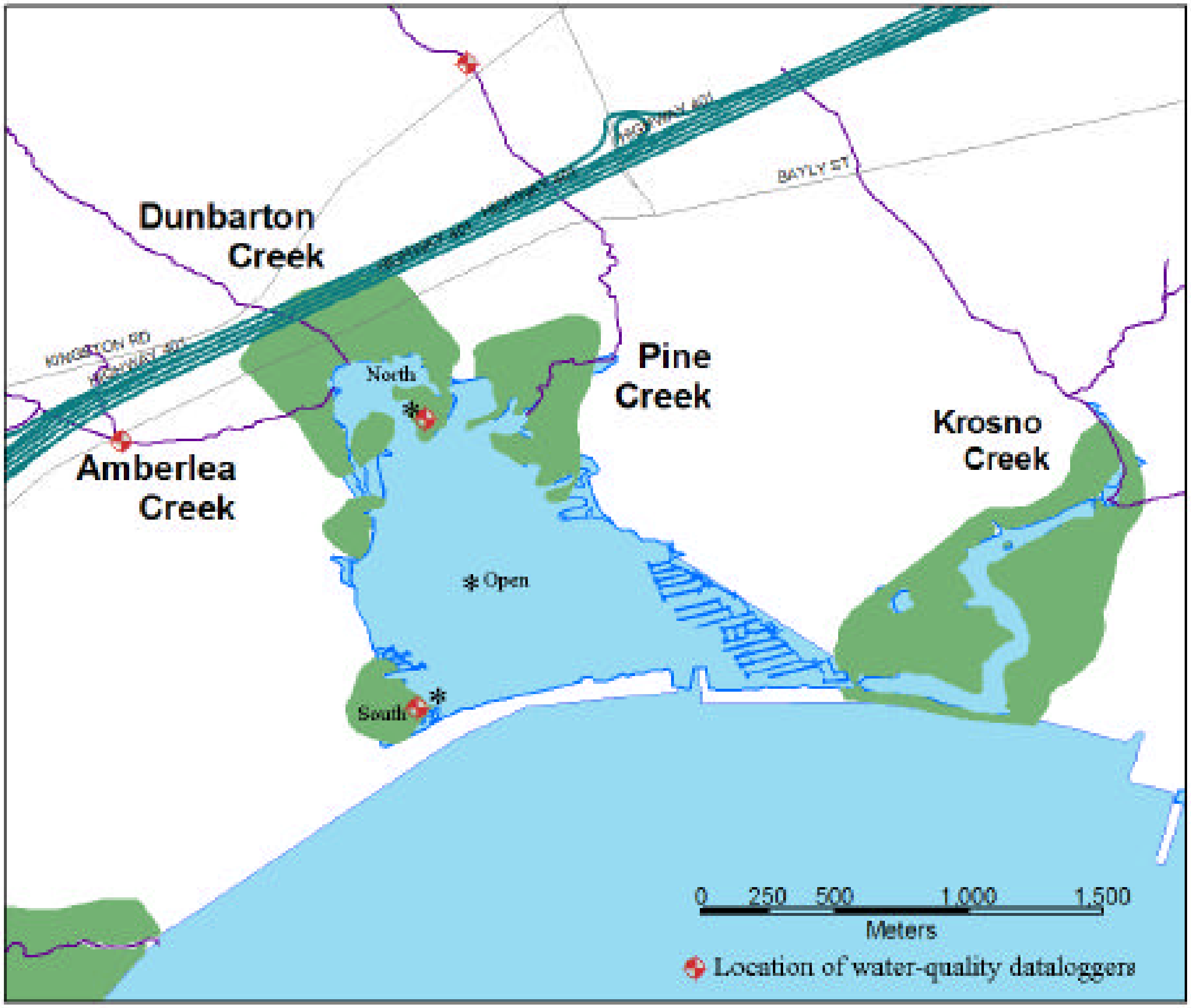

02HC019
02HC049
HIGHWAY 401
Pine Creek
Dunbarton Creek
Amberlea Creek
Krosno Creek
Hydro Marsh
Duffins Creek Marsh
Frenchman's Bay
Petticoat Creek Wetland
Rouge River Marsh
Location of environmental dataloggers
0 1,500 3,000 6,000 9,000
Meters

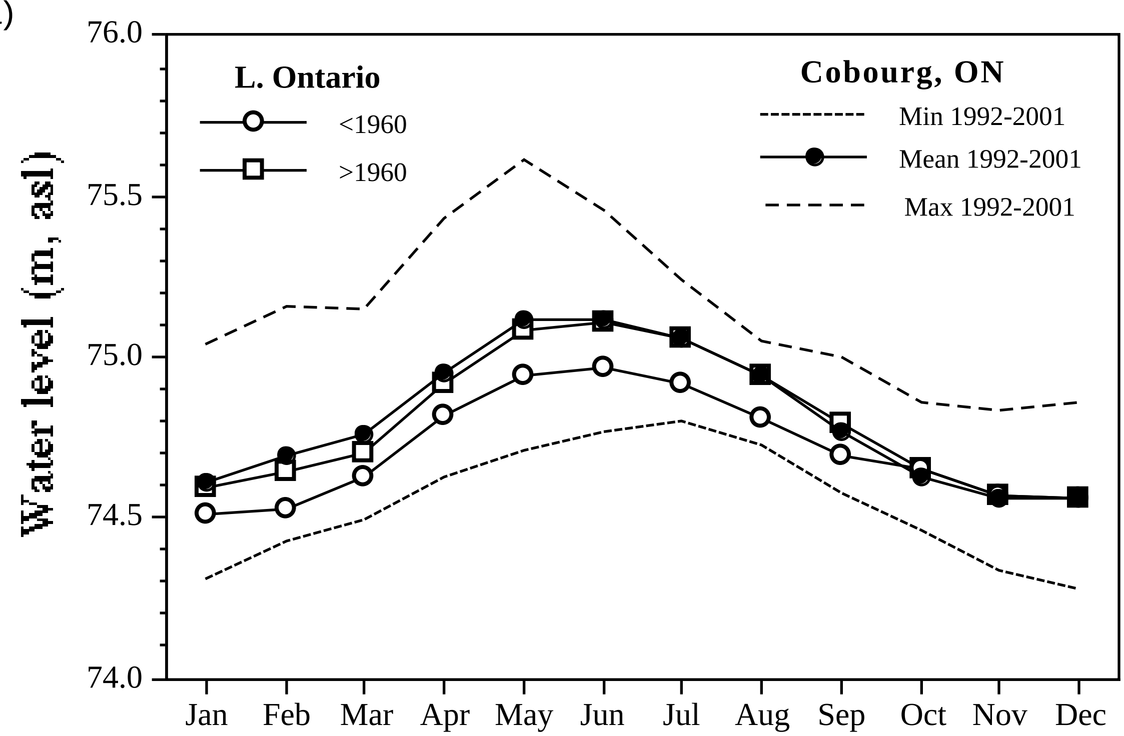
Figure 2



Dunbarton Creek
Amberlea Creek
Pine Creek
Krosno Creek
North
Open
South
BAYLY ST
KINGSTON RD
0 250 500 1,000 1,500
Meters
Location of water-quality dataloggers

Figure 3.

a)


L. Ontario
<1960
>1960
Cobourg, ON
Min 1992-2001
Mean 1992-2001
Max 1992-2001
Water level (m, asl)
76.0
75.5
75.0
74.5
74.0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

b)

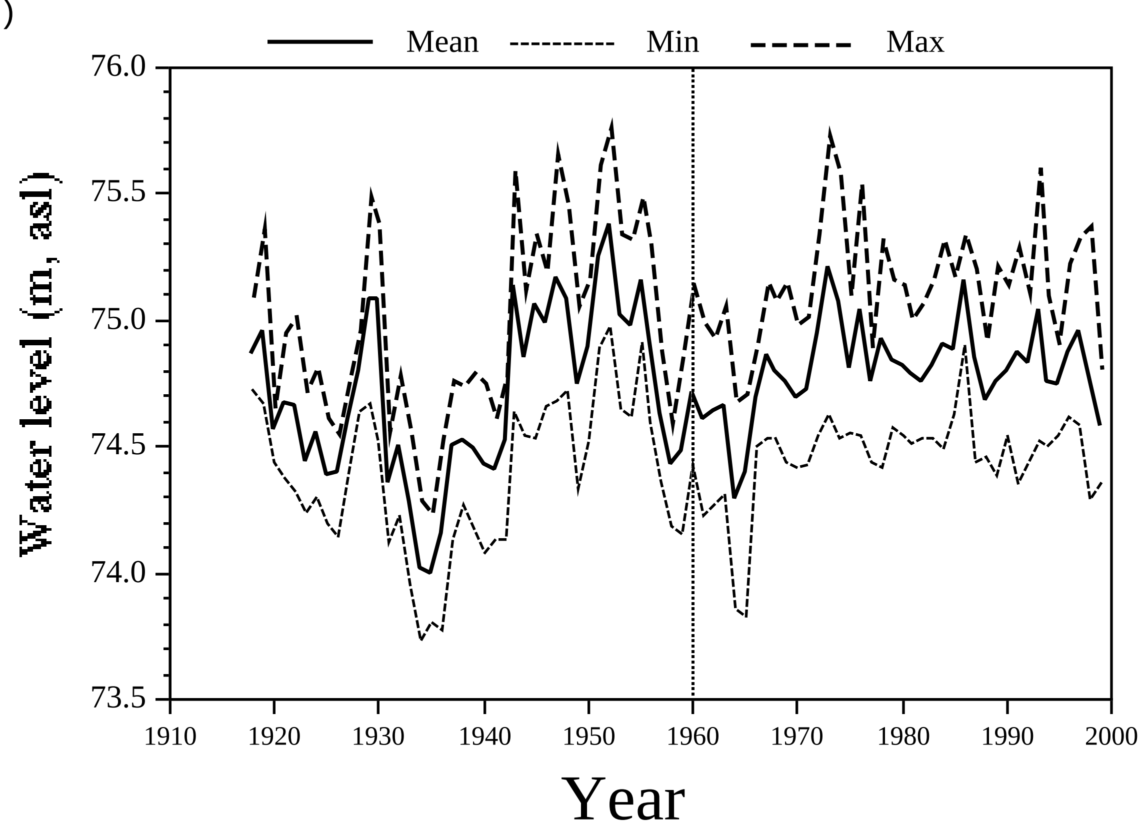
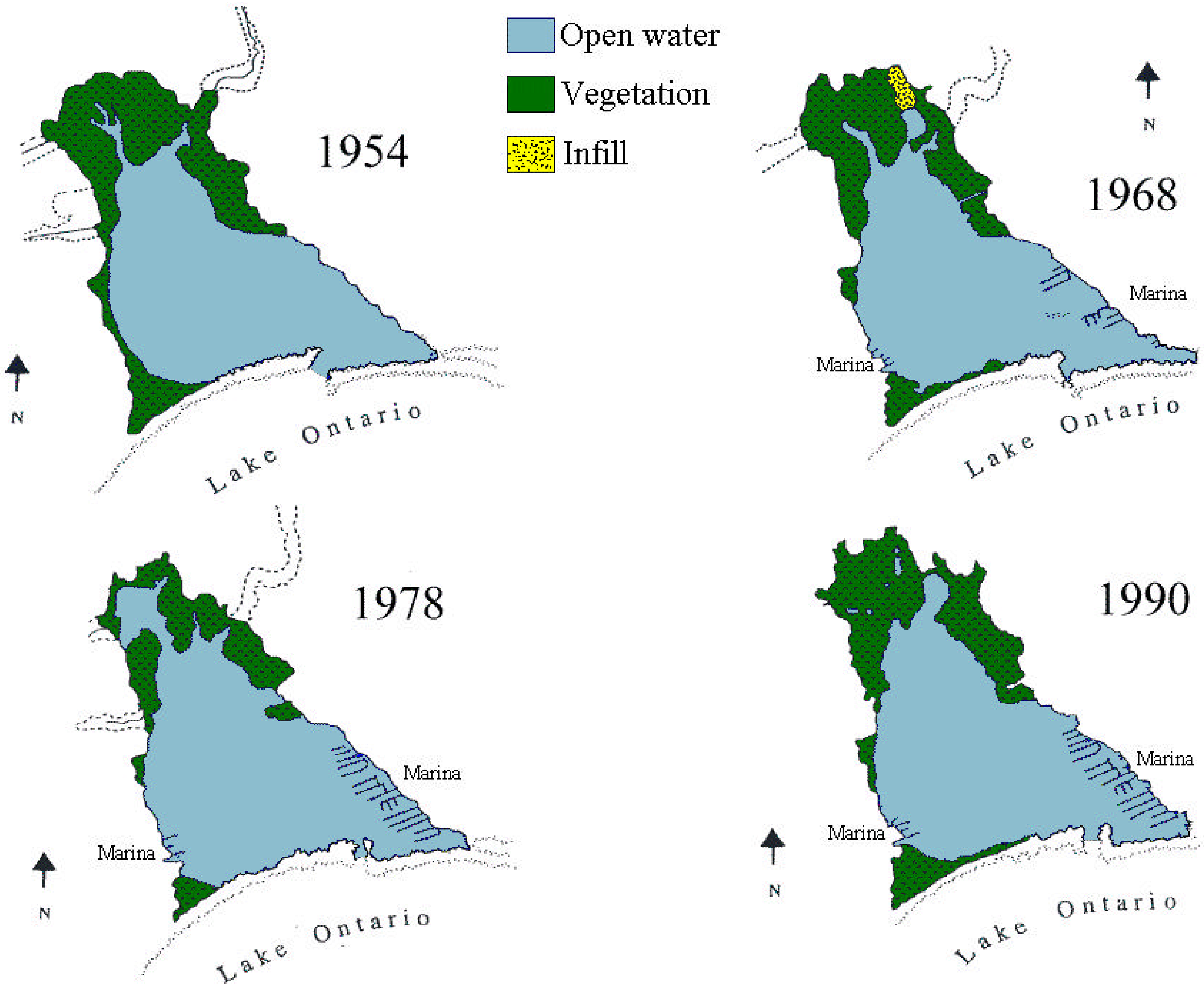

Mean
Min
Max
Water level (m, asl)
76.0
75.5
75.0
74.5
74.0
73.5
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Year

Figure 4.



Open water
Vegetation
Infill
1954
Lake Ontario
N
1968
Marina
Marina
Lake Ontario
N
1978
Marina
Marina
Lake Ontario
N
1990
Marina
Marina
Lake Ontario
N

Figure 5

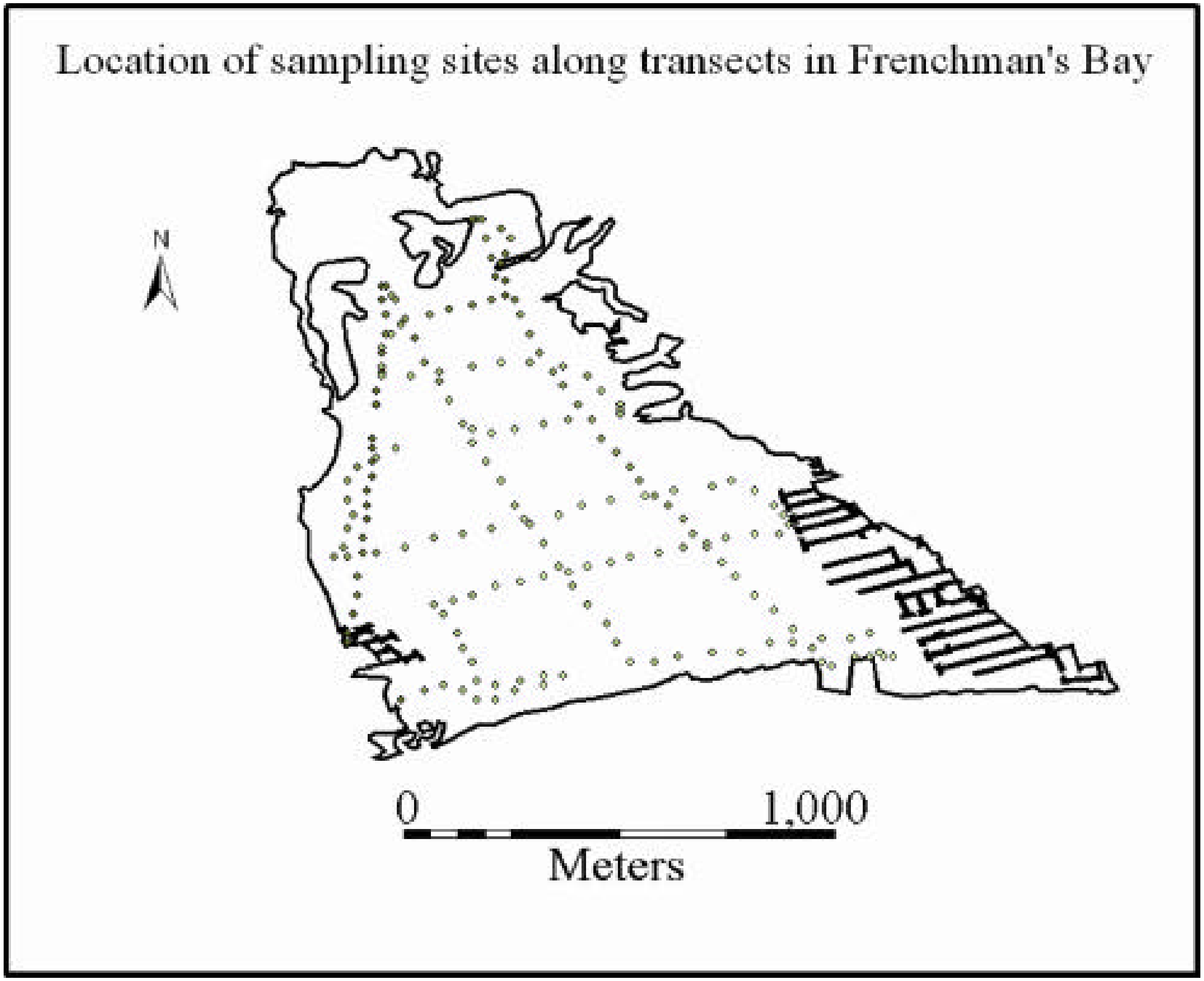
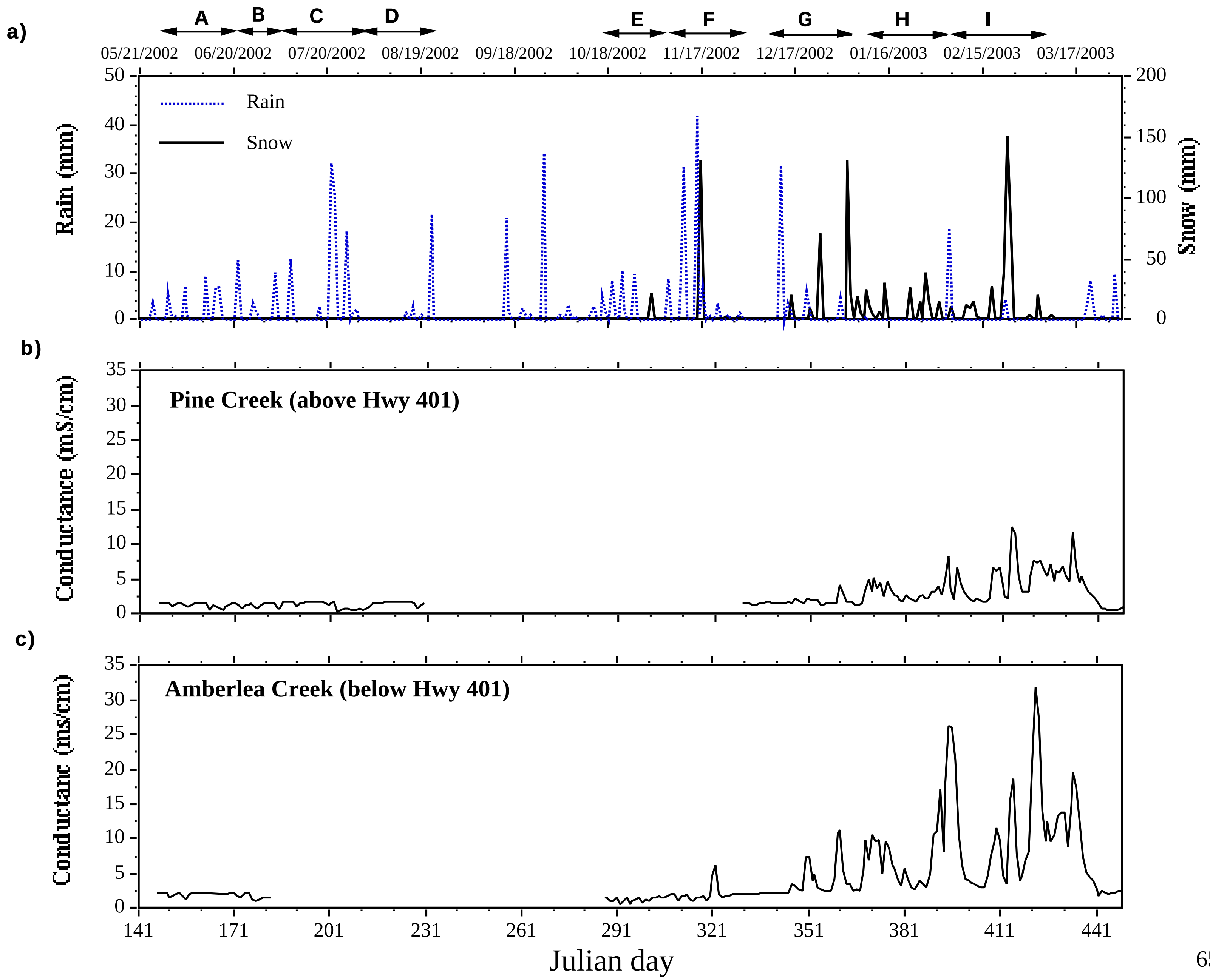

Location of sampling sites along transects in Frenchman's Bay
N
0
1,000
Meters

Figure 6



a)
A
B
C
D
E
F
G
H
I
05/21/2002
06/20/2002
07/20/2002
08/19/2002
09/18/2002
10/18/2002
11/17/2002
12/17/2002
01/16/2003
02/15/2003
03/17/2003
Rain (mm)
Snow (mm)
Rain
Snow
0
10
20
30
40
50
0
50
100
150
200
b)
Pine Creek (above Hwy 401)
Conductance (mS/cm)
0
5
10
15
20
25
30
35
c)
Amberlea Creek (below Hwy 401)
Conductanc (ms/cm)
0
5
10
15
20
25
30
35
141
171
201
231
261
291
321
351
381
411
441
Julian day

Figure 7.

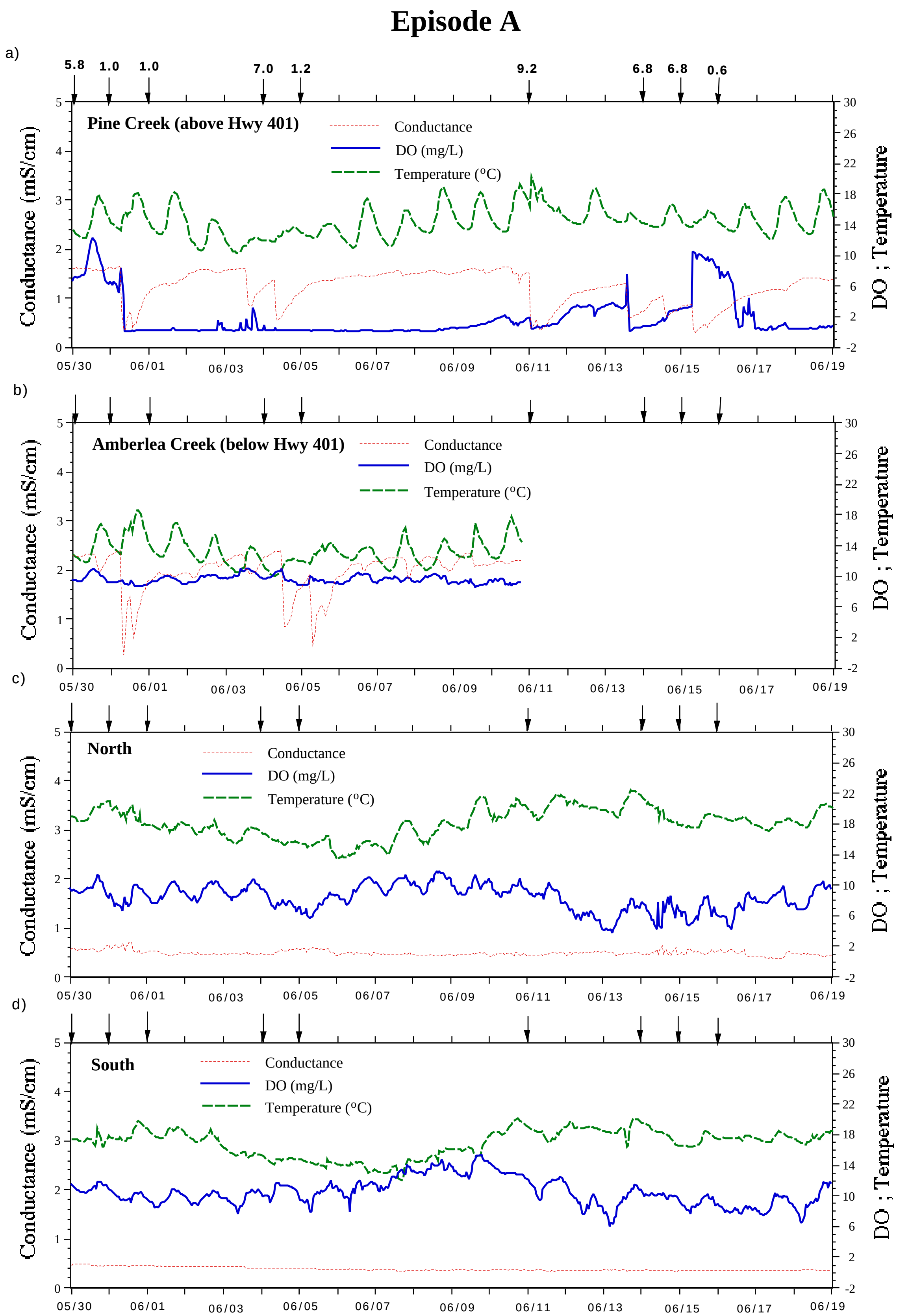

Episode A
a)
5.8
1.0
1.0
7.0
1.2
9.2
6.8
6.8
0.6
Pine Creek (above Hwy 401)
Conductance
DO (mg/L)
Temperature (°C)
Conductance (mS/cm)
DO ; Temperature
05/30
06/01
06/03
06/05
06/07
06/09
06/11
06/13
06/15
06/17
06/19
b)
Amberlea Creek (below Hwy 401)
c)
North
d)
South

Figure 8.

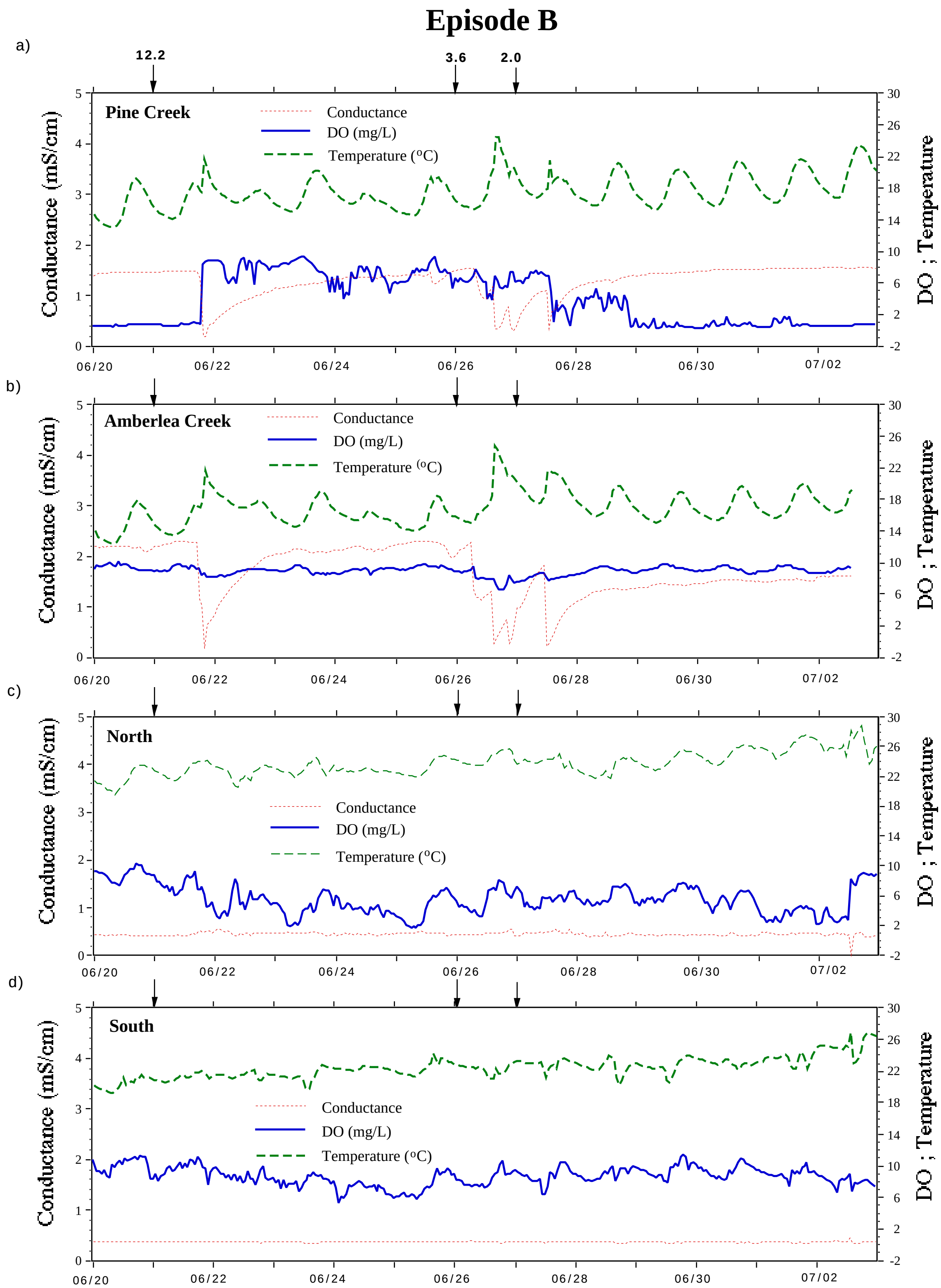

Episode B
a)
12.2
3.6
2.0
Pine Creek
Conductance
DO (mg/L)
Temperature (°C)
Conductance (mS/cm)
DO ; Temperature
06/20
06/22
06/24
06/26
06/28
06/30
07/02
b)
Amberlea Creek
Conductance
DO (mg/L)
Temperature (°C)
c)
North
Conductance
DO (mg/L)
Temperature (°C)
d)
South
Conductance
DO (mg/L)
Temperature (°C)

Figure 9

Episode C

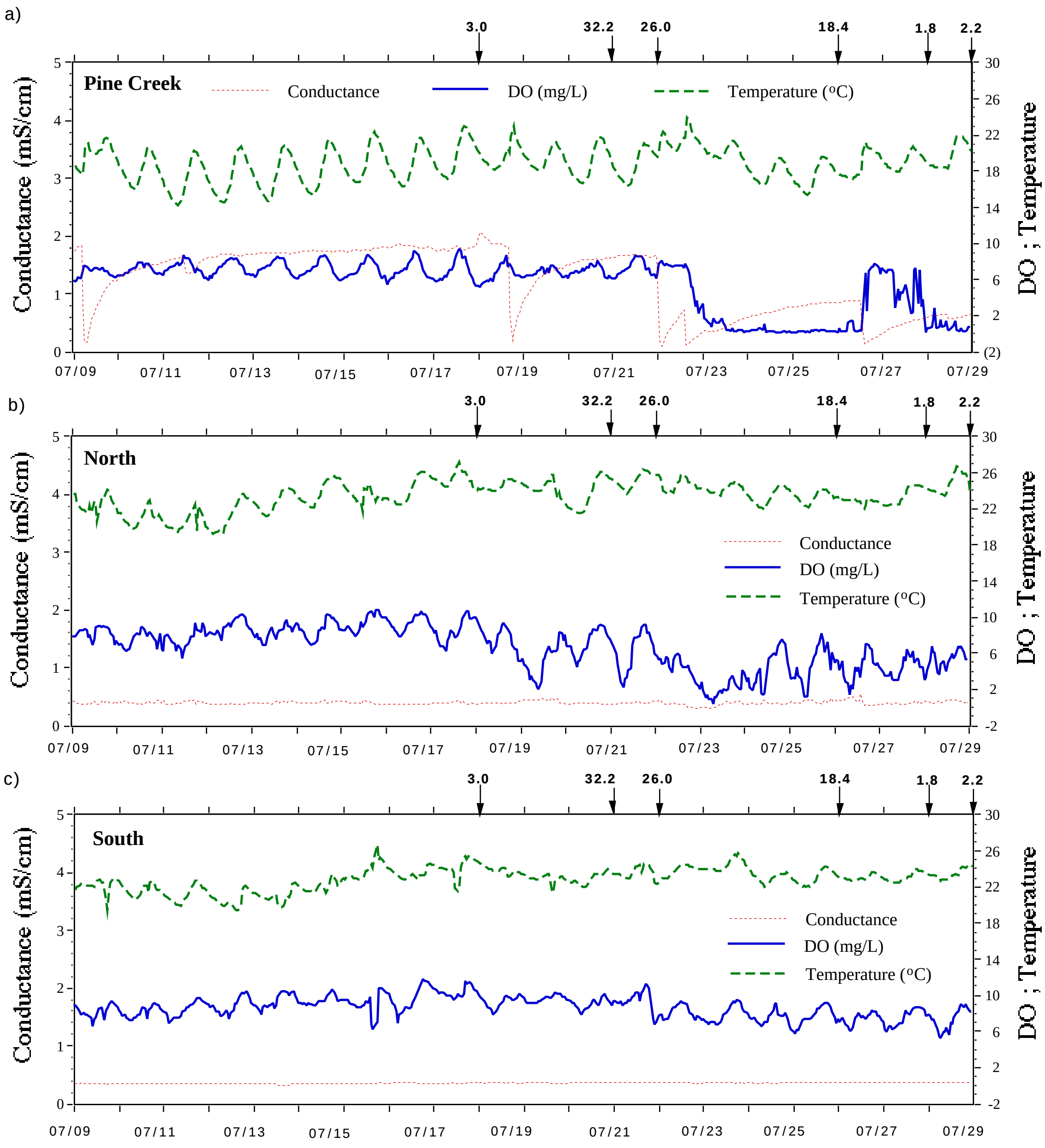


Figure 10.

Episode D

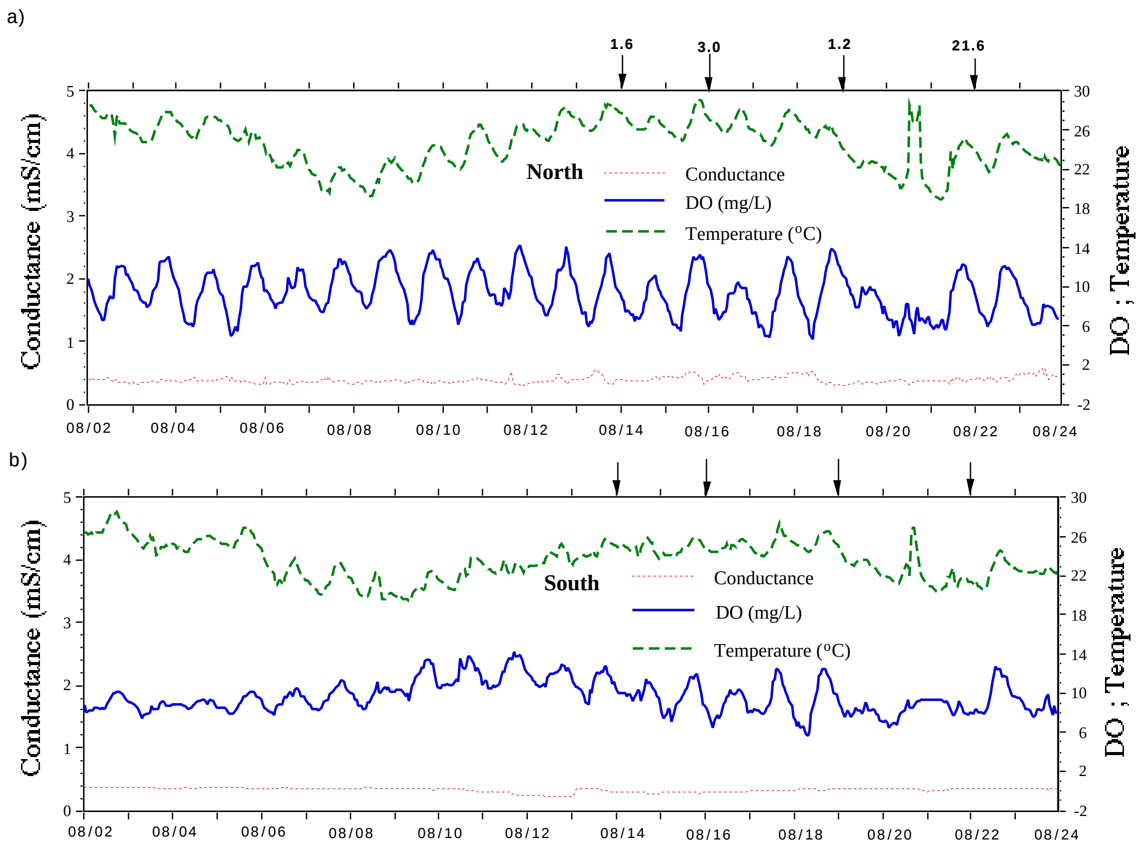


Figure 11.

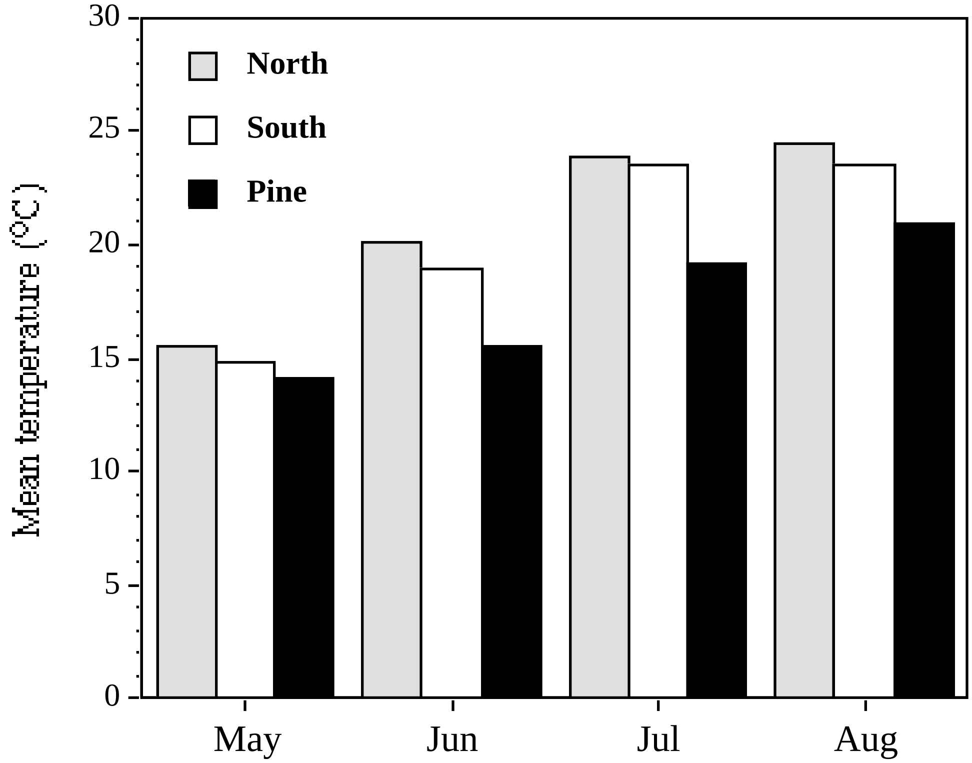

North
South
Pine
Mean temperature (°C)
30
25
20
15
10
5
0
May
Jun
Jul
Aug

Figure 12

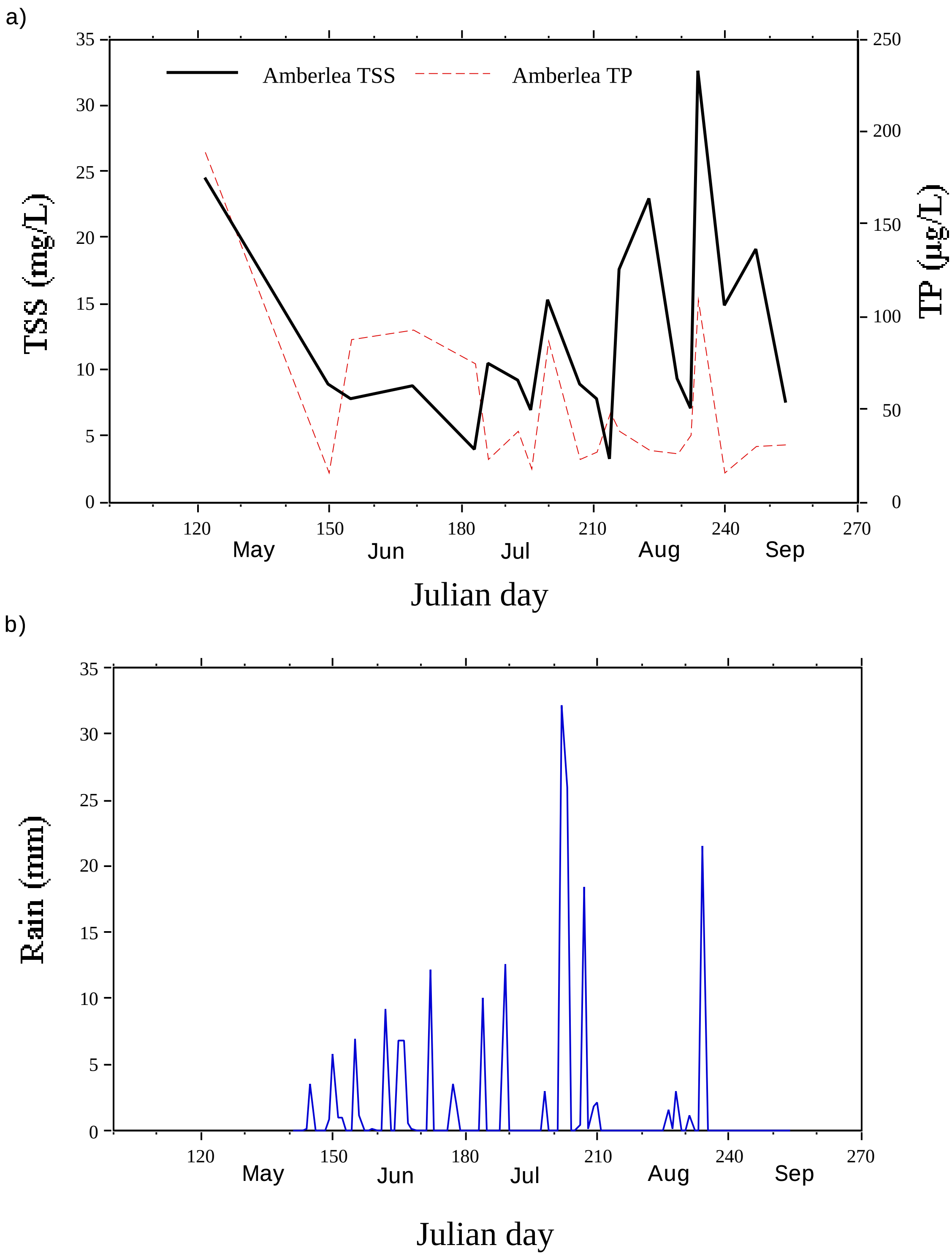
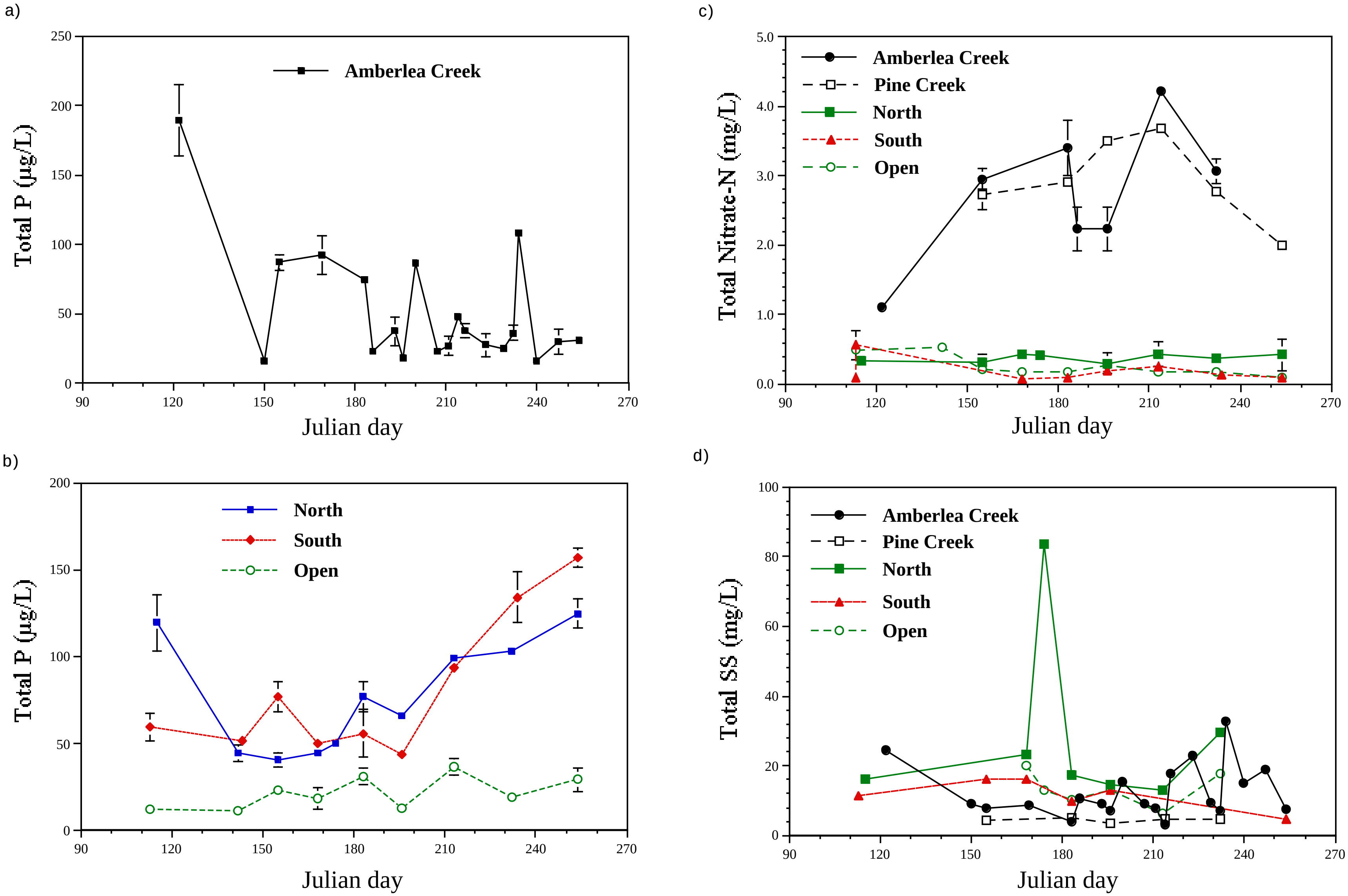

a)
Amberlea TSS
Amberlea TP
TSS (mg/L)
TP (µg/L)
0
5
10
15
20
25
30
35
0
50
100
150
200
250
120
150
180
210
240
270
May
Jun
Jul
Aug
Sep
Julian day
b)
Rain (mm)
0
5
10
15
20
25
30
35
120
150
180
210
240
270
May
Jun
Jul
Aug
Sep
Julian day

Figure13



a)
Amberlea Creek
Total P (µg/L)
Julian day
b)
North
South
Open
Total P (µg/L)
Julian day
c)
Amberlea Creek
Pine Creek
North
South
Open
Total Nitrate-N (mg/L)
Julian day
d)
Amberlea Creek
Pine Creek
North
South
Open
Total SS (mg/L)
Julian day

Figure 14

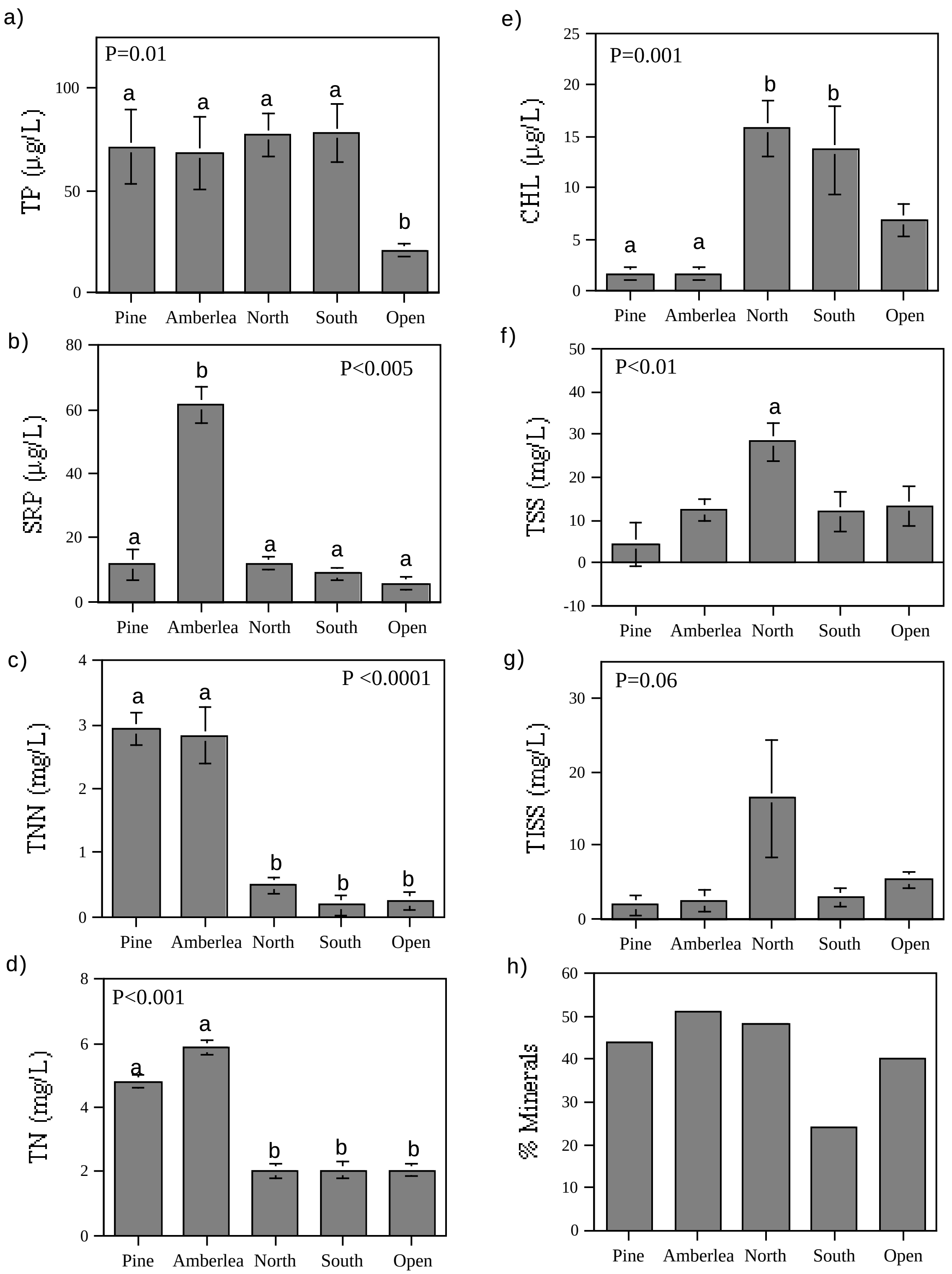

a)
P=0.01
TP (µg/L)
a a a a b
Pine Amberlea North South Open
b)
P<0.005
SRP (µg/L)
a b a a a
Pine Amberlea North South Open
c)
P <0.0001
TNN (mg/L)
a a b b b
Pine Amberlea North South Open
d)
P<0.001
TN (mg/L)
a a b b b
Pine Amberlea North South Open
e)
P=0.001
CHL (µg/L)
a a b b
Pine Amberlea North South Open
f)
P<0.01
TSS (mg/L)
a
Pine Amberlea North South Open
g)
P=0.06
TISS (mg/L)
Pine Amberlea North South Open
h)
% Minerals
Pine Amberlea North South Open

Figure15

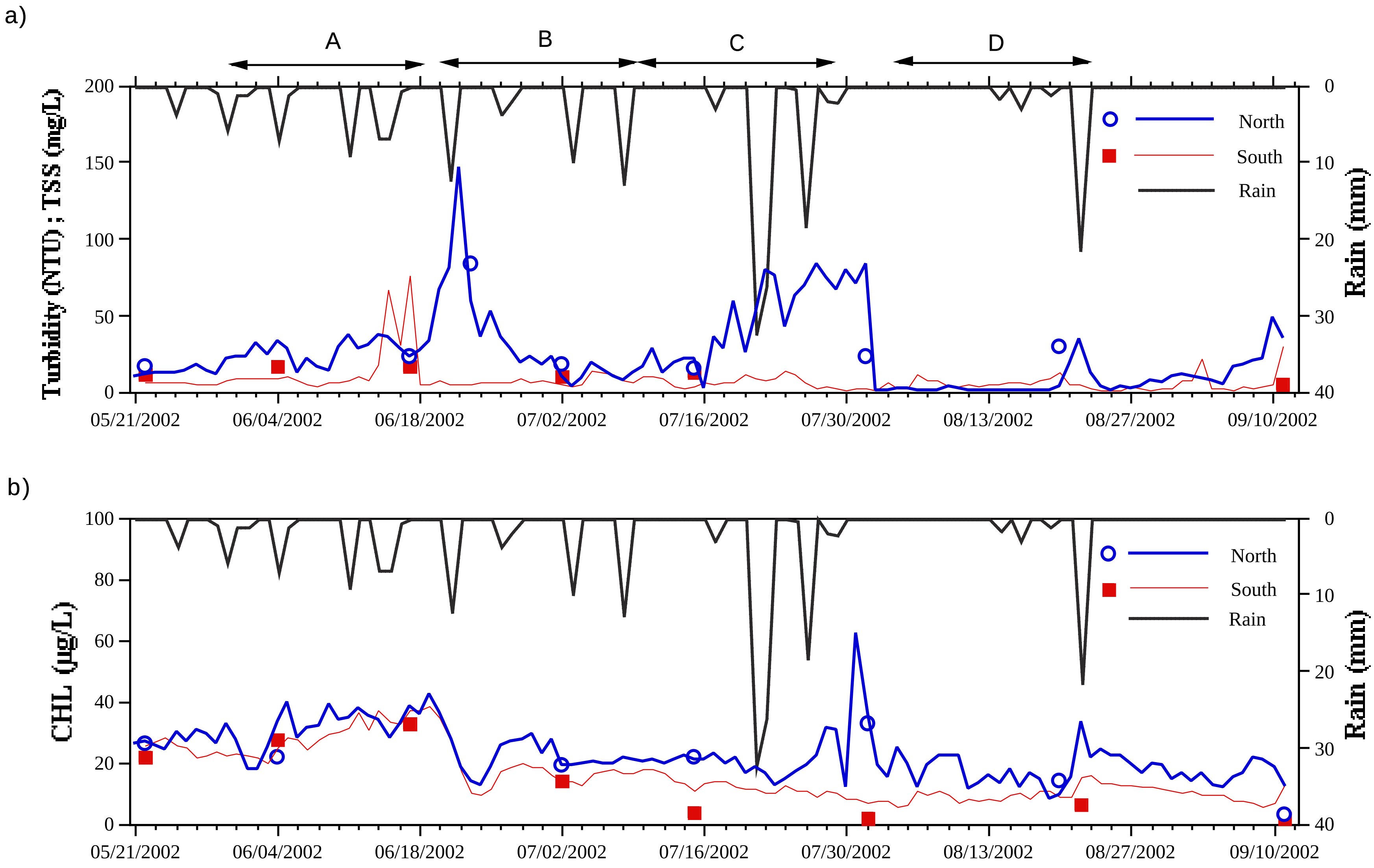
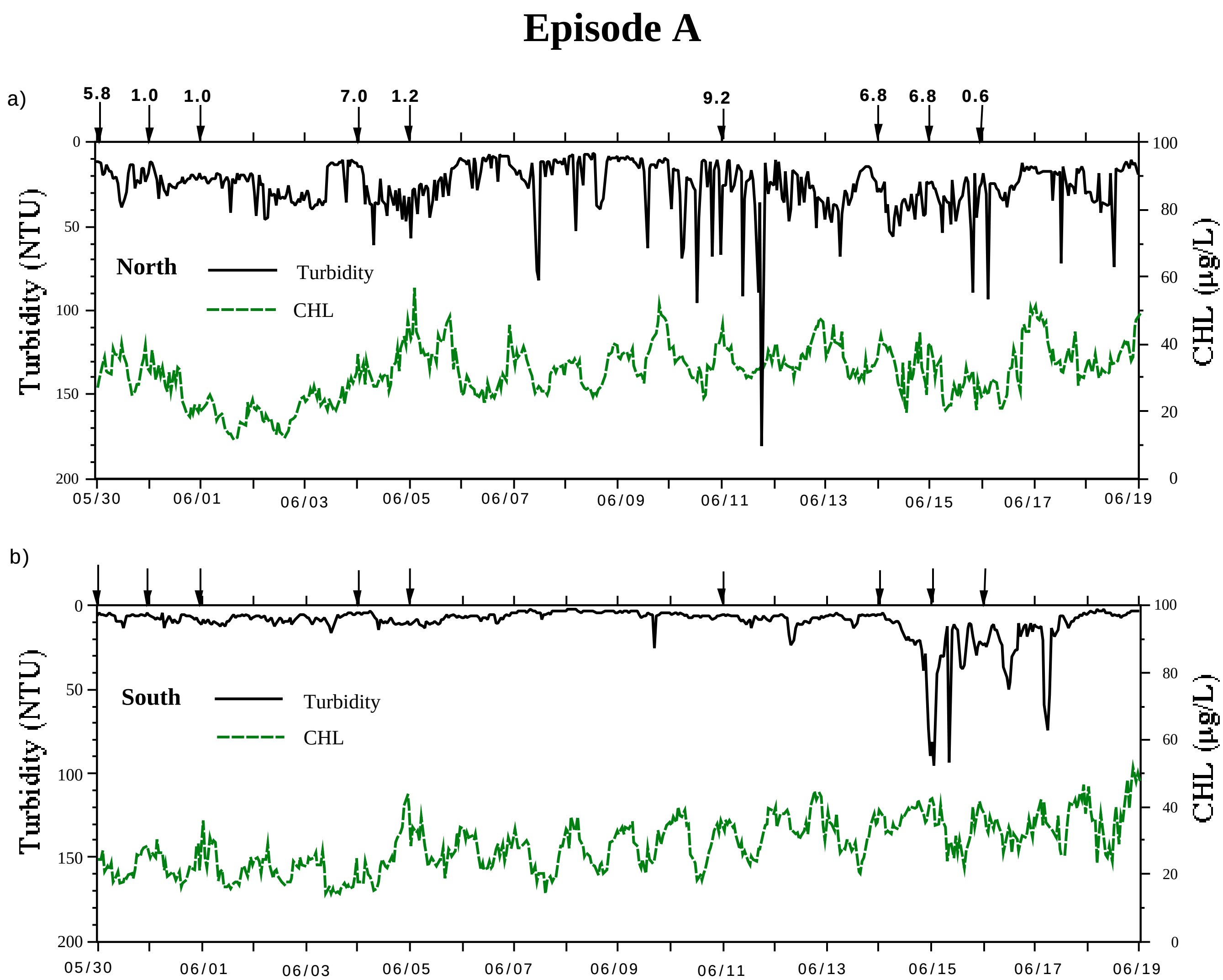
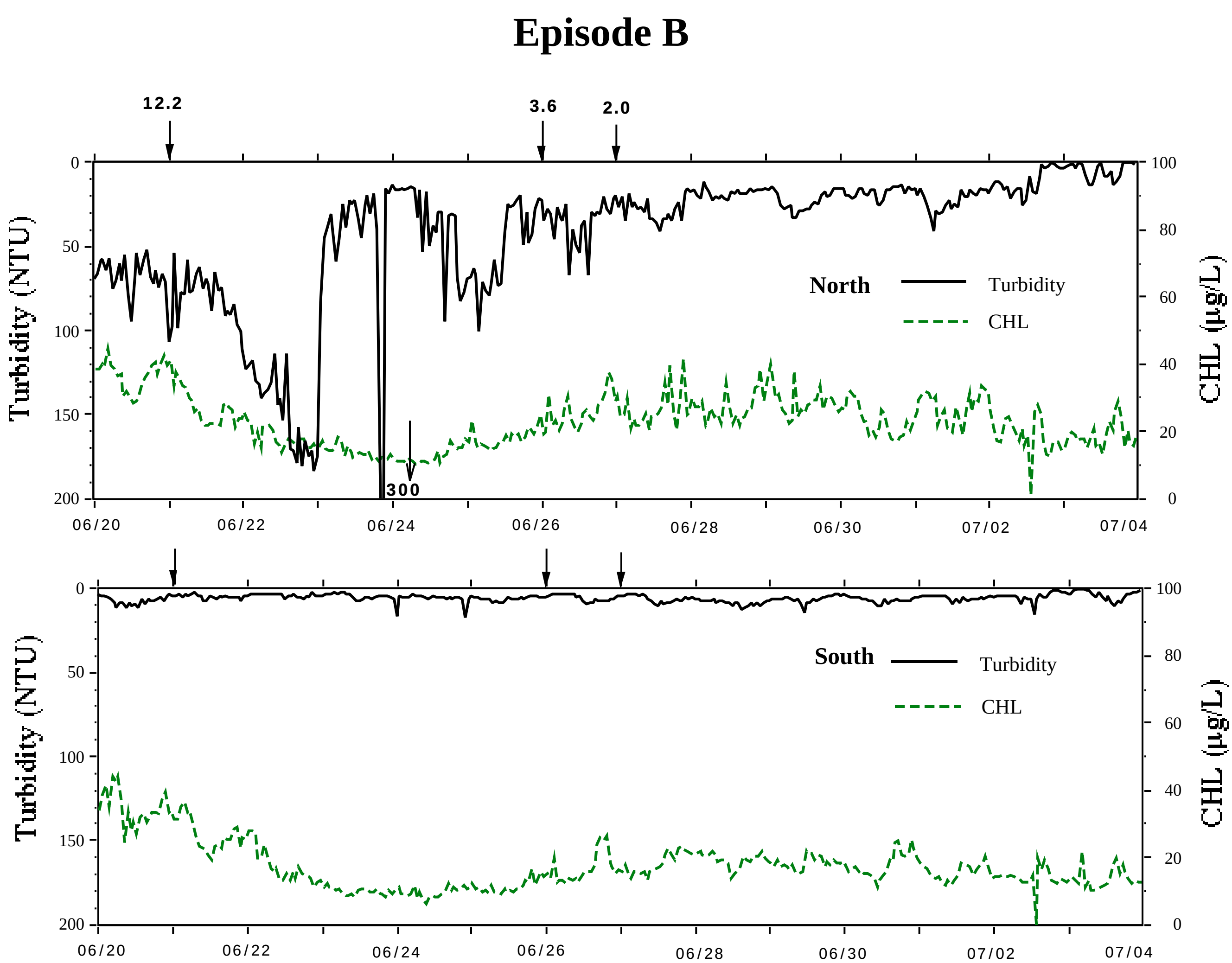

a)
A
B
C
D
Turbidity (NTU) ; TSS (mg/L)
Rain (mm)
North
South
Rain
200
150
100
50
0
0
10
20
30
40
05/21/2002
06/04/2002
06/18/2002
07/02/2002
07/16/2002
07/30/2002
08/13/2002
08/27/2002
09/10/2002
b)
CHL (µg/L)
Rain (mm)
North
South
Rain
100
80
60
40
20
0
0
10
20
30
40
05/21/2002
06/04/2002
06/18/2002
07/02/2002
07/16/2002
07/30/2002
08/13/2002
08/27/2002
09/10/2002

Figure 16



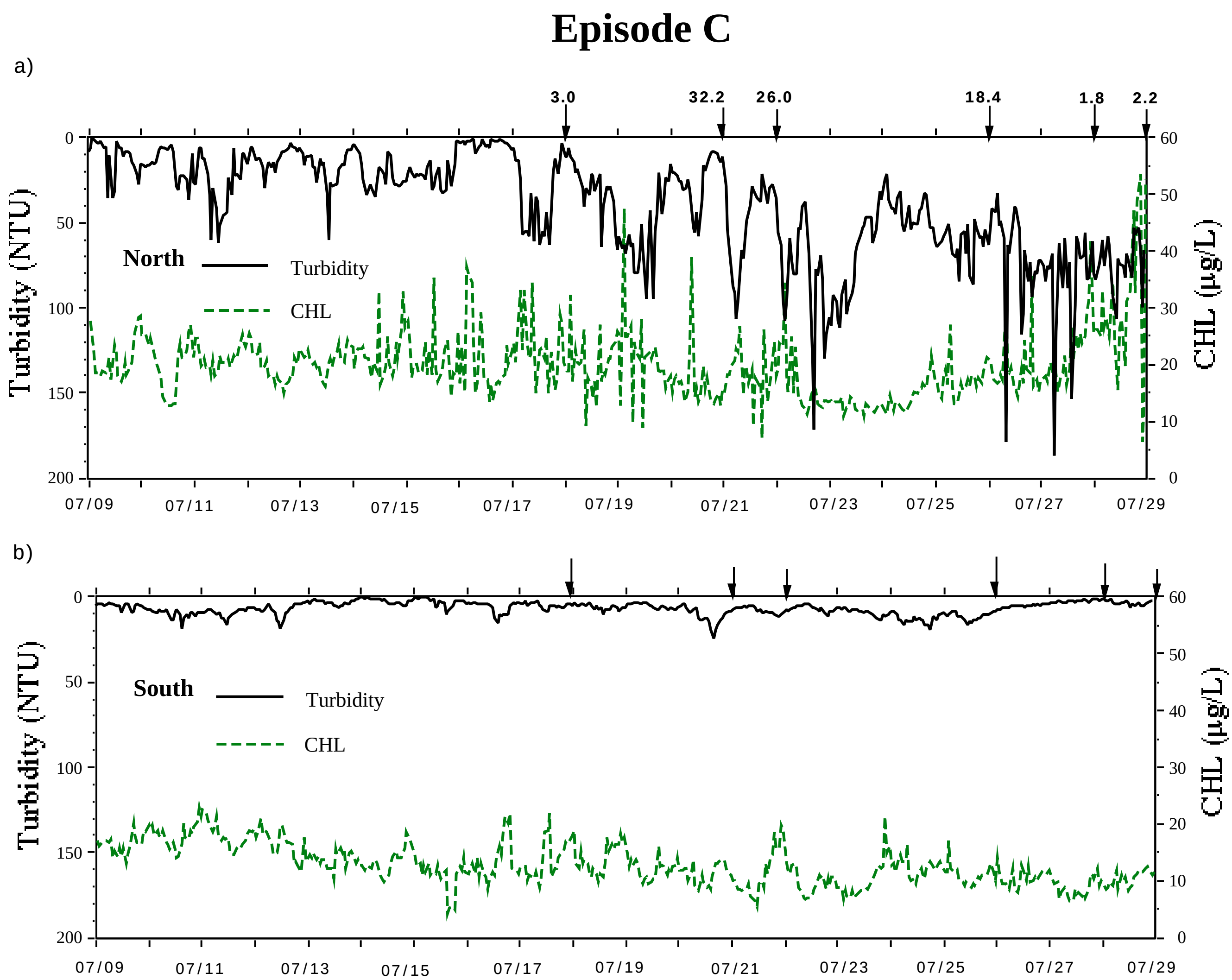
Episode A
a)
5.8
1.0
1.0
7.0
1.2
9.2
6.8
6.8
0.6
North
Turbidity
CHL
Turbidity (NTU)
CHL (µg/L)
0
50
100
150
200
100
80
60
40
20
0
05/30
06/01
06/03
06/05
06/07
06/09
06/11
06/13
06/15
06/17
06/19
b)
South
Turbidity
CHL
Turbidity (NTU)
CHL (µg/L)
0
50
100
150
200
100
80
60
40
20
0
05/30
06/01
06/03
06/05
06/07
06/09
06/11
06/13
06/15
06/17
06/19

Figure 17.



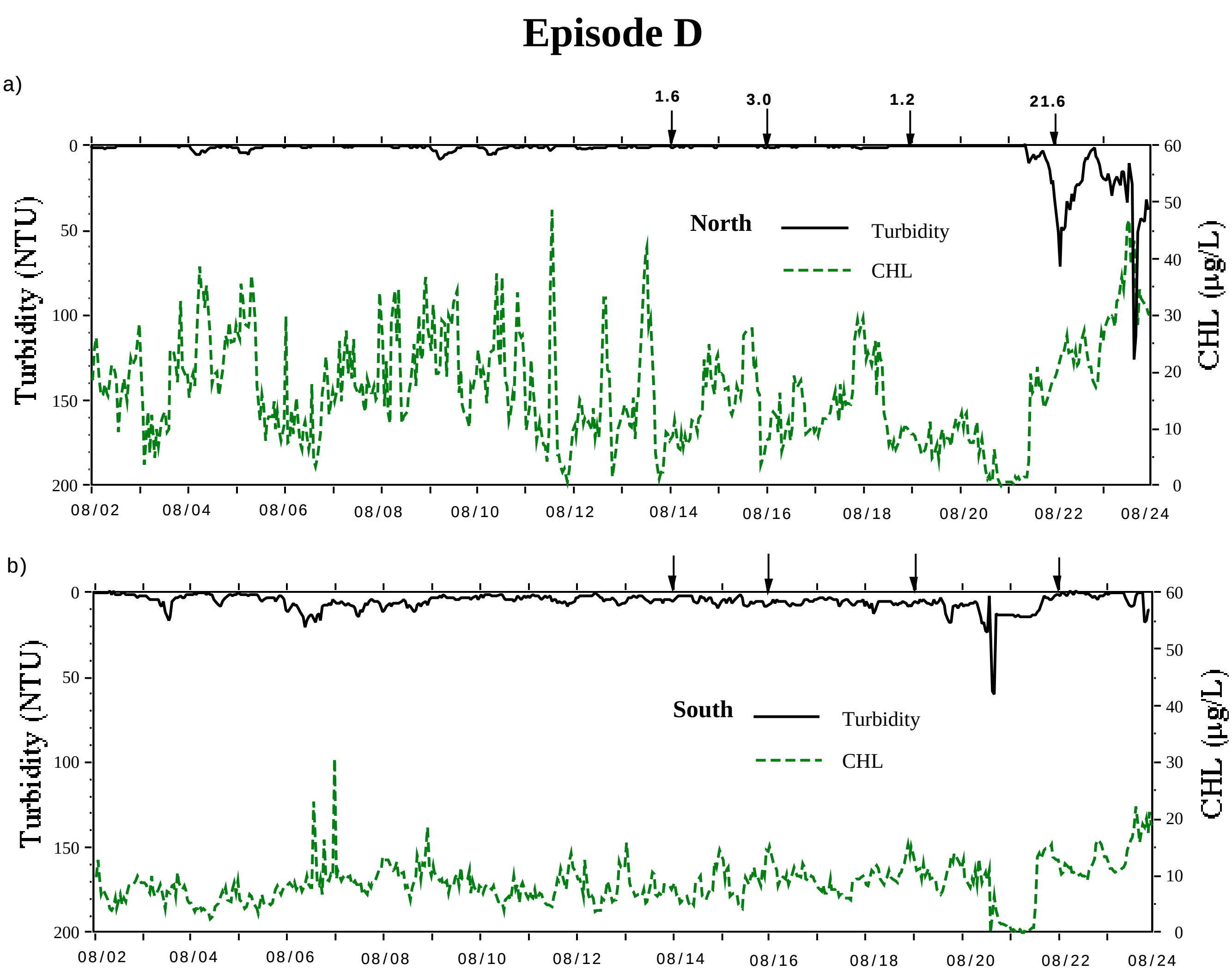
Episode B
12.2
3.6
2.0
300
North
Turbidity
CHL
South
Turbidity
CHL
Turbidity (NTU)
CHL (µg/L)
0
50
100
150
200
100
80
60
40
20
0
06/20
06/22
06/24
06/26
06/28
06/30
07/02
07/04

Figure 18.



Episode C
a)
3.0
32.2
26.0
18.4
1.8
2.2
North
Turbidity
CHL
Turbidity (NTU)
CHL (µg/L)
0
50
100
150
200
60
50
40
30
20
10
0
07/09
07/11
07/13
07/15
07/17
07/19
07/21
07/23
07/25
07/27
07/29
b)
South
Turbidity
CHL
Turbidity (NTU)
CHL (µg/L)
0
50
100
150
200
60
50
40
30
20
10
0
07/09
07/11
07/13
07/15
07/17
07/19
07/21
07/23
07/25
07/27
07/29

Figure 19.



Episode D
a)
1.6
3.0
1.2
21.6
North
Turbidity
CHL
Turbidity (NTU)
CHL (µg/L)
0
50
100
150
200
60
50
40
30
20
10
0
08/02
08/04
08/06
08/08
08/10
08/12
08/14
08/16
08/18
08/20
08/22
08/24
b)
South
Turbidity
CHL
Turbidity (NTU)
CHL (µg/L)
0
50
100
150
200
60
50
40
30
20
10
0
08/02
08/04
08/06
08/08
08/10
08/12
08/14
08/16
08/18
08/20
08/22
08/24

Figure 20

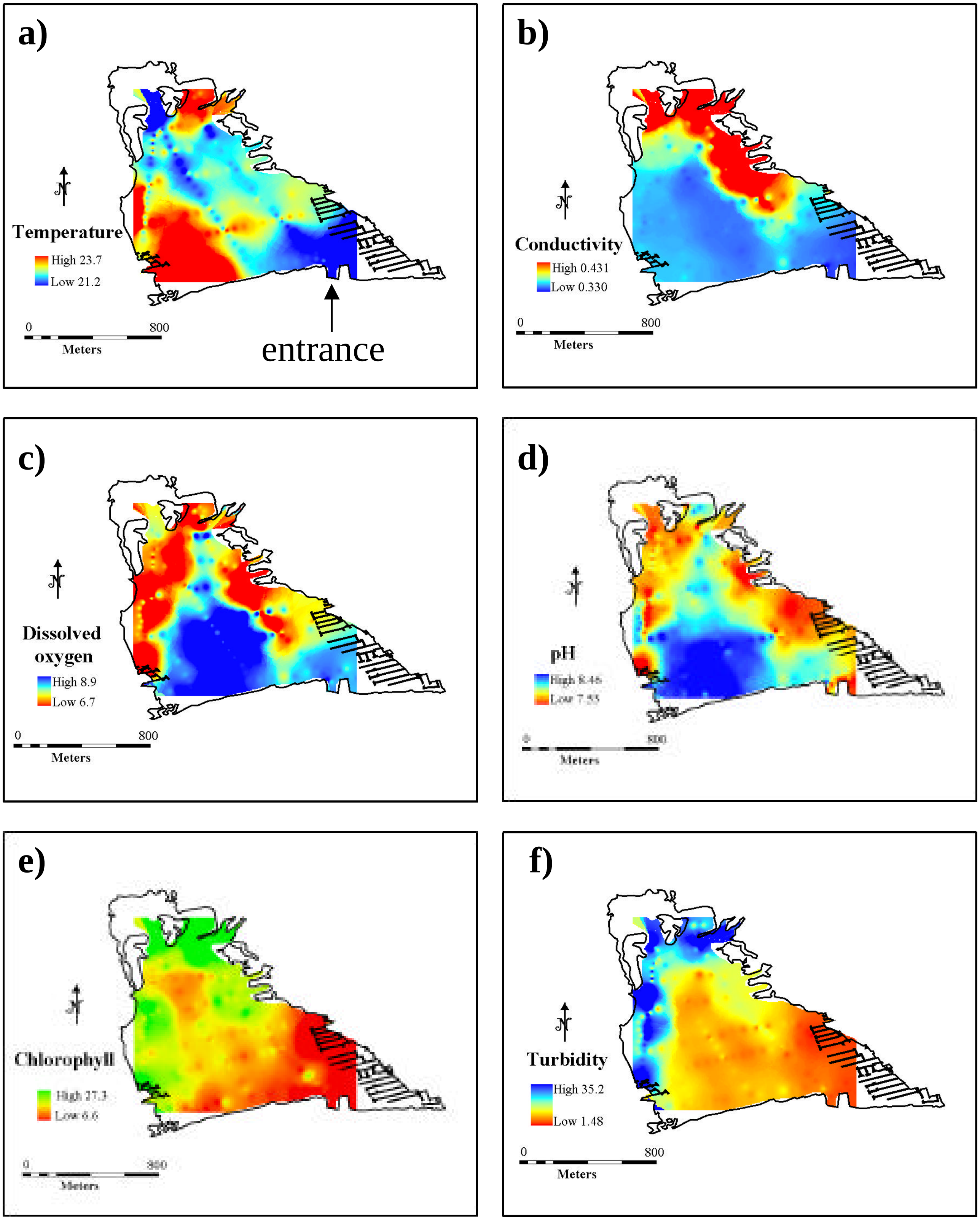

a)
Temperature
High 23.7
Low 21.2
0
800
Meters
entrance
b)
Conductivity
High 0.431
Low 0.330
0
800
Meters
c)
Dissolved oxygen
High 8.9
Low 6.7
0
800
Meters
d)
pH
High 8.46
Low 7.55
0
800
Meters
e)
Chlorophyll
High 27.3
Low 6.6
0
800
Meters
f)
Turbidity
High 35.2
Low 1.48
0
800
Meters

Figure 21

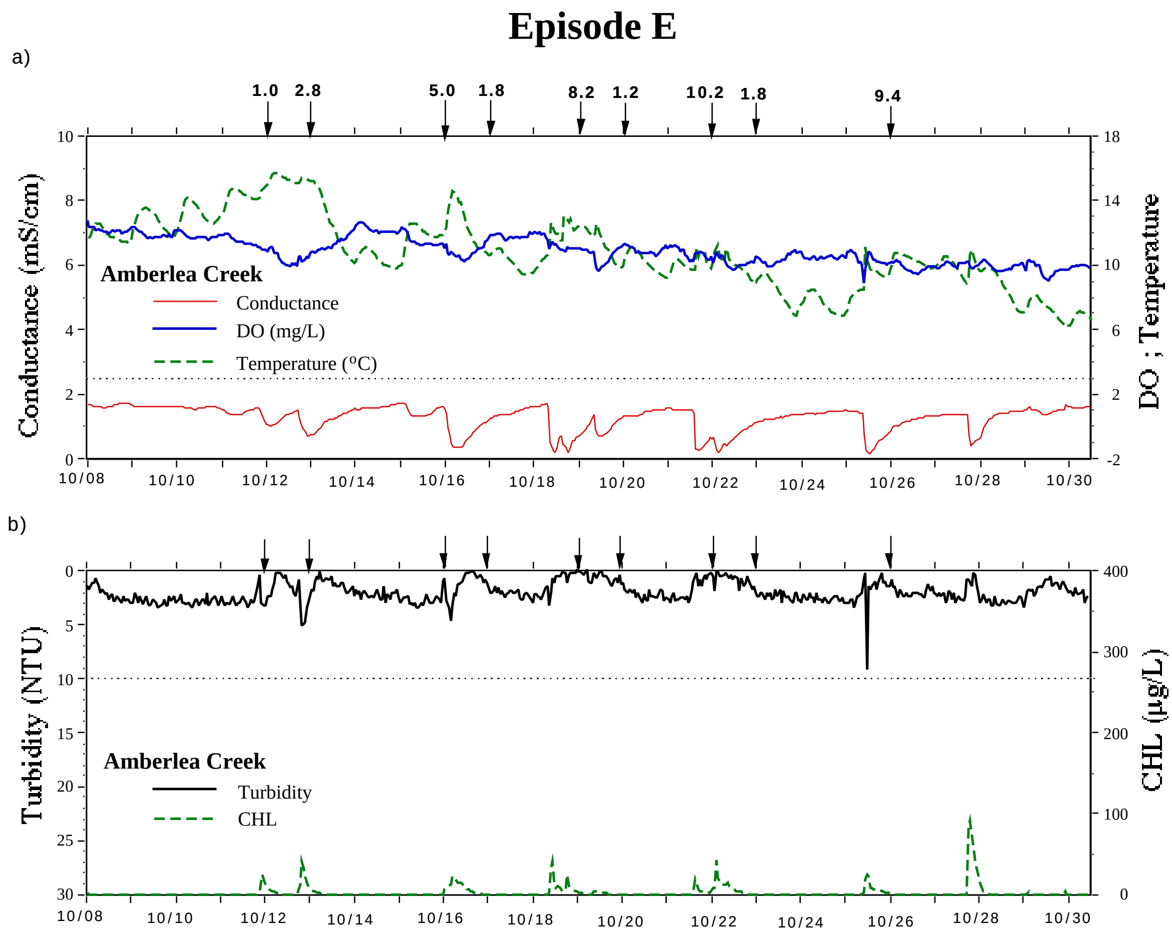

Episode E
a)
1.0
2.8
5.0
1.8
8.2
1.2
10.2
1.8
9.4
Conductance (mS/cm)
DO ; Temperature
Amberlea Creek
Conductance
DO (mg/L)
Temperature (°C)
10/08
10/10
10/12
10/14
10/16
10/18
10/20
10/22
10/24
10/26
10/28
10/30
b)
Turbidity (NTU)
CHL (µg/L)
Amberlea Creek
Turbidity
CHL

Figure 22

Episode F

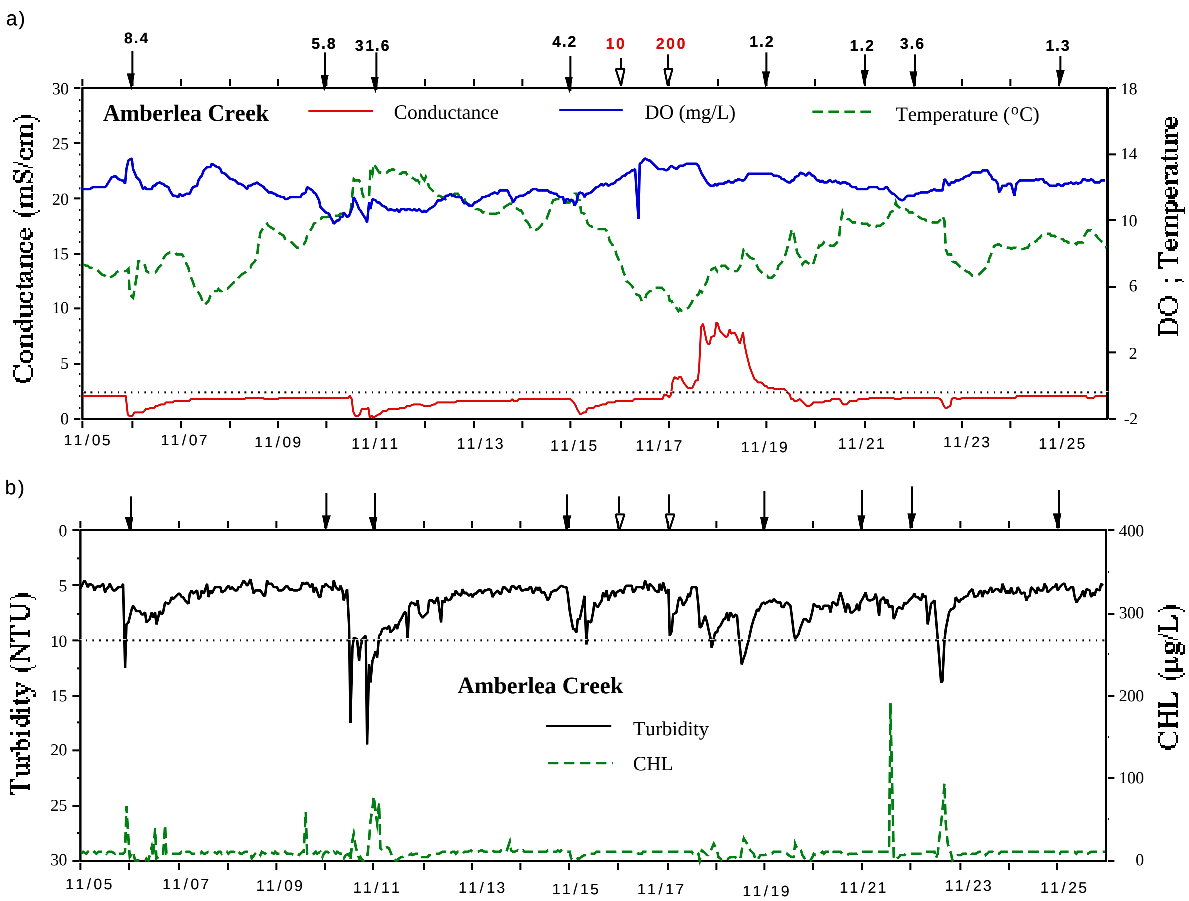
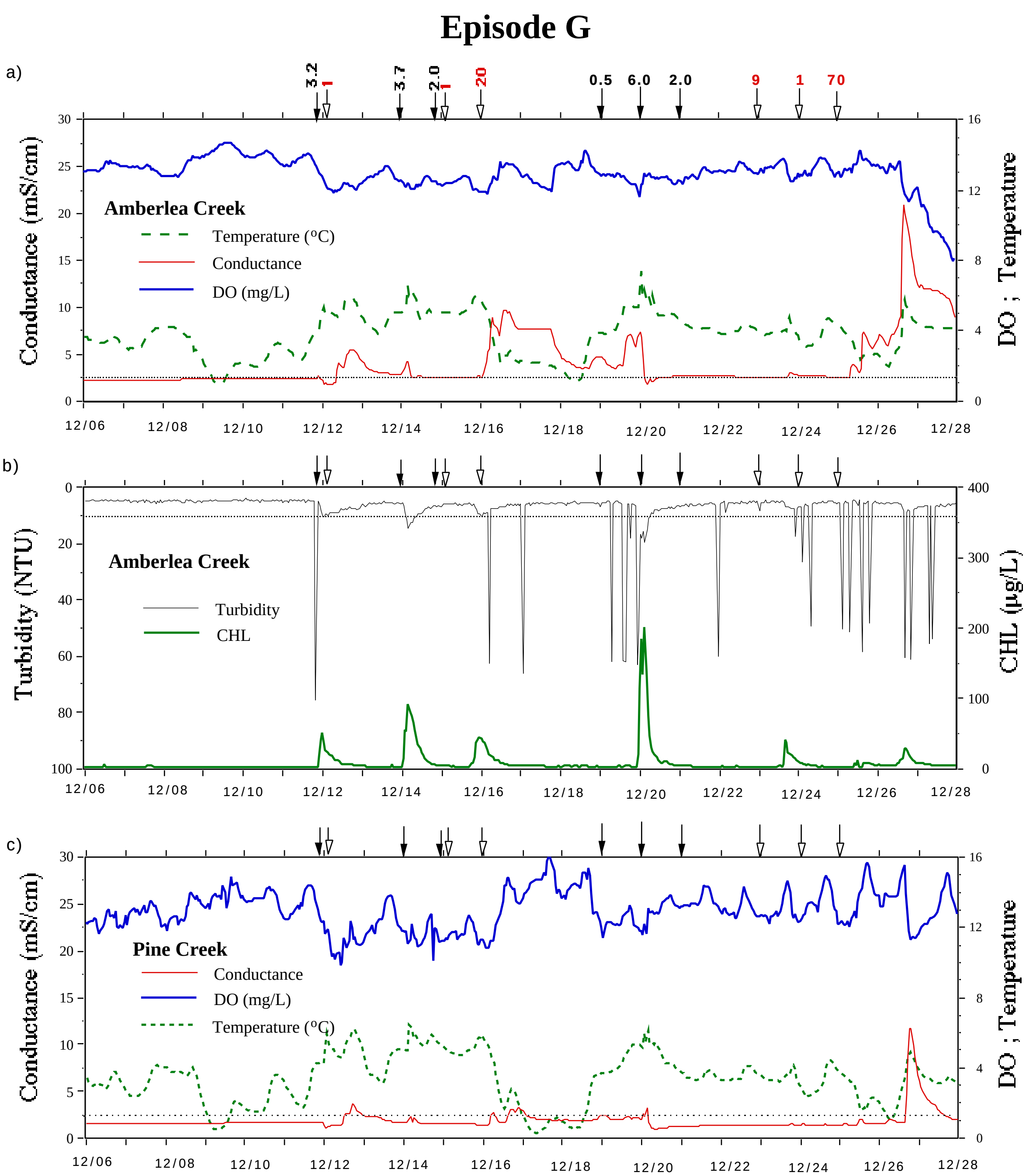


Figure 23



Episode G
a)
3.2
1
3.7
2.0
1
20
0.5
6.0
2.0
9
1
70
Conductance (mS/cm)
DO ; Temperature
Amberlea Creek
Temperature (°C)
Conductance
DO (mg/L)
12/06
12/08
12/10
12/12
12/14
12/16
12/18
12/20
12/22
12/24
12/26
12/28
b)
Turbidity (NTU)
CHL (µg/L)
Amberlea Creek
Turbidity
CHL
c)
Conductance (mS/cm)
DO ; Temperature
Pine Creek
Conductance
DO (mg/L)
Temperature (°C)

Figure 24

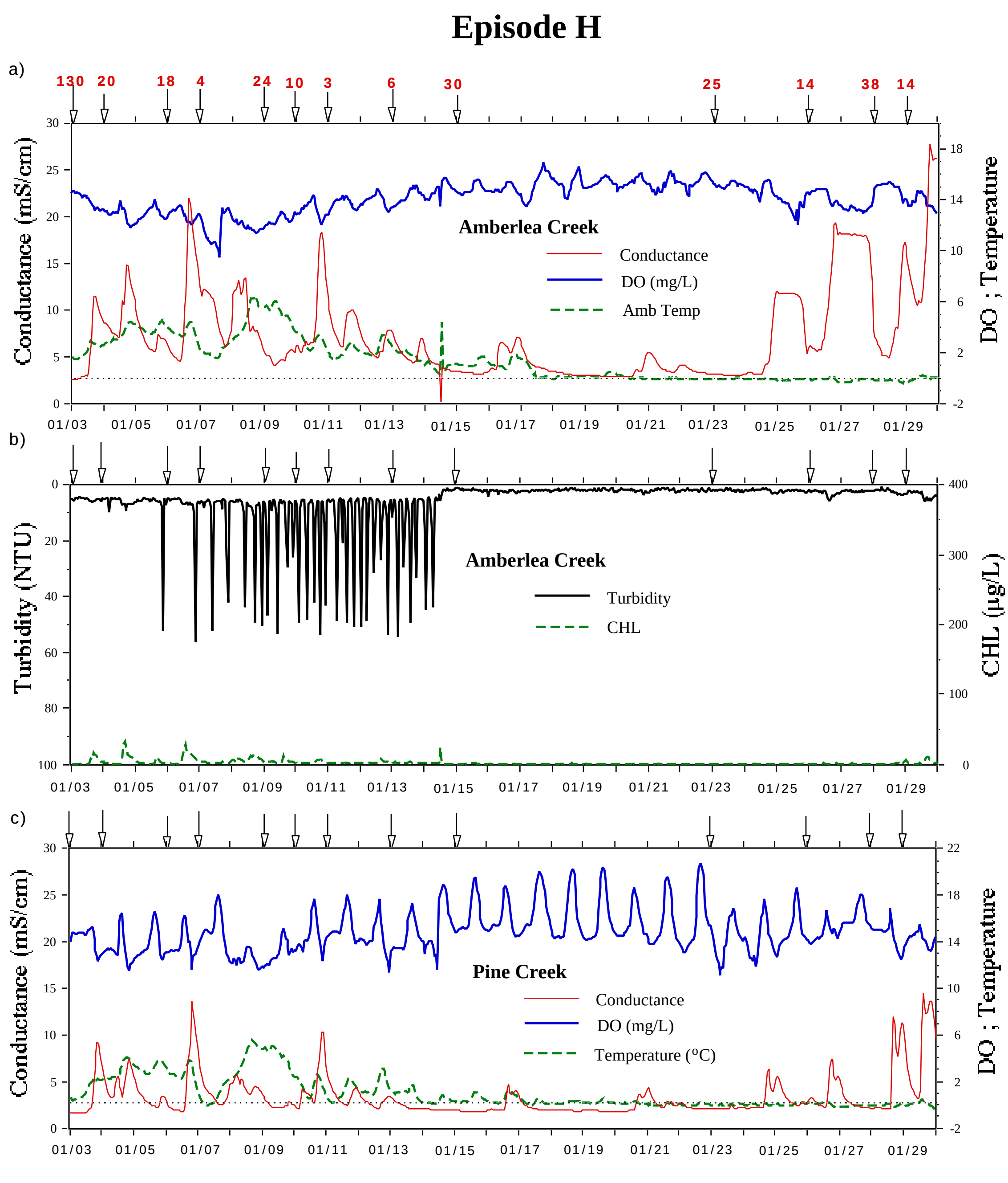
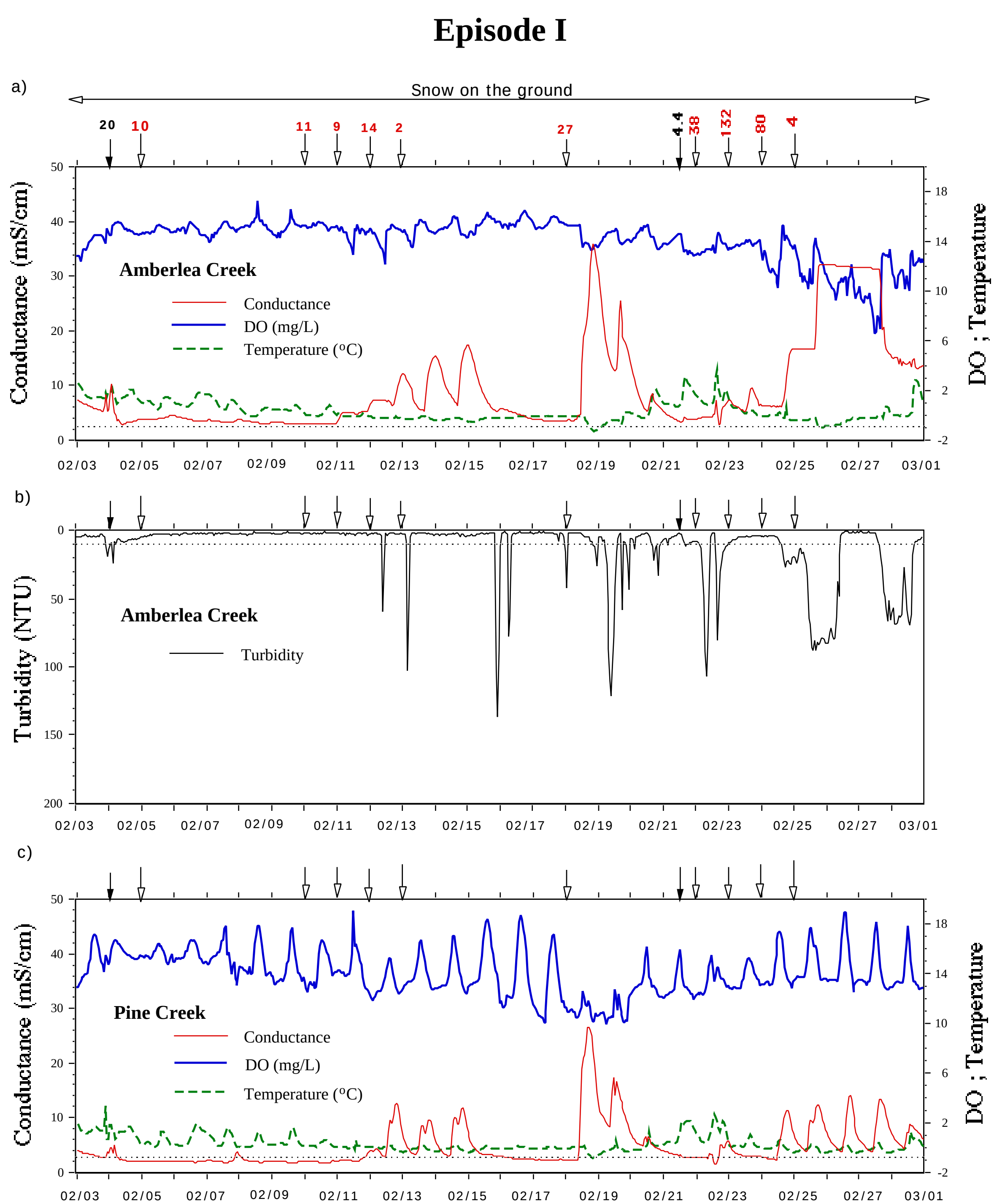

Episode H
a)
130
20
18
4
24
10
3
6
30
25
14
38
14
Conductance (mS/cm)
DO ; Temperature
Amberlea Creek
Conductance
DO (mg/L)
Amb Temp
01/03
01/05
01/07
01/09
01/11
01/13
01/15
01/17
01/19
01/21
01/23
01/25
01/27
01/29
b)
Turbidity (NTU)
CHL (µg/L)
Amberlea Creek
Turbidity
CHL
c)
Pine Creek
Conductance
DO (mg/L)
Temperature (°C)

Figure 25



Episode I
a)
Snow on the ground
20
10
11
9
14
2
27
4.4
38
132
80
4
Conductance (mS/cm)
DO ; Temperature
Amberlea Creek
Conductance
DO (mg/L)
Temperature (°C)
02/03
02/05
02/07
02/09
02/11
02/13
02/15
02/17
02/19
02/21
02/23
02/25
02/27
03/01
b)
Turbidity (NTU)
Amberlea Creek
Turbidity
c)
Pine Creek

Figure 26.

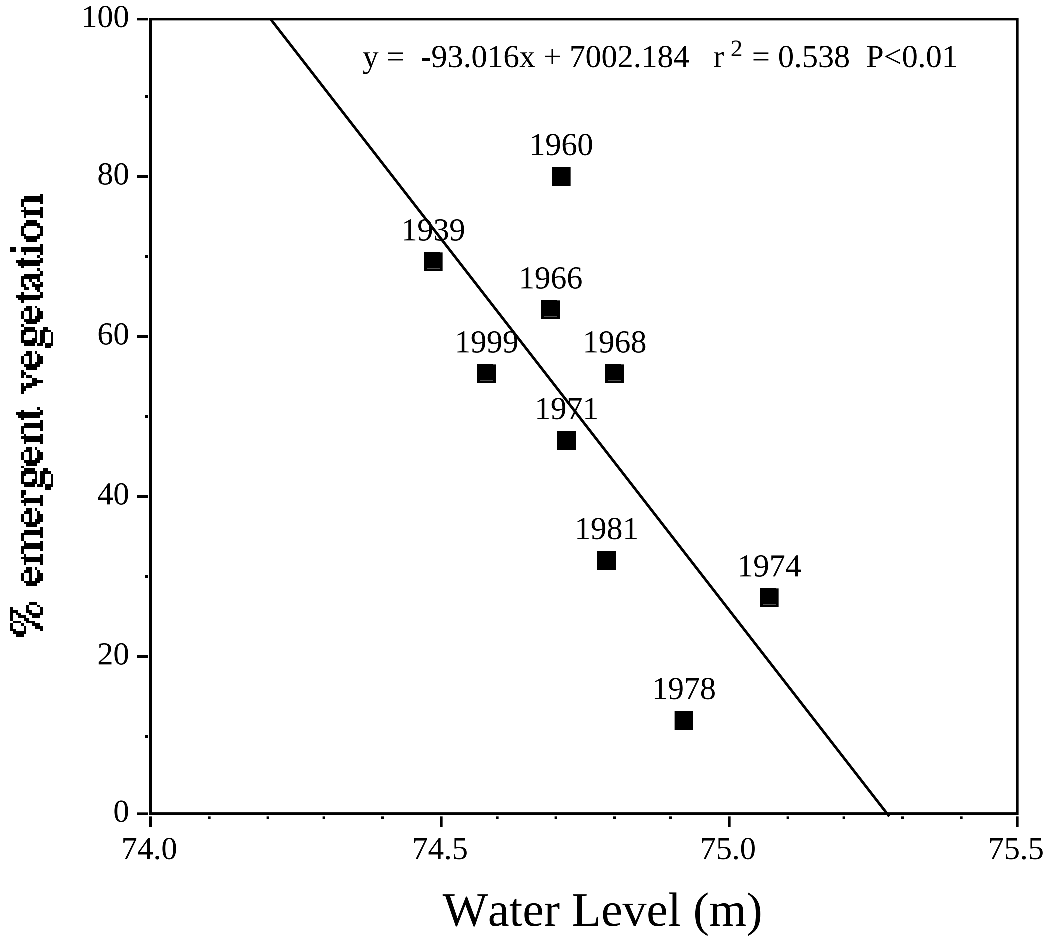
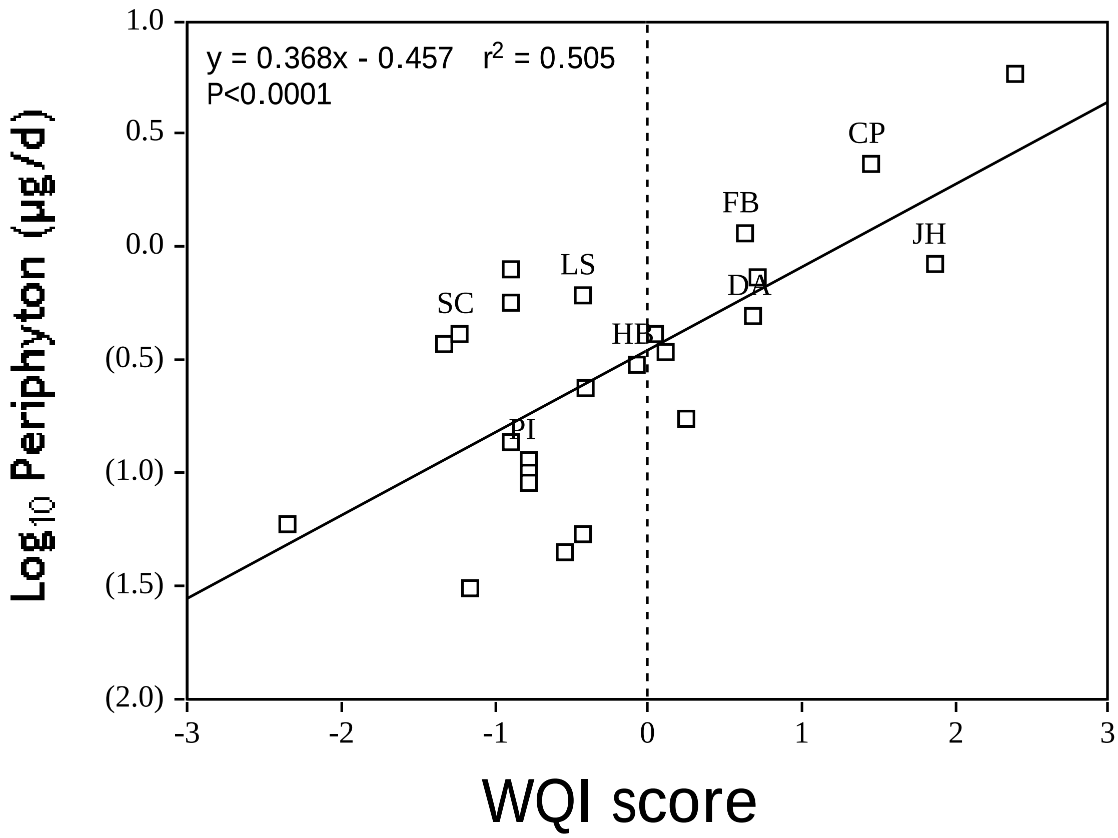
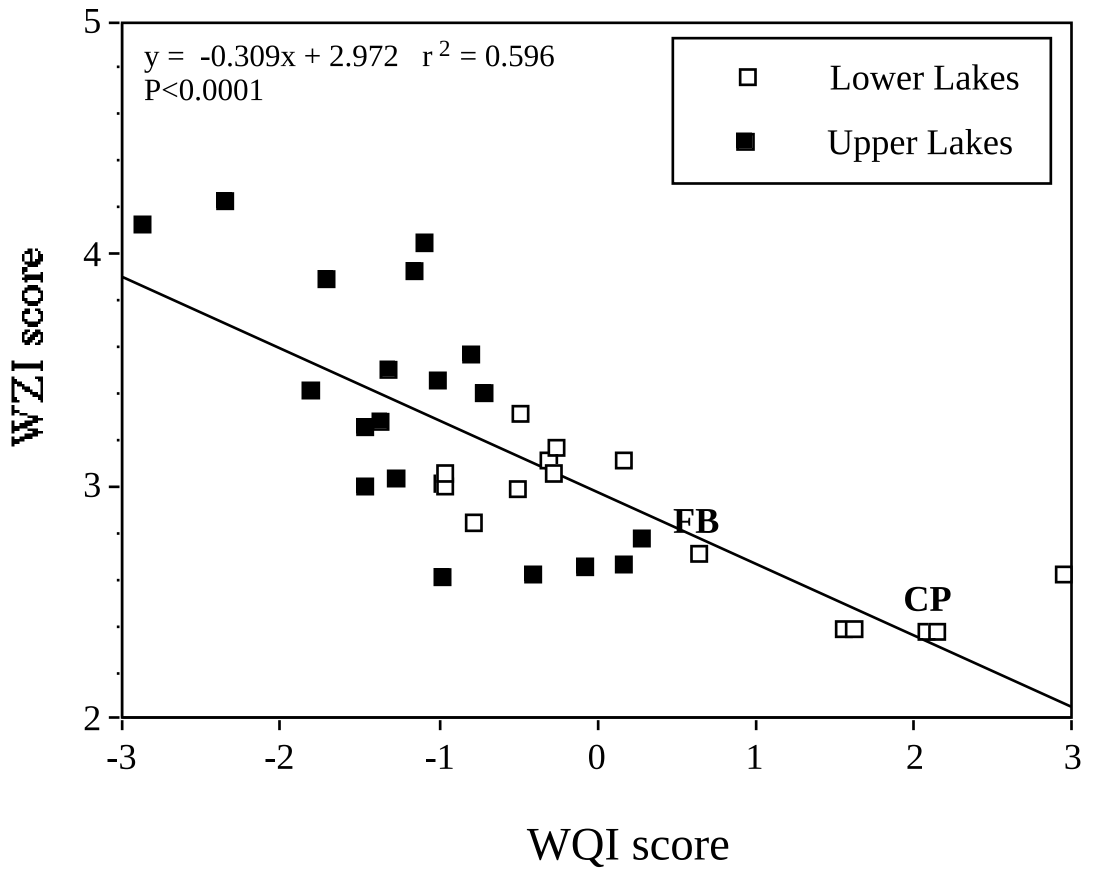

y = -93.016x + 7002.184 r 2 = 0.538 P<0.01
1960
1939
1966
1999
1968
1971
1981
1974
1978
100
80
60
40
20
0
% emergent vegetation
74.0
74.5
75.0
75.5
Water Level (m)

Figure 27



y = 0.368x - 0.457 r2 = 0.505
P<0.0001
1.0
0.5
0.0
(0.5)
(1.0)
(1.5)
(2.0)
-3
-2
-1
0
1
2
3
CP
FB
JH
LS
DA
SC
HB
PI
Log10 Periphyton (µg/d)
WQI score

Figure 28



y = -0.309x + 2.972 r 2 = 0.596
P<0.0001
Lower Lakes
Upper Lakes
WZI score
5
4
3
2
FB
CP
-3
-2
-1
0
1
2
3
WQI score

Figure 29

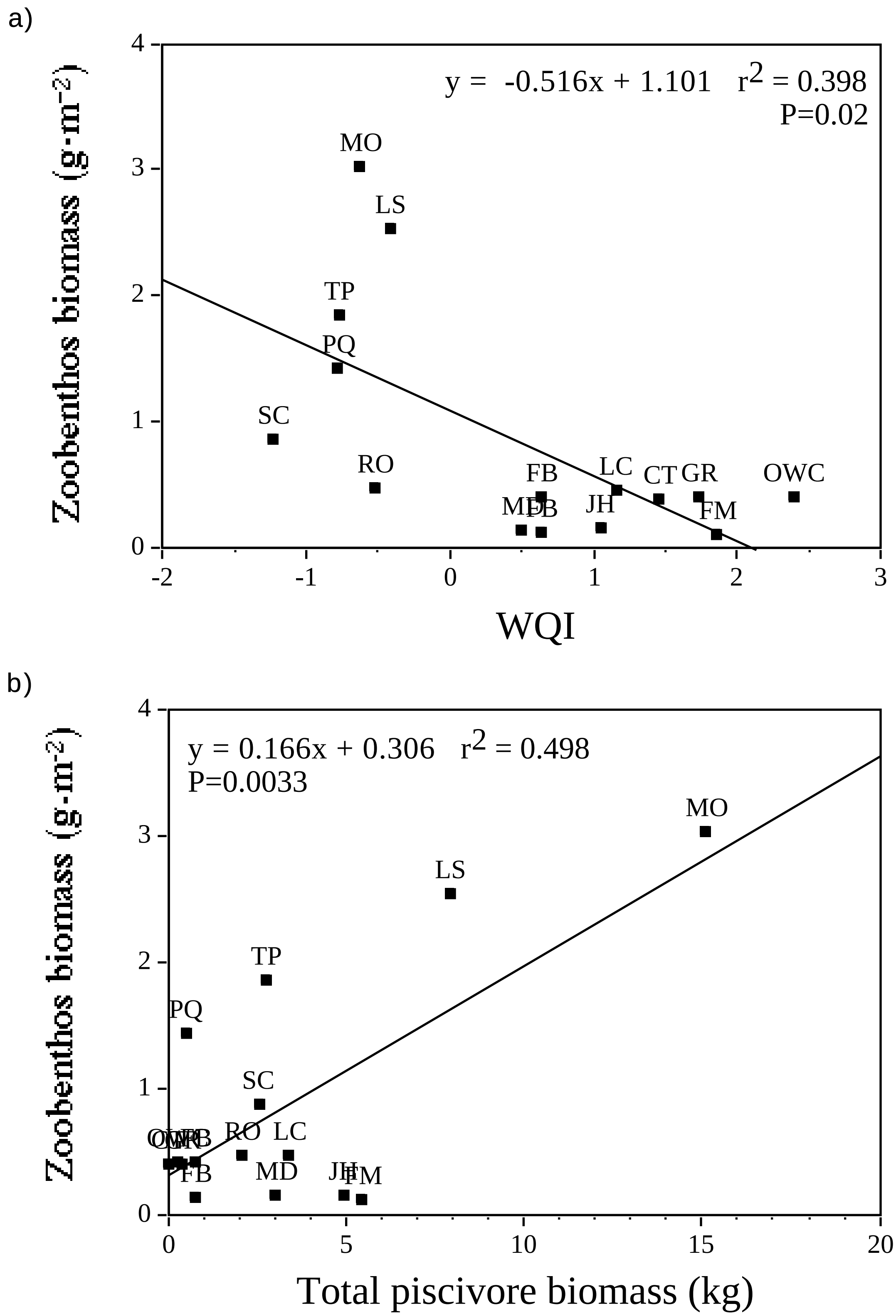
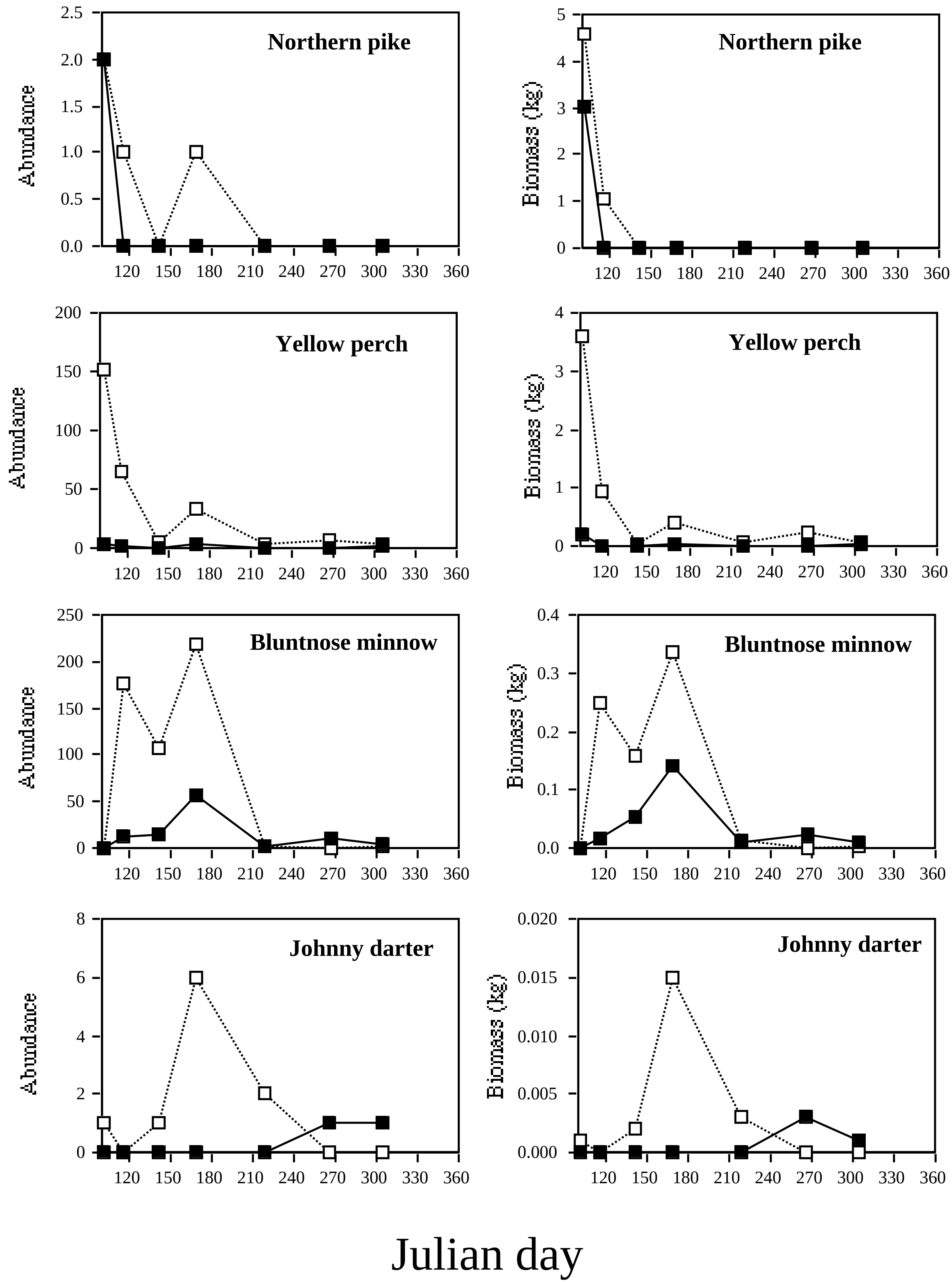

a)
y = -0.516x + 1.101 r2 = 0.398
P=0.02
MO
LS
TP
PQ
SC
RO
FB
LC
CT
GR
OWC
MD
FB
JH
FM
Zoobenthos biomass (g·m-2)
WQI
b)
y = 0.166x + 0.306 r2 = 0.498
P=0.0033
MO
LS
TP
PQ
SC
RO
LC
FB
MD
JH
FM
Zoobenthos biomass (g·m-2)
Total piscivore biomass (kg)

Figure 30



Northern pike
Abundance
2.5
2.0
1.5
1.0
0.5
0.0
Northern pike
Biomass (kg)
5
4
3
2
1
0
Yellow perch
Abundance
200
150
100
50
0
Yellow perch
Biomass (kg)
4
3
2
1
0
Bluntnose minnow
Abundance
250
200
150
100
50
0
Bluntnose minnow
Biomass (kg)
0.4
0.3
0.2
0.1
0.0
Johnny darter
Abundance
8
6
4
2
0
Johnny darter
Biomass (kg)
0.020
0.015
0.010
0.005
0.000
120 150 180 210 240 270 300 330 360
Julian day

Figure 31

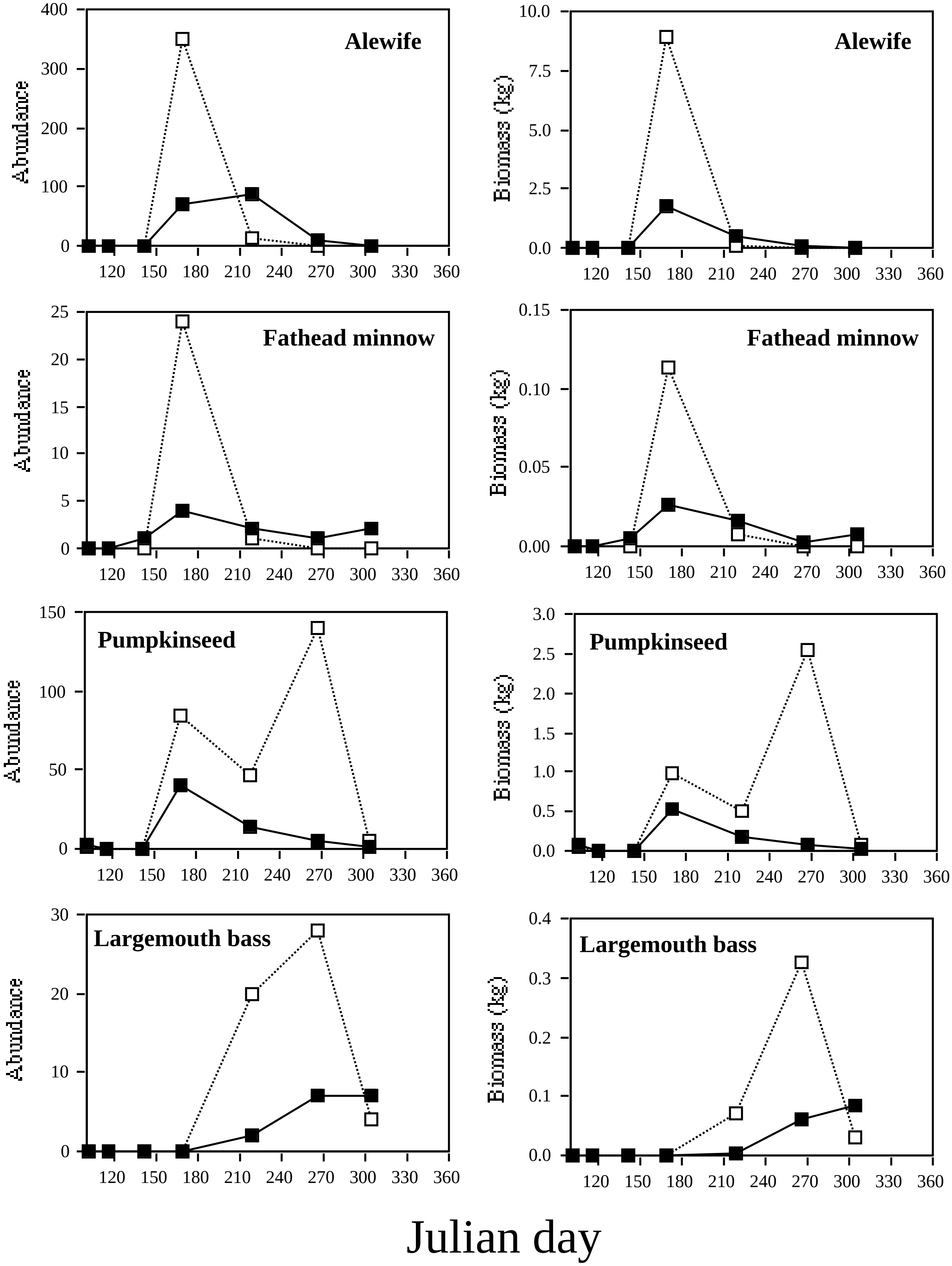
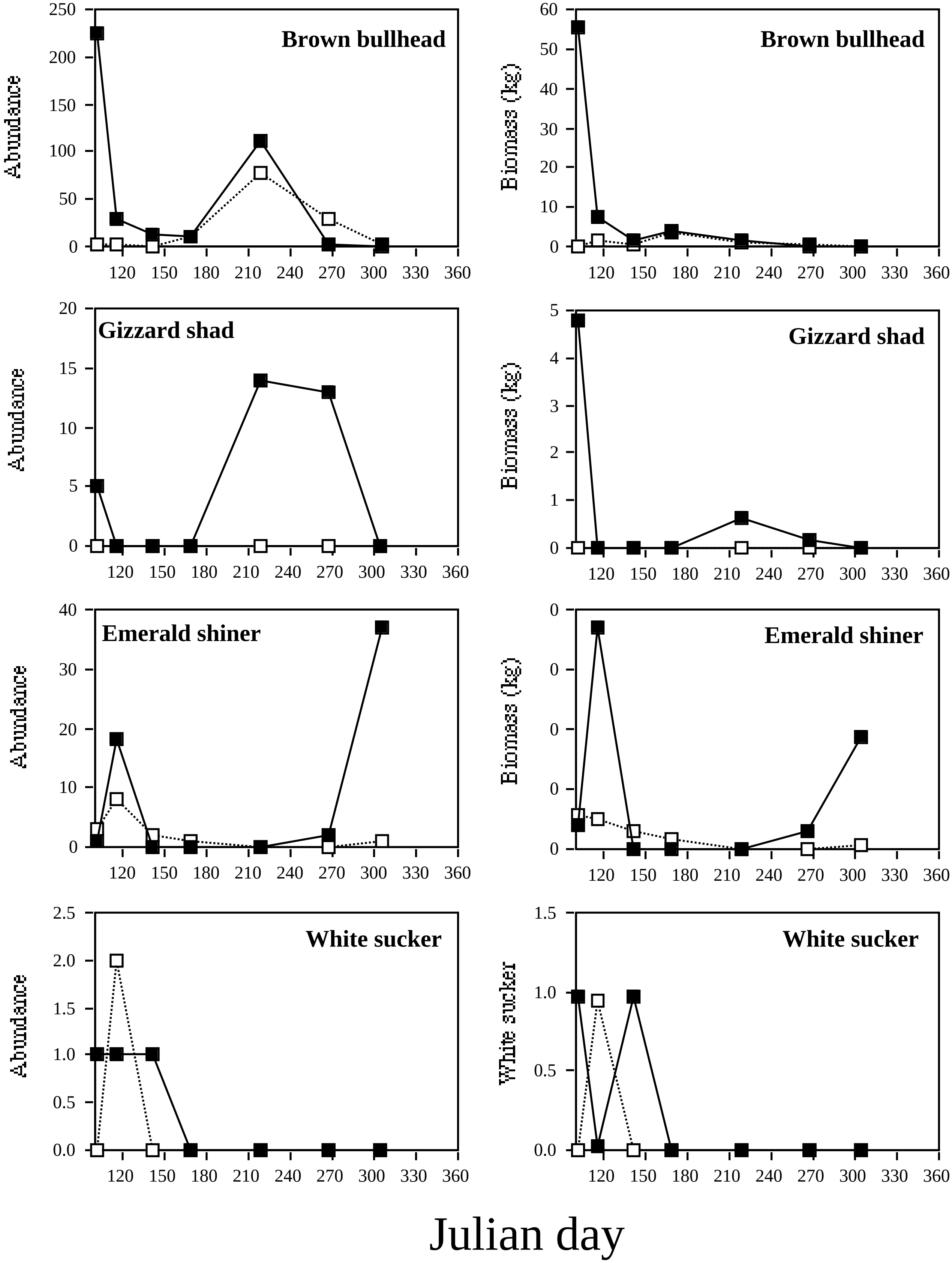

Alewife
Abundance
Biomass (kg)
Fathead minnow
Pumpkinseed
Largemouth bass
120 150 180 210 240 270 300 330 360
Julian day

Figure 32



Brown bullhead
Abundance
Biomass (kg)
Gizzard shad
Emerald shiner
White sucker
250
200
150
100
50
0
60
50
40
30
20
10
20
15
5
4
3
2
1
2.5
2.0
1.5
1.0
0.5
0.0
120
150
180
210
240
270
300
330
360
Julian day

Figure 33

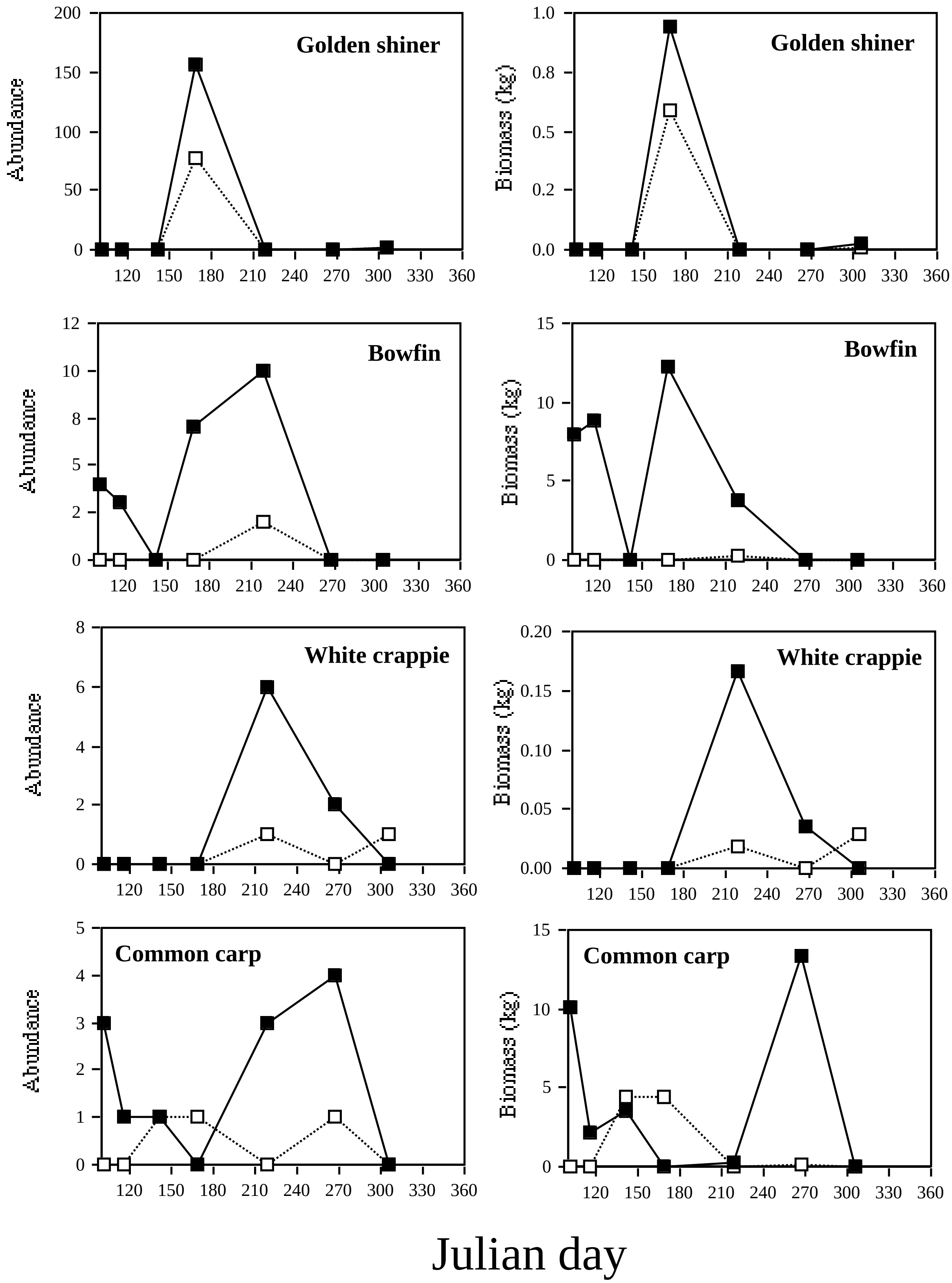

Golden shiner
Bowfin
White crappie
Common carp
Abundance
Biomass (kg)
Julian day

Figure 34

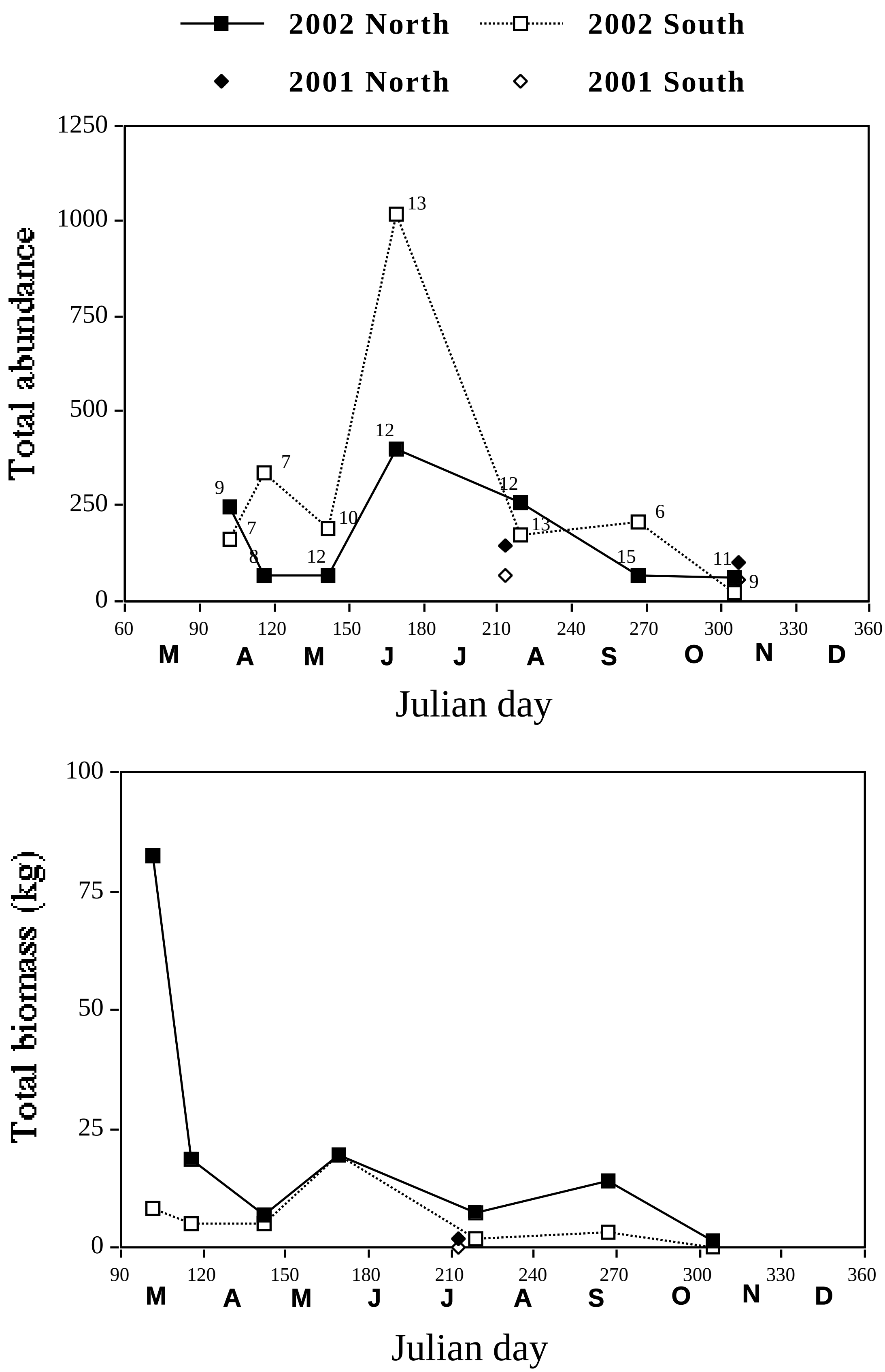

2002 North
2002 South
2001 North
2001 South
Total abundance
1250
1000
750
500
250
0
13
12
9
7
7
10
12
13
6
8
12
15
11
9
60
90
120
150
180
210
240
270
300
330
360
M A M J J A S O N D
Julian day
Total biomass (kg)
100
75
50
25
0
90
120
150
180
210
240
270
300
330
360
M A M J J A S O N D
Julian day

Figure 35

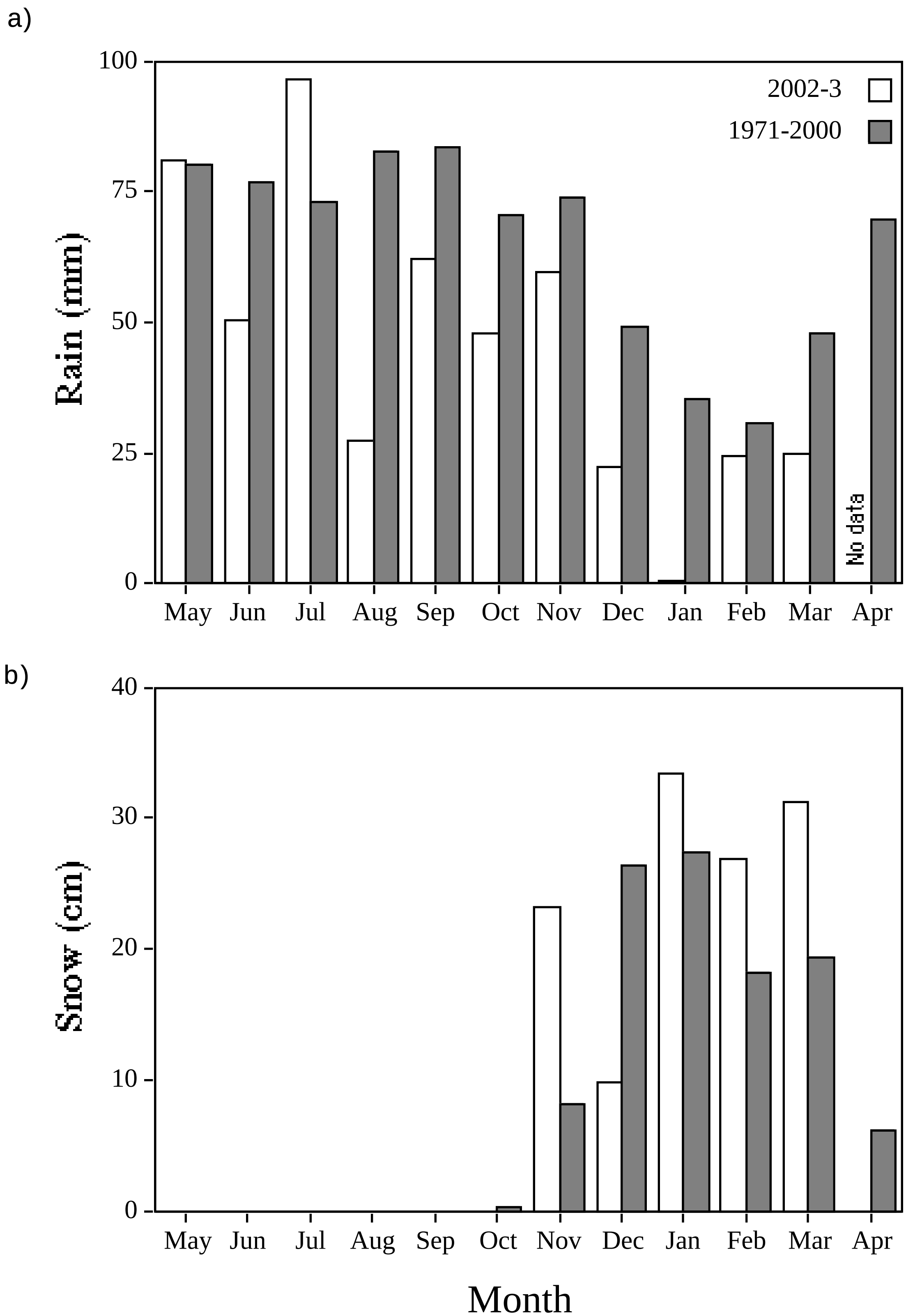
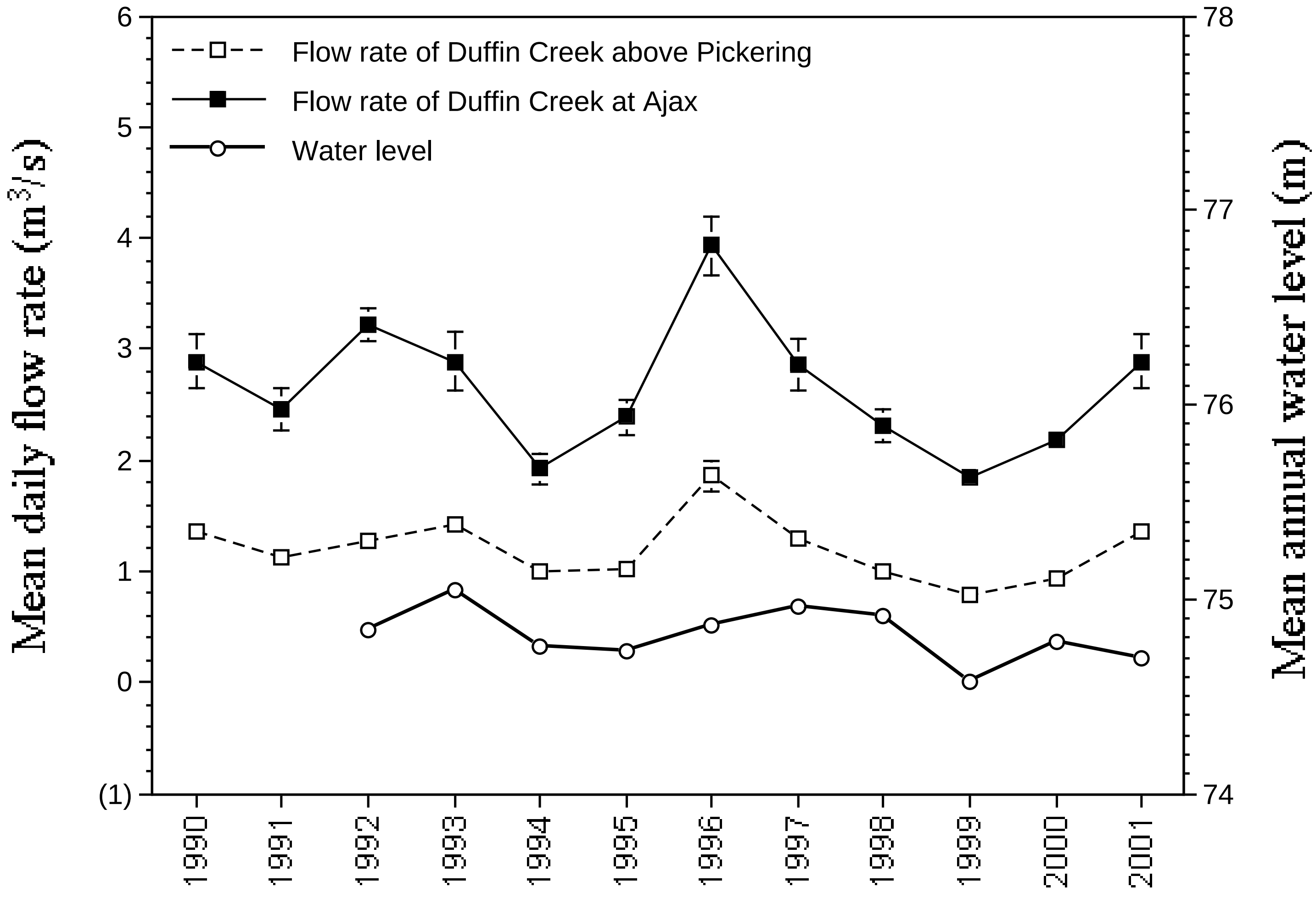
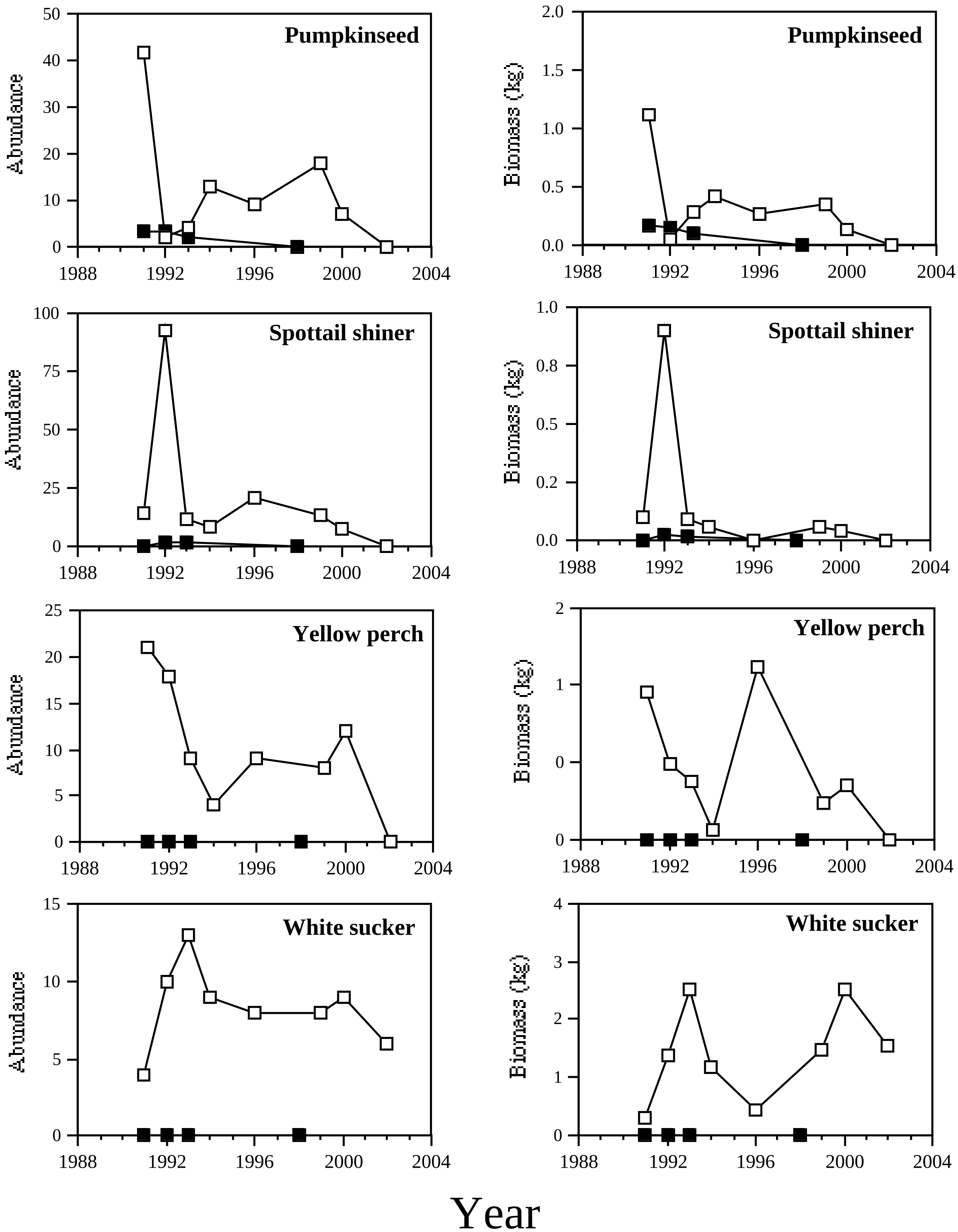

a)
100
75
50
25
0
Rain (mm)
2002-3
1971-2000
No data
May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr
b)
40
30
20
10
0
Snow (cm)
May Jun Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr
Month

Figure 36



Flow rate of Duffin Creek above Pickering
Flow rate of Duffin Creek at Ajax
Water level
Mean daily flow rate (m^3/s)
Mean annual water level (m)
6
5
4
3
2
1
0
(1)
78
77
76
75
74
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001

Figure 37.



Pumpkinseed
Abundance
Biomass (kg)
Spottail shiner
Yellow perch
White sucker
1988
1992
1996
2000
2004
Year

Figure 38.

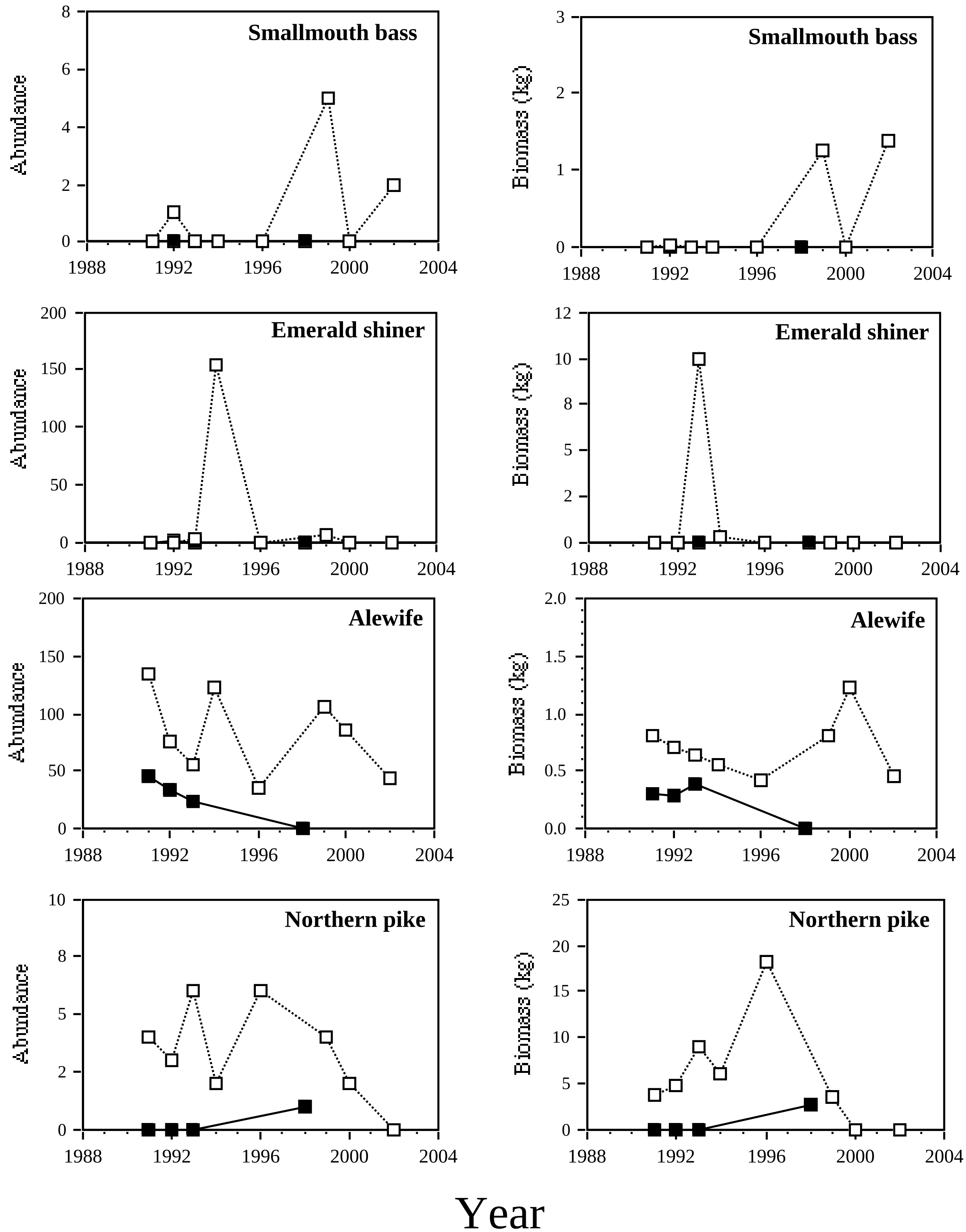

Smallmouth bass
Abundance
Biomass (kg)
Emerald shiner
Alewife
Northern pike
1988
1992
1996
2000
2004
Year

Figure 39

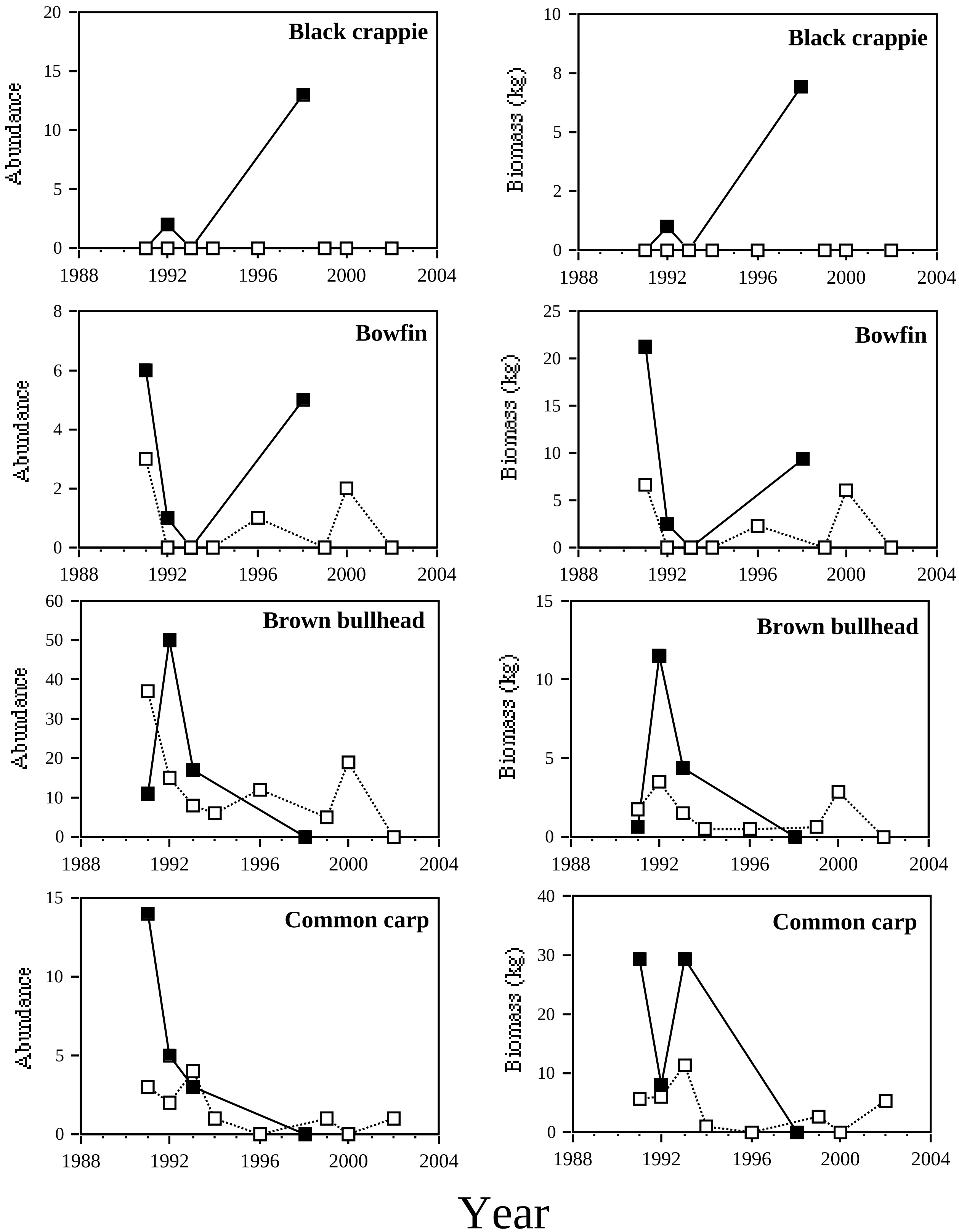

Black crappie
Abundance
Biomass (kg)
Bowfin
Brown bullhead
Common carp
0
5
10
15
20
1988
1992
1996
2000
2004
Year

Figure 40

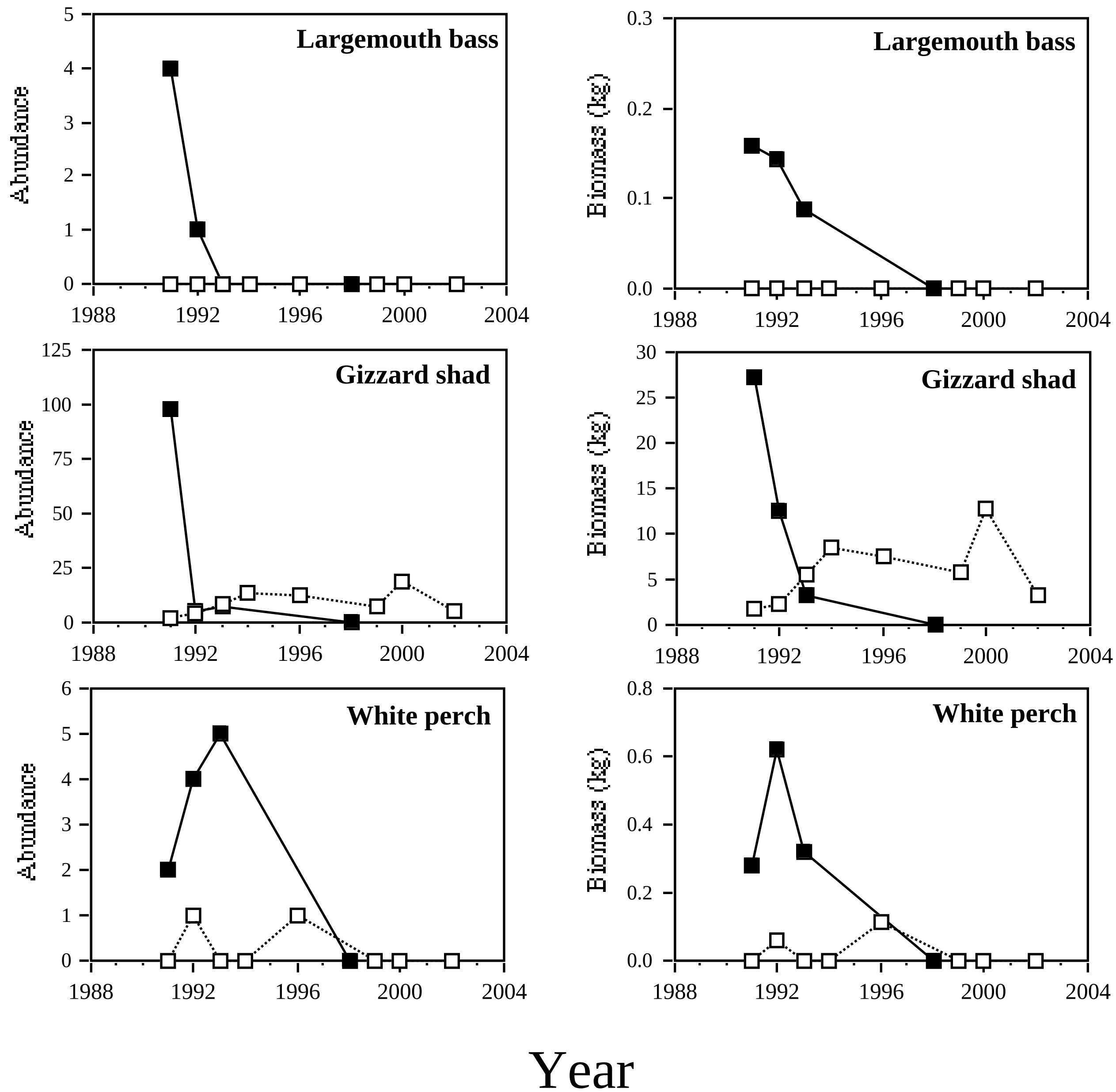

Largemouth bass
Abundance
Largemouth bass
Biomass (kg)
Gizzard shad
Abundance
Gizzard shad
Biomass (kg)
White perch
Abundance
White perch
Biomass (kg)
1988
1992
1996
2000
2004
Year

Plate 1a

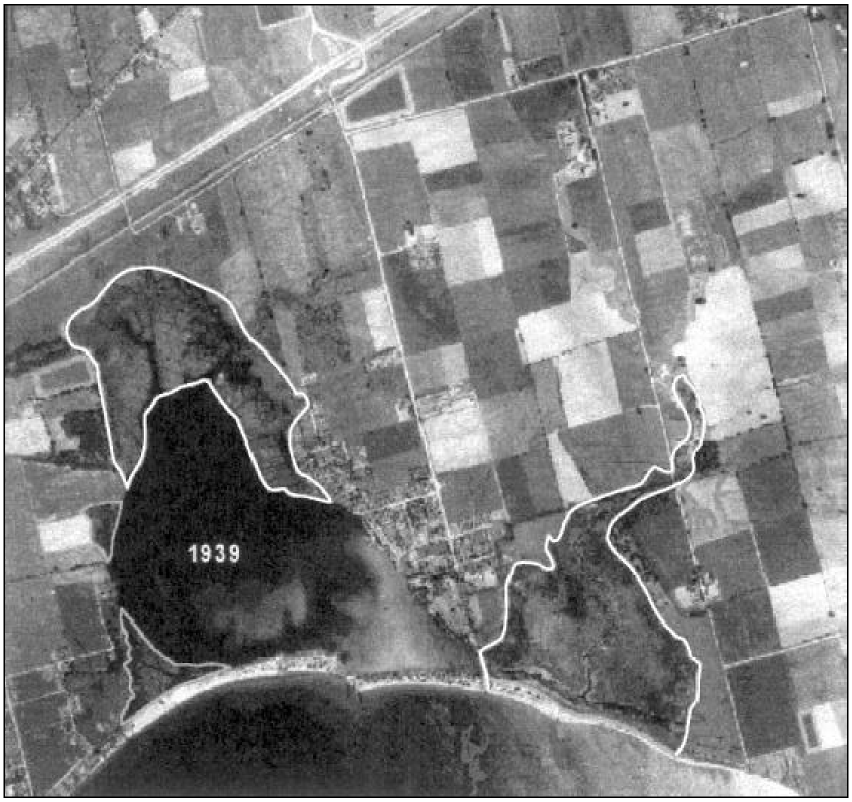


Plate 1b