Discontinuity Bar in a Wetland on Lake Huron's Saginaw Bay

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ABSTRACT

A 500 m transect was established in a large wetland on an exposed shoreline in Saginaw Bay. It extended from shore to just beyond the limit of emergent vegetation. During the spring of the year before development of vegetation, water along the transect had homogeneous characteristics. This was not the case when concentrations of electrolytes, electric conductivity, turbidity, planktonic chlorophyll *a* and periphytic chlorophyll *a* were measured in mid-summer. At that time, submersed and emergent vegetation was at annual maximum biomass and a discontinuity bar existed where parameters changed rapidly with distance along the transect. Location of the bar changed from time-to-time within a zone 250-350 m from shore as water surged shoreward and then receded during seiches. Currents associated with these changes were measured in the vicinity of the bar. They ran perpendicular to the shoreline and were generally on the order of 2-7 cm/s. During a severe storm depth of water in the wetland increased more than 50 cm in one hour with flow rates rising to about 10 cm/s. Mixing between near-shore and offshore water in the wetland occurred during this event, but the discontinuity was not broken down. Temperature and solute-related density differences in water on opposite sides of the discontinuity were always small. Aquatic plants appeared to dampen currents and mixing enough to allow these and other differences to persist as prominent mid-summer features of this wetland.

INTRODUCTION

The existence of thermal discontinuity bars in shorezones of large, coldwater lakes of temperate regions is well known (Wetzel 1983, Goldman and Horne 1983). They exist when temperature-related density differences occur at a vertical front between near-shore water that is warm and offshore water that is cold. These bars develop in springtime and persist until temperature and density differences between inshore and offshore water are small. The front is then broken down by currents that impart sufficient energy to mix the water masses.

The purpose of work described here was to characterize a discontinuity bar that existed in a wetland on Lake Huron's Saginaw Bay. The bay is a large (3,000 km^2), shallow extension of the western portion of the lake, and the wetland occupied more than 15 contiguous kilometers of shoreline near the city of Quanicassee, Michigan (Figure 1).

METHODS AND MATERIALS

In 1989, a transect was established in the wetland at Quanicassee. It ran perpendicular from the shore into the bay in a northwesterly direction (Figure 1). The transect was 500 m long and passed through emergent vegetation typical of the site. Sampling stations were established at 50 m intervals, and sampling was done on August 21-24 1989, July 17-22 1990 and May 22 1991. LORAN-C was used to establish coordinates for the midpoint of the transect at 43° 35′ N, 83° 38′ W.

Depth along the transect generally increase from shore toward open water in the bay. Depth of water at the outer edge of emergent vegetation, a distance of 480 m from shore, was about 60 cm. Bottom topography showed unevenly spaced undulations running parallel to shore. Differences in elevation between troughs and peaks of adjacent undulations were about 10 cm in near-shore portions of the wetland, and between 10 and 20 cm in deeper water. The upper 10 cm of bottom deposits had some gravel but were primarily sand (85-97 %) with lesser fractions of clay (2-8%) and silt (1-6%).

Estimates were obtained along the transect for densities of vegetation standing in the water column. Biomass of emergent plants was overwhelmingly dominated by *Scripus americanus* Pers. Measurements for density of bulrush shoots were made in August 1989 and July 1990. Samples were taken from three 0.25 m^2 quadrats that were randomly placed at each sampling station. Shoots were cut near the sediment surface and then counted. Data obtained in 1989 and 1990 were similar and were pooled to obtain mean estimates for shoot densities. Square quadrats, 25 cm on a side, were used to estimate densities of submersed plants. The work was done in August 1989. Quadrats were randomly placed on the surface of the water every 10 m along the transect. Percentage of sediment surface covered by vegetation was estimated visually. Similar procedures were used in a study of the transect in August 1991. These data were reported elsewhere (McNabb et al. 1991a), and they show the same aspects of submersed plant distribution which we report here.

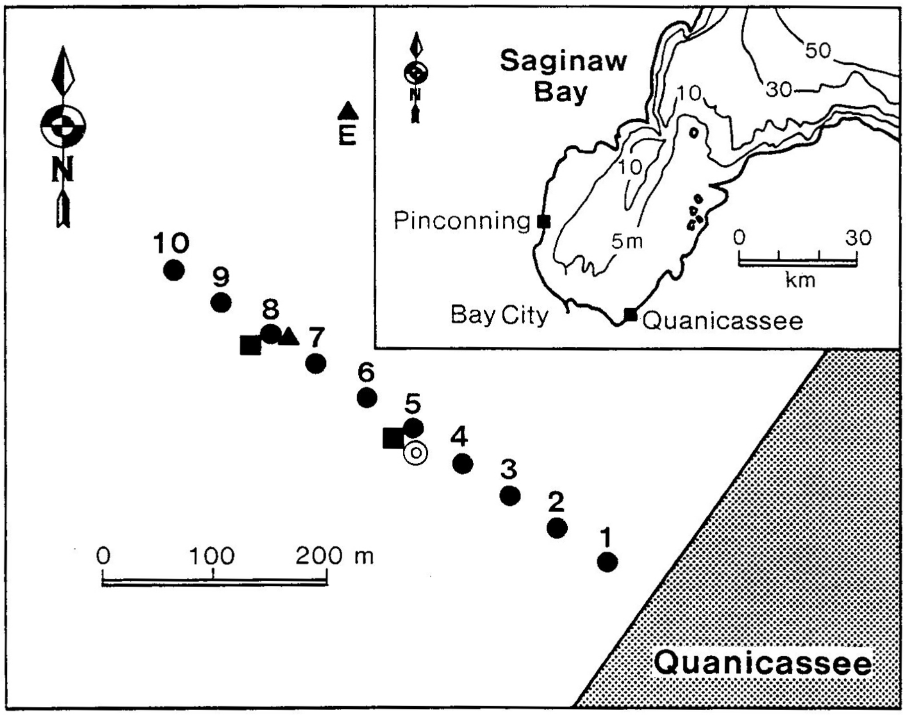

Figure 1. Orientation of study transect in Quanicassee wetland. Shown are sampling stations (•) and locations of recording devices for water level (▲), current direction and velocity (◎), and water temperature and conductivity (■).

Measurements of dissolved electrolytes, conductivity, turbidity and chlorophyll *a* were made at stations on the transect to determine horizontal distribution of these parameters. Initial work was done in August 1989 in the period of maximum density of aquatic vegetation. Conductivity and turbidity were measured again in July 1990 to obtain growing season information on year-to-year variation in distribution of these parameters. Conductivity and turbidity were also measured in May of 1991 to obtain data for a period prior to emergence of wetland vegetation. Water samples for electrolyte analyses were passed through 0.45 µm membrane filters. Na^+, K^+, Mg^{2+} and Ca^{2+} were measured in the filtrate using atomic absorption spectrometry. Cl^- and SO_4^{2-} were measured by ion chromatography. Total alkalinity and pH were used to estimate HCO_3^- according to American Public Health Association (1985). Measurements of conductivity were made with Toho-Dentan model EST-3 and TOA model CM-11P meters. Turbidity was determined with ALEC-PT1 and HACH-2/00A meters. Samples for chlorophyll *a* determinations were filtered through 0.45 µm membranes. Pigments were extracted in aqueous acetone, and concentrations of chlorophyll *a* were obtained using spectrophotometric techniques described by American Public Health Association (1985).

Batterson et al. (1991) reported that changes of several decimeters in water-level were common in Quanicassee wetland during periods of a few hours. Such changes were further investigated in this study to determine correlated effects on the distribution of electrolytes, conductivity and other water quality parameters. Stevens model 68 type F stage height recorders and stilling wells were placed in the Quanicassee wetland, and in a bulrush wetland on the opposite shore of Saginaw Bay near the city of Pinconning, Michigan (Figure 1). Data obtained from recorders were subjected to Fast Fourier Transform analyses. With these techniques, regularly occurring cycles of water-level change in the bay were identified, as were their periods and amplitudes.

In 1990, we determined direction and velocity of currents in the Quanicassee wetland and the degree of mixing that occurred between waters in the wetland that were separated by a discontinuity bar. Continuous records of water-level, current direction, current velocity, conductivity and temperature were obtained for the interval July 18-21. Locations of the recording stations are shown in Figure 1. As above, Stevens stage height recorders were used for measurements of water-level. An electromagnetic current meter (ALEC model ACM-1) was used to record current velocity and direction at 10 minute intervals. Measurements of conductivity and water temperature were obtained at 10 minute intervals using a TOA model PT1 meter.

RESULTS

Growth of aquatic plants from over-wintering structures was well underway in the Quanicassee wetland by mid-June during years of this study. Measurements in August 1989 and July 1990 showed that density of shoots of three-square bulrush tended to decrease along the transect from shore toward the open bay. On the average, densities decreased regularly from about 480 shoots/m^2 at station 1 to 250/m^2 at station 6. Densities were variable between 260 and 150 shoots/m^2 at stations 7 and 8. At station 9, near the outer fringe of emergent vegetation, bulrush densities were about 50 shoots/m^2.

The density (percent cover) of submersed vegetation in the water column also decreased from shore toward the open bay (Table 1). Submersed plants were relatively dense at stations 1 through 4. The portion of the transect between stations 4 and 6 represented a transition from high densities of submersed plants inshore to low densities of submersed plants at stations 6 through 9. The outer depth boundary of submersed plant distribution was approximately 50 m beyond the outer fringe of emergent vegetation at a water depth of 0.9 m. Submersed plants were sparsely distributed there. These measurements of distributions of emergent and submersed vegetation draw attention to differences in plant-related physical features of the underwater environment in near-shore and offshore portions of the wetland.

Table 1. Distribution of submersed and floating-leaved vegetation along the transect in Quanicassee wetland. Species are listed in the order of their frequency of occurrence in quadrats.

Meters From Shore (Transect Station No.)	Percent Cover	Species
0-40	100%	*Cladophora glomerata* *Chara globularis* *Najas flexilis*
40-60 (1)		Transition zone from species above to species below.
60-190 (1-4)	55%	*Chara globularis* *Najas flexilis* *Potamogeton illinoensis* *Cladophora glomerata* *Nymphaea tuberosa* *Lemna* sp. *Potamogeton pectinatus* *Utricularia vulgaris* *Najas marina* *Potamogeton oakesianus*
190-280 (4-6)	26%	*Chara globularis* *Potamogeton illinoensis* *Cladophora glomerata* *Najas flexilis* *Najas marina* *Potamogeton pectinatus* *Utricularia vulgaris* *Vallisneria americana*
280-450 (6-9)	10%	*Vallisneria americana* *Potamogeton illinoensis*

Measurements were made of concentrations of electrolytes in water along the transect under conditions of fully developed vegetation (August 1989). Resulting data showed evidence for discrete near-shore and offshore water masses in the wetland. Data in Figure 2 are typical of conditions observed. Near-shore stations 1 through 5 had higher concentrations of Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-}, and HCO^{3-} than offshore stations 7 through 10. Sulfate (SO_4^{2-}) concentrations were low at near-shore stations and higher at offshore locations. Taken collectively, the data show that stations 5, 6 and 7 were in the vicinity of a discontinuity between near-shore and offshore water masses.

Measurements of conductivity were made on dates when samples were collected for determination of ion concentrations. Conductivity was 400-550 µS/cm near-shore, and on the order of 300 µS/cm in offshore portions of the wetland (Figure 3). A discontinuity existed between near-shore and offshore water where conductivity changed rapidly with distance along the transect. Steepest portions of gradients associated with this front were between stations 6 and 7 on August 22, and between stations 5 and 6 on August 24. Horizontal gradients bayward of station 6 separated clear near-shore water from turbid water toward the outer fringe of emergent vegetation (Figure 3). Turbidity at the outer fringe of emergent vegetation was similar to turbidity of nearby water in the open bay (50 NTU). Conductivity and turbidity were measured again at stations along the transect in May 1991 to test for the presence of a discontinuity early in the growing season before emergent and submersed vegetation was developed in the water column of the wetland. A discontinuity was not present. Conductivity and turbidity were 440-510 µS/cm and 18-32 NTU respectively. Variation occurred among stations in a random pattern.

Short-term changes in depth of water were a striking feature of the physical environment of wetlands on Saginaw Bay. Depth changes recorded in the wetland at Quanicassee and in a wetland at Pinconning on the opposite side of bay are shown in Figure 4. Two cycles of water-level change were apparent. One cycle was associated with large changes and had a period of 24 hours. The other cycle had small amplitude and a period of three hours. The small oscillations with three-hour periods resulted from transverse seiches in the bay (Allender and Green 1967, Schwab and Rao 1977). The large diel changes appeared to be caused by changes in the direction of breezes blowing alternately from the land and from the bay.

Figure 5 shows results of studies designed to determine the strength of currents and the degree of mixing that occurred between near-shore and offshore water masses separated by the discontinuity. A pattern of small amplitude water-level fluctuation was disrupted by a thunderstorm that passed through the site on July 18. The storm was accompanied by development of strong winds that blew onshore from the northwest. In a period of a few hours, water-level in the wetland increased by nearly 50 cm. When the wind declined, water-level dropped very quickly. Depth of water in the wetland then oscillated under the influence of longitudinal surface seiches that had periods of about 12 hrs. On the third and fourth days of the record (July 20 and 21), oscillations in water-level returned to pre-storm status with periods of 3 hrs.

Measurements of direction and velocity of currents were taken on the transect station 5. When currents occurred, they moved parallel to the transect (perpendicular to the shoreline). Velocities were ordinarily 2-3 cm/s. On July 18, current velocities were as high as 10 cm/s as the result of the storm. During major seiches after the storm (July 19), velocities of 5-7 cm/s were observed.

Conductivity measurements for two stations are shown in Figure 5. These stations were chosen to bridge the discontinuity that existed in the wetland between near-shore and offshore masses of water. Station 5 was located shoreward of the discontinuity, and station 8 bayward of it. The data show an intrusion of offshore water with low conductivity into

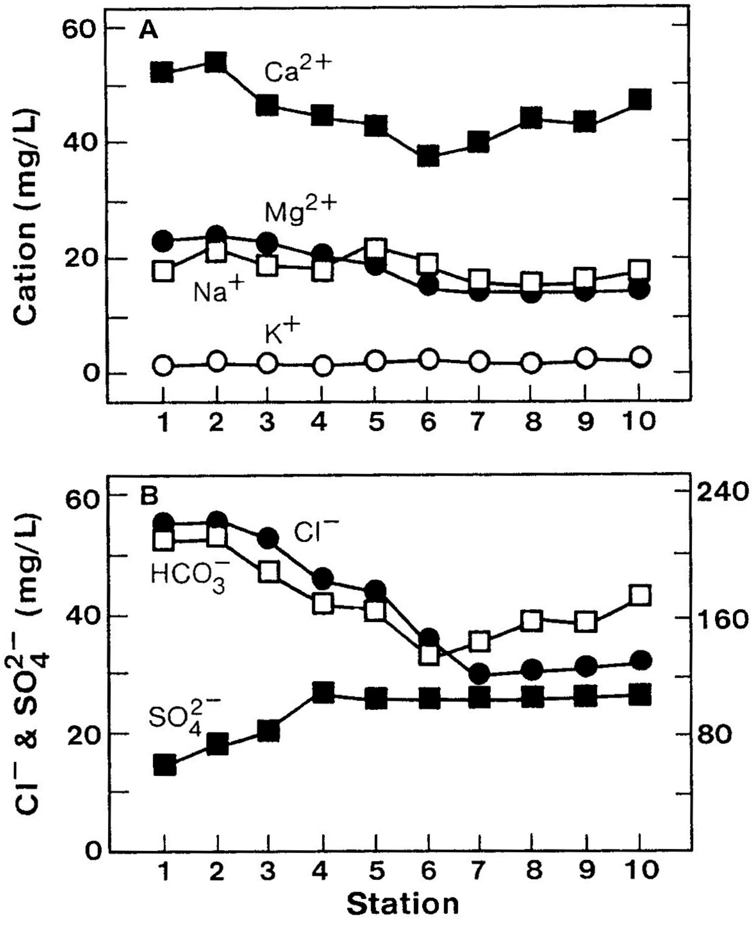

Figure 2. Ion concentrations in water at Quanicassee wetland (August 22, 1989)

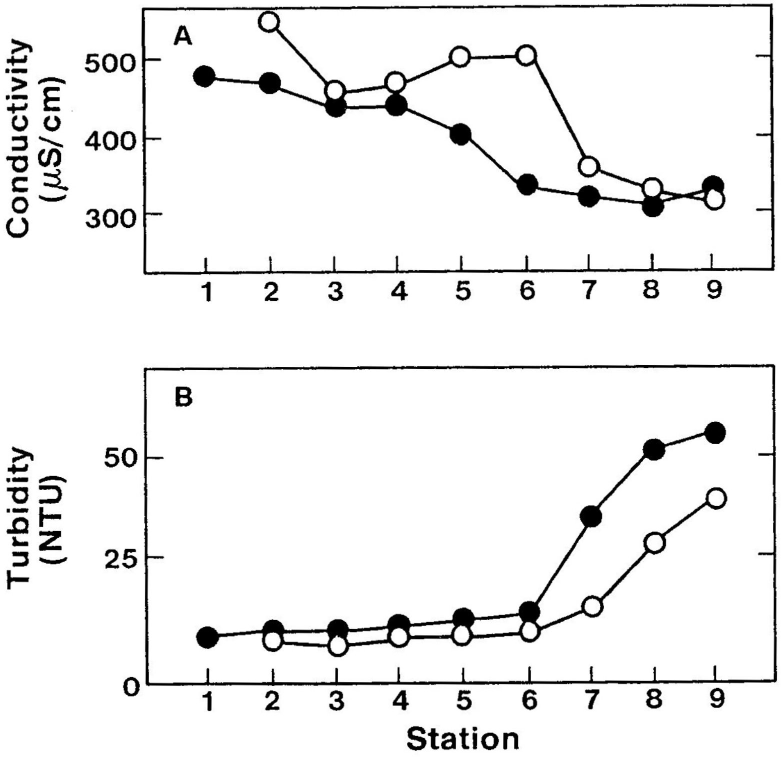

Figure 3. Conductivity and turbidity along the transect at Quanicassee on August 22 (○) and August 24 (●) in 1989.

the vicinity of station 8, and movement of low-conductivity water shoreward of station 5 as the water-level rose during the storm of July 18. As the storm subsided and water-level dropped, conductivity at both stations rose toward pre-storm conditions. Oscillations in water-level dampened during days after the storm. As they did so, conductivities at stations 5 and 8 returned to normal ranges for near-shore and offshore waters in the wetland. Separation of the conductivity graphs for stations 5 and 8 (Figure 5) shows that near-shore and offshore waters in the wetland never completely mixed during the period of record.

Figure 5 shows water temperatures recorded at stations 5 and 8 during the period of this study. Differences between these stations often did not exist; when they did they were on the order of 1-2° C. Near-shore water (station 5) was cooler at night and warmer during the day than water in offshore portions of the wetland (station 8). These data, as well as measurements made at stations on the transect at other times in the study, show that temperature-related density differences between near-shore and offshore water were very small.

Various measures of algal abundance and productivity were made during the course of this study. Figure 6 shows an example of the observed distributions of algal periphyton and phytoplankton along the transect in mid-summer. Substantial changes in the abundance of both kinds of algae occurred in the vicinity of the discontinuity near station 6. Periphyton chlorophyll *a* was near 1 mg/m^2 of submersed surface of bulrush shoots at stations 1 through 5, and twice or more of that amount at stations 6 through 9. Near-shore water at stations 1 through 5 had low abundance of planktonic algae; from 0.5 to 7 mg/m^3 chlorophyll *a* were observed at these stations. Concentrations of planktonic chlorophyll *a* were higher in offshore water in the wetland; between 15 and 30 mg/m^3 were observed at stations 6 through 9. On the line of the transect 50 m bayward of station 9, beyond the fringe of emergent vegetation, the chlorophyll *a* concentration in open water was 42 mg/m^3 at the time of these samples. It is evident from these results that development of a discontinuity bar gave rise to near-shore and offshore environments in the wetland that were not equally acceptable for algae.

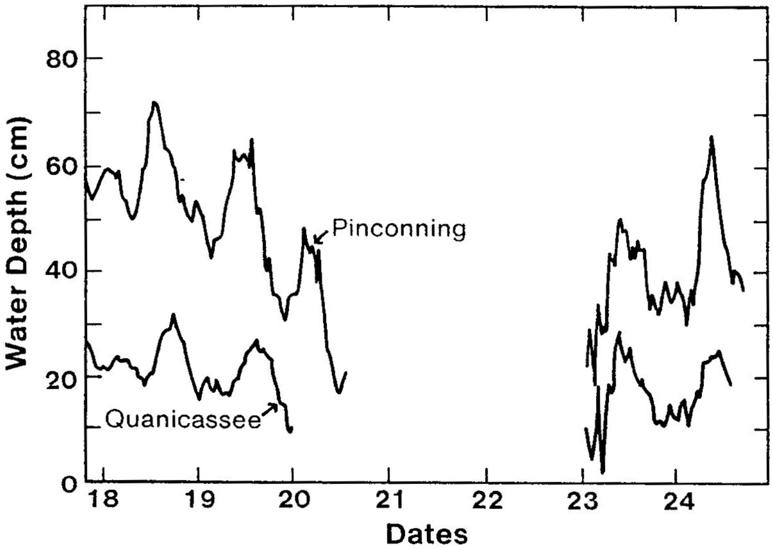

Figure 4. Time sequence of water level fluctuations at two stations on Saginaw Bay in August 1989.

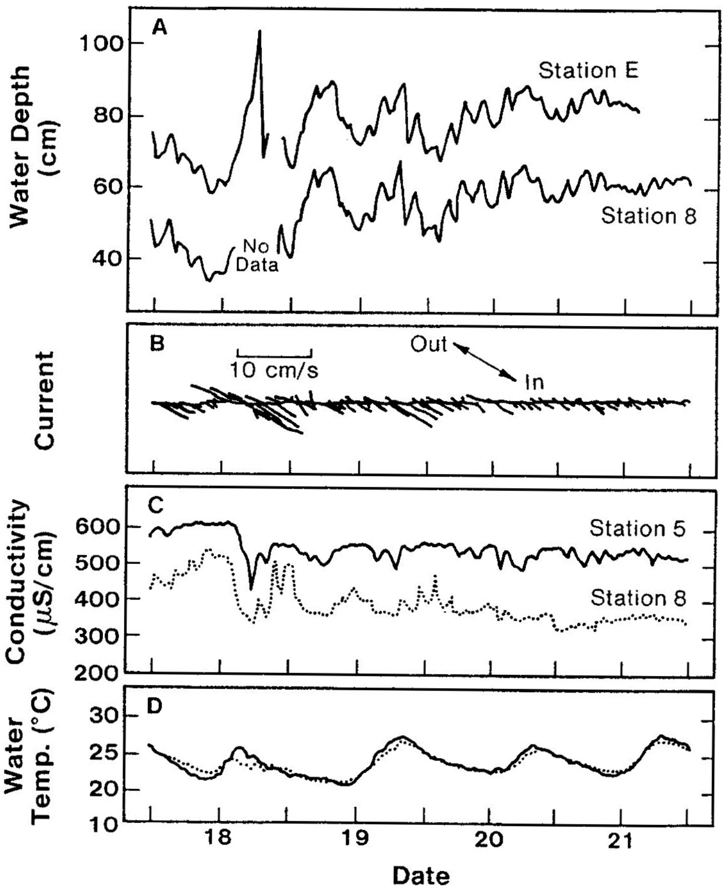

Figure 5. Data collected in July 1990 at two stations in Quanicassee wetland. Locations of stations are shown in Figure 1. *No data* gaps in panel A were due to instrument malfunctions. Panel B shows currents at station 5. *In* and *Out* on panel B give direction for currents in relation to the shoreline. Solid line in panel D is for station 5; dotted line in panel D is for station 8.

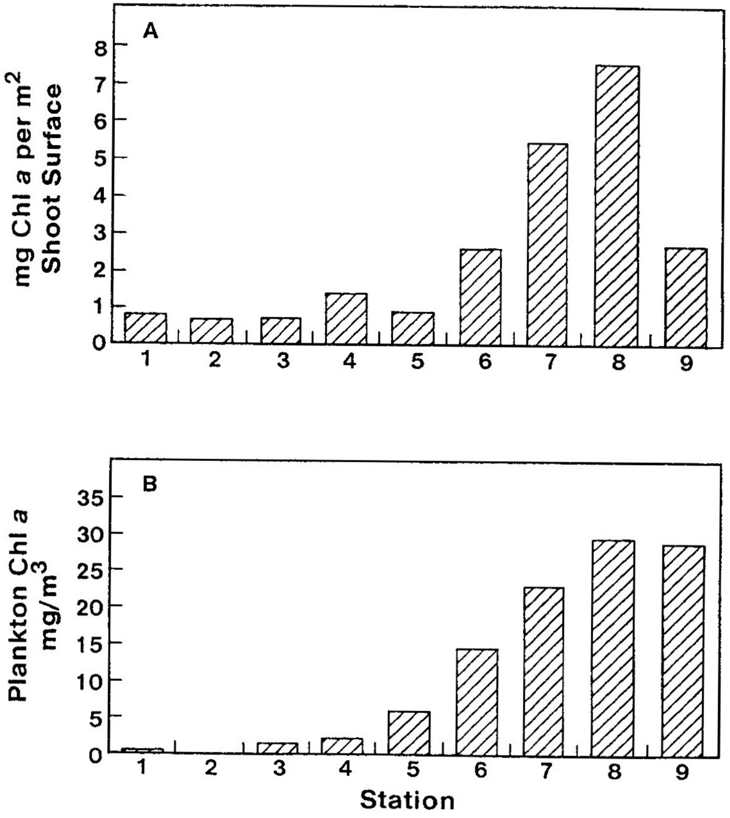

Figure 6. Chlorophyll *a* in periphyton (A) and phytoplankton (B) at stations along the study transect in Quanicassee wetland (August 22-23, 1989).

DISCUSSION

Data reported in this paper were from work done in cooperation with a larger study conducted in the wetland at Quanicassee during the interval 1988-1991 (McNabb et al. 1991b). Records from this work showed that an ice sheet and snow covered the wetland from December to early April in each of these years. After ice-out, temperature in the water and surface sediments warmed reaching 4-6° C in the interval late-April to mid-May. At those temperatures, over-wintering plant propagules began to germinate. Densities of emergent and submersed plants increased in May and June and reached annual maximums in late-July and early August.

At the height of the growing season, a ground-level view of the wetland gave the appearance of a monotypic stand of *Scirpus americanus* Pers. (three-square bulrush). Shoots (culms) of *S. americanus* grew from rhizomes in the sediments and rose between 80 and 100 cm above the surface of the water. Duffy et al (1987) noted that this plant dominated biomass in wetlands on shores in the upper Great Lakes that were poorly protected from wind and waves. The wetland at Quanicassee had poor protection. It was exposed to fetches over the bay of 30 or more kilometers in the compass quadrant running from northwest to northeast. Offshore bars and spits were not present to dissipate the energy of waves. *Elocharis smallii* Britton, a much shorter emergent plant, was scattered at low biomass among the bulrushes. Three additional emergent species were uncommon and grew in relatively small patches; these were *Scirpus acutus* Bigelow (hardstem bulrush), *Scirpus validus* Vahl (softstem bulrush) and *Typha angustifolia* L. (narrow-leaved cattail). These latter species did not occur on the transect. Fifteen species of submersed macrophytes grew in the water column at the base of emergent shoots (Batterson et al. 1991). Densities of plants in the wetland remained near annual maximums from late-July through the first frost of autumn (October).

Two distinct masses of water existed in Quanicassee wetland in July and August of 1989 and 1990. Near-shore water was clear. It had low turbidity, high conductivity and high concentrations of solutes. Water in offshore portions of the wetland was more turbid, with lower conductivity and lower concentrations of solutes. During mid-summer studies, density of aquatic vegetation in the water column was at or near the annual maximum. When studies were conducted in May 1991, distinctly different water masses were not identifiable in the wetland. In this case, wetland plants had recently germinated and few shoots were present. Taken together, these observations suggest that partitioning of the watermass in the wetland was a seasonal phenomenon that accompanied development of aquatic vegetation which inhibited mixing between near-shore and offshore waters.

Mid-summer studies in 1989 and 1990 provided insights on the stability of the discontinuity bar that developed between near-shore and offshore waters in the wetland. Information was obtained from two sets of data. One involved measurements of conductivity and turbidity taken along the transect when water levels were rising or falling in conjunction with seiches that had 24-hour periods. These data showed that the bar moved shoreward along the transect as water rose in the wetland, and bayward as water-level in the wetland receded. Differences in the location of the bar shown in Figure 3 are an example of this movement. The most rapid change in conductivity with distance along the transect occurred between stations 5 and 6 when measurements were made in a period of rising water (August 24). Measurements made in a period of receding water (August 22) resulted in shifting the bar bayward with most rapid change in conductivity over distance occurring between stations 6 and 7. In the case of turbidity, most rapid change over distance with rising water was between stations 6 and 7, and with receding water it was between stations 7 and 8. Both the conductivity and turbidity data show that while the discontinuity bar moved, it was not broken down during 24-hour seiches.

Data related to the storm event of July 18, 1991 (Figure 5) were further instructive in regard to stability of the discontinuity bar. Conductivity at recording stations in the wetland dropped from a pre-storm range of 500-600 μS/cm to 350-420 μS/cm as onshore winds induced a rapid influx of low conductivity water from the bay. Figure 7 shows the distributions of conductivity along the transect in the wetland before and after the storm event. Taken as a whole, water in the wetland had decreased conductivity after the storm.

Data in Figure 7 were used to obtain an estimate of total electrolytes (E) in water in the wetland before and after the storm. The following relationship was used:

$$E = \int_0^L (C(x) - C_0) \cdot D(x) dx$$

where the x-axis is directed from shore outward along the transect, L is the distance from shore to station 10 (500 m), C(x) is conductivity at each station, C_0 is conductivity in intruding bay-water (taken at 300 μS/cm), and D(x) is water depth. The water exchange ratio (R) for the interval between measurements was taken from:

$$R = (E_2 - E_1)/E_1$$

where 1 and 2 designate E values for July 17 and July 19 respectively. Solving for R resulted in a value of 0.17. This result suggests that 17% of water in the wetland was exchanged for water from the bay as a result of the storm event. Figure 7 also shows that during this exchange, the conductivity gradient in the frontal zone between near-shore and offshore water in the wetland was modified but not broken down.

Summertime isolation of near-shore water from water in offshore portions of the wetland is further indicated by data obtained on phytoplankton distribution along the study transect. Plankton chlorophyll *a* was low (0.5-7 mg/m^3) in near-shore water (Figure 6). Bayward of the discontinuity bar, plankton chlorophyll *a* was much higher (23-30 mg/m^3). These latter chlorophyll *a* concentrations are in the range commonly given for eutrophic waters (Wetzel 1983). Stoermer and Theriot (1985) made an extensive study of phytoplankton in Saginaw Bay. Their work suggests that chlorophyll *a* in waters offshore at Quanicassee came largely from species of blue-green algae and diatoms; species typical of eutrophic waters. Others working with nutrient chemistry have verified the eutrophic status of bay waters in the vicinity of Quanicassee (Smith et al. 1977).

Chlorophyll *a* concentrations in water shoreward of the discontinuity bar were much lower than concentrations expected for eutrophic waters. Models in the literature that deal with relationships between chlorophyll *a* and nutrients (Sakamoto 1966, Smith and Shapiro 1981, Vollenweider and Kerekes 1980, Goldman and Horne 1983) predict that near-shore planktonic algae were nutrient limited. Otsuki and Wetzel (1972), Mickle and Wetzel (1978), Goldman and Horne (1983) and others point out that biotic uptake and chemical-physical processes commonly sequester enough mineral nutrients in the growing season to limit phytoplankton production where surface waters are not periodically freshened by flow-through or mixing. Hasler and Jones (1949) drew attention to the generally observed case in which well developed stands of submersed macrophytes in lakes have low standing crops of phytoplankton relative to adjacent littoral or pelagic waters. They implied that submersed macrophytes, like those growing densely in the near-shore portion of the study transect may secrete organic compounds that inhibit phytoplankton. Wetzel (1983) observed that light limitation due to shading by submersed macrophytes and CO_2 limitation at elevated pH imposed by macrophyte photosynthesis are also among factors that could be important. Additionally, Codd (1981) demonstrated that high light intensities in the clear, shallow near-shore water of the wetland would also inhibit phytoplankton production.

We have documented the existence of a chemical, physical and biological discontinuity that developed in the wetland at Quanicassee during early summer. By mid-summer, near-shore and offshore waters were separated by a discontinuity bar that had considerable stability. In freshwaters, stability of such bars is often due to differences in density of water on either side of the discontinuity and inability of ambient currents to sustain mixing at the interface. Differences in density are commonly related to differences in temperatures and concentrations of solutes. In mid-summer, near-shore and offshore waters in Quanicassee wetland tended to have similar temperature-related densities due to similar average daily temperatures. Higher concentrations of solutes in near-shore water caused higher density in that water than in water in offshore portions of the wetland. The solute-related density differences between water masses were small. Using data in Figure 2, for example, the solute-related density difference in water on opposite sides of the discontinuity bar (stations 5 and 6) was on the order of 0.00005 g/L (Wetzel 1983). For comparison, transient temperature differences of 24° to 25° C shown in Figure 5D resulted in a density difference five times greater; about 0.00025 g/L. At Quanicassee, mixing of water shoreward of the discontinuity bar was without doubt impeded by high densities of submersed and emergent aquatic plants. Madsen and Warncke (1983) and Losee and Wetzel (1993) have shown that well developed beds of aquatic vegetation severely reduce ambient flow rates and mixing of water. We found that flow rates in the Quanicassee wetland, including those associated with seiches and storm events, were insufficient to break down the discontinuity between near-shore and offshore water when aquatic vegetation was at its annual maximum density.

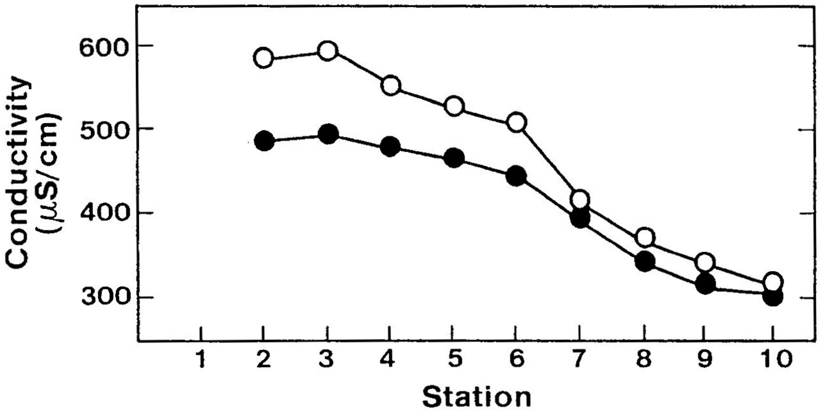

Figure 7. Conductivity along the transect at Quanicassee on days before (o) and after (•) a storm event.

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