The Prediction of Sedimentation Patterns in the Littoral Zones of Lakes Supporting Macrophyte Growth

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ABSTRACT

The Prediction of Sedimentation patterns in the Littoral Zones of Lakes Supporting Macrophyte Growth

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In aquatic environments many contaminants, such as heavy metals and organics are incorporated within or bound upon fine-gained sediments. As sediment associated chemical transfers can occur within a short time-frame, the prediction of sites of temporary accumulation of sediment is a management requirement. In lake environments, the littoral zone is one of high productivity and rapid turnover. This study develops a general model which allows the prediction of zones of accumulation and/or erosion in lake littoral zones.

Reduced water velocity and the physical barrier presented by weedbeds are proposed as possible factors affecting the retention of fine materials. If lake managers are to predict the sites of accumulation, they must know the factors and relationships which enhance sediment retention. By characterizing the energy environments in different positions within a lake's littoral zone and quantifying the role of aquatic plants a predictive model for sedimentation zones can be developed.

In order to develop the predictive model, two hypotheses are defined and tested.

1. The structure of an aquatic plant stand affects the efficiency of particulate trapping; and
2. Available emperical relationships which predict bottom water velocities and sediment entrainment can be combined with macrophyte data to provide an effective method of predecting zones of erosion/accumulation in the nearshore areas of lakes.

Data to test these hypotheses was gathered at lake Memphremagog, Quebec. One season of data collection has yielded only partial results and a second season is required to fully explore both hypotheses.

In aquatic environments many contaminants, such as heavy metals, and organics are incorporated within or bound upon fine-grained sediments (Allan,1971, Thomas,1974, Forstner and Wittmann,1981). These sediments may act as either sinks or sources of contaminants depending upon the ambient chemical, biological and/or physical conditions. In lake environments the accumulation of fine-grained materials has generally been thought to occur in the deep pelagic zone (Lehman,1975, Likens and Davis,1975). Long-term (years or decades) sediment transport tends to result in the removal of fines from the high energy shallow (littoral) areas and the focussing of these materials to the calmer deep waters. While this process tends to be realized in the long-term, it is known that the timescales of the vectors of biogeochemical cycling can be much shorter (days or months)(Forstner and Wittmann,1981). As sediment associated chemical transfers may occur within short time intervals the prediction of sites of temporary accumulations of sediment beomes a management requirement. In lacustrine systems the littoral is a region of high productivity and rapid turnover. Many levels in the food chain (phytoplankton, macrophytes, benthos, zooplankton, fish and water fowl) utilize the resources of the littoral therefore increasing the potential for contaminant transfer or bioaccumulation. There is an obvious dearth in the literature of studies investigating littoral sediment retention on seasonal (or shorter) time intervals, which is the appropriate scale for contaminant transfer in this biologically active region of a lake.

The objective of this study is to develop a general model which allows the prediction of zones of accumulation and/or erosion of fine-grained sediments in lake littoral zones. Lakes of all sizes and morphologies receive nutrient and contaminant loadings (metals, organics and pesticides) from their drainage basin as well as from aerial sources. A general model, incorporating a wide range of littoral conditions, would allow the prediction of sites of sediment accumulation and the accumulation of toxics associated with the fine sediments. Sediment associated contaminants become an environmental concern when they have the potential to be released to the surrounding water and/or incorporated into the foodchain. Littoral zone accumulation of fine-grained sediment represents this potential in aquatic ecosystems.

The erosion or deposition of fine sediments (less than 75 microns) will be a function of the energy imparted to their surroundings, The spectrum of littoral energy environments, which can be represented by the range of conditions existing between rocky exposed headlands and enclosed quiescent bays, would experience a wide variation of sediment retention capabilities. Littoral zones may also support large stands of aquatic weeds which have been noted to attenuate incoming water velocities (Kouwen et al,1969, Li and Shen,1973, Wanlese, 1981). Reduced water velocity and the physical barrier presented by weedbeds have been proposed as possible factors affecting the retention of fine materials in shallow parts of lakes (Rogers and Breen,1980, Eckman,1983).

If littoral tones are capable of retaining fine sediments, lake managers require a method to predict the sites of accumulation. This would be facilitated by knowing the factors and relationships which enhance sediment retention. BY **characterizing** the energy environments in different positions within a lakes littoral zone and **quantifying** the role of aquatic plants a predictive model for sedimentation zones can be developed.

Energy transfers to the nearshore are dominantly imparted by **waves(Donelan,1980,** Hakanson and **Jansson,1983).** Several empirical models *exist* which allow the prediction of wave height and length from windspeeds and fetch **(Donelan,1980, Lick,1982, Bishop,1983).** Bottom water velocities can be determined from equations relating wave characteristics and water depth (Komar and **Miller,1975).** Through the combination of these relationships it is possible to determine the velocities at the sediment-water interface and to evaluate the erosive potential at a site (from Shield's **equation,in Postma,1967** or Hjulstrom's diagram, 1935). While this approach has been used to model sedimentation regimes in several Swedish lakes **(Hakanson,1982)** it deals only with open littoral areas. The confounding effect of aquatic plants In the nearshore has not been incorporated as yet. Water velocities approaching the front edge of a **weedbed** will be transferred into the stand of plants only to be modified by the bed itself (Kouwen et **al,1969,Li** and **Shen,1973).** This reduction of velocity, coupled with the physical barrier presented by the plants themselves will tend to facilitate sedimentation of the suspended load carried by the water mass. As **weedbeds** tend to' increase in biomass over the summer period it can be assumed that they act as more effective traps as the summer progresses. Material moving into the bed would be stored until the fall when the plants die back and the autumn storms completly mix the lake water. Does a seasonal or between-wind event trapping of sediments occur, and if so can we predict where? In lake environments where contaminants are known to be associated with fine Sediments a predictive model of this type would allow the management of aquatic macrophytes such that contaminant transfers to the biota of the littoral would be reduced.

As a first step in developing the model of littoral zone sedimentation the relationships existing between sediment erosion/accumulation and aquatic plant structure (biomass, form, density) will be defined. Hypotheses to be tested are:

1) the structure of an aquatic plant stand affects the efficiency of particulate trapping

2) available empirical relationships which predict bottom water velocities and sediment entrainment can be combined with macrophyte data to provide an effective method of predicting zones of erosion/accumulation in the nearshore areas of lakes.

The approach proposed to test these hypotheses and determine the relationship between plant form and sedimentary process are detailed below. The data set from one study season has been analysed and is presented in order to address the initial hypothesis. The study was undertaken in Lake Memphremagog, Quebec, a large lake which incorporates a wide range of littoral energy environments as well as a spectrum of macrophyte structures (from marshes, mixed dense weedbeds to barren open areas). Sixty-eight sites were characterized in terms of available energy (effective fetch, slope, water depth, distance to shore) and plant characteristics (height', biomass, species composition, growth form and surface area)(plant surface area was determined using the dye method of Cattaneo and Carignan,1983). Subsequently site characteristics were evaluated with respect to surficial (top centimeter) sediment composition.

Sediment composition was determined using several different measures. The analysis involved the separation of the organic and inorganic fraction and subsequent grain size evaluation of the mineral portion of the sediment. Eleven size classes were quantified, using the pipette method of analysis (Krumbein and Pettijohn,1938) for seven classes below 32 microns and sieve size analysis (Krumbein and Pettijohn, 1938) for the four classes above 32 microns.

In the initial analysis sediment grain size was characterized by clay, silt, sand and gravel fractions, which were operationally defined as < 2, < 32, <500, <10,000 microns respectively. The presence of aquatic plant stands were seen to alter relationships between energy and sediment particle size. Fetch, which is a relative potential energy term for all sites was significantly ($p = .05$) negatively related to the percent of clay sized material (<2 microns) at sites where no weeds existed. No significant relationship existed between fetch and the fine particle size composition in sites with weeds. This suggests that plant stands are modifying energy transfers in the littoral.

Multivariate analysis of the data set indicated that fetch, position within the weedbed and surface area (m^2 of plant surface per m^2 of lake bottom) were the dominant factors affecting the proportion of fines at a site. Plant height was correlated with both the silt and clay portions of the sediment at the 99.9% significance level. Silt was found to be linearly related to each of surface area, wet biomass, dry biomass and plant height at the 95% significance level. It was apparent from the preliminary analysis that the presence of plants in the nearshore was associated with differences in the littoral sediment composition,

As a means of addressing the first hypothesis plant and sediment data were evaluated in another manner. Sediment grain size statistics (graphic moment measures) were calculated for each of the 68 sediment samples. These calculations result in quartile, median, mean, standard deviation, skewness and kurtosis values for each of the samples. Equations used in the calulation of sediment moment measures are presented in Friedman and Saunders, 1978.

Moment measures have been used in sedimentology to indicate the energy environment to which the material has been exposed or to evaluate the processes operating where the sediments are deposited. The frequency distribution curve of a sediment population will exhibit some degree of difference from that of a normal population. The extent and directions in which these deviations occur reflect 1) the availability of sites in the parent material and 2) the competency of flow at the site.

The second graphic moment measure, rtandard deviation, is a

• eaeurc of the degree of sorting in a sample. Sorting can be considered the degree to which a sample is focussed towards a single grain size. For example a wave washed shoreline in Maine could be considered well sorted If composed predominantly of sands and gravels, The energy environment represented here could be explained simply as too high to deposit silts and clays and not energetic enough to transport boulders onto the beach. As a sediment sample from this beach would be represented predominantly in the gravel size classes the frequency curve would peak above 500 microns, and have low standard deviation and sorting values (table 1). Glacial tills which have been overlain by lake waters would on the other hand be quite poorly sorted. The initial composition of the till could include boulders, gravels, clays and sands. As the water velocity at the lake bottom is low the only grain sizes which could be selectively removed are the clays. A grain size analysis of this sediment population (figure 1b) would result in a frequency curve which has material represented In most classes, therefore forming a broader, flattened curve with higher sorting values (table 1).

The degree of sorting exhibited by sediments can be calculated by a variety of methods (Folk,1966). The five equations used on this data set were:

graphic standard deviation $= \frac{\mu 84 - \mu 16}{4} + \frac{y 95 - \mu 5}{6.6}$

sorting 1 $= 1/2(\mu 95 - \mu 5)$ simple sorting measure

sorting 2 $= \mu 75 - \mu 25 / 2$ arithmetic quartile deviation

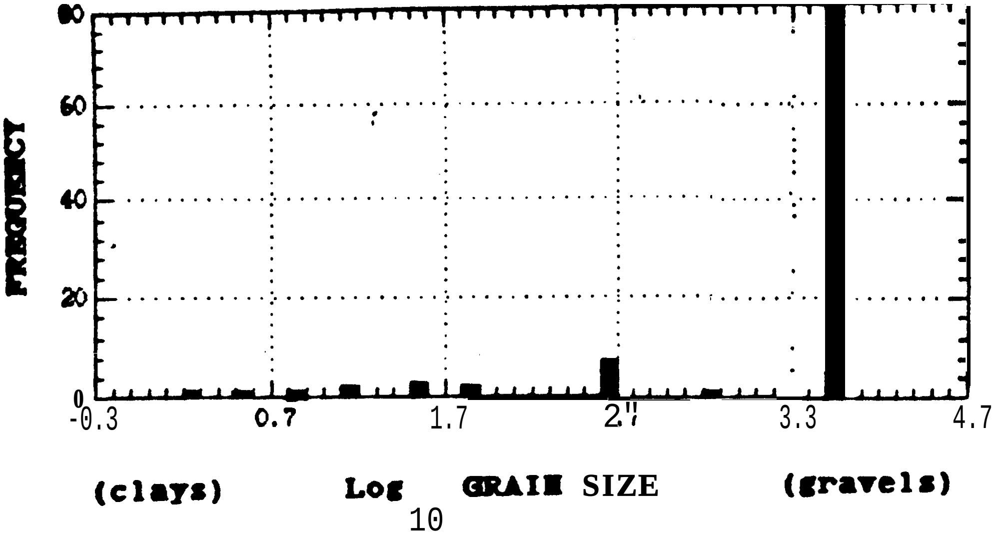
sorting 3 $= (\mu 75 / \mu 25)^{1/2}$ geometric quartile deviation

TABLE 1. Grain Size **Statistics** for **Figures 1a, b.**

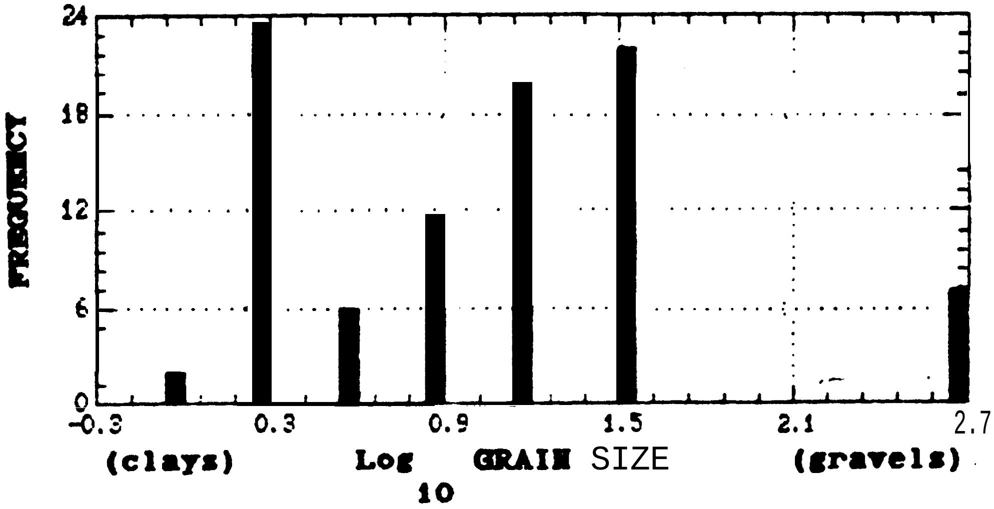
	Well Sorted Beach	Poorly Sorted Till
Mean (microns)	1751	6.1
Median (microns)	6011	7.9
Standard Deviation	7.7	10.4
sorting 1	35.9	197.0
Sorting 2	1.6	3.0
sorting 3	1.1	2.2
Sorting 4	0.02	0.36

Figure 1

a) Frequency Histogram of a Well Sorted Rocky Beach



b) Frequency Histogram of a Poorly Sorted Overlain Till



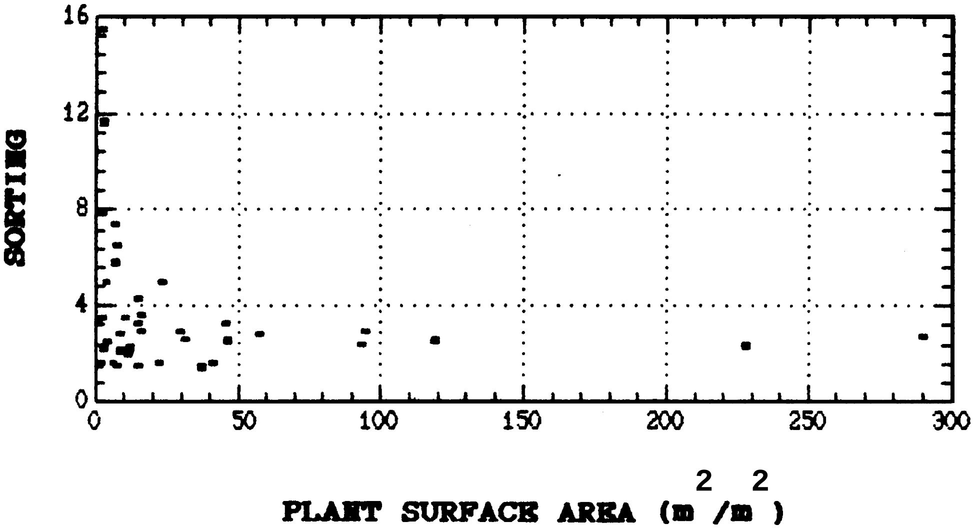
sorting 4 = $\log(\mu 75 / \mu 25)^{1/2}$ log geometric quartile **deviation**

As the sorting parameter can potentially be used to differentiate ambient energy environments, It was selected as a variable for the testing of the first hypothesis. If we assume that the particle size distribution of the material suspended In the water column at the front edge of all weedbeds is similiar then the trapping efficiency of the bed would be reflected in the sorting values of the sediment. Dense beds would exhibit better sorting (smaller values) as they theoretically receive only small particles carried by the water column. As the surficial material represents most recent sedimentation, a long standing dense bed would be expected to have a layer of fine particles, which have settled out of the water column in the less turbulent water inside the bed, covering the source sediments that the weeds initially inhabited. Sorting in the sparse weedbeds is expected to be poorer (higher value) as the littoral energy from waves and currents would be available to, remove and/or carry in a range of sediment sizes.

From the five sorting measures calculated it is apparent that a negative trend (lower sorting values for higher values of plant variables) exists, as was theorited. Figure 2a shows this relationship between plant surface area and sorting (calculated as the arithmetic quartile deviation). This form of scattergram indicates that some threshold level of a plant variable (be it surface area, biomass etc) is associated with an alteration of sediment grain size characteristics. In figure 2a the surface area threshold falls at approximately 25 m^2/m^2. The first moment measure of sediment grain size (the mean grain size of the

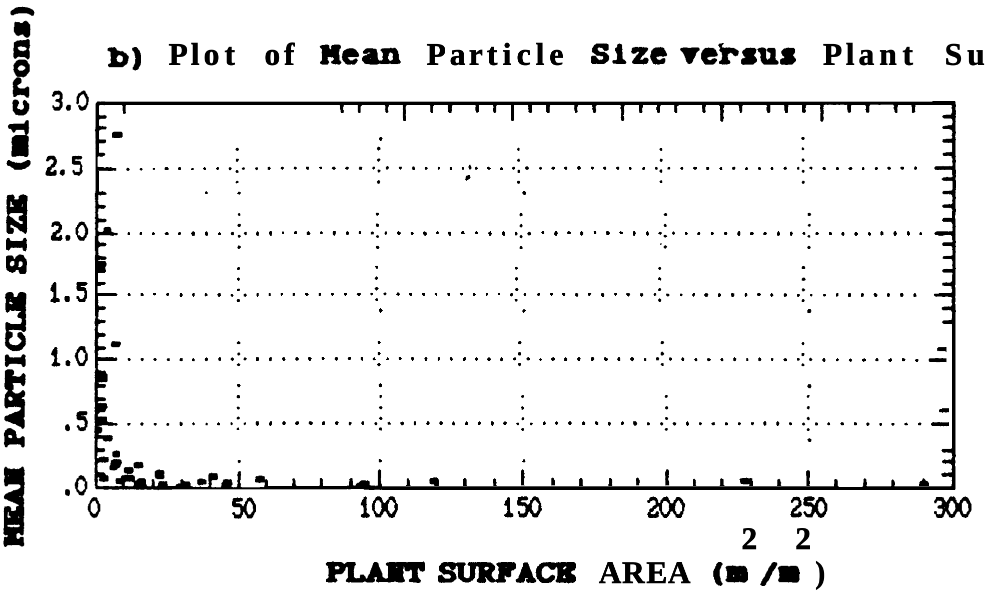
Figure 2.

a) Plot of **Sorting*** **versus** Plant Surface **Area**



* arithmetic quartile deviation

b) Plot of **Mean** Particle **Size versus** Plant Surface **Area**

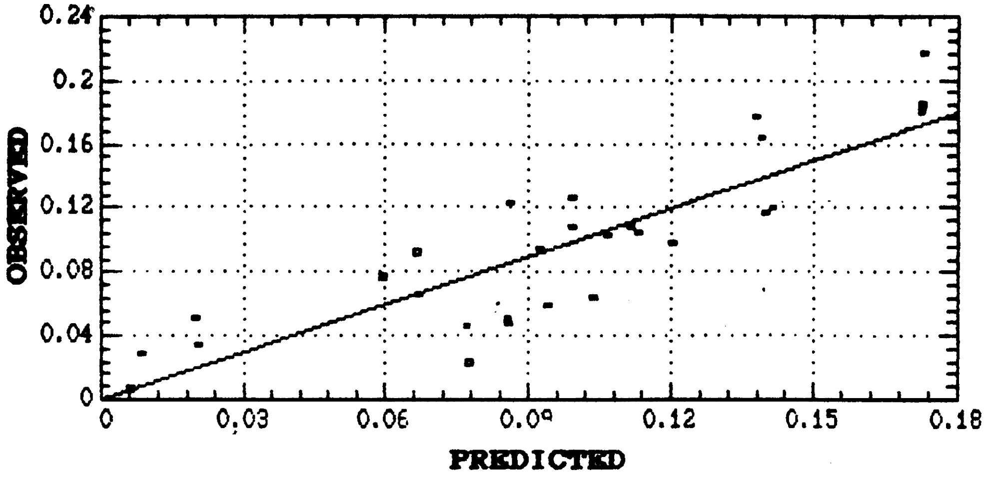


population) also exhibits this strong negative relationship (figure 2b). It appears that the presence of more than 10 m^2/m^2 of plant surface area is associated with a very small range of low mean particle size. Variation of sediment characteristics at sites exhibiting plant values exceeding the threshold is limited. These relationships are useful in that they allow the identification of transition plant value which is associated with a predominance of small grain sizes in a population. They also indicate that trapping efficiency as expressed by a sediment sorting value is related to the form characteristics of the weedbed.

The data set of 68 sites was divided Into two groups, one comprised of the 40 sites which supported plant growth and the second group of 28 sites which did not exhibit macrophytes. As it is of interest to be able to predict the sites at which fines are accumulating the sediment grain size statistics were used in developing multivariate models. It was noted earlier from figure 2 that regions with plant surface areas exceeding 10-25 m^2/m^2 exhibited little variation in sorting values. For the sites that did not support weed growth 70% of the variance in sorting could be explained by the four variables: percent organic matter, fetch, gravel sand ratio amd slope (figure 3a). The range of energy conditions in the 28 sites without weeds was expressed in the sorting 4 measure. The energy transfer into the weedbeds is not recognized by any significant relationships with sorting measures. It would seem that energy differences within beds above the threshold plant level are not extreme enough to

Figure 3.

I) Plot of Predicted Values versus Observed Values for Multiple Linear Regression Model Predicting Sorting*.

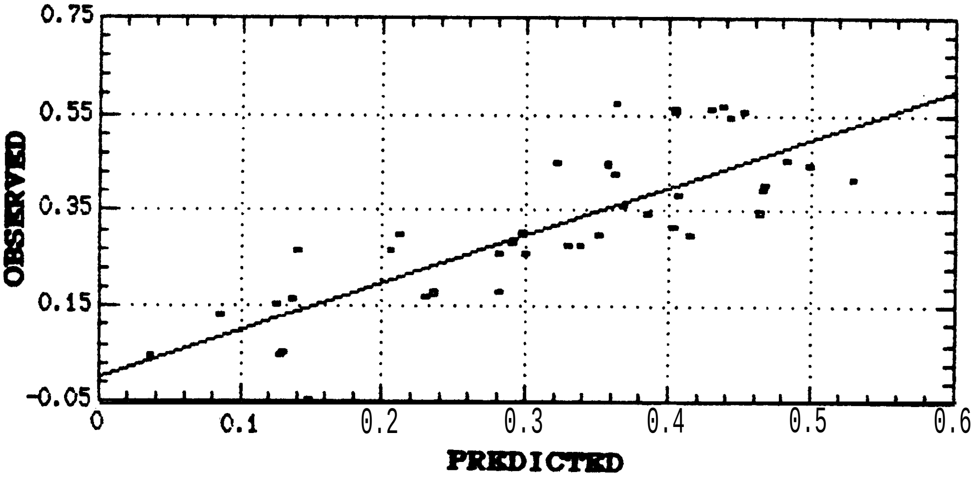


MODEL: Log(sorting*) = 0.003 (% organic matter) - 0.002 (fetch) - 0.0009 **(gravel:sand)** - 0.0016 (slope) + 0.146

r^2 =0.70

* log of **geometric** quartile **deviation**

b) Plot of Predicted Values **versus** Observed **Values** for Multiple **Linear** Regression **Model** Predicting **Median** Grain Size.



MODEL: Log(median grain size) = -0.103 **Log(surface** area) - 0.041 (plant height) -0.012 **(%** organic utter) + 0.576

r^2 =0. 66

differentially sort the sediment populations. However within weedbeds the median grain site, or the grain size for which 50% of the population is finer than, can be predicted using log surface area, plant height and percent organic matter. 66% of the variation in median grain size can be explained in this multivariate model (figure 3b). Enhancement of this model would be extemely useful as the prediction of the median size would allow lake managers to identify areas of accumulating fines. The collection of a larger data set to develop and test this model is required and will be undertaken in the upcoming season.

Future Research Plans

To obtain further data for the multivariate models two approaches will be undertaken. Eleven littoral locations (therefore incorporating 42 sites) in Lake Memphremagog will be sampled approximately twice a month during a summers growing season. Five of these locations represent beds which overwinter while four consist of weedbeds which initiate above-ground growth each spring. The remaining two locations have virtually no rooted aquatic biomass. Changes in particle size over time at different distances from shore will be evaluated. This survey method should allow seasonal trends in particle size composition, as well differences in the overwintering versus new-growth beds to be noted, While this sampling period is not frequent enough to distinguish resuspension events, it can potentially elucidate the biomass required to dampen erosional effect8 (ie. at some biomass level the variation of fine particle composition will be minimized). The range Of initial Wet biomass at the sites of maximum growth (0 g/m^2 to 2100 g/m^2) compared to the range of August maximum biomass (2320 g/m^2 to 8430 g/m^2 should allow the dampening to be noted at different time6 throughout the season in the different beds. The high initial biomass at the overwintering sites should attenuate energy input8 very early in the season while the new biomass site8 are expected to dampen the erosive effect6 later in the season when their biomass reaches a threshold value for the summer energy conditions.

To evaluate the periodicity of the wind-generated wave event8, of sufficient magnitude to resuspend bottom sediment at the front edge of the bed a meteorlogical station is to be installed in the watershed (the closest Environment Canada station is 40 km away which is too great a distance for a region which is relatively hilly). This 10m tower will record wind speed and direction every 10 minutes. In summary, plant characteristics of 12 weedbeds (height, biomass, surface area and form) will be collected to determine if the spatial and/or temporal variation6 are reflected in a changing sediment composition.

A series of experiments, in weedbeds at several locations (6 -10), will be undertaken over the summer season to provide additional information for testing the two stated hypotheses.' To determine the relationship between the structure of an aquatic plant stand and the efficiency of its particulate trapping the selected **weedbeds** will be 'seeded' with an artificial substrate. This technique was performed 3 times In the 1985 field season in order to evaluate the effectiveness of the method and the problems inherent in the approach. Nine positions **(sites)** within each bed will be seeded with lilac pollen. A scuba diver inject6 the pollen Into a closed settling column and leaves the material to accumulate on a sediment surface of 400 cm^2 (this technique has ***been*** tested in the field and has been found to perform well). The sites will be positioned such that 3 are at the front edge of the bed, 3 at the region of maximum biomass and the final 3 in the nearshore shallower portion of the bed.

At the front of the **weedbed** a pressure transducer will be moored to measure wave parameters (height, period and frequency). These will be recorded for 15 minutes every 3 hours. Bottom water current speed and direction will be averaged every 5 minutes at the same location (using an Interocean S4 electromagnetic current meter). Wind speed and direction at the lakeshore location will be recorded at the time of each wave recording. Wind will also be recorded for a time period sufficient to allow the determination of the relationship between speed and direction at the experimental location and the speed and direction of the main met station (which is recording continuously over the summer period).

The pollen erosion experiments will be run for 2-5 days, with the time period dependent upon the wind/wave energy regime experienced. 'Pollen plates' will be sampled when they are first exposed to the energy environment and at the end of the experiment. The change In numbers **over** time represents erosion at the site. For each experimental location the erosion value will be compared to the site plant structure. Energy input6 recorded at the front of the **weedbeds** will be used to compare the erosion values between locations. In this way all site values. can be pooled to develop a general model for erosion within weedbeds.

The recorded energy variables will also be used to evaluate the ability of the available empirical relationships to predict wave height from windspeed and direction, and bottom water velocities from water depth and wave height. From these predicted values one should be able to determine the grain size of entrainable sediment. Losses of pollen at the front edge of the bed will allow a test of this final prediction. While error is incorporated into the prediction of each variable, it **is** of interest to determine if lake managers can estimate the littoral sedimentation regime by **utilizing** only standard meteorological data, water depth and plant biomass.

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