Exploring the influence of sedimentation on the American oyster, *Crassostrea virginica*, in Bedeque Bay P.E.I.

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2013

Canadian Technical Report of

Fisheries and Aquatic Sciences No. 3050

Fisheries and Oceans Canada Pêches et Océans Canada

Canada

Canadian Technical Report of

Fisheries and Aquatic Sciences 3050

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Cat. No. Fs 97-6/3050E-PDF ISSN 1488-5379

Correct citation for this publication:

Zions, V.S., Law, B.A., Milligan, T.G., Bugden, G.L. 2013. Exploring the influence of sedimentation on the American oyster, *Crassostrea virginica*, in Bedeque Bay P.E.I.. Can. Tech. Rep. Fish. Aquat. Sci. 3050: vi + 32.

Table of Contents

List of Figures

List of Tables

Abstract

Zions, V.S., Law, B.A., Milligan, T.G., Bugden, G.L. 2013. Exploring the influence of sedimentation on the American oyster, *Crassostrea virginica*, in Bedeque Bay P.E.I.. Can. Tech. Rep. Fish. Aquat. Sci. 3050: vi + 32.

Since 2002 there has been a marked increase in American oyster mortality during the spring harvest in Bedeque Bay, PEI. It has been hypothesised that mortalities are the result of increased sedimentation primarily due to runoff from agricultural lands. The goal of this project was to assess the sediment dynamics in Bedeque Bay and determine if sediment is associated with problems in the oyster fishery. Surficial sediment grabs and sediment cores were collected during the spring and summer of 2008. Sediment trap samples were collected over the winter by colleagues from the University of PEI. Sediment samples were analyzed for disaggregated inorganic grain size (DIGS) using a Beckman-Coulter electro-resistance particle size analyzer. The DIGS distributions were used to estimate various sediment parameters, including median particle size (d50), floc fraction and floc limit. Core samples were also analyzed for ^{210}Pb and ^{137}Cs to determine sedimentation rates. The *in situ* shear stress was derived by calculating the critical erosion shear stress of the modal diameter of surficial grain samples with the model of Wiberg and Smith (1987). Estimates were compared to the shear stress derived from the AquaDyn tidal model. Where sediment-derived shear stress exceeded estimates from the tidal model, wave resuspension is predominant. These comparisons suggest that on an annual basis, wave resuspension limits sediment deposition in the Bay. This result is supported by radio isotope dating, which revealed a sedimentation rate of 0.9 $cm \cdot yr^{-1}$, typical for maritime estuaries. Sediment trap samples, however, suggest that fine sediments are deposited during winter months when wave energies are depressed by ice formation. Into the spring as wave energies are re-established, fine sediments are redistributed. While oysters may be able to tolerate sediment accumulation on the bottom for weeks or even months, failure to remove this material through wave resuspension in the spring could be a factor in the spring die off. Concern for oyster health may also exist if contaminants such as trace metals and other organic pollutants are associated with the mud fraction.

Résumé

Zions, V.S., Law, B.A., Milligan, T.G., Bugden, G.L. 2013. Étude de l'incidence de la sédimentation sur l'huître américaine, *Crassostrea virginica*, de la baie de Bedeque, à l'Île-du-Prince-Édouard. Can. Tech. Rep. Fish. Aquat. Sci. 3050: vi + 32.

Depuis 2002, il y a eu une nette augmentation de la mortalité de l'huître américaine au cours de la récolte printanière dans la baie de Bedeque, à l'Île-du-Prince-Édouard. Une hypothèse a été formulée selon laquelle ces mortalités seraient causées par une augmentation de la sédimentation provenant principalement du ruissellement à partir des terres agricoles. L'objectif de ce projet a consisté à évaluer la dynamique des sédiments dans la baie de Bedeque et à déterminer s'ils sont responsables des problèmes que connaît l'industrie de la pêche à l'huître. Des échantillons superficiels ainsi que des carottes de sédiments ont été recueillis au cours du printemps et de l'été 2008. Des échantillons provenant de pièges à sédiments ont été recueillis par des collègues de l'Université de l'Île-du-Prince-Édouard. Ils ont été analysés à l'aide d'un granulomètre Beckman-Coulter afin d'évaluer la taille des grains inorganiques non regroupés. Les distributions de grains inorganiques ont été utilisées pour évaluer les paramètres des sédiments, notamment la taille médiane des particules (d50), la fraction de floc et la taille maximale de floc. Des carottes d'échantillonnage ont aussi été analysées pour détecter la présence de ^{210}Pb et ^{137}Cs afin de déterminer les taux de sédimentation. Les contraintes de cisaillement sur place ont été obtenues en calculant les seuils critiques des contraintes sur le diamètre modal des échantillons de grains superficiels, à l'aide du modèle Wiberg et Smith (1987). Les estimations ont été comparées aux contraintes de cisaillement issues de la maquette pour l'étude des marées AquaDyn. Lorsque les contraintes de cisaillement provenant des sédiments dépassent les estimations obtenues à partir de la maquette, la remise en suspension par les vagues est importante. Ces comparaisons semblent indiquer que sur une base annuelle, la remise en suspension des sédiments par les vagues limite leur dépôt dans la baie. Ce résultat correspond à la datation radioisotopique, qui indique un taux de sédimentation de 0,9 cm par année^{-1}, soit un taux type pour les estuaires maritimes. Toutefois, les pièges à sédiments semblent indiquer que les sédiments fins sont déposés au cours des mois d'hiver, lorsque l'énergie des vagues est affaiblie par la formation des glaces. Lorsque cette énergie est rétablie au printemps, les sédiments fins sont redistribués. Bien que les huîtres sont en mesure de tolérer une accumulation de sédiments sur les fonds pendant des semaines, voire des mois, l'absence de remise en suspension de ces sédiments au printemps pourrait être la cause de la mortalité au printemps. La santé des huîtres pourrait également devenir menacée si des contaminants comme des métaux à l'état de traces et d'autres polluants organiques sont liés au fractionnement de la vase.

1.0 Introduction

1.1 Relevant History

Bedeque Bay is located on the South West coast of Prince Edward Island and consists of Summerside Harbour, the Wilmot River, and the Dunk River. Until recently Bedeque Bay had been a prominent location for the oyster fishery because prime growing conditions along with shellfish restoration activities had allowed for a sustainable annual harvest. Between 1989 and 1999 the Department of Fisheries and Oceans Canada reported a yearly landing of 1.2-3.3 million kilograms of oyster per year, which corresponds with a market value of 1.8-7.0 million dollars per year for the Province of P.E.I. (DFO, 2003). The oyster harvest begins on May 1st of each year and closes mid July, during which 200-250 boats may be on the water at once. During the 2002 harvest the oyster fishery began showing signs of decline in landed numbers and in animal health with increased mortalities during the winter months. From 2002 to 2005 the Prince Edward Island Shellfish Association and the University of Prince Edward Island conducted a study to monitor the shellfish population and collected data to help determine the decrease in oyster health in Bedeque Bay. Their study investigated a number of different factors such as oyster health, identification of diseases that may be present in the oyster populations, environmental conditions (i.e. water quality and siltation) and observations of oyster habitat. The report, based on the study by Davidson *et. al.* (2007), outlined an increase in mortalities during the winter and early spring of 2004 and 2005. The study was unable to isolate a cause for the over-winter mortalities.

1.2 Previous Research in Bedeque Bay

Over-winter mortalities were examined by collecting oyster samples through the ice during the winters of 2004 and 2005. During winter months oyster behaviour becomes dormant due to decreased temperatures. Once water temperatures in the lab were brought to room temperature oyster filtering activity would resume. If there was no response to the increased temperature they were dissected to determine their condition index, a proxy for oyster health. Results showed a slight increase in mortalities from 1% in 2004 to 2.4% in 2005, with increased mortalities into the spring months.

The conditioning index for oyster health was determined for the most productive fishing

areas in Bedeque Bay. This was measured as the amount of dry tissue as a percentage of the combined dry tissue and dry shell weight for thirty samples from each site. There was no significant difference between the fall and spring of subsequent years during any of the sampling times. There was however a decrease in oyster health when comparing the fall samples from 2003 to 2004 as well as the samples from the fall of 2004 to 2005. Overall, a general decrease in condition index was observed throughout the study period.

Disease screening was conducted during the spring months of 2003 to 2005, as well as collecting samples during the summer and fall of 2003. Thirty samples were collected on each occasion and sent for analysis at the Shellfish Health Unit, DFO Moncton. There was no disease agent found which could be associated with the mortalities seen in Bedeque Bay. Although a number of parasites were found in all samples of oysters at levels below 20%, they were not associated with the mortalities seen in Bedeque Bay.

Changes to the environment in which the oysters inhabit also affect oyster health. The P.E.I. Shellfish Association examined water quality factors such as salinity, water temperature, and dissolved oxygen concentrations. Throughout the sampling period all measurements were observed within the normal ranges and had similar values between sampling sites. The only anomalous values were between the samples collected through the ice in 2004 and 2005 with temperatures 5°C warmer in winter 2005.

Siltation was examined during their investigation by placing sediment traps at pre-determined sampling locations. Throughout the study there was minimal deposition observed on the traps and oysters themselves throughout the winter, however, siltation increased throughout the spring and into the summer months. The silt-covered oysters from later in the season often had black shells presumably caused from anoxic conditions. Increases in sedimentation could affect oyster health as smothering from silt reduces respiratory functions.

Runoff from the agricultural community was seen to be a possible link between increased sedimentation in the Bay and the decrease in oyster health. With increased land use, sediments become unstable and are more likely to be introduced into the water column. In the Summerside area approximately 11000 hectares of land are being cultivated in the watershed of Bedeque Bay. The runoff into the water column is especially prevalent during times of increased storms when heavy precipitation leads to increased siltation, and possibly increased nutrient

loading and pesticides from agricultural use.

Benthic habitat was examined by visual survey during dives in 2003. Habitat was determined based on sediment type and abundance of vegetation at each sampling site. Only sparse amounts of vegetation were examined throughout the study period. Mud was the most common sediment type observed averaging 85% of the substrates with an average organic content of 2.3%. Only three stations were seen to have critical values for chemical parameters (organic content, redox potential, and sulfide concentration) which implied anoxic conditions.

The report by Davidson *et al.*, (2007), which was produced for the Prince Edward Island Shellfish Association, provides a thorough analysis of the factors which play a role in oyster health in the Bedeque Bay area. The direct cause of increased oyster mortality was not found however and the report suggested that certain factors should be examined in greater detail, including possible changes to sedimentation.

1.3 Flocculation Dynamics and Sedimentation

Understanding the packaging of suspended sediment is important because the deposition and transport of fine sediment is fundamentally affected by aggregation (McCave, 1984; Kranck and Milligan, 1991). Aggregation is the process whereby small particles adhere to other particles to form flocs. Flocs sink much faster than the component particles within them (Sternberg *et al.*, 1999). Under normal conditions clay grains and other smaller particles would not be deposited without floc settling. It is through floc settling that the majority of cohesive sediments or muds are deposited (Kranck, 1980; McCave *et al.*, 1995; Curran *et al.*, 2002).

Despite the importance of aggregation to particle transport and deposition, understanding of the extent of flocculation in the water column and in sediment deposited on the seabed has grown only recently. A promising tool in the understanding of the deposition and transport of fine-grained cohesive sediments is the analysis of disaggregated inorganic grain size (DIGS) distributions (Kranck and Milligan, 1991; Curran *et al.*, 2002; Fox *et al.*, 2004). A DIGS sample is one in which all organics have been removed and only the disaggregated inorganic component grains that compose the sample still remain. In general, this method relies on the assumption that fine sediment is incorporated into the floc structure in an unbiased way. A sediment's DIGS distribution can then be used to help in understanding seabed processes in dynamic areas and

give insight on the environmental conditions such as deposition and erosion (Kranck and Milligan, 1985; Fox *et al.*, 2004). High flow velocities correspond to sorted size classes where the distribution has a narrow range of sizes (ie. Sands) (Kranck *et al*., 1996). Muddy sediments that contain a wide range of sediment sizes are found in depositional areas where bottom stress and water velocities are low.

In this study sedimentation patterns and rates are quantified to help determine if increased oyster mortality and the decline of oyster health in Bedeque Bay is a result of increased sediment loading.

2.0 Methods

2.1 Overview

During the spring and summer of 2008 sediment samples were collected using three methods. An Ekman grab was used for surface sediment collection to determine bottom sediment composition. A benthos gravity corer was used to collect deep sediment cores (>.5 m) and a mini slow-corer was used to collect samples with an undisturbed sediment-water interface. Sediment core samples were subsequently analyzed for grain size and radio isotope dating. Radio isotope dating (i.e. ^{210}Pb and ^{137}Cs) was used to determine sedimentation rate in Bedeque Bay. Finally, a record of precipitation history in Summerside was examined to determine if periods of heavy precipitation correlate with periods of increased sedimentation.

2.2 Sample Collection

Samples were collected throughout Bedeque Bay (Fig. l, Table 1) in 2008 during the spring from May 26-30 and in the summer from August 5-7. Surficial sediment samples were collected using a 30 cm by 30 cm Ekman sampler. The top 0.5 cm of sediment was collected and examined on site to determine if a sediment core could be retrieved depending on the type of sediment present on location. If the position was determined to be composed primarily of mud, a core was taken.

Two different methods for retrieving sediment cores, the gravity corer and mini slow-

corer, were used. The gravity corer was used to obtain fairly deep cores (~1 m) for radioisotope dating. Cores were extruded and sampled at 1cm intervals and refrigerated prior to freeze drying and analysis. A mini slow-corer was used to collect sediment cores for erodability studies. The slow-corer uses hydraulic damping which allows the core barrel to be driven into the sediment slowly thus preventing disturbance of the sediment water interface.

Surface water samples were collected at the top of river inlets where they discharge into Bedeque Bay using a Glug sampler. The Glug consists of a stainless steel holster for a 2 L Nalgene bottle that is attached to a rope. When the uncapped bottle is thrown into the water it fills with water that is retained for analysis. Water samples were filtered through an 8.0 μm Millipore filter for grain size analysis.

Along with the bottom sediment and water samples collected in this study, nine sediment samples from sediment traps were provided by the University of Prince Edward Island and analyzed for grain size.

2.3a Disaggregated Inorganic Grain Size Analysis

The DIGS of the surficial and core sediment samples was determined following the methods described in Milligan and Kranck (1991). Samples were dried at <60°C, digested in 35% hydrogen peroxide and then resuspended in a 1% NaCl solution. Immediately prior to analysis on a Coulter Multisizer IIe, sediment was disaggregated using a sapphire tipped ultrasonic probe. Results are expressed as equivalent weight percent, calculated from the volume analyzed using a density of 2650 $kg \cdot m^{-3}$ and normalized to 100%. The DIGS spectra were plotted as log equivalent weight (%) vs. log diameter to preserve the shapes of the distributions over a wide range of concentrations (Kranck and Milligan, 1991).

2.3b DIGS Model Parameterization

An inverse model (Curran *et al.*, 2004) was run on the DIGS of the grab and core samples to determine the parameters of floc limit, d-hat, and floc fraction. The floc limit is the diameter for which flux to the seabed of flocs equals the single-grain flux. Particles with diameters smaller than the floc limit are deposited predominantly within flocs, and particles with diameters

larger than the floc limit are deposit primarily as single grains. The parameter d-hat is the largest grain size that was transported during formation of the bottom sediment. Floc fraction is simply the volume percentage of the bottom sediment that was deposited in flocs. The values of d50, or median diameter and d75, the minimum diameter of the upper quartile of sediment, of the DIGS were determined using a MATLAB script.

2.4 Radioisotope dating

The use of radio isotopes to determine sedimentation rates in marine environments has been practiced for many years (Nittrouer *et al.*,1979; McHenry *et al.*, 1973). Long term sediment accumulation was determined using lead-210 (^{210}Pb) and cesium-137 (^{137}Cs) which have half lives of 22.3 and 30.7 years respectfully. Analysis was performed in a similar procedure to that of Palinkas and Nittrouer (2007). Lead-210 is part of the uranium decay series where the decay of Radium-226 produces ^{210}Pb in the substrate, and decay of Radon-222 in the atmosphere also produces ^{210}Pb that reaches the marine environment through runoff and precipitation. By measuring the activity of ^{210}Pb down-core the rate of sediment accumulation can be determined as ^{210}Pb activity decreases with depth in the sediment towards levels supported by ^{226}Ra decay. The short time of decay allows for accurate dating on the order of 100 years. Cesium-137 is an anthropogenic radio isotope which was initially introduced to the environment in 1954 with the initial nuclear weapons testing. Within sediment cores the maximum sediment depth with ^{137}Cs activity corresponds with 1954. It has been identified that 1963 is the year with maximum atmospheric fallout of ^{137}Cs and is seen as a distinct peak. There is also a noticeable peak which corresponds with the Chernobyl incident of 1986. These signatures seen in ^{137}Cs profiles are used to ensure the accuracy of measured ^{210}Pb values. The combined data is then used to determine rates of sediment accumulation according to activity measures.

2.5 Hydrodynamic Circulation Model

To examine the role of tidal currents in redistributing the bottom sediments in Bedeque Bay a simple two dimensional numerical circulation model was used to calculate the distribution

of the bottom shear stress developed by the tides alone. Other factors which play a role in the redistribution of the sediment are discharge into Bedeque Bay from the Wilmot and Dunk Rivers and wind-generated waves. The dominant factor will vary according to location; tides dominate in narrow channels away from river mouths and wind waves dominate in shallow locations where sufficient wind fetch is available.

To model the tidal flow a commercially available hydrodynamic simulation package called AquaDyn <www.technum.com > was used (Fig. 2). AquaDyn simulates flows in open channels by solving the 2 dimensional shallow water equations using the finite element method. The package features a sophisticated Graphical User Interface (GUI) and is reasonably easy to set up and run. The coastline and bathymetry for the model domain was developed from Canadian Hydrographic Service (CHS) chart 4459 (Fig. 3). The model was driven on its seaward open boundary by the predicted tides at Summerside. No river discharge was specified at the upstream boundaries.

To calculate the distribution of bottom shear stress due to the model-generated tidal currents, the modulus of the current speed as calculated by the model was averaged over 4 days after allowing 1 day for model spin up. The bottom stress was then estimated by equation 1:

$$\tau = \rho C_d \left| U \right|^2$$

where τ is the bottom stress, ρ is the water density, C_d is the bottom drag coefficient and $\left| U \right|^2$ is the square of the modulus of the current speed calculated by the model. The drag coefficient was taken to be $2.5e^{-3}$.

To determine areas dominated by stresses imparted by forces other than tides, primarily wind and waves, the critical erosion shear stress was calculated from the grain size distribution for each station using the model of Wiberg and Smith (1987) for individual eroding grain diameters. The critical shear stress of the sediment is derived from the balance of forces on individual particles at the surface of a bed. The value for a given grain size and density, depends on the near-bed drag force, lift force to drag-force ratio, and particle angle of repose.

2.6 Precipitation history

The composition of constituents and concentration of sediments within coastal waters is

partially dependent on the frequency and intensity of rainfall. Runoff due to increased precipitation could increase sediment input from terrigenous sources as well as increase the suspension of fine particles in the watersheds. The annual histories of rainfall were retrieved from Environment Canada (Water Survey of Canada) to uncover any correlations between sedimentation and precipitation during the study periods. Hydrometric flow data from the Dunk River was also observed for irregularly high river discharge.

3.0 Results

3.1a Grain Size Analysis (Grab samples)

The grain size of the surficial grabs (i.e. top 0.5cm) in Bedeque Bay was generally composed of fine sands in areas in the outer bay and composed of mud in areas adjacent to the river mouths. All other grab samples were composed of a mixture of sand and mud. The median diameter or d50 of the grab samples ranged from 7.11 µm to 257 µm while d75 ranged from 15.9 µm to 305 µm (Table 2). The d50 values calculated from the DIGS of the grab samples were then used to determine a bottom critical erosion shear stress that would be required to produce each size distribution for a specific sample location. The d50 value was converted to shear stress in Pascals (Pa) using the model of Wiberg and Smith (1987) (Fig. 4). Shear stress values ranged from 0.03 Pa to 0.35 Pa. Floc limit calculated from the grab samples ranged from 7 µm to 32 µm and floc fraction ranged from 1% to 69%. The higher values for floc limit and floc fraction correspond to the fine grained muddy sediments while lower values are indicative of bottom sediments composed mostly of sand.

The source of bottom stress in each of the sample locations was also of interest. When the *in situ* shear stress derived from the model of Wiberg and Smith (1987) was compared to the shear stress derived from the AquaDyn tidal model, the process of sediment redistribution was determined. If the *in situ* shear stress was greater than ten times the estimated tidal stress, it was assumed that other forces such as waves were responsible for the distribution of sediments (Fig. 5).

3.1b Grain Size Analysis (Core samples)

The core samples analyzed in Bedeque Bay showed layers of fine and coarse sediment with depth down core. The d50 and d75 values in core 312036 (Table 3) ranged from 11.1µm to 135µm and from 25.4 µm to 170 µm respectively. Values of d50 and d75 down core 312037 (Table 4) ranged from 5.51 µm to 129 µm and from 12.8 µm to 188 µm. The sediment layers in core 312036 (Fig. 6) have distinct coarse layers from 0-6 cm depth in the core, with alternating coarse and finer sediment with further depth in the core. Fine sediment layers are clear at 7-8 cm, 10-12 cm, 15-19 cm, 22-24 cm, 28-30 cm, and 32-34 cm depth. Core 312037 (Fig. 7) is generally finer throughout the core, with coarse lenses of sediment dispersed throughout. Coarse sediment can be seen at 1-2 cm, 6-10 cm, and 18-19 cm depth.

The floc limit of core 312036 was generally <6 µm however the 1-2 cm and 6-7 cm layers had a floc limit of 11 µm. Within core 312037 layers were generally greater than 11 µm, with fine sediment layers between 0-2 cm, 24-26 cm, 36-38 cm, 44-56 cm, and 60-62 cm.

The parameter d-hat indicates the largest sediment size class that is in flocs. A bottom sediment sample that was deposited with little or no flocculation would have a smaller d-hat value and would be composed almost entirely of larger grain sizes (i.e. coarse silts and sand). Within core 312036 (Fig. 6) the value of d-hat is dominantly >7 µm, however layers 1-2 cm, 3-4 cm, and 6-7 cm depth had values of 16µm, 10µm, and 17 µm respectively.

Floc fraction is the fractional percent of material deposited in bottom sediments as flocs. This value was variable down core within each of the cores (Table 3 and 4) analyzed. Core 312036 ranged from 0.01-0.26, and core 312037 ranged from 0.02-0.69 in floc fraction values.

3.2 Radioisotope Dating

Cores 312036 and 312037 were analyzed for ^{137}Cs and ^{210}Pb down core to determine rates of sedimentation. Core 312036 did not produce clear isotope signals. Results may have been altered due to bioturbation of the sediments by benthic organisms, or through the activity of fishing oysters itself.

Core 312037 had much stronger results for isotope dating as seen in Figure 8. The ^{210}Pb regression curve is consistent with a sedimentation rate of 0.8 $cm \cdot y^{-1}$. The regression line however seems to be skewed when the ^{137}Cs data is used as a reference. The earliest recorded

date of anthropogenic input of ^{137}Cs in the geological record is the late 1950s, with maximum concentrations in 1964, followed by a decrease in concentration. The dated core however shows ^{137}Cs to first appear in the early 1940s. It appears that a 'slump' may have occurred at this location as the ^{210}Pb data points between 1965 and 1990 are linear indicating some process of mixing. If these points are omitted the ^{137}Cs data would be correctly matched with time, and a new sedimentation rate of 0.9 $cm \cdot y^{-1}$ is calculated.

3.3 Precipitation history

Throughout the previous study period of 2004 to 2006 total precipitation amounts varied between years as well as between months (Fig. 9). There were no significantly anomalous data points observed over this time period (National Climate Data and Information Archive).

Hydrometric flow data has been recorded for the Dunk River at Wall Road since 1961. Data from 1975 to 1985 was examined for parallels between the slumped ^{210}Pb data and anomalies in river discharge (Table 5). Mean river discharge for each year was approximately 2-3 $m^3 \cdot s^{-1}$ each day throughout the 11 year interval. Discharge was generally greatest in the winter and early spring months, with yearly maximums in this period. The most pronounced value of river discharge throughout the period was observed for January 27, 1978 with a high of 53.2 $m^3 \cdot s^{-1}$.

4.0 Discussion

Comparing modeled shear stress based on the median grain size of grab samples from Bedeque Bay to the results from the tidally driven Aquadyne model indicates that sediment texture patterns in Bedeque Bay are predominantly controlled by wave-generated redistribution of previously deposited material. Figure 5 shows the locations for which the stress for the bottom sediment was calculated to be more than ten times the bottom shear stress calculated from the tidal model. The fact that the stress calculated from the observed grain size distributions using the Wiberg and Smith (1987) model is much higher than that estimated from the modelled tidal currents alone indicates that the bottom stress in these locations is probably dominated by other factors, such as wind-generated waves. These locations tend to be in shallow areas where sufficient fetch is available to generate wind driven waves of adequate height to dominate the bottom stress. A closer look at Figure 5 shows a general pattern of coarser grained sediments in

the middle of channels towards the mouth of the river, and finer sediments further up the river.

Sediment cores showed alternating layers of coarse sandy sediments and fine muddy sediments. Lenses of coarse and fine sediments down-core generally indicate alternating periods of high stress (i.e. storm events) and calm times such as during the summer when winds are low, or over-winter when ice covers the Bay and allows for the settling of fine grained material. A corresponding variation in the floc limit was also seen down-core with larger floc limit values associated with fine grained lenses.

The floc fraction, or the percentage of material deposited in flocs within a sedimentary environment, can be an important factor in the health of benthic fauna, especially filter feeders. Oysters are suspension feeders and thereby ingest any particles that come in the proximity of their gills, most commonly in the size range of 2-20 µm which is within the size range that makes up most aggregates. A study by Kach and Ward (2008) revealed that bivalves including the Atlantic oyster (*Crassostrea virginica*) that ingested beads of 0.5 µm and 1.0 µm diameter increased their feeding rate when these particles were incorporated into aggregates or flocs. Increases in aggregation can be an indication of increased concentration of sediments as well as organics; organic material being the cohesive property allowing the particles to aggregate. An increased feeding rate in the presence of flocs can also be correlated with an increased ingestion of bacterial constituents (Kach & Ward, 2008), as well as trace metals and pesticide contaminants (Milligan & Loring, 1997) if they are available. Increases in sedimentation could therefore lead to greater uptake of organic matter and contaminants by oysters.

If the concentration of sediment in suspension increases there can also be an increase in floc limit, the parameter describing the degree of flocculation in the overlying water column. More particles in suspension will mean more particle-to-particle collisions and an increased likelihood of creating flocs. The surficial grain size analysis throughout the Bay shows varying values of floc limit from 7 µm to 32 µm with larger values associated with areas of mud. Flocs are responsible for the majority of mud settling to the seabed, and are deposited during times of low stress. Deposited mud settles on the top layer of sediment precisely where bivalves are found. This layer of increased sediment concentration can occur in a fluff layer, which can be easily resuspended during storm events (Milligan and Law, 2013). The samples collected by UPEI in sediment traps and analyzed for grain size shows this relationship (Fig. 10). Figure 10

shows the grain size distributions of suspended sediments through different times of year at the same site, as well as a bottom sediment sample taken at that specific site for comparison. During the winter months and late fall sediments are deposited primarily as mud. This is consistent with times of the year when ice covers the bay and suppresses wave energies, allowing fine sediments to fall out of suspension. In the spring when wave energies are increased the deposited mud is resuspended rapidly and is transported. A sediment sample with similar size distribution to that of the seabed then exists. Conceivably, prolonging the period of time before sediment is redistributed from oyster beds in the spring, could have a detrimental impact on health and lead to increased mortalities. Increased sediment deposition during winter could also impact oyster health but unfortunately there is no long term record of sediment input during this time.

Radio isotope dating was performed on cores to determine modern sedimentation rates within the past 100 years. Results from core 312036 were excluded from this report as constant isotope concentrations down-core indicated that the sediment layers were disturbed. Mixed sediment layers down-core are usually a result of bioturbation or in the case of Bedeque Bay, sediments may have been mixed by fishing for oysters. Oyster fishers use two long rakes attached like a pair of scissors to scrape together a pile of oysters on the substrate before bringing them on board their vessel.

Core 312037 was not disturbed and revealed a sedimentation rate of 0.8 $cm \cdot yr^{-1}$ (Fig. 8). The anthropogenic ^{137}Cs was found at depths in the core that can not be easily explained by a sedimentation rate of 0.8 $cm \cdot yr^{-1}$. The ^{210}Pb curve has a section of constant concentration which may explain the inconsistency of ^{137}Cs data. These constant values may be the result of a slump or rapid sediment accumulation. When the values of constant ^{210}Pb concentration are omitted the ^{137}Cs calibration was shifted to the left and fit with the appropriate dates of ^{137}Cs introduction to the environment. With this new curve the accumulation of sediment in this location appears to be 0.9 $cm \cdot yr^{-1}$, which is a common sedimentation rate in most bays and estuaries without a large sediment supply (J.N. Smith, Pers. Comm.).

Hydrometric data from the Dunk River at Wall Road were viewed for unusually large river discharge between 1975 and 1985, around the time where a slump may have affected the sediment record (Table 5). The most noteworthy value was the maximum discharge of 53.2 $m^3 \cdot s^{-1}$ on January 27, 1978, with the average discharge throughout 1978 being only 2.85 $m^3 \cdot s^{-1}$

(Water Survey of Canada). This event of increased river flow may be the reason for skewed sediment accumulation results. It was also interesting to observe the precipitation data between 2004 and 2006, the time of the first oyster study in Bedeque Bay. Irregularities in rainfall amounts may have been a contributing factor to the increased over winter mortalities seen in Bedeque oysters. Increased precipitation would increase the amount of runoff from terrigenous sources. As P.E.I. is a heavily farmed island any increase in runoff could bring increased pesticides into the environment. The amount of pesticides used by P.E.I. is also the highest in Canada. On average 8kg of pesticides are used per person each year in P.E.I., where only 1.36 kg is the average across Canada (Toughill, 2003). The data from 2004 to 2006 shows variable precipitation between years as well as between months, with no clear anomalous data (Fig. 9). Pesticides may be a contributing factor to increased mortalities; however chemical analysis performed to date on oyster mortalities have all been negative.

5.0 Conclusion

Throughout this investigation many different methods have been used to determine the sedimentary environment in Bedeque Bay, P.E.I.. Through the surficial grain size analysis the areas of the Bay most affected by tides and wind have been identified. In areas where waves affect the distribution of sediments, depression of that wave energy can lead to an increase in the deposition of mud. Cores collected during May 2008 showed a sedimentation rate of 0.8 $cm \cdot yr^{-1}$, which is reasonable for most bays and estuaries with a limited sediment supply. The sedimentation rate represents the net deposition, and since most of the Bay undergoes wave-generated resuspension of the sediment, an apparent increase in mud deposited over winter is not captured in the cores. However, comparison between summer and winter bottom sediment distributions suggests that fine-grained material deposited under the ice is removed in the spring. Extending the period of time before the fine sediment is redistributed could impact oyster health. Increased sediment load from runoff could also be a factor but to determine if input during winter months has increased a longer record of winter sedimentation is required.

Acknowledgements

This research was supported by Jeff Davidson at the University of Prince Edward Island as well as the Department of Fisheries and Oceans Canada. Additional thanks to John Smith and colleagues for their work on the isotope analysis.

References

Curran, K.J., Hill., P.S., Milligan, T.G., 2002. Fine-grained suspended sediment dynamics in the Eel River flood plume. Continental Shelf Research. 22, 2537-2550.

Curran, K.J., Hill, P.S., Schell, T.M., Milligan, T.G. and Piper, D.J.W, 2004. Inferring the mass fraction of floc-deposited mud: application to fine-grained turbidites. Sedimentology. 51, 927-944.

Davidson, J., Arsenault, G., Morrison, A., Smith, M., Burleigh, P., MacNair, N., Landry, T., Stephenson, M. and Hansen, F., 2007. Report for: Prince Edward Island Shellfish Association.

Fox, J.M., Hill, P.S., Milligan, T.G., Ogston, A.S. and Boldrin, A., 2004. Floc fraction in the waters of the Po River prodelta. Continental Self Research. 24, 1699-1715.

Kach, D.J. and Ward, J.E., 2008. The role of marine aggregates in the ingestion of picoplankton-size particles by suspension-feeding molluscs. Marine Biology. 153, 797-805.

Kranck, K., 1980. Experiments on the significance of flocculation in the settling of fine-grained sediment in still water. Canadian Journal of Earth Sciences. 17, 1517-1526.

Kranck, K. and Milligan T.G., 1985. Origin of grain size spectra of suspension deposited sediment. Geo-Marine Letters. 5, 61-66.

Kranck, K. and Milligan, T.G., 1991. Grain size in oceanography. In: Syvitski, J.P.M. (Ed.), Principles, Methods, and Application of Particle Size Analysis. Cambridge University Press, New York, pp. 332-345.

Kranck, K., Smith, P.C. and Milligan, T.G., 1996. Grain size characteristics of fine grained unflocculated sediments II: “Multi-round” distributions. Sedimentology. 43, 597-606.

McCave, I.N., 1984. Size spectra and aggregation of suspended particles in the deep ocean. Deep Sea Research. 31, 329-352.

McCave, I.N., Manighetti, B. and Robinson, S.G., 1995. Sortable silt and fine sediment size/composition slicing: parameters for palaeocurrent speed and palaeoceanography. Paleoceanography. 10(3), 593-610.

McHenery, J.R., Ritchie, J.C. and Gill, A.C., 1973. Nitrogen, phosphorous and other chemicals in sedimens from reservoirs in North Mississippi. In: Proceedings of 8th Mississippi Water Resources Conference, Environmental Sciences and Pollution Management, pp. 1-12.

Milligan, T.G. and Kranck, K., 1991. Electroresistance particle size analyzers. In: Syvitski, J.P.M. (Ed.), Principles, Methods, and Application of Particle Size Analysis. Cambridge University Press, New York, pp. 109-118.

Milligan, T.G. and Law B.A. Contaminants at the sediment-water interface: Implications for environmental impact assessment and effects monitoring. Environmental Science & Technology. 47 (11), 5828-5834.

Milligan, T.G. and Loring, D.H., 1997. The effect of flocculation on the size distributions of bottom sediment in coastal inlets: Implications for contaminant transport. Water, Air and Soil Pollution. 99, 33-42.

National Climate Data and Information Archive. 1 November 2008. Environment Canada. www.climate.weatheroffice.ec.gc.ca (accessed 5 January 2009).

Nittrouer, C.A., Sternberg, R.W., Carpenter, R., and Bennett, J.T., 1979. The use of Pb-210 geochronology as a sedimentological tool: Application to the Washington continental shelf. Marine Geology. 31(3-4), 297-316.

Palinkas, C.M. and Nittrouer, C.A., 2007. Modern sediment accumulation on the Po shelf, Adriatic Sea. Continental Shelf Research. 27, 489-505.

Sternberg, R.W., Berhane, I. and Ogston, A.S., 1999. Measurement of size and settling velocity of suspended aggregates on the Northern California continental shelf. Marine Geology. 154, 43-54.

Toughill, K. Pesticides fail air in P.E.I. – Study links contamination to potato spraying. Toronto Star. September 6, 2003.

Water Survey of Canada – Archived Hydrometric Data. 02 June 2006. Environment Canada. www.rhc-wsc.ec.gc.ca (accessed 15 March 2009).

Wiberg, P. L. and Smith, J.D., 1987. Calculations of the critical shear stress for motion of uniform and heterogeneous sediments. Water Resources Research. 23, 1471-1480.

2000 - 2004 Integrated Fisheries Management Plan - Oyster Prince Edward Island (Inclusive). 24 October 2006. Fisheries and Oceans Canada. www.glf.dfo-mpo.gc.ca (accessed 14 April 2009).

Figures

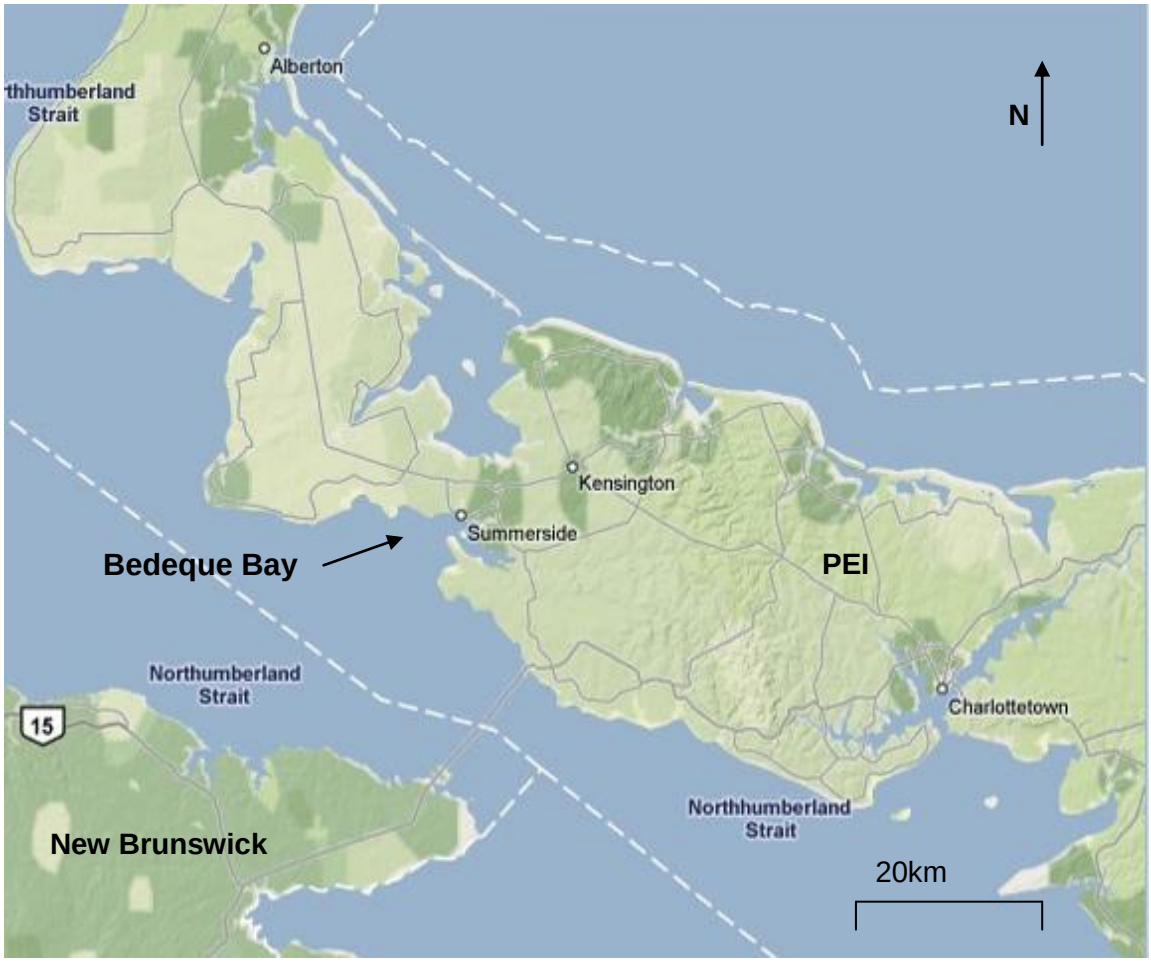

Figure 1. Location map of Bedeque Bay on the south west shore of Prince Edward Island.

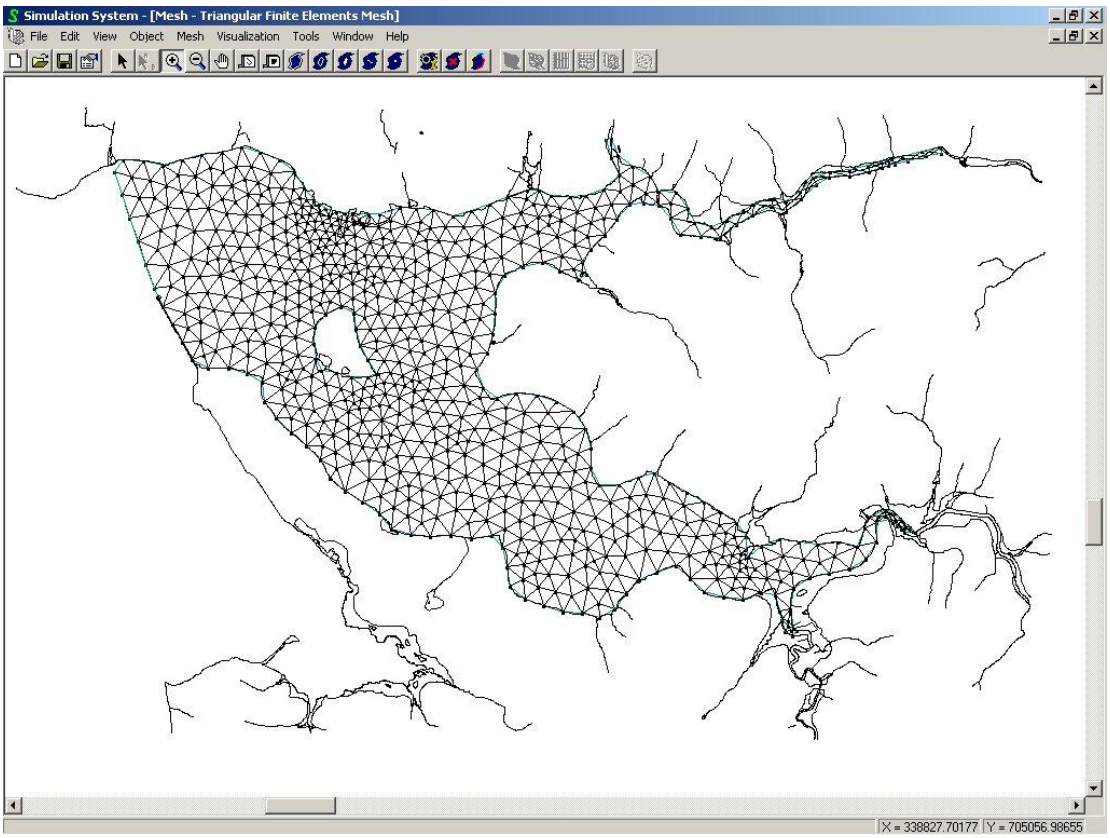

Figure 2. AquaDyn GUI showing finite element model grid of Summerside Harbour.

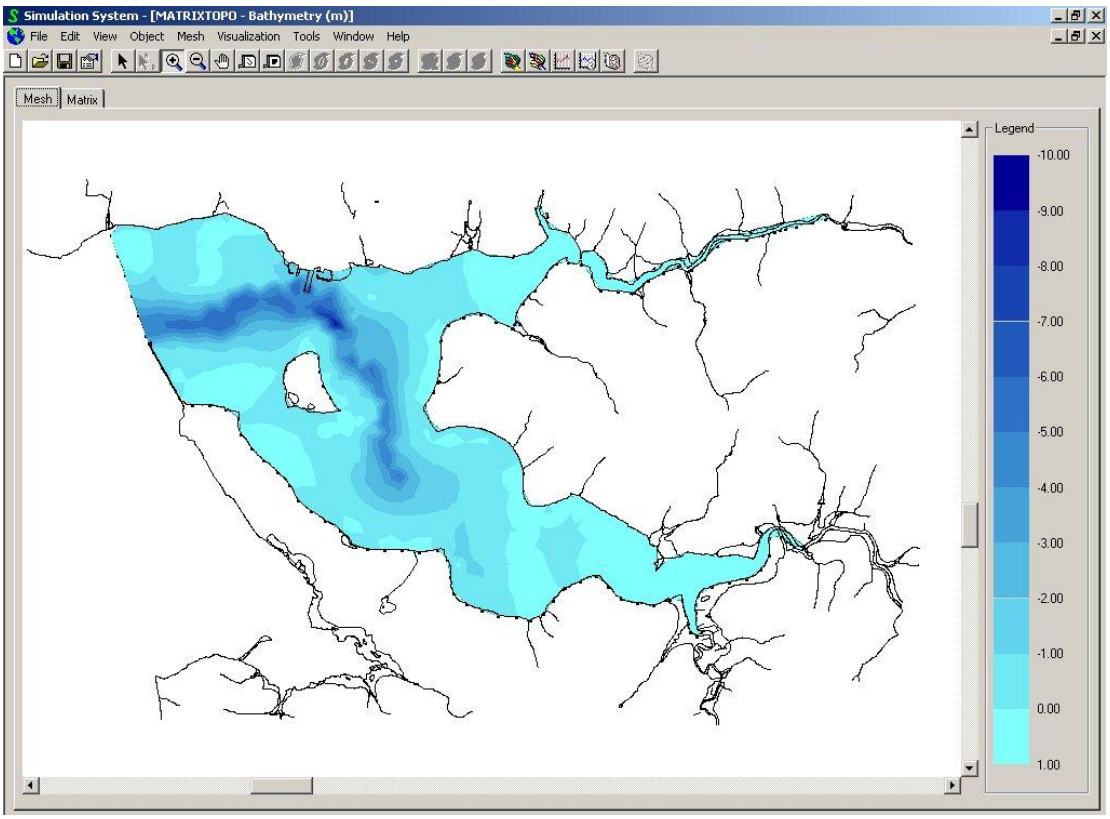

Figure 3. AquaDyn GUI showing model bathymetry developed from CHS Chart 4459.

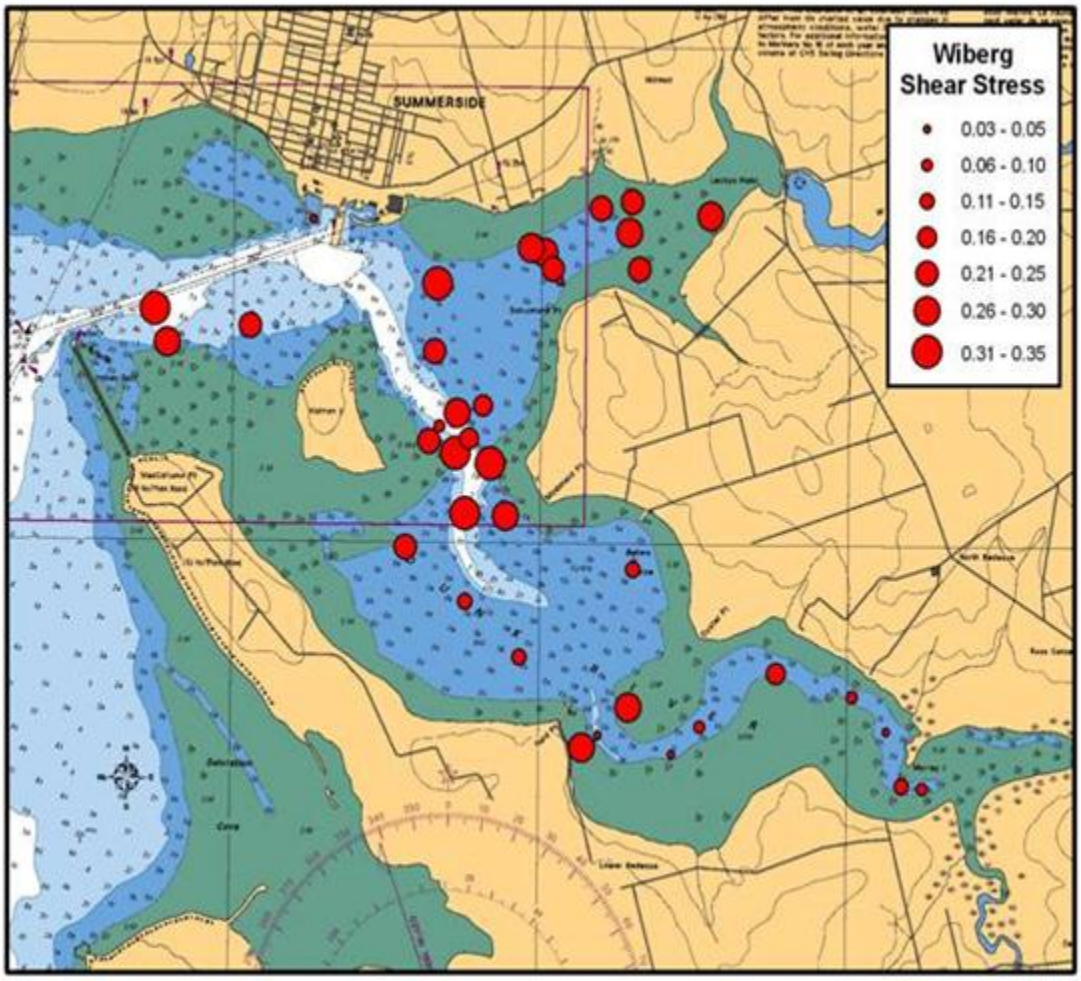

Figure 4. Bottom shear stress (Pa) determined from surficial grain size of grab samples in Bedeque Bay P.E.I.. Wiberg shear stress is represented as filled points at sample locations.

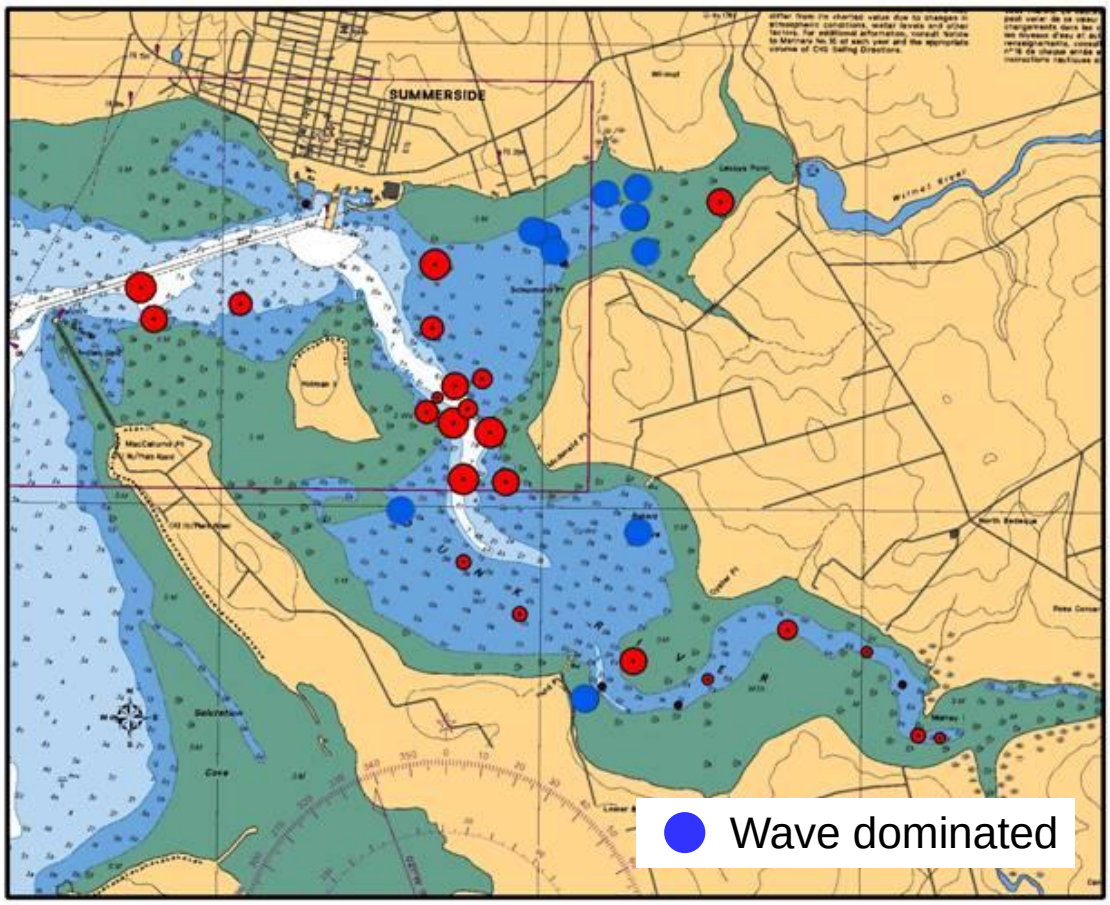

Figure 5. To determine areas dominated by wave action the *in situ* bottom stress was compared with theoretical tidal stress. Where sediments are too coarse to be explained by tidal stress, points are identified in blue. These areas are influenced by wave energies.

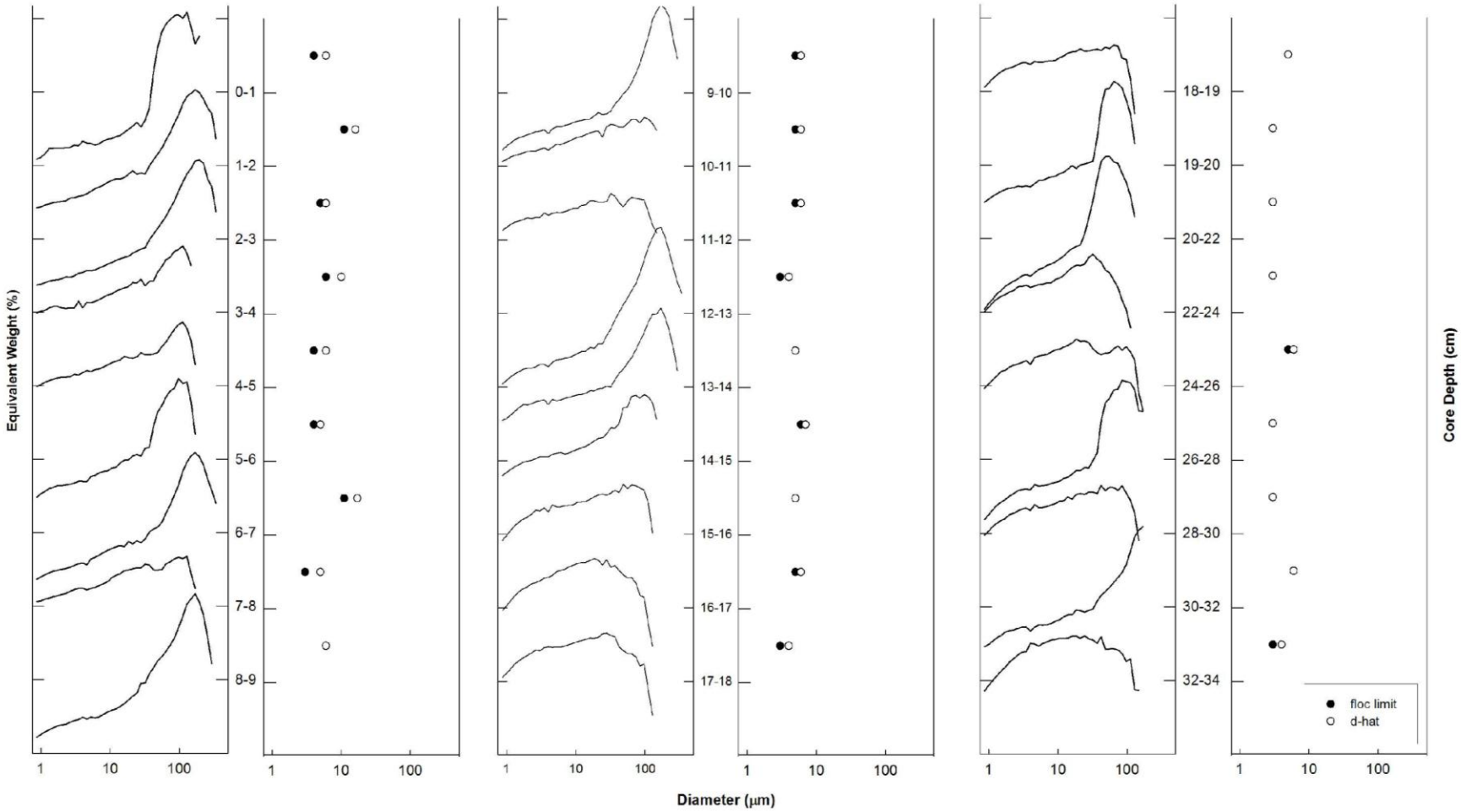

Figure 6. Core 312036 retrieved at the mouth of the Dunk River, P.E.I.. Down core plots showing the disaggregated inorganic grain size and parameters d-hat and floc limit. Disaggregated inorganic grain size is shown as equivelant weight percent versus diameter in microns.

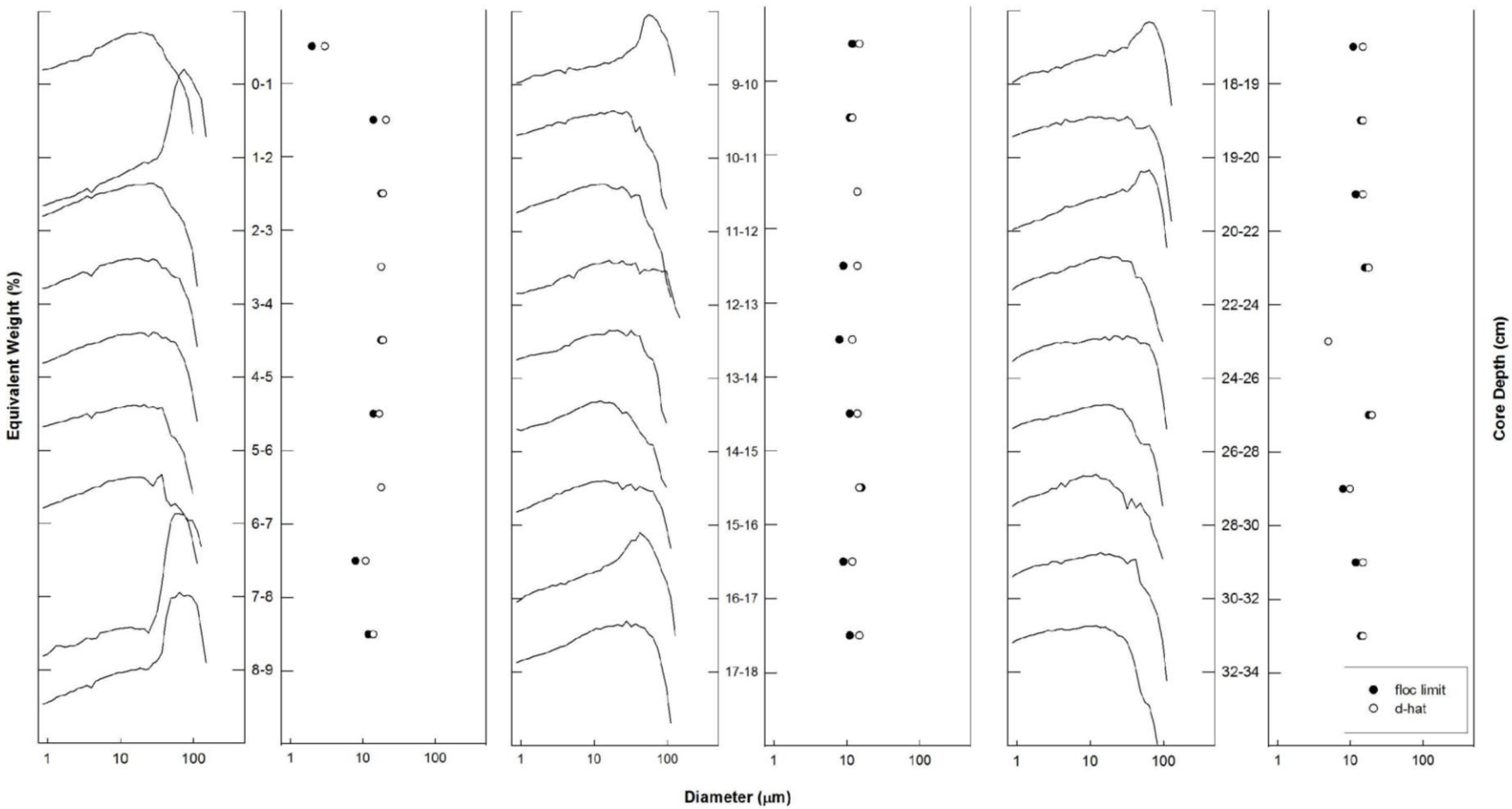

Figure 7. Core 312037 retrieved at the mouth of the Dunk River, P.E.I.. Down core plots showing the disaggregated inorganic grain size and parameters d-hat and floc limit. Disaggregated inorganic grain size is shown as equivelant weight percent versus diameter in microns.

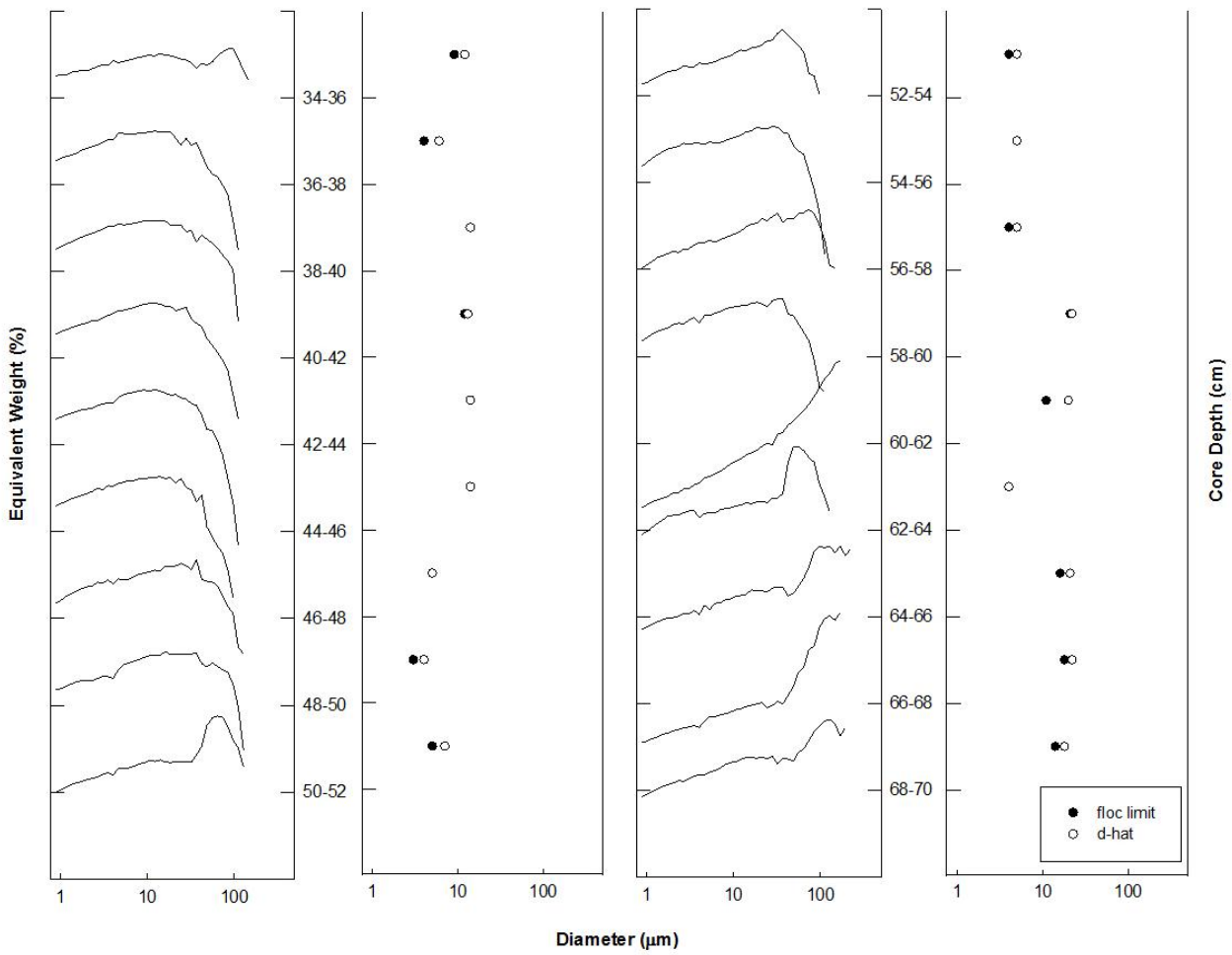

Figure 7. Continued.

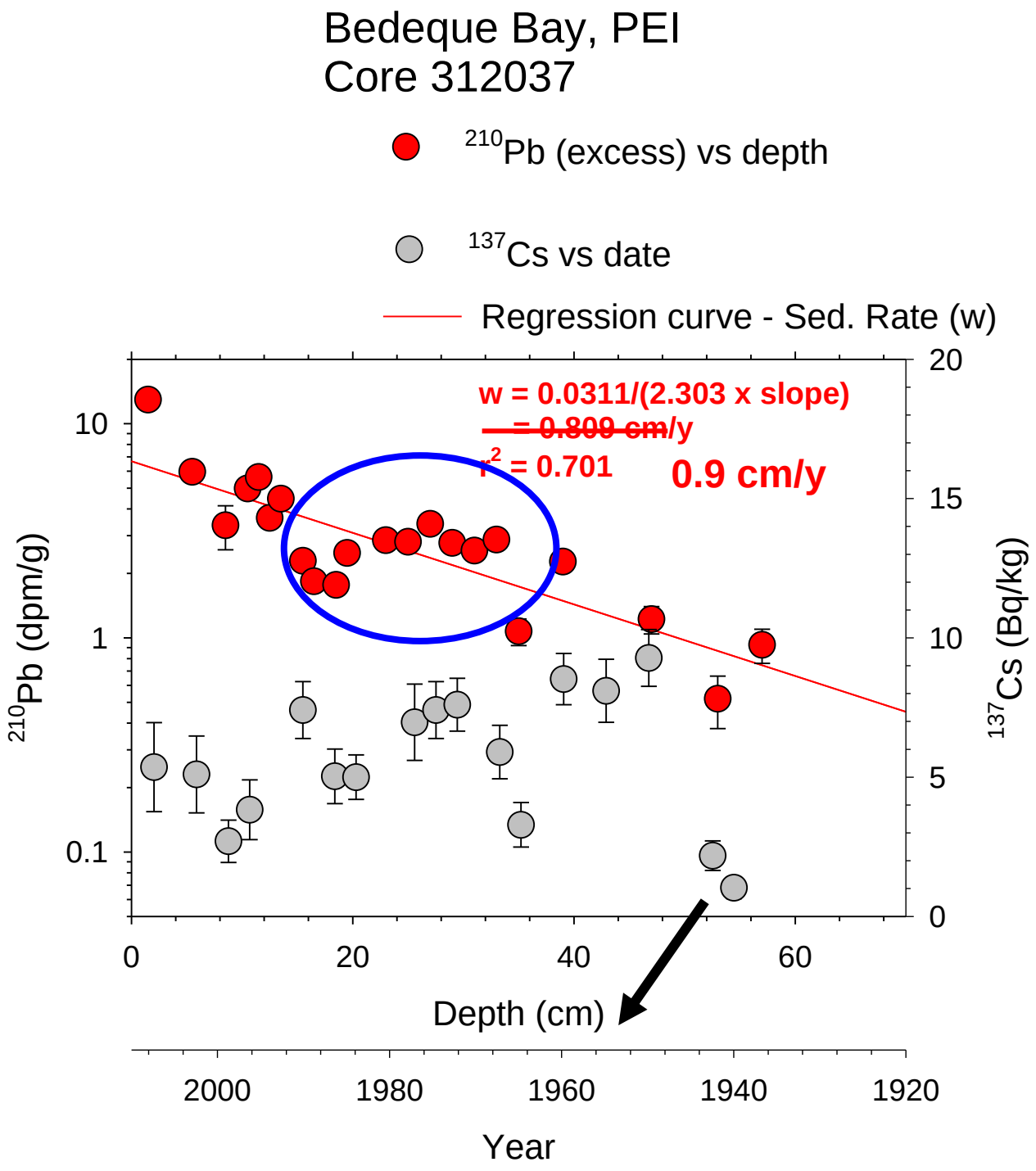

Figure 8. Sedimentation rates determined with ^{210}Pb and ^{137}Cs isotopes. A region of constant ^{210}Pb values (circled) suggests slumping or rapid sedimentation. When the ^{210}Pb curve is corrected (arrow) a sedimentation rate of $0.9 cm \cdot y^{-1}$ is calculated.

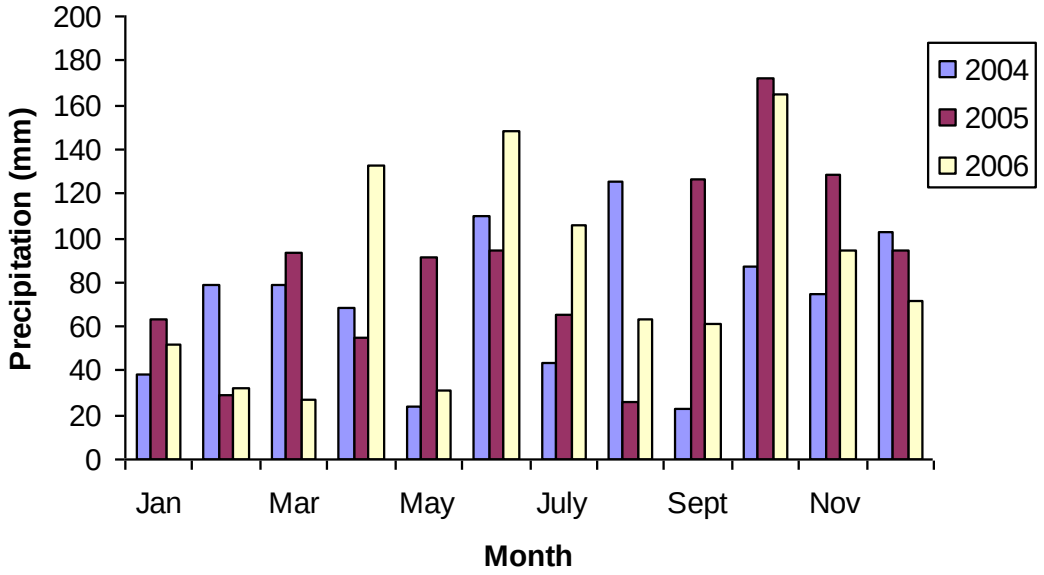

Figure 9. Total precipitation by month from 2004 through 2006 for Summerside P.E.I..

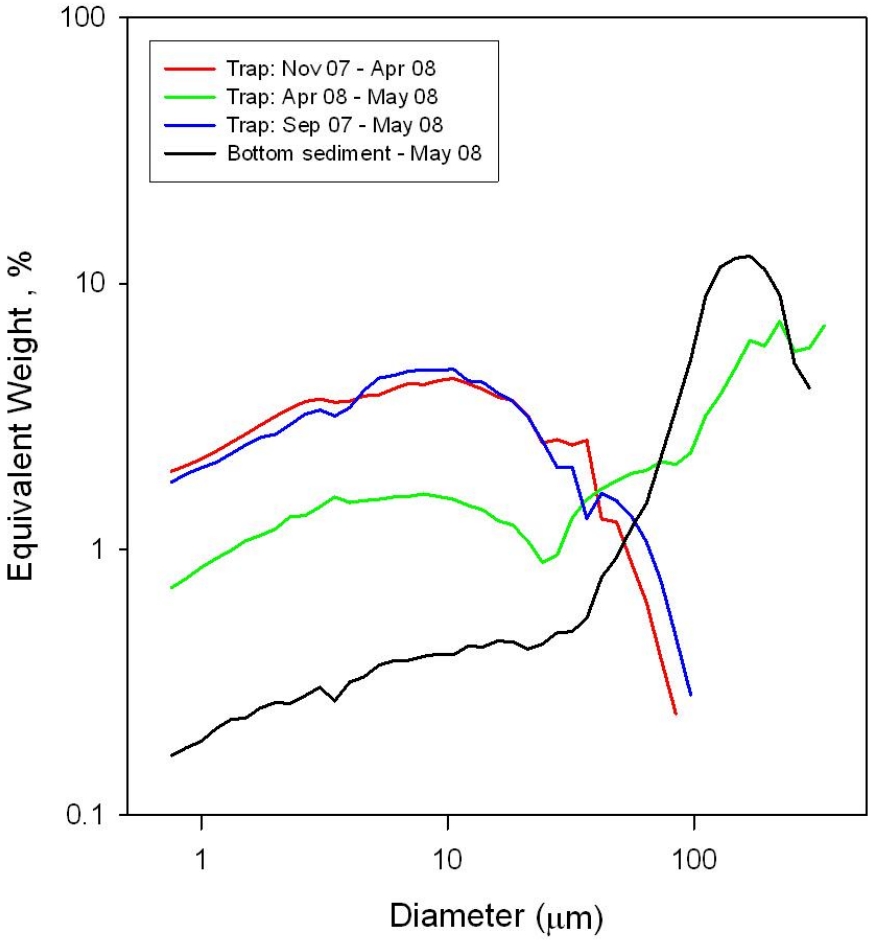

Figure 10. Grain size distributions from sediment traps collected September 2007 through May 2008, and bottom sediment from the same site in Bedeque Bay P.E.I..

Tables

Table 1. Sample location data for all sediment samples collected in NAD83.

ID#	Lat (N)	Long (W)	Sample Type
312001	46.3843	63.7647	Grab
312002	46.3851	63.7655	Grab
312003	46.3862	63.7664	Grab
312010	46.38832	63.79145	Grab
312011	46.38407	63.77797	Grab
312012	46.38653	63.76787	Grab
312013	46.38761	63.75725	Grab
312014	46.38514	63.75612	Grab
312015	46.38967	63.75699	Grab
312016	46.38921	63.76034	Grab
312017	46.3759	63.77297	Grab
312018	46.37347	63.77874	Grab
312019	46.37451	63.77763	Grab
312020	46.37538	63.77577	Grab
312021	46.37205	63.77211	Grab
312022	46.37273	63.77592	Grab
312023	46.37371	63.77446	Grab
312024	46.36638	63.78122	Grab
312025	46.3685	63.77045	Grab
312026	46.36867	63.7748	Grab
312027	46.35303	63.76198	Grab
312028	46.35572	63.757	Grab
312029	46.35388	63.76027	Grab
312030	46.35259	63.75232	Grab
312031	46.35809	63.74107	Grab
312032	46.35654	63.73282	Grab
312033	46.35058	63.7274	Grab
312034	46.35448	63.74928	Grab
312038	46.35423	63.72912	Grab
312041	46.38875	63.74845	Grab
312036	46.35126	63.72754	Core
312037	46.35457	63.74928	Core
	46.3862	63.7664	Trap

Table 2. Parameters of bottom sediment grab samples in Bedeque Bay P.E.I..

ID	Floc Limit (µm)	d-hat (µm)	Floc Fraction	d50	d75	<16µm	<4µm
312001	32	27	0.69	10.87	31.06	57.89	25.53
312002	18	18	0.06	115.36	144.73	6.78	3.16
312003	18	20	0.07	144.14	190.97	6.69	2.85
312010	16	15	0.59	9.64	22.26	63.22	25.04
312011	18	20	0.05	190.10	232.39	5.31	2.32
312012	18	20	0.02	170.30	216.34	2.27	1.10
312013	11	13	0.04	139.54	188.30	5.45	2.22
312014	16	15	0.09	114.12	160.68	9.64	4.37
312015	12	13	0.04	122.11	149.29	4.84	2.31
312016	9	10	0.1	106.89	142.52	13.92	6.25
312017	14	14	0.3	40.12	66.24	34.92	14.98
312018	18	18	0.17	73.56	109.88	17.50	7.32
312019	11	11	0.43	11.30	26.62	57.90	23.31
312020	7	9	0.02	159.61	202.67	3.60	1.77
312021	8	10	0.04	132.67	193.69	6.16	2.57
312022	8	9	0.02	251.29	295.67	3.08	1.51
312023	16	17	0.46	15.23	46.51	49.51	20.07
312024	9	10	0.12	81.85	147.59	17.58	6.74
312025	5	6	0.02	139.03	193.79	4.41	1.96
312026	16	16	0.02	257.90	305.33	2.02	1.05
312027	9	13	0.02	172.83	224.87	3.08	1.51
312028	14	15	0.08	148.33	197.22	9.30	3.82
312029	9	11	0.44	9.81	22.41	62.70	24.51
312030	14	17	0.57	9.56	22.09	63.21	27.24
312031	14	16	0.36	23.59	58.60	40.80	16.72
312032	14	19	0.53	11.86	24.75	57.39	22.90
312033	16	20	0.47	15.95	42.47	48.17	18.77
312034	18	21	0.56	13.05	30.02	53.89	21.24
312038	12	14	0.6	7.50	16.57	71.78	31.41
312040	11	15	0.43	12.53	27.95	55.27	22.57
312041	11	13	0.04	113.64	177.02	6.00	2.70
312123	12	12	0.62	6.65	15.16	74.58	34.10
312124	21	17	0.28	98.62	209.62	28.67	13.35
312125	8	10	0.5	7.12	15.27	74.35	30.63
312126	24	20	0.2	130.02	192.96	18.97	8.24
312127	16	15	0.61	8.90	20.58	65.78	26.48
312128	21	22	0.35	39.06	107.52	32.45	13.04
312129	8	10	0.04	159.37	227.54	5.82	2.11
312130	24	23	0.01	181.49	243.63	0.95	0.32
312131	32	42	0.02	168.62	215.92	1.13	0.47

Table 3. Sediment parameters of core 312036 collected in Bedeque Bay, P.E.I..

Depth	Floc Limit (µm)	d-hat (µm)	Floc Fraction	d50	d75	<16µm	<4µm
0-1	4	6	0.02	80.39	110.39	4.29	2.03
1-2	11	16	0.07	122.60	172.42	9.54	3.92
2-3	5	6	0.03	133.58	180.56	7.95	3.45
3-4	6	10	0.17	41.68	80.36	30.76	13.83
4-5	4	6	0.14	34.38	80.94	34.49	15.18
5-6	4	5	0.04	71.02	96.99	12.23	5.10
6-7	11	17	0.07	126.01	169.80	9.22	3.76
7-8	3	5	0.14	23.31	63.65	39.59	17.35
8-9	6	6	0.03	121.48	156.49	6.43	2.83
9-10	5	6	0.03	135.09	170.30	6.91	3.05
10-11	5	6	0.18	22.83	58.37	41.25	18.17
11-12	5	6	0.24	15.38	41.39	49.26	22.45
12-13	3	4	0.01	126.49	161.17	4.71	2.01
13-14	5	5	0.06	106.15	148.62	13.90	6.42
14-15	6	7	0.13	48.58	78.86	25.00	11.20
15-16	5	5	0.21	18.26	45.65	45.22	19.35
16-17	5	6	0.26	11.41	25.43	58.29	21.83
17-18	3	4	0.2	11.05	26.06	58.19	25.38
18-19	5	5	0.23	14.26	37.29	51.14	23.20
19-20	3	3	0.04	53.04	69.13	12.62	5.37
20-22	3	3	0.02	47.15	63.63	7.74	2.73
22-24	3	3	0.13	14.98	30.06	49.90	21.28
24-26	5	6	0.23	14.99	39.69	49.86	19.75
26-28	3	3	0.02	70.44	95.06	8.58	3.55
28-30	3	3	0.13	18.02	46.11	45.41.34	19.72
30-32	6	6	0.06	122.21	166.93	11.62	5.19
32-34	3	4	0.18	12.22	30.32	55.65	20.70

Table 4. Sediment parameters of core 312037 collected in Bedeque Bay, P.E.I..

Depth	Floc Limit (µm)	d-hat (µm)	Floc Fraction	D50	D75	<16µm	<4µm
0-1	2	3	0.12	9.74	19.58	64.99	23.98
1-2	14	21	0.08	63.26	80.99	8.96	3.45
2-3	18	19	0.64	9.56	21.75	63.30	26.71
3-4	18	18	0.63	9.55	22.49	63.22	26.03
4-5	18	19	0.61	9.95	24.27	61.36	25.95
5-6	14	17	0.61	8.01	18.95	68.00	30.94
6-7	18	18	0.65	9.06	20.68	65.18	26.83
7-8	8	11	0.04	58.54	77.61	6.02	2.56
8-9	12	14	0.12	54.47	75.63	14.42	5.72
9-10	12	15	0.28	34.95	55.78	33.70	16.07
10-11	11	12	0.53	7.82	18.22	68.74	30.71
11-12	14	14	0.61	7.85	17.87	70.02	29.44
12-13	9	14	0.39	12.87	32.56	54.31	21.34
13-14	8	12	0.42	9.56	21.62	63.28	26.15
14-15	11	14	0.57	7.79	16.33	72.04	29.17
15-16	16	15	0.57	9.84	25.14	61.80	25.56
16-17	9	12	0.26	23.76	40.69	37.74	15.55
17-18	11	15	0.43	12.51	27.8	55.33	21.12
18-19	11	15	0.31	24.47	51.79	39.56	17.19
19-20	14	15	0.56	8.74	23.65	63.73	29.82
20-22	12	15	0.35	20.64	45.56	42.48	17.21
22-24	16	18	0.62	9.09	20.19	65.42	27.50
24-26	5	5	0.29	9.19	24.74	62.09	29.60
26-28	18	20	0.72	7.45	16.89	71.16	32.01
28-30	8	10	0.5	7.08	15.16	74.55	31.22
30-32	12	15	0.59	7.58	18.17	69.41	32.38
32-34	14	15	0.71	5.51	12.82	79.49	39.31
34-36	9	12	0.4	11.8	40.69	55.42	25.87
36-38	4	6	0.31	7.24	16.89	71.31	31.25
38-40	14	14	0.6	7.74	19.54	68.33	31.07
40-42	12	13	0.59	7.59	17.45	70.57	30.64
42-44	14	14	0.63	7.31	16.79	71.79	30.99
44-46	14	14	0.64	6.99	15.93	73.02	32.65
46-48	5	5	0.26	10.61	25.34	59.27	26.44
48-50	3	4	0.17	11.76	28.46	56.88	22.58
50-52	5	7	0.18	32.48	59.71	37.29	16.21
52-54	4	5	0.2	14.02	31.21	51.63	22.66
54-56	5	5	0.3	9.97	23.48	61.06	28.51
56-58	4	5	0.17	19.16	46.48	43.48	18.35
58-60	21	22	0.65	10.12	24.18	60.99	26.01
60-62	11	20	0.07	129.55	188.87	8.69	3.09

62-64	4	4	0.13	36.4	55.15	33.90	16.09
64-66	16	21	0.26	63.39	114.66	27.39	11.46
66-68	18	22	0.14	100	142.38	13.46	5.55
68-70	14	18	0.3	39.21	96.85	33.93	14.11

Table 5. Hydrometric flow data from 1975 through1985 from the Dunk River at Wall Road. Values are expressed as daily discharge in m^3/s. Redrawn from Water Survey of Canada Data Products.

Date	**Mean**	**Max**	**Total**
1975	2.27	21.4	827.32
1976	2.68	36	979.496
1977	2.88	49.6	1052.971
1978	2.85	53.2	1039.035
1979	3.12	41.9	1137.946
1980	2.03	17.7	685.902
1981	3.11	45.3	1137.946
1982	3.17	16.7	1039.035
1983	2.42	17.3	1052.971
1984	3.03	33.4	979.496
1985	1.88	14.9	827.32