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A Variable Turbidity Maximum in the Kennebec Estuary, Maine

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ABSTRACT: A turbidity maximum has been observed in the Kennebec estuary during moderate and low flow conditions near the upstream limit of salinity intrusion. Hydrographic, ADCP, and transmissometer data were collected at different river flow levels and seasons during 1995–1998. The location of the tip of the salt intrusion changes dramatically and during high runoff may be flushed from the channel of the estuary along with the accumulated particles in the turbidity maximum. It is hypothesized that the estuarine turbidity maximum (ETM) was absent 18% of the time with occurrences in all seasons during 1993–1999 based on river flow volumes from the Kennebec and Androscoggin Rivers throughout the study period. When the flow is moderate and low, which occurred 73% of the time on average, a region of high turbidity can be found as far as 40 km upstream of the mouth. Suspended particulate loads are low in the ETM, on the order of tens of mg l^{-1} and may vary with the length of time that the ETM has been present.

Introduction

In partially mixed estuaries, a region of elevated particle concentrations known as the estuarine turbidity maximum (ETM) may be sustained by several factors including gravitationally-induced residual currents (Postma 1967; Festa and Hansen 1978) or asymmetry of the tide as it propagates upstream (Allen et al. 1980; Uncles et al. 1992). Tidal straining on the ebb tide confines particles to the lower water column and enhances the trapping of suspended sediment (Geyer 1993). Jay and Musiak (1994) proposed the mechanism of an internal tidal asymmetry where correlation between velocity shear and tidally varying, vertical sediment concentration can serve to transport sediment landward. Concentrations within a typical ETM may range from 10^2 to 10^4 mg l^{-1} depending on sediment availability and tidal range (Dyer 1986). ETMs are typically found in association with a mud reach on the seabed (Wellerhaus 1981). The position of the ETM can shift in response to the tidal amplitude and volume of river flow, and in some cases, may be confined to a section of the estuarine channel by bathymetry (Brenon and Le Hir 1999; Rolinski 1999).

In the Kennebec estuary on the mid-coast of Maine, a seasonally strong two-layered residual circulation and tidal asymmetry have been documented (Kistner et al. 1995) and contribute to the presence of an ETM near the upstream limit of salinity intrusion. Maximum suspended particulate matter (SPM) concentrations are on the order of 10 mg l^{-1}. Variable river flow not only determines the position of the ETM, but whether or not an ETM will be present. High river flow can shut down the mechanisms sustaining the ETM by moving the region of estuarine mixing out of the channel and onto the adjacent shelf.

The seasonal movement of the ETM is relevant to several local issues of economic importance, including the success of dredging operations and the transport of pollutants associated with the trapped particles. Discharge from the Kennebec is turned to the right toward Casco Bay by a western-flowing coastal current. High sedimentary trace metal concentrations, including lead, have been reported in the region just outside the mouth of the Kennebec and in eastern Casco Bay (Gaudette and Larsen 1992). High metal content has also appeared in the livers of commercially important fish with the presumed source being the outflow of the Kennebec.

The Kennebec estuary is one of the major inputs of freshwater to the Gulf of Maine, with an annual mean discharge of 425 m^3 s^{-1} that flows through a narrow, bedrock confined channel 400 m across at its narrowest. Discharge from the Kennebec varies by over an order of magnitude, ranging from 100 to 4,000 m^3 s^{-1}, depending on season, snowpack melt, and precipitation. The Kennebec River supplies 60% of the freshwater volume to the estuary, and the remainder comes from the Androscoggin River. These two rivers join in Merrymeeting Bay, a broad, shallow low-salinity lake 30 km from the mouth of the estuary (Fig. 1). The tidal range at the mouth of the estuary varies from 2.6 to 3.5 m during neap and spring tides, respectively.

Substrate in the channel of the Kennebec estuary is almost exclusively sand and bedrock (Fenster and FitzGerald 1996). The channel is fairly straight and uniform from Fort Popham at the mouth to the city of Bath, 20 km to the north. Two excep-

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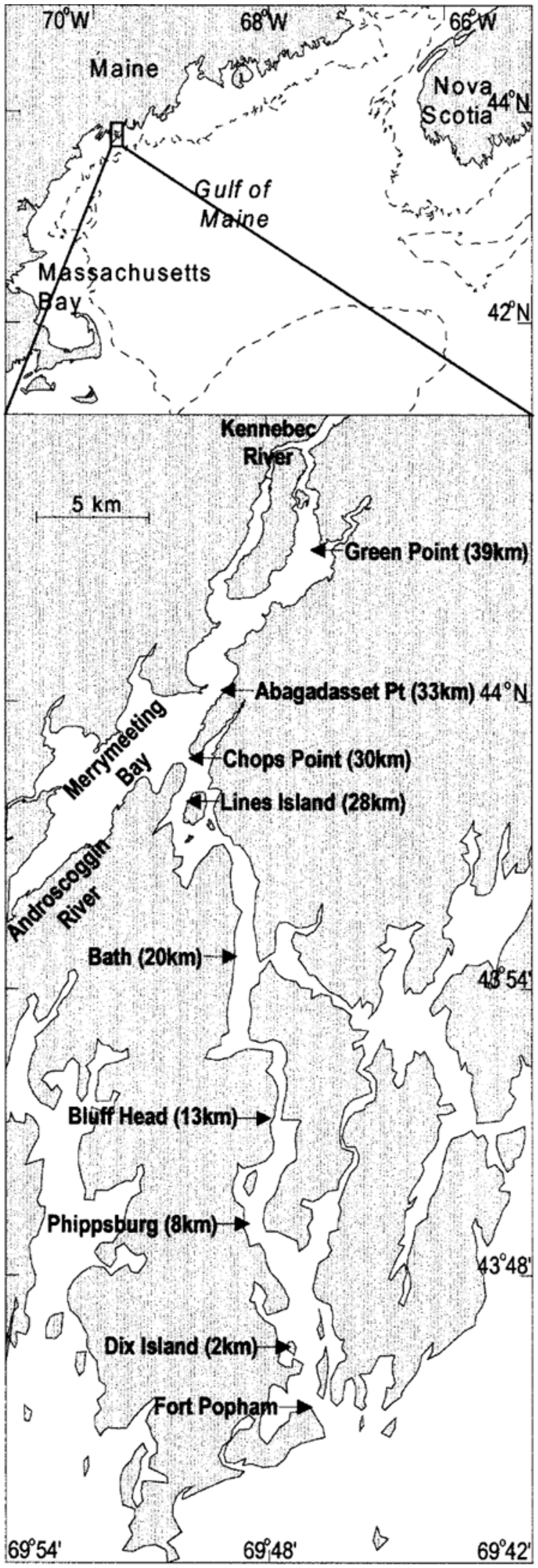

tions are a sudden change in channel width at Bluff Head 12 km from the mouth and a lateral offset at Fiddler Reach 16 km from the mouth. North of Bath, the channel splits around Lines Island and several adjacent muddy coves can be found. The estuary floods into Merrymeeting Bay through the narrow bedrock constriction at Chops Point, where boils and convergent fronts are common. Once in the Bay, the deep part of the channel turns to the north into the Kennebec River, while a smaller channel turns southwest into the Androscoggin River.

There have been few investigations of physical processes in the Kennebec estuary. Currents and hydrography were first measured by Francis et al. (1953) using a Roberts propeller meter and a hydrometer in a study of turbulent mixing processes. They described the very dynamic nature of the estuarine flow including drastic velocity and temperature changes associated with the passing of fronts based on a short shipboard survey.

Fenster and FitzGerald (1996) studied sediment transport in the Kennebec estuary during 1986–1987. Hydrographic measurements were made repeatedly over one semi-diurnal tidal cycle in October of each year using a VSI salinometer and a Marsh-McBirney current meter. From these data, they concluded that the salt encroachment was bathymetrically restricted from penetrating north of Bath. Side scan, fathometer, and grain size data were collected in all seasons to document bedform dynamics and channel geometry. Large ebb-oriented transverse bars were present during the study period throughout the estuary south of the Bath Bridge, with the exception of Fiddler Reach. The bar crests were generally located in the vicinity of abrupt changes in channel morphology. These features maintained their ebb orientation throughout the study period, despite the superimposition of smaller flood-oriented sand waves (Fenster and FitzGerald 1996).

Methods

Cruises were conducted on the R/V *Gulf Challenger* in September 1995, April 1997, June 1997, April 1998, and October 1998 to establish seasonal and yearly variability. An RDI ADCP was deployed over the side at each station. In 1995 and 1997, a 300 kHz Broad Band ADCP was used, and in 1998, a 1200 kHz Narrow Band ADCP was used. Hydrographic instruments deployed on each cruise in-

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Fig. 1. The Kennebec estuary extends south from Merrymeeting Bay, where the Androscoggin and Kennebec Rivers meet.

cluded a Sea-Bird SBE32 carousel water sampling system with twelve 10-l Niskin bottles, SBE 25 Sealogger CTD, Seatech 25 cm path-length Transmissometer, and Wetlabs fluorometer.

The 1995 cruise was conducted as part of a larger study that included sampling for nutrients, particulates, and phytoplankton. All data from the larger study are presented in Mayer et al. (1996). Nutrient analysis is discussed in Schoudel (1996) and phytoplankton assemblages are discussed in Wong and Townsend (1999).

Cruises in 1997 and 1998 were done in cooperation with Maureen Keller of Bigelow Laboratory. An assortment of 500-ml samples from the Niskin bottles were filtered and weighed for SPM determination, according to the methods of Strickland and Parsons (1972). These results were regressed against the attenuation coefficient from the transmissometer to obtain SPM values in mg l^{-1} for all stations.

Sampling cross-sections were chosen based on channel geometry. At some cross-sections, depending on the particular sampling strategy and channel width, several lateral stations were established along the cross section to determine cross channel gradients. The ADCP remained deployed for all lateral stations on a cross-section, then was pulled up so that the ship could steam to the next cross-section. All stations were occupied repeatedly throughout a semi-diurnal tidal cycle at a specified time interval which varied between 75–180 min for particular cruises and sampling strategies. When necessary, measurements were made on two consecutive days so that a larger extent of the estuary could be sampled.

For each repetition, ADCP data was averaged for a minimum of 2 min to obtain what will be considered an instantaneous measurement. These data were interpolated to sigma coordinates in Matlab using a least squares polynomial fit and then averaged to obtain a mean for the tidal cycle.

All discharge values discussed in the present study are from U.S. Geological Survey gages located some distance north of the estuary. The gage on the Kennebec River is currently located near Waterville, Maine, at 44°31′55″N, 69°38′55″W, 40 km north of Chops Point and the confluence with the Androscoggin. The drainage area for this gage is 13,414 km^2. It was relocated here in 1993. Prior to September 1993, flow data for the Kennebec River were from a gage at North Sidney located 4 miles south of the present station. Because flow volume for the two stations are not equivalent except for discharges above 700 m^3 s^{-1}, only values after September 1993 are presented here. The Edwards Dam was previously located 40 km north of Merrymeeting Bay and was removed on July 1, 1999. The presence of the dam during this study may have moderated the effects of river discharge on current dynamics in the estuary.

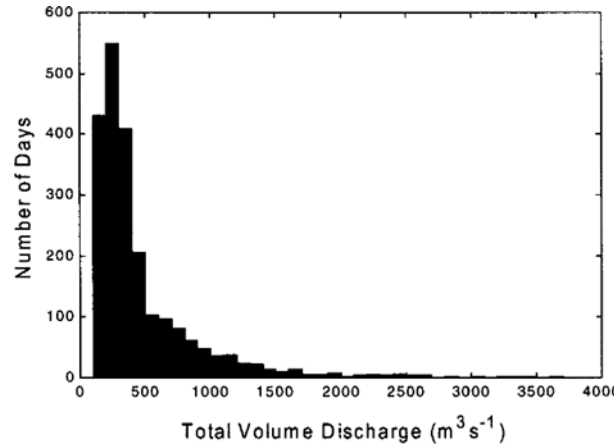

Fig. 2. Frequency distribution of total river discharge in 1993–1999 for the Androscoggin and Kennebec Rivers from U.S. Geological Survey gaging stations.

Discharge values for the Androscoggin River are from a gage near Auburn, Maine, located at 44°04′20″N and 70°12′31″W, 30 km north of Chops Point. The drainage area for this gage is 8,451 km^2 and 63 yr of data exist in this location. The Errol Dam is located 220 km upstream and regulates the flow in the Androscoggin River.

The majority of the study site lies downstream of Chops Point, the confluence of the Kennebec and Androscoggin Rivers, therefore the sum of both rivers will be considered as the effective discharge level. A histogram of combined discharge volumes is shown in Fig. 2. Measurements upstream of Chops Point followed the channel of the Kennebec River. It is recognized that stations north of this point are subject to different gravitational forcing due to the reduced river volume.

Results

Low Flow

Measurements were made in the upper estuary on September 16 and on the lower estuary on September 17, 1995 during a neap tide. The combined discharge of the Kennebec and Androscoggin Rivers on these two days averaged 125 m^3 s^{-1}, the lowest flow rate observed in this study. Salinity at different tidal stages is shown in Fig. 3. At the mouth of the estuary, salinity ranged from 22 to 32 psu during the tidal cycle. At Chops Point, salinity varied from 0 to 5 psu. The maximum penetration of the 2 psu isohaline at high tide was approximately 38 km north of the mouth, almost to Green Point at the northern end of the study area.

A two-layered residual flow was present in the

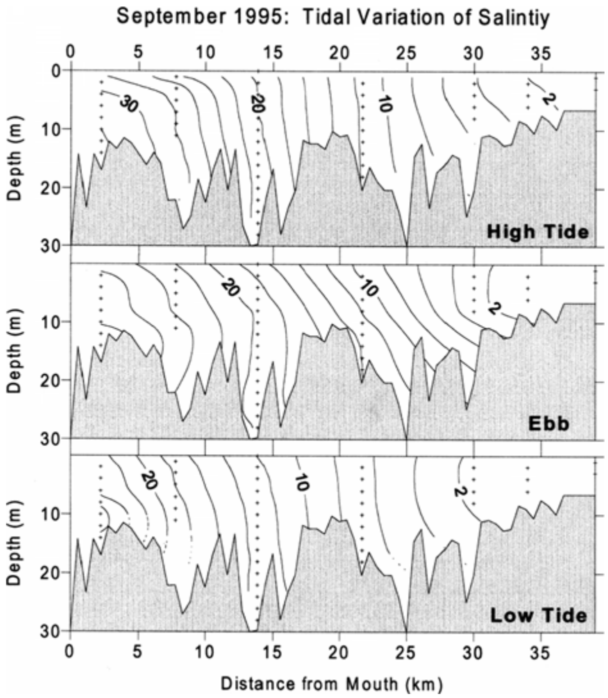

Fig. 3. Tidal variation of salinity on September 16–17, 1995.

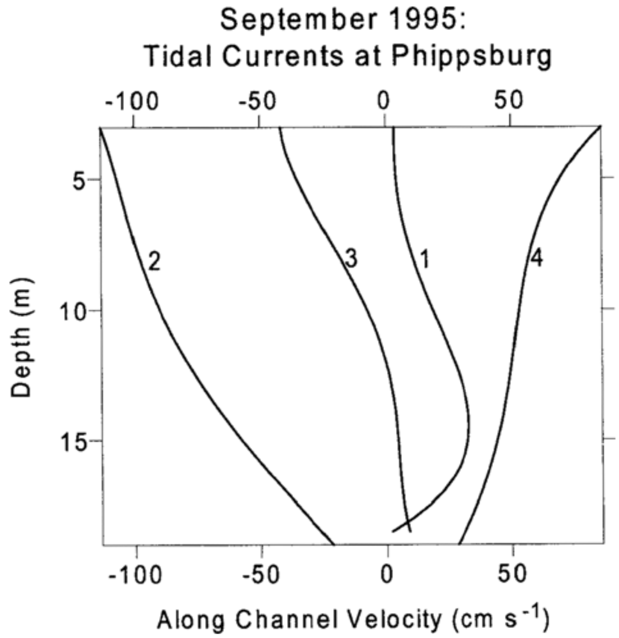

Fig. 4. Tidal currents at 3-h intervals at Phippsburg, 8 km from the mouth, on September 17, 1995. Numbers represent the tidal sequence.

estuary and persisted as far upstream as Merrymeeting Bay, 30 km from the mouth. The level of no motion intersected the bed in the region of Abagadasset Point, 33 km from the mouth. The maximum observed currents of 1.7 and 1.4 m s^{-1}, for ebb and flood, respectively, were at the Chops Point constriction. Otherwise, ebb velocities were strongest at the surface near the mouth, exceeding 1 m s^{-1} (Fig. 4). Flood velocities were typically strongest at mid-depth in the middle section of the estuary, 14 km from the mouth, and near the bottom at the head of the estuary, 34 km from the mouth.

Tidal variation of SPM is shown in Fig. 5. The maximum concentration observed in the estuary was 25 mg l^{-1} near the upstream end of the study site. Typical values in the lower estuary were below 5 mg l^{-1}. At high tide, it appeared as if turbidity simply increased with decreasing salinity, but at low tide, it became apparent that a region of maximum turbidity had moved into the study area with the ebbing tide. This turbidity maximum coincided with where the 2 psu isohaline intersected the bed.

In October 1998, the total discharge was 208 m^3 s^{-1}, an increase of 60% over the September 1995 level and very typical of the low flow season. The 2 psu isohaline penetrated to Lines Island, 27 km from the mouth at high tide, and was pushed 10 km downstream to south of Bath at low tide. The lower part of the estuary was well stratified, while the middle section was fairly homogenous.

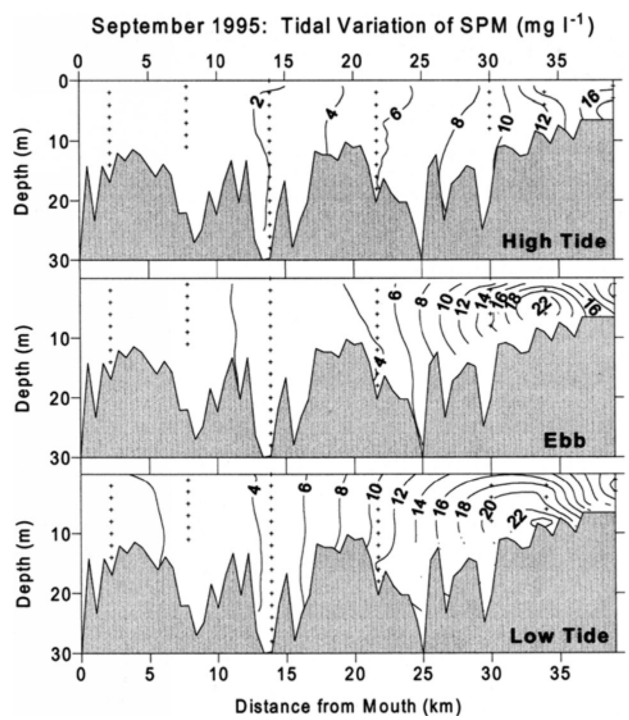

Fig. 5. Tidal variation of SPM on September 16–17, 1995.

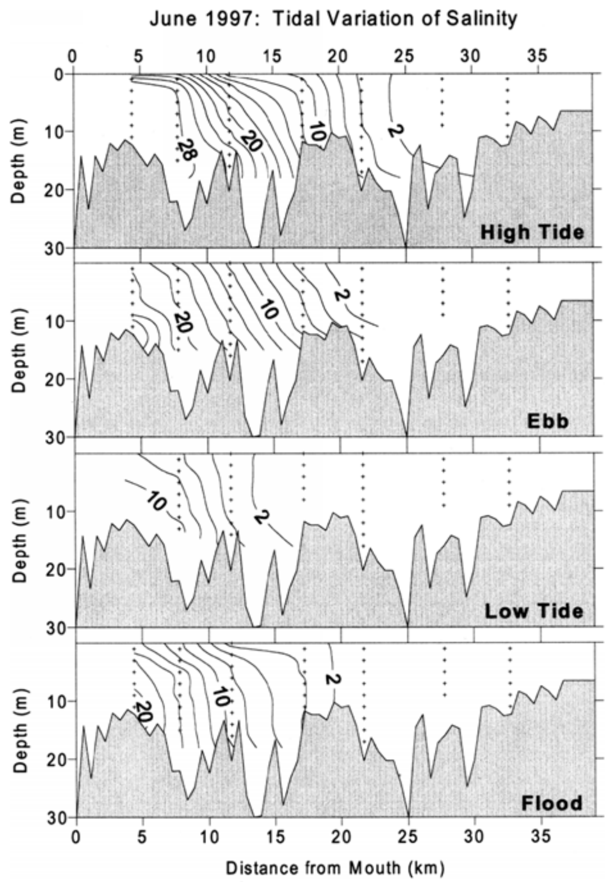

Fig. 6. Tidal variation of salinity on June 4–5, 1997.

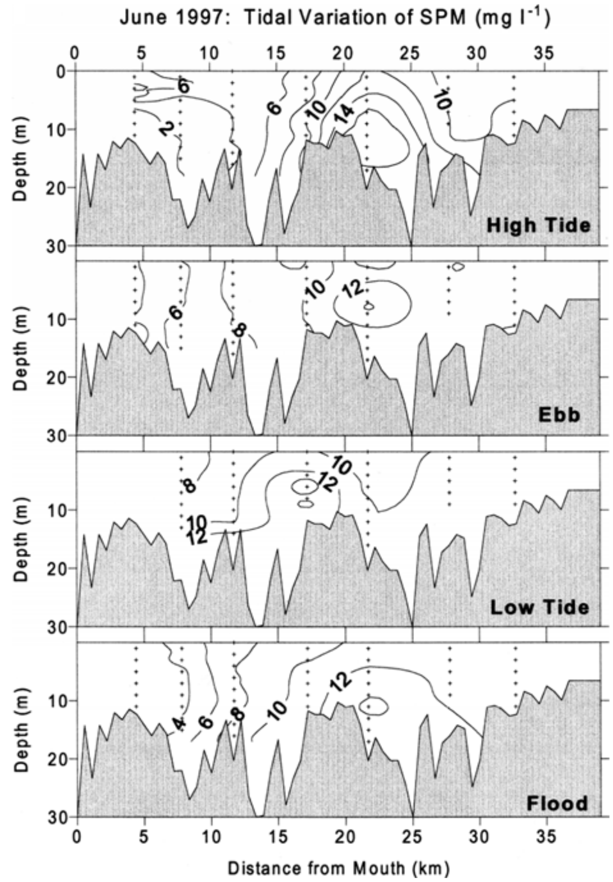

Fig. 7. Tidal variation of SPM on June 4–5, 1997.

There was a strong two-layer flow in the lower and middle estuary. The maximum observed velocities of 1.5 m s^{-1}, both ebb and flood, were again at the Chops Point constriction. The level of no motion was near the south end of Lines Island, 28 km from the mouth, 15 km south of where it was observed in September 1995. The longitudinal profile of suspended particulates in the estuary was similar to that observed in September 1995 with the exception that minimum and maximum features were shifted approximately 15 km downstream.

Moderate Flow

Discharge levels in the Kennebec were still subsiding from spring runoff on June 4–5, 1997. The combined discharge of the rivers was 380 m^3 s^{-1}. Salinity near the mouth ranged from 10 to 30 psu (Fig. 6). The 2 psu isohaline penetrated 12 km north of the mouth at low tide and moved north of the City of Bath at high tide, about 24 km from the mouth, but did not reach Merrymeeting Bay.

The flow in the lower part of the estuary was two-layered with a strong shear on the ebb tide. The maximum observed ebb current was 1.5 m s^{-1} at the surface near the mouth. The maximum observed flood current of 1.2 m s^{-1} was also at the surface near the mouth. The residual current at Bath, 22 km from the mouth, was seaward at all depths, with a maximum of 0.14 m s^{-1} at 7 m depth, and 0.0 m s^{-1} near the bottom. Tidal profiles of SPM are shown in Fig. 7. Concentrations were low and patchy across the channel, with a maximum of 20 mg l^{-1} in the middle part of the estuary. This maximum moved with the tide and coincided roughly with the 2 psu isohaline. A plot of psu versus SPM appears in Fig. 8 and shows the accumulation of particles at low psu.

High Flow

On April 15, 1997, spring freshet was occurring on the Kennebec and Androscoggin Rivers. Measurements were made during a slight lull in the runoff on a neap tide. Total discharge measured at the U.S. Geological Survey stations upstream was 700 m^3 s^{-1} on that day. Flow had peaked 7 d prior at 1,360 m^3 s^{-1}, and peaked again 5 d later at 2,400 m^3 s^{-1}, the maximum flow for that year.

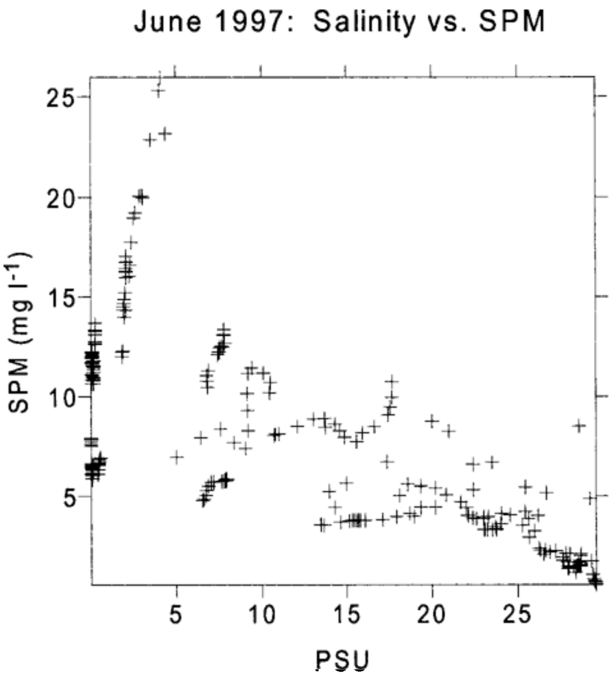

Fig. 8. SPM versus psu on June 4–5, 1997.

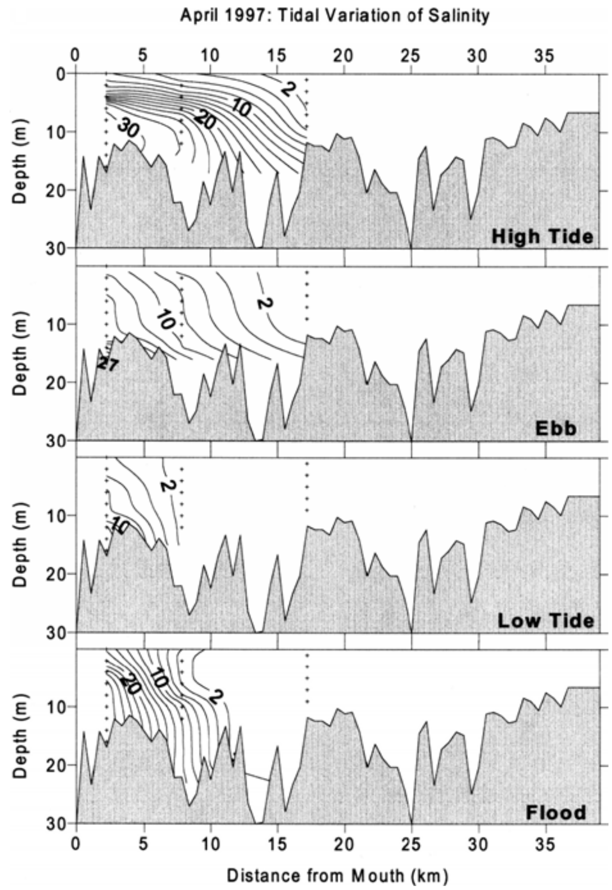

Fig. 9. Tidal variation of salinity on April 15, 1997.

Tidal variation of salinity is shown along the estuary in Fig. 9. The lower estuary was highly stratified, with salinity near the mouth ranging from 10 to 31 psu in the vertical at high tide. The maximum penetration of the 2 psu isohaline at low tide was 8 km from the mouth and at high tide was 17 km from the mouth. The pycnocline was near the surface early in the ebb, and moved down to mid-depth, then to near bottom as the ebb progressed, with another pycnocline forming near the surface.

Tidal currents at Dix Island, 2 km from the mouth, are shown in Fig. 10. Ebb-directed currents persisted for 8 h during the semi-diurnal tidal cycle, and reached a maximum of 1.3 m s^{-1} near the surface and 0.5 m s^{-1} near the bottom. Flood currents reached a maximum of 1.0 m s^{-1} near the surface and 0.5 m s^{-1} near the bottom. The residual current was seaward at all depths and all stations during high flow conditions.

The tidal variation of SPM is shown in Fig. 11. SPM was inversely related to salinity with no apparent trapping of particles. There was a local peak in turbidity near the surface for several hours after slack high tide. This peak corresponded to the bottom of the pycnocline. While turbidity was generally higher in freshwater, there were several times throughout the tidal cycle when a particle maximum occurred in the lower water column at the Phippsburg station, 8 km from the mouth. This maximum appeared to be topographically controlled because it did not shift in the estuary with the salinity and currents and occurred landward of the null point. The peaks occurred when near-bottom currents reached a maximum on either tide exceeding 75 cm s^{-1} and is interpreted as a local resuspension event. The chlorophyll concentration was positively correlated with SPM at Phippsburg,

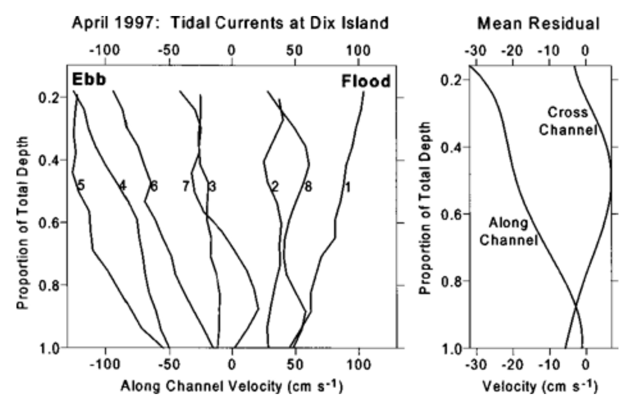

Fig. 10. Tidal currents at 90-min intervals and the mean residual at Dix Island, 2 km from the mouth, on April 15, 1997. Numbers represent the tidal sequence.

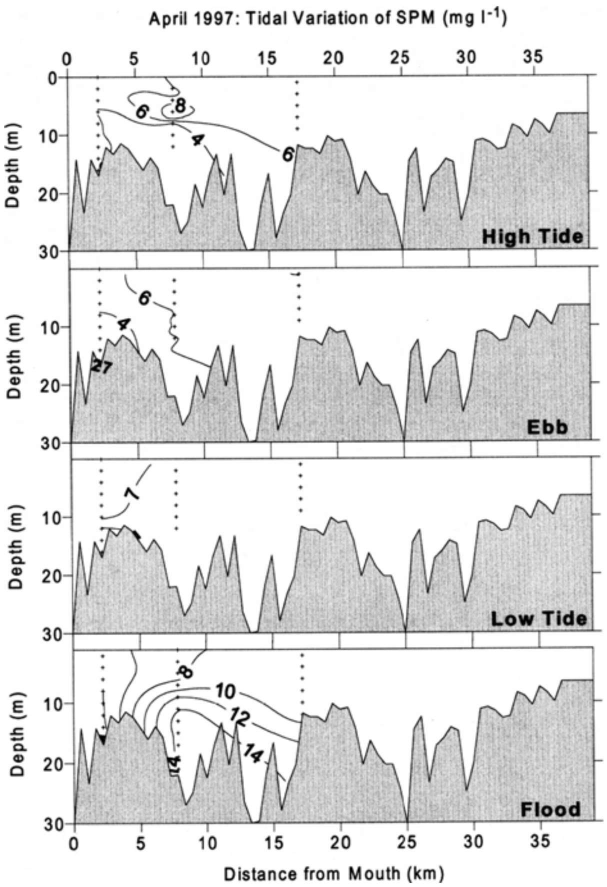

Fig. 11. Tidal variation of SPM on April 15, 1997.

except during the particle resuspension events, further reinforcing this interpretation.

These results were verified for high flow conditions on April 25, 1998 during a stronger freshet of 1,178 m^3 s^{-1}. The results were comparable to the 1997 cruise. While discharge levels were higher, it was during a spring tide so that the distance of salt intrusion into the estuary was similar at high tide, but reduced at low tide. Residual currents at Dix Island were seaward at all depths in the main channel once again. Lateral stations conducted during this year revealed a landward residual flow in the lower third of the water column, 3 m thick, on the east side where there is a shoal. A particle maximum appeared at the Phippsburg station again, during peak near bottom currents on either tide and did not move with the tide.

Discussion

Highly variable discharge levels combined with a narrow channel create conditions in the Kennebec that change dramatically between season and even weeks. Depending on river flow, the length of salt water intrusion varies by up to 30 km, from 5 to 35 km from the mouth.

Low flow conditions in the Kennebec Estuary in September 1995 allowed the development of a turbidity maximum in the region of Merrymeeting Bay that moved up and down the channel with the semi-diurnal tide. Despite particularly low levels of SPM, this ETM is distinct. As isohalines become strained on the ebb tide the particles move lower in the water column so that the ETM becomes concentrated near the bed. On the flood tide, particles are seen higher in the water column and the turbidity gradient increased on the upstream side. The change in position of particles in the water column during the tidal cycle is supported by gradient Richardson numbers that illustrate the greater potential for vertical mixing in the region of the observed ETM and during the flood tide (Kistner and Pettigrew 1998). The Bay represents one of the few places in the estuary where fine sediments may be found in the estuary and may help supply the ETM with particles.

During high flow conditions, salt is pushed almost entirely out of the channel of the estuary at low tide. The limit of salinity intrusion was approximately 20 km south of where it was observed during the extremely low flow conditions in September 1995. Residual currents at the southern-most station of Dix Island were ebb-directed at all depths in the main channel, preventing particles from accumulating at that location or from moving into the estuary. Local resuspension events occur at the Phippsburg station, 8 km from the mouth, when near-bottom currents reach a maximum exceeding 75 cm s^{-1} in either direction.

The ETM was present during moderate flow conditions of June 1997 but did not appear to be very well developed. The isohalines were nearly vertical on the flood tide and strained leaning downstream on the ebb, particularly near the surface. The null point was in the vicinity of the observed particle accumulation. These factors contribute to the formation of an ETM. Despite the ephemeral appearance of the ETM, the accumulation of particles at 2–3 psu is distinct. In the 2 mo prior to these measurements, runoff conditions in the estuary were very high and may have prevented the accumulation of particles by the ETM despite the presence of formation mechanisms at the time of our cruise.

It seems appropriate to define a threshold discharge level below which particles will accumulate and an ETM will be present in the Kennebec estuary. The discharge level of approximately 500 m^3 s^{-1} is an estimate of this threshold, based on the observed position and strength of the ETM throughout this study. During the years 1993–1999, discharge conditions in the Kennebec would have allowed the formation of an ETM approximately 73% of the time based on the threshold of 500 m^3 s^{-1}. This percentage varied from 47% to 84% yearly. Based on the discharge level in spring where the ETM was pushed out of the estuary, it is also realistic to define a discharge level of 700 m^3 s^{-1} above which the ETM will not be present. This condition persisted for 18% of the time on average in the period of study, and ranged from 10% to 34%. The determination of a more precise level between 500 and 700 mg l^{-1} at which particles will be able to accumulate requires additional observations in the estuary and may be complicated by bathymetry near the mouth.

Due to the rapidly changing flow conditions in the Kennebec, a further consideration is the duration of time that river flow has been below the ETM formation threshold, defining an effective age of the ETM or period of time that particles have been accumulating. This is compared to the time-dependent development of an ETM after a period of deterioration due to the tidal cycle (Jay and Musiak 1994) or during the initial stages of a model while base level particle concentrations accumulate (Rolinski 1999). The ETM observed in June 1997 would only have been present 5 d, which may explain the patchy ephemeral nature of SPM concentrations. In October 1998, discharge volumes were 60% higher than September 1995. The ETM was well developed in October 1998 and was moving with the semi-diurnal tide between Bath and Chops Point, approximately 15 km downstream from its observed position in September 1995. Maximum observed particle concentrations were similar in both 1995 and 1998 despite the spatial offset with Merrymeeting Bay in 1998. At both these times, the combined flow level of the rivers had been below the threshold value of 500 m^3 s^{-1} for approximately 100 d prior to these measurements. This suggests that the age of the ETM may be more important in determining particulate concentrations than is the position of the ETM in the channel as dictated by the discharge conditions.

Acknowledgments

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