Chapter 2

Water Quality

A typically tranquil morning on the Abagadasset River, one of six drainages linked to Merrymeeting Bay. Photo: Slade Moore.

The Kennebec Estuary has long been subject to egregious pollution associated with historical land use, industry, and urbanization. Implementation of the Clean Water Act brought such dramatic improvements to water quality in the estuary that only those who experienced it first-hand can now imagine the estuary at the nadir of its ecological functioning. Yet how much have we progressed toward the historical conditions before ecosystem impairment? Currently, a lack of estuary-specific data hinders attempts to assess water quality or characterize its most important influences in this segment of the Kennebec. Emerging evidence—such as information derived from historical data and environmental proxies—suggests that our goals and overall management philosophy might benefit from a reassessment.

Introduction

Offering access to upriver natural resources, transportation routes to markets, and sources of waterpower for industry, estuaries like the Kennebec were among the first areas settled by European colonists in eastern North America (McKeen 1853; Wheeler and Wheeler 1878). Little is known about the Kennebec Estuary's condition prior to European settlement, but northeastern estuarine systems are thought to have historically received few nitrogen or phosphorus inputs from their primarily forested watersheds (Nixon 1997). Although the Kennebec river basin had long been home to native peoples, the period of European colonization and industrialization greatly changed the nature and intensity of human-induced disturbances (Foster 1992; Foster et al. 1998) and the supply of nutrients such as nitrogen and phosphorus (Cooper 1995; Köster et al. 2007).

Erosion of terrestrial soils following widespread land clearance often results in an influx of nutrients to aquatic systems (Cooper 1995). Using this phenomenon as a premise for ecological investigations, researchers from Bowdoin College and the University of Maine used environmental proxies to identify historical shifts in water quality based on sediment cores collected from intertidal mudflats near the Abagadasset River (Köster et al. 2007). Their data indicate that the rates of both sedimentation and phosphorus accumulation in sediments of the upper estuary increased during the 18th century concurrent with the onset of widespread land clearance in Maine (Köster et al. 2007). Not surprisingly, early historical accounts of the Kennebec region support these findings by reporting that land-use modifications along the Androscoggin and other nearby rivers in the 1700s resulted in widespread erosion and sedimentation of Merrymeeting Bay (McKeen 1853). Increases in freshwater benthic diatoms in the upper estuary by 1800 suggested to Köster and colleagues (2007) that, fueled by the influx of erosion-associated nutrients and freshwater runoff due to land clearing, the system became more productive. As industry, agriculture, and human populations in the region continued to grow during the 19th century (Babcock et al. 1995), the structure of diatom communities in Merrymeeting Bay responded to eutrophic conditions by shifting toward more pollution-tolerant species (Köster et al. 2007).

As early as the late 19th century, pollution in the Androscoggin River was already considered problematic (Owen 1936) and by the early 20th century Kennebec River water quality deteriorated as the disposal of municipal and industrial wastes directly into the rivers increased (Whipple 1907). A water quality survey of the Kennebec River near Augusta in 1907 found that wood fiber from paper mills and sawmills formed deposits on the riverbed that were resuspended during high flow conditions, causing increased turbidity (Whipple 1907). The odors of raw sewage and sulphite wastes from paper mills were also detectable for miles downstream of discharge points. During this period, untreated sewage disposal led to bacterial counts that were elevated near urban and industrial centers; 72% of water samples collected from the Kennebec River at Augusta tested positive for the bacterium *Escherichia coli* (Whipple 1907), an indicator of fecal bacterial contamination.

Increasing industrial and municipal development along both the Androscoggin and Kennebec Rivers in the late 19th and early 20th centuries further contributed to the eutrophication of both systems. By about 1930 the cities of Lewiston and Auburn were sources of direct, untreated disposal of wastes from three packing companies, a slaughterhouse, a canning company, several dyeing facilities, a glue manufacturing company, a canning company, a bleachery, five cotton mills, and domestic sewage from a population of approximately 54,000 (Brennan et al. 1931). Both upstream and downstream of Lewiston and Auburn there were also several paper mills along the Androscoggin that discharged untreated waste directly into the river (Brennan et al. 1931).

A reduction in water clarity resulting from eutrophication typically favors the growth of planktonic diatoms in the water column, which then reduces the amount of light available to support the growth of benthic diatoms. During the early 20th century there was a sharp decline in the abundance of benthic diatoms and an increase in the productivity of planktonic species in Merrymeeting Bay, suggesting that the system had become even more eutrophic (Köster et al. 2007). More recently high fluxes of organic carbon, phosphorus, and biogenic silica, as well as high levels of diatom productivity and an altered diatom community assemblage, suggest that Merrymeeting Bay's water quality remains significantly altered from pre-colonial conditions (Köster et al. 2007).

Assessing Water Quality in the Estuary

Suspended Solids

The total suspended solids (TSS) pool is composed of volatile suspended solid (VSS) (organic particles) and fixed suspended solid (FSS) (mineral particles). Among other factors, an overabundance of suspended solids in aquatic systems can reduce water clarity, which influences the ability of sunlight to penetrate the water column. Reduced sunlight penetration has implications for plants that use the process of photosynthesis to support metabolic processes and growth. These plants range from small unicellular forms to those that create lush, subtidal meadows. Significant changes in these plant communities can influence ecosystem function in many ways, such as by reducing the oxygenation of waters and limiting available habitat for fish and wildlife.

The work of Köster and colleagues (2007) suggests that Merrymeeting Bay's waters were historically clear, supporting more benthic plant productivity than they do today. Decreases in Merrymeeting Bay's water clarity are most likely the result of suspended sediment and planktonic algae concentrations that exceed historical levels, but little more information is available to further characterize current conditions. Bowdoin College investigations focusing on the composition of total suspended solids in Merrymeeting Bay found significant differences among three classes of sites in the bay: the large rivers, the small rivers, and the Chops, where ebbing flow exits Merrymeeting Bay

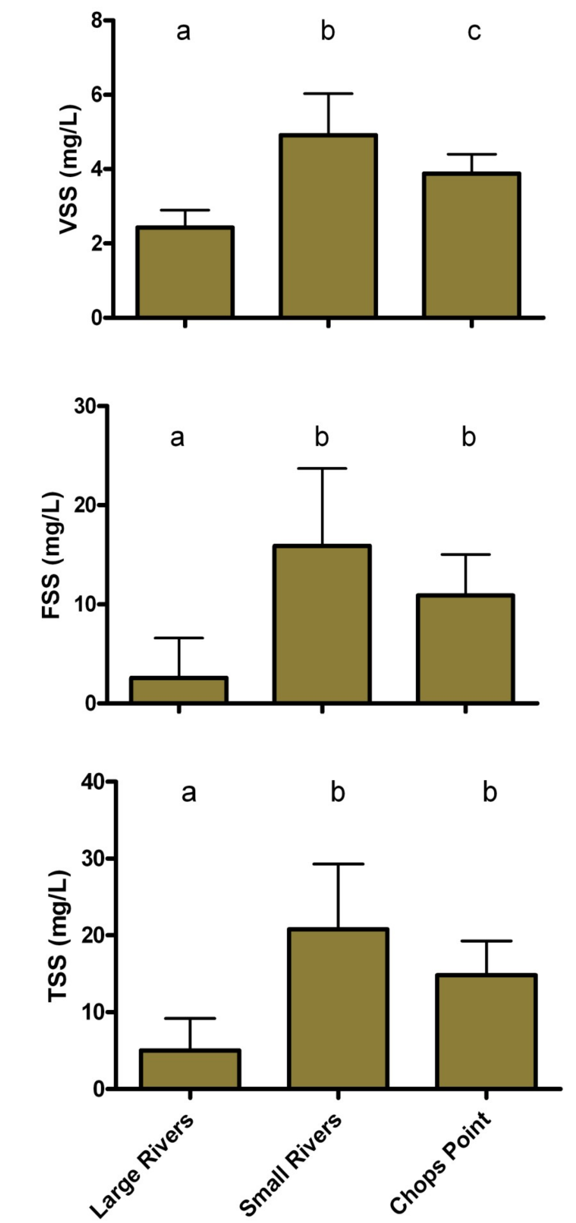

Figure 2-1. The average concentrations of FSS, VSS, and TSS in the large (Kennebec, Androscoggin) and small (Cathance, Muddy, Eastern, Abagadasset) rivers flowing into Merrymeeting Bay and at the Chops where water exits to the lower estuary. Measurements were made at or near low tide on 10 days during summer 2006. Letters above the bars indicate statistically significant differences between the means at α=0.05. Adapted from Burton (2007).

(Fig. 2-1) (Burton 2007). The high proportion of fixed solids in the TSS profile of the small rivers suggests that the majority of suspended solids in these drainages are derived from fine mineral sediments rather than phytoplankton and bacteria. Among the four small drainages, the lower Eastern River has consistently been among the most turbid sampling sites in Merrymeeting Bay (Caron 2005), which the Burton (2007) data tend to reflect. Connors et al. (1982) suggested that causes of the Eastern's high turbidity included foraging activity of the introduced common carp (*Cyprinus carpio*) and wave-driven re-suspension of benthic surface sediments from the intertidal mudflats. Its name notwithstanding, the Muddy River has been among the least turbid drainages in the Upper Kennebec Estuary since at least the late 20th century (Connors et al. 1982).

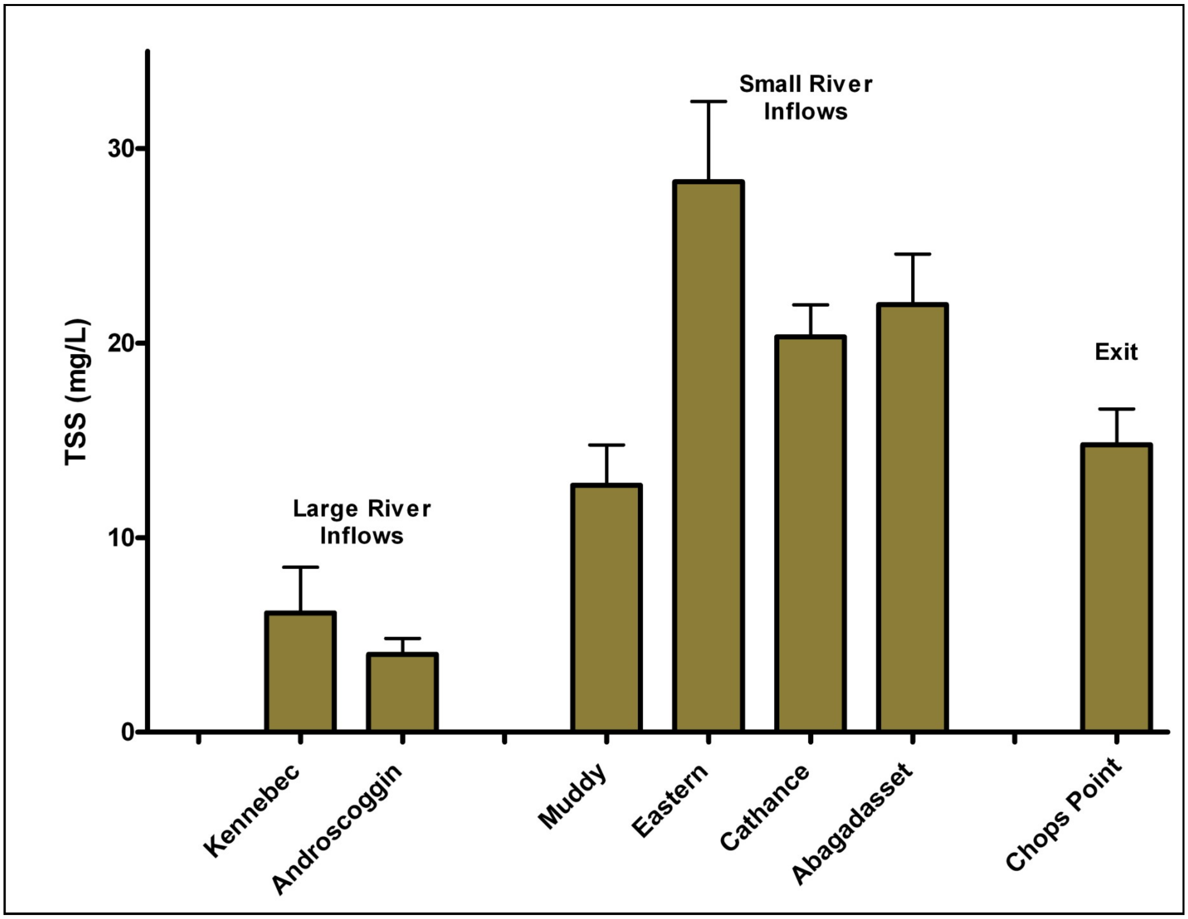

Figure 2-2. Average total suspended solid (TSS) concentrations of Merrymeeting Bay rivers and the Chops. Low tide data collected in summer 2006. Adapted from Burton (2007).

Most of the TSS data discussed above were derived from data collected during one season in 2006 and therefore may not adequately represent the diversity of conditions in the upper estuary. Kistner and Pettigrew (2001) described the movement of a turbidity maximum that moves up and down the estuary depending on discharge rates, which provides some understanding of how turbidity moves within this segment of the Kennebec. More extensive TSS sampling data would allow development of a time-averaged mass balance model that would better explain seasonal patterns of contribution to the TSS pool from the small drainages, large rivers, and Merrymeeting Bay itself. In combination with identification of substrate texture characteristics at various sites in the upper estuary, this model could help identify the most important sources of suspended solids. The knowledge gained through such a model could determine if corrective adjustments to prevailing management goals and land uses are warranted or feasible.

Chlorophyll a and Phytoplankton

Chlorophyll a (chl a), a pigment found in many photosynthetic organisms, is used to estimate algal biomass and productivity in aquatic systems. The first national estuarine eutrophication survey conducted in the late 1990s characterized chl a levels in the Kennebec Estuary as "moderate" (NOAA 1997). While application of national criteria may not be appropriate for characterizing local conditions, sufficient data for the most recent survey were not available to accurately assess chlorophyll levels in the estuary (Bricker et al. 2007). Reported surface and subsurface chl a concentrations in the Kennebec Estuary (Fig. 2-3) are typically less than the U.S. Environmental Protection Agency (USEPA)10 μg/L threshold (2001) that distinguishes oligotrophic systems from mesotrophic systems in the ecoregion. Chl a concentrations in the estuary also fall below the 20 μg/L threshold that the National Oceanic and Atmospheric Administration (NOAA) (1997) uses to distinguish medium chlorophyll levels from high chlorophyll levels in estuaries (J. Reblin and J. Lichter, unpublished data; Mayer et al. 1996; Wong and Townsend 1999; Souther 2005). In surveys of the estuary conducted during the summer of 2004, fewer than 10% of

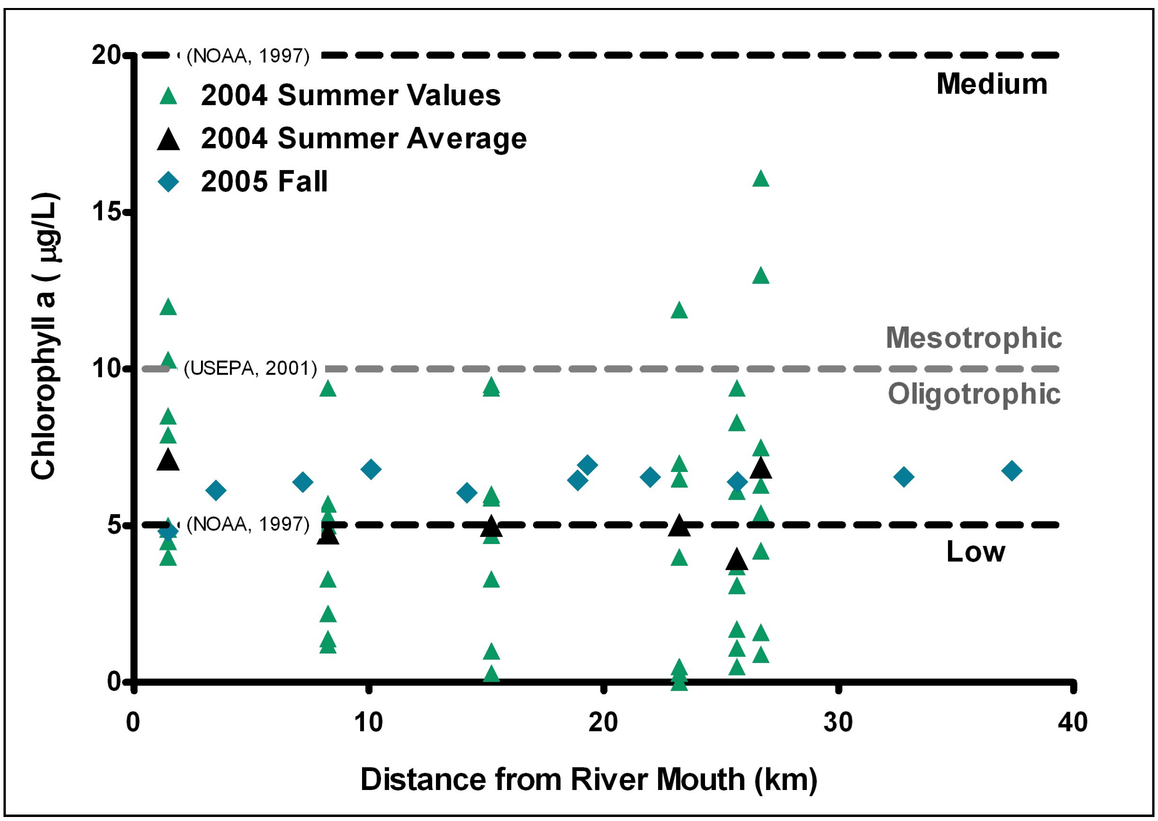

Figure 2-3. Surface chlorophyll a concentrations in the Kennebec Estuary during the summer of 2004 and during one survey conducted in the fall of 2005. Boundaries between mesotrophic and oligotrophic systems are drawn according to USEPA (2001*a*). Boundaries between low and medium chlorophyll a levels are drawn according to NOAA (1997). Adapted from Souther (2005); J. Reblin and J. Lichter, Bowdoin College, unpublished data.

all measurements (Fig. 2-3) indicated mesotrophic conditions (10–30 μg/L) and no measurements were above the USEPA (2001*a*) 30 μg/L mesotrophic-eutrophic boundary (Souther 2005).

Chl a minima typically occur in the mid-estuary (Wong and Townsend 1999; Souther 2005) where salinities range between 10 and 20 ppt, suggesting that phytoplankton productivity is low in this portion of the estuary, at least transiently (Wong and Townsend 1999). Freshwater species tend to dominate the phytoplankton communities in the Kennebec Estuary at salinities below 10 ppt and coastal species dominate at salinities greater than 20 ppt (Wong and Townsend 1999). This mid-estuary transitional zone probably represents a region of reduced productivity resulting from salinity-induced osmotic stress and mortality as freshwater species reach their maximum tolerable salinities and coastal species reach their minimum (Wong and Townsend 1999). In the lower estuary, chl a concentrations are similar throughout

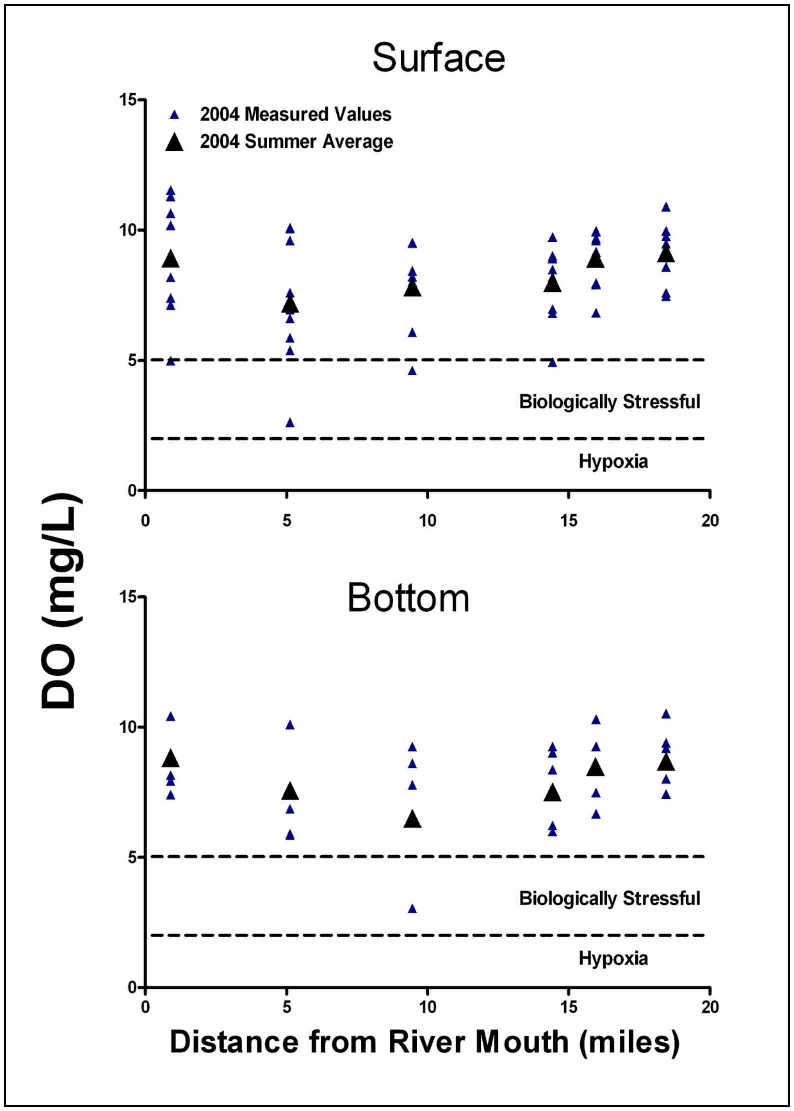

Figure 2-4. Surface and bottom dissolved oxygen (DO) concentrations in the Kennebec Estuary between Fort Popham and Merrymeeting Bay during the summer of 2004. Distinctions between biologically stressful (>2.0 mg/L to ≤ 5.0 mg/L) and hypoxic conditions (≤ 2.0 mg/L to > 0 mg/L) DO levels are made according to NOAA (1997) and USEPA (2007*a*). Adapted from Souther (2005).

a tidal cycle (Fig. 2-4); however, in the upper estuary chl a concentrations are greatest around low tide for sites in Merrymeeting Bay (Mayer et al. 1996).

Wong and Townsend (1999) found that diatoms were the most abundant phytoplankton group sampled throughout the estuary. The lower estuary phytoplankton community was composed primarily of coastal species including *Skeletonema costatum*, *Chaetoceros* sp., *Leptocylindrus minimus*, *Leptocylindrus danicus, Thalassiosira decipiens*, and *Eucampia zodiacus* (Wong and Townsend 1999). In the upper estuary, diatoms, cyanobacteria, and green algae were most prevalent with abundant species represented by *Coscinodiscus rothii, Cyclotella* sp., *Aulacoseira granulata, Asterionella formosa, Lyngbya nana, Oscillatoria acuminata,* and *Nodularia spumigena* (Wong and Townsend 1999). Cyanobacteria in the upper estuary are typically thought to originate in the intertidal zone and marshes, or to be shallow-water epiphytes presumably washed into the system with the ebb and flow of the tides (Wong and Townsend 1999).

Dissolved Oxygen

Oxygen is required to support the metabolic activities of most organisms. Under certain conditions, oxygen supplies in aquatic systems can become depleted, leaving little or none available to support life (Lampert and Sommer 1997). When they are discharged into aquatic systems untreated, organic wastes feed the growth of bacteria that consume oxygen. Decreased oxygen availability leaves only enough for organisms that are suited to such conditions. Consequently, alternate communities and ecosystems develop (Lampert and Sommer 1997). Historically, both industry and municipalities along the Kennebec and Androscoggin Rivers discharged large amounts of organically enriched waste directly into the rivers (Lichter et al. 2006). For example, during the late 1960s and early 1970s, a single paper mill at Winslow annually discharged waste into the Kennebec River equivalent to the amount released by a city of two million people (New England River Basins Commission 1979).

Dissolved oxygen (DO) concentrations greater than 5.0 mg/L are considered “good” by the National Estuary Program, whereas DO levels below 5.0 mg/L are typically either stressful or lethal to most aquatic organisms (USEPA 2007*a*). In water quality surveys of several rivers in Maine conducted in 1930, minimum DO levels in the Kennebec River decreased from ~10 mg/L at Madison to ~4 mg/L in the tidal portion of the river upstream of Merrymeeting Bay (Brennan et al. 1931). At about the same time, DO levels in the Androscoggin River were lowest near Lewiston (~2 mg/L), though they recovered to ~6 mg/L just above the dam at the head of tide in Brunswick (Brennan et al. 1931). In the 1940s, the Androscoggin was frequently anoxic (Lawrance 1967) and DO levels remained low into the 1970s between Jay and Lisbon (MDEP 1979). The Kennebec experienced anoxic conditions in the late 1940s, throughout the 1960s, and into the early 1970s (Lichter et al. 2006).

Implementation of the Clean Water Act of 1972 had rapid, dramatic impacts on DO in the Kennebec (MDEP 1979; Lichter et al. 2006) and Androscoggin Rivers (Lawrance 1978). After 1975, DO concentrations in the Kennebec River increased, reaching a summer minimum between 7–8 mg/L in 1978 (MDEP 1979). Dissolved oxygen concentrations (range 7.5–9 mg/L) in the Kennebec River between Waterville and Richmond were similar in surveys conducted during the summer in 1978 (MDEP 1979) and 20 years later in 1998, averaging between 7.5 and 8.5 mg/L (range 6.5–9.5 mg/L) (MDEP 2000). Improvements in DO concentrations over the last 30 years in the Kennebec and Androscoggin Rivers can be largely attributed to the treatment of municipal and industrial waste (Lawrance 1978; MDEP 1979; Lichter et al. 2006) and the closure of several significant industrial sources of organic waste on both rivers (D. Courtemanch, MDEP, personal communication).

Few recent data are available to assess DO conditions in the estuary (Bricker et al. 2007), but those that are available suggest an improving trend. During surveys of the estuary conducted during summer 2004, average surface and bottom DO concentrations (Fig. 2-4) between Fort Popham and Merrymeeting

Bay ranged from 7.2–9.1 mg/L (Souther 2005). Biologically stressful DO levels (5.0–2.0 mg/L; NOAA 1997) were observed in only 7.5% of surface and 3.6% of bottom measurements made in these surveys (Souther 2005). At no time did DO concentrations reach hypoxic levels (≤ 2.0 mg/L; NOAA 1997). Between July and September 2004, surface DO concentrations at the Chops in Merrymeeting Bay averaged 8.2 mg/L (range 5.7–10.4 mg/L) (P. Lea, Bowdoin College, unpublished data). Less than 1.5% of the roughly 9,700 measurements recorded at this site were below 7.0 mg/L. At Center's Point in Merrymeeting Bay, summer 2005 DO concentrations averaged 8.0 mg/L (range 5.4–10.8 mg/L) with only 0.3% of ~29,000 measurements at or below 6.0 mg/L (P. Lea, Bowdoin College, unpublished data). During fall

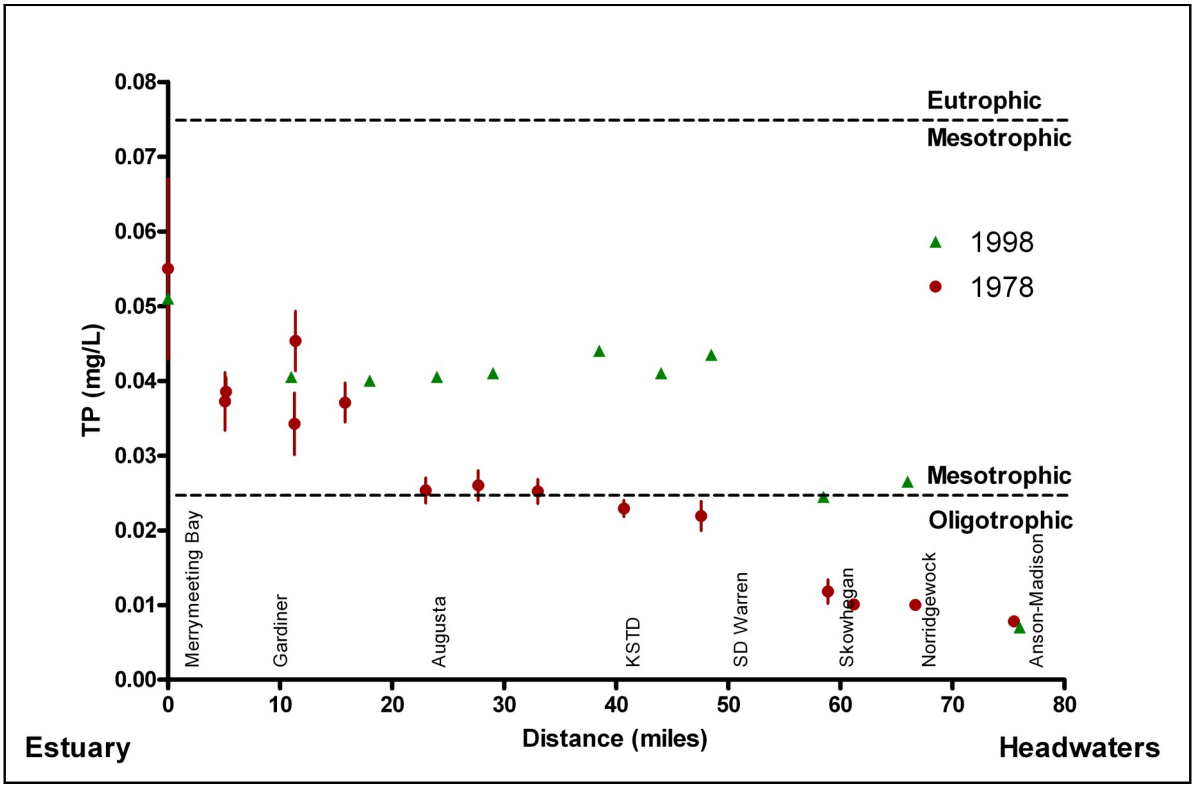

Figure 2-5. Total phosphorus concentrations (TP) in the Kennebec River between Merrymeeting Bay and Anson-Madison in 1978 and 1998 (MDEP 1979, 2000). Trophic state boundaries are drawn according to USEPA (2001*a*). Data are means ± 1 SE in 1978 and are means in 1998.

2005 at the same site, DO concentrations averaged 10.4 mg/L (range 7.4–12.6 mg/L). In the upper Kennebec Estuary, designated as Class B waters, state law requires the dissolved oxygen content to remain not less than 7 mg/L or 75% of saturation, whichever is higher. MDEP considers 6 mg/L the minimum allowable DO content for the more saline portion of the estuary (D. Courtemanch, personal communication). While limited in duration and spatial coverage, available data suggest that DO concentrations throughout the estuary are adequate to support the full suite of aquatic life forms native to available habitats.

Nitrogen and Phosphorus Nutrient Pollution

The transfer of nutrients from the terrestrial landscape to the oceans is a natural process. Productivity in estuaries and coastal systems is typically limited by nitrogen availability whereas productivity in freshwater systems is typically phosphorus-limited (Howarth and Marino 2006; Bricker et al. 2007; Jordan et al. 2008). In the upper reaches of estuaries such as the Kennebec, the mixing of ocean and fresh waters can cause shifts in the spatial and temporal availability of nitrogen and phosphorus (Jordan et al. 2008).

In the last 150 years, nutrient enrichment has been greatly intensified by anthropogenic activities and is currently a major cause of water pollution in rivers (USEPA 2001*a*; Chambers et al. 2006), estuaries, and coastal regions (Bricker et al. 2007). Abnormally high amounts of nutrients in aquatic systems can heighten system productivity, causing increased turbidity, increased metabolic oxygen consumption, decreased dissolved oxygen levels, and changes in overall community structure (Robinson et al. 2004; Howarth and Marino 2006; Smith et al. 2006; Bricker et al. 2007; Jordan et al. 2008). Nitrogen pollution in coastal ecosystems is thought to be among the most important consequences of human-enhanced global change (Vitousek et al. 1997; Boesch 2002; Scavia et al. 2002). In the United States, estimates suggest that human actions have directly increased nitrogen fluxes to coastal regions by a factor of six (Howarth et al. 2002), although such increases are not apparent in Maine (D. Courtemanch, personal communication). Locally, MDEP (2000) predicted that in the coming years, nutrient loading would be a major water quality issue in the Kennebec and Androscoggin Rivers.

Nutrient pollution is typically greatest near urban areas and areas with extensive agricultural activity because of the widespread use of synthetic fertilizers (USGS 1999; Boyer et al. 2002; Bricker et al. 2007). In contrast, the upper Kennebec and Androscoggin watersheds are largely (>79%) forested with relatively little land area in agricultural (<6%) and urban use (<1.1%). As a result, these waters are less affected by nonpoint source nutrients and receive a sizeable fraction of their nutrient load from point sources (Boyer et al. 2002).

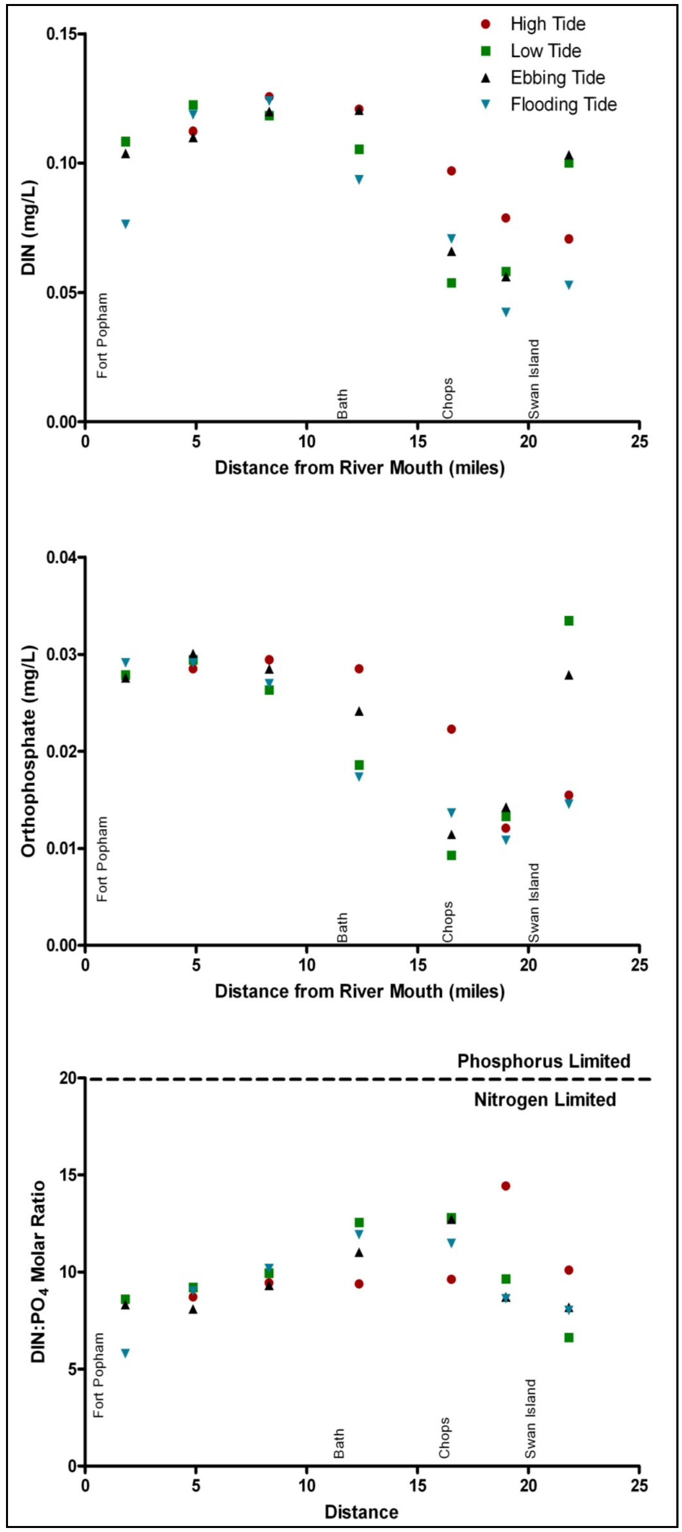

Figure 2-6. Dissolved inorganic nitrogen (DIN), orthophosphate (PO_4), and dissolved inorganic nitrogen to orthophosphate (DIN: PO_4) molar ratios for the Kennebec Estuary. Sampling occurred between Dix Island near the mouth of the estuary and Richmond on the Kennebec River above Merrymeeting Bay throughout a tidal cycle during September 1995. Distinctions between nitrogen and phosphorus limitation are drawn according to Guildford and Hecky (2000). Adapted from Mayer et al. (1996).

Although the upper river reaches are relatively isolated from large urban and agricultural nutrient pollution sources, the water quality of both systems has probably been influenced by land clearance (Köster et al. 2007) and point sources represented by industrial and municipal discharges to the rivers (Lawrance 1978; MDEP 2000; Hunt et al. 2005; Lichter et al. 2006).

During the late 1990s point sources of pollution in the Kennebec River were estimated to be responsible for 85% of the phosphorus loading below Madison, with paper mills being the primary contributor (MDEP 2000). The former S.D. Warren (now Sappi Fine Paper) paper mill alone was responsible for 34.7% of point source phosphorus loading to the Kennebec River above Merrymeeting Bay (MDEP 2000). Perhaps not surprisingly, total phosphorus (TP) concentrations in the Kennebec River (Fig. 2-5) increased markedly downstream of this mill in water quality surveys conducted in 1978, 1997, and 1998 (MDEP 1979; MDEP 2000). Between Fairfield and Gardiner, TP concentrations were actually higher during the late 1990s than they were during the late 1970s (Fig. 2-5), suggesting that both the magnitude and location of phosphorus loading to this segment of the river has changed in the 20 years between the two sampling periods. Whether this apparent trend is an artifact of the timing of several mill start-ups and shut-downs during that period remains in question. More frequent sampling would have allowed a more confident characterization of nutrient loading patterns. In the Androscoggin River, recent data have implicated phosphorus loading from paper mills as the cause of local algal blooms (McCubbin Consultants 2003).

Much of the phosphorus loading from paper mills in recent years was a result of releasing organically enriched wastewaters into the rivers (Woodward and Curran 2003; Chambers et al. 2006). Phosphate is often added in the treatment process to improve treatment efficiency (D. Courtemanch, personal communication). Hunt and colleagues (2005) found that

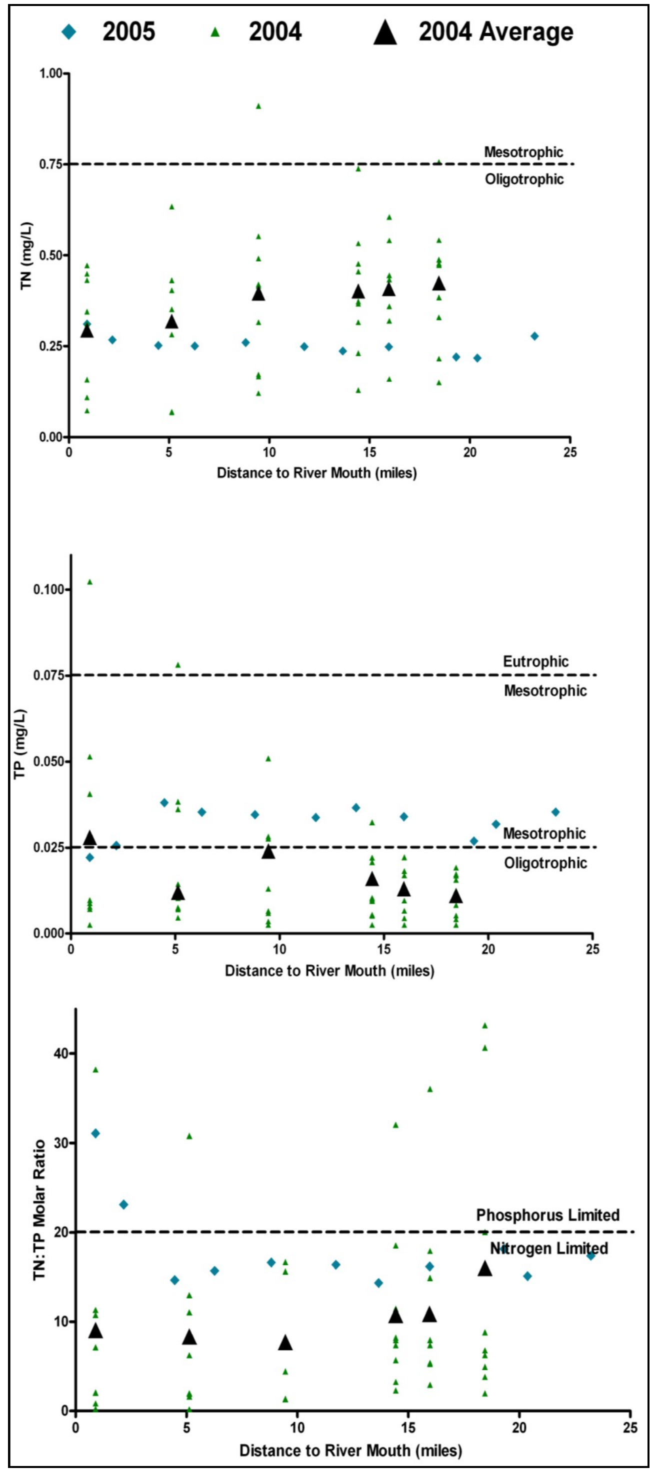

Figure 2-7. Total phosphorus (TP), total nitrogen (TN), and total nitrogen to total phosphorus (TN:TP) molar ratios for the Kennebec Estuary. Sampling occurred between Fort Popham at the mouth of the estuary and Richmond on the Kennebec River above Merrymeeting Bay around low tide. Distinctions between trophic states in the estuary based on nutrient concentrations are drawn according to USEPA (2001*a*). Distinctions between nitrogen and phosphorus limitation in the estuary are drawn according to Guildford and Hecky (2000). Adapted from Souther (2005) and 2005 unpublished data from J. Reblin and J. Lichter, Bowdoin College.

levels of dissolved inorganic nitrogen (DIN) and phosphate (PO_4) in the Kennebec and Androscoggin Rivers increased with proximity to the estuary. They also found a strong positive correlation in the Kennebec River basin between the cumulative upriver density of human populations and concentrations of nitrate and nitrite ($NO_2 + NO_3$), ammonia (NH_4), and phosphate (PO_4) (Hunt et al. 2005). In the Androscoggin River, however, only NH_4 concentrations were positively correlated with the cumulative human population density in the watershed, possibly suggesting that paper mills have a greater impact on nutrients in that river (Hunt et al. 2005). Average DIN levels ($NO_2 + NO_3 + NH_4$) for the Kennebec and Androscoggin Rivers above the head-of-tide ranged between 9.5 and 14.5 µmol/L (0.13–0.20 mg/L) (Hunt et al. 2005). Phosphate levels in the two systems ranged between 0.10 and 0.60 µmol/L (0.003–0.019 mg/L) (Hunt et al. 2005).

Few nitrogen and phosphorus data are available for the Kennebec Estuary below Merrymeeting Bay (NOAA 1997; Bricker et al. 2007). Of nine coastal rivers surveyed in New England between 1992 and 2001 as part of the U.S. Geological Survey National Water Quality Assessment Program, the Kennebec River had the lowest flow-weighted total nitrogen (TN) concentration (0.4 mg/L TN) and relatively low total phosphorus concentrations (<0.008 mg/L) (Robinson et al. 2004). Both TN and phosphorus levels were below the thresholds (0.70 mg/L and 0.025 mg/L respectively) used to distinguish oligotrophic from mesotrophic systems in the ecoregion (USEPA 2001*a*). In the most recent assessment of the Kennebec Estuary as part of the National Estuarine Eutrophication Survey, sufficient data were not available to draw conclusions about the current trophic condition of the system based on nutrient availability (Bricker et al. 2007). However, in the late 1990s the survey listed the trophic condition of the Kennebec Estuary as medium in part based on total dissolved nitrogen (between 0.1 and 1.0 mg/L) and total dissolved phosphorus (between 0.01 and 0.10 mg/L) concentrations (NOAA 1997).

In the Kennebec Estuary during the mid-1990s, DIN concentrations ranged between 0.04 and 0.13 mg N/L during the summer and between 0.19 and 0.24 mg N/L during the winter (Mayer et al. 1996), possibly indicating less uptake in winter (J. Sowles, Maine DMR, personal communication). DIN surface concentrations of less than 0.1 mg/L are considered “good” and concentrations between 0.1 and 0.5 mg/L are considered “fair” by the National Estuary Program (USEPA 2007*a*). During the summer, DIN concentrations peaked in the mid-estuary (Mayer et al. 1996). Wong and Townsend (1999) suggested that this might be caused by the transport of decomposed materials from the two ends of the estuary toward its middle. Orthophosphate and DIN levels (Fig. 2-6) in the Kennebec Estuary below Bath were similar throughout a tidal cycle (Mayer et al. 1996). Between Bath and Merrymeeting Bay, orthophosphate and DIN levels were greatest around high tide (Mayer et al. 1996), suggesting that nutrients transported from the mid-estuary nutrient maxima moved upriver to influence the nitrogen and phosphorus levels in the upper estuary.

More recently, during the summer of 2004 and fall of 2005, TN levels in the Kennebec Estuary (Fig. 2-7) were largely below the 0.75 mg/L threshold (USEPA 2001*a*) that distinguishes oligotrophic from mesotrophic systems in the ecoregion (J. Reblin and J. Lichter, unpublished data; Souther 2005). However, total phosphorus levels were more variable and sometimes exceeded the 0.025 mg/L threshold (USEPA 2001*a*) distinguishing oligotrophic from mesotrophic systems (J. Reblin and J. Lichter, unpublished data; Souther 2005). Between 1990 and 1998, average TN and TP concentrations for the sub-ecoregion including coastal and interior sections of Maine were 0.41 mg/L and 0.026 mg/L respectively (USEPA 2001*a*).

The few available TN to TP molar ratios available for the Kennebec Estuary (J. Reblin and J. Lichter, unpublished data; Souther 2005) are generally less than 20:1 (Fig. 2-7) suggesting that primary productivity in the estuary may be nitrogen limited (Guildford and Hecky 2000). This hypothesis, however, remains to be thoroughly tested. Supporting evidence may be found in the productivity of wild rice (*Zizania aquatica*) on the intertidal flats of Merrymeeting Bay, which appears to be limited by nitrogen availability (J. Lichter, Bowdoin College, unpublished data), although laboratory experiments suggest that both nitrogen and phosphorus may limit phytoplankton productivity in Merrymeeting Bay (J. Lichter, unpublished data cited in Lichter et al. 2006).

In New England coastal river systems, TN, $NO_2 + NO_3$, ammonia, and organic nitrogen concentrations are thought to increase with urbanization and watershed size (Campo et al. 2003), suggesting that future growth in the Kennebec region would result in heightened nitrogen loading. In the Kennebec and Androscoggin drainages, Boyer and colleagues (2002) found that atmospheric deposition accounted for 61% and 59% respectively of the total nitrogen inputs to the watersheds. The total atmospheric deposition of ammonia and nitrate to terrestrial ecosystems has increased from an estimated 17 Tg N (1 Tg or teragram, about 2.2 trillion pounds) per year in 1860 to 64 Tg N per year in the early 1990s, and is projected to increase to 125 Tg N per year by 2050 (Galloway et al. 2004). This suggests that atmospheric deposition of nitrogen to the Kennebec and Androscoggin watersheds may increase in the near future which would probably result in increased nitrogen availability in the rivers and increased productivity.

The extent to which past nutrient loading will continue to impact water quality in the estuary is unknown. Phosphorus sequestered in sediments when water quality was significantly worse (Köster et al. 2007) can be released back into the water column and contribute to eutrophication much later (Coelho et al. 2004). This mechanism is enhanced if sediment and overlying waters are anoxic, a condition that in the past contributed to phosphorus release but should not occur under present water quality conditions (D. Courtemanch, personal communication).

Conclusions

Although sparse, data for some indices of water quality in the Kennebec Estuary (most notably dissolved oxygen) suggest that waters of this system have dramatically improved since the 20th-century peak of cultural eutrophication. Based on federal government benchmarks for productivity, the system is currently classified as either nutrient-poor or moderately enriched by nutrients, also indicating a remarkable improvement since implementation of the Clean Water Act. Beginning in the late 1980s, the state of Maine has progressively upgraded the water quality standards for the Kennebec and Androscoggin Rivers, their confluence in Merrymeeting Bay, and the marine waters of the Kennebec Estuary (D. Courtemanch, personal communication).

However, use of environmental proxies, such as diatom community composition, suggests that the upper estuary may be overly productive (compared to historical conditions), apparently due to nutrient-rich conditions that favor shade-tolerant species. Submerged aquatic vegetation distributional trends (discussed in the next chapter) also suggest that light-limiting conditions may prevail in waters of the upper estuary. The contrasting characterizations of water quality based on either traditional nutrient benchmarks or plant community condition or other ecological indices suggests that a reevaluation of monitoring protocols is warranted. In particular, augmenting traditional water quality criteria with more ecologically meaningful indicators of system health is likely to offer considerable benefits. In other systems, including the nearshore Gulf of Maine (Steneck et al. 2002), dramatic environmental disturbances such as depletion of key marine species have led to alternate stable states or regime shifts that are resistant to restoration efforts. On Merrymeeting Bay, the lack of a robust response by some aquatic plant communities under apparently improving water quality conditions may suggest that the upper estuary has experienced such a shift. Under those conditions, the Kennebec Estuary may require a significantly different water quality restoration strategy than has been employed so far.

Recent work indicates that major challenges to achieving improved water transparency in Merrymeeting Bay may originate in the smaller drainages feeding the Bay. Limited data suggest that these smaller drainages contribute considerable amounts of suspended solids to the Estuary (Burton 2007). The unquantified contribution of carp-associated sediment disturbance will also complicate attempts to identify the major causes of turbidity in the upper estuary. In the absence of expanded sampling and development of mass balance modeling, determining with any certainty the major sources of turbidity in the Kennebec Estuary will remain an elusive goal. Likewise, without a better understanding of the processes and potential factors influencing local water quality conditions in the estuary, the need for and feasibility of adjustments to current water quality management will remain uncertain.

Overall, the findings of this section suggest that continuing the dialogue on water quality is necessary not only to meet new challenges but also to reinvigorate restoration progress. In this discussion, particular focus should be given to the development of water quality benchmarks that are relevant to local ecology and management goals. For example, integrating ecosystem indices and benchmarks, such as acreage and condition of SAV, into water quality characterizations may provide more ecologically meaningful restoration and management targets.