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EFFECTS OF TIDAL RESTRICTIONS AND POTENTIAL BENEFITS OF TIDAL RESTORATION ON FECAL COLIFORM AND SHELLFISH-WATER QUALITY

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ABSTRACT The relationship between artificial tidal restrictions and shellfish-water quality was studied within otherwise sparsely developed estuaries on Cape Cod (Massachusetts, USA). The primary study site, the 600-ha diked Herring River (Wellfleet, MA) estuary, has had a long history of shellfish-water closures because of water-column fecal-coliform (FC) contamination despite the lack of human fecal sources. Ongoing efforts to restore tidal flow to the system have raised questions about the effects on microbiological water-quality on extensive beds of wild oysters (*Crassostrea virginica*) and cultured hard clams (*Mercenaria mercenaria*) in the river mouth. This study combines observations of current spatial and temporal (tidal) patterns of water-column contamination with recent hydrodynamic modeling to predict the effects of proposed tidal restoration on shellfish-water quality. Under presently tide-restricted conditions, high FC is restricted to about 1000 m on either side of the dike structure and only during low tide, preventing the harvest of extensive natural oyster beds; farther downstream, hard-clam aquaculture is marginally protected by relatively coliform-free, high-salinity Cape Cod Bay waters. Modeling of Herring River under tide-restored conditions showed that a predicted 13-fold increase in river intertidal volume, over existing tide-restricted conditions, would dilute measured FC to concentrations that are acceptable for shellfish-growing waters. Restored tidal flow would also reduce coliform survival time by increasing salinity, dissolved oxygen and pH, all presently depressed throughout the system because of the biogeochemical disturbance of diking and drainage. Results from Herring River, plus a preliminary survey of other diked Cape Cod estuaries, suggest a direct relationship between the degree of tidal restriction and surface-water FC, which should be studied further.

KEY WORDS: fecal coliform, diking, salt-marsh restoration, aquaculture

INTRODUCTION

Efforts to restore native habitats in historically tide-restricted salt-marsh estuaries primarily focus on removing artificial barriers to tidal exchange. In the context of past diking, filling and drainage, it is generally agreed that re-establishment of the original hydrology, hydrography, and salinity distribution is fundamental to restoring an estuarine ecosystem (Niering & Warren 1980, Burdick et al. 1997, Roman et al. 1995). Although this is an ecologically reasonable approach for restoring dominant estuarine processes and biota, actual restoration management must also consider human-land-use changes that can affect the nature, and social acceptability, of system response.

A most obvious recent land-use change along the US coast is the rapid increase in human population and development. One outcome of the development increase has been an apparent decline in microbiological water quality, typically monitored using coliform indicator bacteria. In particular, fecal coliform (FC) contamination has forced the closure of shellfish beds throughout the US coasts. Although this pollution is usually attributed specifically to an increase in development-related sources (e.g., agriculture, impermeable-surface runoff and wastewater, Mallin et al. 2001), coastal development has also likely affected bacterial transport and dilution, through altered coastal hydrography including tide restrictions.

Tides were first restricted in New England coastal wetlands, predominantly for road and railway construction and mosquito control, in the late 19th and early 20th centuries. Tide restrictions reduce the tidal prism and thereby limit seawater flushing and dilution of constituents delivered to the estuary in discharging freshwater; this dilution is reduced both landward and seaward of the restricting structure. In this purely physical way, tide restrictions may effectively increase fecal coliform concentrations in coastal waters. Increasing development, road runoff and bacterial loading would have exacerbated the problem.

In addition, disturbance to salt marsh biogeochemical cycling and resulting water-quality degradation caused by diking could contribute to FC survival and management problems in diked wetlands. The blockage of tides reduces salinity; tide-restricted marshes are poorly flushed, leading to high oxygen demand and low summertime dissolved oxygen (Portnoy 1991); and drainage causes acid sulfate soil formation and low water-column pH (Gosling & Baker 1980, Sammut et al. 1995, Portnoy 1999). Low salinity increases coliform survival times in the environment (Carlucci & Pramer 1960, Goyal et al. 1977, Morinigo et al. 1990, Coelho et al. 1999, Lipp et al. 2001, Gabutti et al. 2000, Mallin et al. 2000, Bordalo et al. 2002).

Conversely, tidal restoration would reduce fecal bacteria concentrations, regardless of their source, first through simple dilution because of a much-increased tidal prism. In addition, increased salinity would reduce the survival time of enteric bacteria in the environment, as studies elsewhere have consistently demonstrated (Mallin et al. 1999, Coelho et al. 1999, Gabutti et al. 2000, Mallin et al. 2000, Lipp et al. 2001). Finally, laboratory and field experiments have shown that tidal restoration can quickly restore water-column pH (Portnoy & Giblin 1997a, Easton & Marshall 2000), further depressing coliform survival.

Chronically high fecal coliform and shellfish-waters closures just seaward of a large Cape Cod estuary planned for tidal restoration prompted this study. Extensive beds of eastern oyster (*Crassostrea virginica*, Gmelin 1791) up to 2 km seaward of the diked 600-ha Herring River estuary (Wellfleet, MA, USA) have been closed, at least seasonally, because of fecal coliform contamination since state-wide surveillance increased about 1983. With the largest hard clam (*Mercenaria mercenaria*, Linnaeus 1758) aquaculture beds in Massachusetts just seaward of the zone of chronic closures, there was public concern that tidal restoration could extend the FC problem to close a highly productive fishery. Coastal

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wetlands can be important sources of public-health indicator bacteria, reportedly because of the abundance of organic matter, nutrients and high water-column turbidity promoting bacteria survival (Jenson et al. 1980). Enterocci produced in a California tidal marsh affected surf-zone water quality under specific near-shore flow conditions (Grant et al. 2001).

The Herring River estuary is largely undeveloped, with very few cesspools or septic systems near the river and few road crossings, because of incorporation of 80% of the floodplain into Cape Cod National Seashore in 1961. Therefore, we began the study with the assumption that wildlife within the river basin was probably the major ultimate source of FC in surface water. Waterfowl and other birds can be abundant in or near the river and are probably a major ultimate source of coliform bacteria; these microbes can reportedly survive and perhaps grow in sediment (Gerba & McLeod 1976, Struck 1988). If this is the case for Herring River, bacteria could be resuspended with surficial sediment during periods of high freshwater discharge and/or tidal flow, to constitute an important proximate source to the receiving water column (Mallin et al. 1999, Grant et al. 2001). Because this source has not, given land-use history, recently changed, nor is it likely to substantially change with tidal restoration, we focused instead on the water quality and hydrodynamic factors that would affect coliform survival and transport under both existing and tide-restored conditions. The general goal was to use existing conditions together with recent hydrodynamic modeling results (Spaulding & Grilli 2001, 2005) to predict the effects of tide restoration on bacteria concentrations in downstream shellfish-growing waters.

Specific objectives were: (1) to describe where and when public-health bacteria contaminate presently restricted estuarine surface waters and (2) to predict how restored tidal exchange would affect shellfish-water quality.

STUDY AREA

Herring River

The 600-ha Herring River estuarine complex (42°N, 70°W), occupying a glacial outwash valley on the eastern shore of Cape Cod Bay (Fig. 1), is the largest diked wetland system on Cape Cod (Portnoy 1991). Tidal flow to most of the original salt marsh was eliminated by inlet closures in the eighteenth and nineteenth centuries, and by a dike built across the mouth of the main stream in 1909. Stream channelization and ditch drainage began before dike construction but intensified immediately thereafter; channel and ditch maintenance continued until 1984. The modern dike structure includes three 4-m^2 rectangular sluiceways providing a large opening for freshwater discharge (ranging 0.2–0.5 $m^3\ s^{-1}$) at low tide. During high tide, hydraulic pressure closes top-hinged doors (clapper valves) on two of the sluiceways, preventing seawater flow upstream. The third sluiceway is partially open (cross-sectional area about 1 m^2) allowing some seawater entry; however, seawater flow up the main channel and onto the diked marsh surface is limited to 1,000 m upstream. The dike reduces tidal range from about 2.1 m seaward, to 0.5 m landward of the structure. At high tide in the river, saltwater extends only to Station 3; at low tide, salinity at the dike is about 15 ppt, decreasing to 0–3 ppt at Station 4 (Fig. 1). Because of the previously mentioned lack of tidal flushing and biogeochemical disturbance, the river above the reach of seawater suffers from low pH and low dissolved oxygen (Soukup & Portnoy 1986, Portnoy 1991). Approximately 15 ha of natural

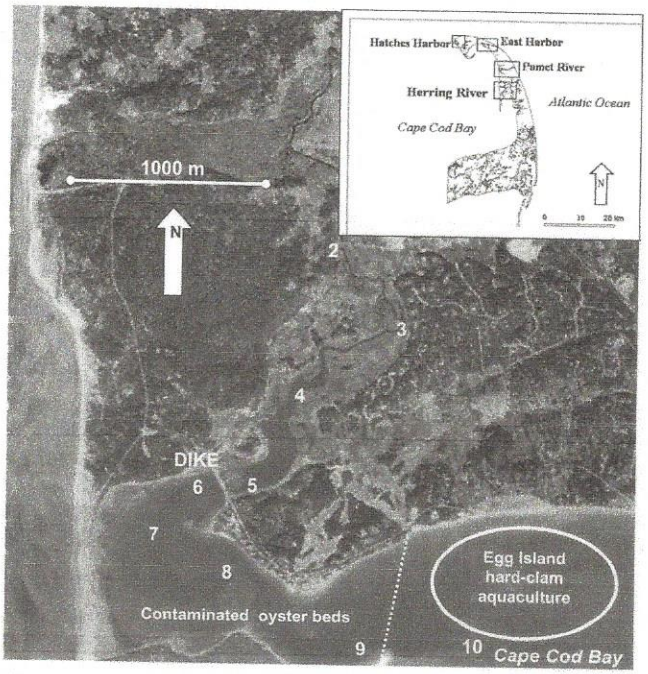

Figure 1. Herring River study area, water-quality sampling stations and location of hard-clam aquaculture and oyster beds. Inset: location of Herring River and other study sites on outer Cape Cod.

oyster beds and 20 ha of hard-clam aquaculture (Egg Island) at the river mouth, and seaward of the dike, are indicated on Figure 1.

Historic photographs taken just before the 1908 diking show an apparently continuous stand of salt marsh grasses along the shore of the Herring River. Core analyses by R. A. Orson (Roman 1987) documented the presence of smooth cord grass (*S. alterniflora, Loisel*) on the floodplain presently vegetated with velvet grass (*Holcus lanatus*, Linnaeus)), meadowsweet (*Spiraea latifolia*, Ahles) and hardhack (*S. tomentosa*, Linnaeus) goldenrod (*Solidago* spp.) and black cherry (*Prunus serotina*, Ehrhart). Because of peat drainage, pore-space collapse and accelerated decomposition (Portnoy & Giblin 1997b), the marsh surface elevation is 0.95–1.01 m NGVD (National Geodetic Vertical Datum), or about 90 cm below modern unaltered *Spartina* marsh seaward of the Herring River dike.

Regarding sources of FC, impermeable surfaces comprise only two paved secondary roads crossing the floodplain, and there is only one domestic wastewater disposal system within 20 m of surface waters. Waterbirds, primarily waterfowl (Anseriformes), are seasonally abundant and probably a principal source of coliform in the river system (Valiela et al. 1991).

Other Sites

The relationship between the degree of tidal restriction and low-tide FC concentrations was studied at several other Cape Cod estuaries in summer 2005. Pamet River (Truro, MA) has been completely tide restricted since about 1867, with no seawater passing through a dike that cuts off all tidal flow from the upper 64 ha of this wetland. The diked wetland is vegetated with freshwater-wetland shrubs, narrow-leaved cat-tail *Typha angustifolia* (Linnaeus) and common reed (*Phragmites australis*, Trinius).

East Harbor (Truro, MA) is a 145-ha back-barrier lagoon and 150-ha emergent wetland, also isolated by diking from the marine

environment since about 1868. Salinities have increased greatly in the East Harbor lagoon since 2002, from 4–20 ppt, when clapper valves in its drainage culvert were opened to improve flushing; however, tidal range remains <0.5 m in creeks immediately above the culvert, and 0 in the lagoon proper because of the small diameter of the culvert relative to lagoon volume. The East Harbor emergent marsh is vegetated with freshwater shrubs, *Typha angustifolia* and *Phragmites australis*.

Hatches Harbor (Provincetown, MA) is a 170-ha back-barrier salt marsh bisected by a dike in 1930; large culverts were installed in this dike and gradually opened beginning in 1999 so that to date (2005) nearly all restriction on tide height and salinity distribution has been removed. As a result of increased salinity, salt marsh herbs are replacing an extensive stand of *Phragmites*.

Like Herring River, these other coastal floodplains are within Cape Cod National Seashore, are consequently sparsely developed and have few sources of anthropogenic coliform pollution.

METHODS

At Herring River, water and sediment sampling focused on nine sites spaced roughly 0.5–1.0 km apart along the main stem from above the reach of seawater (Station 2) to the mouth of the river at Egg Island (Station 10), a sandbar in Wellfleet Harbor used intensively for bivalve aquaculture (Fig. 1). Other estuaries were sampled within 50 m above and below road crossings that restricted tidal flow. Most sampling effort was directed toward FC bacteria because this group is the water-quality standard for shellfish-growing waters per the US Food and Drug Administration's National Shellfish Sanitation Program. Field-work, including periodic surface-water sampling and sediment collections, was conducted from May through October of 2005. Following preliminary surveys of FC throughout the tidal cycle, sampling focused on low tide to characterize worst-case conditions.

Sediment

Sediment was collected by Ponar dredge on two dates at water-quality stations in Herring River. Dredged sediment was dropped upright into a basin and the top 2 cm transferred to a sterile cup using a flame-sterilized spoon. To control for expectedly high spatial variability, three randomly located grabs were collected at each sampling station and combined together in equal volumes.

In the laboratory, these composited samples were thoroughly mixed to homogenize. 20 g of wet sediment were removed aseptically, mixed with 200 mL of phosphate buffer, shaken for 45 min, and allowed to stand for 30 min. *E. coli* MPN (most probable number) in 100 mL of the supernate was determined using the Colilert-18 system (IDEXX Laboratories, Westbrook, Maine); incubation temperature was 35°C. Remaining sediment was dried at 105°C, dry-sieved for particle size distribution and combusted at 550°C. for 2 h to determine organic content. Bacteria concentrations were computed per unit of dry sediment weight.

Water

Surface-water samples were collected aseptically at about 10-cm depth, transported to the laboratory at 4°C and cultured for FC using the membrane filtration method at 44.5°C on M-FC agar with rosolic acid (APHA 1998) within six hours of collection. All water samples were collected and cultured for FC in duplicate; data are presented as means ± 1 SD. On two dates (August 4 and 11, 2000), samples from all Herring River stations, plus Hatches Harbor, East Harbor and Pamet River study sites were also tested for *E. coli* using the Colilert-18 system; as for sediment (above) incubation temperature was 35°C; results are presented as MPN (most probable number) per 100 mL. The Colilert system has been shown to perform as well or better than traditional membrane-filtration methodology for these bacterial indicators (Yakub et al. 2002).

Note that for Herring River sediment, *E. coli* was cultured, as opposed to FC in water samples; this was simply because an FC method was not available for sediment using the IDEXX system. We therefore do not directly compare densities of FC in water and *E. coli* in sediment, but rather compare their respective spatial patterns along the estuarine salinity gradient. *E. coli* is of course a major component of fecal coliform.

Salinity was measured by refractometer. Turbidity was measured with a Hach 2100P turbidimeter, calibrated with primary formazin standards.

RESULTS

Sediment

Highest *E. coli* concentrations were found in sediment at stations 200–1,400 m above the dike (Fig. 2). Because of the tide restriction, this is a reach of limited tidal range and flood-tide velocity; therefore, fine particles tend to deposit directly into the channel. In comparison, concentrations above this river reach were relatively low on both sampling dates. Immediately seaward of the dike, sediment bacteria were moderately high in July but low in August. From about 500 m of the dike structure to the channel south of Egg Island, *E. coli* was low to undetectable on both sampling dates. Bacteria density was related to sediment physical properties as measured at these sampling locations (Table 1): *E. coli* appeared highest in relatively fine-grained sediments with low bulk density and high water content.

Surface Water

A preliminary survey in May 2005 of surface-water FC at 30 min intervals from midebb to midflood tide just seaward of the dike structure (Station 6, Fig. 1), showed that highest concentrations occurred at lowest salinities coinciding with low tide in the diked river (Fig. 3). In addition, a survey of all nine river stations at both low and high tides on the same date in October (Fig. 4) showed a similar relationship between tidal stage and FC: essentially, FC varied inversely with salinity at stations 5 through 10 from just above to 2,000 m seaward of the dike; FC at Stations 2–4 in the diked river proper was similar at both high and low tide. Given these observations, to characterize worst-case conditions most other water sampling was conducted at low tide.

Repeated low-tide sampling throughout the summer months corroborated the relationship between FC and position along the river main stem (Fig. 5): FC was low to moderate at Stations 2 and 3, high at Stations 4 through 8, about 1,000 m above and below the dike, respectively and very low at Stations 9 and 10. On September 18, Tropical Storm Ophelia delivered one of only two substantial (>1 cm) rain events during the summer to the study area. During the resulting freshet, low-tide FC increased 2- to 4-fold at Stations 2 through 8, and about 80-fold at Stations 9 and 10; however, the same relationship between FC and river reach was observed as during drier weather, albeit with much higher values, indicative of increased FC discharge from upstream wetlands (Jenson et al.

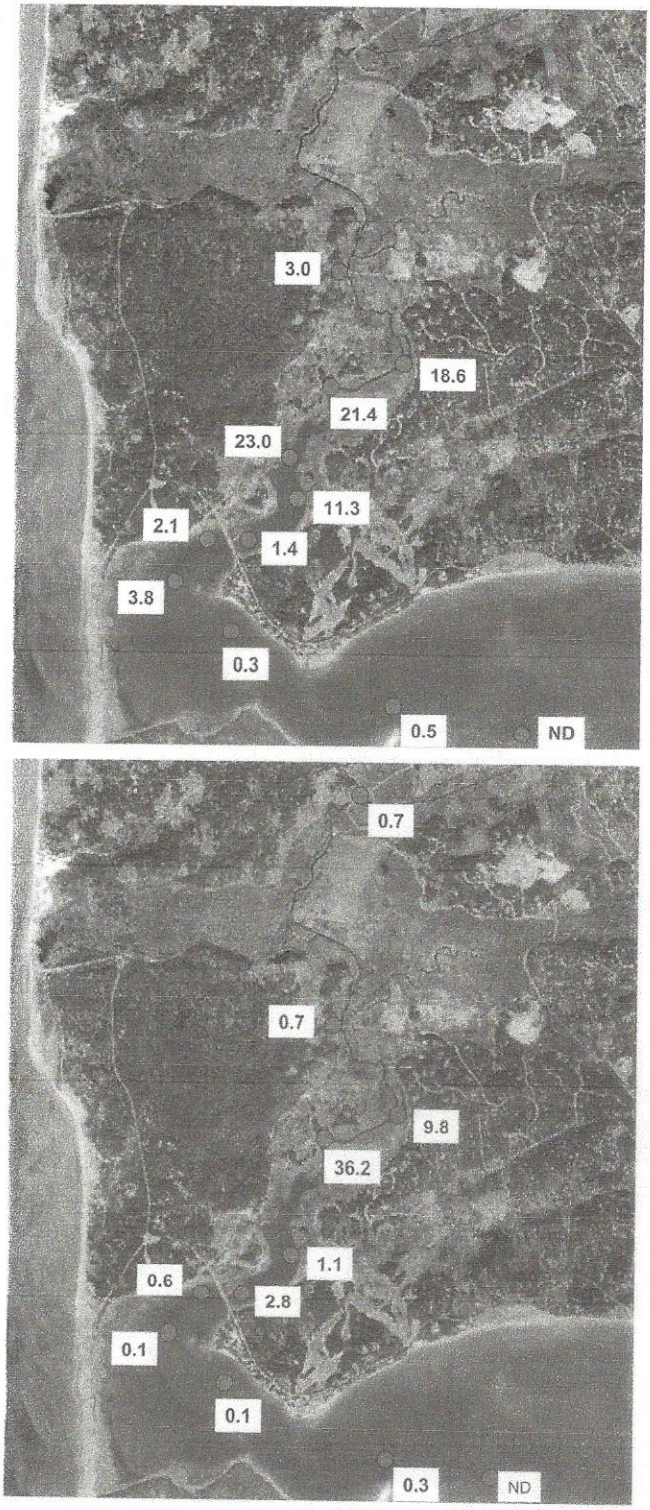

Figure 2. *E. coli* concentrations (colony forming units per g DW) in Herring River sediment on July 20 (top) and August 16 (bottom) 2005.

1980). Concentrations returned to background dry-weather conditions 5 days after the September 18 rain event.

Although highest low-tide, surface-water concentrations of FC consistently occurred at and just seaward of the river reach with highest sediment stocks of *E. coli* (Fig. 2), FC did not vary with

TABLE 1.

Correlation coefficients (Pearson's *r*) between *E. coli* concentrations and sediment physical properties at Herring River stations in summer 2005; $n = 22$. Significance levels are given in parentheses.

Collection Date	Median Grain Size	Water (%)	Organic Matter (% DW)	Bulk Density (g cc^{-1})
20 Jul	−0.638	0.610	0.496	−0.650
	(0.03)	(0.05)	(0.12)	(0.03)
16 Aug	−0.514	0.430	0.286	−0.445
	(0.11)	0.18)	(0.39)	(0.17)

turbidity as from suspended sediment ($R^2 = 0.08$, $P < 0.05$). A plot of all turbidity and FC observations versus salinity showed a complex relationship (Fig. 6), with high turbidity at both freshwater and marine end members, and moderate and low FC respectively; lowest turbidity corresponded with highest fecal coliform concentrations at low-tide salinities of 10–25 ppt, typically within 1,000 m above and below the dike.

Physical Effects of Tidal Restoration

Hydrodynamic modeling, conducted to assess physical alternatives for tide restoration (Spaulding & Grilli 2001, 2005), showed that tidal range could increase from 0.5–2.0 m, and intertidal volume from about 73,000–980,000 m^3. Assuming most of the water that exited the river during the ebb did not return during subsequent flood tides, as evidenced by consistently high flood-tide salinity, the increase in intertidal volume amounts to a 13.4-fold increase in the dilution of river water. Given this dilution factor, and assuming that bacterial loading does not increase, restored tidal flushing should reduce coliform bacteria to concentrations below the standard for shellfish waters (Fig. 7), except for low-tide periods 2–4 days after heavy rain.

Other Study Sites

Although seasonal use by waterfowl, larids and roosting passerines may be one factor contributing to high FC above the Herring River dike structure (Moles 2005), another appears to be the effect of tide restriction itself on water and sediment quality. This is supported by less intensive sampling in the other large diked salt marshes on Cape Cod. We noted on two sampling dates in midsummer that low-tide FC and *E. coli* in the water column at Pamet River and both East and Hatches Harbors related directly to the degree of tidal restriction, indicated by depressed low-tide salinity (Fig. 8).

DISCUSSION

Current Hydrographic Conditions

Chronically high surface-water FC occurred in the principal zone of river- and bay-water mixing, where low-tide salinities ranged from 10–25 ppt; this zone extended about 1,000 m on either side of the dike tidal restriction. Sediment in the upstream reaches of this zone (e.g., Stations 3 and 4, Fig. 1) had high *E. coli* and may have been the proximate source. Abundance of *E. coli* in Herring River sediment corresponded with an open-water habitat above the dike that was highly attractive to waterfowl and larids (Portnoy et

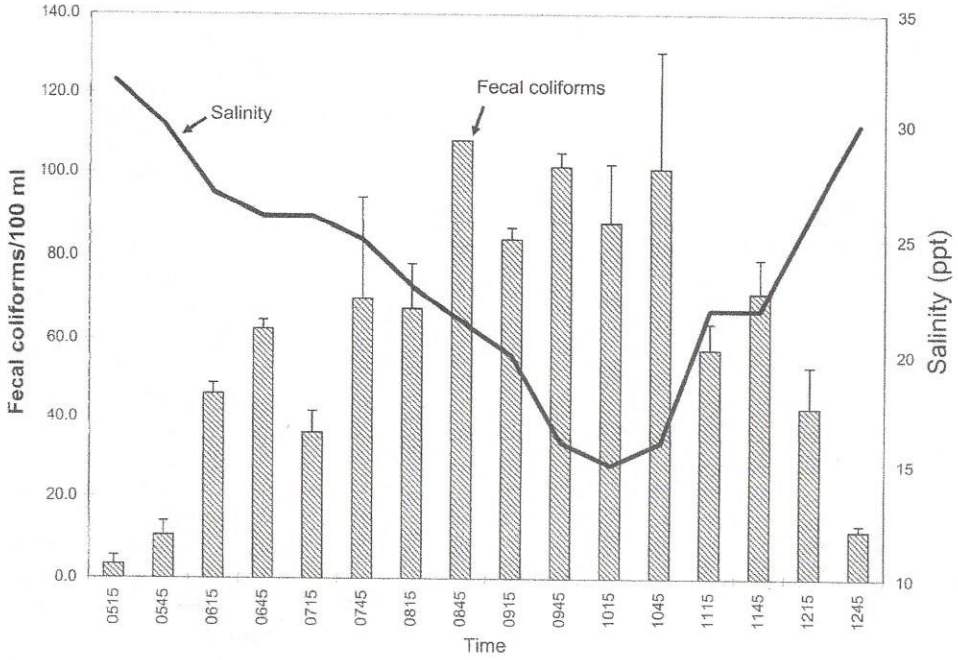

Figure 3. FC concentrations (±1 SD) and salinity in Herring River surface water from midebb to midflood tide, May 26, 2005.

al. 1987) and roosting passerines; it is likely that these animals seed the river sediment with coliform bacteria in their droppings. There is increasing evidence that fecal coliform can survive and even grow in the environment, especially in sediment (Gerba & McLeod 1976, LaLiberte & Grimes 1982, Struck 1988, Davies et al. 1995, Grant et al. 2001). Their survival time in sediment would be extended by low salinity (Mallin et al. 2000, Lipp et al. 2001, Anderson et al. 2005), low pH (Carlucci & Pramer 1960), and high sediment organic content (Gerba & McLeod 1976, Matson et al. 1978, LaLiberte & Grimes 1982)—the very conditions that prevailed in Herring River because of the restriction of tides and ditch drainage (Portnoy 1999).

FC concentrations in river surface water were clearly dependent on tidal stage and the amount of fresh water from the high-FC zone just above the dike relative to the high-salinity, and comparatively low-FC, Cape Cod Bay end member (Fig. 3, 4). Low-tide surveys consistently showed that high FC, exceeding the USDA shellfish-waters standard of 14 CFU (colony-forming units) per 100 mL, was the norm for all river stations; in contrast, dry-weather FC was always low at the most seaward Stations 9 and 10 (Fig. 5), demonstrating the predominance of Cape Cod Bay water in the salt and water budget of Wellfleet Harbor. It should be noted, however, that the protection afforded Wellfleet's Egg Island aquaculture industry by clean Cape Cod Bay water was marginal,

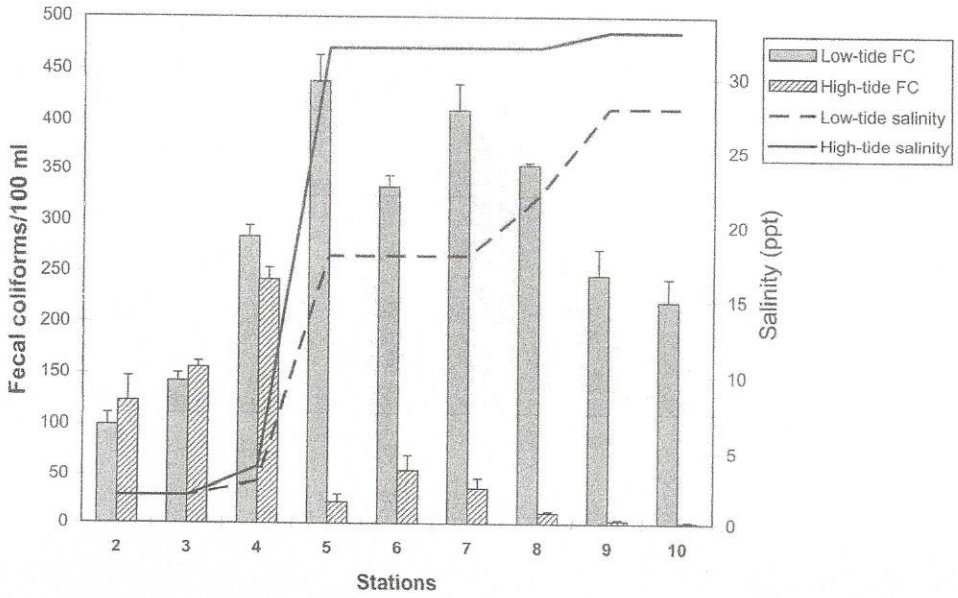

Figure 4. Low- and high-tide salinity and fecal coliform (±1 SD) in Herring River, October 20, 2005.

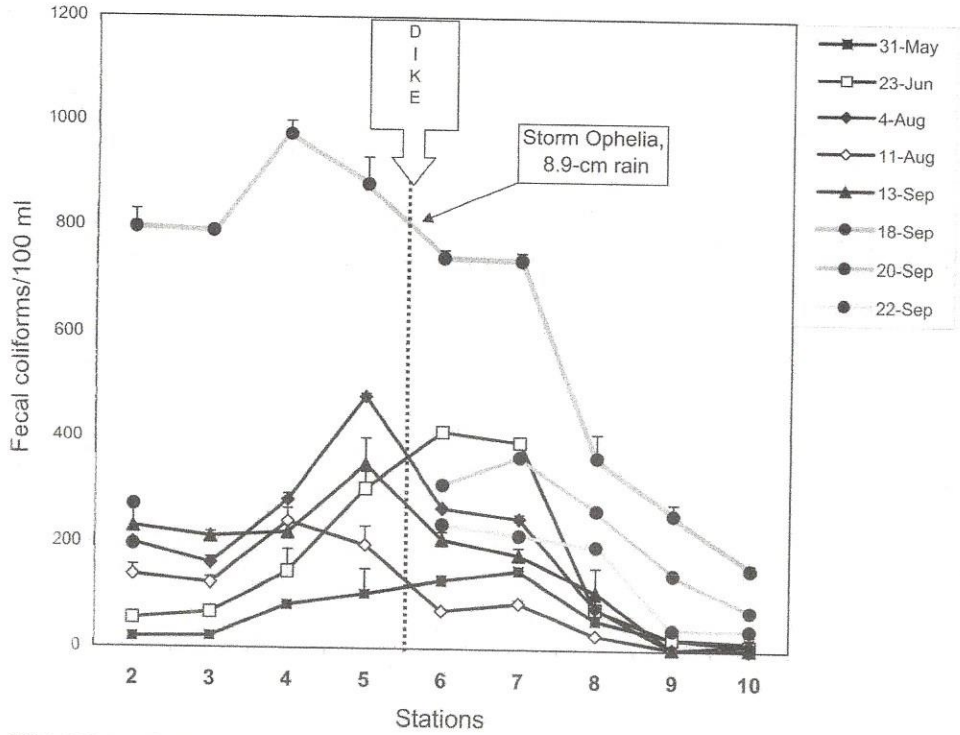

Figure 5. Low-tide FC (±1 SD) at Herring River stations throughout the 2005 summer including days one (Sep 18), three (Sep 20) and five (Sep 22) after a 8.9-cm rain event.

with observed violations of the water-quality standard during wet weather (Fig. 5). Meanwhile, under current tide-restricted conditions, the extensive oyster beds in the river mouth between Stations 5 and 9 (Fig. 1) were chronically contaminated and closed to shellfish harvest.

Fecal coliforms are often associated with sediment (Faust et al. 1975, Valiela et al. 1991) and can be released into the water column by sediment disturbance (Rittenberg et al. 1958, Matson et al. 1978, Coelho et al. 1999, Mallin et al. 1999, Mallin et al. 2000). This can be a concern in tide-restoration projects if hydrodynamic changes trigger resuspension of FC-rich sediment into bathing or shellfish waters. However, FC has not always correlated well with

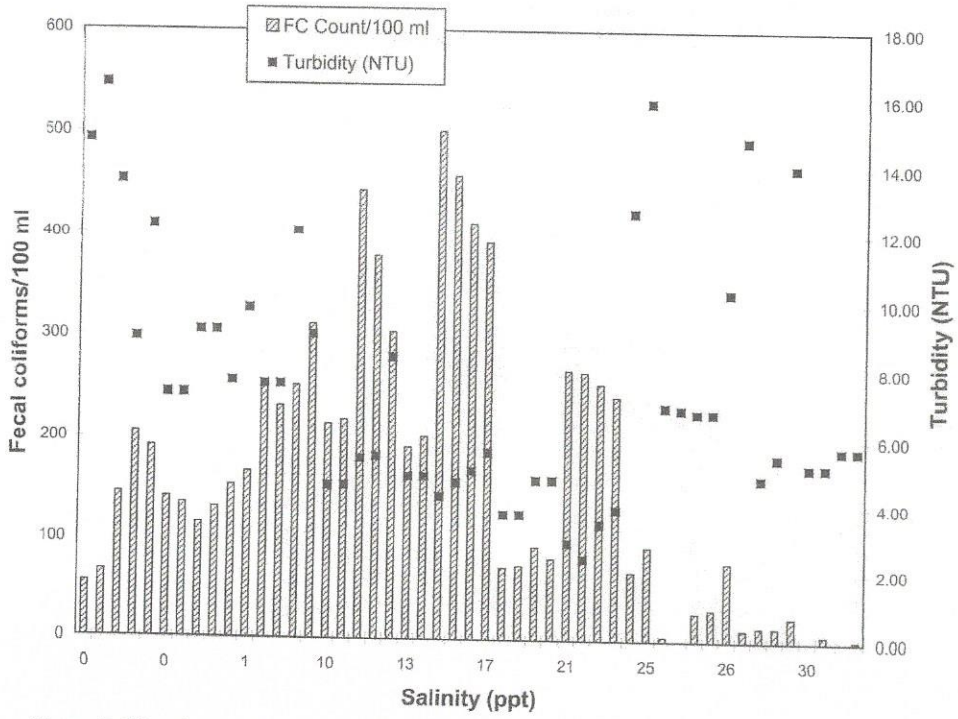

Figure 6. FC and turbidity across the Herring River salinity range, all summertime observations.

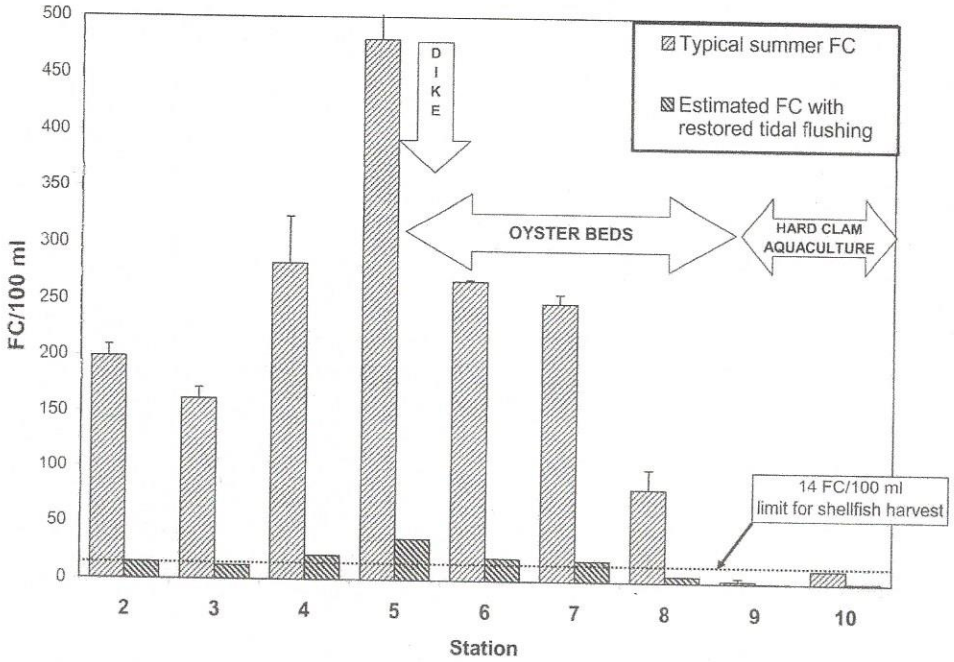

Figure 7. Estimated dilution effects on Herring River fecal coliform concentrations, relative to shellfish-waters standard, given model-predicted increase in intertidal volume and flushing with tidal restoration. Also shown are locations of oyster and hard clam beds relative to river sampling stations.

turbidity as a measure of sediment resuspension in studies elsewhere (Goyal et al. 1977, Jenson et al. 1980). Indeed, sediment resuspension did not appear to be an important mechanism affecting microbiological water quality under existing conditions in Herring River. Highest FC observed in the river channel corresponded with the lowest turbidities, and midrange salinities (10–25 ppt); highest turbidities were at opposite ends of the salinity gradient (Fig. 6). The high turbidity at the river mouth (Stations 6–10) was apparently caused by the flocculation of dissolved organic matter and complexed Fe as salinity and ionic strength increased (Fig. 6), a process that is well described for rivers world-wide (Boyle et al. 1977); it was not the result of sediment resuspension. Thus, as

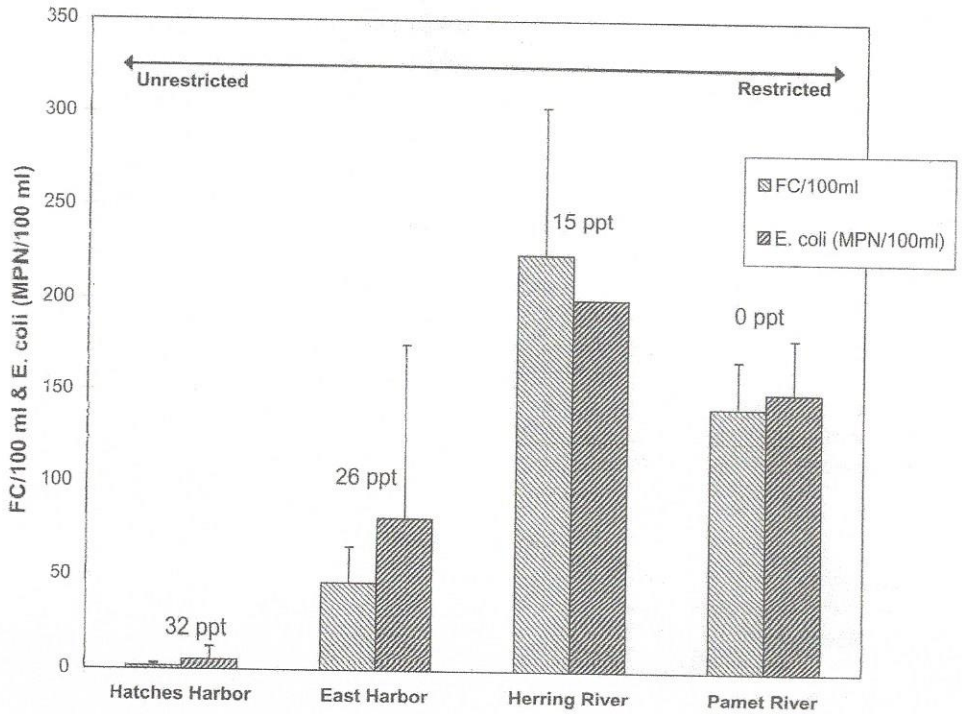

Figure 8. Typical summer fecal coliform and *E. coli* concentrations (mean ± SD, $n = 2$) in tide-restricted and restored Cape Cod estuaries at low tide. The degree of anthropogenic tidal restriction is indicated by low-tide salinity, indicated over bars; with no restriction, low-tide salinity would be about 30–32 ppt.

river water mixed with seawater at the river mouth during ebb tide, turbidity rose and FC declined. High FC at midsalinity Stations 4–8 may have nevertheless been caused by tidal stirring in the river channel (Mallin et al. 1999) that was sufficient to resuspend a bacteria-rich surface film, but insufficient to lift enough sediment to increase measured turbidity significantly. Hydrodynamic modeling results indicate that channel velocities in a tide-restored river would be insufficient to resuspend sediment (see below).

Effects of Tidal Restoration

Besides dilution (Fig. 7), other factors associated with restored tidal flow would depress coliform concentrations even more in a tide-restored Herring River estuary. Restoration will cause a radical change in water chemistry (Portnoy 1999, Spaulding & Grilli 2001). As mentioned, the survival time of enteric bacteria is reduced by high pH (Carlucci & Pramer 1960) and high salinity (Goyal et al. 1977, Bordalo 2002). With tidal restoration, low-tide salinities just above and below the dike structure would increase from the present 20–25 ppt to 30–32 ppt (Spaulding & Grilli 2005), decreasing coliform survival. The resaturation of current acid-sulfate soils (Portnoy & Giblin 1997b) with seawater would rapidly (weeks to months) restore circum-neutral pH of marsh peat and receiving waters (Portnoy & Giblin 1997a). In addition, the physical alternative for restoration comprises a wide culvert, which will not only increase high tide heights but will also improve low-tide drainage (Spaulding & Grilli 2005), greatly improving tidal flushing with generally oxygen-saturated seawater; this should alleviate summertime oxygen stress in the diked estuary (Portnoy 1991). All of these water-quality factors should drive bacteria concentrations below that expected with simple tidal dilution. Meanwhile, although the hydrodynamic modeling indicated that channel velocities would not increase enough to resuspend potentially FC-rich sediment (Spaulding & Grilli 2005), somewhat increased flood-tidal flow velocity and much-increased tide heights would shift fine-sediment deposition from river channels to the wetland surface, where both dessication and light would depress FC survival (Bordalo et al. 2002). Finally, under existing tide-restricted conditions, Herring River sediments with highest FC content are flooded throughout the tidal cycle; tide restoration and better low-tide drainage would expose these sediments to solar UV radiation, further reducing viable bacteria (Fujioka et al. 1981, Sinton et al. 2002) on or near the sediment surface.

Other Study Sites

Although many other differences among Pamet River and Hatches and East Harbors could have affected enteric bacteria, results were consistent with relationships observed at Herring River between the degree of tidal restriction and microbiological water quality. All three tide-restricted sites, except recently tide-restored Hatches Harbor, have established conditions that promote FC retention and survival: specifically depressed tidal flushing, water-column salinity, pH, aeration and increased deposition of fine sediments in main creek channels.

CONCLUSION

The source of fecal bacteria in outer Cape Cod's restricted, but otherwise mostly undeveloped, estuarine watersheds is probably wildlife. Because land use has changed little in many decades, and it is not likely to change significantly in terms of wildlife use of coastal wetlands, attempts to limit this coliform source are unlikely to succeed. Even if it is assumed that FC from wildlife is a good indicator of the presence of human pathogens (Griffin et al. 2001), there would probably be strong public opposition to discouraging wildlife activity. Also, waterfowl (at least) are most abundant during winter when shellfish harvest is limited (Valiela et al. 1991, Weiskel et al. 1996). As an alternate approach, this study suggests that the hydrologic restoration of tide-restricted salt marshes may help to improve shellfish-water quality among its many other social and ecological benefits (Roman et al. 1995, Burdick et al. 1997).

Regardless of the bacterial source, tide restriction has created water and sediment conditions behind dikes that favor coliform accumulation and survival. With limited flushing by relatively coliform-free Cape Cod Bay water, ebb tides carry bacteria-laden Herring River water to downstream shellfish beds, closing many hectares of oysters and threatening extensive hard-clam aquaculture. In addition, the dike's restriction on semidiurnal flooding with aerobic seawater has caused oxygen stress and low salinity; and effective peat drainage has led to high acidity—all of which extend bacteria survival times.

Given observed spatial and temporal (tidal) patterns of water-column fecal coliform abundance in the diked Herring River, the projected physical and water-chemical effects of tidal restoration should cause a substantial improvement in bacteriological water quality. Aside from increases in salinity, dissolved oxygen and pH that should reduce enteric bacteria survival, dilution alone, from radically increased intertidal volume, should reduce coliforms to concentrations that allow reopening of oyster beds closed for many decades. In addition, increased sediment exposure during predicted lower low tides would further reduce bacteria survival. Assuming no new major source of FC within the river system, increased dilution of river water would confer even more protection on hard-clam aquaculture beds from bacterial contamination.

The relationships among tidal restrictions, water quality and public health bacteria should be studied in other coastal ecosystems, particularly those experiencing shellfish-bed closures. These results suggest that hydrodynamic and hydrographic alterations may contribute substantially to coastal coliform contamination even without dense urbanization.

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