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HYDRODYNAMIC STUDY AND WEIR DESIGN OYSTER POND, MA

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SEPTEMBER, 1996

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BY
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ACKNOWLEDGMENTS

This report was written with input from numerous individuals. We would like to acknowledge the support of the Town of Falmouth. Specifically, the Town Engineer, George Calise and the other members of the review committee Barry Norris, Carl Breivogel, and Joanne Muramoto, contributed significantly to this study. The Falmouth Citizen's Coastal Pond Monitoring (Pondwatch) provided much of the water quality data needed for this study.

This report was prepared by John Ramsey and Brian Howes (Woods Hole Oceanographic Institution).

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I. INTRODUCTION

Oyster Pond, a coastal embayment opening to Vineyard Sound via Trunk River, is one of the Town of Falmouth's numerous scenic coastal ponds. Following the development of the Shining Sea Bike path, an enlarged culvert was installed across Oyster Pond Road providing increased tidal action between Trunk River and Oyster Pond. These modifications altered the stable salinity regime observed by K.O. Emery (1969) and changed the ecological balance of the system. Instead, the Oyster Pond system has been subjected to large fluctuations in salinity. Most recently, Hurricane Bob in August, 1991 overwashed Surf Drive, allowing a large influx of highly saline water into Oyster Pond. During the past five years, the average Pond salinity has indicated a return to the brackish conditions of the 1960s; however, continued alteration of the Trunk River, both natural and man-induced, may prevent the system from rebounding completely to its pre-1970 ecology.

Concern over the apparent recent changes to Oyster Pond led to a renewed interest in the functioning of this complex coastal embayment. In keeping with the philosophy of K.O. Emery's original work, a group of citizen volunteers working with scientists from the Woods Hole Oceanographic Institution once again took up the study of Oyster Pond's workings in 1987. The group, the Falmouth Pondwatchers, has continued its efforts focusing upon nutrient-related water quality of the coastal ponds associated with Vineyard Sound. Their approaches have now been adopted by similar programs springing up throughout New England, and their data is finding its way into research journals. Most importantly for Oyster Pond, the data were used to develop a unique ecological management approach to protect this coastal resource into the next century.

To initiate the management plan for Oyster Pond, Aubrey Consulting, Incorporated (ACI), assisted by the Woods Hole Oceanographic Institution (WHOI), was hired by the Town of Falmouth to perform a hydrodynamic study and design a weir. There were three fundamental goals for the weir:

- maintain a pond salinity level between 2 and 4 parts per thousand (ppt)
- ensure the structure is passable by anadromous fish
- prevent increased flooding potential within the confines of Oyster Pond

The study methodology incorporated existing data from Emery (1969) and the Falmouth Pondwatchers program. Once the existing data were reviewed, the need for additional data was evaluated and a field program was designed to collect bathymetric, topographic, and tidal elevation information. These data were input to a two-dimensional hydrodynamic model. This model was utilized to estimate flow characteristics, and to analyze the proposed weir. A complete understanding of the existing bathymetry as well as the freshwater recharge and tidal action driving flow within the system were required to ensure the accuracy of the model. The model provided the design crest elevation of the weir and the dredging requirements for the Trunk River channel. Once the geometry of the modified system was determined, management strategies to ensure appropriate maintenance of the Oyster Pond system were developed. The final weir design is adjustable to assure the proper long-term salinity level in the pond, available passage by anadromous fish, and eliminate potential for increased flooding. Simple mechanisms to adjust the weir height by removing a portion of the structure were included in the design.

II. BACKGROUND AND SYNTHESIS OF EXISTING DATA

In the mid-1980's it became clear that the ecological health of Oyster Pond and many of the other coastal salt ponds on the southern shore of Falmouth, MA, was declining. Initially, nutrient overloading, primarily nitrogen, was suspected due to changing land-use within surrounding watersheds. However, ecological changes within Oyster Pond did not appear to be the result of a single factor, such as nutrients; other processes seemed also to be at work. The documented changes involved both animals, specifically the loss of white perch, and a disappearance of aquatic plants such as water lilies. While the loss of specific animal species could be linked to over-fertilization or eutrophication of pond waters, the changes in aquatic plant communities were not consistent with nutrient overload.

A. Freshwater Balance

A freshwater budget was constructed as part of the recent ecological investigation of Oyster Pond. Freshwater inflow was determined because of its central role in salt balance and as the mechanism for transport of nutrients from the watershed to pondwaters. The salinity of pondwaters helps to structure pond communities. Although many estuarine species are capable of tolerating a wide range of salinities, the site-specific variation and salt concentration strongly influence the development of animal and plant communities. Nutrients in inflowing waters support the growth of phytoplankton and rooted plants which support both permanent and transient animal communities within the pond waters and benthos. Each coastal embayment has a capacity for assimilating nutrient inputs without detectable negative impacts. However, when an embayment's capacity is exceeded, ecological degradation begins to occur. At higher levels of nutrient input, the decay of the excessive production of organic matter reduces oxygen levels in bottom waters. Periodic low oxygen (hypoxic) events cause shifts away from stable animal and plant communities. At higher levels of nutrient loading, prolonged intervals of low oxygen or complete absence of oxygen (anoxia) occur, which prevent survival of most animals and plants and result in the loss of habitat and secondary losses of associated fisheries.

Freshwater and nutrient inputs to Oyster Pond originate primarily within the pond's watershed. The watershed is defined as the land surface where rainwater, which is not lost back to the atmosphere in evapotranspiration, flows into the pond through surface runoff or groundwater pathways. Since the functioning of coastal ponds are in part determined by inputs from their watersheds, ecological and resource management studies must include both pond and watershed. Oyster Pond and its contributing terrestrial area comprise the greater Oyster Pond System. The watershed was determined from groundwater levels with limited reliance on topographic data. The precise borders of the watershed are unclear due to the limited number of water table wells and the fact that watershed boundaries are not fixed but move based upon the groundwater recharge distribution. However, for Oyster Pond the presence of Salt Pond to the east and clear topographic highs to the west result in a fairly well constrained estimate (Figure II-1). The

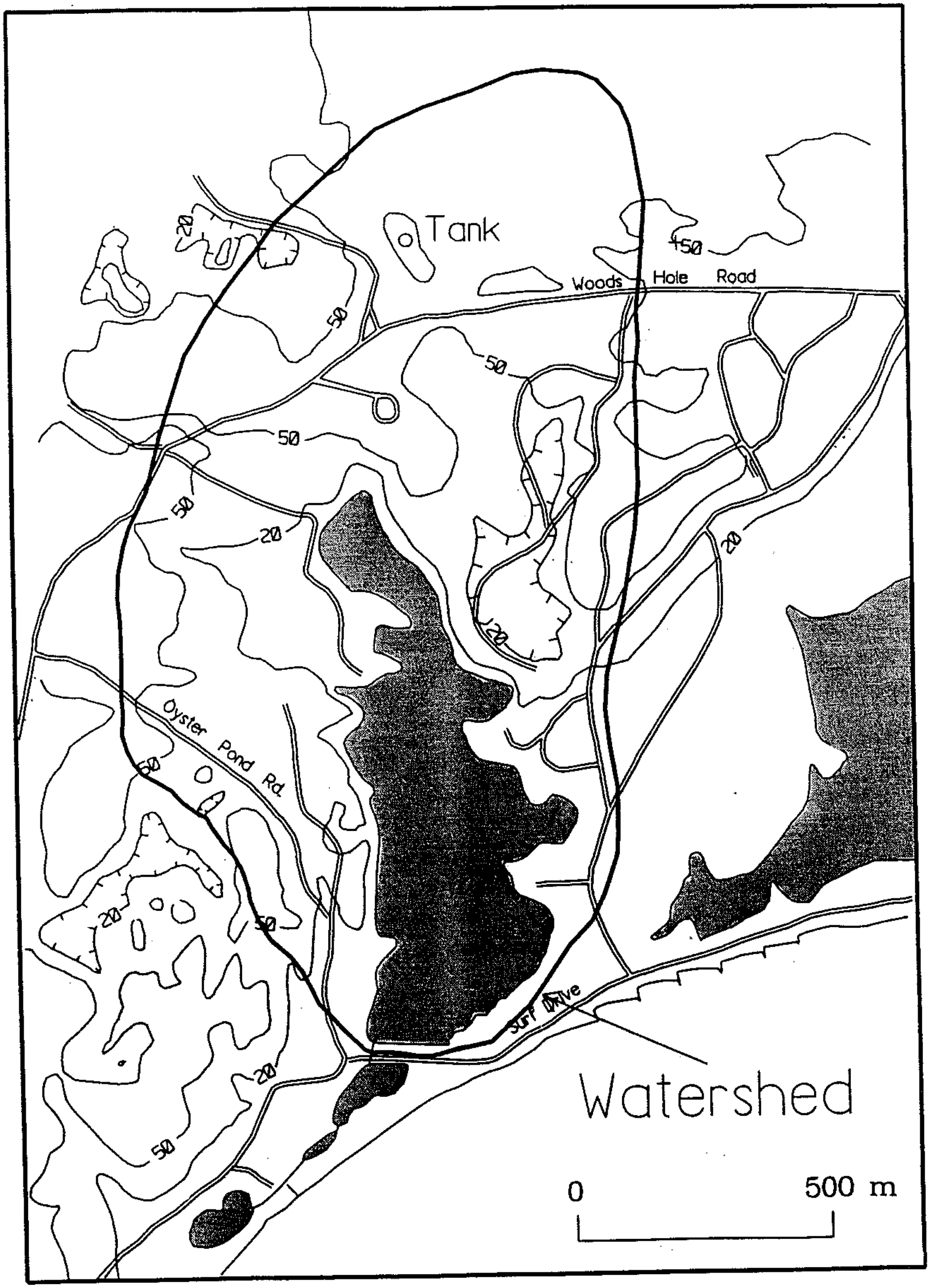

Figure II-1: Map of Oyster Pond and its watershed. The watershed was determined from watertable elevation measurements.

watershed of Oyster Pond is relatively small (0.46 mi^2 (1.2 km^2) compared to its water area (0.09 mi^2, 0.24 km^2) yielding a land/water ratio of only 5. This low ratio compared to other coastal embayment systems with similar land-uses indicates a relatively low potential for nutrient loading.

Total net annual freshwater inputs to pondwaters were relatively high (28,400,000 ft^3, 803,000 m^3 Table II-1) when compared to the total volume of Oyster Pond (26,500,000 ft^3, 750,000 m^3 Emery (1969)). All inputs are "net" in that they are corrected for evaporative losses and, therefore, represent the actual volume input to pond waters. Since stream inflow is virtually non-existent in this system, groundwater is the dominant pathway for freshwater input (86%). The predominance of groundwater inflow is similar to other embayments surrounded by highly permeable aquifers. Of the terrestrial inputs, 94% results from recharge of groundwaters by precipitation within the watershed, while 6% comes from water imported via drinking water supply from Long Pond, located in a nearby sub-watershed to Buzzards Bay. Imported water was estimated from water-use records for all of the houses within the watershed. Direct rainfall on Oyster Pond is also a major source of water being 14% of the total inflow. The predominance of groundwater in the freshwater balance helps to stabilize the daily rate of freshwater discharge due to the long temporal integration of recharge. Several years are required for recharge from the inner regions of the watershed to reach shoreline discharge locations. This long travel time tends to dampen the effects of large rainfall events on pond levels. Rapid increases in pond level when they occur are generally the result of direct precipitation and limited surface runoff.

Since the volume of Oyster Pond does not change due to the limited tidal influence, the net freshwater inflow drives an equivalent water outflow through the tidal inlet of 77,700 ft^3d^{-1}. This outflow is similar to that measured by Emery in 1964 of 41,000-102,000 ft^3d^{-1} (1,160-2,900 m^3d^{-1}), as is the overall freshwater balance. Differences between the estimates result primarily from recent refinements to the approach for estimating freshwater inflows. For instance, our higher inputs of imported water result from inclusion of all houses within the watershed rather than just those within 300 ft of the pond shores. This imported water was included since groundwater originating within the contributing area further than 300 ft from the shore, also reaches the pond.

B. Salinity and Oxygen

Oyster Pond is an estuary, a basin where fresh and salt waters mix. The salinity of Oyster Pond is determined by the relative inputs of freshwaters entering from direct precipitation and the surrounding watershed and inputs of saltwater from Vineyard Sound via tidal exchanges and periodic overwash. Since its birth as a saline pond approximately 3,500 years ago when the freshwater ponds, now the southern basins, were flooded by rising sea-level, the salinity of Oyster Pond has varied. At present we do not know the exact degree of variation, but it is clear that early in its history Oyster Pond salinities were likely to have been close to that of the flooding seawater, given the open nature of the embayment. However, with the joining of the northern basin about 1,300

Table II-1: **Freshwater Inputs to Oyster Pond.**

Source	Freshwater $X\ 10^3 m^3 yr^{-1}$	%
Direct Rainfall (a)	111.7	14
Ground and Surface Water Inflow (b)		
Natural (c)	652.5	81
Imported (d)	38.3	5
Total Freshwater Inflow	802.5 (e)	100

a) Direct precipitation minus surface evaporation.
b) Almost all inflow from watershed enters via groundwater discharge.
c) Based upon 50 cm recharge per year.
d) Imported water supply discharged through septic systems and irrigation.
e) 2200 $m^3\ d^{-1}$ input to pond.

years after the initial flooding, at least a part of the pond was likely brackish. With continuing sea-level rise, Oyster Pond appears to have persisted as a fairly stable open embayment to Vineyard Sound through the mid-years of its estuarine life.

In the nearly 400 years since Bartholomew Gosnold first sailed through the adjacent waters of Vineyard Sound, Oyster Pond has been shifting from an open embayment to a more enclosed coastal salt pond. Whether the baymouth bar formed during the late 18th century or earlier, it is clear that alterations of tidal exchange have accelerated in the post-settlement era. The effect has been a freshening of Oyster Pond waters. During the 100 years before being studied by Emery, Oyster Pond nearly returned to a freshwater system, probably similar to that of the northern basin soon after the initial saline intrusion. The open embayment of Gosnold, with salinities of approximately 32 ppt, was receiving so little saltwater inflow that its waters had declined to only 3-5 ppt salt by the 1940's when the earliest measurements are available. These salinities were also observed during the 1960's suggesting that Oyster Pond salinity had reached a new equilibrium. Indeed, these oligohaline conditions now supported brackish water communities and in the high discharge regions, salt tolerant freshwater plant communities were developing. Waterlilies could be seen in bloom in some of the coves and herring are reported to have been spawning throughout the shores of the basin.

The initial measurements by the Pondwatch Program found a dramatic change in salinity conditions. Between 1964 and 1988 the salinity throughout Oyster Pond had increased more than 4 fold (Figure X-2). In addition, there was an enhanced salinity gradient from the surface waters (12 ppt) to the deepest bottom waters (depth of 20 ft (6 m), 21 ppt). These conditions remained fairly stable through 1991. Given the high volume of freshwater input (1.07 pond volumes yr^{-1}) it was clear that an increase in tidal exchange had occurred to maintain the elevated salinity over several years. It therefore appeared that the immediate cause of the ecological "decline" of Oyster Pond was not nutrient overloading, but a major salinity shift. At these higher salinities certain species common to the pond in the 1960's would not be able to spawn or would be killed outright (e.g. waterlilies) by the increased osmotic stress. The results did not indicate that nutrients were not important, but that the salinity shift was the over-riding factor behind the observed ecological changes within Oyster Pond. Ecological management of Oyster Pond, therefore, required first an assessment of the long-term effects of the increase in water column salinity with subsequent evaluation of nutrient issues.

The increase in salinity in Oyster Pond has both direct and indirect effects on animal and plant community composition and structure. The direct effects are well documented and indicate that a new stable ecological system will develop as long as the salinity remains relatively constant at the new level. The new system will be comprised of more estuarine and marine species than in the previous decades. The indirect effects are not as well defined and are system specific. The major indirect impact of the most recent salinity shift on the ecological health of Oyster Pond stems from the strong salinity gradient within the basins.

The presence of a salinity gradient during the summer indicates that the water column of the pond is not being vertically mixed (Figure II-2). The gradient is created by the sinking of the more dense high salinity Vineyard Sound waters into the basins and by the high inflow of lighter freshwater to the pond surface waters. Where vertical mixing is lacking and a salinity (density) gradient results, the water column is said to be stratified. Water column stratification exists when less dense water is found above more dense bottom water. The density difference can result wholly from temperature differences (colder water on bottom) as in freshwater lakes or from salinity gradients in estuarine systems. In addition, deeper basins are more difficult to mix than shallow basins. To prevent complete vertical mixing the density gradient has to be greater than forcing from the wind or tidal currents. The stratification of Oyster Pond depends upon (1) the density gradient resulting primarily from salinity, (2) the force of the wind, as tidal currents are negligible within the pond, and (3) the depth of the basins since wind-driven mixing attenuates rapidly with increasing depth.

In nutrient rich coastal ponds where plant production is high, oxygen uptake by sediments and bottom waters require oxygen inputs from surface waters and the atmosphere to maintain adequate oxygen levels to support benthic communities. During water column stratification, this mixing down of oxygen rich water is prevented and oxygen depletion occurs (Figure II-3). Periodic oxygen depletions or anoxia for even short-durations (days) generally results in loss of benthic communities and represents a loss of ecological habitat.

The observed salinity stratification in the late 1980's created a vertical zonation of the watercolumn of Oyster Pond which persisted in the northern and southern basins from the first observations in 1987 through 1991. The surface waters tended to be warmer especially during summer and generally 5 ppt fresher than the bottom waters of each basin. The result was a persistent strong density gradient (shown as sigma t, Figure II-4a). The lack of ventilation and the high oxygen demand of bottom waters resulted in a complete consumption of dissolved oxygen. The anoxic conditions allowed an accumulation of sulfide from microbial sulfate reduction primarily within the sediments but also in bottom waters. Within the water column where the sulfitic waters and the oxygenated surface waters meet, a dense population of photosynthetic sulfur oxidizing bacteria developed. These photosynthetic bacteria can be seen in the profile of fluorescence (Figure II-4), and are visually apparent as a pink turbid mixture in water samples. Although the depth of the oxic-anoxic interface fluctuated with season due to wind and temperature variations, the bottom waters throughout more than half of the pond were sulfitic. The result is the loss of the benthic habitat in areas overlain by these anoxic waters.

Water column oxygen-sulfide vertical zonation was also found in Emery's earlier observations. However, the zonation was not persistent throughout the study period (1963-1965). Instead, sulfitic bottom waters were only detected in the northern basin

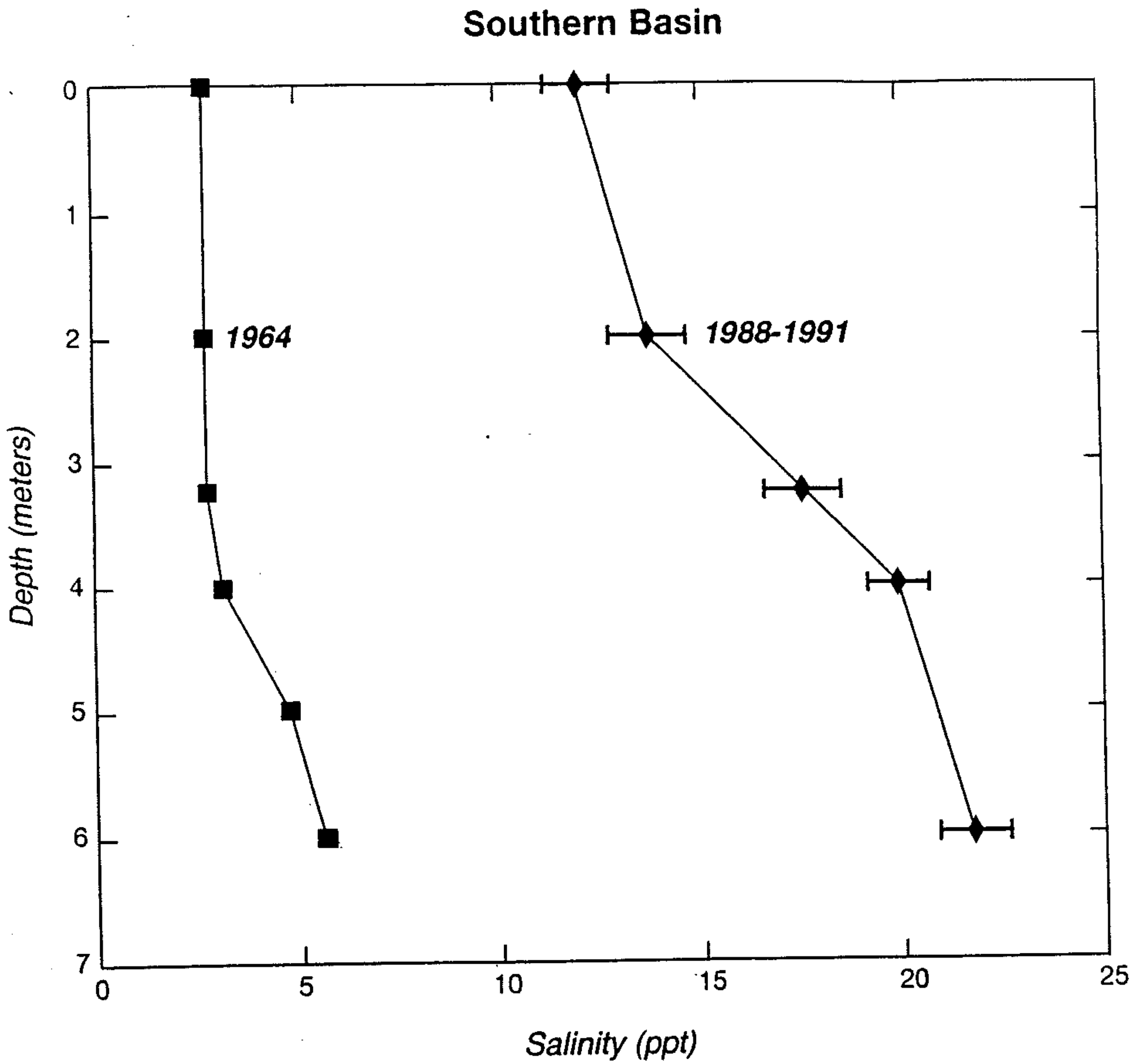

Figure II-2: Comparison of watercolumn salinities in the southern basin in 1964 versus 1988-1991. The large increase in salinity is associated with a change in tidal exchange in the late 1980's. The salinity increase resulted in major ecological shifts within the pond's systems. The 1964 salinity data is calculated from the chlorinity measurements by Emery.

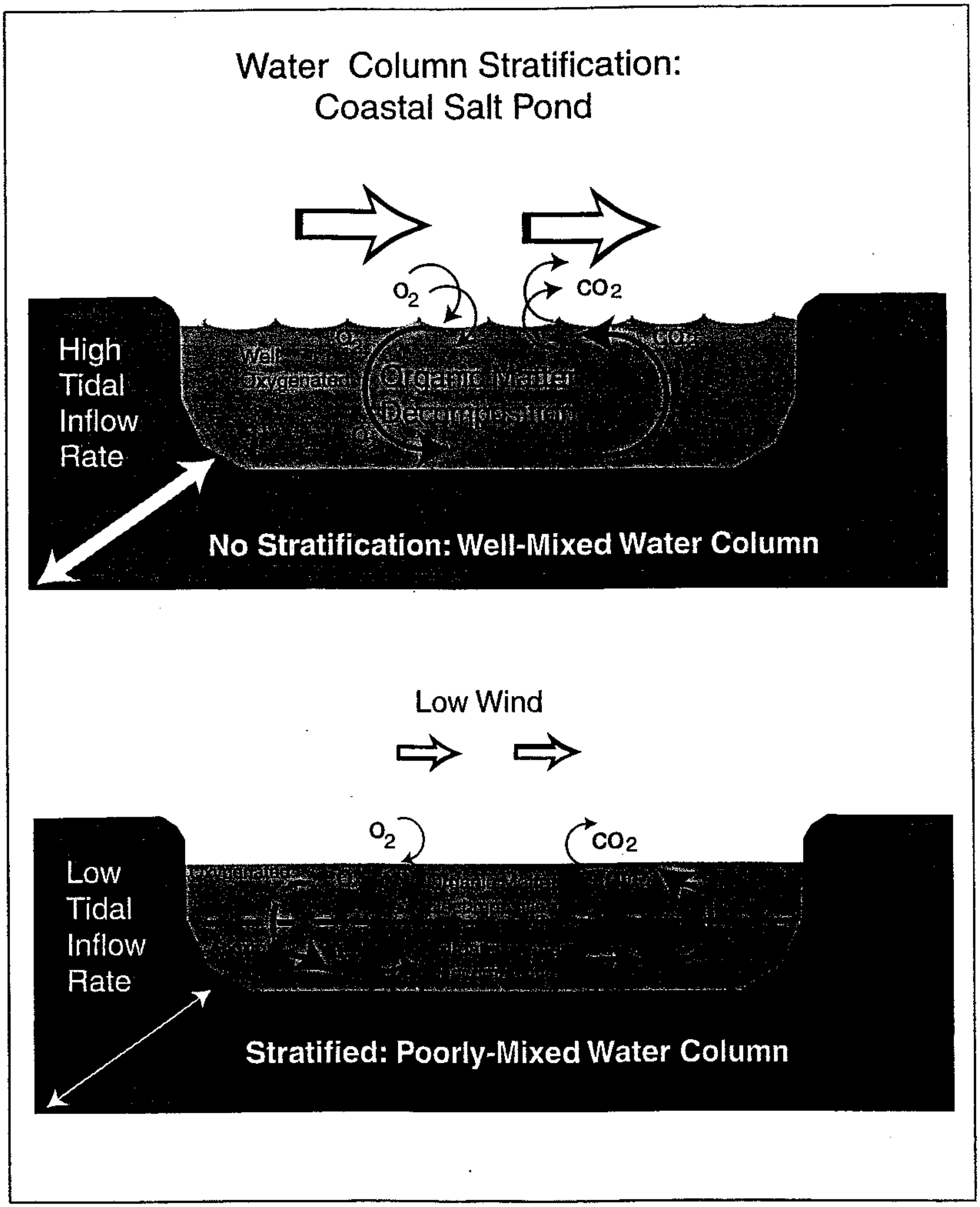

Figure II-3: Illustration of watercolumn stratification within a coastal salt pond. The high organic matter production within coastal ponds requires the input of atmospheric oxygen to maintain watercolumn oxygen levels during decay.

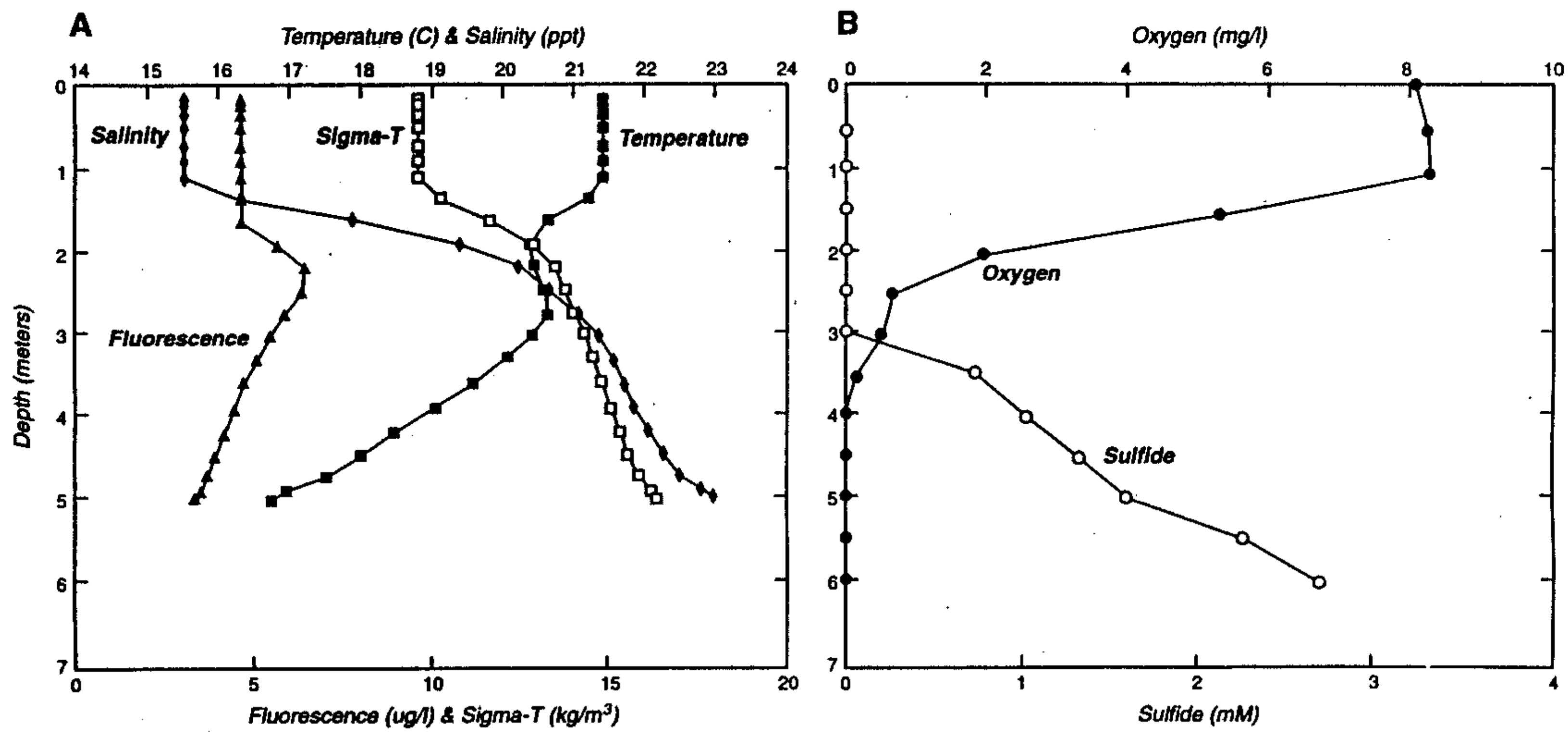

Figure II-4: Profiles within the southern basin of Oyster Pond of (a) temperature, salinity, density and chlorophyll fluorescence and (b) oxygen and dissolved sulfide in late summer 1990. The strong density gradient (sigma t) results primarily from the high salt concentration of bottom waters. Due to the lack of vertical mixing the bottom waters of the basin are anoxic and contain high levels of sulfide. The fluorescence maxima coincides with the oxygen-sulfide interface and results in part from photosynthetic sulfur oxidizing bacteria which flourish in that zone.

during summer (July-August) with oxic conditions throughout the rest of the year. In the deeper more salinity stratified southern basin (Figure II-2), the anoxia was much more persistent but the watercolumn did mix and become oxygenated in December of 1963. In contrast, from 1987-1996 the southern basin remained continuously stratified and anoxic.

The seasonal mixing of the water column observed by Emery was also apparent in data from the 1990's. With the declining temperatures of surface waters in fall and winter, which reduces the density difference between surface and bottom waters, in addition to the higher winds of fall storms, the depth of the mixed layer increases. In Oyster Pond the mixed layer typically reaches about 13 feet (4 meters) by mid-winter. Therefore, the watercolumn throughout the pond is mixed except in the southern deep basin (21 ft, 6.5 m), where the salinity gradient is very large (5-10 ppt). Since almost all of the pond bottom is found at depths shallower than 13 feet (4 meters), Oyster Pond sediments are predominantly overlain by oxygenated water throughout most of the fall to spring period (Figure II-5). With the onset of lower winds and warmer weather, the depth of mixing decreases and anoxia is re-established at depth in the main basins. One of the major changes in the pond coincident with the salinity shift from the 1960's to the 1980's was the extent and duration of the anoxic zone during the summer. Stratification and anoxia was greatest in the late 1980's observations, weakest in the 1960's and appears to have been weakening throughout the 1990's. The reason for this recent lessening of stratification has been a managed freshening of Oyster Pond waters since 1991.

A reconstruction of the recent salinity history of Oyster Pond from available data indicates that pond salinities have been fairly constant for the 40 years of record between 1948 and 1986 (Figure II-6). The large salinity shift appears to have been due to an inlet reconfiguration in the late 1980's not associated with pond management. The large increase in pond salinity took less than a year, explaining the prevalence of visual observations that the pond was "degrading". The annual freshwater inflow to the pond causes the salinity to decline rapidly when long-shore sediment transport periodically restricts tidal flow through the inlet. Subsequent to the restriction of tidal exchange in 1995-1996, seawater only enters Oyster Pond during major storms (Tropical Storm Bertha, 1996) and the highest of spring tides. The decline in salinity requires a minimum freshwater input of 30,000 ft^3d^{-1} and 33,000 ft^3d^{-1} (850 m^3d^{-1} and 930 m^3d^{-1}) for 1995 and 1996 respectively. These are minimum estimates since some saltwater is entering the pond. These values support the estimate of inflow from the freshwater budget (Table II-1) and indicate the large influence of freshwater inputs on the salinity stability of pondwaters.

C. Management Alternatives and Selection of Appropriate Scheme

Given the negative impacts on pond biota of enhanced salinity stratification and large salinity shifts, ecological management of Oyster Pond requires control of salinity levels, hence tidal exchange. Evaluation of management of Oyster Pond involved four options: (1) allow salinity levels to cycle with inlet openings and closings, (2) manage tidal inputs by maximizing tidal exchange by re-constructing the pre-1870 inlet, (3) manage tidal inputs to maintain an oligohaline salinity (2-3 ppt) similar to that of 1948-1986, and

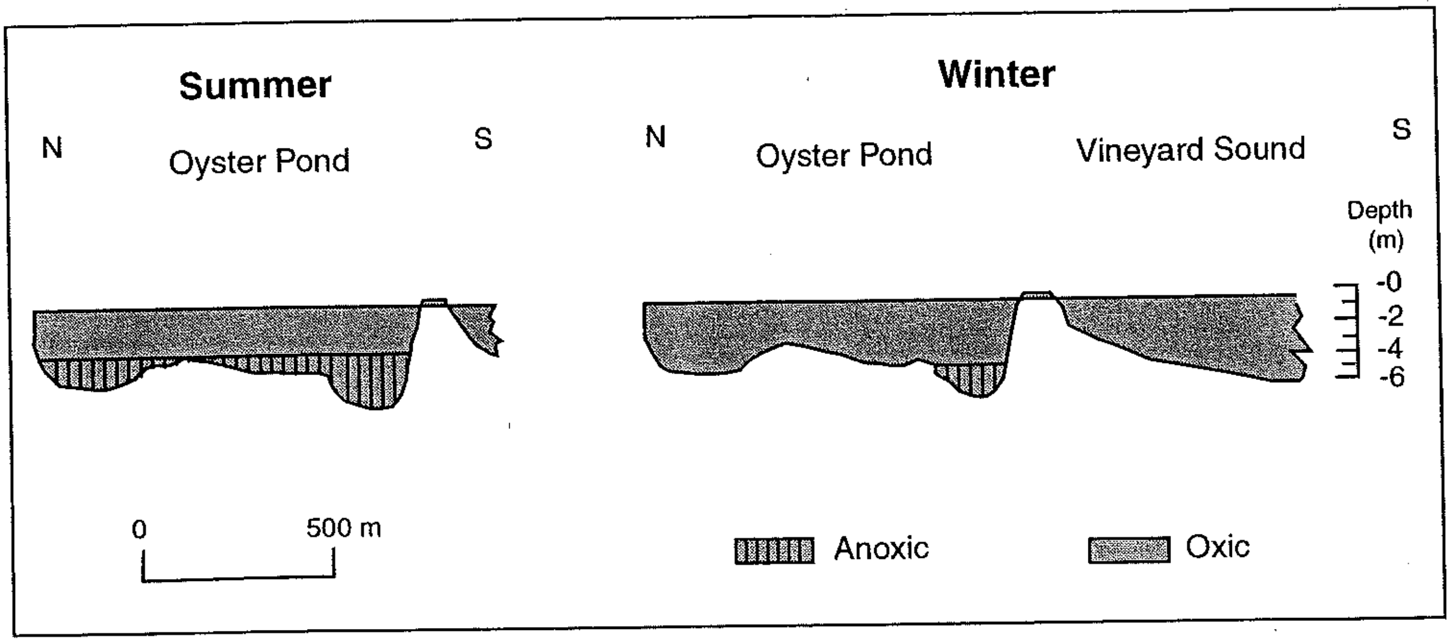

Figure II-5: Seasonal changes in the distribution of sulfitic bottom waters within Oyster Pond. The combination of seasonal temperature changes and higher wind speeds in fall and winter result in the mixing and aeration of the bottom waters of all but the deepest basin of the pond. Vertical exaggeration is 45:1.

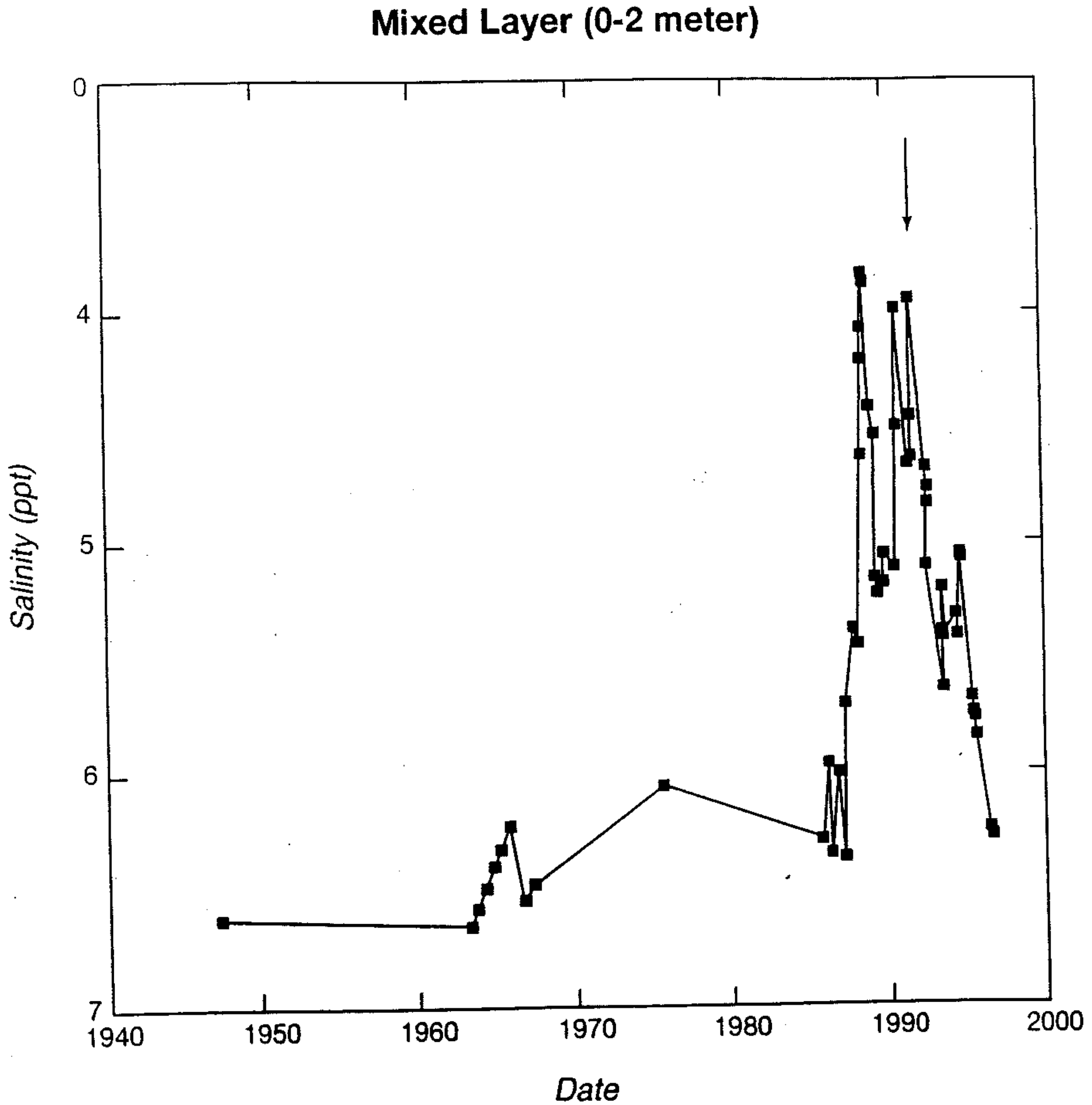

Figure II-6: Salinity history of Oyster Pond surface mixed layer. Oyster Pond was predominantly a brackish system with salinity <5 ppt over much of the past 60 years. The cause of the salinity shift in 1987 appears to have been associated with a reconfiguration of the tidal inlet/channel.

(4) prevent tidal inputs and return Oyster Pond to its freshwater origins. The first and last of these options were rejected on the basis that they would create an ecologically unstable system which would be characterized by periodic full system shifts in animal and plant communities. Allowing salinity to cycle with inlet dynamics would likely cause the types of ecological shifts observed in the 1980's, with periodic returns to low salinity conditions. Similarly, attempts to return the pond to freshwater conditions would result in periodic die-offs of freshwater species as overwash from Vineyard Sound produce pulsed inputs of high salinity waters. Input of seawater over the barrier dune system was observed during Hurricane Bob in 1991 and breaching of the barrier system during the 1938 and 1944 hurricanes. These options would result in an Oyster Pond system continually in transition and likely with continual poor ecological health.

Each of the options for managing the salinity of Oyster Pond were investigated in detail. Attempts to re-construct the original inlet and create a tidal system were seen as less likely to succeed than the approach to create a "stable" brackish water system. Problems with re-creating the inlet were both practical and physical. The new inlet would have to be relatively long to reach Vineyard Sound and would be difficult to maintain given the small tidal range (1.6 ft, 0.5 m) and rapid sedimentation. Variations in the tidal exchange due to sedimentation in the inlet would result in large salinity variations with concomitant ecological impacts. In contrast, in its present configuration a brackish water pond appears to be sustainable over moderate time-scales (Figure II-6). The adopted management plan for Oyster Pond is to return it to the pre-1980's condition. Salinity will be managed by a weir on the pond side of Surf Drive near the present outlet to the pond (Figure II-1). Salinity levels and stratification within the pond will be monitored and the weir adjusted to allow enough saltwater inflow to maintain a salinity in the range of 2 to 4 ppt. Under these conditions periodic storm inputs of seawater should not result in large ecological shifts. Another goal of salinity management is to reduce stratification and decrease the area of the bottomwater subject to seasonal anoxia. Increasing the depth at which bottom waters become anoxic from 10 to 13 feet (3 to 4 meters) nearly doubles the area of usable benthic habitat within Oyster Pond. Tidal inputs to Oyster Pond have been allowed to decline naturally, as a result of inlet sedimentation, since 1991. An adjustable weir is scheduled to be put in place in 1997.

The effects of the freshening of Oyster Pond waters on oxygen levels and impacts of storm inputs of seawater can be gauged from the data from 1987 to 1996 as the salinity has declined. These data can also be used to predict potential increases in benthic habitat. The reduced tidal exchange post-1991 resulted in a decline from about 15 ppt to about 8 ppt (0-13 ft, 0-4 meters) by 1994. During 1994 the Pondwatch Program conducted a detailed study of summer stratification and oxygen conditions in the northern basin. Sampling was conducted at daily intervals between 0700 and 0900 over 2 months by B. Norris, the period of lowest dissolved oxygen. Oxygen levels were high throughout the basin during fall, winter and spring and remained high until late June. During this same interval salinity stratification was weak, <2 ppt from surface to bottom. Oxygen levels in Oyster Pond were found to differ significantly from previous years when salinities were higher and the watercolumn was devoid of oxygen below 10 feet (3 meters) depth throughout the summer. In 1994 the oxic-anoxic interface (depth where oxygen disappears) was below 11.5 feet (3.5 meters) for all but 3 weeks and rose to 10 feet (3 meters) for only about a 7 day period (Figure II-7). While these conditions are not sufficient to significantly expand the extent of benthic habitat, the much shorter duration of anoxia suggested that the freshening of pond waters and the resultant decrease in salinity stratification was having an effect on oxygen depletion. The onset of low oxygen was associated with rain events which presumably increase stratification by surface input of runoff and coincide with low light conditions which reduce oxygen production by phytoplankton. The single day low oxygen events on 14 August and 23 August followed the two largest rain events of the month with 0.87 and 1.60 inches of rain over the previous 2 days (Figure II-7).

Further evidence that reducing the salinity of Oyster Pond may sufficiently reduce stratification and increase benthic habitat quality comes from annual measurements of July and August salinity profiles and bottom water oxygen. From 1987 through 1991 when salinity levels were highest, the bottom waters below approximately 10 feet (3 meters) were consistently anoxic during the summer. After restricting tidal exchange, the salinity of surface waters (0-6.5 ft, 0-2 m) and shallow basin waters (10.5-13 ft, 3.25-4 m) declined to about 4 ppt by 1996 (Figure II-8). As the salinity declined, differences between 0 and 13 feet (0 and 4 meter) salinities also decreased. Prior to freshening there was a fairly consistent 2-5 ppt increase in salinity from the surface to mid water depths. As the pond freshened, salinity stratification decreased and in 1992, 1995 and 1996 almost no salinity stratification was observed. In these years oxygen persisted year-round in waters above the 13 feet (4 meter) depth (Figure II-8). This resulted in a nearly a doubling of the available bottom for utilization by animal and plant communities (Figure II-9). Higher oxygen conditions and a greater area of benthic habitat is generally viewed as an improvement in the overall ecological health of a system like Oyster Pond. In addition, oxygenated bottom waters prevent the build up of hydrogen sulfide which is released each year from the northern and mid basins during fall mixing. The release of this noxious gas has a negative impact on the aesthetic value of this and other coastal systems.

It should be noted that at present the enhancement of habitat quality within Oyster Pond was not sustained. During 1993 and 1994 brief periods of watercolumn anoxia in the inner basins were observed. However, the frequency of high summer oxygen levels appears to be increasing as salinity declines. The extent of continued improvement is unclear, since at the low salinities of the 1960's, periodic low dissolved oxygen was observed in both the northern and southern basins.

The temporal pattern in bottom water salinity within the deep southern basin differs significantly with that of the northern and mid basins. Unlike the inner basins, the deep basin salinity remained virtually constant. The one major salinity shift in the deep basin was not associated with reduced tidal flows, but rather the input of seawater from Vineyard Sound associated with overwash during Hurricane Bob (August 1991). The

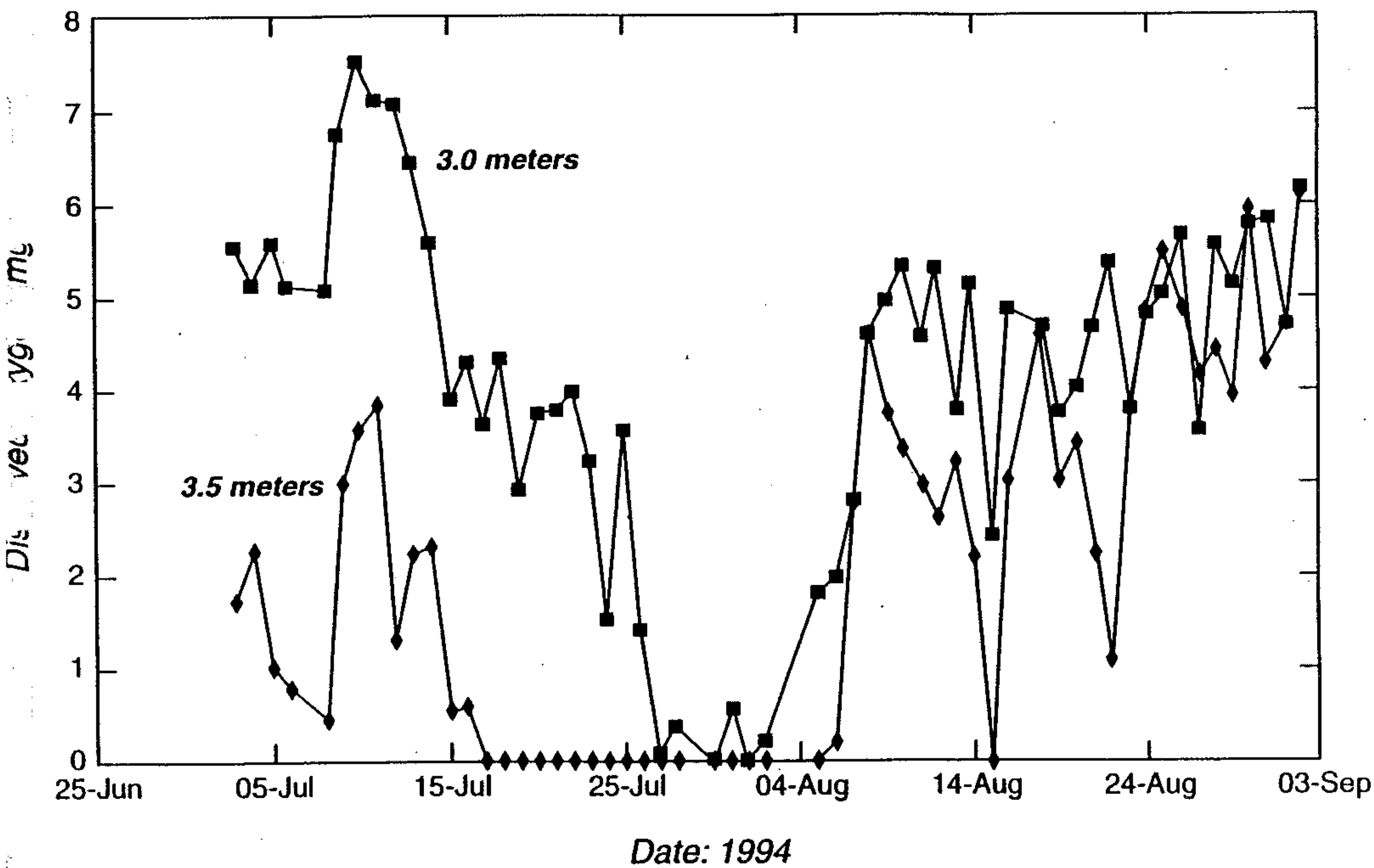

Figure II-7: Temporal changes in bottom water oxygen during summer within the northern basin of Oyster Pond, 1994. Oxygen levels were high throughout the spring and early summer. Anoxic conditions at 3 and 3.5 meters were observed for only 1 and 3 weeks, respectively. The rapid rise in oxygen levels at the end of the first week in August was associated with the break-down of watercolumn stratification.

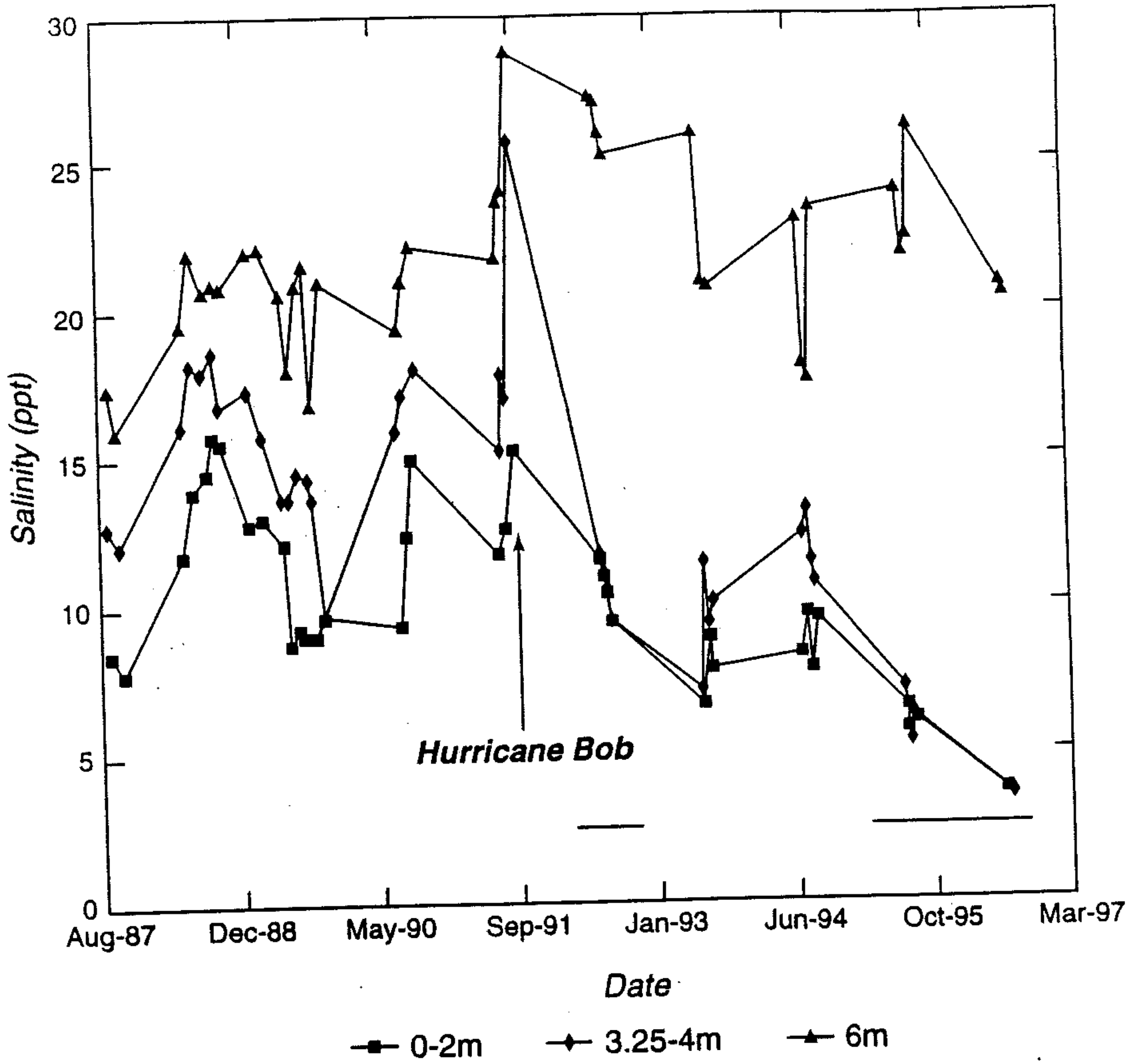

Figure II-8: Changes in the salinity within the surface mixed layer (0-2 m), the intermediate layer (3.25-4 m) and the deep basin (6 m) over the recent study interval. The large increase in intermediate and deep waters was from the input of seawater overwashing from Vineyard Sound during Hurricane Bob. Declining salinities from 1992-1996 are the result of decreased tidal exchange.

OYSTER POND, FALMOUTH

Summer Oxygen Distribution

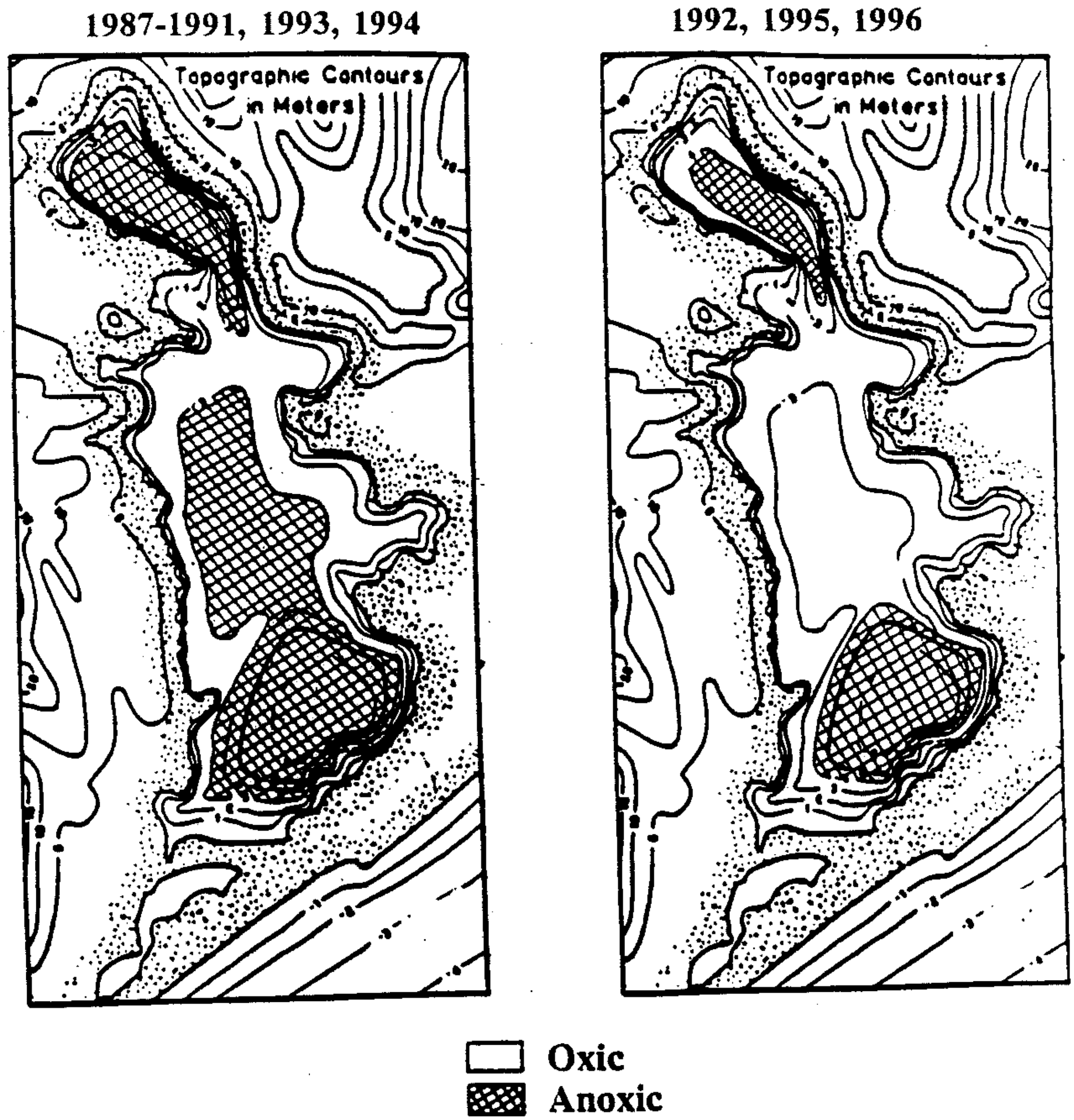

Figure II-9: Summer distribution of oxygenated and anoxic bottom waters within Oyster Pond during recent years. The gradual freshening of pondwaters and the declining stratification has resulted in a decrease in the area of seasonally anoxic waters, hence an increase in usable benthic habitat within the pond.

saltwater pulse increased the salinity of the mid and deep waters, but the surface water was only slightly affected. Vertical mixing of the pond during winter combined with freshwater inflow removed the salinity pulse from the upper 13 feet (4 meters) by the following summer sampling. Since the bottom waters of the deep basin (13-21 ft, 4-6.5 m) were stratified over the 9 years of the study, the loss of salt from this zone is only by diffusion. The observed distribution and timing of changes in salinity, suggest that saltwater entering Oyster Pond via storm or tidal inflows sinks by density flow through the surface waters and into the southern basin (Figure II-10). The saltwater may then gradually move inland along the bottom. However, small pulses of saltwater entering the southern basin were not always detected in the northern basin. As the pond freshened, bottom water (13 ft, 4 m) within the northern basin was frequently >2 ppt higher than water at the same depth in the southern basin. The relative role of estuarine circulation, wind and the shallow divide at the mouth of the northern basin in creating the salinity difference is at present unclear. There was a general flow of fresher surface waters out over the more saline bottom waters. This pattern likely breaks down when wind driven mixing reaches the 11.5 feet (3.5 meter) depth and therefore intercepts the bottom of the mid basin. During these periods, saltwater would be mixed upwards into the surface waters and be diluted before reaching the northern basin. It appears that the mid basin may reduce the potential for the onset of salinity stratification within the northern basin following periodic saltwater inflows. The extent to which further freshening of Oyster Pond waters will result in decreased stratification and increased usable benthic habitat is the subject of ongoing study. However, it appears that a return to a brackish water pond similar to that of the 1960's should result in a more stable and hopefully more productive and diverse ecosystem than that of recent years.

D. Nutrient Issues and Balance

Due to its potential for water column stratification and long residence time, Oyster Pond is likely to have a low tolerance for nitrogen loading. As the pond reaches a new equilibrium and its ecosystems re-adjust as the waters freshen, it will be possible to determine the threshold for nutrient inputs for this system. Although determination of nutrient thresholds must wait for the system to stabilize, we can begin to gauge the likelihood of nutrient related water quality problems in Oyster Pond using current information.

Since most of the nutrients entering Oyster Pond in its new configuration enter from the watershed, it bodes well that the surrounding upland area is relatively small and has only light development. The high water quality of Buzzards Bay is attributed in part to its low land:water ratio and population density. Similarly, Oyster Pond has a smaller contributing area of watershed relative to its water area than other coastal salt ponds in Falmouth and has less than one-third of the population density (Table II-2). As has been stated above, the ability of Oyster Pond to tolerate nutrient inputs from the watershed depends not just on the loading from the land but also oceanic inputs (small), residence time of water within the pond, and water column stratification. However, the small contributing upland area should help to minimize terrestrial loadings. By determining

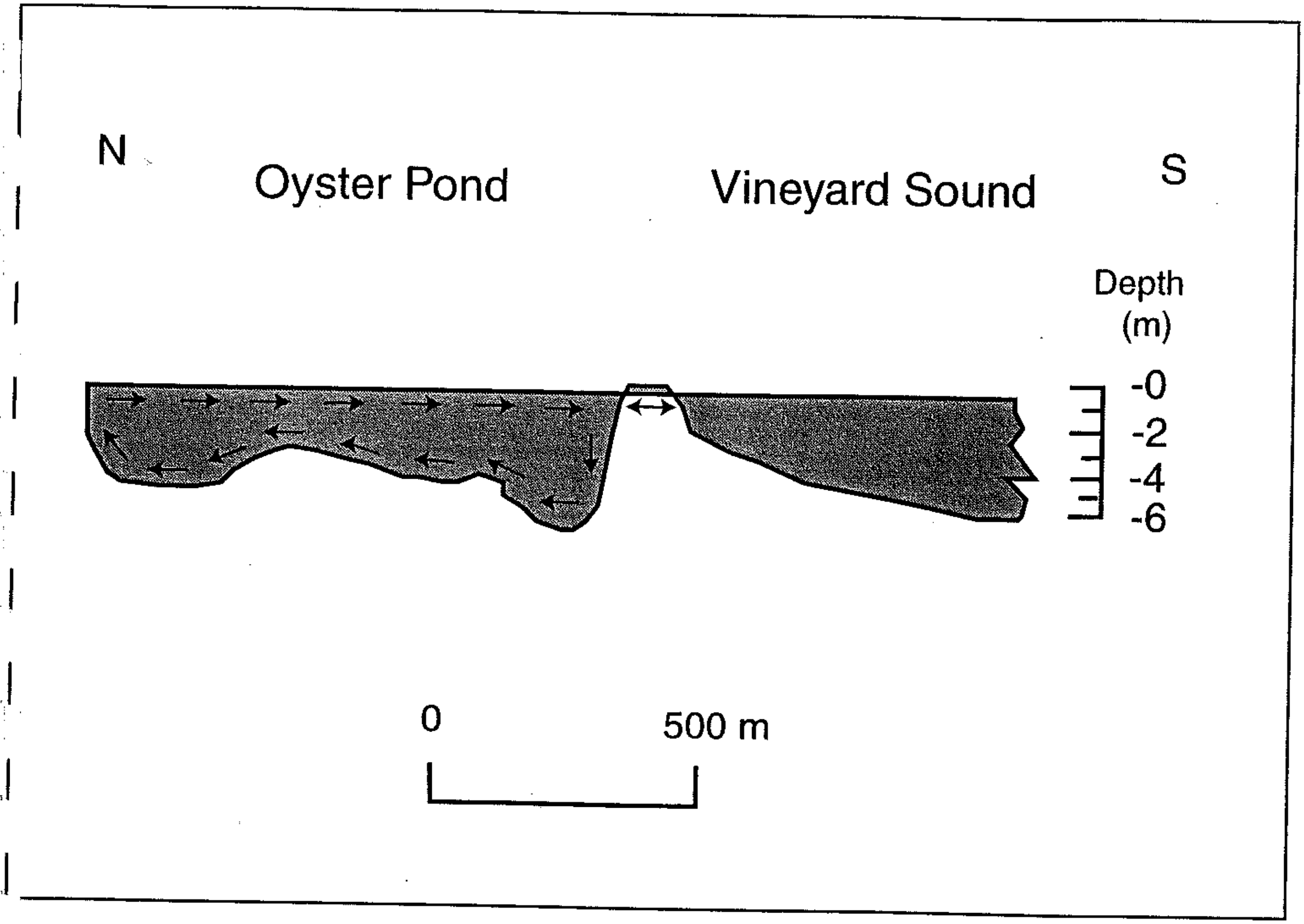

Figure II-10: Conceptual model of seawater inflow (solid arrows) and freshwater outflow (dashed arrows) in Oyster Pond. Large inflows of seawater result in increases in bottom water salinity but have only a small impact on surface waters, cf. Hurricane Bob figure 8.

Table II-2:

Watersheds and Basin Areas of Representative Coastal Embayments in Falmouth Massachusetts, 1995

Embayment	Water Area (km^2)	Watershed Area (km^2)	Ratio: Land/ Water	Population /Bay Area (Pop./Ha)
Buzzards Bay	550	1104	2	5
W. Falmouth Hbr*	0.80	11.8	15	18
Little Pond	0.19	2.2	12	75
Green Pond	0.54	3.4	6	43
Oyster Pond	0.24	1.2	5	8-16**

* As of 1994, Harbor is also recieving nutrients via groundwater transport from the Falmouth WWTP.

**Low estimate from 1990 Census; High estimate from projected full year-round occupancy and house count.

the present land-uses within the Oyster Pond watershed it is possible to model the terrestrial nutrient load to pond waters.

Under present land-use, the nitrogen loading to Oyster Pond through rainfall and freshwater inflow is 97 kmol N yr^{-1} (1358 kg N yr^{-1}, Table II-3). Given its large water area per unit watershed, 16% of the nitrogen input is from direct precipitation. Nitrogen input to groundwater from undeveloped land on Cape Cod is typically small and accounts for only 1% (1 kmol N yr^{-1}) of the nitrogen load to Oyster Pond. The remaining nitrogen inputs from the watershed are a direct consequence of development. On-site disposal of wastewater through septic systems is the single major source accounting for almost two-thirds of the input (61 kmol N yr^{-1}). Lawn fertilizers are the second highest source of N accounting for 10% of the total input. Runoff and rapid infiltration of water from impermeable surfaces such as houses, driveways and roads combine for the remaining 10% of the terrestrial loading. However, it is clear that development of the watershed has greatly increased nitrogen loading to Oyster Pond. Nitrogen loads from developed areas (81 kmol N yr^{-1}) are more than 100 fold higher than from a similar area of undeveloped land. In addition, inputs of nitrogen via rainfall have also increased since the industrial revolution. The combined effect of watershed development and increased atmospheric inputs is that present inputs of "new" nitrogen to Oyster Pond are more than 10 times that during the colonial era. However, in absolute terms these loading rates are still relatively low compared to similar embayments in the region, but their impact on the "new" Oyster Pond cannot be presently gauged.

Temporal changes in nitrogen loading from the watershed can be estimated from the shifts from undeveloped land 400 years ago to agriculture and grazing in colonial times to residential development beginning in the early 1900's. Given early agricultural practices, nitrogen loading to Oyster Pond remained close to undeveloped rates until the advent of on-site wastewater disposal with increasing residential land-use. Of the about 198 houses within the watershed in 1996 almost two-thirds have been constructed the past 20 years. This suggests that the large increase in watershed nitrogen loading to Oyster Pond over the past 1000 years has occurred only recently. Fortunately, the Oyster Pond watershed is approaching buildout, with additional development possible only by special permit. Therefore, if Oyster Pond is presently below its nitrogen loading threshold, it nutrient related water quality declines are not likely to occur in the future. In addition, if the assimilative capacity for nutrients is presently exceeded, the low housing density and small watershed should allow successful implementation of nitrogen management strategies.

Nitrogen levels in the surface waters of Oyster Pond are currently elevated, 52 uM or 0.74 mg N L^{-1} (0-13 ft, 0-4 m). While these levels exceed those specified by the Nutrient Overlay Bylaw of the Town of Falmouth for Oyster Pond, these levels do not necessarily indicate eutrophic conditions. However, due to the absence of mixing of the deep waters of the southern basin and their anoxic condition, nitrogen levels are exceedingly high, >2000 uM or >28 mg N L^{-1} (Figure II-11). These levels result from the accumulation of

Table II-3: **Inputs of "new" nitrogen to Oyster Pond, 1996.**

Source	kmol N yr^{-1}	% of Total
Natural:		
Direct Precipitation	**15.09**	**15.6**
Vegetated Areas	**1.01**	**1.0**
Subtotal =	**16.10**	**16.6**
Developed:		
On-site Wastewater Disposal	**61.21**	**63.2**
Lawn Fertilizers	**9.70**	**10.0**
Impermeable Surfaces		
Housing	**6.52**	**6.7**
Roads	**3.35**	**3.5**
Subtotal =	**80.78**	**83.4**
Total via Freshwater =	**96.88**	**100.0**

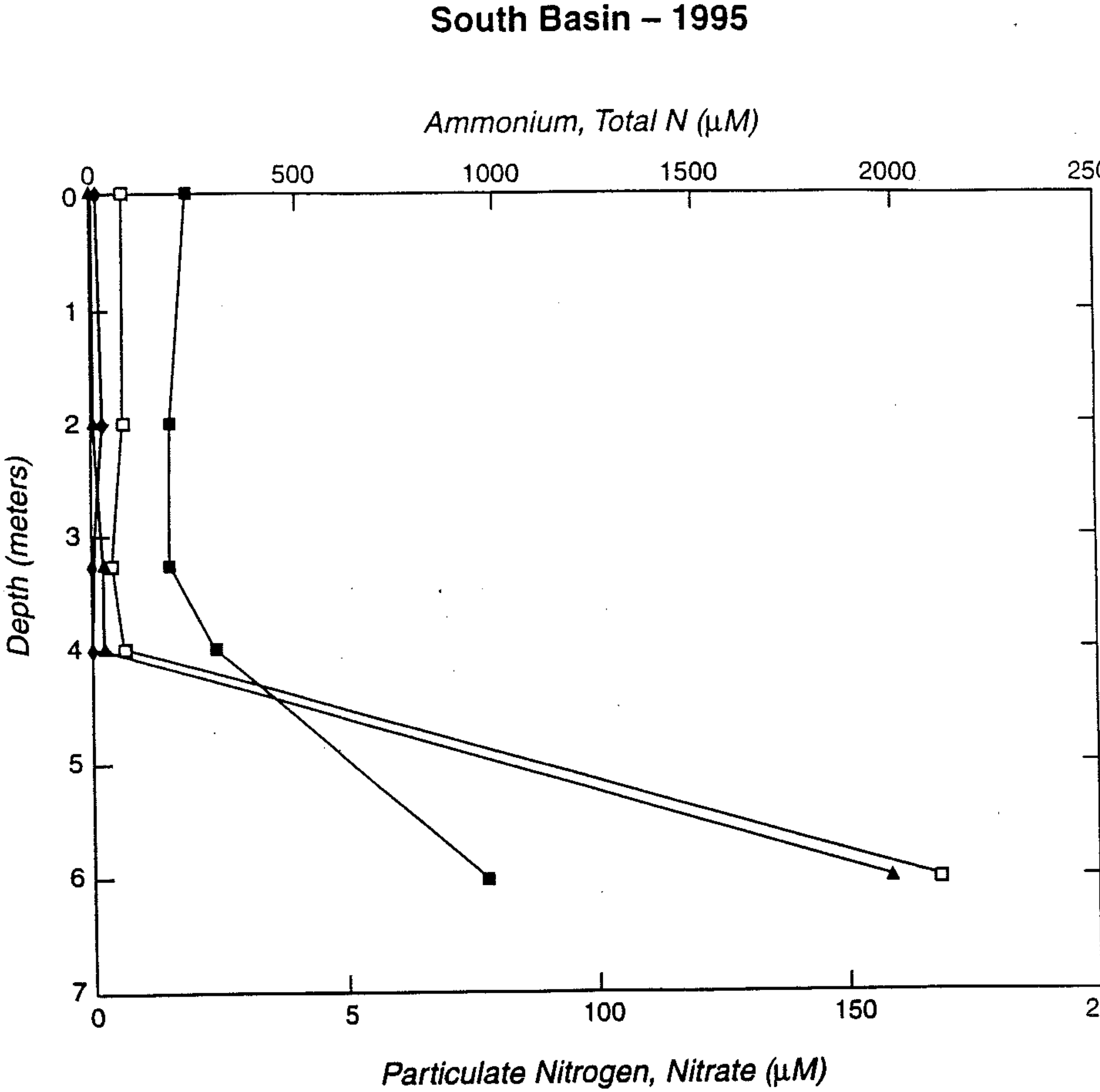

Figure II-11: Current (1995) vertical distribution of nitrogen within the surface waters and southern basin of Oyster Pond. The nearly 20 fold increase in total nitrogen, predominantly ammonium, within the bottom waters is the result of remineralization and retention in this "permanently" stratified basin.

remineralized nitrogen from the decay of phytoplankton which settle to the basin sediments. Almost all of the nitrogen is as ammonium which is readily available for uptake by plants and, therefore, capable of stimulating algal blooms. Although this ammonium pool is naturally derived, its concentration is about 1000 times that of Vineyard Sound waters and represents a source of nitrogen to pond waters if watercolumn mixing is re-established by pond freshening. Injection of this pool into the surface waters of Oyster Pond in a single mixing event would increase the surface water total nitrogen levels from approximately 50 uM to over 400 uM. Depending upon the time of year, this could result in a large algal bloom with significant negative impacts on pond systems. However, mixing events of sufficient magnitude are rare and generally occur during winter when algal production potential is lower. Also, it is more likely that the deep southern basin waters will be mixed upward slowly over several years rather than in a single event, given their high salinity (20 ppt).

Overall, the nitrogen loading to Oyster Pond appears to be relatively low. However, determination of the nutrient assimilative capacity of the pond must wait until its salinity structure and ecosystems stabilize. The low housing density and small watershed approaching build-out increase the likelihood of successful implementation of nitrogen management in this system.

E. Coliform Contamination and Other Management Issues

The primary factors impacting the ecological health of Oyster Pond are salinity stratification, oxygen levels, and nitrogen loading. However, other factors can impact pond systems or utilization of pond waters. Other than discharges of organic contaminants (e.g. oil, solvents etc.) which clearly should be prevented, fecal coliform contamination is of primary concern. Fecal coliforms do not impact ecological systems nor are they a human health threat in and of themselves. Instead, fecal coliform bacteria are used as an indicator of human pathogens associated with disposal of untreated wastewater. Therefore, coliform contamination impacts our use of pond waters but not the animals or plants within the pond. Unfortunately, all warm blooded animals have high concentrations of fecal coliforms within their feces. Due to the presence of both human and animal sources within coastal watersheds, coliform contamination is frequently the result of non-wastewater sources.

Fecal coliform levels within the surface waters of Oyster Pond are monitored relative to human uses of swimming and fishing. A compilation of available coliform data shows a seasonal cycle of highest levels during the warmer summer months and lower levels of contamination during late fall and winter (Figure II-12). This seasonal trend is negatively correlated with observations of waterfowl populations in a nearby embayment, Buttermilk Bay (Weiskel, et al., 1996). Based upon this analysis it is likely that waterfowl are not the cause of the summer increase in coliforms. This trend has also been found in other embayments in southeastern Massachusetts. The only other coliform sources are surface discharge of wastewater (e.g. pipe, overflowing septic system) or surface flow from impermeable surfaces within the watershed. In Buttermilk Bay

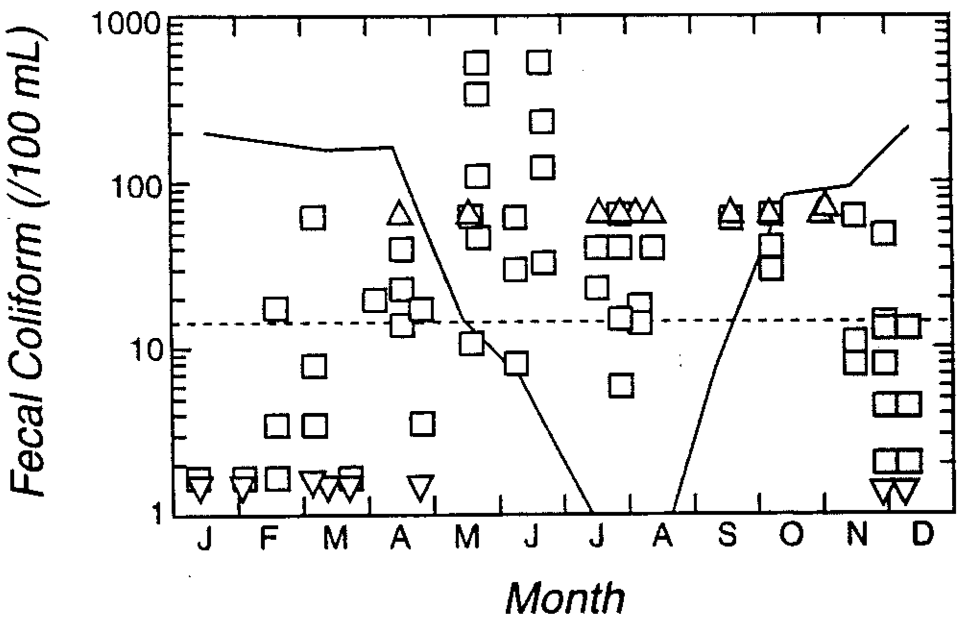

Figure II-12: Annual cycle of fecal coliform bacteria within Oyster Pond waters at three nearshore locations (symbols). Triangles indicate FC >64 per 100 mL and inverted triangles indicate FC <1.8 per 100 mL. Seasonal distribution of waterfowl inputs in 10^9 FC d^{-1} (solid line) are based upon nearby Buttermilk Bay, Wareham (Weiskel, Howes and Heufelder 1996).

accumulation of domestic and wild animal wastes on beaches and roadways accounted for the summer fecal coliform contamination of bay waters. Wastes build up on these surfaces during dry weather and are flushed into the bay via stormwater discharges. While it is difficult to alter the pattern of waste deposition, re-routing surface water flow to the groundwater by constructing rapid infiltration catchments was sufficient treatment to control summer coliform levels.

Prudent management of Oyster Pond should include a cessation of direct stormwater inputs. The high coliform levels in most stormwater flows are removed if discharge is to surface infiltration basins. Catchment basins are also available which will retain oil and grease from road runoff, reducing groundwater contamination and inputs to pond waters. Oyster Pond is part of a greater system which includes the surrounding watershed. Management of this coastal embayment requires a whole system approach. The current salinity management of Oyster Pond represents the first step in the maintenance of this coastal embayment.

III. FIELD MEASUREMENTS

The quantitative analysis required for the weir design included a numerical hydrodynamic model to simulate freshwater recharge and tidally-driven saltwater flow. The model required bathymetric information, freshwater inflow estimates, and tide measurements as input to define the system hydrodynamics. Although existing data (from Emery, 1969) provided the bathymetry of Oyster Pond, a supplemental bathymetry/topography survey was required to include Trunk River and the lagoon connecting Oyster Pond and the river. Additionally, a salt water balance was developed from data collected by the Falmouth Pondwatchers and was used to develop an average freshwater recharge rate to the Pond. Tidal forcing information as well as tide data within the system were needed to calibrate the model. Tide measurements were recorded with three (3) tide gauges.

Oyster Pond is located in the Town of Falmouth adjacent to Vineyard Sound (Figure III-1). A 4 ft diameter culvert connects Oyster Pond to the tidal lagoon across Surf Drive. At the southern extreme of the lagoon, a narrow channel (Trunk River) connects Vineyard Sound to the lagoon. This channel has a jettied entrance along the Vineyard Sound shoreline. Visual observations at various phases of the tide indicated that Vineyard Sound tides rarely reach the elevation required to reverse the flow direction and cause Sound waters to enter Trunk River. A sand and gravel sill in the vicinity of the bike path bridge over Trunk River appeared to control upstream water elevations at a level above typical high tide elevations.

A. Temperature-Depth Recorders

To evaluate tidal flow in the Oyster Pond system, a one-month field observation program was staged from 12 July through 18 August, 1996. Temperature-depth recorders (TDRs) were used for the data acquisition at three locations: seaward of the Trunk River entrance, the lagoon, and Oyster Pond (Figure III-2). In addition, a gauge that measured atmospheric pressure was deployed in Falmouth during the same period. Data from this gauge provided atmospheric corrections to ensure accurate measurement of water levels. Each TDR contained a pressure sensor and thermistors. These sensors were coupled to dataloggers which record the temperature and sea-level data over the deployment interval, giving information on tidal behavior in the estuary. The pressure ports of all three gauges were surveyed to a known vertical datum (NGVD, 1929) for inter-comparison of the elevation data.

The TDRs measured temperature and pressure at 10 minute intervals throughout the deployment. The pressure readings were reduced to water surface elevation and plotted against time. Harmonic analysis (see Aubrey and Speer, 1985, for discussion) was used to reduce the tide into its constituents, reflecting both astronomical forcing and non-linear hydrodynamics. Tidal constituents refer to the time periods over which tides vary (diurnal, semi-diurnal, ter-diurnal, quarter-diurnal, etc.). Harmonic analysis is a widely used technique applied to sea surface elevation data to decompose the data

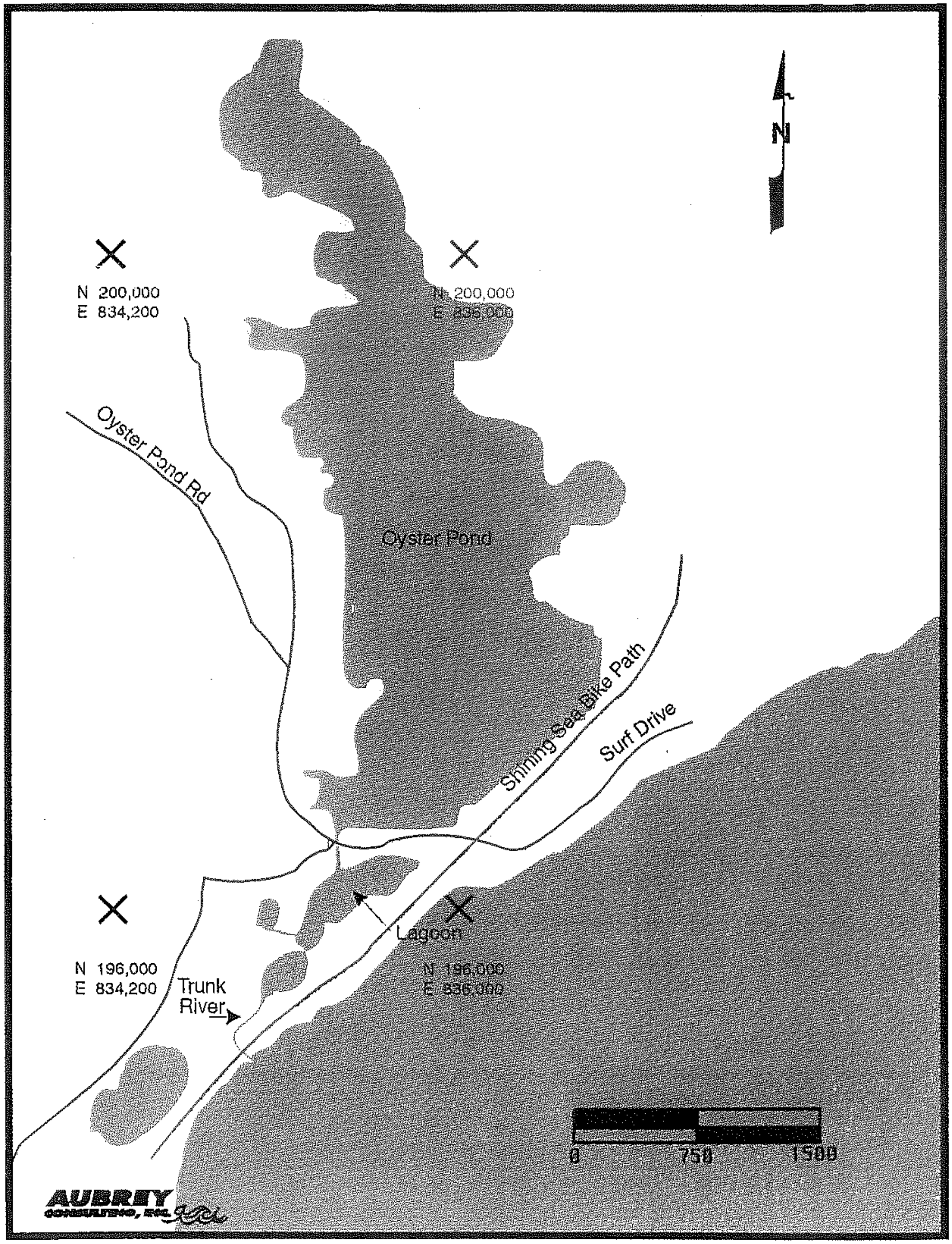

Figure III-1: Location map of Oyster Pond in Falmouth, Massachusetts.

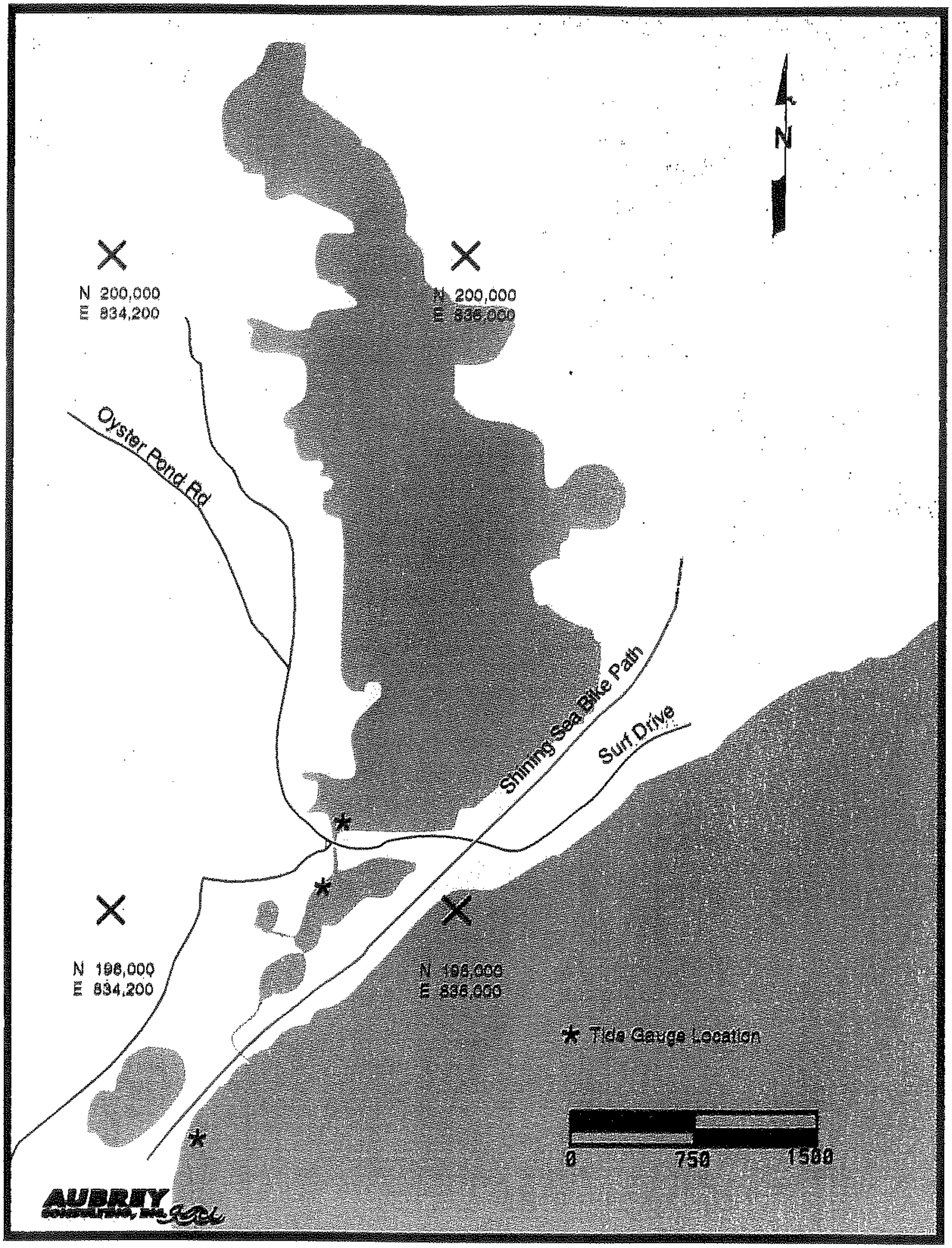

Figure III-2: Locations of the three TDRs used to measure water elevations in the Oyster Pond estuary.

into tidal constituents. Tidal behavior responding to non-linear hydrodynamic effects is critical for determining the extent of mixing and water exchange.

Results of the tidal elevation measurements collected during the study period are shown in Figure III-3. Full data recovery was achieved for all three TDRs; however, the two TDRs located within the lagoon and Oyster Pond exhibited a negligible tidal signal. This lack of tidal signal above Trunk River is likely due to the sill formed in the vicinity of the bike path bridge inhibiting tidal waters from entering the system. The tides at the remaining TDR were predominantly semi-diurnal; there were approximately 12 hours and 25 minutes between successive high tides and approximately 12 hours and 25 minutes between successive low tides. However, typical of Vineyard Sound, one of the two daily tidal cycles had a larger amplitude than the other.

Gravitational attractions of the moon and sun on the earth's surface water cause the rise and fall of tides. Tides vary depending upon the relative positions of the moon and sun, the characteristics of nearby land masses, and a variety of other factors. For example, high spring tides occur during the new and full moons when the sun and moon are aligned. More remarkable are the 30+ ft tides in the Bay of Fundy amplified by the funnel-shaped shorelines and the resonance of the tide in the Gulf of Maine.

The complexities of tidal motions can be examined by evaluating the individual constituents of tides caused by the sun, moon, landform geometry, bottom friction, etc. Doodson (1921) identified characteristics of 396 different tidal constituents; however, only a handful of constituents are significant in Vineyard Sound in Falmouth. Each tidal constituent is a wave with site-specific height and phase (time and position of occurrence). Conceptually, the superposition (addition) of all tidal constituents equals the measured tide, although the influence of non-gravitational atmospheric forces (e.g. wind and barometric pressure) complicate the phenomenon.

The dominance of the semi-diurnal tide in the Oyster Pond system is indicated by results of the harmonic analysis of tidal heights (Table III-1). The tidal signal was divided into components, where a different gravitational phenomena (sun, moon, etc.) is responsible for each component. For the offshore TDR, the M_2 constituent, also known as the principal lunar semi-diurnal constituent, was dominant with an amplitude of 0.59 ft. The second and third largest tidal constituents were the K_1 and N_2, respectively.

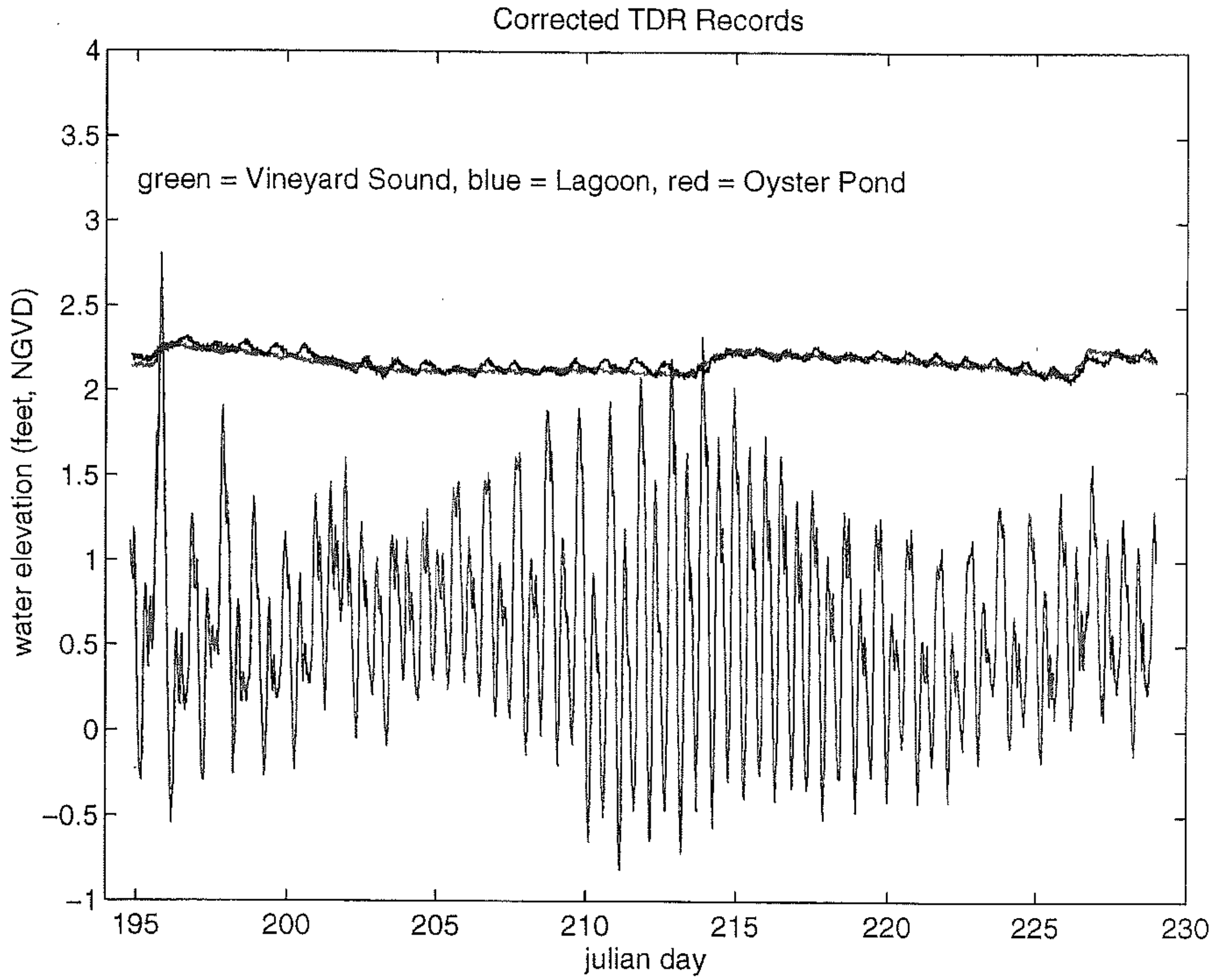

Figure III-3: Time series from the three TDRs deployed in the Oyster Pond system.

Table III-1
Tidal Constituents for Vineyard Sound TDR.

Constituent	Period (hrs)	Amplitude (ft)	Amplitude (cm)
K_1	23.98	0.25	7.71
M_2	12.42	0.59	18.05
M_4	6.21	0.20	6.06
S_2	12.00	0.10	2.92
N_2	12.66	0.25	7.58
O_1	25.82	0.18	5.34

Based on the relative tidal constituent heights, other significant constituents were:

- N_2 - Monthly variation in lunar distance.
- O_1 - Principal lunar diurnal constituent.
- K_1 - Solar-lunar constituent.
- S_2 - Principal solar tide.
- M_4 - Lunar quarter-diurnal (occurring four times daily) harmonic.

The relative importance of several constituents accounts for the variation in spring and neap tidal cycles observed in Figure III-3. In many places along the U.S. East Coast, spring tides occur every 14.7 days because M_2 and S_2 are the dominant tidal constituents. However, the significance N_2, O_1, and K_1 complicate the long-term tide range variation in this portion of Vineyard Sound. However, a 14.7 day record does provide the range of tides expected during one lunar cycle. Figure III-4 shows a comparison of the tide reconstructed from the constituents and the measured tide in Vineyard Sound. Since the tide range offshore of Falmouth is relatively small, climatological influences (wind, etc.) tend to distort the tidal signal to a larger degree than regions of large amplitude tides. Therefore, the smoothed constituent derived tidal signal was chosen to drive the model.

As shown in Figure III-3, the water surface elevation measurements for the TDRs in the lagoon and Oyster Pond show no tidal influence. The slight time varying behavior of the two curves can be attributed to changes in strain gauge readings resulting from the daily fluctuation in water temperatures, especially within the shallow lagoon. The three jumps in elevation over the one-month deployment period were likely the result of rock dams constructed by recreational users of the beaches adjacent to Trunk River. These dams caused a rapid rise in the observed pond levels.

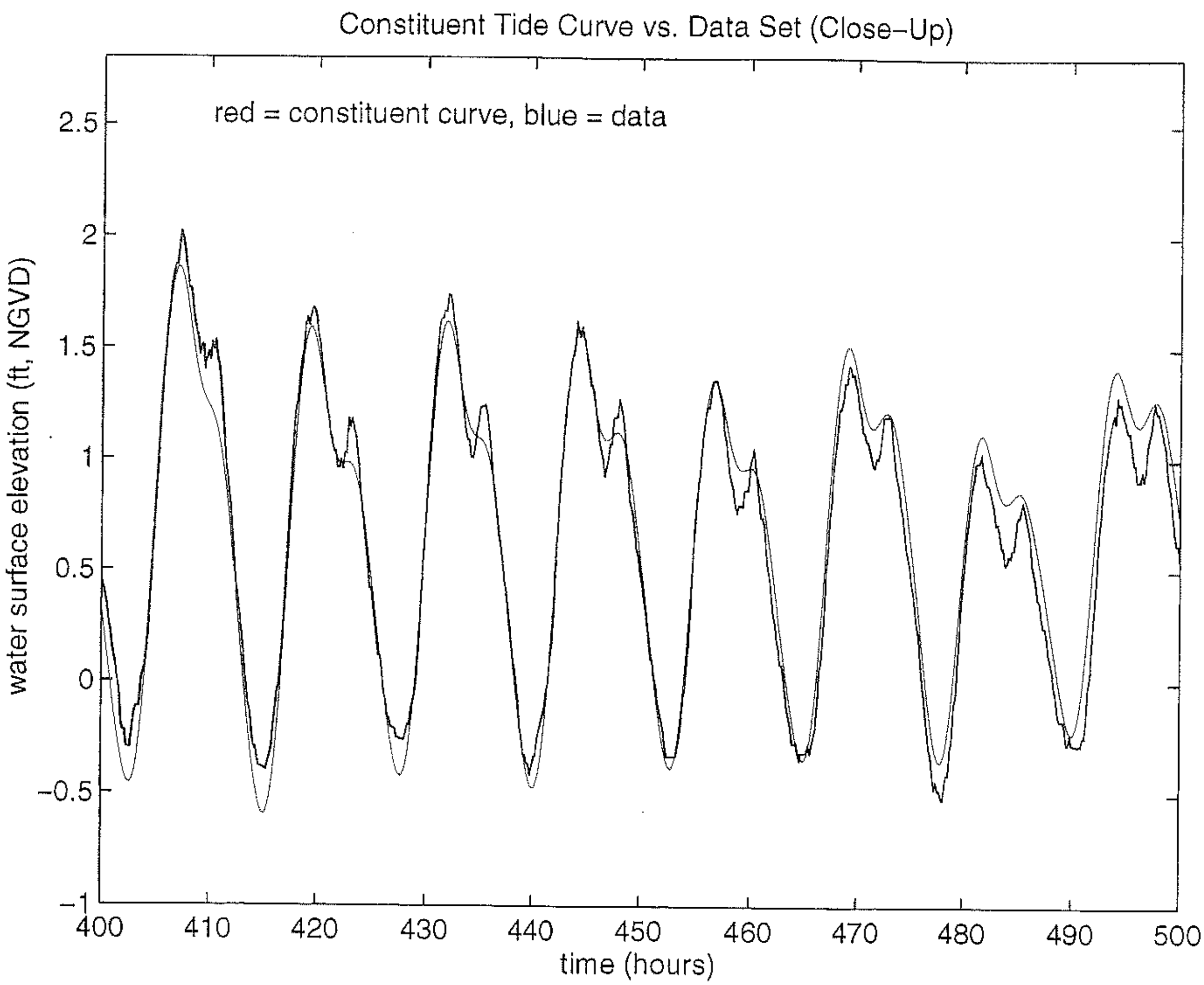

Figure III-4: Comparison of the tide measurements in Vineyard Sound. and the tide reconstructed from the tidal constituents.

B. Bathymetric Mapping

The bathymetry of the Oyster Pond system was developed from the work of Emery (1969), a topographic survey of the lower portion of Trunk River, and a bathymetric survey of the lagoon. The areas covered during the mapping included Trunk River, the lagoon, and Oyster Pond. Topographic mapping of the portion of Trunk River from Vineyard Sound to the river bend approximately 30 ft landward of the bike path bridge was performed using standard surveying techniques (Figure III-5). For the bathymetric survey, depth measurements were obtained using a stadia rod and a differential GPS (to provide x-y position). Using this system, approximately 50 depth and position measurements were recorded. These measurements were recorded in Northings and Eastings, referenced to the Massachusetts State Plane Coordinate system. Based on the TDR measurements, water elevations for every 10-minute interval were calculated in reference to National Geodatic Vertical Datum (NGVD). Depth and position information developed from the three data sources was supplied to the numerical model in digital format. This allowed accurate representation of the system geometry.

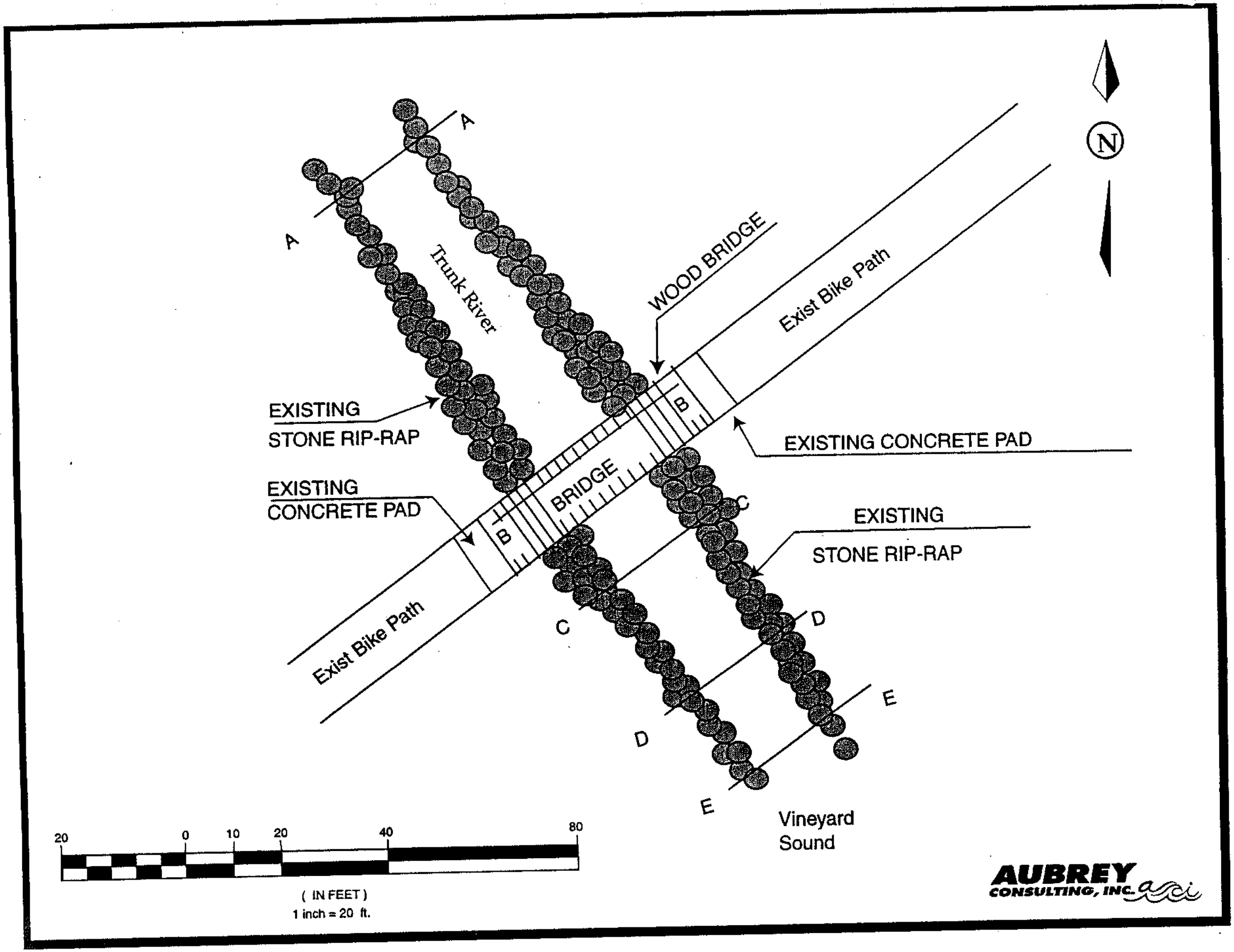

Figure III-5: Location of the four transects utilized to characterize the Trunk River channel.

IV. HYDRODYNAMIC MODELING

Recognizing that more detailed, site-specific scientific work to evaluate/design the proposed weir was required, the Town Engineering Department supported this project to numerically model the Oyster Pond system. To develop a quantitative understanding of the salt balance within tidally influenced estuaries, a thorough evaluation of the hydrodynamics of the estuarine system was performed. In addition to salinity, estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straight-forward extensions of the hydrodynamic modeling. The salt balance may be evaluated from salinity data and tidal current information developed by the numerical models.

This study of the Oyster Pond system utilized a two-dimensional depth-averaged numerical model to evaluate the hydrodynamics of the system. The particular model employed was the RMA-2V finite element model developed by Resource Management Associates (King, 1990a). It is capable of simulating either time-dependent or steady-state systems, and is well suited to analysis of estuary or river systems.

A. Model Theory

In its original form, RMA-2V was developed by William Norton and Ian King under a development contract with the U.S. Army Corps of Engineers (Norton et al., 1973). Further development included the introduction of one-dimensional elements, state-of-the-art pre- and post-processing data programs, and the use of elements with curved borders. The version used for this study was updated in 1993.

RMA-2V is a finite element model designed for the simulation of one- and two-dimensional depth-averaged hydrodynamic systems. The dependent variables are velocity and water depth, and the equations solved are the depth-averaged Navier Stokes equations. Reynolds assumptions are incorporated as an eddy viscosity effect to represent turbulent energy losses. Other terms in the governing equations permit friction losses (approximated either by a Chezy or Manning formulation), Coriolis effects, and surface wind stresses. All coefficients associated with these terms may vary from element to element.

The model utilizes isoperimetric quadrilaterals and triangles to represent the prototype system. Element boundaries may either be curved or straight. A Galerkin weighted residual approach is used to develop the finite element integral equations and Gaussian quadrature is employed to evaluate the final integral forms.

The time dependence of the governing equations is incorporated by using a modified Crank Nicholson solution technique to solve the set of simultaneous equations. This technique is implicit and, therefore, unconditionally stable. The equations are non-linear and are solved by using the Newton Raphson Method to develop a locally linear set of equations. Once solved, corrections to the initial estimate of velocity and water elevation are employed and the equations are re-solved until the convergence criteria are met.

B. Model Setup

To properly employ the RMA-2V model, generally three steps are required: creation of a finite element grid which adequately represents the bathymetry, development of boundary conditions, and determination of friction, turbulence, and wind stress coefficients. Information regarding the boundary conditions was supplied by the TDR data and fresh water inflow estimates based on the salt balance. The various coefficients were "tuned" by making trial model runs and changing the coefficients. Since tides did not propagate into Oyster Pond as a result of the present bathymetric conditions along Trunk River, reasonable estimates (Henderson, 1966) were used for both friction and turbulent exchange coefficients.

1. Finite element grid generation

The grid generation process was simplified by the use of a data pre-processing program, RMAGEN, developed by Resource Management Associates. The digital shoreline and bathymetry data were imported into this program and a finite element grid was generated to represent the estuary. Figure IV-1 shows the finite element grid for the Oyster Pond system. The finite element grid contained 527 nodes which formed 137 elements. The grid generation program was used to develop quadrilateral and triangular two-dimensional elements. The water depths at each nodal position were interpreted from the bathymetric map. In addition, widths of Trunk River and the culvert under Surf Drive were specified along these sections.

Figure IV-1 illustrates the varying grid sizes employed in this study. Areas of relatively high velocity flow and where flow directions were expected to change over a short distance had closely spaced nodes. The length of Trunk River from Vineyard Sound to the lagoon is an example of this type of region. Water flowing into the embayment during Spring tide has a relatively high velocity in the entrance channel; however, this area of flow concentration appears to diverge and decrease in velocity as it enters the main portion of the lagoon (illustrating both a rapid change in direction and velocity). Other regions of the embayment system, which have shown slowly-varying flow properties, have widely spaced nodes. Detailed bathymetric and velocity information in these regions was not required. The node spacing in the main portion of Oyster Pond is an example of widely spaced nodes.

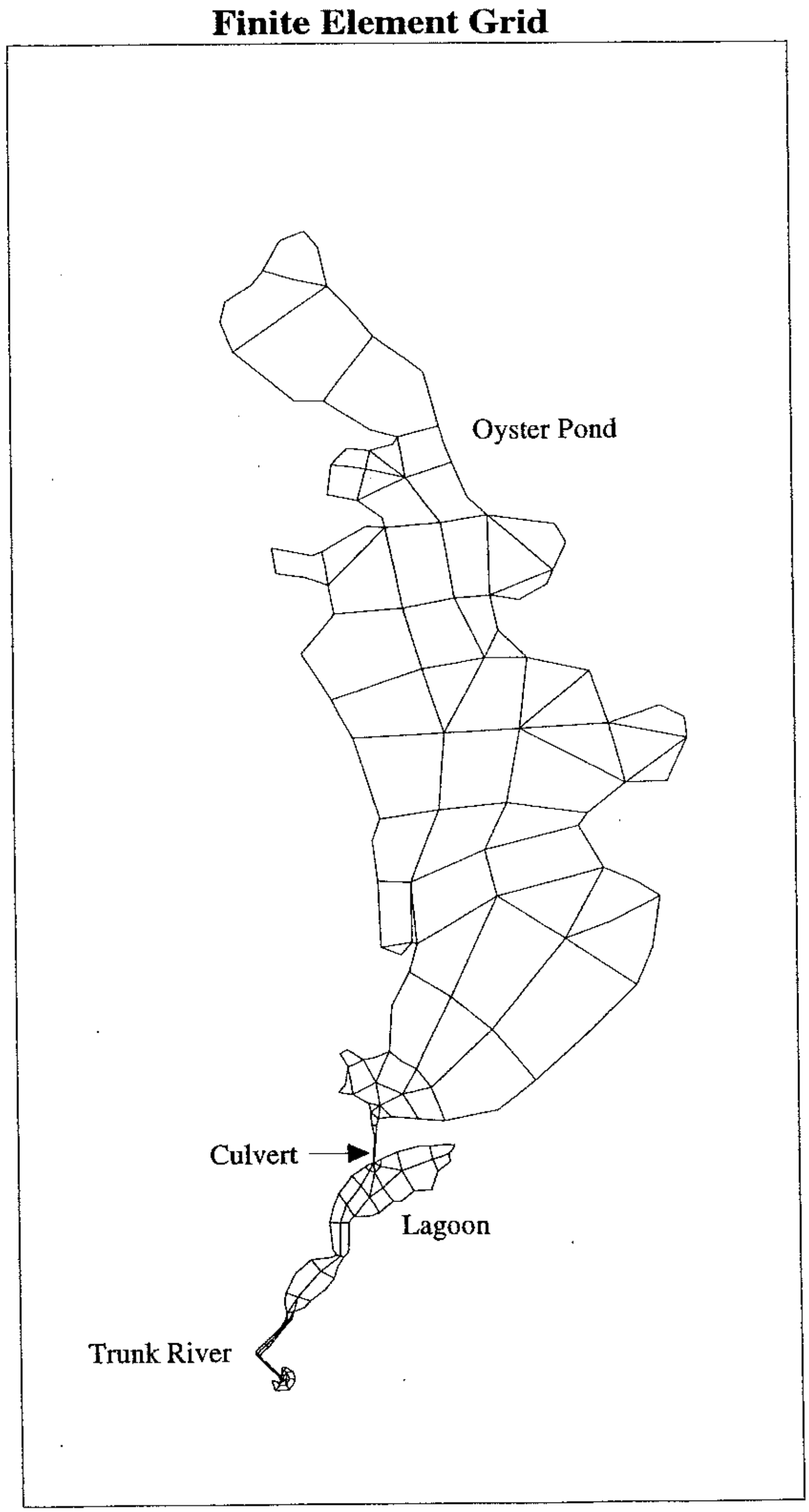

Figure IV-1: Finite element grid for Oyster Pond system

2. Boundary conditions

Three types of boundary conditions were employed for the RMA-2V model: "slip" boundaries, freshwater inflow boundaries, and tidal elevation boundaries. All of the elements which had land borders were required to have "slip" boundary conditions. At these locations, the direction of flow was constrained to be along the shoreline. The model generated all internal boundary conditions from the governing conservation equations.

The freshwater inflow boundaries were specified within the northern, central, and southern portions of Oyster Pond. Since no major tributary supplies surface freshwater to the system, the groundwater inflow was simulated as entering through the bottom of the pond. While this simplification of the boundary conditions does not represent the true groundwater flow which would be distributed around the perimeter of the pond, the volume of inflow is small and the simplified conditions have no impact on the system hydrodynamics.

The offshore tidal boundary was developed from TDR data taken from the gauge deployed seaward of the Trunk River entrance. A harmonic analysis was performed on the TDR data and a 14.7 day tide record was developed from constituents (Figure IV-2). This tide record exhibits the major long-term fluctuations in the offshore tidal record within this region of Vineyard Sound. A daily variation in the amplitude of high water exists for many of the tidal signals around Cape Cod. Although the variation between the amplitudes of the two daily high tides in Vineyard Sound is typically less than 40 percent, the accurate determination of flow rates must account for fluctuations of this nature. In addition, a substantial variation in tide range exists between Spring and Neap cycles, where the tidal amplitude more than doubles during Spring tide. An accurate depiction of the daily and fortnightly variation in tidal properties must be employed in the modeling to ensure the proper assumptions regarding the hydrodynamics of the system.

3. Determination of coefficients

Values for eddy viscosity and friction were required for this application of the RMA-2V model; however, since the wind field was ignored, no coefficients related to wind stress were involved in the analysis. Typically, the calibration procedure for hydrodynamic models requires an alteration of coefficients until modeled tides match measured tides. However, the super-elevated region of the Trunk River acted as a dam during the period of study and Oyster Pond was not influenced by tidal action (with the exception of the tropical storm Bertha). Instead, the calibration procedure consisted of varying the coefficients within the ranges presented in literature and evaluating the model results (e.g. Henderson, 1966 and Lindeburg, 1992). Trial runs of the hydrodynamic model were performed to determine appropriate values for the various coefficients. In addition, coefficient values were chosen that matched the physical representation of the estuary. Past tidal hydrodynamic studies supplied the proper range for these coefficients.

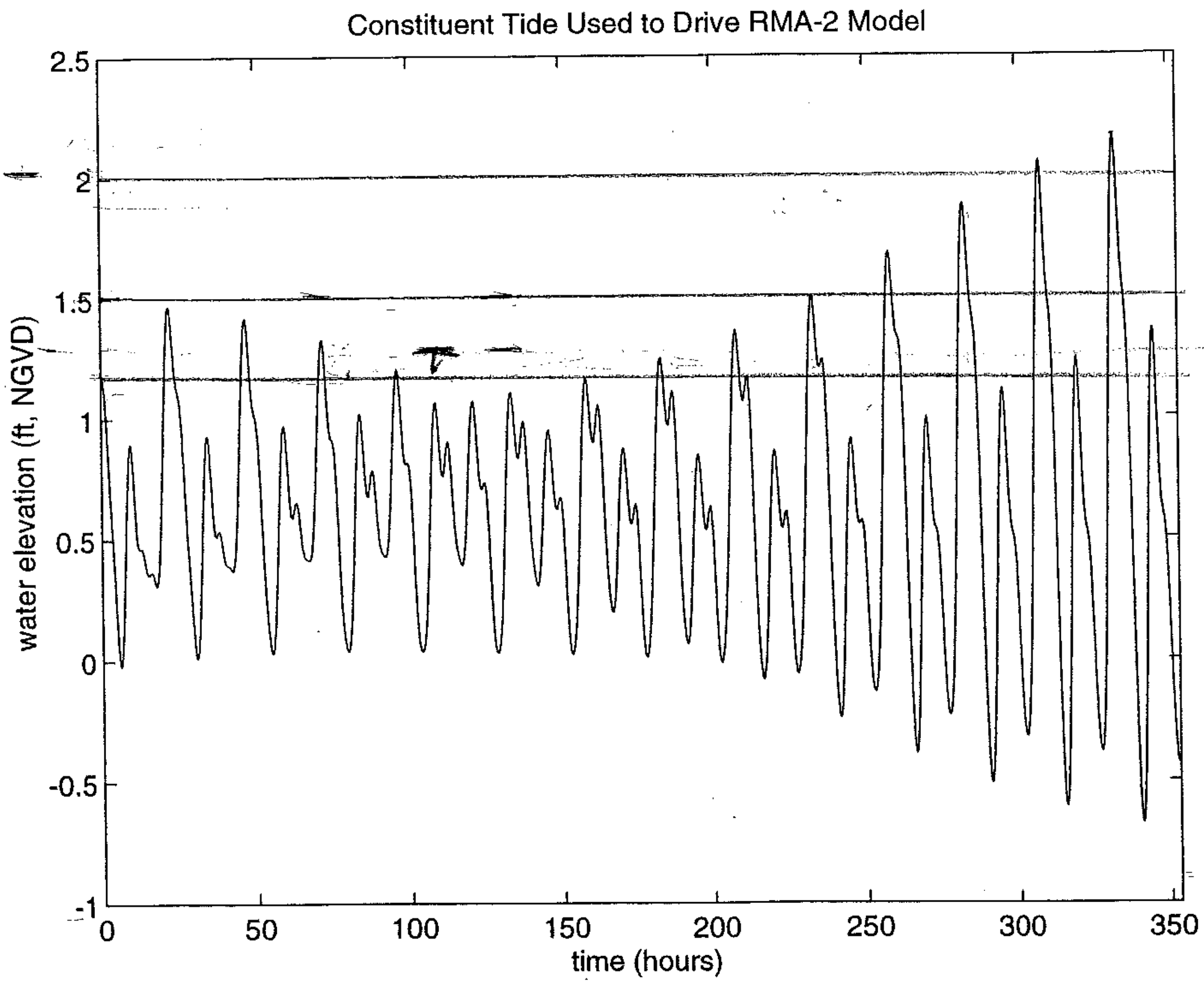

Figure IV-2: 14.7-day tide record developed from constituents

a. Friction coefficients

To improve model accuracy, friction coefficients were varied throughout the model domain between a range of 0.01 and 0.04. The Oyster Pond estuary included a range of bottom types, which were characterized with separate bottom friction coefficients. For example, lower friction coefficients were specified for the smooth sandy/gravel channel along Trunk River, versus the silty, vegetated bottom of the lagoon which provided significant flow resistance. Side friction also was specified for all elements, and was slightly higher than bottom friction since channel walls were more rough than channel bottoms. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within the estuary. Manning's values for different bottom types were selected based on the Civil Engineering Reference Manual (Lindeburg, 1992) and to obtain a close match between measured and modeled tides. Final calibrated friction coefficients are summarized in the Table IV-1.

TABLE IV-1

Manning's Roughness Coefficients
Input to RMA-2V

Embayment	Bottom Friction	Side Friction
Trunk River	0.010	0.03
The Lagoon	0.025	0.06
Culvert	0.010	0.03
Oyster Pond	0.025	0.06

b. Turbulent exchange coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is more swift, such as inlets and bridge constrictions. According to King (1990a), these values are proportional to element dimensions and flow velocities. The model of Oyster Pond was not particularly sensitive to turbulent exchange coefficients because there were no areas of swift, turbulent flow. Consequently, final calibrated turbulent exchange coefficients were specified as 0.50 times the element dimension throughout the estuary. This was the lowest possible value, which permitted evolution of complex flow patterns, such as eddies, while maintaining model stability. King (1990a) recommended using the lowest possible values for turbulent exchange coefficients to prevent artificial damping of unique flow features.

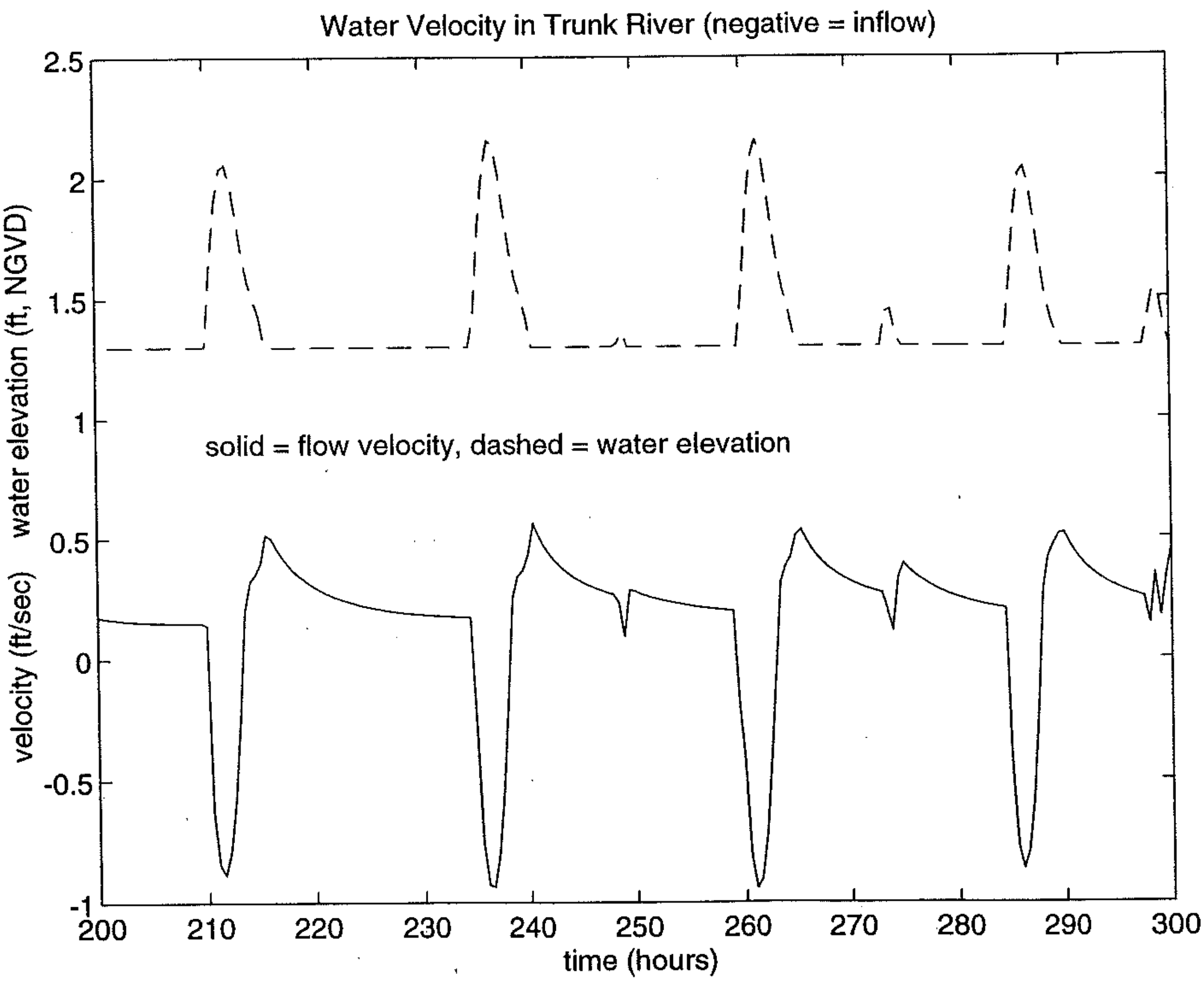

Figure IV-3: Water velocity and elevation within dredged Trunk River channel.

to allow adequate tidal exchange.

Due to the existing and historic conditions of the Oyster Pond system, a location for the weir was chosen approximately 30 ft north of the culvert under Surf Drive (within the outlet channel to Oyster Pond, see Figure IV-4). This location will allow the lagoon to exchange saltwater freely with Vineyard Sound and allow Oyster Pond to develop the brackish conditions similar to conditions during the 1960's. A salt/freshwater balance was developed to determine the proper amount of tidal exchange based on the average freshwater recharge calculated and average salinity values for Vineyard Sound taken from Falmouth Pondwatcher's data (32.59 ppt). Using a freshwater recharge rate of 0.90 ft^3sec^{-1} (2,200 m^3day^{-1}) the saltwater inflow rate needed was 0.06 to 0.13 ft^3sec^{-1} for a salinity of 2 to 4 ppt in Oyster Pond, respectively.

The weir was simulated in the model by creating a dam with various elevations across the Oyster Pond outlet channel (Figure IV-4). The model was run for the different weir heights and the average saltwater inflow over the 14.7-day period modeled. A design rating curve was developed from these runs to determine the appropriate height of the weir (Figure IV-5). Based on this curve, the weir should initially be designed with a crest height between 1.37 and 1.55 feet NGVD. Since the most recent salinity measurements indicated a relatively high salinity in Oyster Pond (>5 ppt), the initial design height was chosen at the high end of the acceptable range of weir elevations, 1.5 feet NGVD. In addition to evaluating, the appropriate weir height, the water elevation within Oyster Pond was determined for comparison to existing conditions. Based on the results of the modeling, the elevation of the Pond should be maintained at an elevation approximately 0.5 ft below its existing level (lowering from 2.1 ft NGVD to 1.6 ft NGVD). While existing salinity values may be above the suggested 2 to 4 ppt, the average salinity continues to drop as a result of the sedimentation in Trunk River. Since construction is not planned until the spring of 1997, the salinity is anticipated to be in the proper range by this time. Regardless, adjustments to the weir allow the pond to remain at an elevation that will continue to lower the salt content, if required.

D. Design Considerations

The weir was designed to provide the appropriate brackish conditions in the pond and allow simple adjustment for the range of anticipated tide and freshwater recharge conditions. The initial design height is 1.5 feet NGVD; however, the design allows for the height to be altered by +/- 0.5 feet. The crest width was established as 5.0 feet to be similar in width to the Trunk River channel and prevent severe constriction of the flow. Based on the range of anticipated heights, the maximum elevation between the upstream and downstream water levels is 0.30 feet, with a mean difference of 0.18 feet. Consideration of anadromous fish passage for the maximum anticipated water level difference between the pond and the lagoon was utilized to determine whether the design should incorporate some type of fish ladder. Typically, the design of fish ladders for blueback herring utilizes step heights between 6 and 8 inches (personal

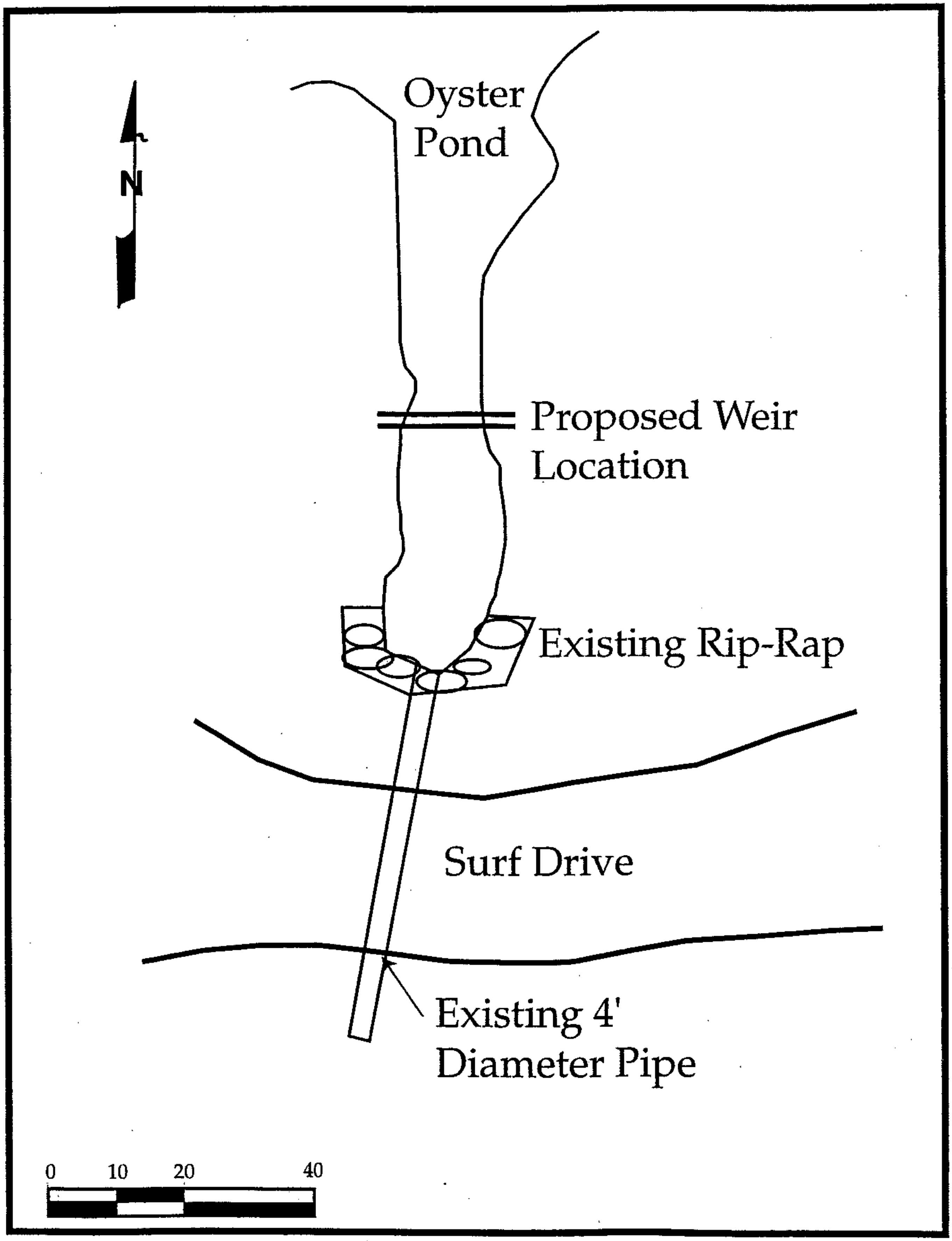

Figure IV-4: Approximate location of the Oyster Pond weir north of Surf Drive.

communication, Massachusetts DMF, 1996). Based on the model results, the maximum water elevation differential across the weir is less than a step size for a standard fish ladder; therefore, a fish ladder may not be required.

Although the weir elevation was specified by the hydrodynamic analysis, several weir design variations are possible. The base structure of the weir will be constructed of concrete and removable 'slats' will be added to allow alteration of the effective weir height (Figure IV-6). The slats will allow the minor adjustments in elevation necessary to 'fine-tune' the pond salinity. In addition, the entire middle section can be removed after severe storm overwash to prevent flood waters from super-elevating the pond for extended periods. During significant storms, the weir will slow flood waters entering the pond via Trunk River; however, once overwash of Surf Drive occurs, the weir could inhibit the rapid relaxation of flood waters through the culvert and Trunk River. Therefore, the middle section of the weir has been designed to be removable. This removable section will have a cross-sectional area equal to or larger than the cross-sectional area of the culvert under Surf Drive to ensure the weir does not inhibit flood water relaxation following extreme storm events.

The schematics for the design is illustrated in Figure IV-6. Several designs were considered; however, the single removable weir section provided the simplest solution. A more narrow crest width may be advantageous during low-flow periods to aid juvenile herring migrating to Vineyard Sound, but this type of design would reduce tidal exchange across the weir during Spring tide conditions. The design with the rectangular middle section, (a), will allow a standard length construction for the removable baffles. In addition, grooves in the upper portion of the wood weir section could be created to aid juvenile herring traveling toward Vineyard Sound during the low flow periods in the Fall. Therefore, this rectangular weir section was chosen for this project.

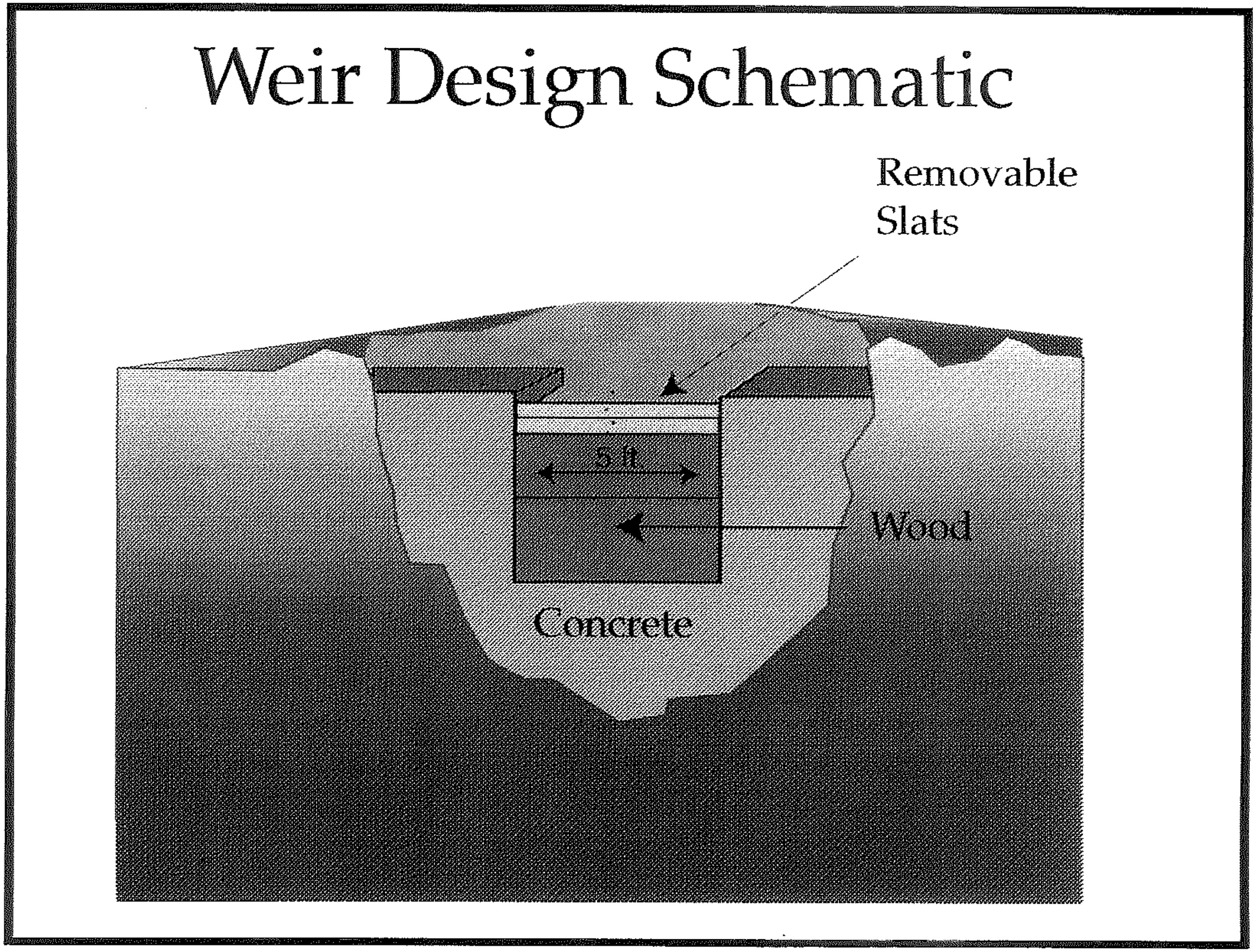

Figure IV-6: Weir design schematic.

V. SUMMARY AND POND MANAGEMENT ISSUES

The rational behind the proposed pond management strategy is to return Oyster Pond to the ecologically stable system that existed prior to man-induced changes in the early 1980s. As the first step of the pond management, a weir has been designed to inhibit tidal exchange between Vineyard Sound and Oyster Pond for all but the higher Spring tide conditions. The intent of this structure is to stabilize the salinity conditions within the Pond and maintain a long-term average value between 2 and 4 ppt. In addition, dredging activities required in the Trunk River channel will allow tidal waters to enter the lagoon during most high tides. Allowing an increase in tidal action through this region will prevent fine sediment deposition and should improve water quality in this region.

The present study consisted of data collection and hydrodynamic modeling to evaluate installation of a weir at the outlet of Oyster Pond. In addition, a weir was designed to provide the appropriate brackish conditions in the pond and allow simple adjustment for the range of anticipated tide and freshwater recharge conditions. The initial design height is 1.5 feet; however, the design allows for the height to be altered by +/- 0.50 feet. The crest width was established at 5.0 feet to minimize flow restriction. Based on the range of anticipated heights, the maximum elevation between the upstream and downstream water levels is 0.30 feet, with a mean difference of 0.18 feet.

To develop the hydrodynamic model used to evaluate the weir design, various data were required to define the Oyster Pond system parameters. Bathymetric data collected by Emery (1969) provided information within Oyster Pond; however, additional bathymetry/topography data was required for the lagoon and Trunk River. In addition, tidal measurements in Vineyard Sound, the lagoon, and Oyster Pond were taken to adequately describe the tidal signal attenuation between the open ocean and the pond. Typically, the tidal wave will propagate through an inlet and some reduction of wave amplitude as well as a time lag between offshore high tides and those within the system will occur. This tidal "damping" results from energy losses associated with bottom drag and turbulence as the tidal currents enter the inlet.

Due to the existing bathymetric/topographic conditions in the Trunk River channel, tide propagation into the inlet is negligible. The sand/gravel sill or bar that has developed immediately upstream of the bike path bridge prevents all but the highest Spring tides from entering the Oyster Pond system. Even the tropical storm Bertha (July 14, 1996), with a maximum surge elevation of 2.8 feet NGVD (Figure III-3, Julian Day 195), had a negligible effect on tidal response within the lagoon and Oyster Pond. The formation of the sill inhibits the exchange of tidal waters between Vineyard Sound and the Oyster Pond system. To change the hydraulic control from this sill to the proposed weir, dredging of the Trunk River channel to an elevation of 1.2 ft, NGVD or below will be required. Having the hydraulic control moved upstream to the Oyster Pond outlet will allow the lagoon to maintain the existing salt marsh plant species. In addition, the weir will prevent most of the highly saline waters from entering Oyster Pond, allowing it to stabilize as a brackish water body.

The weir also will prevent storm surge flood waters from entering Oyster Pond until the water elevation in Vineyard Sound exceeds 1.5 ft NGVD. During typical storm conditions, the weir will prevent pond flooding more effectively than the existing Trunk River system. However, severe storm surge conditions can overwash the barrier beach separating Oyster Pond from Vineyard Sound. During these severe conditions, the weir could inhibit the super-elevated from draining rapidly. Therefore, the weir has been designed with a removable gate to enhance relaxation of flood waters following severe storm conditions.

Concerns about anadromous fish also were considered. The weir design will cause a maximum height differential between the pond and lagoon of 0.3 ft. This differential is within the range of typical fish ladder steps utilized for herring runs along the south shore of Cape Cod. During low flow periods, typically the late summer months, the depth of flow over the weir may be reduced making migration of juvenile fish toward Vineyard Sound more difficult. To aid flow depths and the related juvenile herring migration during drought conditions, the upper boards of the weir could be designed with grooves or holes to concentrate flow over a narrow cross-section.

The weir design will enhance the ecological stability of Oyster Pond by creating a brackish ecosystem with an average salinity between 2 and 4 ppt. While the long-term salinity balance will depend on the frequency of storms causing overwash of the Surf Drive barrier beach, a simple weir system can be designed to stabilize the salinity regime for typical tide conditions (monthly variations associated with the phase of the moon, etc.). This system will emulate the Oyster Pond conditions prior to the man-induced changes in the early 1980's. Once the weir is installed and the Trunk River channel is dredged, the following changes can be expected:

- The mean pond elevation will drop approximately 0.5 ft from the observed elevation in July, 1996 (from 2.1 ft NGVD to approximately 1.6 ft NGVD). This will return the pond to an elevation similar to the pre-1995 level.

- Trunk River and the lagoon area will be subjected to more frequent tidal exchange with Vineyard Sound, where nearly half the high tides will cause some flow reversal in Trunk River.

- Flushing will improve in the lagoon, preventing additional accumulation of fine-grained sediments and possibly scouring existing areas of sediment build-up.

- Aesthetics of the lagoon should be improved by the increased tidal action, since the tidal currents should decrease detrital accumulation.

- Salinity levels within Oyster Pond should stabilize between 2 and 4 ppt.

- No adverse impacts to fish migration should result from the project.

Depending upon sedimentation of the inlet and the frequency of storm surge waters entering Oyster Pond, maintenance of the system will likely be required. Continued observations by the Falmouth Pond watchers will form an integral part of the long-term management for Oyster Pond. The weir design allows for fine-tuning of the crest elevation for this purpose. Fluctuations in freshwater recharge and storm frequency will influence the system on a seasonal and, in the case of storms, an event basis. Management of the weir system will require a review of salinity data, initially on a monthly basis, to determine the appropriate weir height. Once a stable salinity regime has been established, seasonal and/or post-storm reviews of salinity data should be utilized to adjust the weir elevation. In addition, emergency procedures should be developed to remove the weir to enhance flood relaxation following severe storms that overwash the barrier beach.

VI. REFERENCES

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