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AN EVALUATION OF ALTERNATIVES FOR ESTUARINE RESTORATION MANAGEMENT:

The Herring River Ecosystem
(Cape Cod National Seashore)

DRAFT

Report Appendicies

CENTER FOR COASTAL AND ENVIRONMENTAL STUDIES
NATIONAL PARK SERVICE COOPERATIVE RESEARCH UNIT

AN EVALUATION OF ALTERNATIVES FOR ESTUARINE RESTORATION MANAGEMENT: THE HERRING RIVER ECOSYSTEM (CAPE COD NATIONAL SEASHORE)

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REPORT APPENDIX 1

HERRING RIVER ESTUARY:
HISTORIC VEGETATION DEVELOPMENT

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INTRODUCTION

For over 80 years scientists have been investigating various aspects of the geologic, geomorphic and ecologic development of Cape Cod, Massachusetts (Shaler 1898, Woodsworth and Wigglesworth 1934, Mather et al. 1942, Butler 1959, Redfield and Rubin 1962, Chamberlain 1964, Strahler 1966, Redfield 1967a, 1972). To date, one of the most comprehensive works on tidal marsh development was conducted at the Barnstable marshes by A. C. Redfield (1972) . These marshes, located approximately 65 km southwest of Herring River, developed within a drowned coastal embayment, while the Herring River system is a flooded river valley. Similarities in marsh development between these systems do exist, yet, interpretation of Herring River marsh development cannot be based solely on the Redfield model as it is clearly evident that some significant differences do exist (Orson et al. In Press). For example, sedges appear to be more important in the development of estuaries than in coastal embayments.

Cape Cod has been subsiding since the termination of the Pleistocene Epoch. Redfield and Rubin (1962) found relative submergence rates have averaged approximately 1.0 meter per 1000 years (1.0 mm/yr) over the last 4000 years, a rate also found in other areas of New England (Bloom and Stuiver 1963, Hill and Shearin 1970, Keene 1971). More recent investigations have suggested that rates of submergence have accelerated over the last ca. 100 years and are now approaching rates comparible to those of the pre-4000 year datum (2.5 mm/yr)(Flessa et al. 1977, McCaffrey 1980, Clark and Patterson 1985). For purposes of this report a long-term accretion rate of 1.0 meter per thousand years will be applied to peat depths exceeding 1.0 meter below the present surface. For depths of less than 1.0 meter this long-term accretion rate will not be applicable for reasons to be discussed below.

This project was initiated to document the historic distribution of salt marsh vegetation within the Herring River estuary Wellfleet, Massachusetts. This study is based on the interpretation of rhizome and sedimentological characteristics of peat cores taken throughout the system. Radiocarbon dates are anticipated, yet not available for inclusion in this report. These dates should significantly aid in the core interpretation. The model of Herring River development offered in this paper is based on the interpretation of previously published chronologies, core analysis, historic records and recent topographic maps.

STUDY SITE/METHODS

Nine complete peat cores ranging in depth from 1.0 to 3.5 meters were removed in successive half-meter sections using a side chambered Russian peat sampler (core locations are shown on Figure 1). Each core was identified as to the relative abundance of dominant plant taxa and major sedimentalogical characteristics according to proceedures previously described by Niering _et_ _al_. (1977) and Orson (1982). In addition, a basal sample was set aside for each core for radiocarbon analysis to be completed at a later date. Once established, the time line chronologies will be ammended to this report.

RESULTS AND DISCUSSION

Development Scenario

The following is a theoretical model of development for the Herring River estuary during the last 3.5 meters of substrate accumulation (Figure 2 a,b,c,d). The model proceeds from the past to the present in successive half-meter intervals with emphasis placed on the top two meters of development. The maps included in this report are one possible conceptual interpretation based on the information available. Due to the fact that living rhizomes primarily occupy the top 20 cm of substrate the maps are based on a twenty centimeter development buffer zone. The authors recognize that gaps in the data do exist and a more detailed study of the substrate would be necessary to more precisely define wetland development at Herring River.

Development to 2.0 meters

Evidence suggests that contemporary tidal salt marshes of New England began forming at a maximum of about 4000 years B.P. (Bloom and Stuiver 1962, Keene 1971, Redfield 1972). The deepest cores taken at Herring River shows salt marsh and tidal flat complexes beginning between 2.7 and 3.2 meters in depth below the surface (see Core Log, HR-1, PDC-2). Using Redfields (1967b) submergence curves and a proposed accretion rate of 1.0 mm/yr this depth range represents a time frame of development of about 3000 years B.P. and falls within the proposed 4000 year datum for maximum development.

As sea level rose, developing salt marsh was widely distributed throughout the estuary, as depicted by the conceptual view of the system at 2 meters (Figure 2a). Cores HR-2, BB-1 and PDC-2 at approximately 2 meters show a predominance of fine marine sediments and sparse _Spartina_ _alterniflora_ rhizomes, thus suggesting developing salt marsh and tidal flat complexes. Cores in the vicinity of the openings of Bound Brook and Duck Harbor (BB-2, DH-1) reveal a relative high sand component reflecting the influence of the developing spits.

FINAL FIGURE IN PREPARATION

Fig. 1. Location of nine peat cores.

Fig. 2 a,b,c,d. Theoretical model of marsh development in the Herring River basin (Wellfleet, Massachusetts). Based on the interpretation of nine peat cores (location shown), the model suggests what the distribution of marsh and estuarine habitats may have been in past time intervals. These time intervals are indicated by half-meter segments of the peat record.

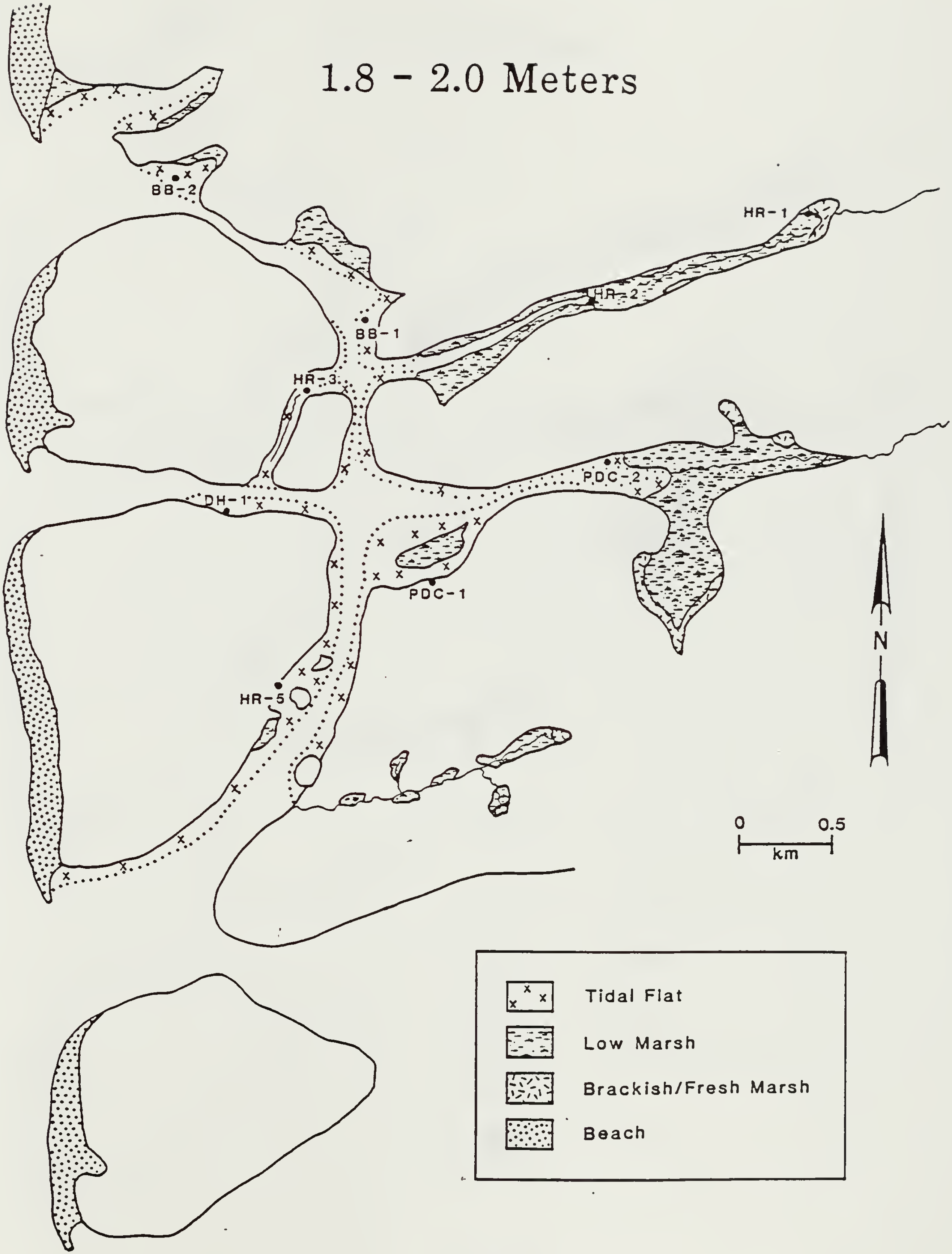
1.8 - 2.0 Meters
BB-2
HR-1
HR-2
BB-1
HR-3
PDC-2
DH-1
PDC-1
HR-5
N
0
0.5
km
Tidal Flat
Low Marsh
Brackish/Fresh Marsh
Beach

Fig. 2a.

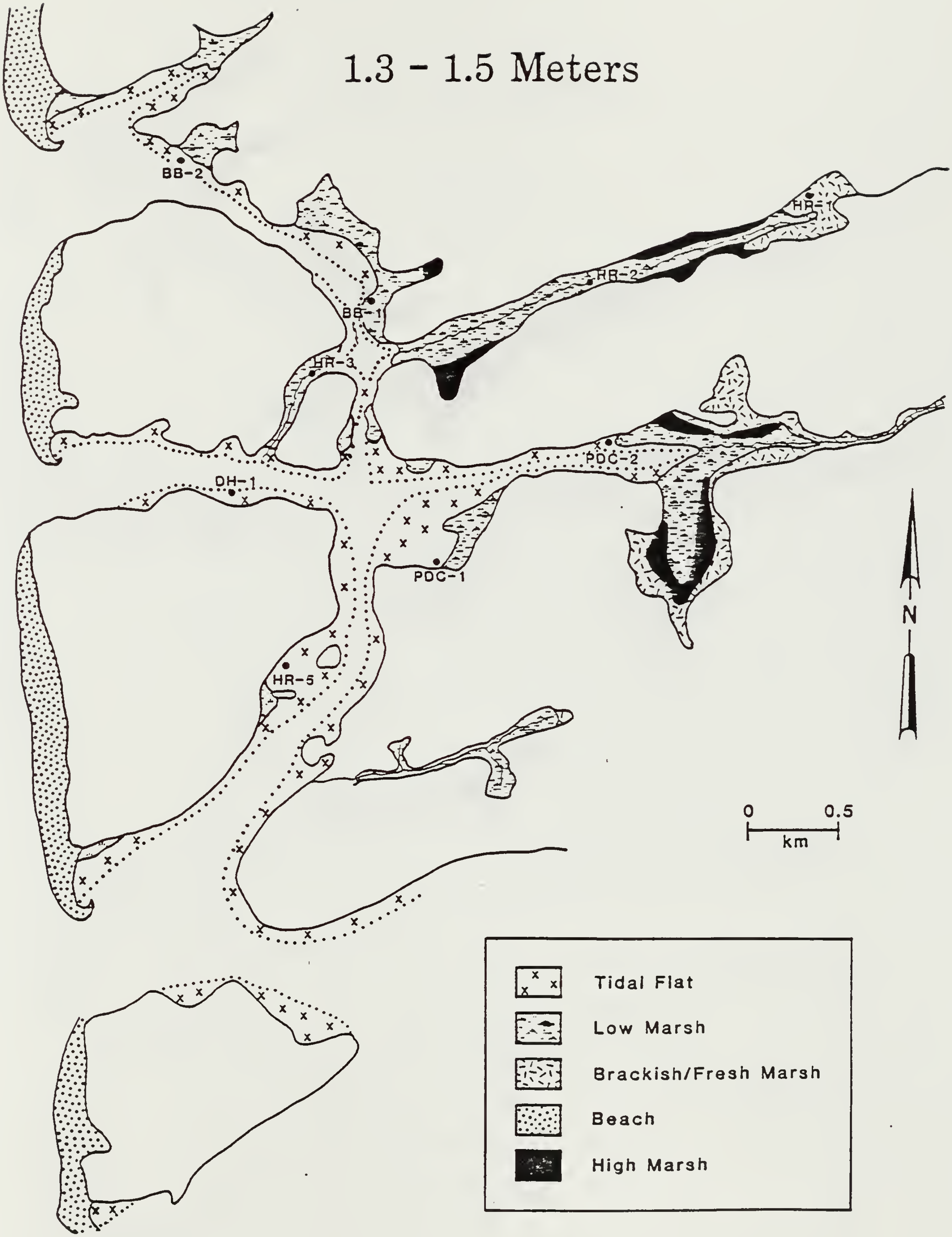
1.3 - 1.5 Meters

Fig. 2b.

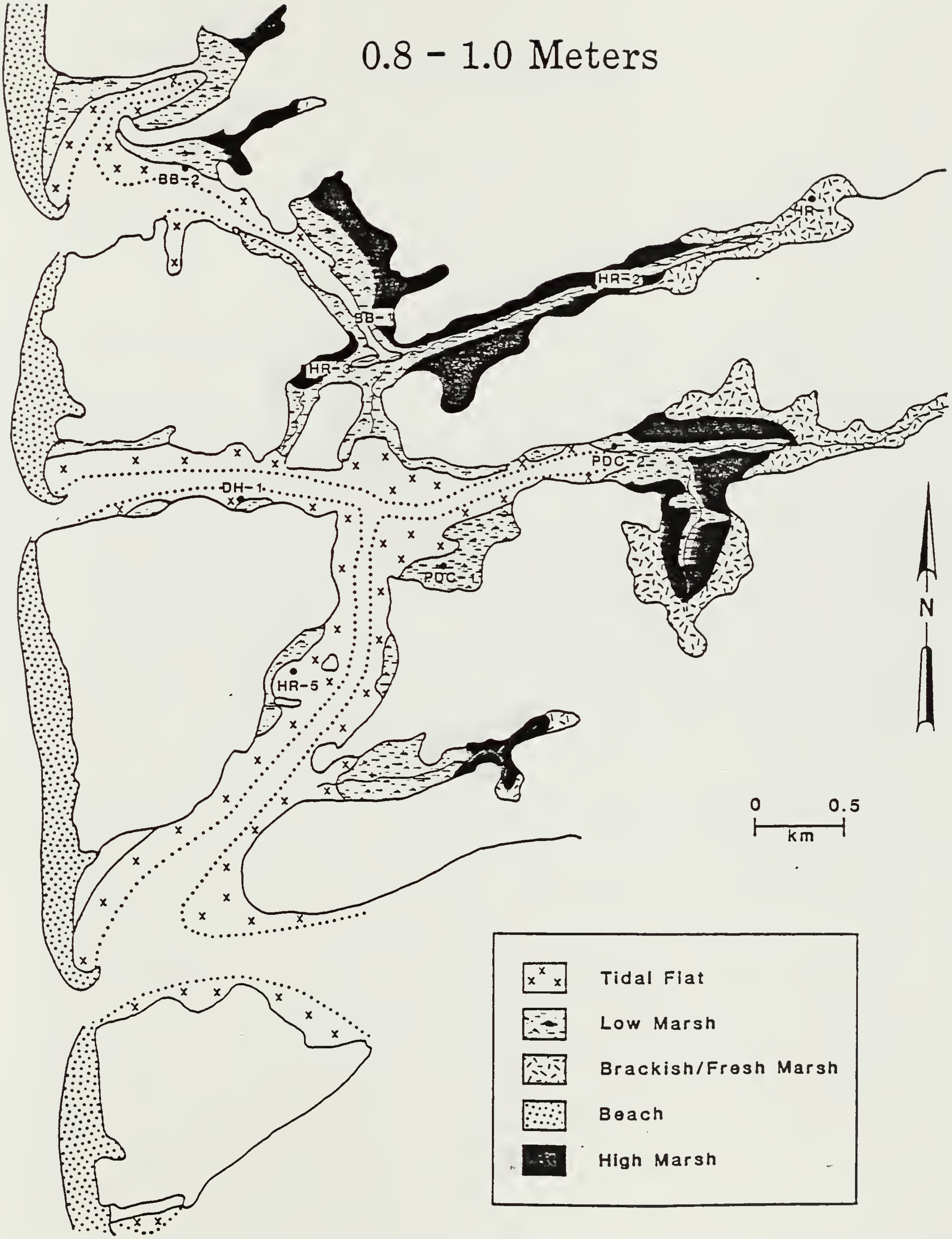
0.8 - 1.0 Meters
BB-2
HR-1
HR-2
BB-1
HR-3
DH-1
PDC-2
PDC-1
HR-5
N
0
0.5
km
Tidal Flat
Low Marsh
Brackish/Fresh Marsh
Beach
High Marsh

Fig. 2c.

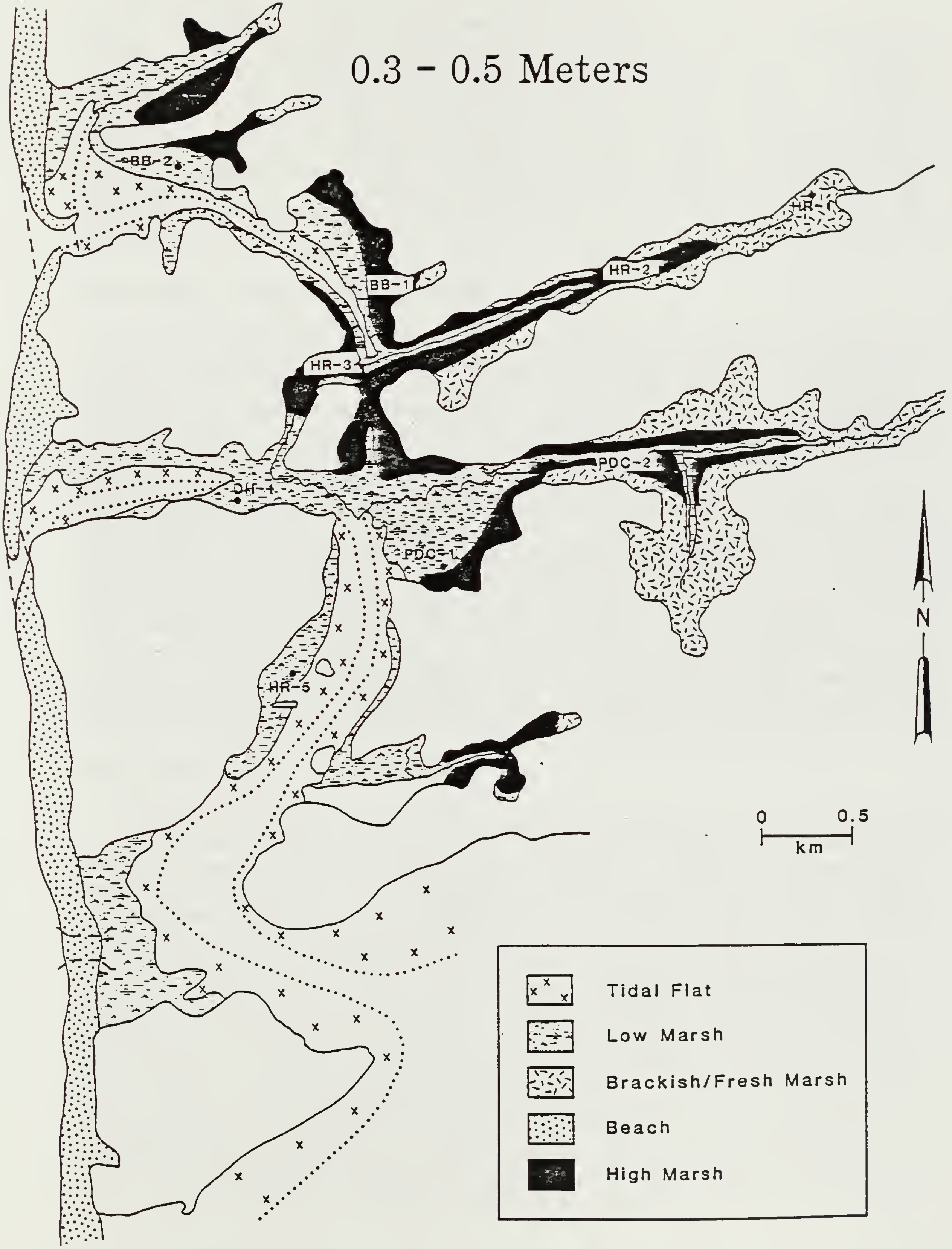
0.3 - 0.5 Meters
BB-2
BB-1
HR-1
HR-2
HR-3
DH-1
PDC-1
PDC-2
HR-5
N
0
0.5
km
Tidal Flat
Low Marsh
Brackish/Fresh Marsh
Beach
High Marsh

Fig. 2d.

As shown on Figure 2a, it is assumed that both harbors and the mouth of Herring River were open water habitats with fringing salt marsh. More extensive marsh areas probably existed in the upper reaches of Herring River, Pole Dike Creek and Mill Creek. Brackish marshes may have occurred at the extreme upstream arms of these basins, as supported by the identification of sedge rhizomes and fine sediments near the 2 meter level of core HR-1. Within a range of site specific variations, this sequence of development described for Herring River to 2.0 meters is typical of coastal estuaries and embayments of New England (Keene 1971, Redfield 1972, Orson *et al*. In Press).

Development from 2.0 to 1.5 meters

During the next 0.5 meter of development many upland areas were further inundated with tidal waters and marsh begins a period of infilling on many of the tidal flat areas (Figure 2b). Cores HR-2, HR-3 and BB-1 show a relative increase in abundance of *S. alterniflora* rhizomes from 2.0 to 1.5 meters, suggesting the occurrence of fairly well developed low marsh habitat. Salt marsh development was less evident in other parts of the system as indicated by sparse *S. alterniflora* rhizomes near the 1.5 meter level for cores BB-2, DH-1, PDC-1 and PDC-2. A somewhat open or sparsely vegetated estuarine environment probably prevailed, as suggested in Figure 2b. This is further supported by shells of estuarine invertebrates found in cores HR-5, DH-1 and PDC-2 near the 1.5 meter level. Core HR-1 indicates that brackishwater (*Typha* and sedges) marshes have increased in the upstream areas of the system from 2.0 to 1.5 meters. This apparent increase in brackishwater habitat may be associated with decreased estuarine exchange due to barrier spit elongation and restriction of flow by the increased vegetated area of the basins.

Development from 1.5 to 1.0 meters

During the next stage of development (Figure 2 b,c) the infilling of low lying areas apparently increases as tidal flat/low marsh complexes begin replacing open water habitats. This may be partially due to the effects the elongating spits are having on estuarine circulation patterns. The reduction in estuarine circulation would facilitate the aggradation of mud flats and establish base material on which future marsh development can occur. Along the Herring River and portions of Bound Brook, high marsh (*Spartina patens*/*Distichlis spicata* associations) begins to dominate replacing low marsh as evidenced by cores HR-2 and BB-1. Brackishwater marsh has probably increased by 1 meter as shown in Figure 2c. Again this may be related to decreased flushing throughout the system. By 1.0 meter Herring River was a well developed salt/brackish marsh habitat typical of estuaries of New England. Due to factors such as the autocompaction of peat (Kaye and Barghoorn 1964) and/or land modifications the last meter of development probably represents a time frame of less than 1000 years, however, a precise estimate is not possible at this time.

Development from 1.0 to 0.5 meters

Between 1.0 and 0.5 meter of development (Figure 2 c,d) the system undergoes some major changes. First, it appears that by 0.5 meters the estuary may have significantly accumulated tidal flat/marsh complexes. This is supported by changes from sparse to dense low marsh vegetation in cores HR-5, BB-2, DH-1, PDC-2 and PDC-1 and changes from sandy open water substrates to clay dominated flats in cores BB-2 and HR-3. These data suggest either a reduction in water movements and/or an increase in sedimentation has occurred. It is not possible at this time to discern if this change in sediment composition is related to a complete, or near complete closure of the Bound Brook and Duck Harbor spits (note: this is represented by a dashed line along spits on Figure 2d). However, it is clear from the data that circulation has been greatly reduced and that spit elongation is probably responsible.

In core DH-1 a sand layer appears at 0.7 meters and is directly accompanied by changes in vegetation towards less salt tolerant species. This sequence is repeated in core BB-2 at 0.4 meters. The suggestion here is that due to spit elongation bay exchange was significantly reduced within the harbors between 0.4 and 0.7 meters. Inspection of the other cores (Core Log) tends to support the contention that a change did occur at or near 0.7 meters throughout much of the estuary. Thus, by 0.5 meters the Herring River was the major source of salt water to the entire estuarine environment.

Areas along Pole Dike Creek are shown to support expanses of marsh and as suggested by BB-2, both Duck and Bound Brook Harbors resemble open low marsh areas rather than the open water habitats more commonly associated with harbors. Along the Herring River brackish conditions are extending downstream replacing high marsh habitat.

Development from 0.5 meters to the Present

Within the top half-meter of peat all cores indicate that open water and sparsely vegetated flats have been replaced by a marsh/swamp complex. Marsh development over accumulated mud flats saw the conversion from tidal flats to a mostly vegetated system dissected by tidal creeks. Also, within this stage of development most of the salt marsh is replaced by freshwater herbaceous and woody plant species. Decreased circulation has contributed to a drying of the marsh substrate and increases in decomposition as suggested by the loose fragmented peat between the surface and 0.5 meters. At present, salt marsh is only found in close proximity to the dike along Herring River. Here the marsh grasses are mixed with species such as *Phragmites australis* and *Scirpus* spp. suggesting more brackish conditions throughout. The changes in vegetation and substrate structure noted at Herring River have been shown to also occur on restricted wetlands in Connecticut (Roman *et al*. 1984).

SUMMARY

Vegetation changes within the Herring River system appear to be consistent throughout. A generalized scheme for vegetation transition within this estuary is as follows;

tidal flat/low salt marsh - high salt marsh - high marsh/sedge/forbs - forb/Typha - Typha/forb/shrub - shrub/forb/grass

This sequence of transition can be seen naturally occurring in systems where emergent coastlines or high sedimentation rates are evident or induced as tidal retrictions limit the duration and amplitude of salt water flushing as seen in the Herring River system.

Within the peat stratigraphy two transitional indicators appear consistantly throughout the system. In cores where a disturbance or a restriction in tidal exchange is evident Distichlis spicata often increases in occurence and is typically followed by a corresponding increase in high marsh vegetation. This sequence can be seen in cores HR-2 and HR-3 (Core Log) at about 0.8 meters and has been shown to occur in systems elsewhere in New England (Niering et al. 1977, Orson et al. In press). At Herring River the transition to D. spicata and high marsh vegetation is followed closely by an increase in brackish plant species suggesting a shift to less saline conditions. A second indicator of change within the system is the increase in sedges (Scirpus spp.) and forbs as salt marsh vegetation drops out of the peat record. Quite often this transition is accompanied by an increase in Typha (Core Log ; BB-1, BB-2, HR-1, HR-2, PDC-2) and soon the Typha/forbs community dominates. This community can dominate until the drying of the marsh substrate permits the introduction of woody dicots, shrubs and grasses forming a wet meadow complex. Genera here might include Spirea, Rosa, Solidago and Poa, among others. A sites proximity to the restriction will determine how much of this vegetation sequence will be preserved in the peat record. Cores HR-5 and BB-2 both located near restrictions change directly from a low marsh to a Typha/forb/shrub community, while cores HR-2 and HR-3 located away from restrictions show a more complete transitional response.

To summarize, the core data clearly shows that salt marsh habitat (tidal flat/low marsh, low marsh and high marsh) was found in all areas of the estuary including areas east of Route 6 towards Herring Pond. Thus, within the last two meters of development the structure of the entire estuary has been altered drastically from salt marsh to a shrubby wet meadow. Tidal restrictions induced by natural and to a lesser extent cultural modifications have been the primary cause for changes observed within the Herring River estuary. Naturally, the southerly spit elongation from the mainland at Truro continuing to Great Island has contributed to significant tidal restriction. Culturally, roads, railroad embankments and the Herring River dike have contributed to further reductions in tidal inundations. The cumulative influence of these tide restricting forces has affected vegetation development of the entire system.

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Key to Core Log

Br - brown

Gr - gray

Bk - black

St - silt

Cl - clay

Sd - sand

Sa - *Spartina alterniflora*

Sp - *Spartina patens*

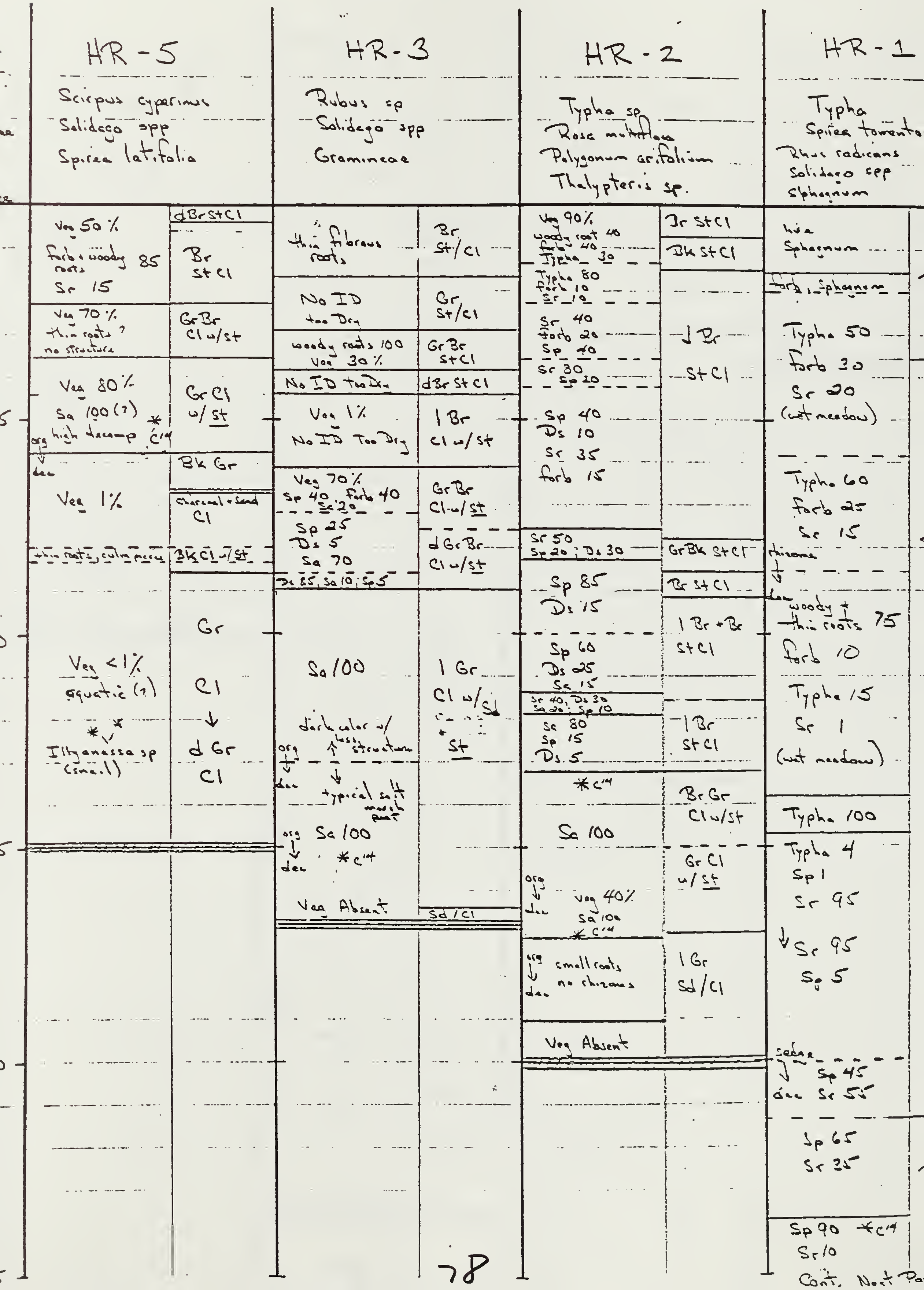
Ds - *Distichlis spicata*

Sr - sedges

veg - total percentage of roots and rhizomes

①

Herring River Cores



HR-5

Scirpus cyperinus
Solidago spp
Spirea latifolia

Veg 50 %
forb + woody roots 85
Sr 15

dBrStCl

Br
St Cl

Veg 70 %
thin roots ?
no structure

GrBr
Cl w/st

Veg 80 %
Sa 100 (?)
high decomp
* C14
org ↓ dec

GrCl
w/ St

Bk Gr

Veg 1%

charcoal + Sand
Cl

thin roots, culm pieces

BkCl w/St

Gr
Cl
↓
d Gr
Cl

Veg <1%
aquatic (?)

* *
Illyanassa sp
(snail)

HR-3

Rubus sp
Solidago spp
Gramineae

thin fibrous roots

Br
St/Cl

No ID
too Dry

Gr
St/Cl

woody roots 100
Veg 30 %

GrBr
StCl

No ID too Dry

dBr St Cl

Veg 1%
No ID Too Dry

l Br
Cl w/st

Veg 70 %
Sp 40, Forb 40
Sr 20

GrBr
Cl w/St

Sp 25
Ds 5
Sa 70

d GrBr
Cl w/St

Ds 85, Sa 10; Sp 5

Sa 100

l Gr
Cl w/Sd
St

dark color w/ less structure
org ↓ dec
↑
↓
typical salt marsh peat

org ↓ dec
Sa 100
* c14

Veg Absent

Sd / Cl

HR-2

Typha sp.
Rose multiflora
Polygonum arifolium
Thalypteris sp.

Veg 90%
woody root 40
forb 40
Typha 30

Br StCl

Bk StCl

Typha 80
forb 10
Sr 10

Sr 40
forb 20
Sp 40

Sr 80
Sp 20

l Br
StCl

Sp 40
Ds 10
Sr 35
forb 15

Sr 50
Sp 20; Ds 30

GrBk StCl

Sp 85
Ds 15

Br St Cl

Sp 60
Ds 25
Sa 15

l Br + Br
StCl

Sr 40, Ds 30
Sa 20; Sp 10

Sa 80
Sp 15
Ds. 5

l Br
StCl

* c14

Sa 100

BrGr
Cl w/St

org ↓ dec
veg 40%
Sa 100
* c14

GrCl
w/St

org ↓ dec
small roots
no rhizomes

l Gr
Sd/Cl

Veg Absent

HR-1

Typha
Spirea tomento
Rhus radicans
Solidago spp
Sphagnum

live
Sphagnum

forb, Sphagnum

Typha 50
forb 30
Sr 20
(wet meadow)

Typha 60
forb 25
Sr 15

rhizome ↓ dec

woody + thin roots 75
forb 10
Typha 15
Sr 1
(wet meadow)

Typha 100

Typha 4
Sp 1
Sr 95

↓ Sr 95
Sp 5

sedge ↓ dec
Sp 45
Sr 55

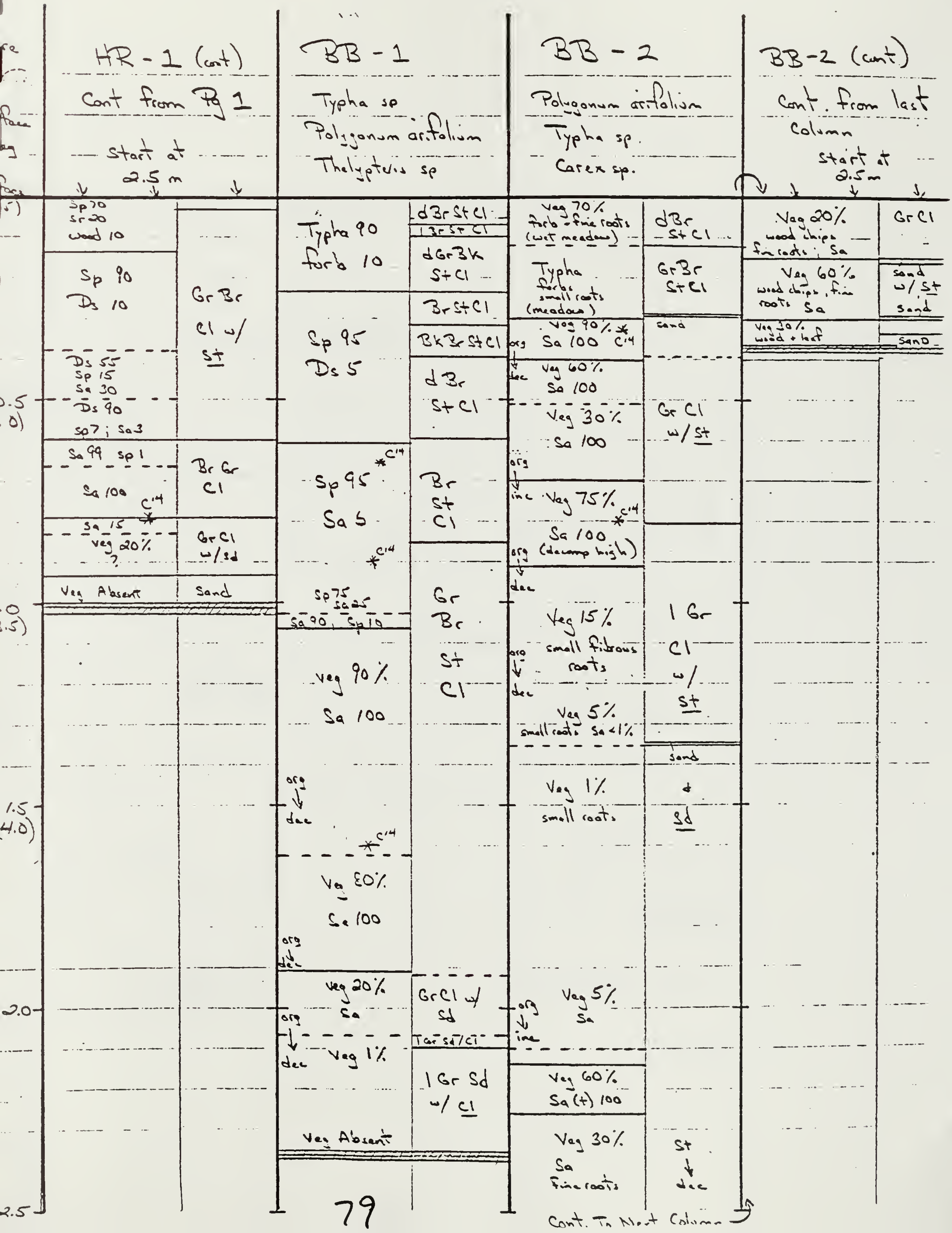
Sp 65
Sr 35

Sp 90 * c14
Sr 10

Cont. Next Pa

②

Herring River Cores



③ Herring River Cores

DH - 1

Rubus sp
Solidago tenuifolia
Rumex sp

Veg 70% forbs, stems, culms roots (meadow) | dBr St Cl
Veg 20% fine fibrous roots leaf pieces | GrBr St/Cl
Veg 50% fine roots, stems forbs (structure weak) | yellow/Gray clay; lGr St/Cl
Veg 90% forb -40 (?) Sa 60 (dryer) | Br St Cl
*C14
Veg 50% Sa 100 | sand; Gr Cl w/ St
org ↓ dec
Veg 5% Sa
*C14
Veg 3% Sa + plant litter (leaf + stem pieces) culms | Gr Cl w/St; BkGr Cl w/St; Gr Cl
Note: Many small clams + snails (Gemma gemma)
Veg <1% | sand; lGr Cl; Gr Cl w/Sd
sand < GrCl Sd

PDC - 1

Solidago sp.
Gramineae

Veg 40% fine roots, forbs | dBr St/Cl
Veg 10% thin roots No ID - Too Dry | Br St/Cl
org ↓ inc
Veg 60% small roots, debris No ID - Too Dry | BkBr St Cl
Veg 10% No ID - Too Dry | Gr Cl w/St Note: Sulfur + Fe precip
*C14 Veg 60% Sa 100 | lGr Cl w/ St
org ↓ dec *C14 | Gr Cl w/st
Veg 10% Sa 100 | dGr Cl
org ↓ dec
Veg 1% Sa | BkGr Cl w/ Sulfur precip
Veg 1% rhizome absent | sand; d Gr Cl

PDC - 2

Rosa sp.
Typha sp.
Polygonum arifolium
Spirea sp.

[illegible] 80 forbs 20 | dBr St Cl
Veg 30% No ID - Too Dry | GrCl w/Sd + St
Veg 50% No ID | BkGrCl w/St
Veg 75% ID difficult some Typha To Dry | St ↓ dec
org ↓ dec
1 Sa rhizome* | Gr Cl w/ some silt
Dry Veg 5% Typha Sa culm pieces
org ↓ inc
Veg 40% Sa 100
org ↓ dec
Veg 10% Sa (+) 100
*C14 (low marsh)
mussel shell
*C14 Veg 1% Sa | sand; sand <
Veg 90% Sa compacted | lGrCl w/Sd
lGrCl/Sd
Veg <1% scattered Sa rhizome | l Gr Cl
org ↓ inc
Cont to Next Column

PDC-2 (cont.)

cont. from last Column
Start at 2.5m

org ↓ inc
Veg 75% Sa 100 | Gr Cl
org ↓ dec
Veg Absent | Gr Sd w/

REPORT APPENDIX 2

HERRING RIVER ESTUARY:
FISH SURVEY, JULY AND SEPTEMBER 1984

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INTRODUCTION

The present study is a part of a larger Herring River Estuary (Cape Cod National Seashore) project. This project evaluates environmental consequences under different management alternatives associated with restoration of the Herring River marsh-estuary complex. The objectives of this study were to assemble information on the composition, distribution and abundance of the fish fauna in the freshwater and saltwater portions of the Herring River estuary and predict changes in fish communities under the proposed management alternatives.

METHODS

Fish were collected at seven sample sites on July 25-26, 1984 and September 28-29, 1984 (Figure 1, Table 1). Stations 7 and 6 are located in the upper freshwater part of the Herring River, station 5 on the boundary of fresh and salt waters, stations 4 and 3 in the brackish water, station 2 just below the dike in saltwater and station 1 at the mouth of the river.

Collections were made with a 48-ft seine in July and 50-ft and 10-ft seines in September. The smaller seine was used at the upstream stations. All samples were preserved in 10% formalin at the sample sites. All individuals were identified to species and counted. Alewifes (*Alosa pseudoharengus*), bluebacks (*Alosa aestivalis*) and Atlantic menhadens (*Bevoortia typrannus*) were weighed to 0.01 gm and standard length measured to the closest mm. Diet analyses on alewifes, bluebacks and menhaden caught in September at high tide (morning sample) and low tide (afternoon sample), were performed using scoring procedures based on fullness of stomachs (0=empty, 1/4, 1/2, 3/4, 1=full). Stomachs receiving the score of 1/4 had only digested unidentifiable food items in the distal part of the stomach. Abundance of each food item was determined by percent cover over a 0.5-cm squared grid.

RESULTS

A total of 18 fish species representing 14 families were collected at the 7 sample stations (Tables 2-4). All species except Hickory shad (*Alosa mediocris*) were represented in the July sample of 4456 individuals, while only fifteen of the species were encountered in the September collection of 2988 individuals. The most abundant species in July were, Atlantic menhaden (29.0% of total catch in July), mummichog (24.7%), Atlantic silverside (18.6%) and striped killifish (10.6%). The most abundant species in September were, striped killifish (53.3% of total catch in September) and alewifes (14.7%).

Estuarine organisms have been classified into different groups depending on distribution with regard to salinity, type of habitat utilization and life history patterns. Using a slightly modified version of the classification described by McHugh (1967), the fish collected in the Herring River system can be divided into five basic groups (Table 5).

1) Freshwater species

2) Truly estuarine species, which spend their entire lives in the estuary

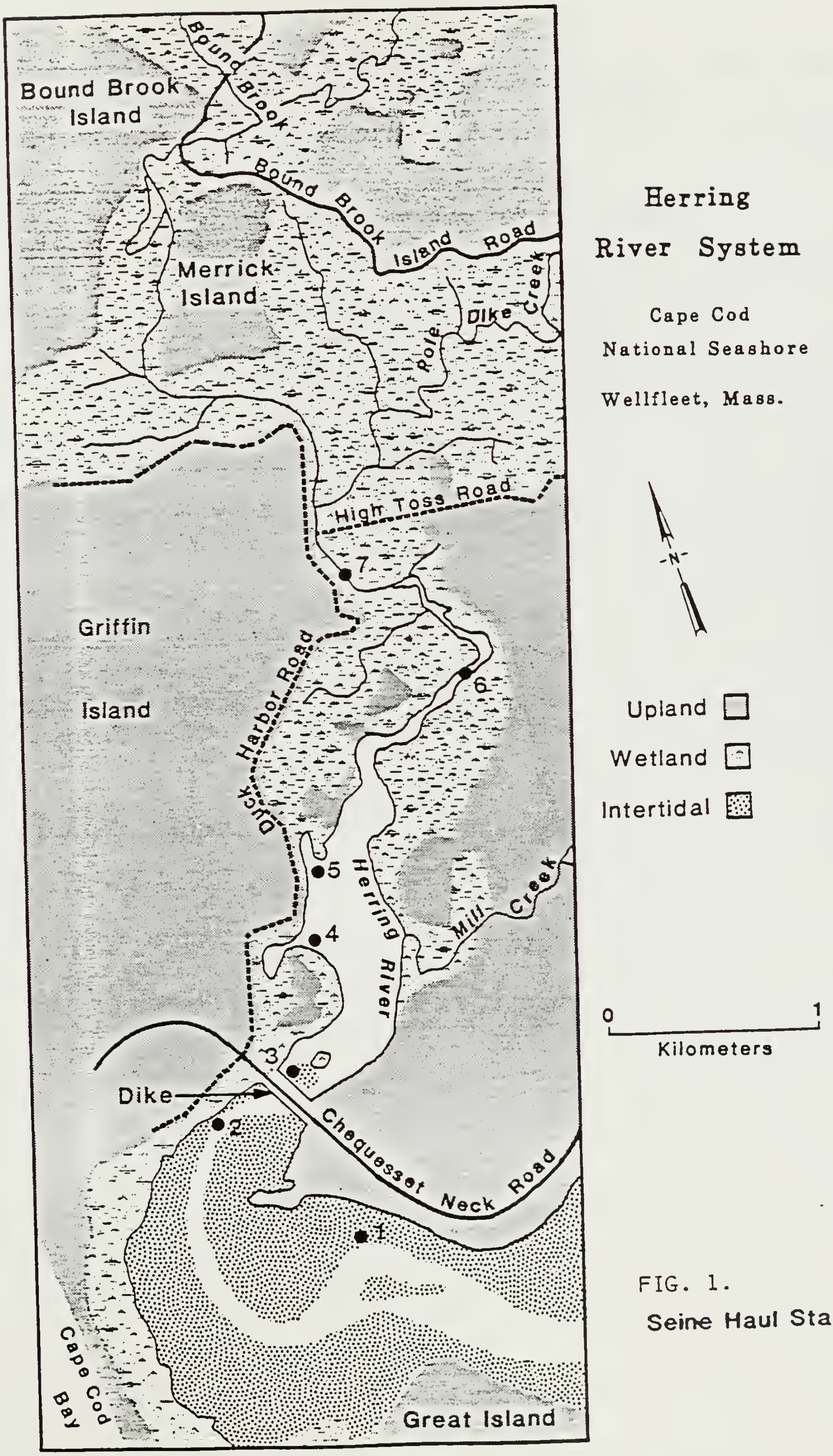

FIG. 1.
Seine Haul Stations

Table 1. Fish sample locations in Herring River. Salinity ranges cover 13 hour period on August 23, 1984. Data provided by Roman.

STATION	SALINITY (ppt)	
	SURFACE	BOTTOM
7	0.0 - 0.0	0.0 - 0.0
6	0.0 - 0.2	0.0 - 0.2
5	0.6 - 8.5	0.6 - 9.7
4	2.0 - 23.0	2.0 - 23.0
3	5.5 - 24.0	7.0 - 24.0
2	24.0*	
1	29.0*	

*Only one recording at high tide in September.

Table 2. Species abundance in the freshwater portion of Herring River.

Species	July	September	Total
STATION 7			
Alewife	-	7	7
Golden shiner	-	3	3
STATION 6			
Alewife	-	18	18
American eel	2	-	2
Fourspine sticklebacks	11	2	13
Chain pickerel	1	-	1
Pumpkinseed	1	-	1

Table 3. Species abundance in the brackish water upstream from the dike in Herring River.

Species	July	September	Total
STATION 5			
Alewife	15	-	15
Blueback	5	-	5
American eel	-	1	1
Fourspine stickleback	114	150	264
Atlantic menhaden	290	-	290
Common killifish	5	14	19
Striped killifish	1	15	16
Tidewater silverside	12	1	13
Atlantic silverside	7	-	7
White perch	7	-	7
Golden shiner	1	-	1
STATION 4			
Fourspine stickleback	4	-	4
Atlantic menhaden	90	-	90
Common killifish	121	-	121
Striped killifish	17	-	17
STATION 3			
Alewife	-	2	2
Blueback	4	-	4
Fourspine stickleback	16	2	16
Atlantic menhaden	2	-	2
Common killifish	441	19	460
Striped killifish	39	32	71
Atlantic silverside	105	6	111
Winter flounder	-	7	7
Northern pipefish	-	2	2

Table 4. Species abundance at locations downstream of the dike in the Herring River system.

Species	July	September	Total
STATION 2			
Alewife	320	3	323
Blueback	182	1	183
Hickory shad	-	School	
American eel	5	-	5
Fourspine stickleback	13	-	13
Atlantic menhaden	636	-	636
Common killifish	330	141	471
Striped killifish	54	5	59
Atlantic silverside	330	125	455
White perch	20	-	20
Winter flounder	5	-	5
Bluefish	-	School	
Northern pipefish	8	-	8
STATION 1			
Alewife	4	140	148
Blueback	2	416	418
Atlantic menhaden	272	14	286
Common killifish	203	10	213
Striped killifish	362	1537	1849
Atlantic silverside	384	302	686
Bluefish	3	-	3
Atlantic mackerel	1	-	1
Northern pipefish	-	3	3
Winter flounder	-	2	2

Table 5. List of species found in the Herring River estuary. Classification follows McHugh (1967).

1. FRESHWATER

Chain pickerel	*Esox niger*
Pumpkinseed	*Lepomis gibbosus*
Golden shiner	*Notemigonus chrysoleucas*

2. TRULY ESTUARINE

Fourspine stickleback	*Apeltis quadracus*
Common killifish	*Fundulus heteroclitus*
Striped killifish	*Fundulus majalis*
Northern pipefish	*Syngnathus fuscus*
White perch	*Morone americana*

3. ANADROMOUS AND CATADROMOUS

Blueback herring	*Alosa aestivalis*
Alewife	*Alosa pseudoharengus*
Hickory shad	*Alosa mediocris*
American eel	*Anguilla rostrata*

4. MARINE MIGRANTS, UTILIZING ESTUARY AS A NURSERY

Atlantic mehanden	*Brevoortia tyrannus*
Tidewater silverside	*Menidia berilyna*
Atlantic silverside	*Menidia menidia*
Winter flounder	*Pseudopleuronectus americanus*

5. OCCASIONAL VISITORS

Bluefish	*Pomatomus saltatrix*
Atlantic mackerel	*Scomber scombrus*

3) Anadromous and catadromous species.

4) Seasonal marine migrants that use the estuary primarily as nursery sites, usually spawning and spend much of their adult life at sea, but often returning seasonally to the estuary.

5) Occasional visitors with no estuarine requirements.

1) Freshwater species.

The freshwater portion of Herring River was the poorest habitat both with regard to number of species and number of individuals captured (Table 2). Only three freshwater species were captured, represented by only 7 individuals. This is consistent with the sampling performed by Hartel in 1981, when only 2 pumpkinseed (*Lepomis gibbosus*) were collected from the freshwater portion of the system.

2) Truly estuarine species

Of the native species the mummichog (*Fundulus heteroclitus*) and striped killifish (*Fundulus majalis*) were most abundant. The mummichog was more common in the brackish water upstream from the dike while the striped killifish dominated the shallow waters below the dike (station 1) (Table 3 and 4). Only seven adult white perch (*Morone americana*) were caught in the brackish water (station 5) and 20 juveniles were caught in saline waters below the dike (Table 4). Of other natives, fourspine sticklebacks (*Apeltis quadracus*) were limited to the brackish water upstream from the dike and only a few northern pipefish (*Syngnathus fuscus*) were caught in saline waters (Tables 3 and 4).

3. Anadromous and Catadromous species.

Three anadromous species, hickory shad (*Alosa mediocris*), alewife (*Alosa pseudoharengus*) and blueback (*Alosa aestivalis*) herring, and one catadromous species, American eel (*Anguilla rostrata*) were captured. Of the herring species only alewifes were caught in the freshwater portion of the system. Both bluebacks and alewifes were caught in the brackish water above the dike (Tables 2 and 3). The majority of the herrings were caught below the dike, with highest frequency of occurrence at station 2 in July and station 1 at the mouth of the river in September (Table 4). Bluebacks were slightly shorter than alewifes both in July and September at station 1 (Table 6). Weight differences between bluebacks and alewfies were non-significant (one-way ANOVA) in July while bluebacks were significantly lighter in September.

Most of the blueback stomachs analyzed were found to be empty (Figure 2) or to contain well digested food items in the distal part of the stomachs. Few blueback stomachs contained recently consumed food items in the morning sample (e.g. 1/4), while no individuals were found with 1/4 stomach content in the afternoon. Alewifes, on the other hand, had been foraging in early morning while feeding apparently stopped during the middle of the day resulting in mainly empty stomachs in the afternoon catch. In contrast, most alewifes caught

Table 6. Mean standard length, weight, standard deviations (parentheses) and sample sizes for herrings caught in July and September in Herring River. Data are for seine haul station 1.

Species	July	September
Alewife length (mm)	35.1 (6.3)	62.0 (7.8)
weight (gm)	0.4 (0.4)	2.8 (1.1)
n	30	47
Blueback length (mm)	31.4 (3.4)	57.9 (6.3)
weight (gm)	0.3 (0.2)	2.0 (2.0)
n	30	17
Menhaden length (mm)	32.9 (3.9)	59.2 (5.7)
weight (gm)	0.4 (0.2)	3.4 (0.9)
n	30	14

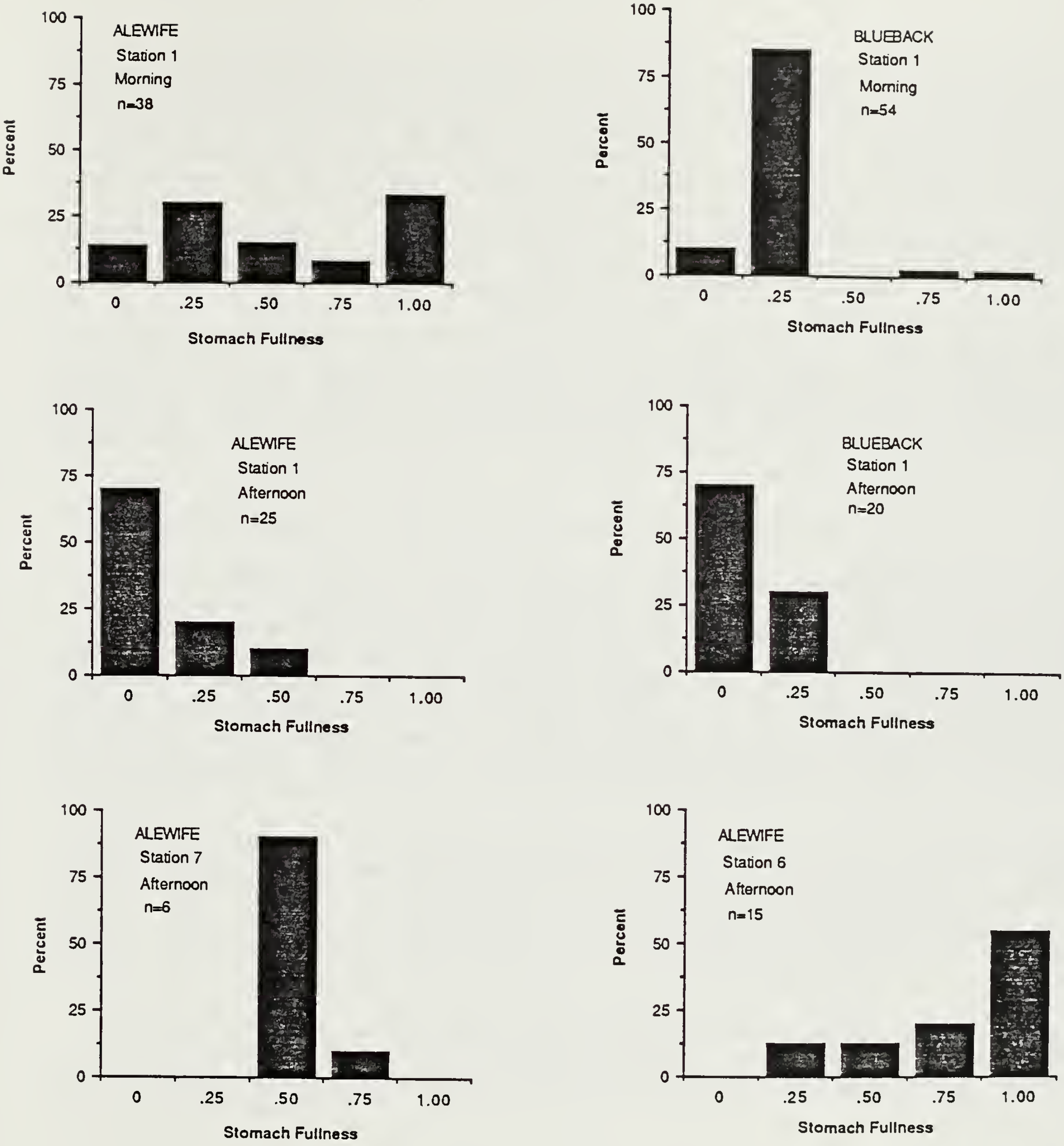

Fig. 2. Relative amount of food found in the stomachs (0=empty, 1=full) of Alewifes and Blueback Herring. Data are presented as a percent of the number of stomachs analyzed.

in the fresh water (station 3 and 4) were actively foraging during the middle of the day, as all food items in stomachs were recently consumed. The majority of the alewifes diet in saline water was planktonic (Table 7), with amphipods and shrimps (Caridian) encountered most frequently. The few bluebacks with full stomachs were also feeding on shrimp and amphipods, while traces of digested items in the distal part of the stomachs indicated algae to be frequently consumed. Alewifes in freshwater seemed to be consuming benthic food items or to be picking in the vegetation. The diet was quite variable with chironomid larvae found in all stomachs and vegetation frequently consumed.

Although hickory shads were observed in schools at the dike on the downstream side in September, no adult or juvenile shads were caught in the seines. Of other species in this category, only eight eels were captured, indicating that eels may be relatively rare in the estuary although gear selectivity undoubtedly influences the number of eels caught.

4) Migrating species utilizing the estuary as a nursery site.

Considerable numbers (382) of Atlantic menhaden were caught in the brackish water, upstream from the dike in July, although the majority were found downstream from the dike (Tables 3 and 4). Few menhaden remained in the area in September, indicating that the fall migration into coastal waters was nearly complete. Menhadens were of similar weight but showed intermediate length between alewifes and bluebacks in July (Table 6). In September menhadens had gained much more weight than both bluebacks and alewifes, while the length was still intermediate (Table 6). All of the menhadens analyzed had 0.25-0.50 empty stomachs with traces of detritus and unicellular algae in the guts.

Few juvenile winter flounders were caught (Tables 3 and 4). Juvenile winter flounders have been reported abundant in other locations within Wellfleet Harbor. For example, 146 juveniles were taken with a beach seine at Town Pier in July 1969 (Curley et al. 1972). The sampling performed by Curley et al. further indicates that the Harbor may be primarily utilized by the winter flounder as a nursery, where 94% of their catch were juveniles.

Only 13 tidewater silversides were caught in the brackish water at station 5. The majority of the Atlantic silversides were caught on the harbor side of the dike although 111 individuals were found in the brackish water above the dike (Tables 3 and 4).

5. Occasional visitors.

Only three bluefish and one mackerel were caught in the seine at station 1 in July, but a school of bluefish were observed feeding at the dike in September.

DISCUSSION

The importance of estuaries as a major unit in the food web that support the coastal fisheries is well known. Estuarine areas are recognized to have a major function as spawning and/or nursery grounds. The young of 60-70% of the

Table 7. Percent of the total number of individual herring analyzed feeding on each particular food type.

Food Type	Alewifes	Bluebacks
STATION 1		
Amphipods	57	3
Shrimp	54	3
Vegetation	28	3
Ostracods	14	1
Fish scales	11	n=3
Algae	7	
Crab legs	7	
Horseshoe crabs	7	
Cumacean	4	
Isopods	4	
Seeds	4	
	n = 28	
STATION 7 and 6		
Chironomids	100	
Ostracods	86	
Copepods	76	
Seeds	57	
Vegetation	57	
Fish scales	52	
Cladocera	38	
Insects	33	
Sand	28	
Shrimp	9	
Isopods	5	
	n = 21	

economically important Atlantic species are thought to inhabit the estuarine environment at some time during their first year of life (McHugh 1966; Clark 1967), utilizing the food resources and benefiting from protection provided by the estuaries.

The diking of Herring River has resulted in reduction of the mean tidal range. This has dramatically decreased the submerged wetland area in the upper proportions of the system. Further perturbations in the system have resulted from mosquito control activities. Dissolved oxygen (DO) levels of 2.0 ppm and lower appear to be related to ditching activities (Portnoy 1984). Lowering of the water table by drainage activities results in leaching of chemical compounds from the old salt marsh sediments with subsequent decreases in pH (e.g. as low as 3.0; Portnoy and Soukup 1982). In Herring River, a dramatic effect of high acidity, low DO and/or toxic aluminium and sulfate levels on the fish populations has been suggested. A massive die-off of the American eel population was observed in 1980 (LeBlond 1982), and several thousands of dead herrings were recorded under low DO conditions in 1984 (Portnoy 1984).

The existence of the tidal gates is likely to affect the distribution pattern of fish species in the estuary, but a striking difference in individual abundance is apparent when comparing collections upstream from the dike to those downstream from the dike (Table 8). A total of 1586 (21%) individuals representing 15 species were collected upstream, while 5841 (79%) individuals comprising 14 species were collected downstream at station 1 and 2 (catching efforts are listed in Table 9.

Freshwater species

The freshwater fish fauna on Cape Cod is recognized as being depauperate since these habitats are recent and have only been available for colonization since the end of the Pleistocene epoch (K. Hartel, personal communication). However, the species composition and abundance in the freshwater portion of the Herring River system is strikingly low. This species poorness may result from the low dissolved oxygen and the acid nature of the habitat. Fish populations are known to decline in waters subjected to increased acidity (Haines 1981). However, species diversity and abundance has been reported for some acid water systems (Rahell 1982; Dunson et al. 1977). The Mullica River in the New Jersey Pine Barrens contains 13 acid tolerant fish species (Hasting 1984). These species were collected in water with pH levels as low as 4.0. The acid tolerance of species inhabiting habitats such as the New Jersey Pine Barrens, presumably results from a long-time evolution and adaptations, while the situation in Herring River is due to recent perturbations. Only one of the acid tolerant species, e.g. the chain pickeral (_Esox niger_), found in the Mullica River was also found in Herring River. The other two freshwater species in the Herring River system, pumpkinseed (_Lepomis gibbosus_) and golden shiner (_Notemigonus crysoleucas_), were reported as peripheral in the Mullica River, only found at pH 5.5 or higher.

Herrings

The most important commercial species utilizing the Herring River system as spawning and nursery sites are the two _Alosa_ species (bluebacks and alewifes)

Table 8. Total number of individuals of each species caught downstream (stations 1 and 2) and upstream (stations 3-7) of the Herring River dike in July and September 1984.

Species	Downstream		Upstream		Total No.
	July	Sept	July	Sept	
RESIDENT SPECIES:					
Chain Pickerel	-	-	1	-	1
Pumpkinseed	-	-	1	-	1
Golden Shiner	-	-	2	3	5
White Perch	20	8	7	-	35
Common Killifish	533	151	567	33	1284
Striped Killifish	416	1542	57	47	2062
Tidewater Silverside	-	-	12	1	13
Atlantic Silverside	714	427	112	6	1259
Fourspine Stickleback	13	-	145	154	312
Northern Pipefish	8	3	-	2	13
NON-RESIDENT SPECIES:					
American Eel	5	-	3	-	8
Alewife	184	417	15	20	636
Blueback	324	143	9	-	476
Hickory Shad	-	School	-	-	+
Atlantic Menhaden	908	14	382	-	1304
Winter Flounder	5	2	-	7	14
Bluefish	3	School	-	-	3+
Atlantic Mackerel	1	-	-	-	1
TOTAL	5841		1586		7427

Table 9. Number of seine sweeps and seine size (parentheses). Each seine haul covered approximately 30 meters.

Stations	July	September
Downstream of dike		
1	2 (48')	4 (50')
2	3 (48')	3 (50')
Upstream of dike		
3	1 (48')	3 (50')
4	1 (48')	
5	2 (48')	1 (10')
6	2 (48')	2 (10')
7	2 (48')	2 (10')

and the Atlantic menhaden. Alewifes and bluebacks are heavily fished during spawning runs throughout their range. Combined landings of alewfies and bluebacks along the Atlantic Coast was 4,948 metric tons in 1980, with an average of 5,0003 mt/yr over the period of 1977-1981 (Fay et al. 1983). Alewifes (and presumably bluebacks) were at one time very abundant in Wellfleet Harbor, supporting a profitable fishery on Herring River (Curley et al. 1972). A large decline in population size occurred early this century, attributed to over exploitation (Belding 1921) and additionally to restriction of spawning runs due to the construction of the tidal gates (Curley et al. 1972).

Alewifes and bluebacks are also important ecologically as secondary producers. Both of these species feed on zooplankton throughout their life span and are in turn heavily foraged on by several marine and estuarine species such as bluefish (Pomatomus saltatrix), weakfish (Cynoscin regalis) and striped bass (Morone saxatilis) (Fay et al. 1983).

Alewifes and bluebacks are anadromous, migrating into freshwater in early spring to spawn. First spawning takes place at the age of three among both species (Fay et al. 1983). The bluebacks enter freshwater later than alewifes or not until the water temperature has reached 14^{o}C, while alewifes run at a minimum temperature of 10.5°C (Cianci 1969; Loesch and Lund 1977). Alewifes are reported to arrive in inshore waters in southern New England during March-April, while bluebacks usually arrive a month or so later (Bigelow et al. 1967). Bluebacks apparently do not ascend the rivers as far as alewifes, preferring spawning sites with fast currents and hard substrate (Loesch and Lund 1977). Alewifes, on the other hand, spawn in fresh water ponds as well as mid-river sites (Bigelow et al. 1967; Kissil 1974). Adults of both species migrate rapidly downstream after spawning, and the total spawning time is short (5 days for a single migrating group; Fay et al. 1983, and references therein). The development of blueback eggs is rapid, taking only 50 hours (Crecco and Blake 1983) while the incubation time for alewife eggs spans 6 days (Hildebrand and Schroeder 1972). The newly hatched larvae migrate downstream shortly after hatching (downstream migrations of herring larvae were observed on July 6 in Herring River by Portnoy, 1984), and forage in the estuary until late Fall. After about a 4-5 month stay in the estuary the juveniles migrate into deeper coastal waters.

The construction of the tidal gates across the mouth of the Herring River may attribute to the decline of the herring populations (Curley et al. 1972). In addition to preventing adults from reaching the spawning grounds, the tidal gates may also increase the mortality of postspawners migrating back into the coastal waters. The natural mortality of postspawning alewifes is known to be high (estimated as 57.4% by Kissil, 1974), so hazards on the back migration may further affect the mortality of the already exhausted postspawning adults. This may in turn affect the size of successive spawning runs. Frequency of repeated spawners has been reported as 60% (Nova Scotia) and 61% (York River, Virginia) for alewifes, and for bluebacks 75% (Nova Scotia) and 65% (York River) (Joseph and Davis 1965; O'Neill 1980).

However, the high acidity and low DO levels in the upper parts of the system may be more critical in decreasing the population size of these species. Alewife and blueback juveniles have been shown to prefer areas with dissolved oxygen levels ranging from 2.4 to 10.0 ppm, and pH from 5.2 to 6.8 (North Carolina, Davis and Cheek 1966). Alewifes and bluebacks were not found in high

acid areas in the Mullica River N.J., although they were abundant elsewhere in the system (Hastings 1984). High concentrations of suspended solids may also affect the alewfie and blueback populations. Suspended solids have been recorded as high as 300 ppm in the upper part of the Herring River system (Portnoy 1984). This high level of suspended solids can lead to direct mortality of adult migrating individuals, but more importantly it is likely to influence the success of spanwing by reducing the viability of embryos. High levels of suspended sediment have been shown to increase infection rates of alewife eggs and by naturally occurring fungi in the sediment (Schubel and Wang 1973). The hostile environmental condition in Herring River is thus expected to increase mortality of adults, and has been reported to result in a massive mortality of larvae migrating through the area (Portnoy 1984).

The present population of herring larvae in the estuary did apparently not suffer from lack of food over the two month period sampled in 1984. Alewifes were found to sevenfold their weight and bluebacks sixfolded their weight. Both species reached standard length (Alewifes, mean length = 62.0 mm; bluebakcs mean length = 57.9 mm, at station 1 in September, Table 6) comparable to what is reported for these species elsewhere (Bigelow et al. 1963; Davis and Cheek 1966). However, as the submerged brackish water areas and marsh creeks were dramatically decreased by the construction of the dike, it is questionable whether the Herring River estuary is capable of supporting a larger number of juveniles of these species at this time.

The dietary analysis conducted on the herring species, revealed unexpected patterns of foraging. Most of the stomachs collected from alewifes and bluebacks during day hours were found to be empty, with only digested food items in the distal part of the stomachs, indicating that feeding was exclusively performed during the night and early morning. This is in contrast with what is known about the feeding behavior of these species, as herrings are known to be active day feeders (Burbridge 1974). However, those few individuals caught in the brackish and freshwater parts of the system were actively feeding during the day hours. This apparent night dominated foraging pattern may result from heavy predation on the species preventing them from feeding activity during the day due to lack of appropriate shelter and protection in the open beach habitats at the mouth of the river.

Atlantic Menhaden

Commercially, Atlantic menhaden is one of the most important species along the Atlantic Coast of North America. The combined landings of menhaden constitutes the largest part of the U.S. fishery (25-40%; Rogers and Auyle 1983). Atlantic menhaden are also ecologically important as prey items for other species and are likely to be important with regard to exchange and conversion of energy in the biological web due to their great abundance and extensive migration patterns (Rogers and Auyle, 1983).

Menhaden along the Atlantic coast constitute a single populaton that intermixes during winter (November-March) in ocean waters south of Cape Hatteras, NC (Nicholson 1978). The peak spawning in the Mid-Atlantic region occurs from December through February in shelf water from 100-200 m, probably within 70 m of the surface (Reintres and Pachico 1966). Northward movement of part of the population starts in late winter-early spring, where the oldest individuals migrate further north (Nicholson 1971). During the migration,

spawning occurs closer inshore as the fish move further north (Rogers and Auyle, 1983). Spawning in the New England area is thought to occur in saline waters in late spring (Bigelow and Schroeder 1953). The eggs are pelagic and hatch after 203 days at 15.5°C (Hettler 1960). The larvae enter estuaries 1-3 months old (Reinthjes 1961) and forage in the shallow portions of the estuaries through out the summer (Rogers and Auyle 1983 and references therein). Emmigation and southward migration from the estuaries starts in August in the North Atlantic region (Nicholson 1978).

Although Atlantic menhaden do not compete for food with alewifes and blueacks, as they forage on detritus, algae and phytoplankton (Peters and Schaff 1981) the juveniles do depend on the salt marsh both as a food resource and as providing protection from predators. The number of menhaden able to utilize the inner marsh area will thus be limited by the size of the submerged marshland and the availability of entrance into the marsh.

White Perch

The white perch is commercially important and a popular game fish wherever it is abundant in tide water. In the North Atlantic, 72% of white perch caught by marine recreational anglers in 1979 were from Massachusetts (Stanley and Danie 1983). White perch can exist as residents in freshwater or as marine populations migrating into fresh and brackish water to spawn (Bigelow and Schroeder 1953). Spawning takes place in early spring, staring in March/early April among the northern populations (Hardy 1978). During spawning, the eggs are spread randomly, and may be released two to three times over a 10 to 21 day period (Hardy 1978, in Stanley and Danie 1983).

The great success of white perch in areas of occurence, may be partially due to the high fecundity characteristic for this species. Fecundity has been estimated as high as 56,200 eggs/kg of fish during one spawning (Auclair 1956, in Stanley and Danie 1983). Observations on abundance of white perch in the Herring River system, may be biased due to gear selectivity, as seining may not be an effective method to catch this fast swimming fish. Similarly, striped bass was not encountered in the sampling but is known to occur in the estuary and is caught by sport fishermen along with the white perch at the Herring River dike. However, the dike may influence the population size of these species by restricting migration and spawning runs into the freshwater part of the system.

Winter Flounder

Adult winter flounder move into shallow coastal waters and estuaries in fall and winter. In the New England area, spawning is thought to take place from January to May on a sandy bottom in shallow waters (Bigelow and Schroeder 1953). The frys remain in the estuary until they are 2 years old (Frame 1974).

It appears that Wellfleet Harbor may be utilized extensively as a nursery ground by winter flounder, as large numbers of juveniles were caught by Curley et al. (1972). The dike at the mouth of Herring River may eliminate migration of flounder into the inner marsh areas. The small area submerged by brackish waters may limit the number of juvenile flounder able to forage in the estuary.

Bluefish and Mackerel

Economically important species such as Atlantic mackerel and bluefish which forage in the estuary on juvenile fish, are known to exist in Wellfleet Harbor. These species support an active sport fishery both from shore and from boats (Curley et al. 1972). The low abundance represented here is apparently influenced by gear selectivity and sample methods. A school of bluefish was observed feeding at the dike. The existence of the dike is not expected to affect these species directly, but is likely to influence the abundance of these species by limiting prey availability and by preventing them from entering marsh areas.

Common killifish

Of the resident species in the estuary, the mummichog, or common killifish, is the most abundant. Mummichogs move onto the upper marsh areas at high tide to feed and return at low tide to the open water where they may be subjected to foraging by commercially important species (Valiela et al. 1977). The mummichog is thus recognized as an important link in the transfer of energy from the marsh surface into the open estuary (Kneib and Stiven 1978).

The mummichog depends on the marsh area with regard to spawning and survival of juveniles. They deposit their eggs in mats of vegetation close to the high water mark at spring tides, allowing the eggs to develop above the water level until immersion of water on the next spring tide followed by the hatching of the eggs (Able 1984). The young larvae forage in shallow tidal pools on the marsh surface, which provides shelter from predators and strong tidal currents. The existence of the dike at the mouth of Herring River, may affect the population size of the mummichog as well as it's importance in the estuarine system. As the dike construction has resulted in lowered water levels in the inner marsh, appropriate spawning sites and habitats for the juveniles of the mummichog may be limited. The dike construction may also restrict migration of adults from the marsh surface into the open estuary limiting the function of the mummichog in transferring energy into the open coastal waters.

Striped killifish

The population size of the striped killifish is expected to be much less influenced by the dike construction as this species prefers higher saline waters than the mummichog. The striped killifish spawns in sand on open beaches and is much less dependent on the inner marsh areas than the mummichog. This may be expressed by the overall higher abundance of the striped killifish in the Herring River system, downstream of the dike.

Silversides

Silversides are known to be important secondary producers and very abundant where they occur (Conover and Ross 1982, and references therein). Silversides have been reported to provide forage for several game fish species, such as mackerel and bluefish (Merriman 1941, Schaefer 1971). Atlantic silversides are sexually mature at one year old and migrate inshore in spring were spawning

takes place in the intertidal zone. Silversides are repeat spawners and release eggs several times during the season (4-5 times, Conover 1979). Juvenile and adult Atlantic silversides forage in the estuary throughout the summer and into the fall (Warfel and Merriman 1944, Bayliff 1950, Hoff and Ibara 1977), after which they migrate offshore (Conover and Murawski 1982). The silversides were caught in much greater numbers below the dike than above, indicating that the distribution pattern may be affected by the existence of the tidal gates.

CONCLUSION

The diking of Herring River along with perturbations resulting from mosquito control activities is expected to have affected the fish species inhabiting the system in different ways. Table 10 summarizes the causes of major disturbances and how they are likely to affect each species.

Although the freshwater fish fauna of Cape Cod is known to be species depauperate, the hostile environmental conditions (high acidity and toxic chemical levels, as well as periods of low dissolved oxygen) characteristic for the upper part of the system, are likely to reduce the number and abundance of local species. Similarily, those species such as the herrings, that migrate through the freshwater part of the system, are known to suffer from high mortality during periods of low dissolved oxygen and high acidity.

The existence of the tidal gates is likely to affect most of the estuarine fish species. The herrings are expected to suffer from increased mortality of spawning and post spawning adults, due to a restricted migration route. Similarily, the Atlantic menhaden may be subject to increased mortality of juveniles (utilizing the estuary as a nursery) during migration through the tidal gates. The tidal gates are also likely to affect other commercially important species, such as white perch, winter flounder and top predators, like bluefish and mackerel, by restricting or even preventing access to the inner marsh areas.

Although food and space have not been shown to be limiting factors or direct causes for high mortality, all of the estuarine fish species are likely to benefit from expansion of submerged wetland areas, through increased availability of proper habitats and food resources. With regard to fish populations, the Herring River system would thus benefit in every way from the opening or removal of the tidal gates.

Table 10. Major perturbations in the Herring River system, and how the individual fish species may be affected.

SPECIES	PERTURBATION	EFFECT
Pickerel Golden shiner Pumpkinseed	High acid and toxic chemical level, low dissolved oxygen, due to mosquito control activities	High mortality of adults and juveniles
Alewifes Bluebacks	Restricted migration route between FW and SW, due to the existance of the tidal gates	Increased mortality of spawning and post spawning adults. Increased mortality of juveniles migrating seaward
	Restricted tidal range and reduced intertidal area, due to tidal gates	Limitation of nursery grounds
	High acid and toxic chemical levels, low dissolved oxygen, high concentration of suspended solids, due to mosquito control activities	Increased mortality of adults and juveniles migrating through the freshwater portion of the system. Reduced viability of embryos
Atlantic menhaden	Restricted migration route	Increased mortality of juveniles migrating into the marsh area in spring and seaward in fall
	Restricted tidal range	Limited nursery grounds
White perch	Restricted migration route	Increased mortality of adults during spawning migration
Winter flounder	Restricted migration route	Limiting migration of adults into the marsh areas
	Restricted tidal range	Limited nursery grounds
Bluefish mackerel	Restricted migration route	Reduced prey availability

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REPORT APPENDIX 3

HERRING RIVER ESTUARY:
MACROINVERTEBRATE SURVEY, JULY AND AUGUST 1984

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INTRODUCTION

The present study is part of an investigation of management alternatives for the Herring River estuary (Cape Cod National Seashore). The purpose of the investigation is to assess environmental impacts of several management alternatives concerned with the water control structure/causeway ("dike" herein) on the estuary and adjacent areas. The present report contains a description of areas sampled, methods used, and preliminary species lists for the macroinvertebrates collected during July and August 1984. All field collections were made by R.E. Grizzle, with G. Marteinsdottir and/or C.T. Roman. All organisms in samples from freshwater areas (stations 6S, 7S, and 8S) were identified by Rosemary Gatter (Rutgers Univ. Graduate Program in Ecology); all other organisms were identified by R.E. Grizzle. Jeffrey Crooms sorted the benthic core samples.

METHODS

Macroinvertebrates were collected using several types of gear. Sampling was conducted on July 24-27, 1984 and August 7-10, 1984. This section and the results section are subdivided with respect to the organisms sampled and the method(s) used: 1) commercially and recreationally important species; 2) epibenthic species; 3) subtidal benthos; 4) intertidal benthos; and 5) saltmarsh macroinvertebrates.

Commercially and Recreationally Important Species

Oysters (Crassostrea virginica) and hard clams (Mercenaria mercenaria) were sampled at station 2I (Fig. 1) using three randomly placed 1.0-m^2 quadrats. A roped marked at 0.25-m intervals was stretched parallel to the shoreline, sampling locations were chosen using a random numbers table. In all other areas oysters and clams, and all other commercially and/or recreationally important species, were not abundant and were only noted as "not observed," "rare," or "common." Visual inspection was made at low tide of the entire intertidal area at station 3I, and several hundred meters upstream and downstream of stations 1I and 2I.

Epibenthic Species

Epibenthic species were collected using either a 10-ft or 30-ft minnow seine. Stations 1I, 2I, 3I, 4S, 5S, and 6S were sampled as part of the fish sampling efforts (Fig. 1) and methods are given in more detail in the fish report. Briefly, the seine was hauled about 20 to 50-m at each station. Seine hauls were generally run along the vegetated marsh edge. All invertebrates were removed and fixed in 5-10% formalin the same day, then transferred to 70% isopropanol.

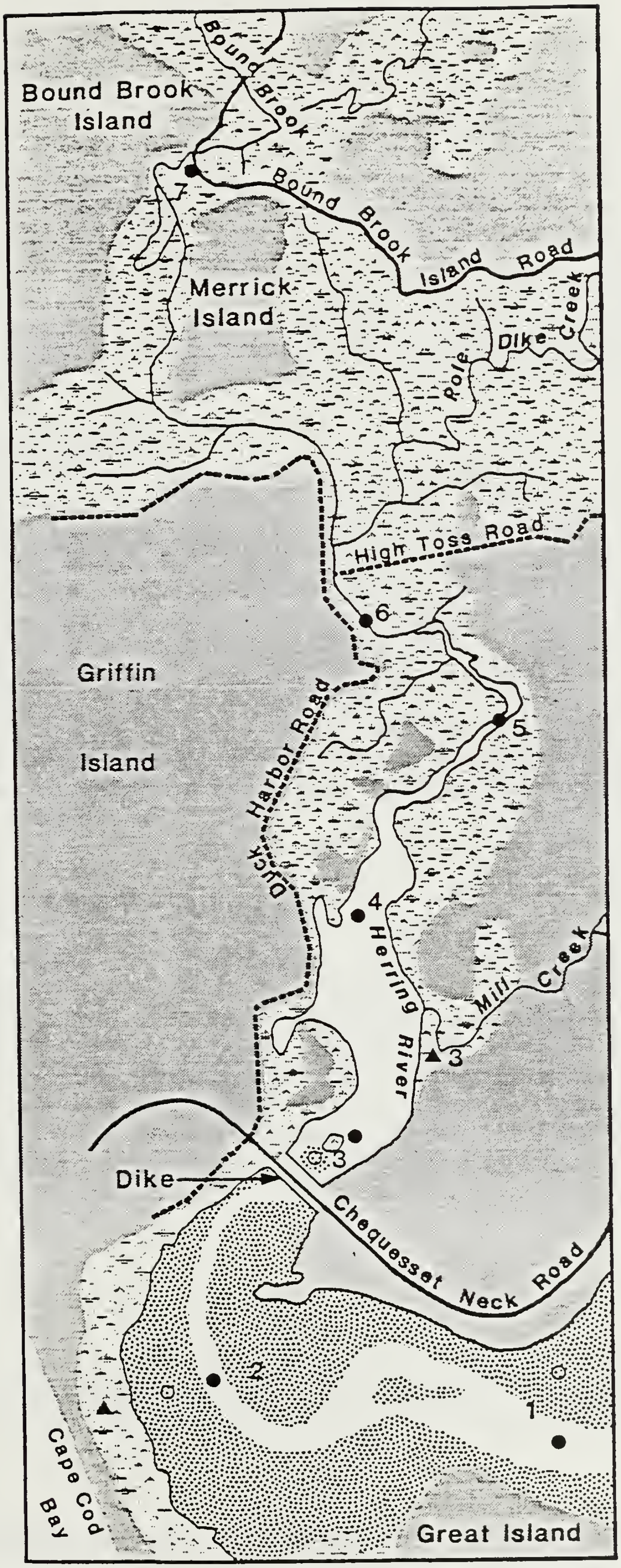

FIG. 1.

Macroinvertebrate Stations

● Subtidal

○ Intertidal

▲ Salt Marsh

Subtidal Benthos

Stations 1S-8S (Fig. 1) were sampled at approximately mid-channel using a flow-through PVC coring device with a 0.5-mm mesh screen in the top to prevent escape of organisms. One of two corers was used at each station; both were 10.16-cm in diameter, one penetrated to 10-cm the other to 15-cm sediment depth. A sample consisted of five randomly selected core sampling units, each of which was washed on a 0.5-mm mesh sieve, fixed in 5-10% formalin, sorted under 2x magnification, and preserved in 70% isopropanol. Wet weights were made by major taxa of the preserved organisms. A sample from the upper 5-cm of sediment was taken from an additional core for grain size analysis.

Intertidal Benthos

Stations 1I, 2I, and 3I (Fig. 1) were sampled for macrofaunal benthos in two ways. Smaller organisms were collected using the 10.16-cm diameter by 10-cm length PVC corer mentioned above. These samples consisted of five randomly selected (see above) sampling units which were treated as the subtidal benthos subsamples. Larger organisms were sampled at station 3I by excavating 3, 1.0-m^2 quadrats to a depth of about 20-cm with a shovel, and washing the sediment on a 5.0-mm mesh sieve. Station 2I was sampled for oysters and clams only, by excavating 3, 1.0-m^2 quadrats by hand. Only 1, 1.0-m^2 quadrat was excavated at station 1I using methods as at station 3I. All sampling units were randomly selected using a marked rope (see above) stretched parallel to the shoreline. One core of sediment for grain size analysis was taken at each station using methods above.

Saltmarsh Macroinvertebrates

Saltmarsh at stations 2M and 3M (Fig. 1) was sampled using the following methods. A marked rope (see above) was stretched parallel to the shoreline in areas dominated by short *Spartina alterniflora* (SAS), tall *S. alterniflora* (SAT), and *Spartina patens* (SP) at each station. Three, 0.25-m^2 quadrats were randomly placed along the rope. The vegetation was clipped to near-sediment level, and all macroinvertebrates (except insects, arachnids, isopods, and amphipods) were identified and counted. The sediment was not excavated so only a few fiddler crabs (*Uca pugnax*) were captured. Fiddler crab density estimates were made by counting burrow entrances.

RESULTS

A total of approximately 65 species of macroinvertebrates was collected from the estuarine portion of Herring River and adjacent saltmarshes (Tables 1, 2, 3, and 4). The freshwater portion (stations 6S-8S) yielded 22 species (Table 7).

Commercially and Recreationally Important Species

Oysters were only abundant downstream of the dike (Fig. 1; Table 1). Their distribution and abundance appeared to be uniform enough at station 2I and along

Table 1. Larger invertebrates sampled by excising triplicate 1.0 m^2 quadrats (for these species a m^{-2} value is given), or relative abundance ("-" indicates not observed, "rare," or "common" is denoted) estimated by visual inspection.

Taxon	Station 1I	2I	3I
Bivalvia			
Argopecten irradians	rare	-	-
Crassostrea virginica	rare	21 m^{-2}	rare
Ensis directus	common	-	-
Mercenaria mercenaria	-	1m^{-2}	-
Gastropoda			
Polinices duplicatus	-	-	1m^{-2}
Decapoda			
Carcinus maenas	-	common	-
Eurypanopeus depressus	-	-	common
Pagurus longicarpus	common	common	common
Sipuncula			
Golfingia gouldi	5m^{-2}	-	-

Table 2. Decapod crustaceans collected by seine. All values are in percent of total organisms (decapods) collected; "-" denotes not collected.

Taxon	Station		
	1I	2I	3I
Crangonidae			
Crangon septemspinosa	-	14	4
Palaemonidae			
Palaemonetes pugio	6	70	96
Palaemonetes vulgaris	1	15	-
Portunidae			
Carcinus maenas	6	1	-
Ovalipes ocellatus	87	-	-

Table 3. Macrofaunal benthos from intertidal (stations 1I-3I) and subtidal (stations 1S-5S) areas. Mean densities in # of individuals m^{-2} and biomass in g wet weight m^{-2} calculated from 5 subsamples.

Taxon	Station							
	1I	2I	3I	1S	2S	3S	4S	5S
	Density (# individuals m^{-2})							
Annelida								
Polychaeta								
Capitellidae								
Heteromastus filiformis	7159	4256	4059	12374	5043	2657	886	–
Chaetopteridae								
Spiochaetopterus oculatus	98	25	–	148	25	369	–	–
Cirratulidae								
Tharyx sp.	984	–	–	246	–	25	–	–
unidentified species (1)	369	–	–	–	–	–	–	–
Cossuridae								
unidentified species (1)	25	–	–	–	–	–	–	–
Dorvilleidae								
Schistomeringos caeca	–	25	25	–	–	–	–	–
Glyceridae								
Glycera dibranchiata	197	25	–	467	25	–	–	–
Hesionidae								
Microphthalmus sczelkowii	49	–	–	–	–	–	–	–
Lumbrineridae								
Lumbrineris tenuis	–	–	–	49	–	–	–	–
Nephtyidae								
Nephtys picta	–	–	–	25	–	–	–	–
Nereidae								
Nereis acuminata	–	–	221	–	–	–	–	–
Nereis succinea	–	25	–	–	–	–	–	–
Orbiniidae								
Scoloplos fragilis	25	–	–	–	197	–	–	–
Scoloplos robustus	246	25	246	148	–	49	–	–
Pectinariidae								
Pectinaria gouldii	25	74	–	–	49	–	–	–
Phyllodocidae								

Table 3. Continued.

Taxon	Station							
	1I	2I	3I	1S	2S	3S	4S	5S
Eteone heteropoda	1058	295	2066	590	615	1082	221	-
Eteone lactea	-	-	25	-	-	25	-	-
Phyllodoce arenae	74	25	-	49	-	25	-	-
Spionidae								
Polydora ligni	-	-	-	-	1230	-	-	-
Polydora sp.	148	-	-	25	-	-	-	-
Prionospio heterobranchia	25	-	-	-	-	-	-	-
Pygospio elegans	197	-	25	123	-	-	-	-
Scolelepis squamata	-	25	-	-	-	-	-	-
Scolelepis (?)	246	-	-	-	-	-	-	-
Scolecolepides viridis	25	-	4822	221	49	2780	3050	492
Spiophanes bombyx	49	-	-	-	-	-	-	-
Streblospio benedicti	4600	2657	75	4453	320	344	172	-
unidentified species (1)	-	-	-	98	-	-	-	-
Syllidae								
Parapionosyllis longicirrata	25	-	3247	-	-	-	-	-
Syllis sp.	-	25	-	25	-	-	-	-
Oligochaeta (all unidentified)	590	-	2977	418	25	369	1279	4477
Mollusca								
Bivalvia								
Corbula sp.	-	-	25	-	-	25	-	-
Gemma gemma	-	74	25	-	-	887	197	-
Geukensia demissa	-	-	-	-	-	-	25	-
unidentified species (1)	74	-	-	-	-	-	-	25
Gastropoda								
Hydrobia totteni	-	-	-	-	-	25	25	-
Ilyanassa obsoleta	689	763	-	517	517	-	74	-

Table 3. Continued.

Taxon	Station							
	1I	2I	3I	1S	2S	3S	4S	5S
Arthropoda								
Crustacea								
Amphipoda								
Ampelisca abdita	25	25	-	98	271	-	-	-
Ampelisca verrilli	74	-	-	-	-	-	-	-
Ampithoe valida	-	-	51	-	-	123	25	-
Gammarus fasciatus	-	-	-	-	-	-	25	1599
Decapoda								
Crangon septemspinosa	-	-	-	25	-	-	-	-
Pinnixa chaetopterana	-	-	-	74	-	-	-	-
Isopoda								
Asellus sp.	-	-	-	-	-	-	-	25
Edotea triloba	74	123	1279	49	25	49	148	-
Ostracoda								
unidentified species	-	-	-	49	-	74	25	-
Tanaidacea								
Leptochelia savignyi	-	-	25	-	-	74	74	-
Merostomata								
Xiphosura								
Limulus polyphemus	-	221	-	-	-	25	-	-
Platyhelminthes (unidentified species)	74	98	25	-	49	148	-	25
Rhynchocoela (unidentified species)	74	-	-	172	74	25	-	-
Sipunculida (unidentified species)	25	-	-	-	-	-	-	-

Table 3. Continued.

Taxon	Station							
	1I	2I	3I	1S	2S	3S	4S	5S
Mean for Total Community:	17323	8786	19218	20443	8514	9180	6226	6643
(1 Standard deviation)	(4800)	(3701)	(4915)	(8708)	(7960)	(5574)	(3364)	(4772)
				Wet weight (g m^{-2})				
Annelida	18	8	34	15	11	67	55	3
Mollusca	312	186	<1	327	240	7	53	–
Arthropoda	1	4	<1	1	1	1	–	3
Platyhelminthes	1	–	<1	–	–	–	–	–
Rhynchocoela	3	–	–	2	1	–	–	–
Sipuncula	7	–	–	–	–	–	–	–
Total:	342	198	35	345	253	75	108	6
(1 Standard Deviation)	(184)	(66)	(17)	(157)	(253)	(85)	(43)	(4)

Table 4. Macroinvertebrates collected from saltmarsh at stations 2M and 3M (Fig. 1); SAS = short _Spartina alterniflora_, SAT = tall _S. alterniflora_, SP = _Spartina patens_. All values are in # of individuals m^{-2}. A "-" denotes not observed.

Taxon	Station 2M			Station 3M		
	SAS	SAT	SP	SAS	SAT	SP
Bivalvia						
Crassostrea virginica	-	24	-	-	-	-
Geukensia demissa	16	188	36	-	12	-
Gastropoda						
Ilyanassa obsoleta	-	52	-	-	-	-
Littorina littorea	-	116	20	-	-	-
Melampus bidentatus	12	-	652	-	12	600
Crustacea						
Carcinus maenas	-	-	1	-	-	-
_Uca pugnax_*	32	?**	120	-	-	-

*Number given represents density of burrow holes.
**Not able to count burrows because of water covering the substrate.

a stretch several hundred meters upstream so that a quantitative estimate of densities could be made. Three 1.0-m^2 quadrats had densities of 19 to 24 individuals each, giving a mean of 21 m^{-2} (Table 1). Local commercial fishermen also reported that oysters are relatively dense for several hundred meters downstream of station 2I. Hard clams were much less abundant at station 2I, with only two individuals collected from one of the three quadrats. Local commercial fishermen reported that they generally are much less abundant than oysters, but there are patchy areas where they are abundant downstream of the dike. Only one live bay scallop (Argopecten irradians) was collected; however, empty valves were scattered on the intertidal flats near stations 1I and 2I. Several razor clams (Ensis directus) were observed in the area of station 2I, but not in other areas.

Epibenthic Species

The epibenthic species collected by seine were mostly decapod crustaceans (Table 2); specimens of Ilyanassa obsoleta and Polinices duplicatus were collected by seine, but because they were quantitatively sampled by other methods they were discarded. (Decapods were also collected by other methods and data are presented in Tables 1, 2, 3, and 4.) Sand shrimp (Crangon septemspinosa were only abundant at station 2I where they represented 14% of the decapods collected (Table 2; Fig. 2). They were not collected by seine at station 1I, but were collected by PVC corer from the nearby subtidal station 1S (Table 3). Palaemontes pugio penetrated farther into the estuary than Palaemonetes vulgaris, and was the numerically dominant grass shrimp at all three stations. Green crabs (Carcinus maenas) were not collected upstream of the dike. They were not dominant in any of the seine samples (Table 2), but they were observed to be common in the area of station 2I (Table 1). Lady crabs (Ovalipes ocellatus) were collected only from station 1I where they were numerically dominant. Other common epibenthic species included moon snails (Polinices duplicatus) and hermit crabs (Pagurus longicarpus).

Subtidal Benthos

Numerically dominant taxa (in alphabetical order) from the estuarine areas included: Edotea triloba, Eteone heteropoda, Heteromastus filiformis, Ilyanassa obsoleta, Oligochaeta, Scolecolepides viridis, and Streblospio benedicti (Table 3; Fig. 3). Of these, only S. viridis and unidentified oligochaetes were collected from station 5S, the estuarine station farthest upstream; only six species were collected at this station. At station 4S fourteen species, including the remaining five species listed above were collected. All seven taxa were consistently present at stations 1S-4S, except I. obsoleta which was not at station 3S. There was a general increase in total benthic species collected progressing from station 5S downstream: #5S - 6 species; #4S-14; #3S-20; #2S-15; #1S-23. Biomass and total community densities also showed an increasing down-estuary trend (Table 3). Sediment types ranged from nearly pure mud (grain size less than 0.063-mm) at stations 2S, 3S, and 4S, to muddy, fine-to-coarse sand at stations 1S and 5S (Table 5). Numerically dominant taxa (in alphabetical order) from freshwater areas included: Asellus sp., Helobdella elongata, Oligochaeta, Musculium sp., and Pisidium sp. Station 8S, the one farthest upstream, had eighteen species; 6s had ten, and 7s had seven (Table 7).

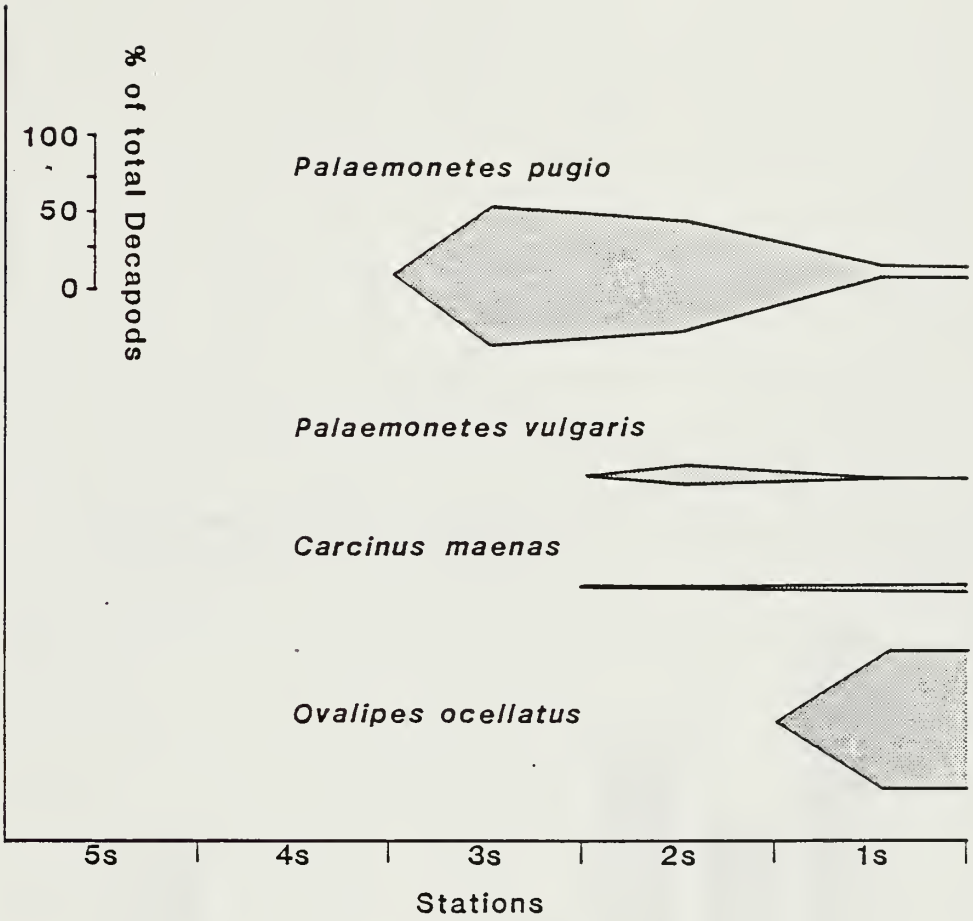

Fig. 2. Relative abundances in percent of total decapods collected for decapod species collected by seine.

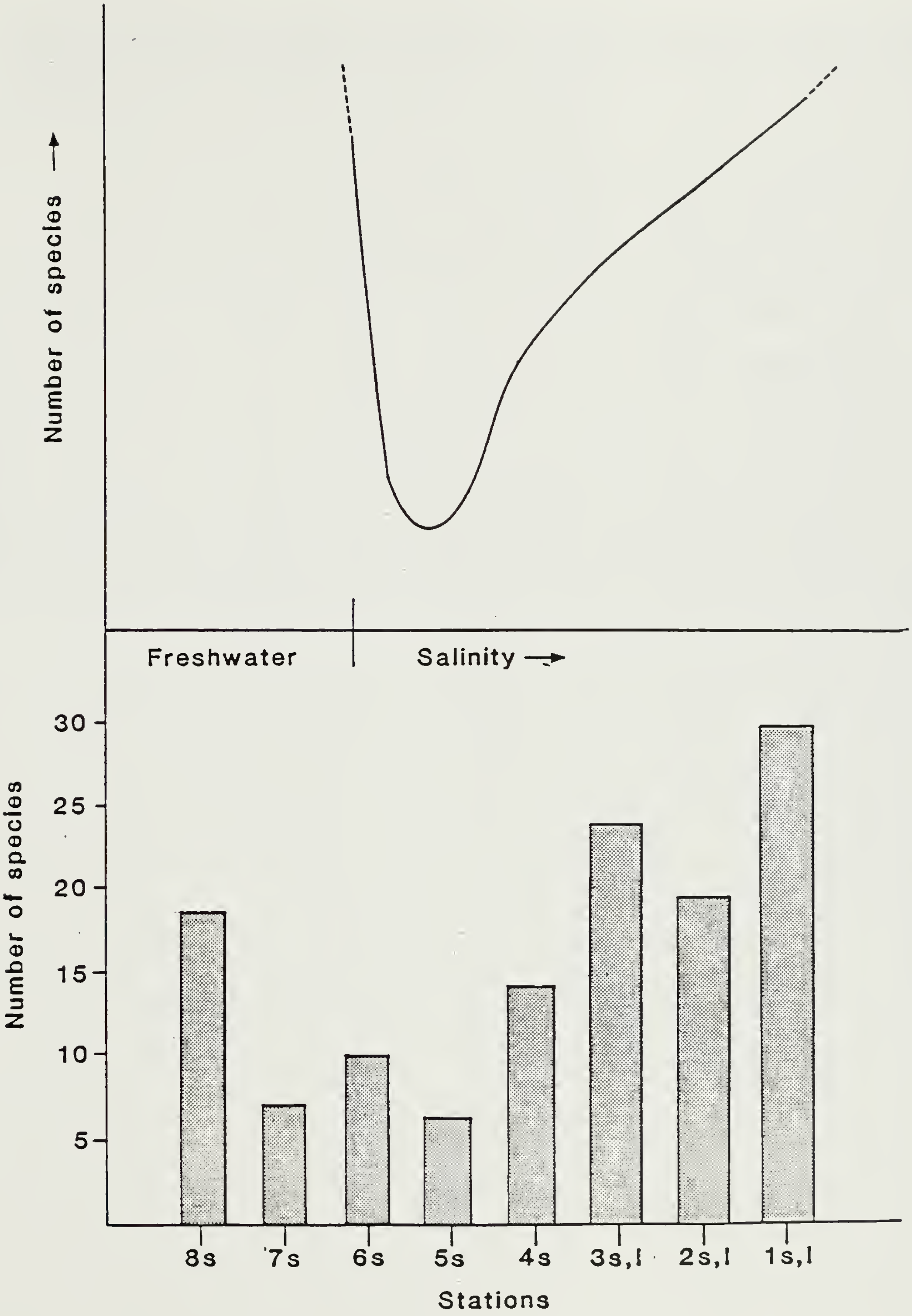

Fig. 3. Comparison of total macroinvertebrate benthic species collected by PVC corer compared to Remane's classic (Remane and Schlieper 1971) species vs. salinity curve.

Table 5. Grain size characteristics of sediment from subtidal and intertidal stations. All values are in percent of total dry weight.

Grain size (mm)	Station										
	1I	2I	3I	1S	2S	3S	4S	5S	6S	7S	8S
>0.5	62.4	-	69.7	41.4	-	-	-	34.7	42.9	29.5	29.1
0.25-0.5	21.5	-	26.6	26.5	-	-	-	38.6	45.0	24.9	46.5
0.125-0.25	9.9	-	2.0	19.5	-	-	-	17.7	9.6	10.6	19.5
0.063-0.125	3.5	-	0.1	7.8	-	-	-	3.9	0.7	8.5	2.4
<0.063	2.7	100	1.6	4.8	100	100	100	5.1	1.8	26.5	2.5

Table 6. Selected salinity data from stations near those depicted in Fig. 1. Actual sampling locations varied, but were within about 50-m of the station listed. All values are in parts per thousand.

Date	Station			
	3S	4S	5S	6S
23 Aug. 1984*	7 - 24	1 - 10	1 - 4	-
5 Oct. 1984*	8 - 27	-	-	-
2 Dec. 1984**	22	15	5	-
3 Dec. 1984**	27	24	13	-

* = range for one tidal cycle.
** = high water, near-bottom sample.

Table 7. Macrofaunal benthos from freshwater portion of Herring River. Mean densities in # of individuals m^{-2} calculated from 5 core sampling units at each station.

Taxon	Station		
	6S	7S	8S
Annelida			
Hirudinea			
Batracobdella phalera	0	0	25
Erpobdella punctata	49	0	0
Helobdella elongata	123	74	246
H. fusca	0	0	98
H. stagnalis	25	0	123
H. triserialis	0	0	25
Nephelopsis obscura	0	0	25
Placobdella ornata	0	0	25
Oligochaeta			
Niadidae			
sp. 1	1230	4477	0
sp. 2	3738	2706	0
Tubificidae			
Limnodrilus sp.	0	0	418
Arthropoda			
Crustacea			
Amphipoda			
Hyella azteca	0	0	787
Isopoda			
Asellus sp.	197	295	148
Ostracoda			
unidentified sp.	25	0	49
Insecta			
Coleoptera			
unidentified sp. (larvae)	0	0	25
Diptera			
Ablebesmyia sp.	0	0	197
Pentaneura sp.	74	0	0
Trichoptera			
Cheumatopsyche sp.	0	0	25
Mollusca			
Bivalvia			
Musculium sp.	3715	4453	1550
Pisidium sp.	418	836	861
Sphaerium sp.	0	517	664
Gastropoda			
Amnicola limosa	0	0	74
Mean for Total Community: (1 standard deviation)	9594 (3771)	13358 (11064)	5365 (2988)

Intertidal Benthos

There was only a small (several hundred m^2) intertidal area above the dike at station 3I (Fig. 1). The expansive intertidal flats below the dike were sampled at two sites: stations 1I and 2I (Fig. 1; Tables 1 and 3). The smaller organisms (sampled with PVC corer) were represented by the same numerically dominant species and in similar abundances as at the corresponding subtidal stations (see above; Table 3). Larger macroinvertebrates showed distinct differences in distribution and abundances between stations. All these species except *P. longicarpus* were only observed at one of the three stations. *P. longicarpus* was common in all three areas (Table 1).

Saltmarsh Macroinvertebrates

The two areas of salt marsh were quite different in macroinvertebrate species composition and abundances (Table 4). Station 3M, located above the dike (Fig. 1) had a total of only two species (*Geukensia demissa* and *Melampus bidentatus*) in all three vegetation zones sampled. Seven species were collected from station 2M below the dike. Several *Uca pugnax* were collected in all three zones, and its burrows were abundant. *G. demissa* was abundant in all zones, and only in the *Spartina patens* zone was another species more abundant; *Melampus* was the numerical dominant in that zone.

DISCUSSION

The distribution patterns of numerically dominant macroinvertebrates in Herring River estuary clearly show trends with respect to position (upstream-downstream). The dike at Chequesset Neck Road is related to the observed patterns, particularly because of its effect on tidal movements and salinity fluctuations. Opening of one of the three tide gates on the dike for 3 days in Decmeber 1984 resulted in movement of brackish water 1+ km upstream from its normal limit (C.T. Roman, pers. comm.). The normal tidal range upstream of the dike is about 0.5-m, compared to a mean range of 2.5-m downstream (C.T. Roman, pers. comm.). The attenuation of tidal ranges results in changes in current velocities, and probably sedimentation patterns in the immediate vicinity of the dike and to an undetermined distance upstream and downstream. There are also substantial water quality changes in the mid-river portion upstream of the dike compared to the headwaters and mouth (C.T. Roman, pers. comm.). Thus, the distribution patterns of macroinvertebrates in Herring River are certainly related to effects of the dike.

In the present report the major factor that will be considered in predicting changes in these distribution patterns relative to management alternatives will be salinity. The distributions of animals in estuaries have long been explained by changes in salinity. It is well-established that osmoregulatory characteristics of species are related to reported distribution patterns (see references in Carriker 1967, Green 1968, Remane and Schlieper 1971), eventhough, other factors are involved and the relationship between salinity and faunal distribution patterns is not simple (e.g. Sanders et al. 1965, Day 1967, Wolff 1973, Boesch 1977). Nevertheless, salinity differences

(associated with position in the estuary) correspond quite well to spatial variations in distributions and abundances of the numerically dominant species of macroinvertebrates in Herring River estuary. Therefore, a cause and effect relationship is assumed. Salinity, in conjunction with data on sediments, potential predators, and other factors will be used in the following discussion to make predictions on possible changes in distribution patterns of the numerically dominant species with respect to management alternatives. Table 8 summarizes some of these predicted changes with management.

Commercially and Recreationally Important Species

Curley et al. (1972) provide a good summary of data on commercial species from Wellfleet Harbor and the mouth of Herring River, especially from a historical perspective. The major economic species have been hard clams and oysters. Occasionally soft clams (*Mya arenaria*) and bay scallops have been harvested.

Curley et al. (1972) report average densities of less than 1 m^{-2} but up to 8 m^{-2} for hard clams in 1969 in several areas of Wellfleet Harbor, including Herring River. The one site in the present study (station 2I, Fig. 1) at which a quantitative estimate was made had 1 m^{-2} (Table 1). No hard clams were collected upstream of the dike, and it is likely that existing salinities are too low in these areas to allow establishment of a population (Table 6). Optimum hard clam production is generally reported from sandy mud to muddy sand sediments (but they are found in sediment ranging from pure mud to coarse sand) in areas with a salinity range of 15 to 35 ppt (see review by MacKenzie 1979). Downstream of the dike existing environmental conditions (i.e. a range of sediment types, see Table 5; and salinities generally greater than 20 ppt, see Table 6, and Curley et al. 1972) are adequate in most areas for hard clams to exist, and they are present (see above). Invertebrates reported (MacKenzie 1979) to consume hard clams and collected in the present study include: moon snails (*Polinices duplicatus*), green crabs (*Carcinus maenas*), and mud crabs (*Eurypanopeus depressus*) (Table 1). Management alternatives that would result in minimum salinities remaining near or above 15 ppt in any area could result in expansion of the hard clam into that area. Hard clam predators are common in Herring River, but it is not possible with available data to assess their potential impact on the hard clam.

Four areas in Herring River downstream of the dike were sampled for oysters in 1969 (Curley et al. 1972); densities ranged from 0.1 to 2.3 m^{-2} for "legals" and from 1.9 to 20 m^{-2} for "sub-legals." Curley et al. reported the Herring River to be one of the best spawning and setting areas for oysters in the Wellfleet Harbor area. The present study also showed substantial densities of oysters downstream of the dike, but few upstream (Table 1). Oysters are usually restricted to waters that rarely fall below 5 ppt or exceed 30 ppt (Galtsoff 1964). They can occur on a variety of bottom types, but are initially established on a hard substratum. The substratum must also be stable enough to support the oyster as it grows (Galtsoff 1964). Oyster predators include the same species listed above for hard clams. The paucity of oysters upstream of the dike may be a combination of unsuitable sediments and abundant predators. The sediments in the area of station 3I are mostly coarse and shifting sands, and they are affected by the strong flooding tidal currents coming through the gates in the nearby dike.

Table 8. Summary of predicted trends in changes of relative abundances of major estuarine macroinvertebra species resulting from opening of tide gates on the dike. See text for detailed discuss "Estuarine endemic," "euryhaline," and "stenohaline" correspond to Boesch's (1977) spe categories.

	Relative Abundance Upstream of Dike		
Organism	Summer 1984	After Opening Gates	Basis for Prediction
oyster (*Crassostrea virginica*)	rare	possible increase	Existing sediment types apparently not suitabl possible improvement via cultch. Opening gate would result in tidal and salinity conditions like existing downstream conditions where oyst do well.
hard clam (*Mercenaria mercenaria*)	absent	common, in suitable sediments	Increased salinities should allow hard clams t penetrate further upstream.
Freshwater species:			
Asellus sp, *Gammarus fasciatus*	common far upstream	their distribution would be pushed further upstream; similar abundances	Penetration of saline waters further upstream.
Estuarine endemic species: *Scolecolepides viridis*	abundant	abundant further upstream	Penetration of saline waters further upstream.
Euryhaline species: *Edotea triloba*, *Eteone heteropoda*, *Heteromastus filiformis*, *Streblospio benedicti*	common	common further upstream	Penetration of saline waters further upstream.
Stenohaline speices: *Glycera dibranchiata*, *Spiochaetopterus oculatus*	rare or absent	present	Penetration of saline waters further upstream.
Palaemonetes pugio	common	common further upstream	Penetration of saline waters further upstream.
Palaemonetes vulgaris	absent	present	Penetration of saline waters further upstream.
Carcinus maenas	absent	present	Penetration of saline waters further upstream.
Ovalipes ocellatus	absent	absent (?)	This species was only abundant at mouth of estuary, but it could perhaps move upstream of dike sporadically.

Moon snails, an oyster and hard clam predator, were abundant in the area (Table 1). Frequent periods of salinity concentrations below 5 ppt (Table 6) likely eliminate oysters from areas further upstream than station 3I. Management alternatives resulting in normal salinity ranges falling in the 5-30 ppt range could result in increased oyster production in those areas. In some areas (e.g. likely unsuitable sediments in vicinity of station 3I) major physical alterations of the environment such as removal of existing sediments and replacement by more desirable sediments might be necessary.

There has been some concern over the possibility of the existing clams and oysters downstream of the dike being affected by heavy suspended sediment loads if the tide gates on the dike are opened. This may be a possibility. However, if any changes in gate openings are done slowly and during the cooler months when animal metabolism is very low, and the suspended sediment load is well-monitored, then such problems could likely be avoided. If there is a lot of scouring in the vicinity of the dike and deposition downstream then it might require several months or years to fully implement a management alternative.

Other species with commercial and/or recreational potential include bay scallops (Argopecten irradians), razor clams (Ensis directus), and soft clams (Mya arenaria). Only one bay scallop was collected in the present study. Curley et al. (1972) report that the Wellfleet Harbor area is not optimum habitat mainly due to its large tidal range. Razor clams were only observed in the area of station 1I. They are not known to be of commercial value, but some are perhaps taken by recreational harvestors. No soft clams were collected in the present study, however they have been harvested from Wellfleet Harbor area (Curley et al. 1972). The soft clam is usually found in a salinity range of less than 5 to 35 ppt (MacKenzie 1979). Of these three species, the soft clam is the only one likely to be found further upstream than the mouth of Herring River, and thus much affected by any of the management alternatives. Because the soft clam can tolerate a wide range of salinities, and sediments ranging from mud to sand (MacKenzie 1979), there may be some potential for this species in Herring River. However, it was not collected in the present study, and no estimation of potential impacts of management alternatives can be made.

Epibenthic Species

The species discussed in this subsection are all decapod crustaceans (see Results). Sand shrimp (Crangon septimspinosa) were only collected from stations 1S at the mouth of Herring River (Table 3, Fig. 1) and 2I near the mouth (Table 2). This species is restricted to sand sediments, but can penetrate into low salinity (Lippson and Lippson 1984). Two species of grass shrimp (Palaemonetes pugio and Palaemonetes vulgaris) were collected in the present study. P. vulgaris was not collected upstream of the dike (Table 2; Fig. 2), and it is generally found in waters where the salinity is usually greater than 15 ppt (see references in Williams 1984). P. pugio showed a trend of increasing relative abundance up-estuary (Table 2; Fig. 2). It is generally reported to be most abundant in waters of 10-20 ppt, although it tolerates salinities of less than 10 ppt (Williams 1984). Those management alternatives resulting in salinity changes in a given area to stay above 15 ppt would favor P. vulgaris; salinity changes toward a range of less than 10 to 20 ppt would favor P. pugio. Green crabs (Carcinus maenas) were not collected upstream of the dike (Table 2).

(However, they were collected in the vicinity of station 3S during a sampling trip in September 1984, G. Marteinsdottir, pers. comm.). They are usually found in salinities of 10-33 ppt, and on a variety of bottom types (Williams 1984). Any management alternatives resulting in salinities in this range could allow green crabs to move into that area. Lady crabs (*Ovalipes ocellatus*) were only collected from the mouth of Herring River at station 1I (Table 2). They are typically a high salinity species (e.g. Lipson and Lippson 1984), and would probably not be affected much by any of the management altnernatives.

Subtidal Benthos, Intertidal Benthos

These two categories are combined here because there were no clear-cut differences in macrofauna sampled by the PVC corer relative to tidal exposure (see Results, and Table 3), and because only brief comment can be made (see last paragraph in this subsection) on the larger species sampled in the intertidal habitat.

Total macrofaunal species collected by PVC corer showed moderate species numbers in the freshwater portion, low numbers in less-saline areas, and high numbers near the mouth; this is shown in comparison to the well-known species vs. salinity graph of Remane in Fig. 3 (Remane and Schlieper 1971). There was also an increasing down-estuary trend in total community densities and biomass (Table 3), as reported in other areas (e.g. Chester et al. 1982). Boesch's (1977) proposed scheme for estuarine benthic zonation is used in the present report to analyze the estuarine benthic species data. His scheme is based largely on data from the Chesapeake Bay and two of its sub-estuaries, a system with salinities varying little over each tidal cycle but typically varying on a seasonal basis. The Herring River typically shows a wide range of salinities over each tidal cycle at the estuarine stations sampled upstream of the dike (Table 6). Seasonal variations are also likely, but complete data are not available. The distributions of some of the species assemblages defined by Boesch coincide well with the Herring River data. *Asellus* sp. and *Gammarus fasciatus* (both not in Boesch 1977) are freshwater taxa generally restricted to salinities of less than 3 ppt (Bousfield 1973; Smith 1964). The isopod *Asellus* was only collected at station 5S, and the amphipod *G. fasciatus* from 4S and 5S (Table 3, Fig. 4). Station 5S is the station farthest upstream where brackish waters are usually found (Table 6). Station 4S is the next down-estuary station; it typically has a wide range of salinities over a tidal cycle, from less than 5 ppt to over 20 ppt (Table 6). *Scolecolepides viridis*, a spionid polychaete, is in the "estuarine endemic" assemblage of Boesch, which is the group typically occurring farthest up-estuary. This species reportedly penetrates further upstream than any other polychaete in the Woods Hole region (Smith 1964). It was the only polychaete present at station 5S; it occurred at higher densities at stations 4S and 3S, and then declined at stations 2S, 1S, and 1I (Table 3; Fig. 4). The "euryhaline opportunists" and "euryhaline marine species" of Boesch include *Edotea triloba* (an isopod), *Eteone heteropoda* (a phyllodocid polychaete), *Heteromastus filiformis* (a capitellid polychaete), and *Streblospio benedicti* (a spionid polychaete), which were the numerical dominants in the present study. These four species were present from station 4S downstream, and generally with increasing densities down-estuary (Table 3; Fig. 4). Boesch's final category, "stenohaline marine species" included *Glycera dibranchiata* (a glycerid polychaete) and *Spiochaetopterus oculatus* (a chaetopterid polychaete). *G. dibranchiata* occurred from station 2S downstream; *S. oculatus* from station 3S downstream (Table 3, Fig. 4). Most of the above

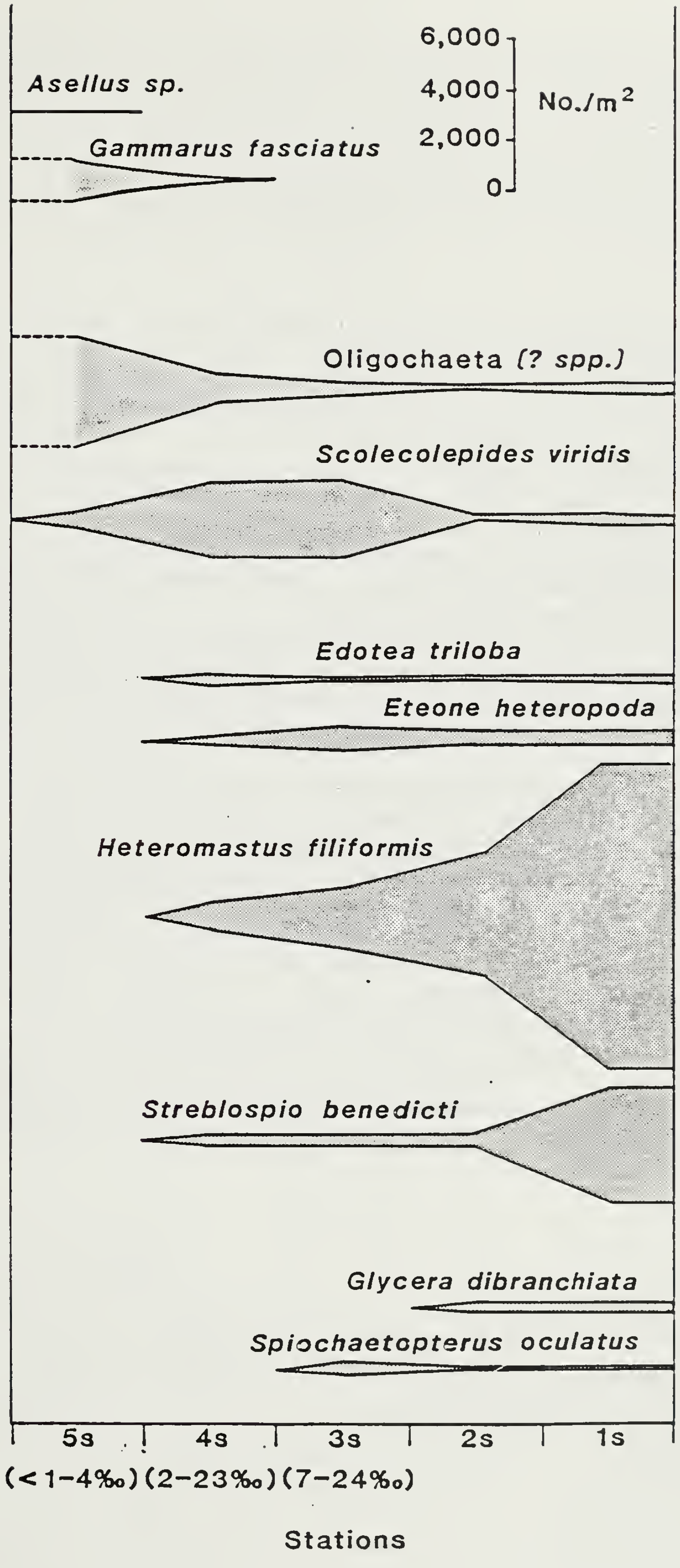

Fig. 4. Quantitative data (number of individuals/m^2) for numerically dominant benthic species collected by PVC corer. Salinity range over one tidal cycle in August(1984) is shown.

species (all in Fig. 4) are found on a variety of sediment types (see Whitlatch 1982 for summary), and from intertidal to various subtidal depths (see Pettibone 1963, and Day 1973 for polychaetes). Therefore, even though a comprehensive explanation for the distribution of macrofaunal benthos in estuaries is not available (see above), it is suggested that prediction of salinity changes associated with each management alternative will likely be adequate to predict general changes in distribution patterns of these major macrofaunal benthic species.

Freshwater benthic data (stations 6S, 7S, and 8S) do not show a trend with respect to position in the river, as do the estuarine data discussed above. Further, there are substantial environmental differences between the three freshwater stations. Sediment was similar at 6S and 8S, but 7S had much greater mud (grain size less than 0.063-mm) content (Table 5). Station 7S was in an area that has been channelized, and it is regularly disturbed by maintenance operations during the summer (C.T. Roman, pers. comm.). Submerged aquatic vegetation was abundant at 8S but not at 6S or 7S. Also, there are probably significant water quality differences between these three areas (C.T. Roman, pers. comm.; Beskenis and Nuzzo 1984). Emphasis in the present study was on the estuarine portion of Herring River, and it is not possible using benthic data herein to characterize the freshwater portion of the river. In general it may be predicted that any of the management alternatives will result in an upstream shift of the freshwater benthic communities. The distance of the shift will be largely determined by changes in the salinity regime.

The larger intertidal benthic species (not already discussed above in the commercial and recreationally important species subsection) include: *Polinices duplicatus* (moon snail), *Eurypanopeus depressus* (mud crab), *Pagurus longicarpus* (hermit crab), and *Golfingia gouldi* (sipunculid) (Table 1). *P. duplicatus* was only collected at mid-estuary at station 3I, but it is typically (e.g., Lippson and Lippson 1984) found in areas of high salinity. *E. depressus* was also only collected at 3I, where there was a lot of shell in the sediment; but it is usually most abundant in the fouling community, particularly oyster bars (Williams 1984), and was thus probably not adequately sampled. *P. longicarpus* was common in all three intertidal areas, thus showing no trend in distribution pattern. *G. gouldi* was only collected at station 1I, an area not likely to be affected by the management alternatives. Therefore, for the reasons mentioned above, no predictions are made for these species with respect to management alternatives.

Saltmarsh Macroinvertebrates

The two saltmarshes sampled in the present study differed dramatically in macroinvertebrates present (Table 4). Station 3M above the dike (fig. 1) only had two species: *Geukensia demissa* in the high *Spartina alterniflora* (SAT) zone and *Melampus bidentatus* in the SAT and *Spartina patens* zones. Seven species were collected from station 2M downstream of the dike, and these were present in densities typically found in New England saltmarshes (see summary in Fell et al. 1982). Various characteristics of saltmarshes have been correlated with tidal range (Ranwell 1975, Daiber 1982). Fell et al. (1982) showed a positive correlation between tidal range and abundances of *G. demissa* and *M. bidentatus*. Upstream of the dike in the vicinity of station 3M the tidal range is about 0.5-m, compared to a downstream range of about 2.5 to 4-m. Also, 3M is probably less

exposed to waves from storms, and 3M is in an area of reduced salinities compared to station 2M. There may be other important differences between the two sites, but effects related to tidal range and salinity offer a reasonable explanation. Thus, it is predicted that management alternatives resulting in greater tidal range and salinities at 3M will result in increases in species numbers and abundances. None of the management alternatives will likely affect station 2M.

Trophic Relationships for Non-economically Important Species

Small annelid worms (e.g. oligochaetes, *Scolecolepides viridis*, *Heteromastus filiformis*, *Streblospio benedicti*) numerically dominated the benthos (Table 3; Fig. 4). Many of these species (especially when immature) inhabitat only the upper few cm of sediments, and they are heavily consumed by predatory fish and crustaceans (Festa 1979, Virnstein 1979, Stoner 1980). Amphipod crustaceans were also common in Herring River (Table 3), and they are an important fish food (Festa 1979, Virnstein 1980). The following fish species collected in Herring River consume benthic macroinvertebrates, based on studies in other areas (Allen et al. 1978; Festa 1979); mummichog (*Fundulus heteroclitus*), striped killifish (*Fundulus majalis*), winter flounder (*Pseudopleuronectes americanus*), American eel (*Anguilla rostrata*), fourspine stickleback (*Apeltes quadracus*), northern pipefish (*Sygnathus fuscus*) and white perch (*Morone americana*). Grass shrimp (*Palaemonetes* spp.) were abundant in Herring River (Table 2). These organisms eat detritus (Williams 1984), and they may also consume other macroinvertebrates (Virnstein et al. 1983); they are consumed (Festa 1978) by several fish species (e.g. white perch, winter flounder) collected in Herring River. Species that consume clams and oysters (e.g. *Carcinus maenas* and *Eurypanopeus depressus*) probably also consume other benthos (Williams 1984). In summary, the non-economic macrofaunal benthic species collected in Herring River have been shown by studies in other areas to be heavily preyed upon by fish and macroinvetebrates species also found in Herring River. Benthic organisms are probably a major pathway for energy flow in Herring River.

Future Macroinvertebrate Studies

The sites sampled during the present study may be used in the future to assess management alternatives. It is recognized that estuarine ecosystems are typically dynamics sometimes with drastic changes in biota resulting from sporadic natural events such as storms, unusual drought, etc. Thus, the results of any sampling program aimed at impact assessment must be interpreted in a proper temporal (and spatial) framework. The present study provides a description of the assemblages of macroinvertebrates inhabiting Herring River during mid-summer, and the species distributions were correlated with variations in salinity and other factors as discussed above. Future studies designed to assess impacts of management alternatives would be most meaningful if done in mid-summer, and when patterns of rainfall and other conditions affecting salinity fluctuations are similar to 1984 conditions. Exceptions to this general recommendation may be possible for long-lived species such as hard clams and oysters. Also, it would be desirable to re-sample as many as possible of the sites sampled in 1984 immediately prior to implementation of any management alternatives. Sampling methods used in all future work should be as similar as possible to 1984 methods. Green (1979) provides good general direction for design of "before and after" studies.

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REPORT APPENDIX 4

AN AVIAN CENSUS OF THE HERRING RIVER, WELLFLEET, MASSACHUSETTS

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January 1986

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DESCRIPTION OF THE STUDY AREA

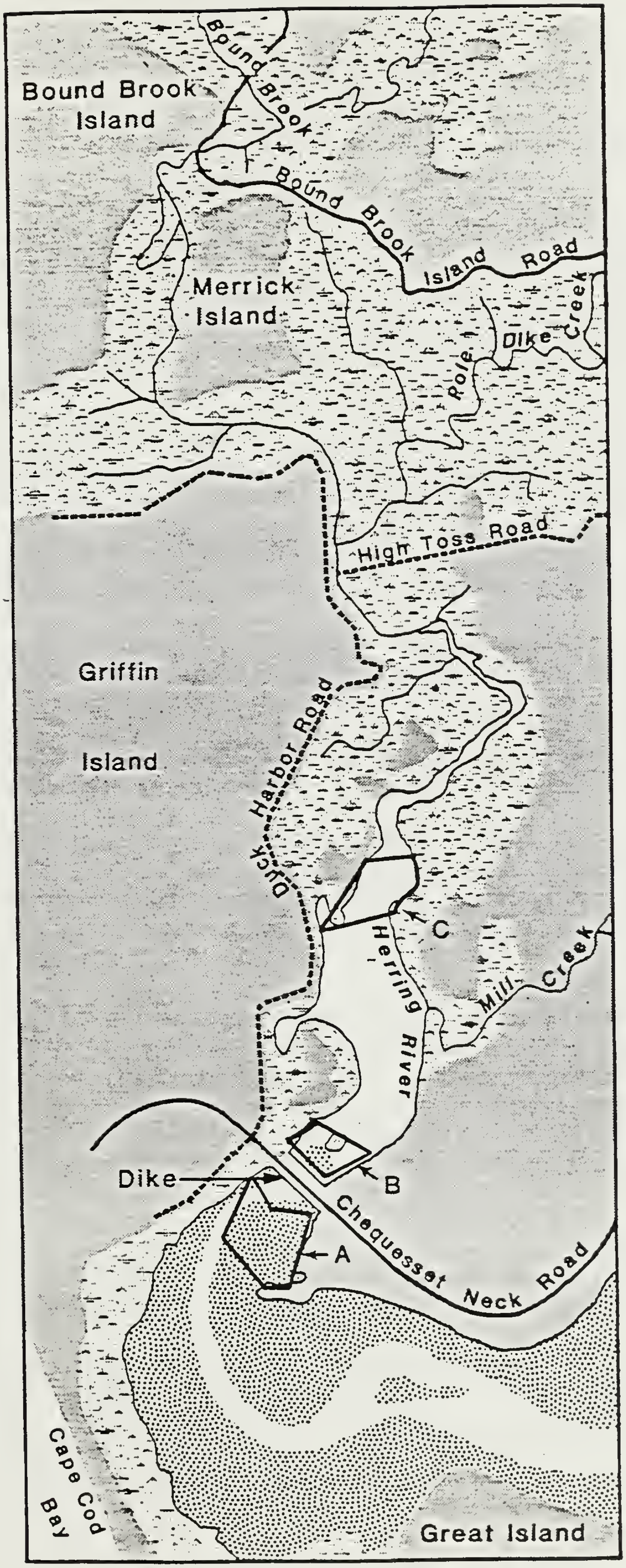
The Herring River is a tidal estuary that empties into the northwest corner of Wellfleet Harbor. Near its mouth it is bisected by a man-made dike which restricts the tidal flow upriver from the dike and has affected many aspects of the system's ecology.

To study waterbirds using the Herring River system, three census sites were chosen and designated "A", "B" and "C" (Fig. 1). No areal measurements were taken at the sites but visual boundaries were established to make the sites comparable in total area. Site A was located at the mouth of the river south of the dike, and consisted primarily (approximately 75-80%) of intertidal mudflats, exposed at low water and inundated at high water. It was bordered on the east and west by saltmarsh vegetated with *Spartina*. A creek averaging 15-20m in width at low water transected the site in a SW-NE direction. Site B was located approximately 20m north of the dike. Approximately 65-70% of the site was subtidal and 20-25% intertidal. It was bordered in the NW and SE by the river banks which were vegetated primarily with *Spartina alterniflora*. A small island, approximately 10m x 5m and vegetated with *S. alterniflora* was located near the center of the site. Due to restricted waterflow through the dike, the tidal cycle at site B averaged 2-3 hours later than site A. Site C was located upriver approximately 450m northeast of the dike. Although there was some tidal fluctuation, the site was almost entirely (±90%) subtidal, except for a few small patches of river bank exposed during periods of low water. The riverbanks were vegetated with dense stands of *Phragmites australis* and some *S. alterniflora*.

METHODS

Avian censues were conducted on nine dates during the period 15 August to 30 October 1985, to determine species composition and usage patterns. Sites A and B were censused from the dike, site C from a hill 75m to the west that provided a clear view of the site without disturbing the birds present. Viewing was done with 10X binoculars and a 20X telescope. All the waterbirds present at a site at the start of the census were counted and recorded on data sheets. Birds were identified to species and categorized according to the habitat they occupied and the activity in which they were engaged. Habitats were divided into four categories: saltmarsh (SM), marsh edge (ME), intertidal flat (ITF) and subtidal (ST). Avian activity was divided into two categories: feeding and non-feeding (e.g., roosting, preening, bathing).

The time, the state of the tide (relative to the scheduled low tide), and the percentage of intertidal flat exposed (at sites A and B only) were recorded for each census. Censuses took from 1-5 minutes to complete per site, depending upon the number of birds present. Sites A and B were generally censused alternately, usually at 5-minute intervals, while site C was censused at irregular intervals.



Herring River System

Cape Cod National Seashore

Wellfleet, Mass.

FIG. 1.

Avian Observation Sites

RESULTS

A total of 301 censuses were conducted over the 9 dates, 114 at site A, 112 at site B and 75 at site C. A total of 5776 individual birds were recorded; 1967 at site A, 3603 at site B and 186 at site C. Overall, an average of 19.1 birds per census was recorded, with a range of 0-91 birds per census. The average number of birds per census varied considerably between sites: 17.2 at site A, 32.2 at site B, and only 2.5 at site C (Tables 1 and 2). Overall, 30 species of birds were recorded, 21 species at site A, 24 at site B and 11 at site C. Site C also had the lowest frequency of birds recorded: one or more birds were recorded on 92% of the censuses at site A, 96% at site B, but only 37% at site C.

Three groups of birds, waterfowl (ducks, geese, grebes and coot), gulls, and shorebirds (sandpipers, plovers and their allies) comprised 97.3% of the total birds recorded. Waterfowl (particularly Black Ducks) were by far the most numerous component of the avifauna, comprising 47.3% of the overall total. Gulls comprised 28.4% and shorebirds 21.6% of the total. The remainder, 2.7%, was comprised of herons, cormorants, terns and rails.

Species composition varied considerably between sites. At Site A, shorebirds were the numerically dominant group (51.1% of the total), followed by gulls (28.5%) and waterfowl (16.2%). At site B, waterfowl dominated (62.4% of the total), followed by gulls (29.8%) and shorebirds (6.5%). Waterfowl were also the most numerous at site C (83.3%) with only a few shorebirds (2.7%) and no gulls recorded at that site.

Species distribution also varied widely between sites. Among shorebirds, 80.8% of the total were recorded at site A, 18.7% at site B and only 0.4% at site C. Of the total waterfowl, 11.7% were at site A, 82.6% at site B and 5.7% at site C. Gulls were distributed between site A (34.3%) and site B (65.7%), with none at site C.

At site A, bird usage showed a pronounced tidal influence with peak numbers occurring from the period 2 hours before low to 2 hours after low tide (Fig. 2). Bird usage at site B was also strongly influenced by tide (except for waterfowl), but peak numbers occurred from the period 2 hours after low to 4 hours after low tide. This 2-4 hours lag behind site A reflected the lag in the tide resulting from the restricted water flow through the dike. There was no obvious tidal influence on bird usage at site C.

Activity patterns also showed a significant difference between sites (Table 3). Overall 59.1% of the birds recorded were feeding. However, at site A, 78.4% were feeding while at site B only 48.1% were feeding and at site C, 66.1%.

Habitat usage was generally similar at all sites with 62.7% of the total birds using subtidal, 31.7% intertidal, 5.3% marsh edge and 0.3% saltmarsh (Table 4). These figures are roughly equivalent to the proportion of each habitat available at the study sites. Birds using the saltmarsh were difficult to detect and that category may be slightly under respresented in the results.

Table 1. Species observed and abbreviations used during an avian census of the Herring River, Wellfleet, MA. 15 August - 30 October, 1985.

PBGR - Pied-billed Grebe (Podilymbus podiceps)
DCCO - Double-crested Cormorant (Phalacrocorax auritus)
GBHE - Great Blue Heron (Ardea herodias)
SNEG - Snowy Egret (Egretta thula)
GRHE - Green-backed Heron (Butorides striatus)
CAGO - Canada Goose (Branta canadensis)
GWTE - Green-winged Teal (Anas crecca)
BLDU - American Black Duck (Anas rubripes)
MALL - Mallard (Anas platyrhynchos)
AMWI - American Wigeon (Anas americana)
BUFF - Bufflehead (Bucephala albeola)
RBME - Red-breasted Merganser (Mergus serrator)
VIRA - Virginia Rail (Rallus limicola)
AMCO - American Coot (Fulica americana)
BBPL - Black-bellied Plover (Pluvialis squatarola)
LGPL - Lesser Golden-Plover (Pluvialis dominica)
SEPL - Semipalmated Plover (Charadrius semipalmatus)
GRYE - Greater Yellowlegs (Tringa melanoleuca)
LEYE - Lesser Yellowlegs (Tringa flavipes)
SPSA - Spotted Sandpiper (Actitis macularia)
RUTU - Ruddy Turnstone (Arenaria interpes)
SESA - Semipalmated Sandpiper (Calidris pusilla)
LESA - Least Sandpiper (Calidris minutilla)
UNSA - unidentified small sandpiper (Least or Semipalmated)
DUNL - Dunlin (Calidris alpina)
LAGU - Laughing Gull (Larus atricilla)
RBGU - Ring-billed Gull (Larus delawarensis)
HEGU - Herring Gull (Larus argentatus)
GBBG - Great Black-backed Gull (Larus marinus)
COTE - Common Tern (Sterna hirundo)
LETE - Least Tern (Sterna antillarum)

additional abbreviations:

TOT = total birds (all species combined)
TOSH = shorebirds (plovers, sandpipers and their allies; suborders Charadrii & Scolopaci)
TOGU = total gulls
TOWA = total waterfowl (includes all ducks, geese, grebes and coot)

Table 2. Summary of avian census data indicating, by species, the mean number of a particular species recorded per census, the range of the number of a particular species recorded per censes, and t frequency, or percent of total census that one or more of a particular species was recorded. S Table 1 for abbreviations of species and summary totals.

SPECIES	SITES									SITES COMBINED		
	A			B			C					
	mean	range	%freq.	mean	range	%freq.	mean	range	%freq.	mean	range	%freq.
PBGR	0	0	0	0.15	0-4	11	0.27	0-5	12	.12	0-5	07
DCCO	0.19	0-2	16	0.04	0-1	04	0	0	0	.09	0-2	07
GBHE	0.08	0-2	05	0.22	0-7	09	0.33	0-7	12	.20	0-7	08
SNEG	0.03	0-1	03	0.03	0-1	03	0	0	0	.02	0-1	02
GRHE	0.24	0-3	17	0.12	0-3	10	0	0	0	.13	0-3	10
CAGO	0	0	0	0.25	0-7	04	1.0	0-9	19	.34	0-9	06
GWTE	0	0	0	0.04	0-2	02	.05	0-2	03	.03	0-2	02
BLDU	0	0	0	16.4	0-67	88	0.52	0-7	15	6.25	0-67	36
MALL	0	0	0	3.03	0-18	64	.13	0-4	09	1.16	0-18	26
AMWI	0	0	0	0.05	0-1	05	0	0	0	.02	0-1	02
BUFF	0	0	0	0.02	0-2	01	0	0	0	.01	0-2	01
RBME	2.80	0-30	32	0.09	0-2	06	.03	0-1	03	1.10	0-30	15
VIRA	0	0	0	0	0	0	.01	0-1	01	.01	0-1	01
AMCO	0	0	0	0	0	0	.03	0-1	03	.01	0-1	01
BBPL	2.25	0-21	51	0.34	0-3	22	0	0	0	.98	0-21	28
LGPL	0.06	0-1	06	0	0	0	0	0	0	.02	0-1	02
SEPL	3.46	0-33	28	0.34	0-7	08	0	0	0	1.44	0-33	14
GRYE	0.99	0-9	43	1.15	0-10	32	.03	0-2	01	.81	0-10	29
LEYE	0.04	0-1	04	0.04	0-1	04	0	0	0	.03	0-1	03
SPSA	0.25	0-3	18	0.10	0-2	07	0	0	0	.13	0-3	09
RUTU	0.04	0-2	04	0	0	0	0	0	0	.02	0-2	01
SESA	0.37	0-7	11	0.03	0-3	01	0	0	0	.15	0-7	04
LESA	0.52	0-11	11	0.09	0-5	04	0	0	0	.23	0-11	06
UNSA	0.79	0-10	12	0	0	0	.04	0-3	01	.31	0-10	05
DUNL	0.06	0-7	01	0	0	0	0	0	0	.02	0-7	01
LAGU	1.28	0-14	37	3.48	0-24	35	0	0	0	1.78	0-24	27
RBGU	1.47	0-14	40	4.46	0-38	36	0	0	0	2.22	0-38	29
HEGU	1.12	0-10	58	0.87	0-9	34	0	0	0	.75	0-10	35
GBBG	1.04	0-8	64	0.79	0-4	42	0	0	0	.68	0-8	40
COTE	0.11	0-8	04	0	0	0	0	0	0	.04	0-8	01
LETE	0.06	0-3	04	0.02	0-7	01	0	0	0	.03	0-7	02
TOSH	8.81	0-62	66	2.08	0-21	42	0.07	0-3	03	4.13	0-62	41
TOGU	4.91	0-29	88	9.58	0-56	47	0	0	0	5.43	0-56	51
TOWA	2.80	0-30	32	20.07	0-91	91	2.07	0-16	32	9.04	0-91	54
TOT	17.2	0-93	92	32.2	0-97	96	2.5	0-16	37	19.12	0-91	79

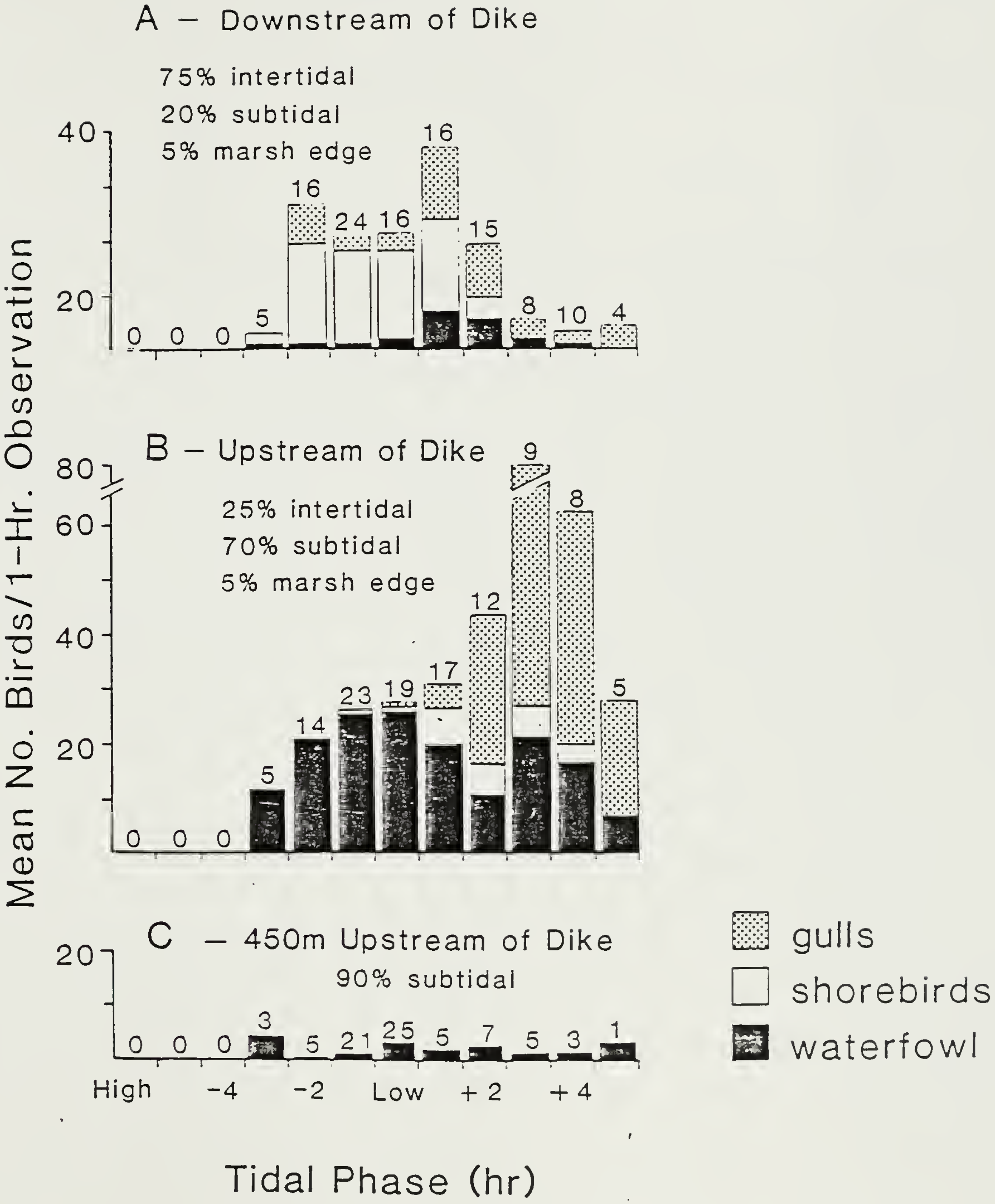


Figure 2. Gull, shorebird and waterfowl abundance at three sites along the Herring River, downstream and upstream of the dike. Tidal phase is indicated by hours ± low water. Numbers above bars are counts per 1-hr period.

Table 3. Activity patterns of birds at the three sites.

Site	No. Birds Feeding	Tot. No. Birds Observed	% Feeding
A	1543	1967	78%
B	1733	3603	48%
C	123	186	66%
TOTAL	3399	5754	59%

Table 4. Habitat utilization of birds at the three sites. Number of individuals observed in a habitat and percent of the total number of individuals observed at the site (parentheses) are indicated.

Site	Habitats[1]				Total No. Birds
	SM	ME	ITF	ST	
A	14(0.7%)	130(7%)	533(27%)	1290(66%)	1967
B	0(0)	131(4%)	1293(36%)	2197(61%)	3603
C	1(0.5%)	43(23%)	0(0)	142(76%)	186
TOTAL	15(0.3%)	304(5%)	1826(32%)	3611(63%)	5754

[1] SM = Salt Marsh
ME = Marsh Edge
ITF = Intertidal Flat
ST = Subtidal

CONCLUSIONS

Some pronounced differences in avian usage of the 3 sites are evident in the results. Site A was used primarily during the lower half of the tidal cycle as a feeding area by shorebirds and gulls. Avian usage at site A declined dramatically as the rising tide inundated the mud flats. Late in the season, migrant Red-brested Mergansers arrived and used site A for both feeding and non-feeding activities throughout the tidal cycle.

Site B was heavily used by waterfowl, particularly Black Ducks, for both feeding and non-feeding activities throughout the tidal cycle. It also was used by gulls and shorebirds for roosting during the short (1-2 hour) period just after the flats in site A became covered but before the flats in site B covered.

Site C received far less usage than the other sites and was used primarily by small numbers of waterfowl for both feeding and non-feedling activities.

REPORT APPENDIX 5

TIDAL HEIGHT MODEL OF THE HERRING RIVER, CAPE COD NATIONAL SEASHORE

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August 1985

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MODEL TYPE

In its present, obstructed condition the Herring River estuary receives tidal flow from Wellfleet Harbor only through a tight constriction, the dike beneath the Chequesett Neck Road causeway. The small cross-sectional area of the dike constriction together with the relatively short length of the estuary indicate that tidal oscillations inside it should be similar in dynamics to that found in harbors or lagoons which communicate with the nearshore ocean through a narrow, short inlet, e.g., Nauset Marsh. Modelers have been relatively successful (Keulegan, 1967) with such systems by treating them as reservoirs of nearly uniform water level at any instant of time which are filled and emptied by the flow through the inlet channel. The word "channel" implies that the governing dynamics are simplified to allow variations in water height and current in only one space dimension and time. This simplification, in turn, permits treating the highly nonlinear flows that are typical of such systems.

For the water body of interest to behave as a reservoir it is necessary that at any time, t, the water height, y, be nearly invariant with horizontal position within, i.e., that y = y (t) only. This, in turn, requires that the spatial extent L (the length, for example) of the water body be a small fraction of the effective tidal wavelength l, since it is on the latter length scale that spatial changes occur. For example, regions of ebb flow are typically separated from those of flood flow by distances along an estuary of about $l/2$. The wavelength may be estimated from $l = c\ T$ where c is the phase speed of the tidal disturbances and T the tidal period. Since the tides propagate as long waves, $c = (g\ h)^{\frac{1}{2}}$ where g is the acceleration of gravity and h the mean water depth. For the Herring River $h \cong 0.3$ m, so that $c \cong 1.8$ m/s or 6.5 km/h. Thus, with T = 12.4 hr we have $l \cong 80$ km. In contrast the present effective length L of the Herring River, the distance from the dike to High Toss Road culvert, is only about 2 km, or L/l 0.025. Even if the estuary upstream of High Toss Road became tidally active again, L would increase to only about 5 km so that L/l would still be quite small. In consequence, the phase difference between the tidal flow at the dike and that at the upstream end should be small so that, for example, high water should occur at High Toss Road only a short time after the dike, roughly a time TL/l later, about 20 minutes. Consequently, water height should be everywhere nearly independent of distance, or y = y (t) only.

Supporting evidence for this conclusion is shown in Figure 1. Water height relative to mean low water (MLW) was recorded during August 29, 1984 at hourly intervals at four tide staffs from staff #2 just upstream of the dike to #5 at High Toss Road. Note that at any given time during the tidal cycle the height is within a few centimeters at all staffs. High water occurs at about 1730 with y = 1.8m at all stations. Modest differences in y at low water are present and are associated with the tidally averaged or mean downstream slope required to produce a mean downstream flow or net ebb volume flux, as discussed further in section 4. However, since the main use of the model results will be to predict y at high water, the modest differences that do occur at low water are not important. Thus, use of a model which treats the estuary as a simple reservoir wherein y = y (t) only is well justified.

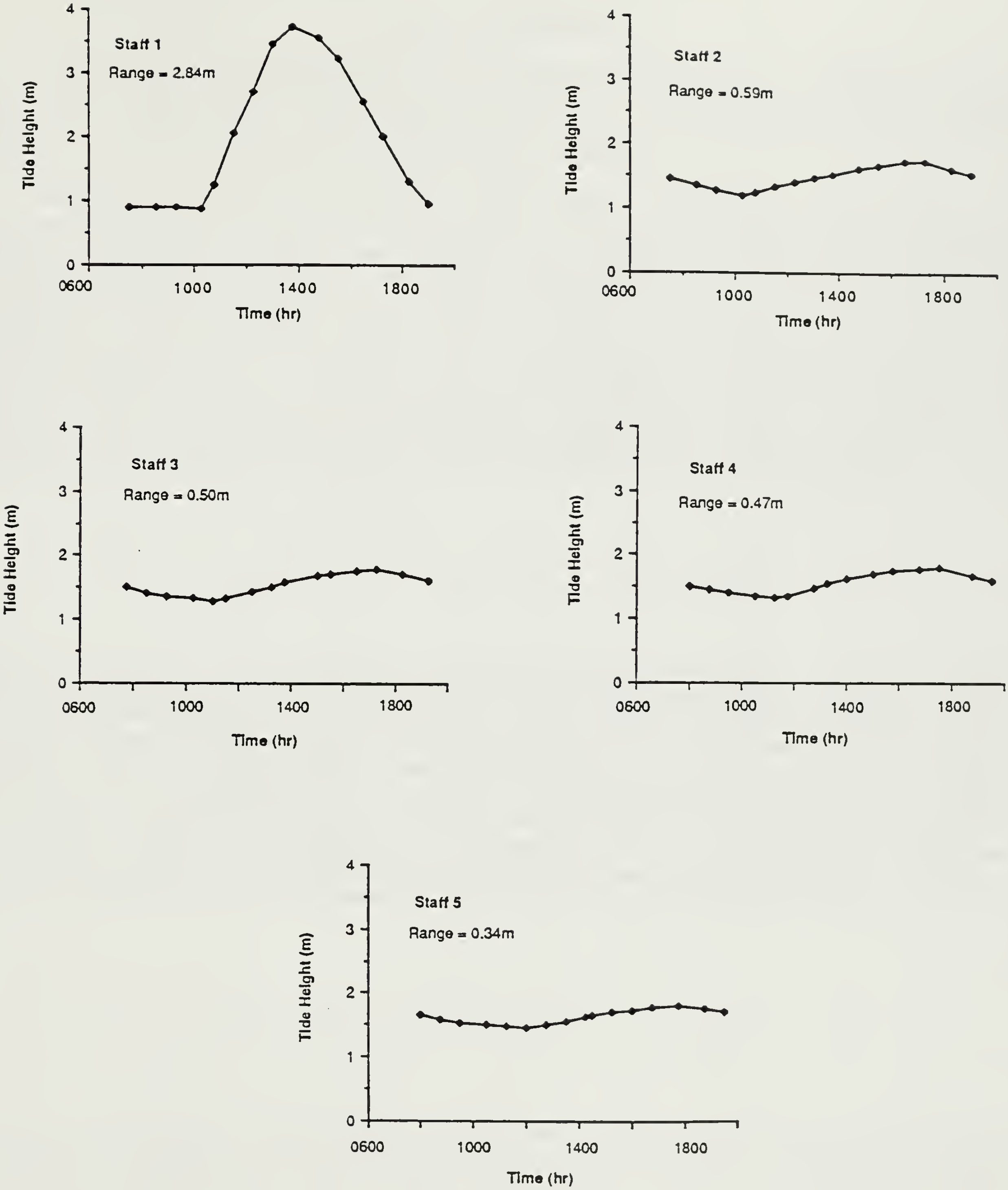

Fig. 1. Water height, y(t), observed at five stations in the Herring River on August 29, 1984. Tide staff 1 is downstream of the dike. Staffs 2-5 are from just upstream of the dike to High Toss Road. See Data Appendix 1 for location of the tide staffs.

MODEL FORMULATION

There are two principal parts to the model formulation: a momentum balance applied to the flow through the dike driven solely by the water height difference across it, and a volume conservation (continuity) equation which accounts for the accumulated volume in the reservoir.

Because the flow through the three dike channels is both short and intensely frictional, the inertial terms in the along-channel momentum equation may be neglected so that the balance is simply one between the horizontal pressure gradient produced by the water height difference across the dike and opposing friction applied at the channel surfaces. Consequently, for any given channel the volume flux Q_i (where i denotes the channel with i = 1,2,3 in the direction from east to west) is simply proportional to the square root of the height difference $y_h - y_r$ (where y_h is the height at the harbor or downstream side of the dike and y_r at the river or upstream side). In practice the proportionality coefficient is determined empirically. Manning's law is used (Linsley and Franzini, 1979) such that the momentum balance has the form

$$Q_i = \frac{A_i^{5/3}}{n_i \; P_i^{2/3}} \left[\frac{|y_h - y_r|}{L_d} \right]^{\frac{1}{2}} \frac{(y_h - y_r)}{|y_h - y_r|} \qquad (1)$$

Here Q_i (t) is the volume flux, positive toward upstream, passing through channel i at time t in m^3/s, n_i is Manning's coefficient for the channel, A_i the cross-sectional area in m^2 of the flow, P_i the wetted perimeter in m (the length of the intersection in the cross-sectional plane in contact with the solid surface), and L_d the channel length for the dike. A_i and P_i are simple functions of the average water depths in the channel, and hence are easily computed for given y_h and y_r, though time dependent. The Manning coefficient n_i, however, must be determined by calibration and must also be time dependent if a sluice gate is present in the channel. The empirical form used to account for the additional friction generated by a sluice gate, if present is

$$n_i = n_o + s \left(\frac{130 - G}{G} \right) C \qquad (2)$$

Here n_o is Manning's coefficient in the absence of any sluice gate effect, s is an empirical constant, G is the vertical gate opening in cm (maximum of 130 cm for the existing gate), and C is the water depth in meters on the harbor side between the water surface and the gate bottom, i.e., the height of the gate covered by water. The gate imparts additional friction only when it is fully or partly covered, i.e., when C>0; consequently, when C<0, C is taken at zero so that $n_i = n_o$. Note that for $G \rightarrow 0$ (gate closed) equation (2) gives $n_i \rightarrow \infty$ so that $Q_i \rightarrow 0$ by equation (1). Conversely, when the gate is fully open (G=130 cm), the gate has no effect on n_i.

In its present configuration the dike has only one sluice gate which is installed in channel 1, the eastern most. Both channels 2 (the center) and 3 (the western most) lack sluice gates but have tide gates in the form of flapper valves. These are forced shut by flood currents so that little volume flux passes then, but open during ebb current presenting negligible resistance. This mechanical action favoring ebb over flood currents in the river contributed massively to both flow restriction and to nonlinearity in the dynamics. Consequently, it is essential to model this action. In the model this is done simply by setting the cross-sectional areas A_2 and A_3 to zero for all phases of the flood cycle, apart from cases where the flow was simulated when one or both tide gates were assumed absent or held open.

The following physical dimensions were obtained from on-site measurements of the channels: average widths were 1.83 m, 2.19 m, and 2.10 m (in the order i = 1,2,3), average height of the floor above MLW was 0.53 m, and average maximum height from floor to ceiling was 1.75 m. The length L_o was 20.4 m. These values allowed computations of A_i and P_i for given y_h and y_r.

The second principal component of the model is given by the mass conservation or continuity equation applied to the river.

$$\frac{dV_r}{dt} = A_r \frac{dy_r}{dt} = Q + Q_f \qquad (3)$$

Here V_r (t) is the volume of water in the river. Its time rate of change is simply the horizontal area of the water surface A_r (t) times the rate of surface rise. The change in volume is produced solely by the total inflow through the dike $Q = Q_1 + Q_2 + Q_3$ and the freshwater inflow Q_f. The latter, however, is neglected, since its typical value, 0.25 m^3/s, is small compared to typical values of tidal flux Q, about 5.0 m^3/s, and maximum flux Q often above 10 m^3/s. Consequently, the right hand side of equation (3) is computed from summing the three components Q_i from equation (1).

For a simple reservoir A_r is constant. For the Herring River, however, A_r is a strong function of water height y_r with rising levels permitting the water to spill outward first within the channels of the estuary and subsequently beyond these to the marsh surface. By using bottom profile data for the existing main channel and elevation data for the wetlands above the channels a piecewise linear function for A_r (y_r) was developed. For $y_r \le 1.8$ m (MLW) A_r has a gradient $dA_r/dy_r = 1.07 \times 10^5$ m^2/m and reaches 6.34×10^5 m^2/m at y_r= 1.83 m. At this height the area begins to widen more rapidly as y_r increases above the level of the wetland now present downstream of High Toss Road. For 1.8 m < y_r ≤2.6 m the gradient was 9.91×10^5 m^2/m with A_r reaching 31.1×10^5 m^2/m when y_r = 2.6 m. This latter height marks the average height of the upper part of the basin, including the three principal arms called Bound Brook, Duck Harbor, and Pole Dike Creek, and Mill Creek. This would appear to have been the surface of the former salt marsh in the nineteenth century prior to the original dike's installation. As this height is reached water would spread over the old marsh surface until it reached the edge of the upland, roughly where y_r = 3.0 m.

For $2.6 \text{ m} \leq y_r < 3 \text{ m}$ thus, dA_r/dy_r was taken as constant at $60.0 \times 10^5 \text{ m}^2/\text{m}$ with A_r reaching $121.0 \times 10^5 \text{ m}^2/\text{m}$ at $y_r = 3.0$ m. For yet greater heights A_r was kept at this value because the slope of the upland is so great as to make dA_r/dy_r negligible in comparison. Thus, from $y_r = 1.2$ m to 3 m the area as modeled changes from 4.21×10^5 to $121.0 \times 10^5 \text{ m}^2/\text{m}$, roughly a 29 fold increase. As equation (3) indicates, the strong rise of A_r with y_r sharply reduces the water height that would otherwise occur in a simple, vertical-sided reservoir.

The model assumes that High Toss Road is not a barrier for $y_r \geq 2.6$ m. However, the actual elevation of High Toss Road averages 3.0 m, therefore, as the high marsh surface floods at $y_r \geq 2.6$ m flow to marsh areas upstream of High Toss Road will be greatly reduced and excessive flooding of the lower basin will occur. For model predictions of $y_r \geq 2.6$ to be realized, High Toss Road from Griffin Island westward to the upland must be removed, or at a minimum, frequent bridged openings along the road must be made. These openings should encompass 30-50% of the length of High Toss Road along this expanse.

Equations (1) and (3) are solved numerically for the Q_i (t) and y_r (t) given the harbor tide y_h (t), for example, as a simple harmonic (sinusoidal) function of given amplitude and period, or as a data time series from observations. Only an initial value of y_r is needed to begin calculations. Then the initial values of the Q_i are computed from equation (1) for subsequent use in (3). Simple numerical integration of equation (3) then gives y_r at the next time step $t + \Delta t$. Where observations are available the initial value of y_r is, of course, known and subsequent values can be compared with model calculations. Such calculations are discussed in the next section. If instead, the response is sought to a harmonic variation for the harbor tide of repeated but stationary nature, any initial guess for y_r is practical. After the computations are continued through two tidal cycles the flow "forgets" the initial guess because of the strong friction and a stationary, i.e., repeated, response for y_r is found thereafter. This technique is used in section 4 for exploring the response of the estuary to harmonic forcing by the harbor when different channel configurations are present, for example, absence of tide gates.

CALIBRATION AND TESTING

Three sets of detailed observations of water height were available for model calibration and testing, each for roughly a semi-diurnal tidal period. Heights were observed at intervals of 1/2 hour or less both at tide staff #1 just downstream of the dike on the harbor side and at #2 just upstream on the river side on August 21 and December 4, 1984 as well as on May 17, 1985. These data were used to perform calibration trials in order to select optimal values of the friction parameters n_o and s and subsequently to test the model predictions for y_r (t) against the data from tide staff #2. For all three observation periods both tide gates were operative but the sluice gate heights differed with G = 130 cm on December 4 (fully open), 61 cm on May 17, and 51 cm on August 21.

Since the sluice gate was fully open on December 4, it would have had a negligible effect with $n=n_o$, as equation (2) indicates. Consequently, this case offered a chance to select an optimal value of n_o. This selection was conducted by making successive model runs with differing values of n_o between which the root mean square (rms) difference (Δy_r) between measured (y_m) and computed river (y_r) heights were compared. (This difference definition was used because it avoids cancellation of differences of opposite sign in computing a mean difference, and thus helps to better define model performance.) For December 4 the optimal value of n_o was found to be 0.090 with Δy_r = 0.06 m. The computed and measured heights are plotted *vs* time in Figure 2. As the rms difference indicates, y_r and y_m are quite close at all phases of the tide. In fact, no objective improvement in the agreement is physically realistic, since wind induced height fluctuations within the estuary (which are likely present in the data but not accounted for by the model) would typically be a few centimeters. Predicted high water, the maximum computed for y_r, was 1.98 m *vs* 1.95 m measured. The time of the predicted high was t = 5.0 hr or 3.0 hr after the harbor tide reached its high, while the time of the observed high was 2.5 hr after the harbor. The predicted low was 1.30 m *vs* 1.31 m measured. Thus, the predicted range was 0.71 m *vs* 0.64 m measured.

Figure 3 shows the results for May 17 where n_o = 0.090 again and s = 0.013, the optimal value. These values for the friction parameters were used in all subsequent computations. The rms difference was poorer at 0.09 m, mostly attributable to an early rise in the measured time series y_m beginning at about t = 1 hr. This rise is anomalous, since pure tidally driven flow could not develop a rising surface until after the harbor tide exceeded the river tide, as in the model results. Again some wind effects or other outside disturbances were likely at work. The agreement is, nevertheless, sufficiently good. Predicted high water was 1.80 m *vs* 1.83 m measured, while low water was 1.24 m *vs* 1.26 m measured, or a range both predicted and measured of 0.56 m.

Results are shown in Figure 4 for August 21 when the sluice gate opening was G = 51 cm. This run should give a good estimate of the model's predictive skill, since the same friction parameters as before were used while the harbor tide characteristics and gate opening were different than the previous two cases used for calibration. The rms error was 0.07 m, predicted high 1.78 m *vs* 1.72 m measured, predicted low 1.33 m *vs* 1.21 m measured, and predicted range 0.45 m *vs* 0.51 m measured.

In summary, the model testing indicates that, at least for the range of river heights experienced of about 1.22 m to 1.98 m, the model has sufficient skill to be useful as a predictive tool. For higher river heights, as would be the case when one or both tide gates were held open, for example, no corresponding measurements are available, so that the model predictions for higher stages discussed in the next section must stand on their own.

PREDICTIONS FOR ALTERED DIKE CONFIGURATIONS

To investigate the predicted effect of altering the configuration of the present dike, model runs were made where the flow was driven by a simple harmonic function for the harbor tide given by

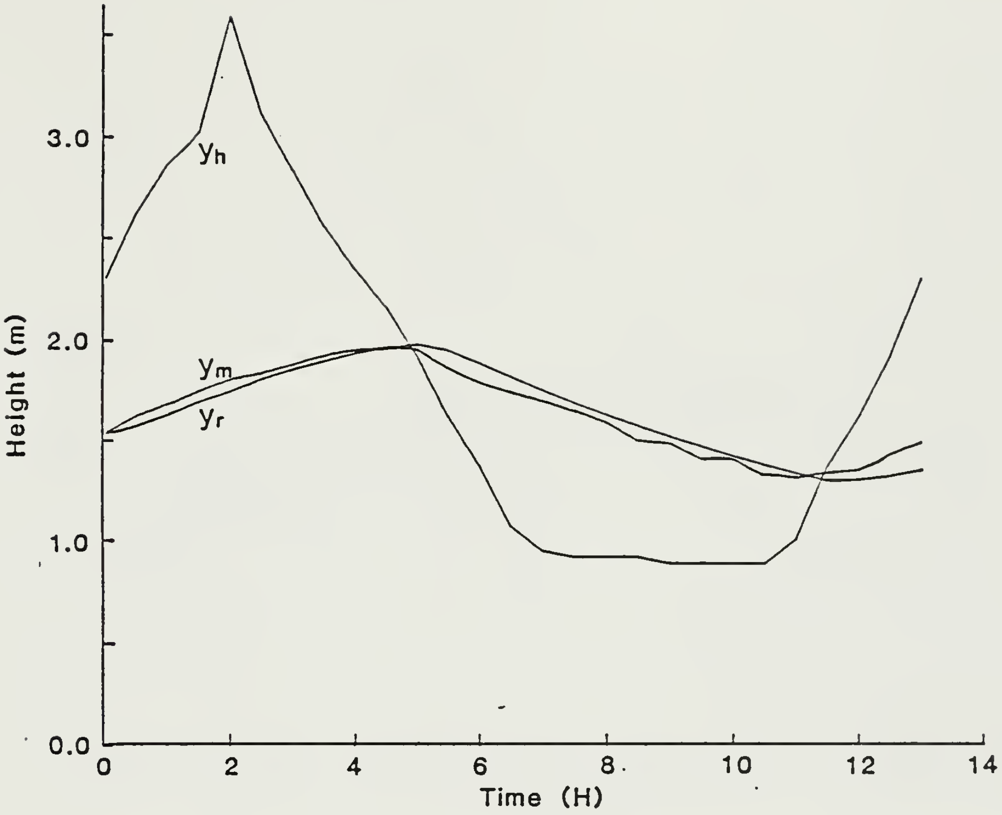

Fig. 2. Water heights for December 4, 1984. y_h is the measured harbor tide, y_m the measured river tide and y_r the computed river tide. Sluice gate opening was G=130cm (Case 3). The root mean square difference, Δy_r, was 0.06 m.

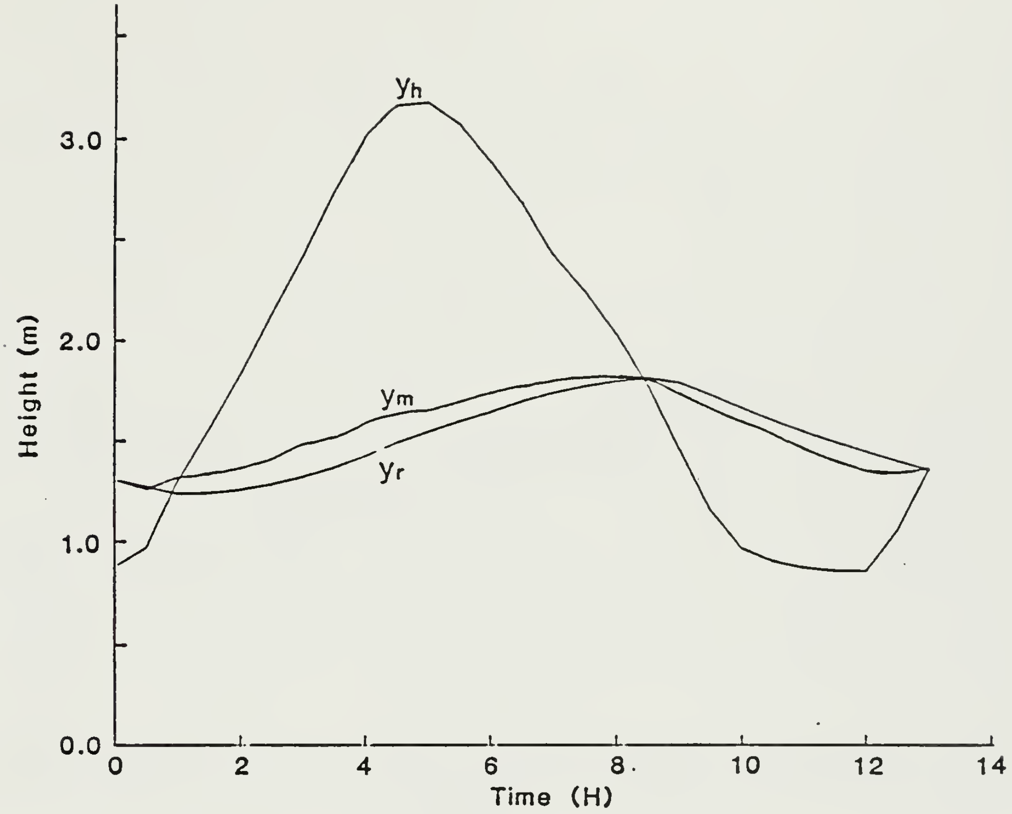

Fig. 3. Water heights for May 17, 1985. The rms difference $\Delta y_r = 0.09$
G = 61 cm (Case 2).

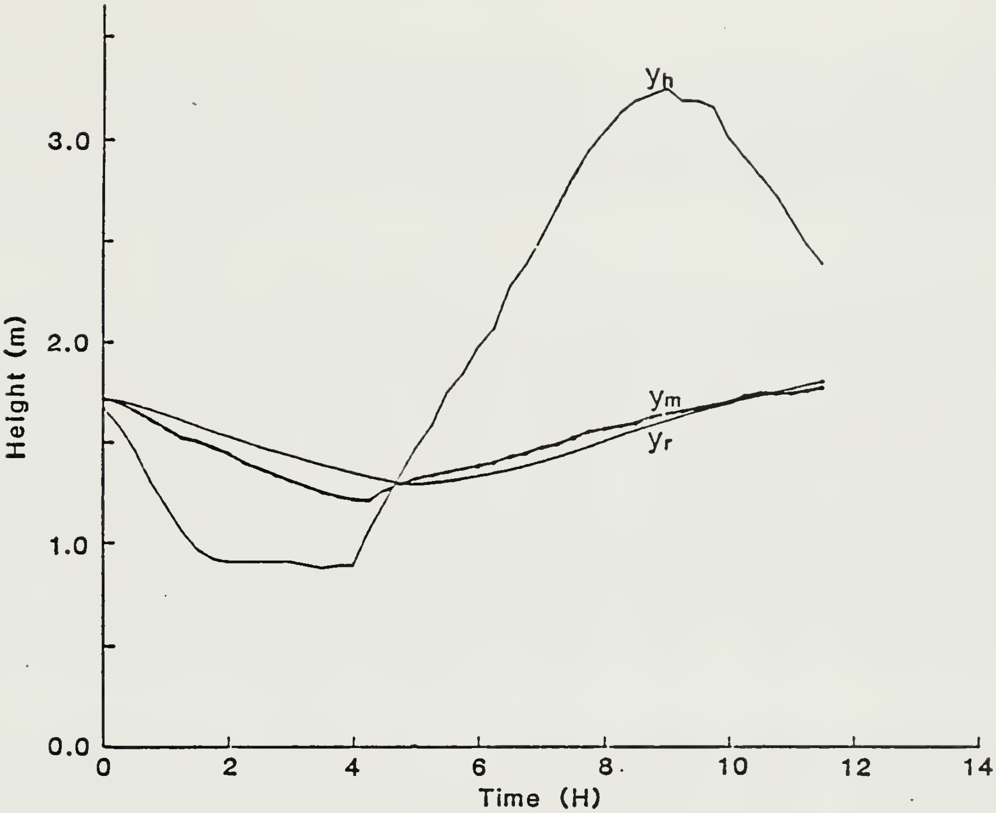

Fig. 4. Water heights for August 21, 1984. The rms difference Δy_r = 0.07 m, G = 51 cm (Case 1).

$$y_h(t) = a_h \sin(2\pi\, {}^t/T) + \bar{y}_h \qquad (4)$$

where a_h is the tidal amplitude (half the range), $\bar{y}_h$ the mean height, and T the period. For all runs a_h was 1.19 m (or a range of 2.38 m, a typical value for Wellfleet Harbor), $\bar{y}_h$ was 1.83 m, and T was 12.42 h, the period of the M_2 tidal constituent, the dominant one. The model was run for three full periods. A stationary state was reached after two periods and the results shown below are taken from the third period.

Nine different cases corresponding to different dike configurations were treated. Cases 1-3 had both tide gates operative, but the sluice gate at various openings (i.e., G = 51 cm, 61 cm, 130 cm). In case 4 only the central (channel 2) tide gate functioned; the other (channel 3) tide gate was kept open, as was the sluice gate. For case 5 both tide gates were inoperative and the sluice gate was again fully open; thus, this configuration has the least possible dike restriction for the flow. Cases 6 through 9 then gave the response to the same harbor tide, but with sluice gates installed in all three channels in place of two tide gates and one sluice gate, as now. Case 5, in effect, shows this installation with all sluice gates fully open (G = 130 cm), while cases 6 through 9 provide results for gate openings of 120 cm, 76 cm, 51 cm, and 25 cm, respectively. Results for the nine cases are presented in Table 1, while cases 3-9 are plotted in Figures 5-11.

The dike configurations for cases 1-3 were the same as for the previously discussed calibration runs. Case 3 is as the December 4 run (Fig. 2). Then, the harbor tide range was 2.71 m *vs.* 2.38 m for the nine cases. Thus, the model results for December 4 should have been greater for high water level and range and lesser for low water level. They were, with corresponding values for high water of 1.98 m *vs.* 1.93 m in case 3, for range of 0.68 m *vs.* 0.55 m, and for low water of 1.30 m *vs* 1.38 m. Case 3 may thus be regarded as the standard response for the given simple harmonic harbor tide of equation (4) for the dike in its present configuration.

For estimates of salinity variations along the estuary it is useful to know the total value of the tidal volume passing into and out of the estuary for a given period. This volume exchange is often termed the volume of the tidal prism. Table 1 lists values for both the ebb and flood portions of the M_2 cycle for the nine cases. These are always close in value, though different in sign with positive values corresponding to flow into the estuary (flood phase). The difference is always negative, of the order 0.57×10^4 m^3, and represents the Eulerian (fixed point) mean volume exchange per cycle. Corresponding to it dynamically is the mean downstream surface slope discussed in section 2. For an estuary with no fresh water input, as in the model here, the mean volume exchange computed by following the fluid motion, the Lagrangian mean, must vanish, since there clearly is no net change in fluid volume within the estuary when averaged over a cycle for a pure harmonic driving force, as here. The difference between the Lagrangian mean and the Eulerian mean, equal to $-V_f - V_e$ here, is the Stokes volume exchange (Longuet-Higgins, 1969), that is, the transport carried into the estuary by the propagating tidal wave which here originates in the harbor. In the present case the upstream Stokes volume

Table 1. Model results for nine dike configurations.

Case	Configuration	High (m)	Low (m)	Range (m)	V_5^e ($10^5 m^3$)	V_5^f ($10^5 m^3$)
1	1 sluice gate, G=51 cm 2 tide gates	1.81	1.32	0.49	-0.82	0.79
2	1 sluice gate, G=61 cm 2 tide gates	1.85	1.34	0.51	-0.88	0.85
3	1 sluice gate, G=130 cm 2 tide gates	1.93	1.38	0.55	-1.02	0.99
4	1 sluice gate, G=130 cm 1 tide gate	2.20	1.62	0.58	-1.81	1.76
5	no gates	2.33	1.80	0.54	-2.34	2.25
6	3 sluice gates, G=102 cm	2.32	1.77	0.55	-2.28	2.20
7	3 sluice gates, G=76 cm	2.29	1.74	0.55	-2.16	2.10
8	3 sluice gates, G=51 cm	2.23	1.69	0.55	-1.90	1.85
9	3 sluice gates, G=25 cm	2.11	1.60	0.52	-1.39	1.36

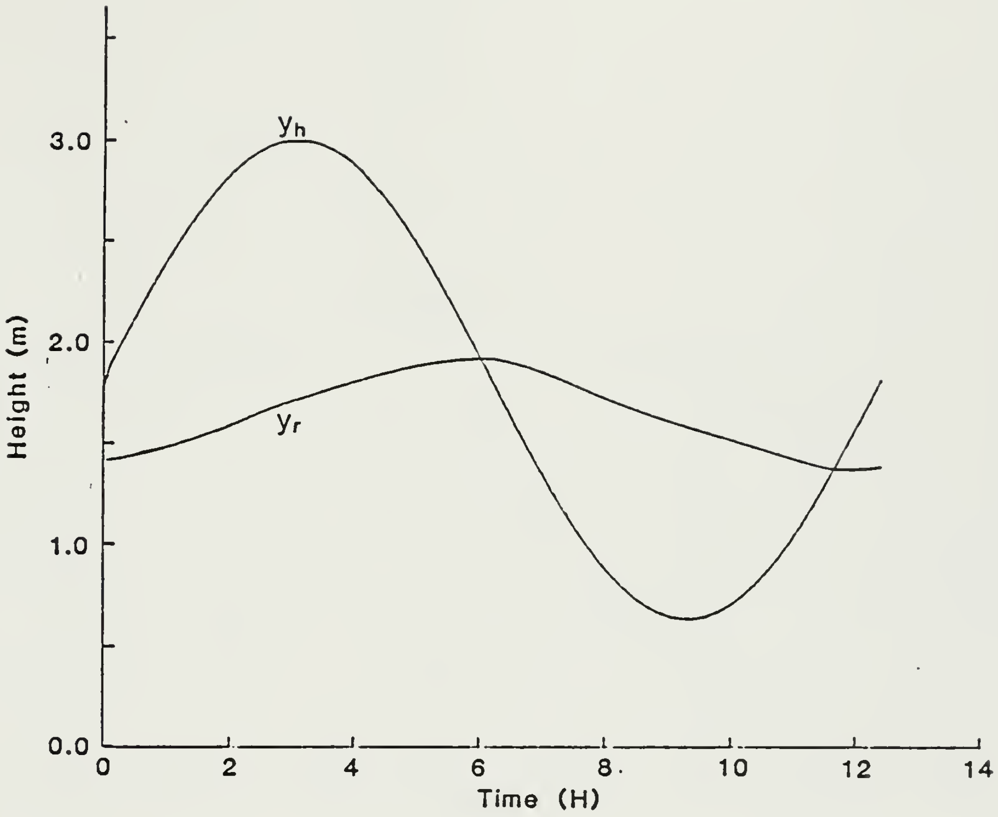

Fig. 5. Case 3. y_h is generated by the single harmonic of equation (4). y_r is the model response for the river with both tide gates operative, but the sluice gate fully open (G = 130 cm).

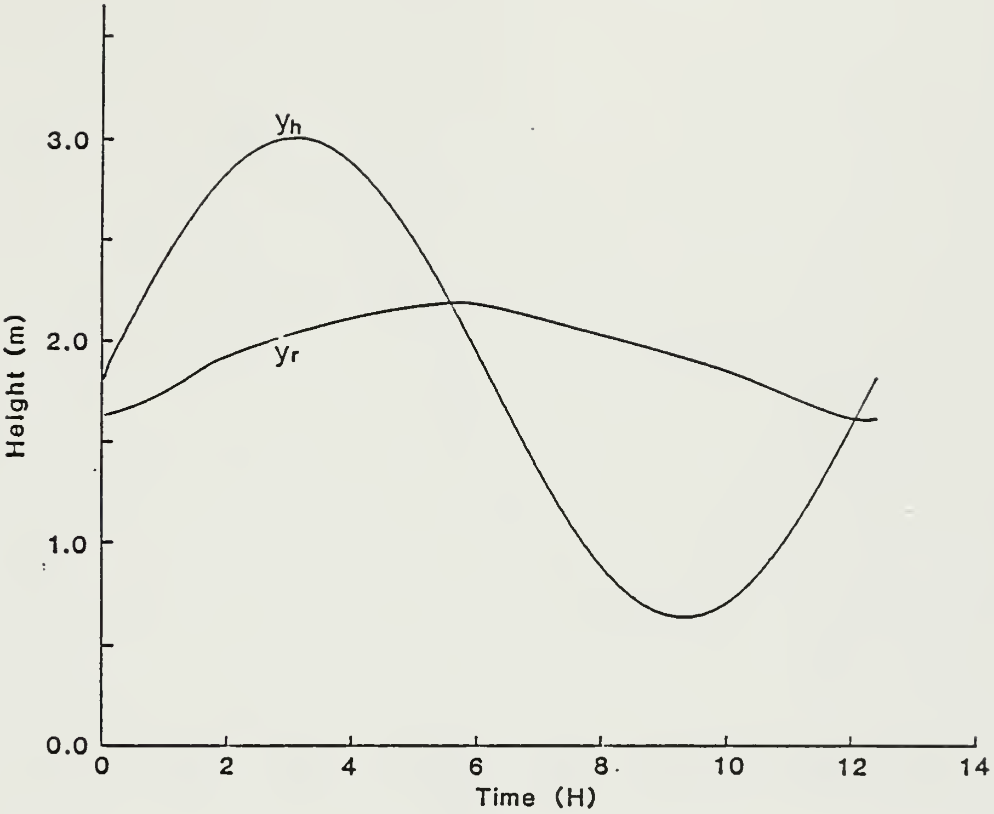

Fig. 6. Case 4. As in Fig. 5, but with only the center channel tide gate operative.

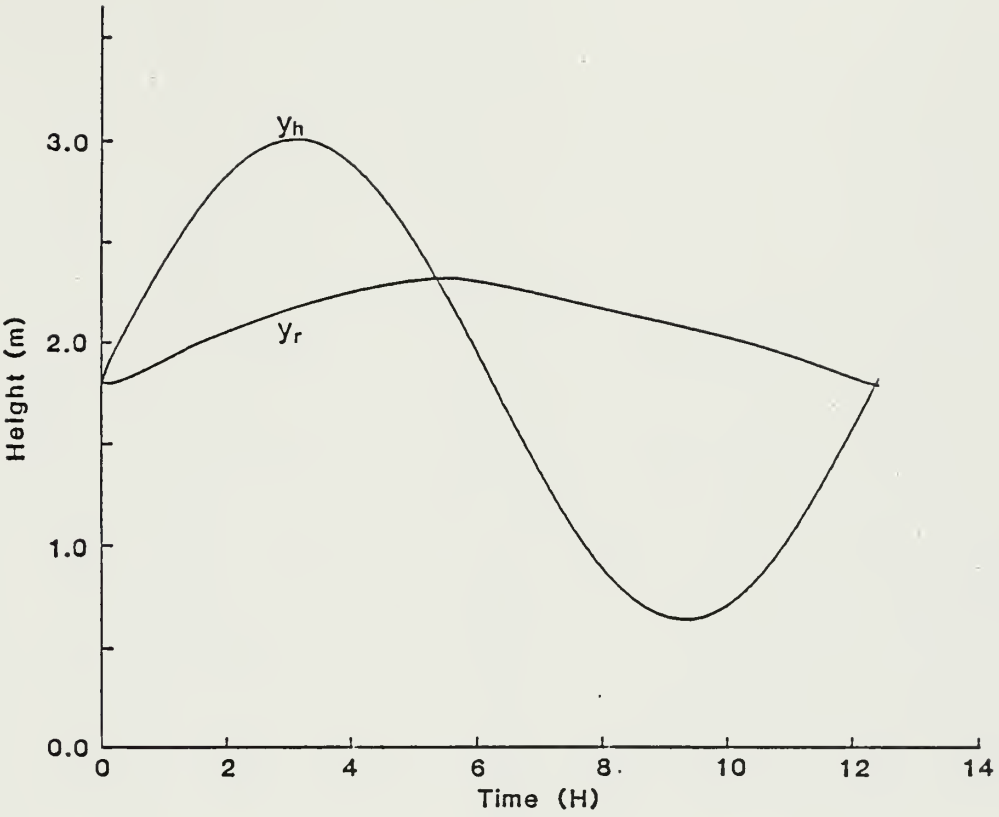

Fig. 7. Case 5. As in Fig. 5, but no tide gates operative.

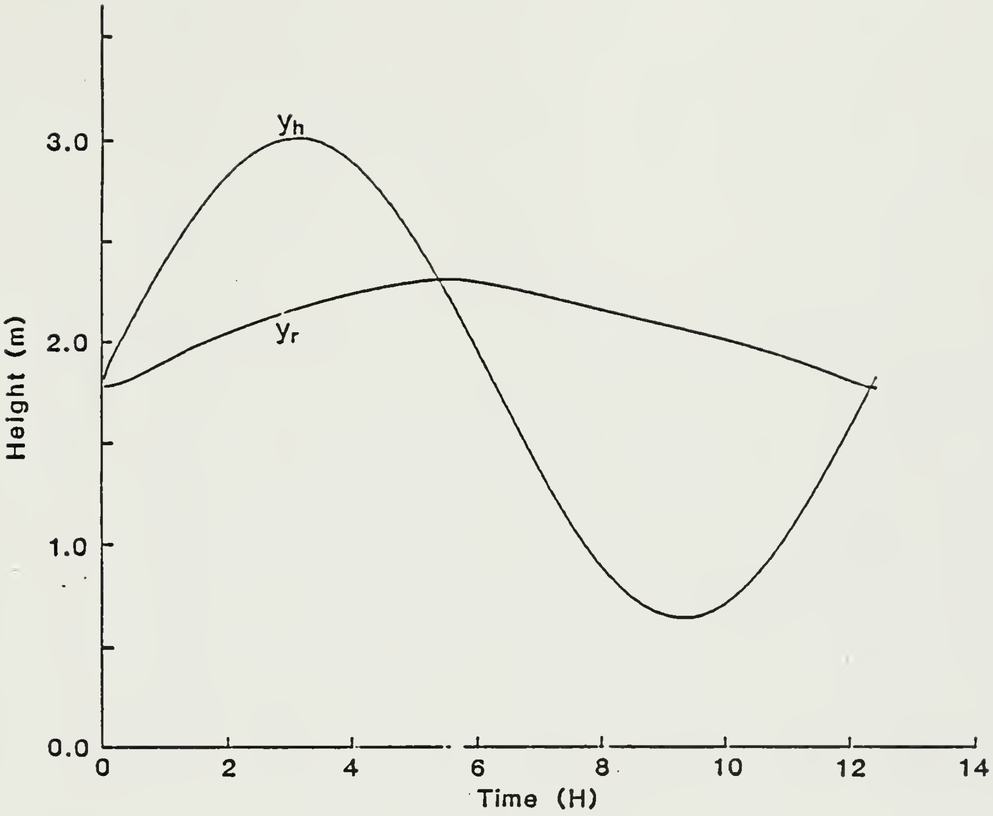

Fig. 8. Case 6. All three channels have sluice gates. G = 102 cm.

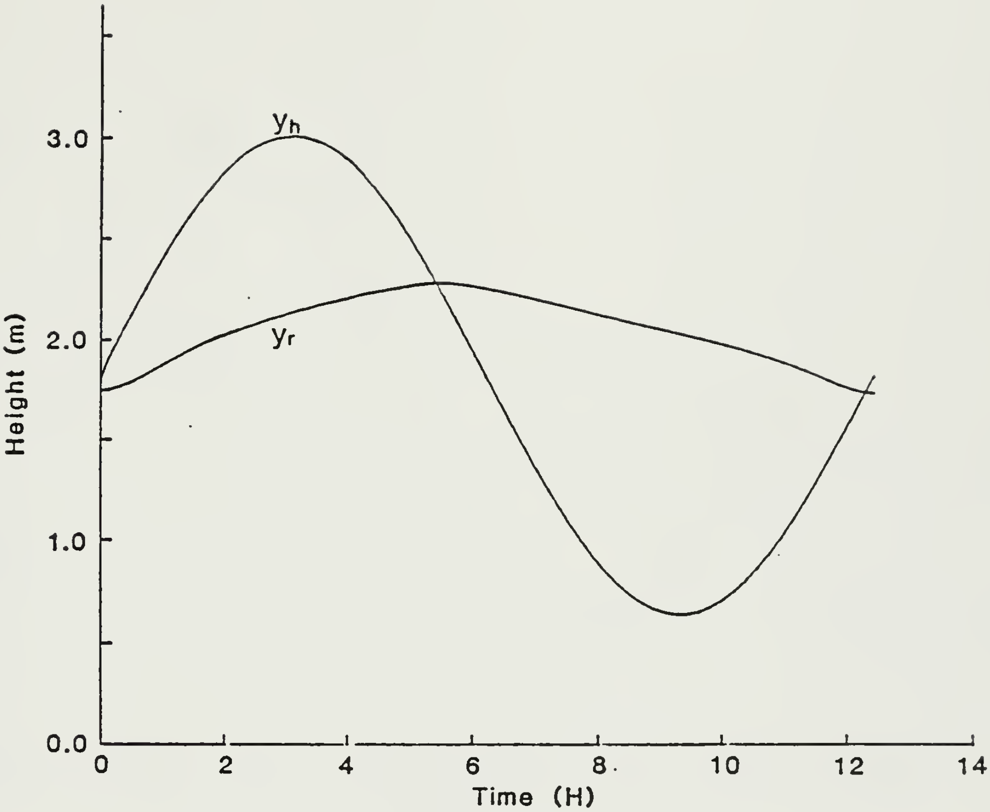

Fig. 9. Case 7. Three sluice gates with G = 76 cm.

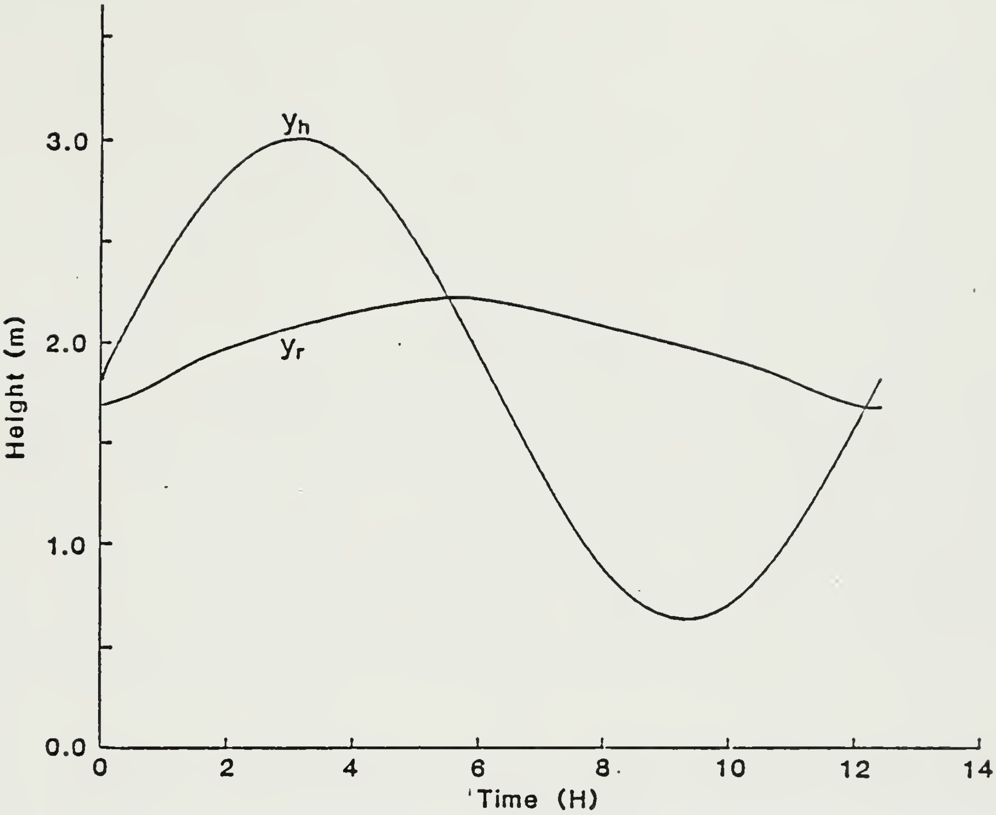

Fig. 10. Case 8. Three sluice gates with G = 51 cm.

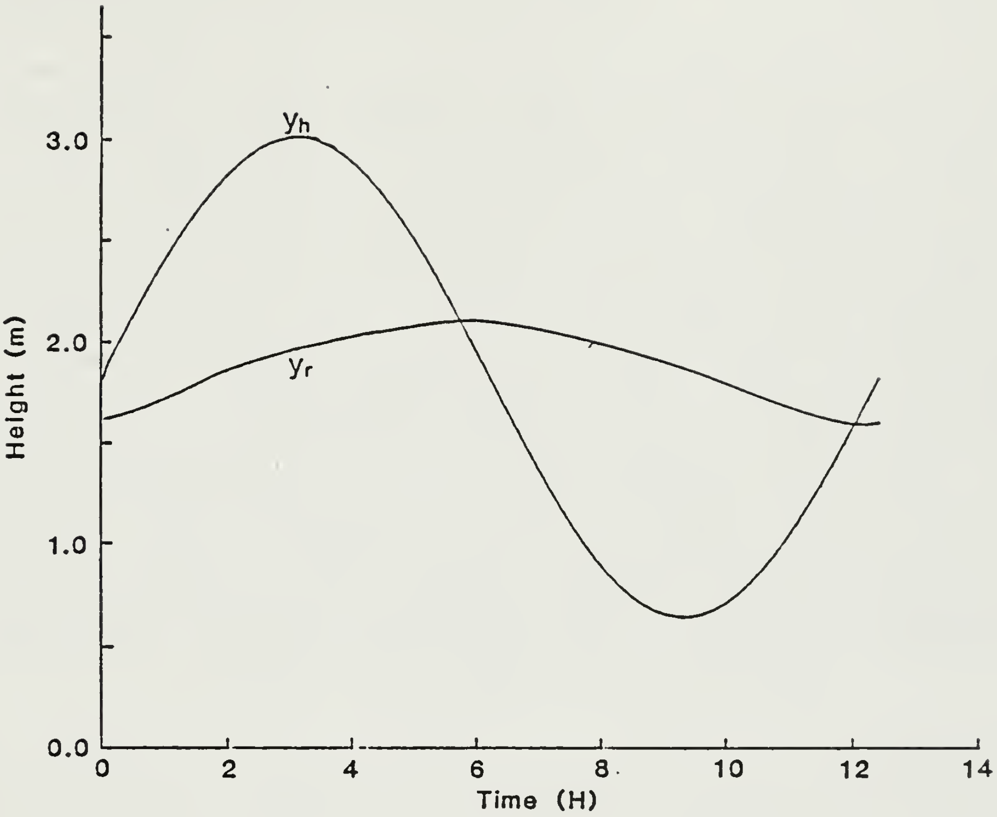

Fig. 11. Case 9. Three sluice gates with G = 25 cm.

exchange simply cancels the downstream Eulerian mean volume exchange to give zero Lagrangian exchange. As one would expect, lesser dike flow constriction corresponded to greater magnitudes in tidal volume exchange (V_e or V_f) with the maximum magnitude being about 2.3 x 10^5 m^3 for case 5 (least constriction) and the minimum being only about 0.80 x 10^5 m^3 for case 1.

Against the standard of case 3 we may compare the following six. Case 4 shows the predictions when the channel 3 tide gate is removed. High water increases to 2.20 m and the tidal volume exchange to about 1.8 x 10^5 m^3, nearly double case 3. As a comparison of y_r (t) in Figure 5 *vs.* Figure 6 shows, the essential effect of removing one tide gate is to increase the water level in the river by about 0.24 m over the whole cycle; the range, in contrast increased little, only by 0.03 m. This general trend continues for case 5 where all channel restrictions are removed, so that this case forms a second standard, one of minimum possible flow restriction for the existing dike. The water level is about 0.40 m higher throughout the cycle than in case 3 and the tidal volume exchange is over twice as large, about 2.3 x 10^5 m^3. The range, conversely, actually drops to 0.54 m, less than for both case 3 and 4. These results follow from the increasingly large horizontal area A_r available in the estuary as the restrictions at the dike diminish. As the mean river water level over a cycle increases, more water from the increased volume exchange is diverted laterally to flood the wetland surface (above 1.8 m, but below 2.6 m). Consequently, the range actually falls and with it the level of high water, because at high water the increased storage area available more than compensates for the tidal volume increase. This highly nonlinear mechanism is quite effective in reducing the incremental levels of high water as dike restrictions are removed.

In case 6, sluice gates with openings all at G=102 cm are present for all three channels. As Table 1 shows, modest reductions in high water level and volume exchange develop as compared to case 5 where there were no restrictions (or equivalently, where all three sluice gates were fully open to G=130 cm). These differences intensify gradually as the gate openings are reduced successively in cases 7,8, and 9 to 76 cm, 51 cm, and 25 cm, respectively. Again, the major effect of adding flow constriction is to reduce the water level almost uniformly over the cycle so that the range changes little, while the volume exchange falls monotonically. Between case 5 (G=130 cm) and case 9 (G=25 cm) the water level drops about 0.21 m while the volume exchange falls from about 2.3 to 1.4 x 10^5 m^3, or nearly by half. The net restriction induced by the three sluice gates at G=51 cm (case 8) is nearly the same in terms of water level and volume exchange as for the dike with only one tide gate (case 4). The dike with both tide gates, as now, (case 3), is even more restrictive than three sluice gates at G=25 cm (case 9). Thus, in the present dike configuration the two tide gates are much more effective than the single sluice gate as a barrier to tidal exchange, even though they impose no additional flow impedance during ebb. This results because they greatly reduce the flood volume entering the estuary so that there is accordingly less ebb flow as well, despite the low resistance to ebb current. If there were three tide gates, of course, no tidal exchange at all would occur, since no volume could enter during flood.

In these nine cases the highest river water level predicted was 2.33 m for high water in case 5 (no restrictions). This is 0.40 m above the high water value found, for standard case 3. The modest size of this increment is largely a result of the sharp increase in horizontal area A_r available at the higher

water levels. Between the lowest low water, 1.38 m for case 3 and the highest high, 2.33 m for case 5, A_r increases from 1.45 to 6.91 x 10^5 m², or by a factor of 4.77. Because of this increase, the model predicts that, even with all dike channel restrictions removed, for an M_2 tide of 2.38 m range no water would flood onto the high marsh (average height 2.6 m MLW). This finding may even be conservative, since that volume of water which would pass upstream through the culvert beneath High Toss Road during flood is reckoned by the model to be restricted instead to the estuary downstream.

Another management alternative to consider would be complete replacement of the dike structure with a bridge. Evaluation of tide heights under such an alternative is beyond the scope of this model. However, it can be assumed that tides upstream of Chequesett Neck Road would approach harbor tides with a bridge of adequate dimension (e.g., 15-20 m opening). Of course some restriction would still occur from the road (a filled causeway). Assuming a typical harbor tide range of 2.38 m, high water would be 3 m and low water 0.6 m. This high water elevation is equivalent to the mean elevation of High Toss Road.

PREDICTIONS FOR A "100 YEAR" FLOOD

In the previous section model predictions were discussed for different dike configurations with the harbor tide driven by a single harmonic constituent of 2.38 m range. In this section different configurations are again considered but now the harbor tide will be simulated by the February 1978 storm water levels. This storm, a violent wintertime northeaster, is often used for planning purposes as one typical of those with a 100 year recurrence, or "100 year" storm (Federal Emergency Management Agency, 1984). For model application the tidal heights for Wellfleet Harbor (y_h) were taken from available hourly heights at Boston (corrected to MLW) from 0400 hr on February 6 to 1700 hr on February 7, very nearly 3 M_2 periods. Because of the large scale nature of both tides and storm surges, the actual values in Wellfleet Harbor, though unmeasured, were very likely within 0.3 m of Boston at all times. The highest water level used was y_h = 4.51 m MLW at 1000 hr on February 7.

Figure 12 shows the results for the dike in its present configuration with two tide gates operative and the sluice gate set to an opening of G=61 cm. Roughly three tidal cycles are shown beginning at 0400 hr on February 6. Each successive high for y_h exceeded the last, and, in consequence, the computed highs for y_r do the same with a peak height of 2.08 m reached at 1500 hr on February 7, or 5 hr after the harbor tide peaked.

In contrast Figure 13 shows the results for the same harbor tide but with the dike channels fully open. The water levels in the estuary are appreciably higher with the peak of 2.76 m occurring at 1400 hr on February 7. At this level, the highest computed for any of the model runs, the high marsh upstream of High Toss Road would be flooded. This assumes that High Toss Road were removed, or at least, that adequate openings for surface flow into the upper basins were created. Although not modelled, with the road remaining, water would be backed up in the lower basin to an elevation > 2.76 m. With the assumption that High Toss Road were removed, still higher levels (y_r > 2.76 m) would require considerably greater harbor water levels, since at this river level the rate of increase of high marsh area with river height is so great (nearly 61 x 10^5 m²/m).

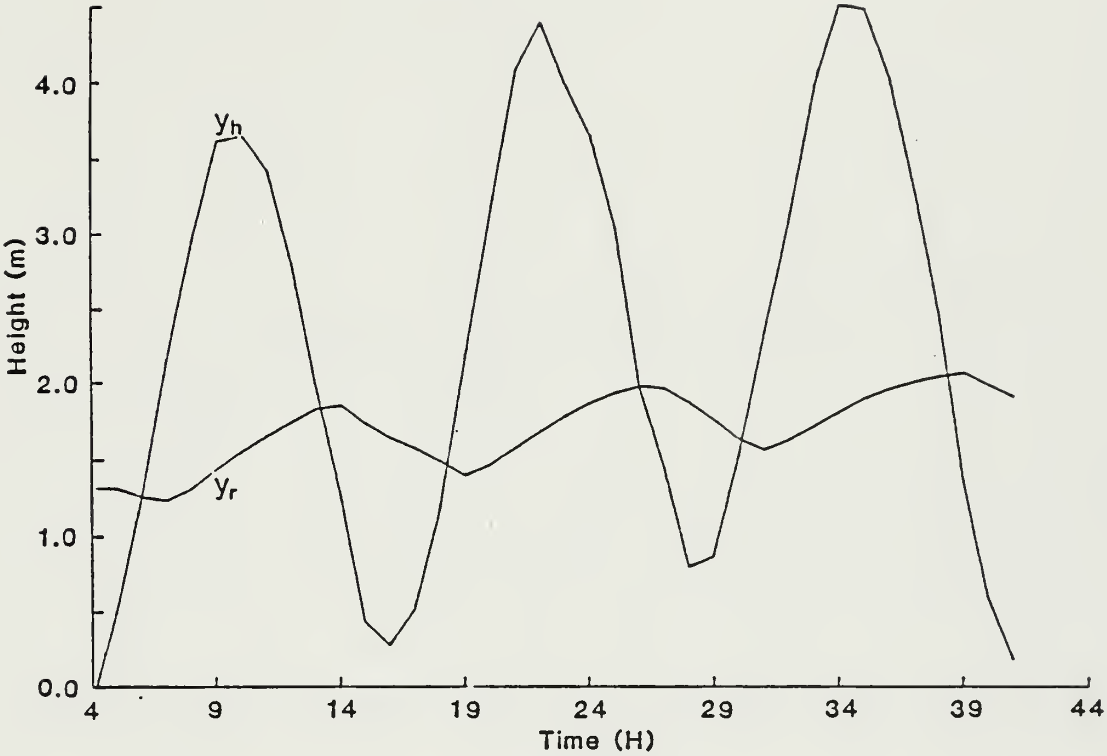

Fig. 12. Predicted river water height for the February 1978 storm for the dike with two tide gates and one sluice gate at G = 61 cm. Time = 0 corresponds to midnight on February 6.

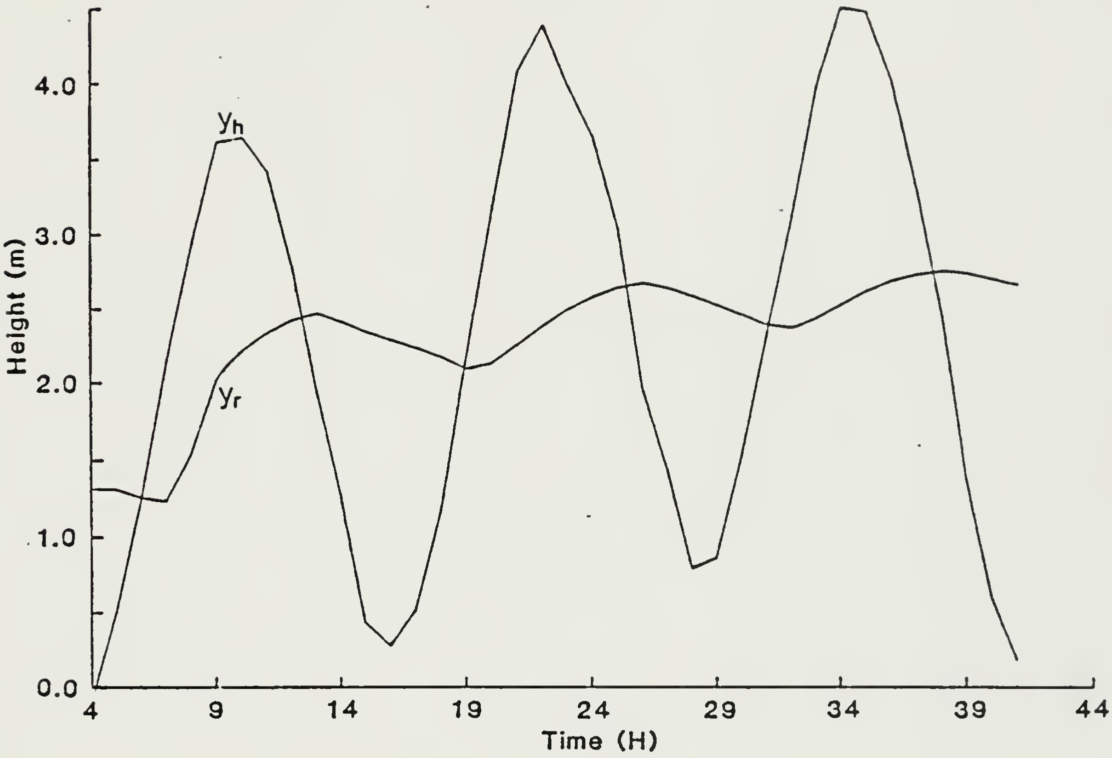

Fig. 13. As for Fig. 12, but all gates open.

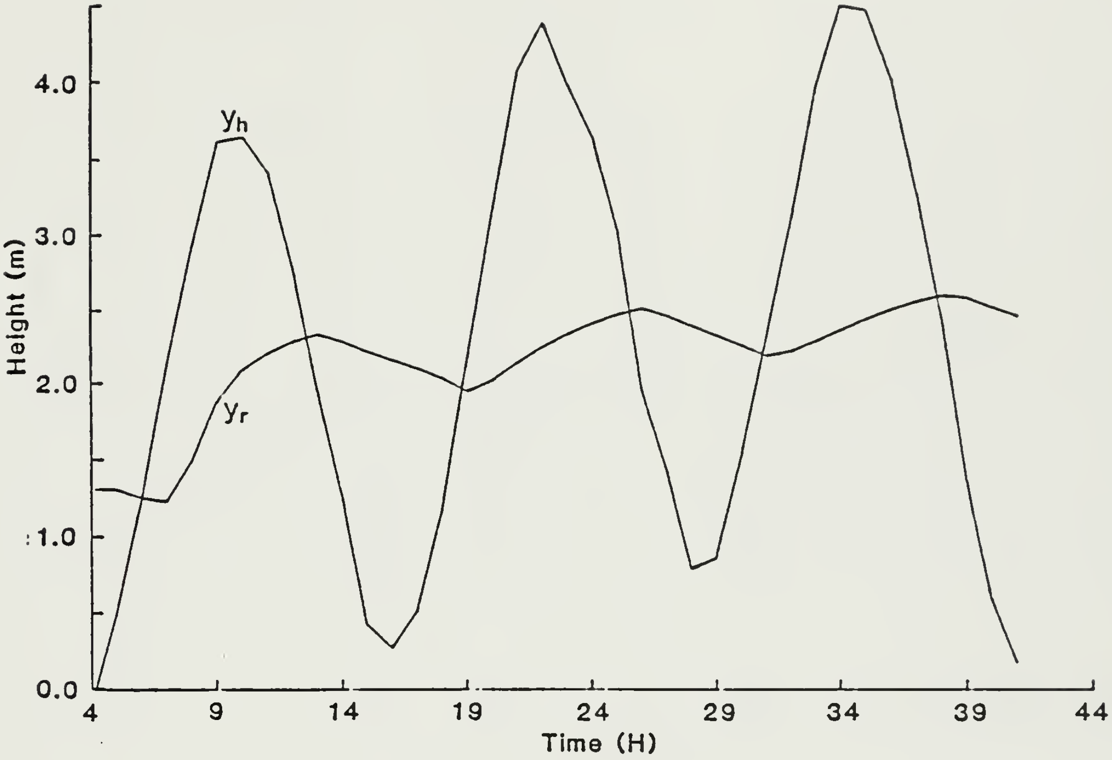

Fig. 14. As for Fig. 12, but three sluice gates at G = 61 cm.

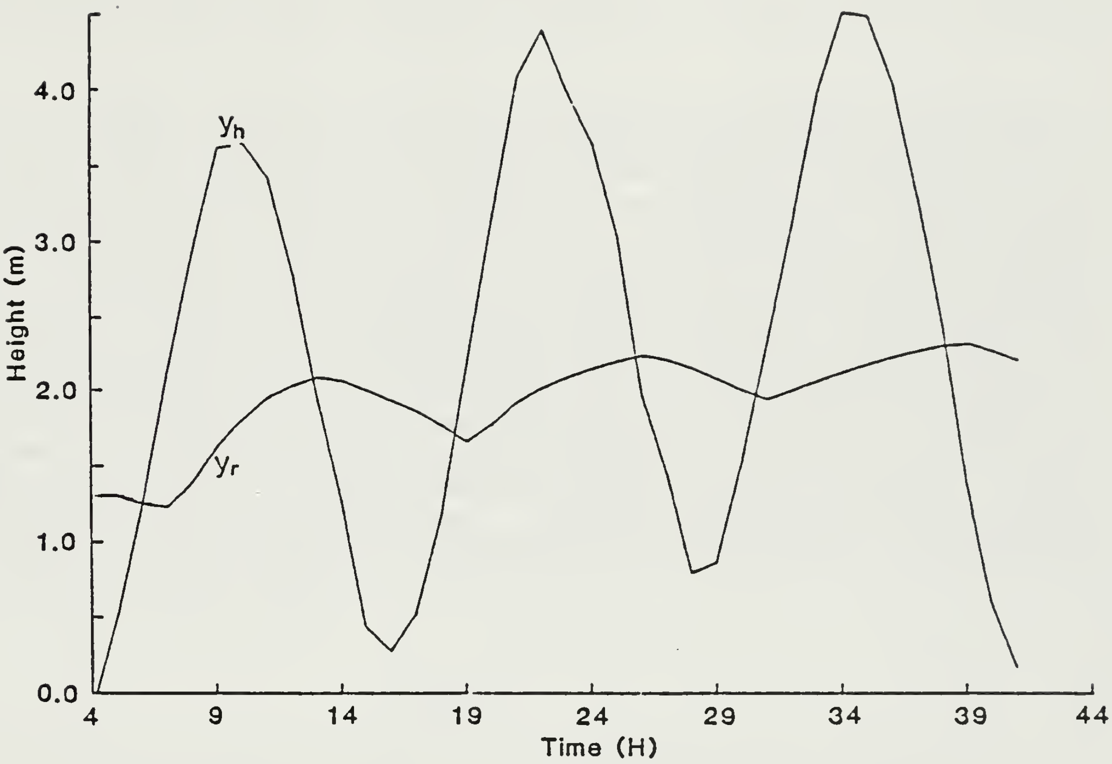

Fig. 15. As for Fig. 12, but three sluice gates at G = 25 cm.

Figures 14 and 15 show the effects of adding three sluice gates for the same storm. At G=61 cm the maximum height is reduced to 2.62 m, about 0.15 m reduction from the unrestricted case, while at G=25 cm it is reduced to 2.34 m, about a 0.43 m reduction, but still about 0.27 m above the high for the case for two tide gates (Figure 12). As we saw in the last section, with sluice gates the opening must be rather small to provide equivalent restriction to two tide gates.

The model results indicate that with the dike operating with minimal restriction, i.e., with no tide gates and the sluice gate fully open (case 5), the highest water level reached in the river for the February 1978 storm would have been about 2.7 m. What would this level have been if the entire dike structure had been absent, not just the gates? A conservative or upper bound estimate would be that y_r would have peaked at about the level of the harbor tide with little time lag, i.e., would have reached about 4.6 m MLW at or near 1700 hr on February 7. Then the entire estuary would have been flooded with the high water level some 2.0 m above the level of the high marsh surface and with the water line following the relatively steep slopes of the upland that surround the estuary basin. This estimate is conservative in the sense that some flow constriction would still have been present, especially in the estuary mouth between Chequesett Neck and Griffin Island, which would have produced lower water levels upstream with some phase lag. Nonetheless, the water level would have been closer to 4.6 m than the 2.7 m predicted by the model with the dike structure in place but fully open.

SUMMARY

A mathematical model was developed for the Herring River estuary based on simplified tidal dynamics where the estuary itself is treated as a reservoir with sloping bottom wherein the water level varies only with time and where the flow enters and departs through the inlet channels of the dike structure. The inlet flow is governed by a momentum balance between the horizontal pressure gradient induced by the different water levels between the downstream or harbor side and the upstream or river side of the dike and frictional forces generated by flow through the dike channels, including tide gates and sluice gates. An equation expressing conservation of water volume for the reservoir completes the mathematical system, which is then solved numerically.

Calibration of the model was performed by using water level measurements for two different tidal cycles to select optimal values of the two frictional parameters. A comparison of results for the time history of river water level between the model and measurements for these two cycles and one other, independent one showed that the root mean square differences were of the order of .09 m at any tidal stage for the conditions of the measurements when the river heights were between 1.2 m and 2.0 m MLW.

The river response to a standard, single constituent harmonic tidal variation for the harbor was computed for nine different dike configurations representing various degrees of flow constriction. These included one and two operative tide gates, no restrictions, and three sluice gates at a variety of openings. The primary effect of diminishing dike flow constriction is to raise

the river water level almost uniformly over the tidal cycle while increasing the tidal exchange volume but leaving the tidal range relatively unchanged. The tidal exchange volume increased more rapidly than the water height, because as the mean water level rises in the river greater horizontal area is available for water storage, especially when the level rises above the marsh surface. As flow restrictions, tide gates are more effective than sluice gates.

Model runs simulating the river response to the February 1978 storm, regarded as a "100 year" storm, were done for four different dike configurations. With two tide gates operative and the sluice gate open 61 cmthe river height peaked at 2.08 m, with three sluice gates open 25 cm it peaked at 2.34 m, and with no gates at 2.76 m.

Testing of the model for river heights above 1.98 m was not possible as measurements are lacking. While below this level an uncertainty of ± 0.09 m is associated with the model predictions, because of the sparsity of elevation data, primarily, the uncertainty for higher levels is probably about double, or ± 0.18 m. This level should still be sufficiently small to allow practical use of the model results for predictions.

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REPORT APPENDIX 6

SALINITY MODEL OF THE HERRING RIVER, CAPE COD NATIONAL SEASHORE

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September 1986

MODEL TYPE

In a natural state the Herring River would have a salinity distribution typical of small U.S. east coast estuaries of the well mixed or weakly stratified class. The ratio of its mean fresh water to tidal volume fluxes, termed P, would likely be from about 10^{-3} to 10^{-2}, quite small. However, in its present, obstructed condition because of the dike structure at its present head adjoining Wellfleet Harbor, the tidal volume flux is greatly diminished while the mean fresh water volume flux Q_f is unchanged. The tidal height model described elsewhere in this report found tidal mean volume fluxes ranging from 3.6 m^3/s for Case 1 (sluice gate open to 51 cm and two tide gates operative) to 10.5 m^3/s with no gates (Case 5). Field measurements conducted for the present study showed a typical value for Q_f of about 0.28 m^3/s (10 ft^3/s), so that the ratio P would range from 0.027 for Case 5 to 0.078 for Case 1, consistent with a moderately stratified estuary and relatively short flushing times. Furthermore, the low tidal volume fluxes imposed by the dike structure greatly lower the tidal mean water depth of the estuary compared to its unobstructed condition of the last century such that its low tide total volume is only about five times greater than the volume of fresh water discharged to it per tidal cycle. Typical water parcel horizontal tidal excursions are large because the intertidal volume is about the same as the low tide volume.

Classical methods for estimating salinity distribution and flushing time, e.g., Ketchum (1951) and Dyer and Taylor (1973), are thus not applicable. Instead, a simple balance of downstream advection of fresh water against upstream turbulent diffusion of salt by tidal stirring is used to estimate the tidally averaged salinity distribution and flushing time for each of the nine cases treated in the tidal height model.

MODEL FORMULATION

Let A(x) represent the tidal mean cross-sectional area of the water in the estuary at distance x upstream from the dike, u(x) and S(x) the tidal mean current and salinity there averaged over area A, and K the longitudinal eddy diffusivity. Then, the advective <u>vs</u>. diffusive salt balance may be expressed by

$$\frac{d}{dx} (AuS) = \frac{d}{dx} \left(KA \frac{dS}{dx}\right) \qquad (1)$$

By integrating this equation once over x and stipulating that for upstream both S and dS/dx must vanish we obtain

$$\frac{dS}{dx} = - \frac{Q_f \; S}{KA} \qquad (2)$$

where $u(x)\; A(x) = -Q_f$ = constant has been used, reflecting the tidal mean downstream continuity of input fresh water through the estuary.

Since Q_f is known and A(x) may be computed, numerical solution of equation (2) is simply done by computing the right hand side at x=0 (the dike) where S = S(o) is known from observations to have a tidal mean value of about 18 to 20 ppt. For lack of better evidence, we assume K is a constant with a value found here empirically by best matching the only observed set of salinity values from August 23, 1984.

Before presenting numerical results, however, we first illustrate the general nature of the salt balance. For a simple tidal channel of <u>constant</u> cross-sectional area A we may integrate (2) analytically to give

$$S(x) = S(0) \exp \left(- \frac{Q_f}{KA} x \right)$$

The salinity thus falls from its value at the dike, S(o), to zero far upstream as a decaying exponential in x. The rate of decrease in S depends only on the length scale X_e=KA/Q_f. For example, S/S(o) falls to 0.1 (10%) at x = 2.30 X_e, a measure of the salt penetration distance upstream. Consequently, for S(o) = 20, A = 10 m^2, Q_f = 0.28, and K = 10 m^2/s, S = 2 at x = 0.82 km. Greater area A and diffusivity K increase this penetration distance, while greater fresh water flux Q_f decreases it.

To perform computations one must approximate the area distribution A (x) over the estuary reach of interest. This was affected by combining the measured bottom profile and land transect data obtained during the field work at eight stations from the dike to High Toss Road, the latter being generally above the reach of salt for all but high tide stage. These areas were computed at each station for five tidal mean water levels h_m from 1.22 m to 2.44 m (4 ft. to 8 ft.) above MLW. Upon plotting the results against x for the five heights h_m it was found that a "raised Gaussian" function could serve as an adequate fit having the following form:

$$A(x) = A_{up} + (A_{max} - A_{up}) \exp \left[- \left(\frac{x - x_{max}}{a} \right)^2 \right] \qquad (3)$$

Here A_{up} is the upstream ($x \rightarrow \infty$) limit of A taken as independent of x, A_{max} is the maximum of A occurring at x = x_{max}, and a is the decay scale for the exponential. These were found to depend on h_m in the following way:

$$A_{up} = 6.6\ h_m - 6$$

$$A_{max} = 179\ h_m - 196$$

$$a = 0.52 + 0.194\ (h_m - 1.22)^2$$

$$x_m = 0.45$$

where A_{up} and A_{max} are in m^2 while h_m, a, and x_m are in km.

Once S(x) is determined the flushing time t_f for the estuary may be computed from (Officer 1976)

$$t_f = \frac{V_f}{Q_f} \qquad (4)$$

where V_f is the tidal mean volume of fresh water in the estuary given by

$$V_f = \int_0^{X_L} [1 - \frac{S(x)}{S(0)}] A(x)\, dx$$

where X_L is the upstream limit of possible salt penetration, taken here as 3 km. This time represents the average time for a conservative property of the water introduced in the fresh water to be flushed from the estuary through tidal mixing and downstream advection.

For the case of constant area A discussed above the integral for V_f may be found analytically to give

$$t_f = \frac{A}{Q_f} [X_L + X_e (1 - e^{-X_L/X_e})]$$

or, since X_L/X_e is usually large, $t_f = A (X_L + X_e)/Q_f$. Thus, increased salt penetration (increased X_e) corresponds to increased flushing time for fixed X_L. For the values above and X_L = 3 km, t_f = 1.39 days.

MODEL RESULTS

To obtain the optimum value for diffusivity K equation (2) was solved numerically with S(o) and h_m chosen to match the salinity data of August 23, 1984, the only set of salinity data available which permitted tidal mean values to be computed throughout the reach of salt penetration. With S(o)=18 and H_m = 1.57 m, K = 6 m^2/S gave the best fit to the observed values. (This value is typical of estuaries with moderate stratification, as here.) The results are shown in Table 1 where both computed and observed values are listed at values of x corresponding to the seven salinity stations used for observations. While the overall match between model and observed values is acceptable, consistent differences may be noted. The model results show an almost uniform rate of salinity decrease from the dike up to about x = 1.0 km after which the rate of decrease intensifies until about x = 1.5 km where it slows. In contrast the observations show a very slow decrease until about x = 0.85 km (station S3) after which the fall is rapid until x = 1.24 km (station S5). Thus, the model results are low up to about x = 1.0 km and then high until about x = 1.5 km. The salt penetration distance X_f, here defined as the distance upstream where S reaches 10% of its value at the dike (0.1 S(o) or 1.8 ppt for this case), is 1.42 km from the model results and about 1.25 km from the observations. The flushing time t_f computed from equation (4) is 1.27 days for the model results and 1.24 days for the observed values, nearly perfect agreement. The model with K = 6 m^2/s thus appears to give useful results.

A summary of results corresponding to the nine cases of the tidal height model is provided in Table 2. Salt penetration distance x_p and flushing time t_f are listed along with tidal mean height h_m and S(o). Case 1 corresponds to the results just discussed and given in Table 1. Because it has the least tidal exchange, reflected in Table 2 by the lowest h_m, it has the smallest values for x_p and t_f. The latter, only 1.27 days, highlights the severe restriction of the tidal exchange by the dike in the face of unchanged fresh water flux Q_f. As the tidal exchange is increased, as reflected by h_m, x_p and t_f increase reaching maximum values for case 5 of 1.87 km (near salinity station S7) and 1.77 days, respectively. These values correspond to all three dike channels wide open (no gates) and thus represent the maximum values predicted by the model for the present dike structure during an average harbor tide of 2.38 m range. Higher harbor tide ranges, as during spring tides, would produce yet greater values of x_p and t_f, while lower ranges, as during neap tides, would produce lesser. For all nine cases the salt penetration is modest, less than 2 km or below High Toss Road for the tidal mean. (High water salt penetration would be somewhat greater, perhaps another 0.5 km.) For all nine cases the flushing time is short, less than 2 days or 4 tidal cycles.

Table 1. Model results for tidal mean salinity with K = 6 m^2/S *vs* observed values for August 23, 1984.

Station	x (km)	Model S (ppt)	Observed S (ppt)
S1	0.00	18.0	-
S2	0.45	13.2	16.9
S3	0.85	10.1	14.1
S4	1.03	8.2	3.8
S5	1.24	5.0	1.3
S6	1.55	0.8	1.1
S7	1.86	0.1	0.1
S9	2.19	0.0	0.0

Table 2. Salinity model results for salt penetration distance X_p and flushing time t_f for the nine cases of the tidal height model.

Case	h_m (m)	S (o)	X_p (km)	t_f (days)
1	1.57	18	1.42	1.27
2	1.60	18	1.46	1.30
3	1.66	18	1.51	1.36
4	1.91	20	1.72	1.61
5	2.07	20	1.87	1.77
6	2.05	20	1.85	1.75
7	2.02	20	1.82	1.72
8	1.97	20	1.77	1.67
9	1.86	20	1.68	1.56

REFERENCES

Dyer, K.R. and P.A. Taylor. 1973. A simple, segmental prism model of tidal mixing in well-mixed estuaries. Estuarine and Coastal Marine Science 1:411-418.

Ketchum, B.H. 1951. The exchanges of fresh and salt water in tidal estuaries. Journal of Marine Research 10:18-38.

Officer, C.B. 1976. Physical Oceanography of Estuaries. John Wiley & Sons, New York. 465 p.

SALINITY MODEL

Model runs for the nine cases. Tidal mean salinity at 0.1 km intervals from the dike (0 km) toward upstream is indicated along with other model output.

```
&INPUT
CK=   6.00000000000000000      ,H=   1.57000000000000006      ,IXW=                5,SD=
  18.0000000000000000
&END                                   S
    X (km)     S(ppt)   A(m^2)     F= 1 - ----
                                           S
                                            (o)

   0.00     18.00    45.03     0.00
   0.10     16.45    57.67     0.09
   0.20     15.30    69.66     0.15                 CASE 1
   0.30     14.38    79.12     0.20
   0.40     13.58    84.35     0.25
   0.50     12.85    84.35     0.29
   0.60     12.13    79.12     0.33
   0.70     11.38    69.66     0.37
   0.80     10.56    57.67     0.41
   0.90      9.61    45.03     0.47
   1.00      8.47    33.36     0.53
   1.10      7.11    23.69     0.61
   1.20      5.52    16.40     0.69
   1.30      3.81    11.37     0.79
   1.40      2.24     8.17     0.88
   1.50      1.09     6.30     0.94
   1.60      0.44     5.28     0.98
   1.70      0.15     4.77     0.99
   1.80      0.05     4.53     1.00
   1.90      0.02     4.43     1.00
   2.00      0.00     4.39     1.00
   2.10      0.00     4.37     1.00
   2.20      0.00     4.36     1.00
   2.30      0.00     4.36     1.00
   2.40      0.00     4.36     1.00
   2.50      0.00     4.36     1.00
   2.60      0.00     4.36     1.00
   2.70      0.00     4.36     1.00
   2.80      0.00     4.36     1.00
   2.90      0.00     4.36     1.00
   3.00      0.00     4.36     1.00
   3.10      0.00     4.36     1.00
  TF(DAYS) =     1.27

    (Flushing Time)
```

```
INPUT
K=  6.0000000000000000     ,H=  1.6000000000000009     ,IXW=           5,SD=
 18.000000000000000
END
   X        S        A        F

  0.00    18.00    48.30     0.00                   CASE 2
  0.10    16.55    61.65     0.08
  0.20    15.46    74.27     0.14
  0.30    14.59    84.20     0.19
  0.40    13.83    89.69     0.23
  0.50    13.13    89.69     0.27
  0.60    12.44    84.20     0.31
  0.70    11.71    74.27     0.35
  0.80    10.92    61.65     0.39
  0.90     9.99    48.30     0.44
  1.00     8.89    35.91     0.51
  1.10     7.56    25.58     0.58
  1.20     5.99    17.75     0.67
  1.30     4.26    12.30     0.76
  1.40     2.60     8.81     0.86
  1.50     1.33     6.74     0.93
  1.60     0.57     5.61     0.97
  1.70     0.21     5.03     0.99
  1.80     0.07     4.76     1.00
  1.90     0.02     4.64     1.00
  2.00     0.01     4.59     1.00
  2.10     0.00     4.57     1.00
  2.20     0.00     4.56     1.00
  2.30     0.00     4.56     1.00
  2.40     0.00     4.56     1.00
  2.50     0.00     4.56     1.00
  2.60     0.00     4.56     1.00
  2.70     0.00     4.56     1.00
  2.80     0.00     4.56     1.00
  2.90     0.00     4.56     1.00
  3.00     0.00     4.56     1.00
  3.10     0.00     4.56     1.00
 TF(DAYS) =    1.30
```

```
&INPUT
CK=  6.0000000000000000     ,H=  1.6599999999999992     ,IXW=           5,SD=
 18.000000000000000
&END
    X        S         A         F

   0.00    18.00     55.10      0.00
   0.10    16.72     69.81      0.07
   0.20    15.74     83.62      0.13                CASE 3
   0.30    14.95     94.42      0.17
   0.40    14.25    100.37      0.21
   0.50    13.60    100.37      0.24
   0.60    12.96     94.42      0.28
   0.70    12.29     83.62      0.32
   0.80    11.55     69.81      0.36
   0.90    10.69     55.10      0.41
   1.00     9.65     41.31      0.46
   1.10     8.39     29.67      0.53
   1.20     6.87     20.71      0.62
   1.30     5.14     14.37      0.71
   1.40     3.38     10.23      0.81
   1.50     1.90      7.73      0.89
   1.60     0.91      6.32      0.95
   1.70     0.38      5.59      0.98
   1.80     0.15      5.23      0.99
   1.90     0.05      5.07      1.00
   2.00     0.02      5.00      1.00
   2.10     0.01      4.97      1.00
   2.20     0.00      4.96      1.00
   2.30     0.00      4.96      1.00
   2.40     0.00      4.96      1.00
   2.50     0.00      4.96      1.00
   2.60     0.00      4.96      1.00
   2.70     0.00      4.96      1.00
   2.80     0.00      4.96      1.00
   2.90     0.00      4.96      1.00
   3.00     0.00      4.96      1.00
   3.10     0.00      4.96      1.00
TF(DAYS) =     1.36
```

```
&INPUT
CK=  6.0000000000000000       ,H=  1.9099999999999992     ,IXW=                5,SD=
  20.000000000000000
&END
    X        S       A        F

   0.00    20.00   87.77    0.00
   0.10    19.08  107.07    0.05
   0.20    18.33  124.51    0.08                        CASE 4
   0.30    17.70  137.78    0.12
   0.40    17.12  144.96    0.14
   0.50    16.58  144.96    0.17
   0.60    16.04  137.78    0.20
   0.70    15.47  124.51    0.23
   0.80    14.85  107.07    0.26
   0.90    14.14   87.77    0.29
   1.00    13.29   68.77    0.34
   1.10    12.25   51.75    0.39
   1.20    10.97   37.68    0.45
   1.30     9.40   26.89    0.53
   1.40     7.55   19.16    0.62
   1.50     5.56   13.97    0.72
   1.60     3.69   10.70    0.82
   1.70     2.19    8.77    0.89
   1.80     1.18    7.69    0.94
   1.90     0.60    7.12    0.97
   2.00     0.29    6.84    0.99
   2.10     0.14    6.70    0.99
   2.20     0.06    6.65    1.00
   2.30     0.03    6.62    1.00
   2.40     0.01    6.61    1.00
   2.50     0.01    6.61    1.00
   2.60     0.00    6.61    1.00
   2.70     0.00    6.61    1.00
   2.80     0.00    6.61    1.00
   2.90     0.00    6.61    1.00
   3.00     0.00    6.61    1.00
   3.10     0.00    6.61    1.00
TF(DAYS) =    1.61
```

```
&INPUT
CK=  6.0000000000000000     ,H=  2.0700000000000006     ,IXW=                  5,SD=
  20.000000000000000
&END
    X        S       A       F

   0.00    20.00   112.51   0.00
   0.10    19.26   133.64   0.04
   0.20    18.65   152.24   0.07                 CASE 5
   0.30    18.12   166.13   0.09
   0.40    17.63   173.58   0.12
   0.50    17.16   173.58   0.14
   0.60    16.69   166.13   0.17
   0.70    16.21   152.24   0.19
   0.80    15.68   133.64   0.22
   0.90    15.08   112.51   0.25
   1.00    14.39    91.02   0.28
   1.10    13.55    70.95   0.32
   1.20    12.53    53.56   0.37
   1.30    11.27    39.46   0.44
   1.40     9.74    28.70   0.51
   1.50     7.96    20.96   0.60
   1.60     6.05    15.69   0.70
   1.70     4.23    12.29   0.79
   1.80     2.70    10.21   0.86
   1.90     1.61     9.00   0.92
   2.00     0.90     8.34   0.95
   2.10     0.49     7.99   0.98
   2.20     0.26     7.81   0.99
   2.30     0.14     7.73   0.99
   2.40     0.07     7.69   1.00
   2.50     0.04     7.67   1.00
   2.60     0.02     7.67   1.00
   2.70     0.01     7.66   1.00
   2.80     0.01     7.66   1.00
   2.90     0.00     7.66   1.00
   3.00     0.00     7.66   1.00
   3.10     0.00     7.66   1.00
 TF(DAYS) =     1.77
```

```
&INPUT
CK=  6.0000000000000000      ,H=  2.0500000000000004      ,IXW=           5,SD=
  20.000000000000000
&END
    X         S         A        F                           CASE 6

   0.00     20.00    109.26     0.00
   0.10     19.24    130.21     0.04
   0.20     18.62    148.71     0.07
   0.30     18.07    162.57     0.10
   0.40     17.57    170.00     0.12
   0.50     17.10    170.00     0.15
   0.60     16.62    162.57     0.17
   0.70     16.13    148.71     0.19
   0.80     15.59    130.21     0.22
   0.90     14.98    109.26     0.25
   1.00     14.27     88.03     0.29
   1.10     13.41     68.32     0.33
   1.20     12.35     51.34     0.38
   1.30     11.06     37.65     0.45
   1.40      9.48     27.30     0.53
   1.50      7.67     19.91     0.62
   1.60      5.75     14.93     0.71
   1.70      3.94     11.75     0.80
   1.80      2.47      9.82     0.88
   1.90      1.44      8.72     0.93
   2.00      0.79      8.12     0.96
   2.10      0.42      7.81     0.98
   2.20      0.22      7.66     0.99
   2.30      0.12      7.58     0.99
   2.40      0.06      7.55     1.00
   2.50      0.03      7.54     1.00
   2.60      0.02      7.53     1.00
   2.70      0.01      7.53     1.00
   2.80      0.00      7.53     1.00
   2.90      0.00      7.53     1.00
   3.00      0.00      7.53     1.00
   3.10      0.00      7.53     1.00
TF(DAYS) =      1.75
```

```
&INPUT
CK=  6.0000000000000000     ,H=  2.0200000000000002     ,IXW=                5,SD=
  20.000000000000000
&END
    X         S        A        F

   0.00     20.00   104.47    0.00
   0.10     19.21   125.13    0.04
   0.20     18.56   143.45    0.07
   0.30     18.00   157.23    0.10
   0.40     17.49   164.63    0.13
   0.50     17.00   164.63    0.15
   0.60     16.51   157.23    0.17
   0.70     16.00   143.45    0.20
   0.80     15.45   125.13    0.23
   0.90     14.82   104.47    0.26
   1.00     14.08    83.67    0.30
   1.10     13.18    64.50    0.34
   1.20     12.08    48.13    0.40
   1.30     10.73    35.07    0.46
   1.40      9.09    25.31    0.55
   1.50      7.23    18.43    0.64
   1.60      5.29    13.87    0.74
   1.70      3.53    11.00    0.82
   1.80      2.15     9.29    0.89
   1.90      1.21     8.33    0.94
   2.00      0.65     7.82    0.97
   2.10      0.34     7.56    0.98
   2.20      0.17     7.43    0.99
   2.30      0.09     7.37    1.00
   2.40      0.05     7.35    1.00
   2.50      0.02     7.34    1.00
   2.60      0.01     7.33    1.00
   2.70      0.01     7.33    1.00
   2.80      0.00     7.33    1.00
   2.90      0.00     7.33    1.00
   3.00      0.00     7.33    1.00
   3.10      0.00     7.33    1.00
 TF(DAYS) =     1.72
```

CASE 7

```
CK=  6.0000000000000000      ,H=  1.9699999999999997     ,IXW=              5,SD=
  20.000000000000000
&END
    X        S        A        F

   0.00    20.00    96.71    0.00
   0.10    19.15   116.80    0.04
   0.20    18.46   134.77    0.08                    CASE  8
   0.30    17.87   148.36    0.11
   0.40    17.33   155.69    0.13
   0.50    16.82   155.69    0.16
   0.60    16.31   148.36    0.18
   0.70    15.78   134.77    0.21
   0.80    15.19   116.80    0.24
   0.90    14.53    96.71    0.27
   1.00    13.74    76.68    0.31
   1.10    12.78    58.46    0.36
   1.20    11.60    43.13    0.42
   1.30    10.15    31.11    0.49
   1.40     8.41    22.30    0.58
   1.50     6.48    16.23    0.68
   1.60     4.54    12.30    0.77
   1.70     2.88     9.89    0.86
   1.80     1.66     8.50    0.92
   1.90     0.89     7.74    0.96
   2.00     0.46     7.35    0.98
   2.10     0.23     7.16    0.99
   2.20     0.11     7.07    0.99
   2.30     0.06     7.03    1.00
   2.40     0.03     7.01    1.00
   2.50     0.01     7.01    1.00
   2.60     0.01     7.00    1.00
   2.70     0.00     7.00    1.00
   2.80     0.00     7.00    1.00
   2.90     0.00     7.00    1.00
   3.00     0.00     7.00    1.00
   3.10     0.00     7.00    1.00
TF(DAYS) =     1.67
```

```
INPUT
CK=  6.0000000000000000     ,H=  1.8600000000000010     ,IXW=               5,SD=
  20.0000000000000000
END
    X        S        A        F

   0.00    20.00    80.65    0.00
   0.10    19.00    99.20    0.05                    CASE 9
   0.20    18.20   116.08    0.09
   0.30    17.53   129.01    0.12
   0.40    16.93   136.03    0.15
   0.50    16.36   136.03    0.18
   0.60    15.79   129.01    0.21
   0.70    15.19   116.08    0.24
   0.80    14.53    99.20    0.27
   0.90    13.78    80.65    0.31
   1.00    12.87    62.58    0.36
   1.10    11.77    46.60    0.41
   1.20    10.40    33.59    0.48
   1.30     8.73    23.77    0.56
   1.40     6.81    16.88    0.66
   1.50     4.81    12.35    0.76
   1.60     3.02     9.57    0.85
   1.70     1.69     7.97    0.92
   1.80     0.86     7.10    0.96
   1.90     0.41     6.65    0.98
   2.00     0.19     6.44    0.99
   2.10     0.09     6.34    1.00
   2.20     0.04     6.30    1.00
   2.30     0.02     6.29    1.00
   2.40     0.01     6.28    1.00
   2.50     0.00     6.28    1.00
   2.60     0.00     6.28    1.00
   2.70     0.00     6.28    1.00
   2.80     0.00     6.28    1.00
   2.90     0.00     6.28    1.00
   3.00     0.00     6.28    1.00
   3.10     0.00     6.28    1.00
  TF(DAYS) =    1.56
```

REPORT APPENDIX 7

THE EFFECT OF MODIFICATIONS TO THE TIDAL REGIME OF THE HERRING RIVER ON THE HYDROLOGY OF MILL CREEK

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SYNOPSIS

The primary effect of proposed changes to the tidal regime of the Herring River on Mill Creek will be to restrict the drainage of fresh water. Mitigation of this effect may be possible through channel improvements in Mill Creek or by pumping to augment natural drainage. The magnitude of fresh water drainage must be determined before the feasibility of these actions can be evaluated.

PRESENT CONDITIONS

The low areas in the Mill Creek watershed are wet and poorly drained. The water table observed in several wells and drainage ditches during a visit to the golf course on December 13, 1985 was within 24 inches of the surface along the fairways. Standing water was observed in many places on the fairways and generally saturated soil conditions prevail. The groundskeeper reports that limited pumping is necessary to remove water from two of the fairways after a rainfall. This is the case for hole three, which has flooding problems unrelated to Mill Creek and for the hole immediately in front of the club house, which is in the Mill Creek drainage basin. The groundskeeper also reports that conditions are generally drier during the late summer months but that water levels in the Mill Creek at that time are still within one or two feet of the surface in the low areas.

Conditions in the Mill Creek watershed are controlled by the levels of Wellfleet Harbor to the south and the Herring River into which Mill Creek drains, and by the seasonal balance between precipitation, evaporation and drainage in the watershed. The general hydrologic setting is sketched in Fig. 1. Generally, it can be seen that water levels in the Mill Creek watershed are only a foot or two above the mean high water levels in the Herring River and in Wellfleet Harbor. The upland areas in the watershed are composed of sandy glacial deposits and are probably indicative of the material that underlies the old salt marsh and marine sediments in the low areas. If this is the case then the groundwater in the watershed is in direct contact with the water in Wellfleet Harbor. This is consistent with the observation of tidal influence on the groundwater level at hole three. The tides in the harbor may also be responsible for the variation in water level in the wells closer to Mill Creek, but this variation may be the result of localized influence of the smaller tidal range of the creek itself.

Water levels in the Mill Creek watershed stand somewhat above the levels in either Wellfleet Harbor or the Herring River for two reasons. First, a static lens of fresh water may be trapped under the watershed, essentially floating on sea water. Fresh water is less dense than sea water so the upper surface of the fresh water lens will be higher than the surrounding sea level. The second is that surface and subsurface drainage may be an important part of the water balance of the Mill Creek watershed in which case the difference in water level between Mill Creek and the Herring River is that which is necessary to drive the flow of water out of the watershed. The observation that Mill Creek flows, albeit slowly, throughout the year is evidence that drainage to the Herring River is an important factor controlling the present water levels in Mill Creek.

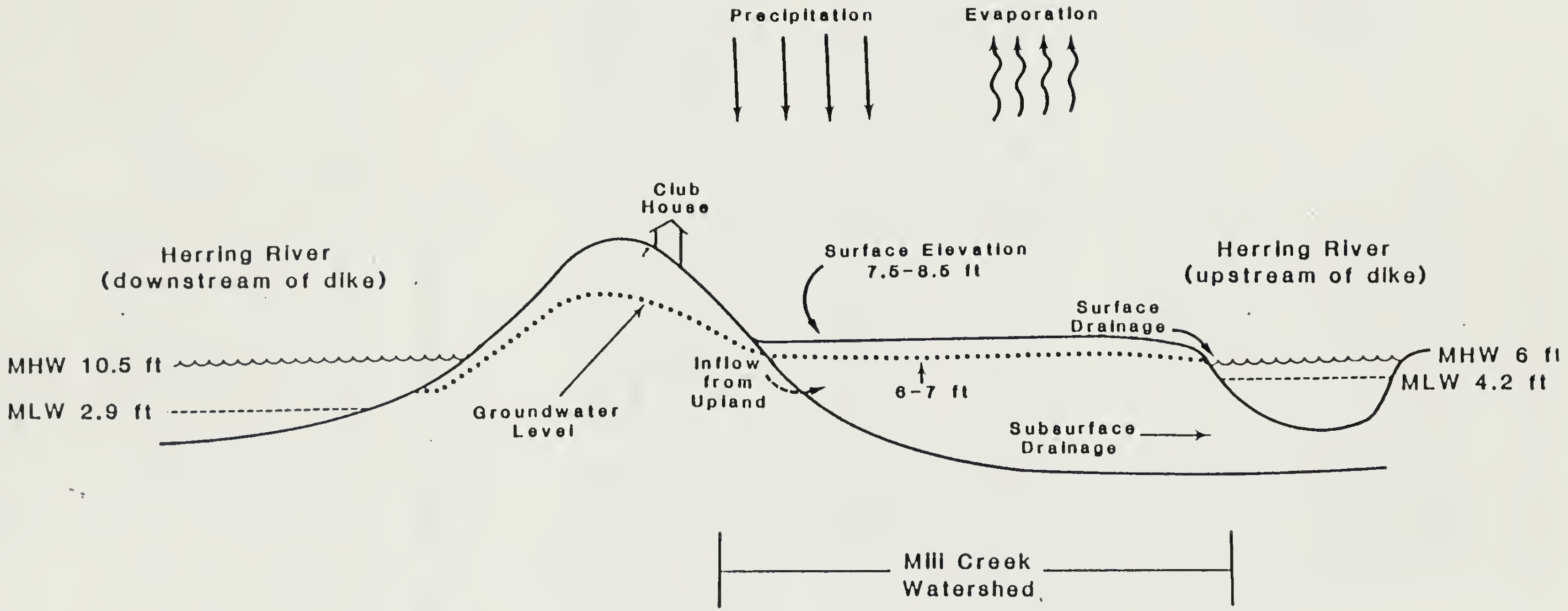

Fig. 1. Hydrologic setting of Mill Creek (conceptual view).

EFFECTS OF PROPOSED CHANGES TO THE HERRING RIVER

The net effect of proposed modifications of the Herring River dike will be to increase the mean level of the Herring River. A minimal increase in tidal range is anticipated. This will have two impacts on Mill Creek. First, the higher mean level of Herring River means that a greater proportion of the Mill Creek watershed will be susceptible to flooding by sea water at high tide. Second, increases in the mean level of the Herring River will impede drainage of fresh water from the Mill Creek watershed by reducing the available head drop between the watershed and the river. The drainage component of the water balance in the Mill Creek watershed can be considered to be constant in the short term. The hydrologic response in the watershed to increased levels in the Herring River will be a comparable increase in water levels in the creek and in the ground and a consequent degradation of already marginal conditions over much of the golf course.

A dike has been proposed to be built across the mouth of Mill Creek to prevent flooding by sea water. This is an appropriate and effective solution to the surface flooding problem. Simple dikes have been constructed for this purpose throughout the area and the remains of one or two dikes can be seen in the Mill Creek watershed. Salt marsh and marine sediments are relatively impermeable compared to the sandy soils that make up the uplands. A dike can be constructed directly on the existing soils without concern for seepage through salt marsh sediments provided attention is paid to seeing that the dike itself does not fail due to compaction of the sediments.

Construction of a dike will not solve the problem of reduced fresh water drainage. This is related directly to the increase in the mean level of the Herring River relative to existing water levels in the watershed. At best the presence of the dike will have no additional effect on drainage. However it can anticipated that there will be problems with any kind of flow control structure, such as a flapper valve, built into the dike to allow fresh water drainage at low tide and that these problems will exacerbate the fresh water drainage problem.

REMARKS AND RECOMMENDATIONS

There are two possible actions that can be taken to resolve the drainage problem that will accompany an increase in the mean level of the Herring River; 1) increase the efficiency of surface drainage by cleaning out the channels of Mill Creek, and 2) augment natural drainage by pumping. Cleaning out the channel of Mill Creek may allow it to maintain the required flowrate even though the available head drop is decreased. However this will only be effective provided that surface drainage of fresh water from the Mill Creek watershed is much larger than subsurface drainage. Pumping will be effective in any case and need not be expensive. If the required flow rate is small then a low-technology option such as windmill pumping may be all that is required.

A study to characterize the water balance in the Mill Creek watershed is necessary before the feasibility of either option can be evaluated. Such a study would include the following components: 1) A topographic survey to establish controls for water level observations in the Mill Creek basin, in the lower

reach of the Herring River and in Wellfleet Harbor. 2) Occasional monitoring of groundwater levels using simple shallow wells. 3) Continuous monitoring of discharge in Mill Creek using a Stevens water level recorder or equivalent. The installation and calibration of this instrument will require several periods of concurrent water velocity measurements. 4) Observation of meteorologic variables at Mill Creek or nearby Wellfleet. Variables needed include precipitation, dry bulb temperature, some measure of humidity, and cloud cover. Data from a pre-existing observatory can be used if it is characteristic of the Wellfleet area.

The period of data needed for this will be at least one year, so automatic monitoring of stream flow and meteorology is suggested. Groundwater levels can be monitored less frequently so these data can be obtained by hand.

The purpose of the study is to characterize the drainage component of the water balance. This will be done by constructing a simple hydrologic model of the Mill Creek watershed. Calibration with a year's worth of data will enable the model to predict the watershed response to extreme conditions that is necessary to know in order to evaluate the channel improvement and pumping options.

SEA LEVEL CHANGE CONSIDERATIONS

The hydrologic effects on Mill Creek described above for the proposed changes in the Herring River are bound to evolve over time throughout the Herring River basin due to continued increases in sea level, whether or not the proposed changes in the Herring River are carried out. The historical rise in sea level along the North Atlantic coast has been a linear increase at the rate of about a foot per century over the last 100 years (Changes in relative mean sea level, EOS Transactions, American Geophysical Union, v66: 754-756, 1985). At this rate effects equivalent to those of the proposed changes to the Herring River would not be realized for about 150 years if no changes are made. However, climatic changes related to increased levels of CO_2 are expected to accelerate the rise in sea level over the next ten to twenty years. The possible long term effect of sea level change should be kept in mind when evaluating the effects of proposed actions regarding the tidal regime of the Herring River.