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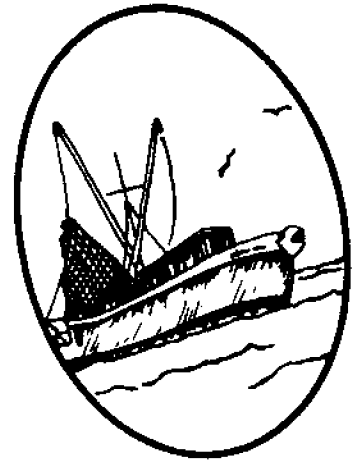
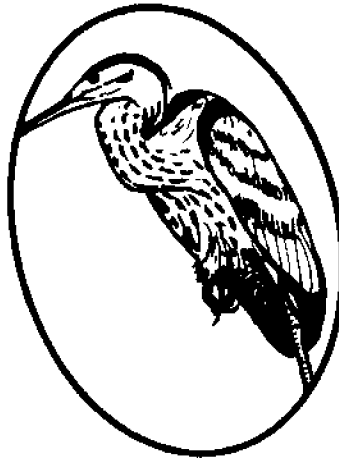
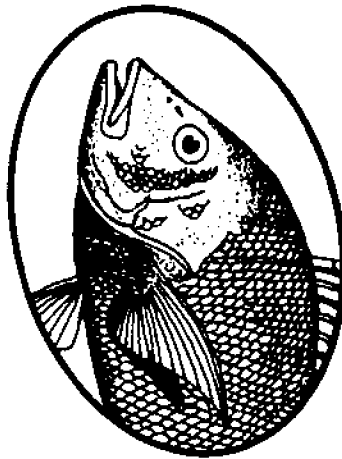
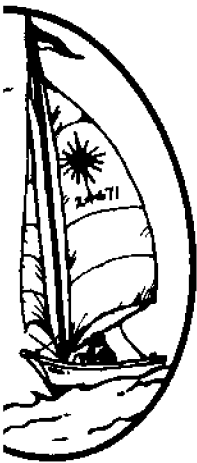
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Water Management And Estuarine Nurseries

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WATER MANAGEMENT AND ESTUARINE NURSERIES

by

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PREFACE

The extensive estuarine system of North Carolina supports productive fishery and recreation economics important to North Carolina and the East Coast. There are over two million acres of estuaries, of which around 75,000 acres are classified as nursery areas. These nurseries are essential for the propagation of over 90% of the commercial fisheries catch and a majority of the coastal recreational fish. Thus, it is imperative to maintain adequate environmental management programs designed to protect the ever critical primary nursery areas.

The major estuarine systems are surrounded by low lands, which are poorly drained in their natural condition. This land was in native permanent vegetation from which the excess rainfall was slowly removed by surface runoff and percolation through fringing marshes and swamps. A large portion of the land area now contains drainage ditches designed to remove surface water to facilitate agricultural and forestry development. Some of these drainage canals were constructed as early as the 1700's, but because of the lack of sufficient technology, many farming

ventures on drained land in this area failed. In recent years, however, management techniques have improved and some of these soils have been found to be some of the most agriculturally productive in the United States. This information, combined with the increasing need for more productive cropland, has provided the incentive to significantly increase the number of acres adjacent to estuaries under artificial drainage. Improved drainage is absolutely essential for agricultural production on these lands. Large networks of canals, especially in the Albemarle-Pamlico peninsula, exist in some areas and the water drained from the new agricultural fields ultimately reaches the estuaries. In some cases these canals are routed directly to primary nursery areas in estuaries. More than two million acres in coastal North Carolina are subject to draining. The freshwater flow to estuarine systems is an important national component of the total productivity; thus, the problem concerning improved drainage around estuaries is not simply that freshwater enters the estuary. Timing and the volume of flow are the critical factors.

Three characteristics of nursery areas have frequently been cited as critical to the production of juvenile estuarine organisms: a refuge from predation, an adequate food supply, and a benign abiotic environment. Each of these is addressed by

projects in our Estuarine Studies section of the University of North Carolina Sea Grant College Program.

This report is a compilation of preliminary results from three projects (R/ES-35, R/ES-36, R/ES-37) on land use alterations and runoff, response of the estuary to freshwater inputs, and response of juvenile fish and shellfish to freshwater input to nursery areas, respectively. Additionally, more comprehensive reports on this important research will be produced as the research continues to its programmed completion.

The Broad Creek Project, a demonstration study under the auspices of the North Carolina Department of Natural Resources and Community Development and specially funded for three years by the North Carolina General Assembly, is just getting underway. This project is designed, as recommended by the Governor's Task Force on Coastal Water Management, to directly test imposed freshwater inflows on juvenile fish and shellfish response. Thus, on-going research will continue to yield better and more relevant information to deal with the development of a rational management plan for estuarine nursery areas.

AGRICULTURAL RUNOFF AND WATER QUALITY IN COASTAL AREAS

K. Konyha, R. W. Skaggs and J. W. Gilliam*

The lands of the Tidewater region play a vital role in the ecosystem of the Carolina sounds. One of the most fundamental parts of this shallow-water shore bound system is fresh-water inflow. This paper summarizes our present understanding of the freshwater and nutrient flows from natural areas and developed agricultural land.

Farmers in the Coastal Plains and Tidewater regions require drainage for efficient agricultural production. Drainage is needed to provide trafficable conditions so the farmer can prepare seedbed, plant, cultivate and perform other essential operations in a timely fashion. Drains also protect the crop by removing excess water that would otherwise drown the plant and kill the roots. Of course the extent and frequency of the drainage requirements depend on the climate, the soil and the crop, but drainage is essential for agricultural production in most years.

Good water management balances the needs for increased drainage against the need for sufficient water to grow to maturity. Because the amount of rainfall cannot be increased and, in drought years is barely adequate or not adequate at all, the farmer is becoming increasingly aware of the benefits of careful water management to prevent excessive drainage and conserve water for the growing crop.

Agricultural Drainage Methods

Conventional drainage systems are primarily intended to remove water from the surface of the fields. They provide some subsurface drainage, depending on the soil, but are primarily surface drainage systems. Often

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this drainage intensity is not sufficient to prevent large crop losses during wet years. In the Coastal Plains this system can be recognized by shallow ditches (4 feet deep) spaced about 100 to 150 yards apart, and draining into deeper collector canals about 1/2 mile apart. These then drain into major drainage canals which flow into the estuaries and natural rivers of the area. Such systems are effective in preventing flooding which would otherwise occur during the heavy rains typical of the region.

By installing subsurface drain tubing at closer spacings, again depending on the soil and crop, the farmer is able to achieve an added measure of control over the water table position and can guarantee that in most years his tractors and machines can get out into the fields to plant and harvest. The increased cost of the subsurface drains must be recovered in long term increased profits. The economics are favorable for many soils but not for all.

The highest level of control over the water supply comes from the use of controlled drainage and/or subirrigation. Here control structures are placed in the outlet ditches so that the water level can be raised or lowered by the farmer as needed. Some benefits are achieved by using conventional drain spacings, but to be effective as an irrigation system, the drains should be placed somewhat closer together. While more expensive, this system gives some protection from droughts as well as flooding and high water tables. Again, economic considerations may make such systems profitable on some lands and unprofitable on others. Facilities required for controlled drainage alone, however, are not very expensive and will pay for themselves by permitting only a small increase in crop yield. These systems are gaining wide acceptance in the Coastal Plains and Tidewater regions. In addition to agricultural benefits, they provide the flexibility of managing the drainage systems to reduce detrimental off-site impacts.

Regardless of the type of agricultural drainage management, all require outlets. Where there is sufficient elevation and topography allows, the drainage ditches and canals are structured so that the land is drained by gravity. In many areas near the coast it is necessary to place dikes around the land and install pumps for adequate drainage. Pumping for agricultural drainage has been used in eastern N.C. since early in this century.

Let us look at the quality and quantity of water leaving several types of agricultural systems common to the region. Several studies have been conducted to determine the effects of drainage on the quantity and quality of the outflow (Gambrell et al., 1974; Gilliam et al., 1978; Skaggs et al., 1980; Gregory et al., 1984; Deal et al., 1985). Studies are continuing under sponsorship of the North Carolina Sea Grant and Water Resources Research Institute programs. Experimental results from these studies as well as results from simulation models developed during the course of the research are used herein to show the effects of agricultural water management systems on outflow quality and quantity.

Fresh Water Outflow from Forested and Agricultural Lands

Figure 1 shows the average monthly outflow from a forested area (native vegetation) and from the same soil in agricultural production. The average outflows were obtained from simulations for a 25 year period. The average annual outflow from the forested area was 40 cm (16 in.) compared to 44 cm (17 in) from the agricultural land use. In both cases the highest runoff occurred in the winter months with about 48% of the total during December through March for both the forested and agricultural land uses. In comparison, only about 16% of the total outflow occurred during the months of April through July. Outflow in the winter months is high because ET is greatly

reduced. Rainfall in excess of ET raises the water table to near the surface and increases both surface and subsurface drainage rates. Average annual outflow rates for the agricultural land use is only about 10% higher than for native vegetation on these high water table soils. The difference is caused by lower ET rates from the agricultural land when the crop is young or the soil is fallow.

While freshwater outflow from agricultural lands is only slightly higher than from lands in forest or native vegetation, there is a large variation from month-to-month and year-to-year for both land uses. Figure 2 shows predicted outflows for the month of March for the 25-year period (1955-1979). The variation from year to year is large and mirrors an equally variable rainfall pattern. The mean March flow is 4.1 cm for the forested land compared to 4.3 cm for agriculture. Outflow volumes ranged from 0 to 16 cm for both land uses. Standard deviations for March were 3.88 cm for forest and 3.93 cm for agriculture.

While land under corn-wheat-soybean farming has somewhat higher outflows than from forested land, the month to month and year to year fluctuations for either land use is much larger than the differences caused by choosing one land use over another. This would hold true for any land use application. The differences in flows from the various methods will not be anywhere near as large as the difference in flows from year to year.

While total annual drainage outflows from watersheds having native vegetation are only about 10% greater than agricultural watersheds, peak outflow rates are much higher. Our research shows that peak outflow rates at the field edge are 3 to 4 times higher from agricultural fields than from fields with native vegetation. The differences in outflow rates from a large area are much less, however, because of the capacities of the canal network and the time lags of peak flows from individual fields.

Management to Reduce Freshwater Outflow

A water balance representing the hydrologic cycle for the soils in the lower Coastal Plains and Tidewater Regions may be written as follows:

$$\text{Precipitation} = \text{Subsurface Drainage} + \text{Surface Runoff} + \text{ET} + \text{Deep Seepage} + \text{Change in Profile Storage}$$

where ET is evapotranspiration. Deep seepage is negligible for most of the lands in the coastal area and the change in profile storage can also be neglected by taking the water balance over a long period of time. The total freshwater outflow is the sum of subsurface drainage, that water that travels through the soil profile to the drain tubes or ditches, and surface runoff. Then the water balance may be written as,

$$\text{Precipitation} = \text{Total Outflow} + \text{ET}$$

Since there is nothing we can do to reduce precipitation, the only alternative for reducing the volume of freshwater outflow is to increase ET. One way to increase ET is to keep a crop on the soil as much of the time as possible. The surface of a fallow soil may dry out reducing ET because of the lack of plant roots to remove soil water from the profile. Figure 3 shows the average effect of a cover crop on monthly flow. The solid line shows the average monthly flow from a field planted only to corn and with no cover crop in the winter months. The dashed line is for a field kept under a cover crop-corn-winter wheat rotation. During the summer months the flows are identical. In winter the higher ET from the cover crop tends to reduce the runoff slightly. This effect is more noticeable in the drier years (Figure 4) but outflows were unaffected by the cover crop in wet years.

The planting date can also affect flow because the young plants have shallower roots and fewer leaves/and tend to transpire less. This is shown

in Figure 5, where the summer months have higher flow (lower ET) when the corn is planted late. Here again the effect was more pronounced in dry years and almost nonexistent in wet years.

In short, there is little to be done through crop management to reduce the total outflow. While some measures are effective for drier years, the wet years are largely unaffected.

Water Quality

Annual nutrient effluxes for soils under forest and cropped conditions with conventional drainage systems are given in Table 1. Both N and P losses from cropped lands are higher than from similar forested soils because of the fertilizers applied in agricultural production. In general farmed organic soils have less nitrate-N and higher P losses than do mineral soils. Total-N losses are about the same from both soils.

Table 2 shows the effect of subsurface drainage on nutrient losses from a mineral soil in eastern N.C. As subsurface drainage increases from poor to good, $\text{NO}_3\text{-N}$ and Total-N increase rather dramatically. On the other hand P losses decrease. Although not shown, sediment losses would also decrease with improved subsurface drainage. Improving subsurface drainage lowers the water table and causes a greater portion of the total water loss to move through the soil profile rather than over the soil surface as runoff. This generally reduces denitrification and increases the loss of nitrates, which are mobile in the soil profile, while decreasing surface runoff which carries most of the P and sediment lost by mineral soils. Therefore, if the water quality goal is to decrease P and sediment outflow, practices to improve subsurface drainage, increasing the amount of water drained through the soil profile and reducing surface runoff, should be encouraged. If the

goal is to decrease NO_3^- N outflow, surface drainage and controlled drainage practices discussed in the following section should be emphasized.

Table 1. Average annual nutrient effluxes from cropped and forested mineral and shallow organic soils in eastern N.C.

Nutrient	Mineral Soil (Wasda)		Shallow Organic (Belhaven)	
	Cropped	Forest	Cropped	Forest
	----- lb/ ac -----			
NO_3^- -N	3.7	0.4	1.3	0.2
NH_4^+ -N	3.3	0.5	1.4	0.8
Total-N	13.6	3.2	14.3	5.1
Total-P	0.5	0.2	6.8	0.2

Table 2. Effect of subsurface drainage on nutrient effluxes.

Nutrient	Subsurface Drainage of Fields		
	Poor	Moderate	Good
	----- lb/ac/yr -----		
NO_3^- -N	3.7	15.7	32.4
Total-N	13.6	20.0	42.1
Total-P	0.5	0.3	0.2

Agricultural Water Management Alternatives

A type of control practiced by all farmers is the selection of a water management system. Three water management alternatives for soils requiring drainage are shown in Figure 6. The conventional open ditch drainage system is designed to remove water from the surface rapidly but its removal of subsurface water is generally not good. By putting ditches closer together or using drains tubes as shown in Figure 6, good subsurface drainage can be obtained. This draws down the water table, which allows a greater portion

of the rainfall to infiltrate into the soil instead of running off the surface.

Figure 7 shows the difference in outflow rates between a field with good subsurface drainage and a field with poor subsurface drainage for a moderately large storm event. These data were obtained from two identical (except for the drainage system) 90-acre fields in Beaufort County. The peak runoff rate for the field with good subsurface drainage (Watershed B) is about half that which occurred for the field with conventional open ditch drainage (Watershed A). The total outflow for the two fields was about the same, 2.5 to 2.7 cm. However the field with good subsurface drainage released water more slowly over a longer period of time. The field with poor subsurface drainage had the water table closer to the surface when rainfall began. The water table rapidly rose to the surface and excess rainfall ran off at much higher rates than occurred for the better drained soil.

Improving subsurface drainage is the most effective method that we've found for reducing peak outflow rates from the high water table soils in the coastal area.

Another water management alternative that can be used to improve the quality of water leaving the fields and conserve water is controlled drainage. Water level control structures are installed in the outlet ditches, so that the water level can be raised after the crop is planted to conserve water for later use by the plant. Simulation analyses showed that drainage control on the two Coastal Plains soils during the winter and most of the growing season resulted in approximately 2 cm less runoff (Table 3). Controlled drainage also resulted in a higher percentage of the drainage water leaving the field as surface runoff. These analyses did not consider the effect of the raising the water table on seepage from the field. This would

have tended to further reduce the total outflow; so the results given represent conservative estimates of the effects of controlled drainage.

Controlled drainage affects nitrate efflux in the drainage water in two ways. First, the soils stay wetter which promotes denitrification and lowers nitrate concentration in the subsurface drainage water. The increase in surface drainage at the expense of subsurface drainage also tends to decrease the NO_3 efflux. The predicted drainage control effect for two soils is a 32% decrease in NO_3 -N efflux (Table 4). The decrease in NO_3 efflux under controlled drainage is accompanied by an increase in organic nitrogen efflux because of the increase in loss of sediments carried by the higher surface runoff. However, this increase in organic N is much less than the decrease in NO_3 -N so controlled drainage decreases the loss of total N. Also, the environmental problems caused by organic N loss would be much less than that of NO_3 -N because of the lower bioavailability of the organic nitrogen. It should also be noted that because the drained soils are very flat, the increase in surface runoff resulting from drainage control does not cause sediment or erosion problems.

Table 3. Predicted annual drainage utilizing controlled and conventional drainage management on two soils.

Soil	Conventional Drainage			Controlled Drainage		
	Surface	Subsurface	Total	Surface	Subsurface	Total
Portsmouth	1.7	14.5	16.2	4.5	10.3	14.8
Wasda	2.1	12.5	14.6	3.9	9.6	13.5

For the same reason that organic N loss is greater under controlled drainage, total P loss is also greater. The losses are relatively low under both drainage systems, but because surface runoff water contains higher P

Table 4. Predicted annual nutrient efflux utilizing controlled and conventional drainage management on two soils.

Soil	Conventional Drainage			Controlled Drainage		
	NO ₃	Total N	Total P	NO ₃	Total N	Total P
	-----kg ha ⁻¹ -----					
Portsmouth	39.1	44.4	0.05	26.4	31.2	0.16
Wasda	27.8	33.2	0.18	19.1	22.5	0.28

concentration than subsurface drainage water, there is a significant increase in P loss under the controlled drainage water management scheme.

In the simulation and field experiments utilizing drainage control, it was assumed that the manager of the system would manage the water during the growing season for maximum yields and simply leave the control structures to maintain a high water table during the winter when wet soils are not a problem. However, the drainage could be managed during the winter to minimize environmental problems. For example, surges of freshwater into estuarine nursery areas are considered a problem. By lowering the control structures slowly after a wet period brings the field water table to a high level, drainage flows could be made much more even. The gradual drawdown of the water table would provide continuous flow as well as provide storage in the soil for the next rainfall event. Management in this way would also provide much of the water quality benefits. The high water table, after a rainy period, would promote denitrification thus reducing NO₃ efflux. The gradual drawdown would reduce surface runoff as compared to continuously leaving the control structure at a high level. Any decrease in surface runoff results in a decrease in organic N and total P efflux in drainage water.

Flow into the Estuary and Choice of Outlets

The flow rate at the drainage outlet (inlet to the estuary) will not be the same (per unit area) as the flow rate at the field edge. The fields are distributed all along the canals at different distances from the outlet so the peak flow rates do not add in a linear fashion. As a result peak outflows from large storm events can be considerably attenuated (Figure 8). Therefore the effect of subsurface drainage and other methods of controlling outflow rates must be routed through the canal network to determine their impact at the outlet. The same is true for water quality effects. The interactions between the field and the canal network is not yet well understood. The effects of control structures, pumping stations and storage ponds on estuary inflow is the topic of ongoing research and it is as yet unknown how much of a role watershed and canal network management can be expected to have on the estuary's health. The use of buffer areas to clean the discharge waters from pumping stations is also an area of current research.

While a good outlet is essential for agricultural drainage, there are usually a number of alternative locations for outlets in coastal areas. A simple way of avoiding problems in the estuary is to select an outlet in open water as far removed as possible from marshes and inlets that serve as nursery areas. This measure was recommended by the Water Management Task Force appointed by former Governor Hunt and is an effective means of avoiding potential problems.

SUMMARY

The quantity of drainage water from agricultural land in the coastal areas of eastern N.C. is about 10% higher per unit area than from similar land in forest or native vegetation. Nearly half of the runoff occurs in the months of Dec. through March. Variation in runoff volumes from month-to-month and from year-to-year is much greater than the differences in runoff between land uses. Peak outflow rates at the field edge are about three times higher than from lands with native vegetation. However these differences are moderated as the water makes its way through the canal system to the outlet.

Agricultural lands release significantly greater amounts of nitrogen and phosphorus than do undeveloped areas. Nitrate-nitrogen losses increase while phosphorus and sediment losses decrease with improvement of subsurface drainage.

Controlled drainage utilizing flashboard risers can be utilized to change both the hydrologic characteristics and the nutrient effluxes. Under the conditions simulated, controlled drainage reduced the nitrate efflux by as much as 34% but the reduction varied with soil and management conditions. Controlled drainage may increase the P efflux, however.

Research is ongoing to better define the effects of canal networks, control structures, pumping stations and storage ponds on inflow to an estuary. Drainage outlets should be located in open water as far removed as possible from marshes and inlets that serve as primary nursery areas.

There are many different management schemes which can be used to satisfy agricultural drainage needs. We believe that careful selection and control of water management systems has the potential to offset detrimental environmental impact while providing adequate drainage protection for crop production.

References

- Deal, S. C., J. W. Gilliam, R. W. Skaggs and K. D. Konyha. 1983. Prediction of nitrogen and phosphorus losses from selected North Carolina Coastal Plains soils as related to drainage system design. In Review. Journal of Environmental Quality.
- Gambrell, R. P., J. W. Gilliam and S. B. Weed. 1975. Nitrogen losses from soils in the North Carolina Coastal Plain. Water Resources Research Institute of the University of North Carolina. Report No. 93.
- Gilliam, J. W., R. W. Skaggs and S. B. Weed. 1979. Drainage control to diminish nitrate loss from agricultural fields. J. Environ. Qual. 8:137-142.
- Gregory, J. D., R. W. Skaggs, R. G. Broadhead, R. H. Culbreath, J. R. Bailey and T. L. Foutz. Hydrologic and water quality impacts of peat mining in North Carolina. Water Resources Research Institute of the University of North Carolina. Report No. 214.
- Skaggs, R. W., J. W. Gilliam, T. J. Sheets and J. S. Barnes. 1980. Effect of agricultural land development on drainage waters in the North Carolina Tidewater Region. Water Resour. Res. Inst. of Univ. of North Carolina Rep. No. 159.

Comparison of Monthly Flows 25 Year Averages - Forested vs Cropped Land

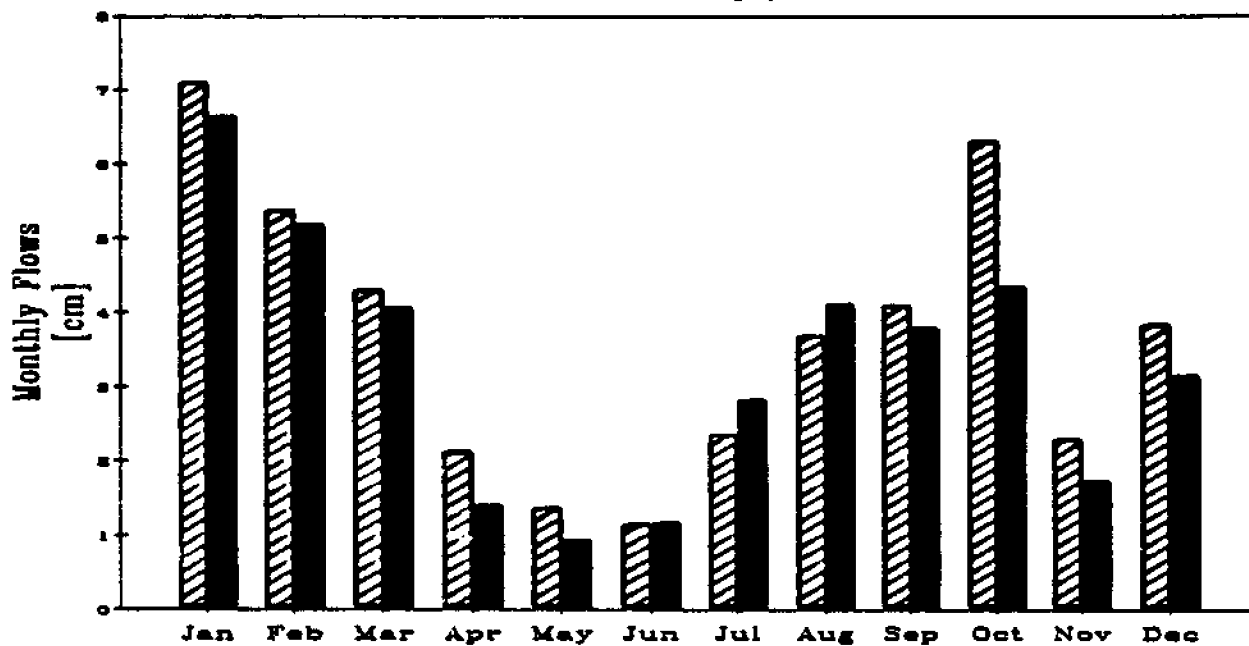


Fig. 1. A comparison of outflow volumes from forested and cropped lands.

Variation in Flow for March Cropped vs Forested Land

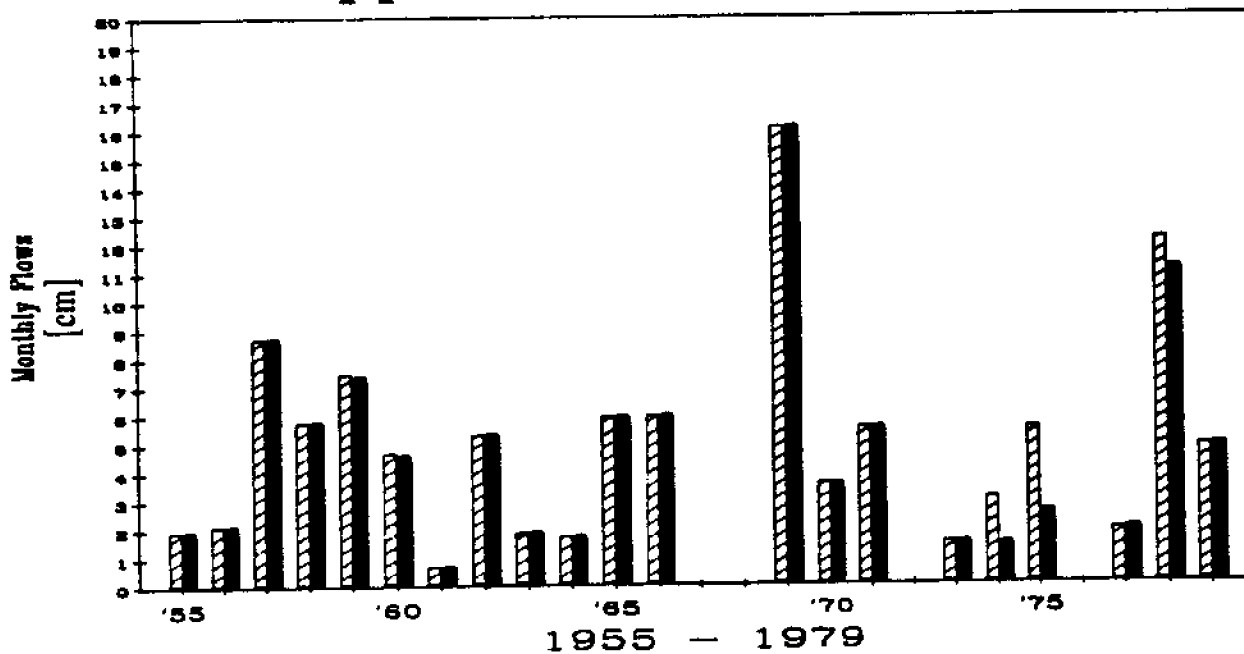


Fig. 2. The variability of monthly outflow volumes from forested and cropped lands.

FOR GOOD SUBSURFACE DRAINAGE

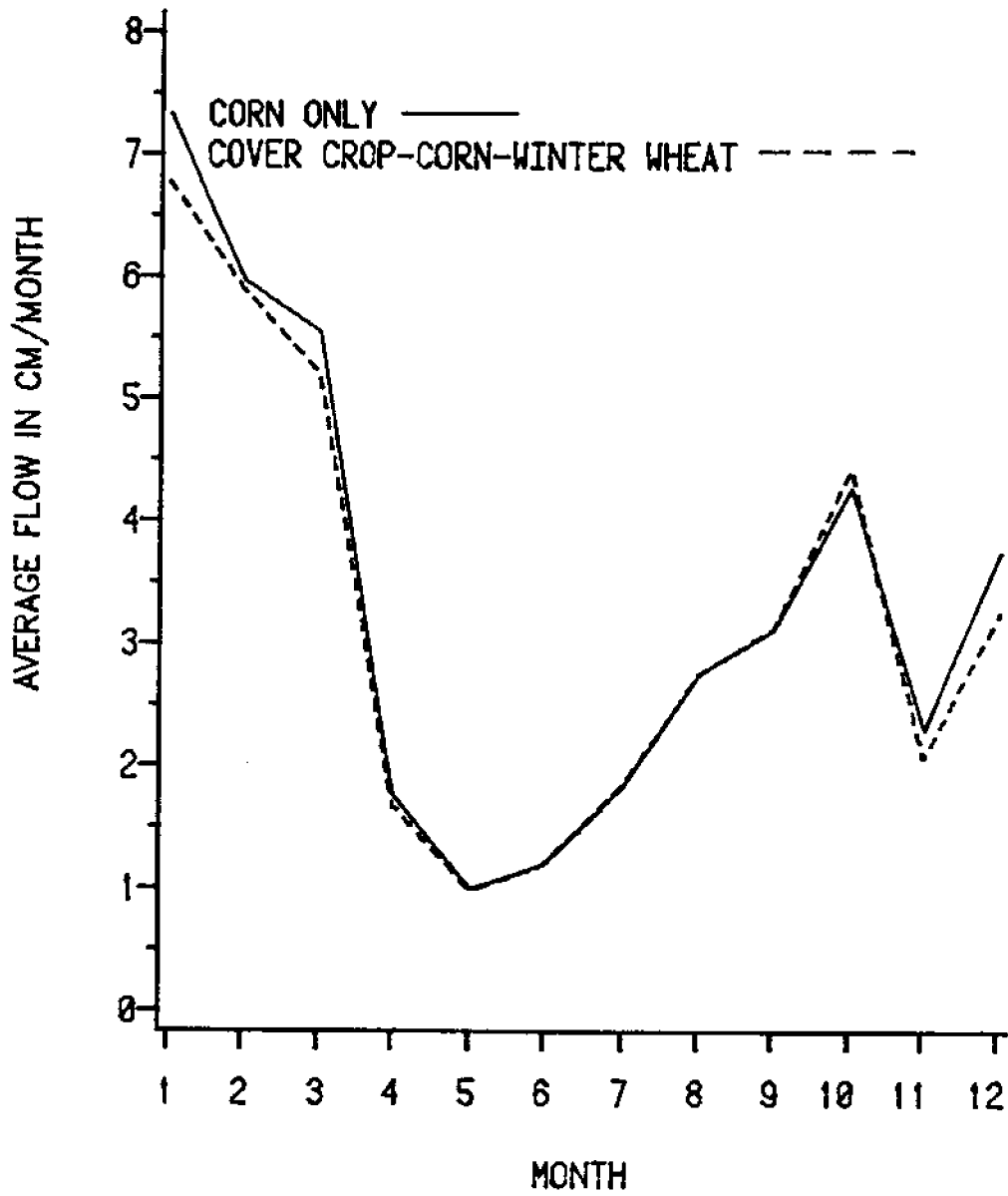


Fig. 3. The effect of cover crop on outflow for a well drained field.

FOR A DRY YEAR WITH GOOD SUBSURFACE DRAINAGE

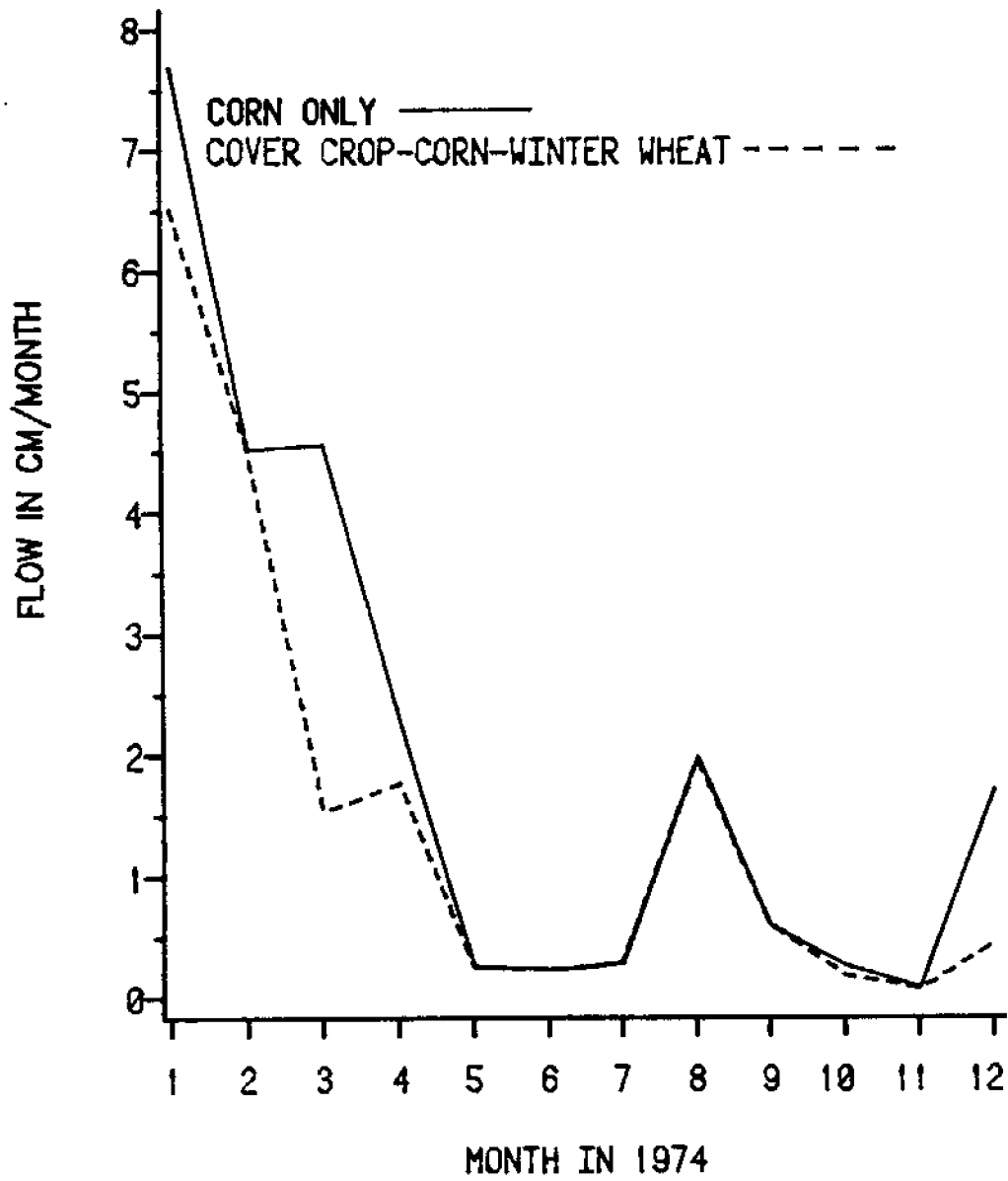


Fig. 4. The effect of cover crop on outflow during a dry year.

FOR GOOD SUBSURFACE DRAINAGE

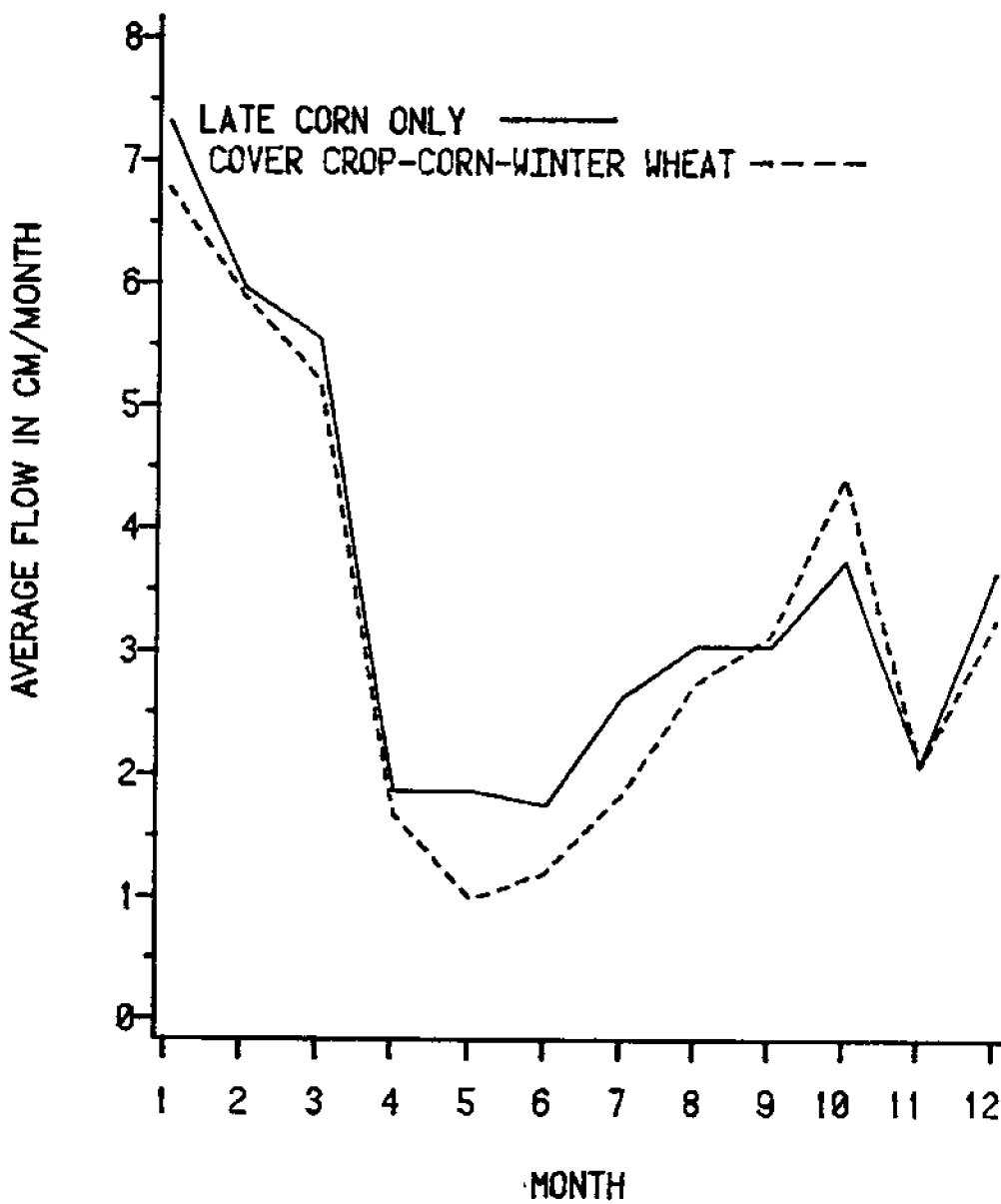
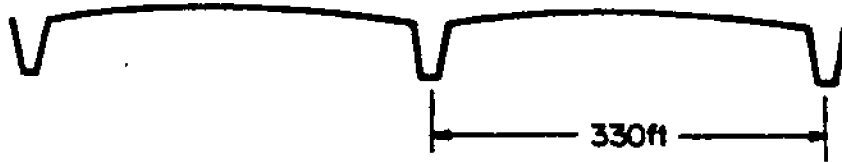
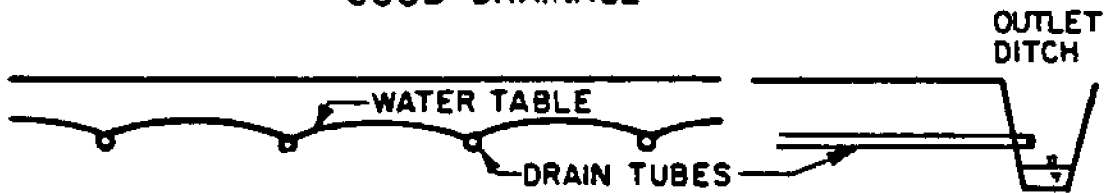


Fig. 5. The effect of planting date on outflow for a well drained field.

CONVENTIONAL OPEN DITCH DRAINAGE



GOOD DRAINAGE



CONTROLLED DRAINAGE AND SUBIRRIGATION



Fig. 6. Schematic diagrams of (1) conventional open-ditch drainage (top); (2) good subsurface drainage with no irrigation (middle); (3) a controlled drainage - subirrigation system (bottom).

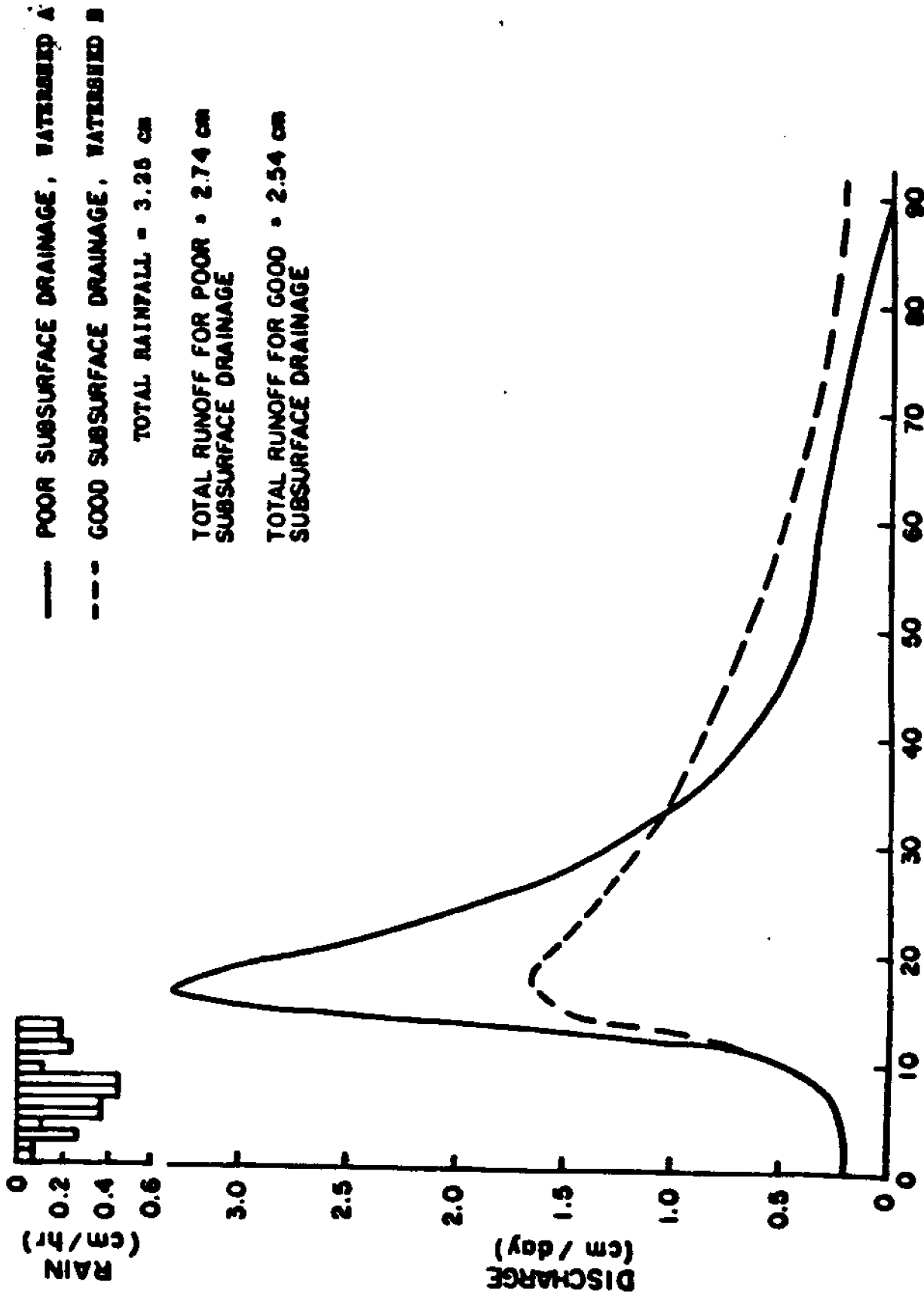


Fig. 7. Runoff hydrographs for 3.25 cm rainfall event on Feb. 28, 1983. The peak runoff rate for watershed A with poor subsurface drainage was more than twice that from the adjacent watershed B which had good subsurface drainage.

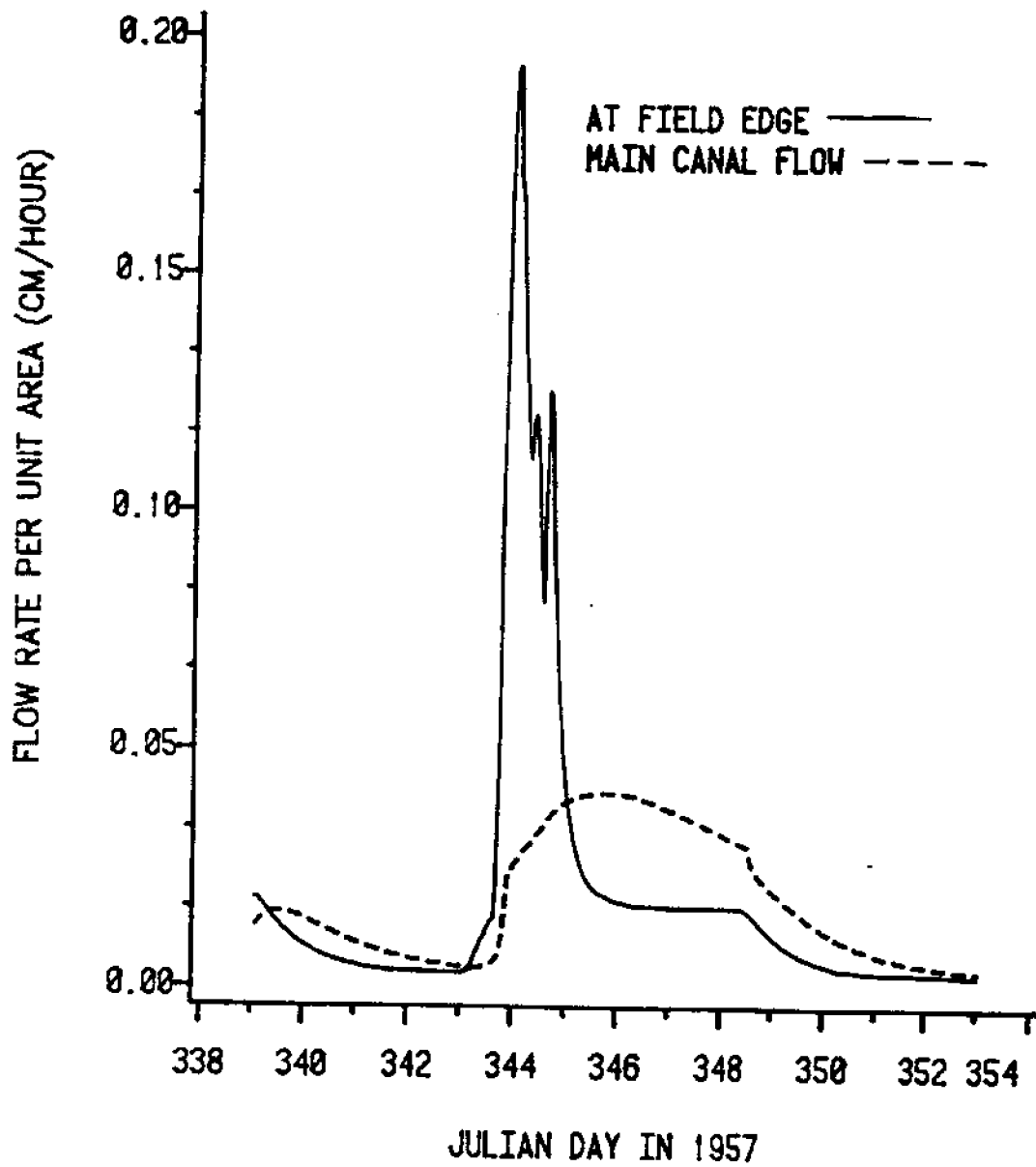


Fig. 8. The impact of the canal on flow rates during a large runoff event.

RESPONSE OF ROSE BAY TO FRESHWATER INPUTS

L.J. Pietrafesa

I. INTRODUCTION

Over the past several years, NCSU investigators have monitored salinity (actually temperature, conductivity and pressure) at a series of fixed locations in and about Rose Bay (cf. Figure 2) and Juniper Bay (cf. Figure 3), along the southwestern mainland coast of Pamlico Sound (cf. Figure 1). The point of the study was to determine the spatial and temporal variability of salinity, and the sources of this variability well enough to establish a predictive capability of the variable. The predictive model is on line and is undergoing final refinement and verification.

Salinity is a property of North Carolina estuarine nurseries which has been monitored relatively successfully using present technology. While measuring salinity, time series of atmospheric wind magnitude and direction, water level elevation and slope, current speed and direction, precipitation, atmospheric temperature and pressure, and of course, water temperature, pressure and conductivity were also monitored at the sites shown in Figures 2 and 3. Representative examples of mooring configurations with sensors in-place are shown in Figures 4-11.

The salinity model methodology and data analysis techniques used in this study were derived from Weisberg and Pietrafesa (1983). The model methodology is succinctly summarized in Figure 12.

We next discuss the "setting" in Section II and present a summary of field results in Section III. In Section IV a model of Pamlico Sound circulation with selected results is presented to allow the dominant forcing function to be appreciated. A final summary is provided in Section V.

II. PAMLICO SOUND NURSERY SETTING

Pamlico Sound, North Carolina, contains the principal nursery areas along

its main and periphery for fish juveniles in N.C. The Sound has come under scrutiny in recent years because of increased utilization of water and adjacent lands by commercial, municipal and recreational users and because of its ultimate importance to the commercial fishing interests of N.C.

The Pamlico Sound, is the largest barrier island estuary in the United States (shown in Figure 1). Its approximate dimensions are 110 km in the northeast-southwest direction and 25-55 km in the northwest-southeast direction, and its approximate area is 4350 km². (Roelofs and Bumpus, 1953). A relatively deep water area is located in the west end of the sound with a maximum depth of about 6 m. Shoaling regions are found near the mouths of the Neuse and Pamlico Rivers and close to the inlets of the Outer Banks. Because of the extensive shoals around the margin and projecting into the sound, the mean depth is about 5 m. The main inlets connecting the Pamlico Sound to the Atlantic Ocean are Ocracoke, Hatteras and Oregon. The system is fully depicted in Figure 13.

Fresh water flows into the sound from the Neuse and Pamlico Rivers and from the Chowan and Roanoke Rivers, which empty into the Albemarle Sound and then into the Pamlico Sound via the Roanoke and Croatan Sounds. Evaporation exceeds rainfall in the summer and the converse occurs in winter. Annually, the rainfall into the Sound and the evaporation from the Sound are nearly equal.

The water temperature within the sound is generally isothermal. Roelofs and Bumpus (1953) claim that vertical temperature differences within the Sound do not exceed 2°C. Horizontal temperature gradients occur near the inlets due to temperature differences between the Sound and coastal ocean. Horizontal temperature differences within the Sound itself are smaller than the diurnal variability of up to 3°C.

It has been suggested by Roelofs and Bumpus (1953), Posner (1959), and Woods (1967) that wind and freshwater runoff are the factors controlling the horizontal salinity distribution in Pamlico Sound. This is not the entire story. The combination of northerly winds and freshwater inflow from Albemarle Sound drives low salinity water down into northern Pamlico Sound. Winds from the southwest have the opposite effect. In the southern part of the Sound, highest salinities (9-19‰) are found at Ocracoke Inlet. In the northern part of the sound, the lowest salinities occur near the Albemarle Sound. It should be noted that the inlets are the source of salt with Ocracoke and Hatteras supplying Gulf Stream derived high salinity water to the Sound. As with temperature, salinity tends to be well mixed vertically within the Sound. Roelofs and Bumpus (1953) estimated the average surface to bottom salinity differences to be 0.66‰.

Miller, Reed and Pietrafesa (1984), discussed the migratory routes of five species of estuarine dependent fish larvae and juveniles along the North Carolina continental shelf. They found that these particular finfish, which constitute only 10% of the types of fish species, yet comprise 90% of the annual commercial catch in N.C. coastal waters, all spawn in winter near the Gulf Stream, migrate 100 km to major inlets in the barrier islands and then another 25-100 km to juvenile estuarine nursery areas across Pamlico Sound (shown in Figure 13). The migration scenario is presented in Figure 14.

III. OBSERVATIONAL FACTS

There is no relationship between the changes in water level in Rose Bay proper and the discharge from, or flow into, the Lake Mattamuskeet Canal mouth, which connects directly with Rose Bay Creek (as is revealed by representative data shown in Figure 15).

The seasonally averaged salinity at the head of Rose Bay Creek (cf. Figure 2) is nearly a constant from summer through winter, varying between a nine-month low of 6.8 ppt which occurs in summer to a wintertime high of 6.95 ppt. This finding belies the fact that at this site, salinity fluctuations are a maximum relative to those measured at any other site in the Rose Bay system. During the spring, the value at this site drops to between 3.7 - 4.9 ppt depending on the amount of precipitation during March, April or May, with the lower value evident during the Spring of 1983 and higher value measured in 1984. In fact between February - April, 1983, a 9.6 inch differential of additional rain fell relative to the like period in 1984.

There is a 4 ppt increase in salinity from the head of the Creek to the Creek Mouth, i.e. to the point of intersection of Creek to Bay, during winter. The value drops to 3.1 ppt during summer. The value of S at the surface of the Creek Mouth, or equivalently, the Bay Head, are equal to the bottom salinities at the Creek Head. This translates to a 3-4 ppt increase in S over 1 meter of water at site 1 (cf. Figures 2,5).

The seasonal means of salinity at the Bay Head (actually site 6 in Figure 2) reaches its yearly high of 11 ppt during winter, and descends to between 5.6 - 8.2 ppt, depending on whether the spring is relatively wet vs. dry, respectively. During summer, mean S is at 10 ppt and by fall, the value has risen to 10.5 ppt.

In the middle of Rose Bay, at sites 5 and 4 (cf. Figure 2), seasonal mean values of S are alike those at the Bay Head (site 6) but are approximately 1.6 ppt higher, i.e. a wet spring reflects a mean salinity of 7.2 and a dry spring reaches 9.8, ppt.

In the lower reaches of the Bay, mean salinities are generally 1-2 ppt higher than at the Bay Head and outside of the Bay Mouth, seasonal mean salinities in ppt are approximately 14 - 15 during winter, 6.5 - 8 during

spring, and 12 - 13 during summer and fall.

Salinity Histograms (eg. Figure 1b) reveal the fluctuation variability as a function of frequency, of particular salinity value realization and of location within Rose Bay proper, up the Creek and at the Bay mouth.

At the head of the Creek, above the intersection of the mouth of the Lake Mattamuskeet Canal and the Creek, salinity values range from 0 - 13 ppt during any period of the year. Seasonally averaged values at the surface range between 6.8 and 7.0 ppt year round while at the bottom, values range from 7.0 to 10.2 with the latter a summer value and the former the winter condition. The variability, about the seasonal mean, at this site is more pronounced than anywhere else in the Rose Bay system. One standard deviation is equivalent to 3.4 ppt and during the period January - March, salinity values are within 1 ppt unit value of the mean, only 22% of the total time. In fact, salinity varies more than ± 1 ppt, a 2 ppt differential from zero, during any consecutive 12 hour period, more than 45% of the time. Incredibly, 19% of the time, consecutive 12 hour salinity values fluctuated between $\pm 4 - 6$ ppt over any consecutive 12 hour period. This is not the case at any other Rose Bay station.

The mouth of the Lake Mattamuskeet Canal intersects with Rose Bay Creek. At this site, salinities range from 0 - 13 ppt during any period of the year. The seasonal mean ranges from 6 - 8 ppt with the former a winter value and the latter, the summer counterpart. Salinity fluctuations at this location are similar to those at the Creek Head site with values more greatly centered about the mean. There is a tendency, however, for salinities to drop suddenly. While salinities increase between 1 - 2 ppt, 10% of the time, they drop 1 - 2 ppt, 46% of all consecutive 12 hour periods; the obviousness of fresh water discharge.

At the Creek intersection with Rose Bay, summertime values range from

7 - 14 ppt, with a mean of 10 ppt, fall sees a range of 8 - 13 ppt centered about 10.5 ppt, wintertime values are between 4 - 15 ppt centered at 11 ppt and spring values range from 1 - 10 ppt centered at 6 ppt. During the summer and fall, salinities vary less than ± 1 ppt 99.5% of any consecutive 12 hour block. During the period January - March salinity is most variable at this upper bay site with less than ± 1 ppt changes occurring only 77% of any consecutive 12 hour period. Twenty-three percent of the 12 hour time increments, the S fluctuations are between $\pm 2 - 4$ ppt with the weighting towards occurrences of decreases due to fresh water discharge pulses. From April - June the site becomes relatively more stable with a greater than 90% occurrence of variations with a magnitude of less than ± 1 ppt.

In the middle of Rose Bay the average salinity values and ranges are: 12 and between 9 - 14 ppt during summer, 11 and from 7 - 14 during late winter dropping to 6 and 3 - 9 during late spring. Fluctuations in excess of ± 1 ppt over any 12 hour period occur less than 3% of the time from late spring to winter, increasing to approximately 25% during late winter.

In the lower reaches of the bay, salinities approach values akin to those in southwestern Pamlico Sound with values ranging from 7 - 16 about an 11 ppt mean during summer, and fall and 6 - 18 and 13 ppt mean during late winter. The spring range is 2 - 11 about a 6 ppt mean. Throughout the entire year, fluctuations in salinity exceed ± 1 ppt less than 10% of the time over any consecutive 12 hour period at the top and less than 15% at the bottom over any consecutive 12 hour period. This reflects the fact that sub-diurnal frequency forcing is occurring at the mouth via Pamlico Sound. It should be noted that the range of salinity values is larger at the bay mouth than at either the upper bay proper location or at mid-bay where the spread in salinity is a relative minimum, but the lower bay fluctuations occur over periods of several

days rather than over several hours to a day.

In the southwestern corner of Pamlico Sound, we see a summer salinity range of 7 - 17 ppt, a fall range of 7 - 18 ppt, a winter range of 6 - 18 ppt and a spring range of 2 - 13. Means are 12, 12.5, 14 and 7 ppt during the summer, fall, winter and spring periods respectively. In order, summer, fall, winter and spring realizations of salinity fluctuations occurring within ± 1 ppt over consecutive 12 hour periods are 81%, 93%, 85% and 92%, respectively.

In summary, at the Creek Head, salinity does not vary more than one ppt over any consecutive 12 hour period only 22% of the time during the period January - March and no more than 33% thereafter. At the Canal mouth the like figures are 26% and 37%. As we move to Rose Bay proper, the upper bay indicates more stability in that salinities are within 1 ppt 38% of any consecutive 12 hour period during winter and 44% thereafter. The Creek realizes the most rapidly varying salinity fluctuations. The bay mouth, while less influenced by high frequency phenomena than the Creek is more stable than either the upper or middle bay where the system's salinity varies more slowly. A representative composite of histograms of salinity and salinity fluctuation distributions is presented in printout Figures 16 and 17.

Figure 18 provides a pictorial depiction of the varying degrees of sub-diurnal frequency salinity fluctuations throughout the Rose Bay system. Even at periods longer than 2 days, the dramatic fluctuations which occur at the mouth versus the more quiescent Bay middle are evident. Higher frequency fluctuations showing the rapidity of salinity fluctuations within the Creek and at the lower extremities of the Bay, i.e. near the junction with Pamlico Sound, are shown in Figure 19.

The question is then, what is responsible for the observed variability of salinity within the Rose Bay system.

If we consider the swath of data collected between 1982 and 1984 within Rose Bay, we reach the following conclusions:

- (1) Salinity fluctuations in the middle of Rose Bay are controlled by both land drainage of fresh water due to precipitation and by "non-local" forcing which occurs at the mouth of the Bay, i.e. at the juncture between Pamlico Sound and Rose Bay. The fluctuations occur over a several day period after either a rain or wind event and are generally within ± 1 ppt. Salinity will drop by 1 to 2 ppt due to rain events the order of 0.3 to 0.6 inches with a time span of 2 - 4 days. Salinity will decrease (rise) 1 to 2 ppt due to a northeastward (southwestward) wind event which causes Rose Bay to drain (fill up) into Pamlico Sound (with Sound waters).
- (2) Salinity fluctuations at the Bay mouth are virtually totally controlled by the nuances of the wind induced circulation in the south and western portion of Pamlico Sound. The fluctuations in salinity occur within 10 hours of the onset of a wind event and persist for the length of the event. Fluctuations can rise or fall as much as 4 ppt within 12 hours given typical energetic winter storms which are omnipresent in the Cape Hatteras region where major atmospheric systems meet.
- (3) Salinity fluctuations at the Bay Head are jointly controlled by drainage from precipitation events, discharge from the Mattamuskeet Canal and the effects of non-local forcing at the Bay mouth by Pamlico Sound. Precipitation and drainage events lower salinities by 1 - 3 ppt between 0.5 to 5 days and drive flow away from the Head towards the mouth. Northeastward wind events have the like effect. Alternatively, southwestward wind events drive relatively higher

salinity Sound derived waters towards the head within 10 hours to 5 days. If rain accompanies the southwestward wind event then surface salinities may either increase or decrease as a function of relative effect while bottom water will become more saline.

- (4) Salinity fluctuations in the southwestern corner of Pamlico Sound are controlled by the wind induced circulation within the Sound over periods of hours to a month. Over periods of weeks to seasons, Pamlico Sound salinity fluctuations are caused by ocean induced currents, which enter and leave the system through the barrier island inlets carrying relatively more or less salty water as they move. The net effects of winter versus spring seasonal values of salinity is a change of 7 ppt in salinity in the southwest corner of the Sound; at the mouth of Rose Bay. The net effects of 1 - 10 day wind events on salinity in the SW corner of Pamlico Sound is a variation in S by as much as ± 4 ppt within 12 hours.
- (5) The Head of Rose Bay Creek is graced by salinity fluctuations which astound the unsuspecting scientist. The Creek Head, which is only 2 meters deep can be overwhelmed by rain events, discharge from the Mattamuskeet Canal or non-local forcing of Rose Bay by Pamlico Sound. The system can be vertically well mixed and within a day realize vertical salinity differences of 5 ppt over 1 meter. Salinities can range from 0 to 13 ppt during any time of the year and in fact has been known to vary by 10 ppt within a 12 hour period via the penetration of a slug of Sound water or alternatively the incursion of fresh Canal or rain-water. The salinity distribution at this site looks like a block (as shown in Figure 16), a standard deviation is equal to 3.5 ppt, and a time series of S looks like a random walk with a constant (cf. Figure 17).

We can visually understand how precipitation events can cause salinities to drop or how land drainage can effect 5 - 10 day reductions of salinity and moreover how an unusually rainy year or how deforestation can result in a net dilution of salt but what of the most dominant forcing agent for salinity fluctuations; the Non-Local Forcing Mechanism? For this we consider the data set shown in Figure 20. Briefly, we note that when a wind blows from the directions of north and clockwise, southeast, a buildup of water is realized at the mouth of Rose Bay and the flow is into the Bay. With winds blowing towards the east and clockwise, to the north, there is a drop of water level in Rose Bay, water exits the Bay and the level of salinity drops. Conceptually, we see a pictorial response alike that shown in Figure 21. We now turn to a model of Pamlico Sound to corroborate or better understand the phenomena.

IV. WIND LOCAL FORCING, OF ROSE BAY BY THE WIND INDUCED CIRCULATION IN PAMLICO SOUND: A MODEL

We consider the subtidal frequency time dependent circulation in Pamlico Sound to be due to the atmospheric windfield. The density field is taken as uniform. The ratio of the baroclinic to the barotropic pressure gradient for Pamlico Sound, is 0.05, so a homogeneous model is acceptable. Also, since the ratio of surface elevation variation to water depth, η to H , is generally <0.01 , the model is assumed linear. While spatial variations of temperature and salinity may be important as a cue to the fish, the fronts are not important to the overall physical dynamics. We allow our model to be three-dimensional; as opposed to vertically integrated.

Previous sea level investigations in the Pamlico Sound have been limited to numerical simulations based upon simplifications to the vertically integrated momentum and continuity equations. These include Jarret, 1966; Smallwood and Amein, 1967; Hammack, 1969; Chu, 1970; Amein, 1971; Airan, 1974; and Amein and Airan, 1976. They support the observation of Roelofs and Bumpus (1953) that the wind is the major factor influencing circulation in the Pamlico Sound. Nonetheless these models all fail in their basic physics. In all of these models the bottom stress is taken to oppose the mean motion but, in reality the bottom stress opposes the mean bottom motion, which is frequently in opposition to the mean or vertically integrated motion. Hence, the bottom stress is incorrectly specified for wind driven cases by the above list of vertically integrated models. The time dependent wind stress is assumed spatially uniform. Turbulent, eddy stresses are modeled using a constant eddy viscosity coefficient. The Coriolis acceleration terms are retained in the model but since the vertical Ekman number is of order unity, the rotational effect is only slight.

The system of equations are now analyzed in detail.

We now present results from the model. Results of surface and bottom velocities and water level variation at ten hours after the onset of a 5 m/s wind blowing from the northeast (southwest) using an eddy viscosity of $100 \text{ cm}^2/\text{sec}$ are shown in Figures 22 and 23 (Figures 24 and 25). A time step of six minutes (well within the CFL criterion) is utilized in the computation. This model-run, used 42 seconds of computer time on the Triangle Universities Computational Center (TUCC) computer.

This model suggests that Pamlico Sound "spins up", i.e., reaches a quasi-steady state condition, in a period of less than ten hours after the onset of a steady wind. Recent studies of the coastal meteorology in this region (Weisberg and Pietrafesa, 1983) indicate that while there are monthly to seasonal mean winds which generally repeat from year to year, the major portion of the wind variability occurs over time scales of 2 days to 2 weeks.

Now on the coastal, seaward side of the barrier islands, the basic wind-driven dynamics have been described by Janowitz and Pietrafesa (1980) and Chao and Pietrafesa (1980). An example of coastal sea level at Cape Hatteras, an open coastal station, responding to local winds is shown in Figure 26. In effect, northward to northeastward winds cause sealevel to drop at the coast in concert with a surface Ekman transport offshore and vice-versa for winds which are southward to southwestward; i.e. sealevel rises at the coast. The response occurs within a period of 8-10 hours. This response has been shown by Pietrafesa, Chao and Janowitz (1980) to occur from Cape Hatteras to Charleston and undoubtedly occurs at the Pamlico Sound barrier island inlets as well with southward or northward winds being important for coastal convergence or divergence, respectively. The question then is, does this phenomenon occur at the inlets and if so what are its implications?

The barrier island inlets experience the effect of non-local forcing, or one-sided divergences and convergences of water on either side. As it occurs, given the basin-barrier island geometry, when the flux of water is away from the offshore side of the barrier islands, there is a flux towards the backside, or Sound side of the islands. The opposite scenario also holds true. These inshore divergences (convergences) in sync with offshore convergence (divergences) create pressure gradients, sea level drops (rises) from ocean to sound through the inlets which cause tremendous "floods" ("ebb") jets through the inlets.

V. SUMMARY

Several years of salinity and other physical oceanographic data have been culled to evaluate the nature and source of salinity variability in juvenile fish nurseries located along the periphery of Pamlico Sound. Rose Bay and Juniper Bay are the two specific nurseries studies. The end product of this effort was to be twofold: Firstly, a description of the salinity fluctuations was to be established along with an assessment of the causal functions; secondly, a predictive capability, i.e. a cause and effect transfer function model of salinity was to be established. The first end product has been accomplished, i.e. the field work support monies have run out. The second product is on-line and is being verified using 1985 Rose Bay data and 1983-85 Juniper Bay data.

The maximum variability of salinity which was observed in two primary nurseries occurred in the upper reaches of the nursery where the diffuse salt block meets the volumetrically largest amount of fresh water. Direct rainfall, lake canal freshwater discharge sources and land drainage contend with salty sound waters to make for a salinity structure which changes over periods of hours.

Bay mouths are next in order of salinity variability. Here the dominant influence is the Sound with secondary influence due to land drainage derived effects.

The most quiescent part of the nursery Bays appears to be mid-bay. At this local the system is receiving input from either end, the top and the sides and consequently tends to be alike the middle of a pot of stirred stew. There is a little of everything already there and adding more or less does not have the dramatic effect that is realized at either end, particularly the upper end.

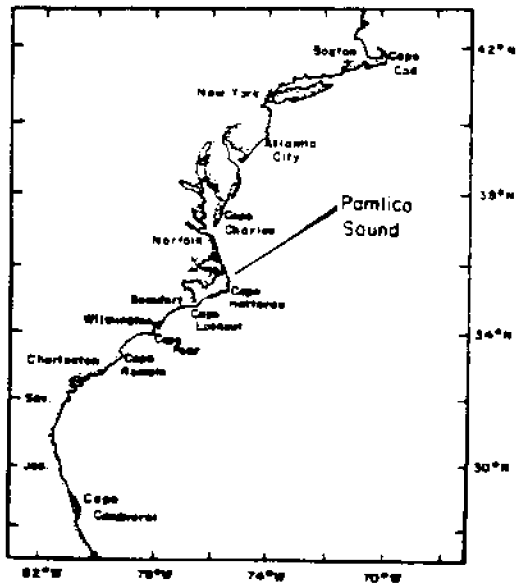
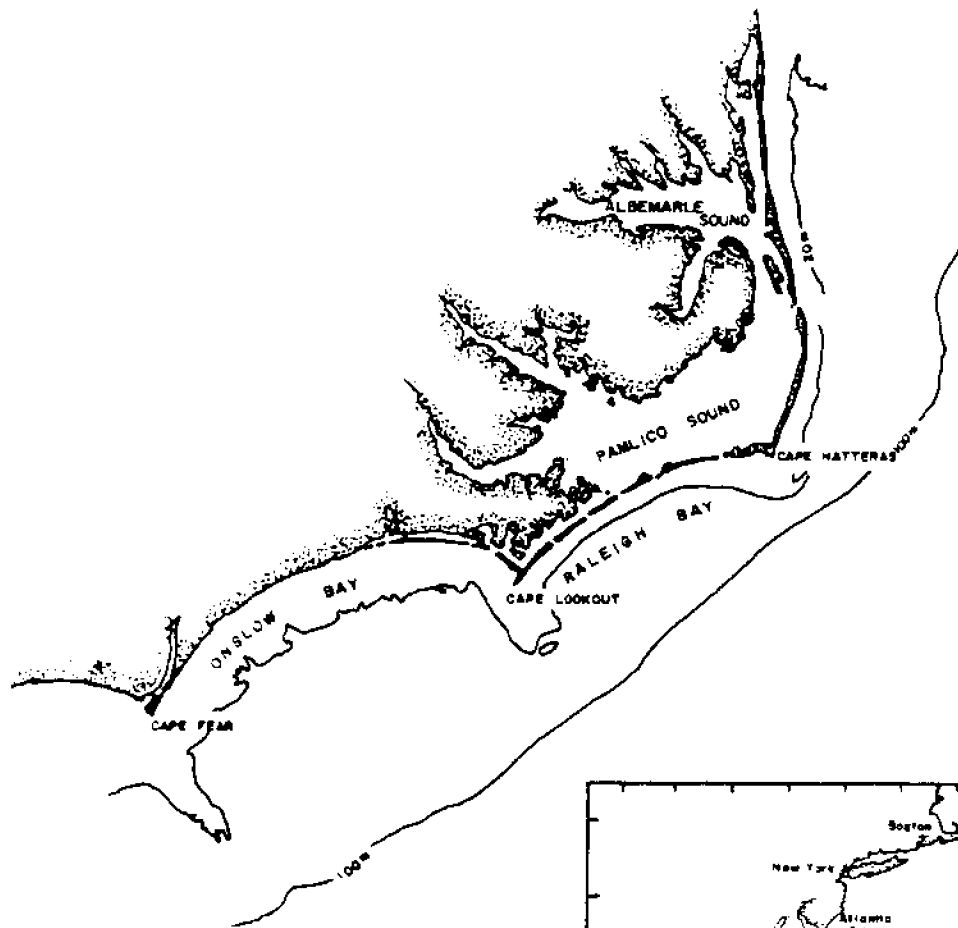


Figure 1. Pamlico Sound

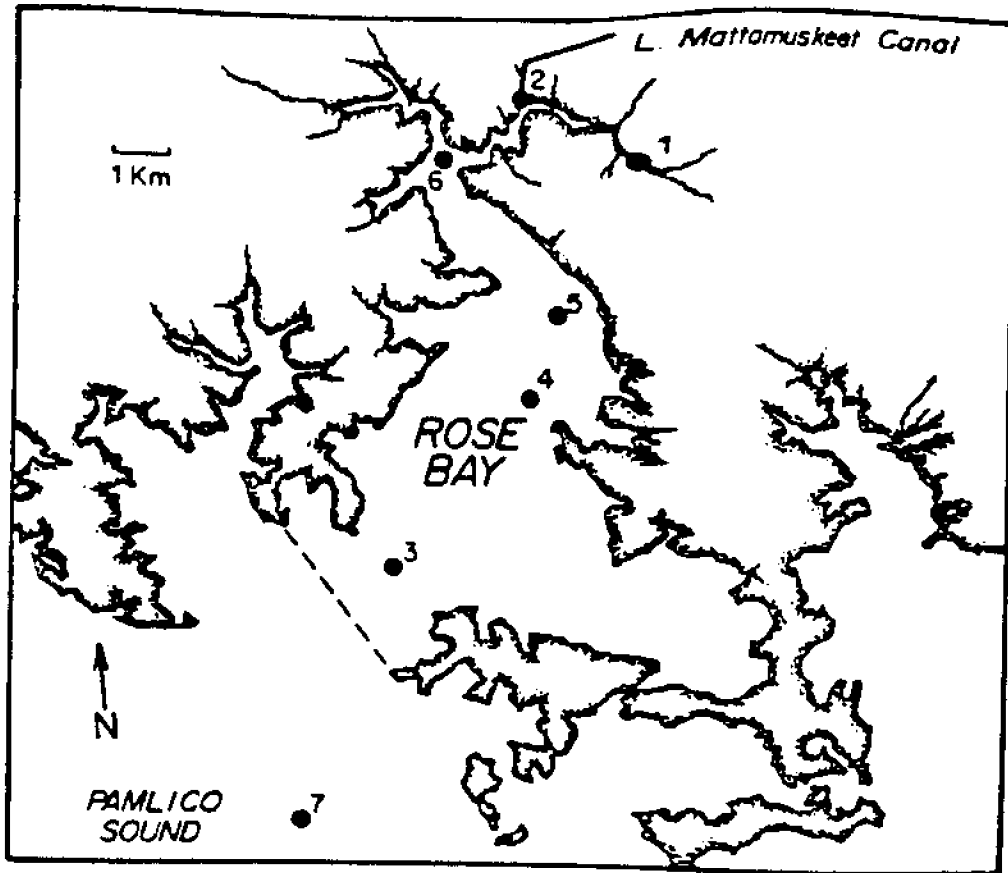


Figure 2. Rose Bay
Experiment Mooring Locations.

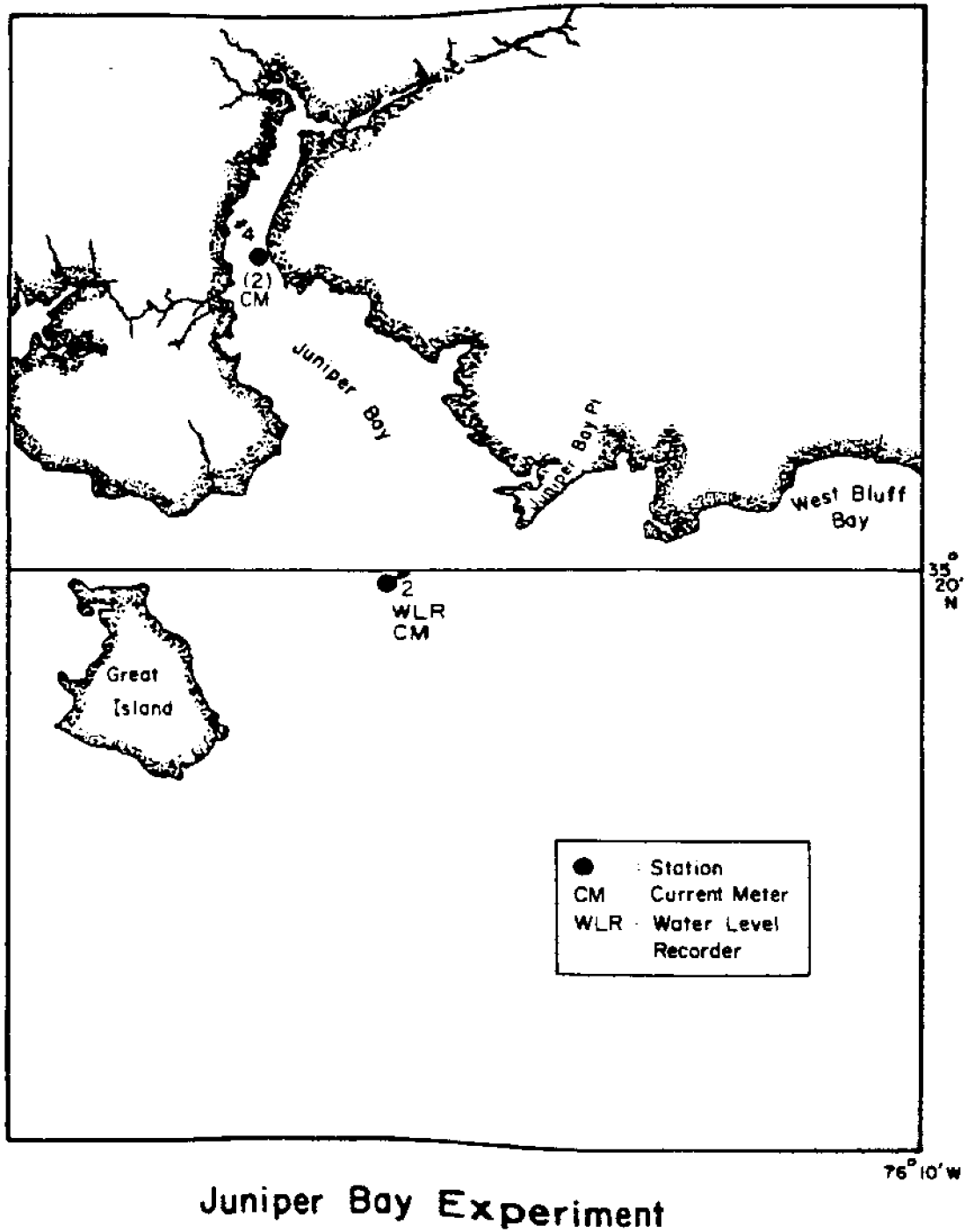
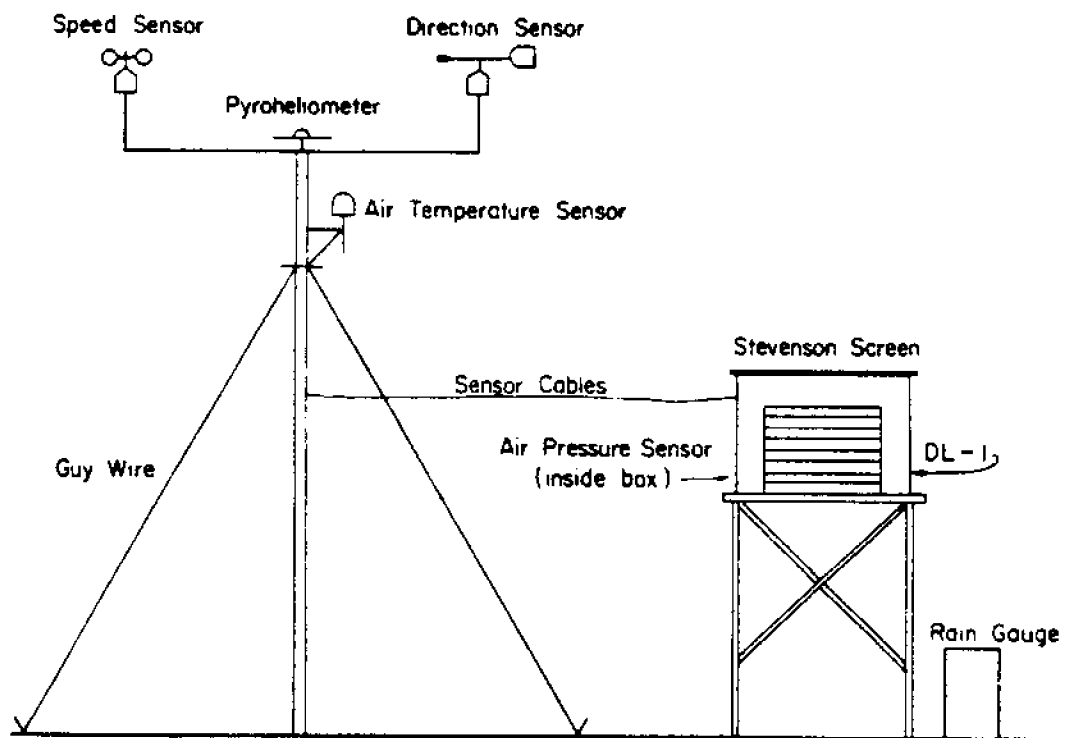


Figure 3. Juniper Bay Experiment Current Meter Locations.



**WEATHER STATION
ROSE BAY EXPERIMENT**

Figure 4.

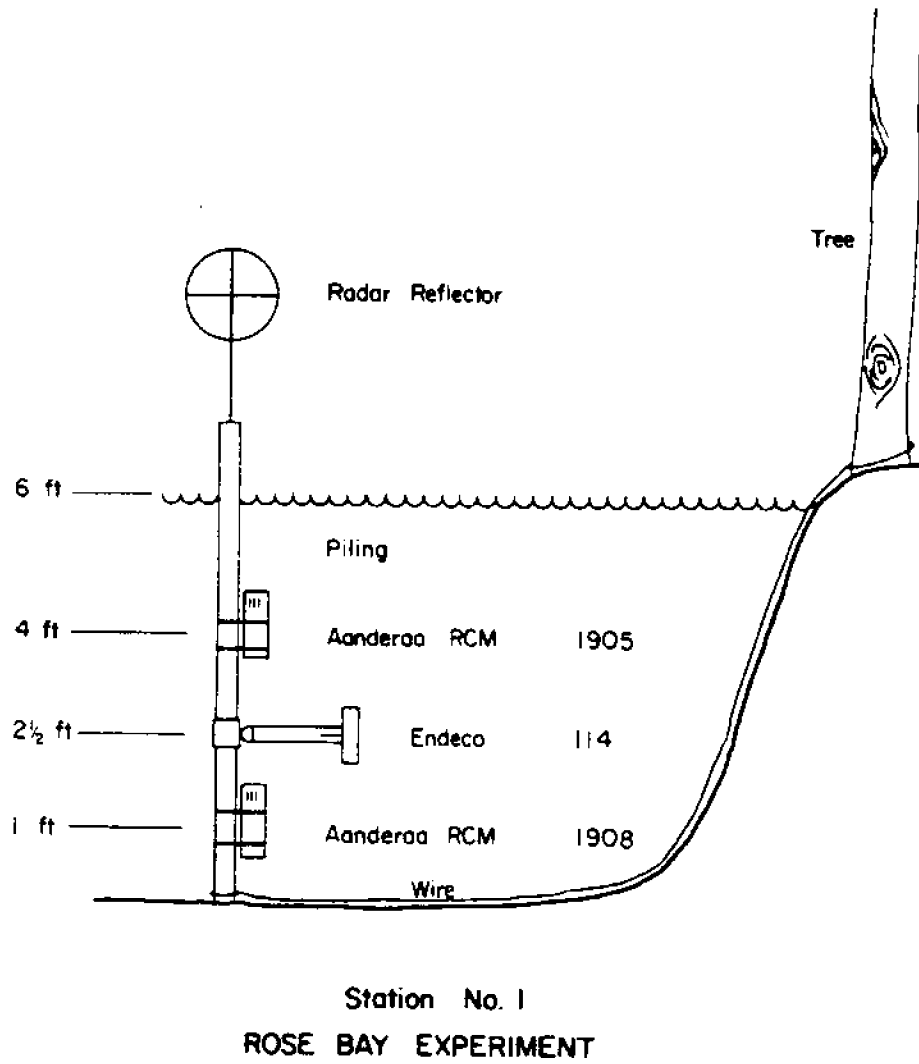
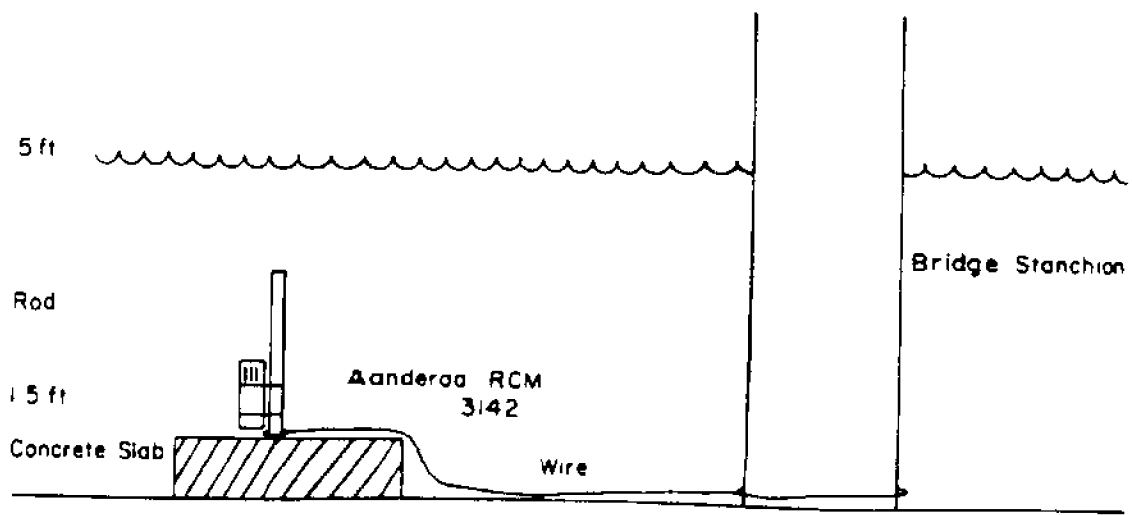
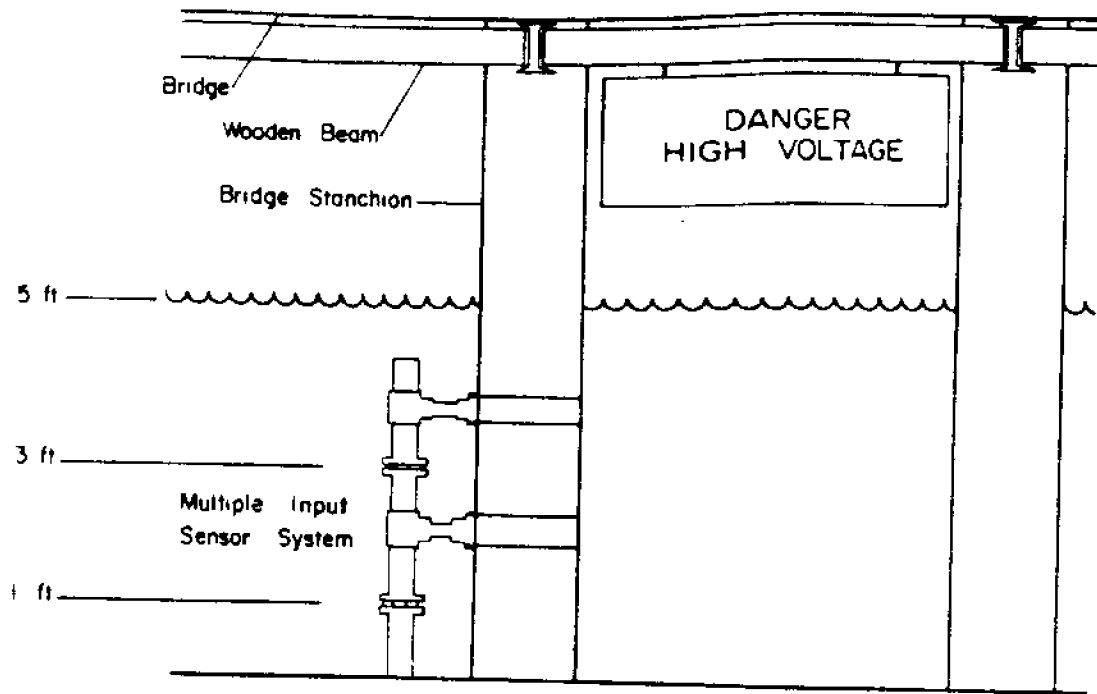


Figure 5.



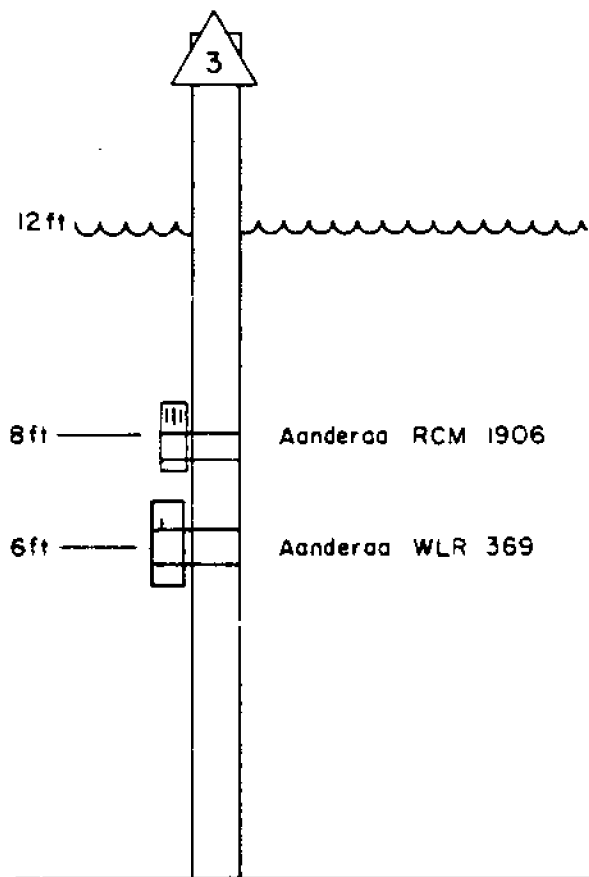
Station No. 2
ROSE BAY EXPERIMENT

Figure 6.



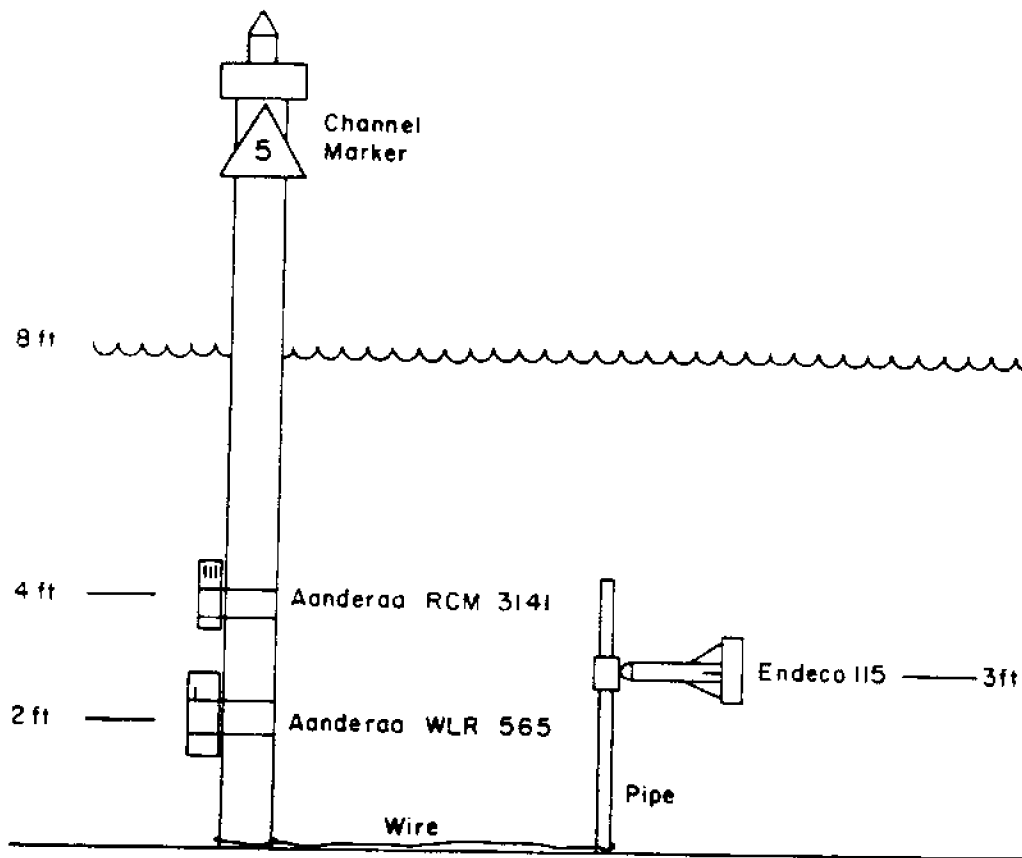
Station No. 2b
ROSE BAY EXPERIMENT

Figure 7.



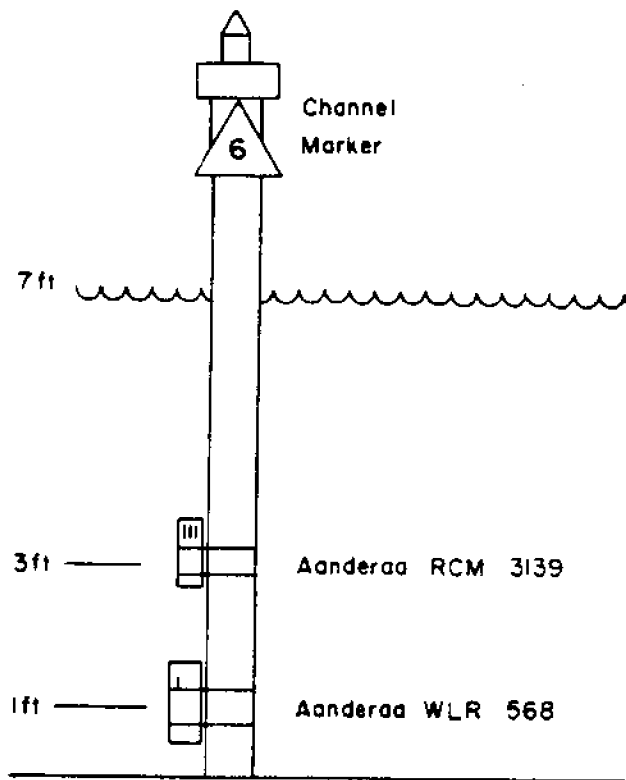
Station No. 3
ROSE BAY EXPERIMENT

Figure 8.



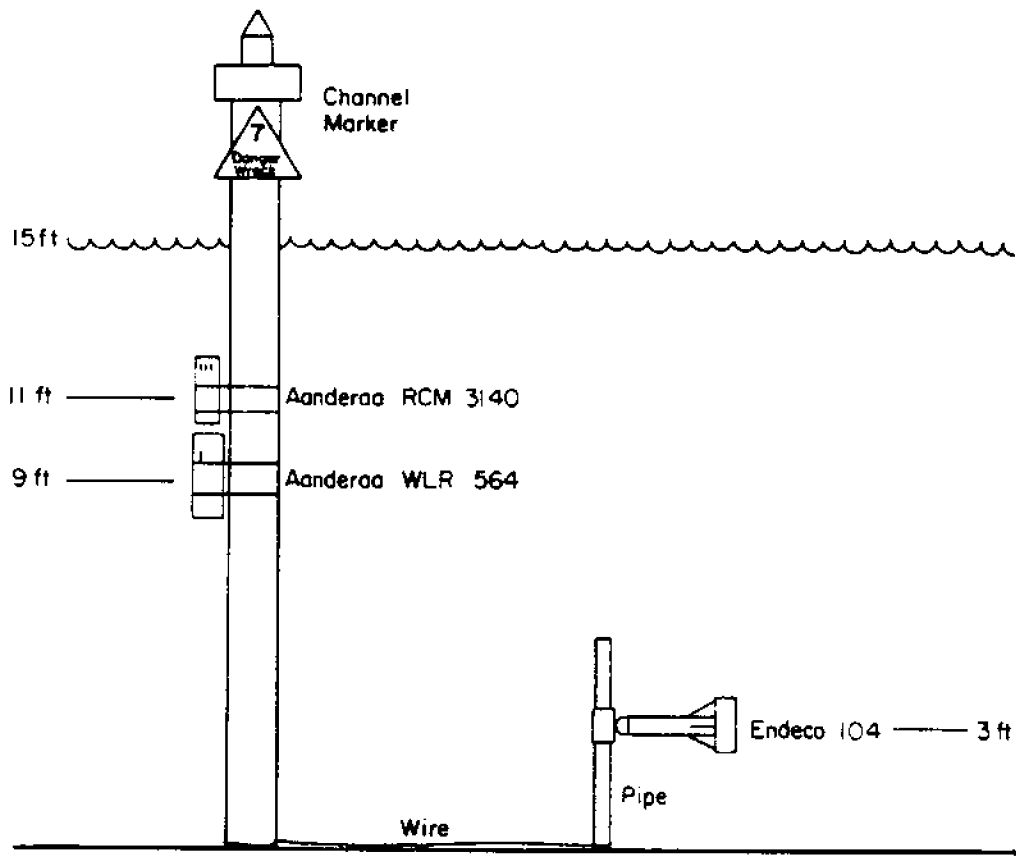
Station No. 5
ROSE BAY EXPERIMENT

Figure 9.



Station No. 6
ROSE BAY EXPERIMENT

Figure 10.



Station No. 7
ROSE BAY EXPERIMENT

Figure 11.

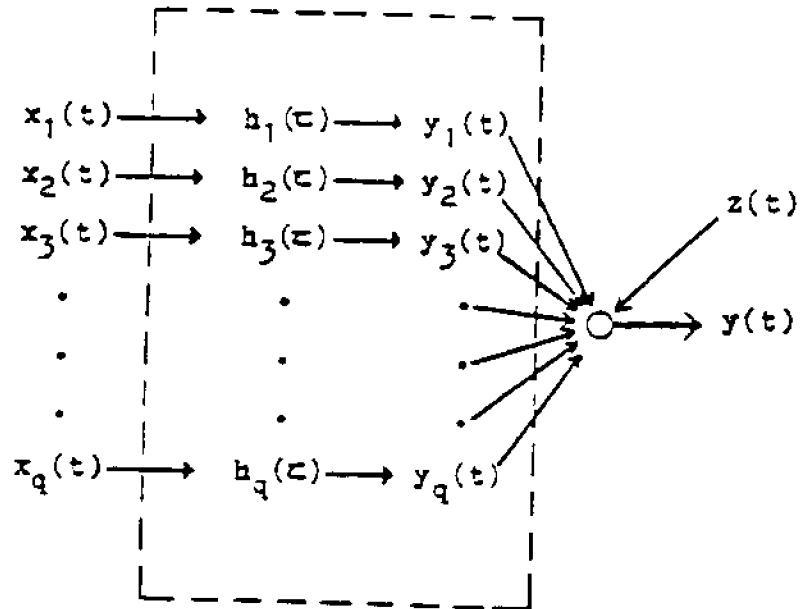


Figure 12. A schematic diagram of a multiple input linear system used for computing transfer functions and coherencies. where $x_1, x_2, x_3 \dots$ $y(t)$ is the sum of the q inputs $x_i(t)$ convolved with impulse functions $h_i(t)$ plus a residual term $z(t)$.

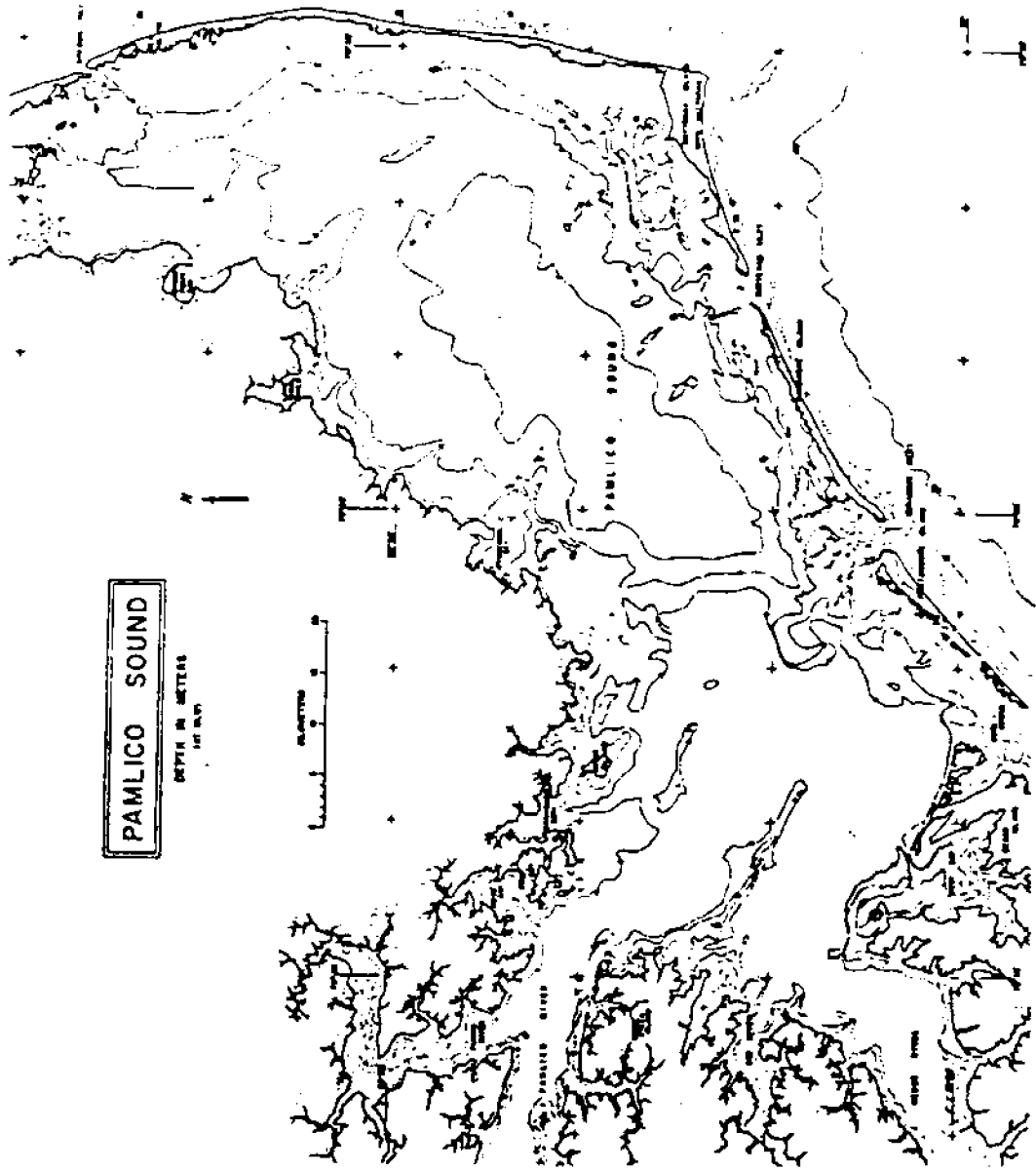


Figure 13.

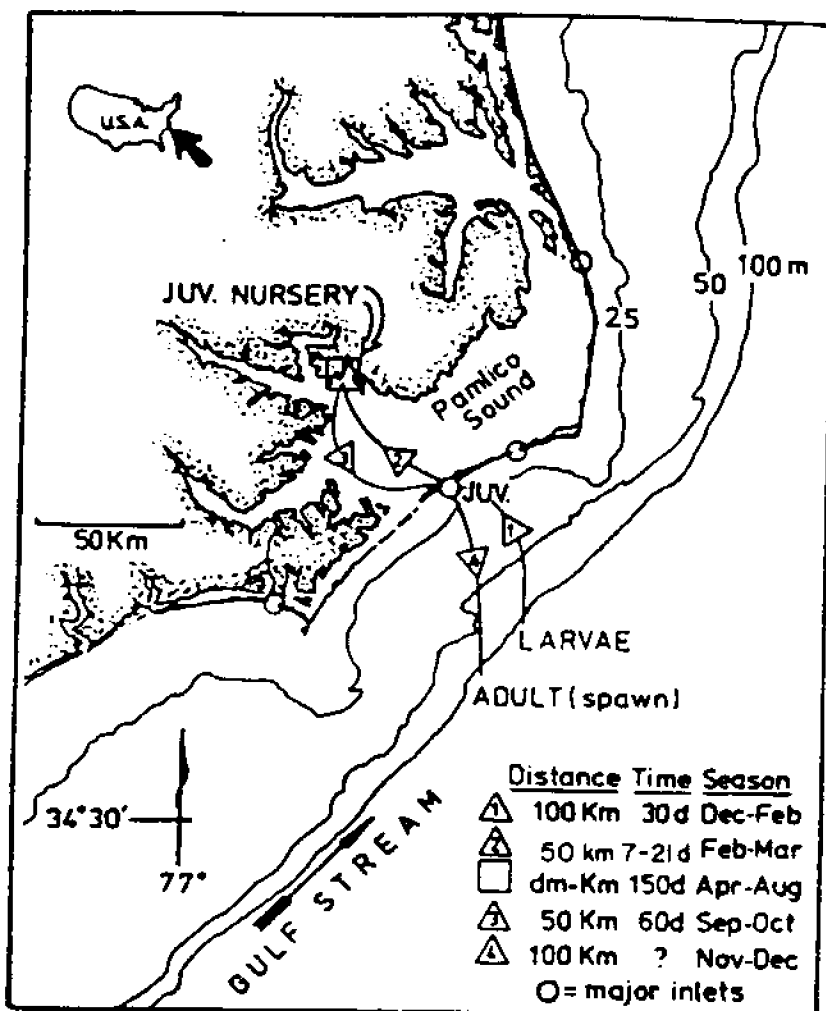


Figure 14. Migration pattern of five dominant fish species of North Carolina, including: Menhaden (*Brevoortia Tyrannus*); Spot (*Leiostomus Xanthurus*); Croaker (*Micropogonias Undulatus*); and Flounder (*Paralichthys Dentatus* and *Lethostigma*). From Miller, Reed and Pietrafesa (1984).

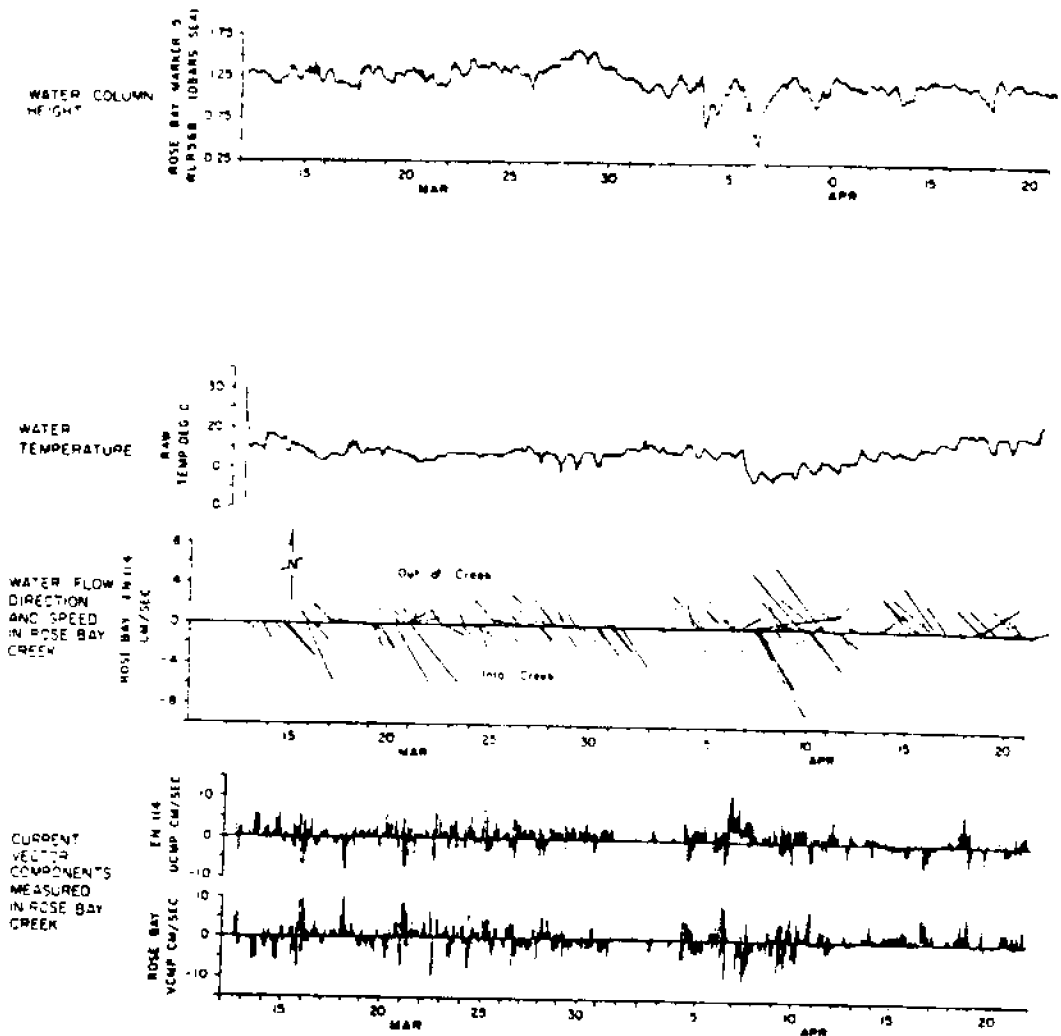


Figure 15. Height of water column in Rose Bay vs. discharge out of Lake Mattamuskeet Canal. The discharge has little effect of elevation.

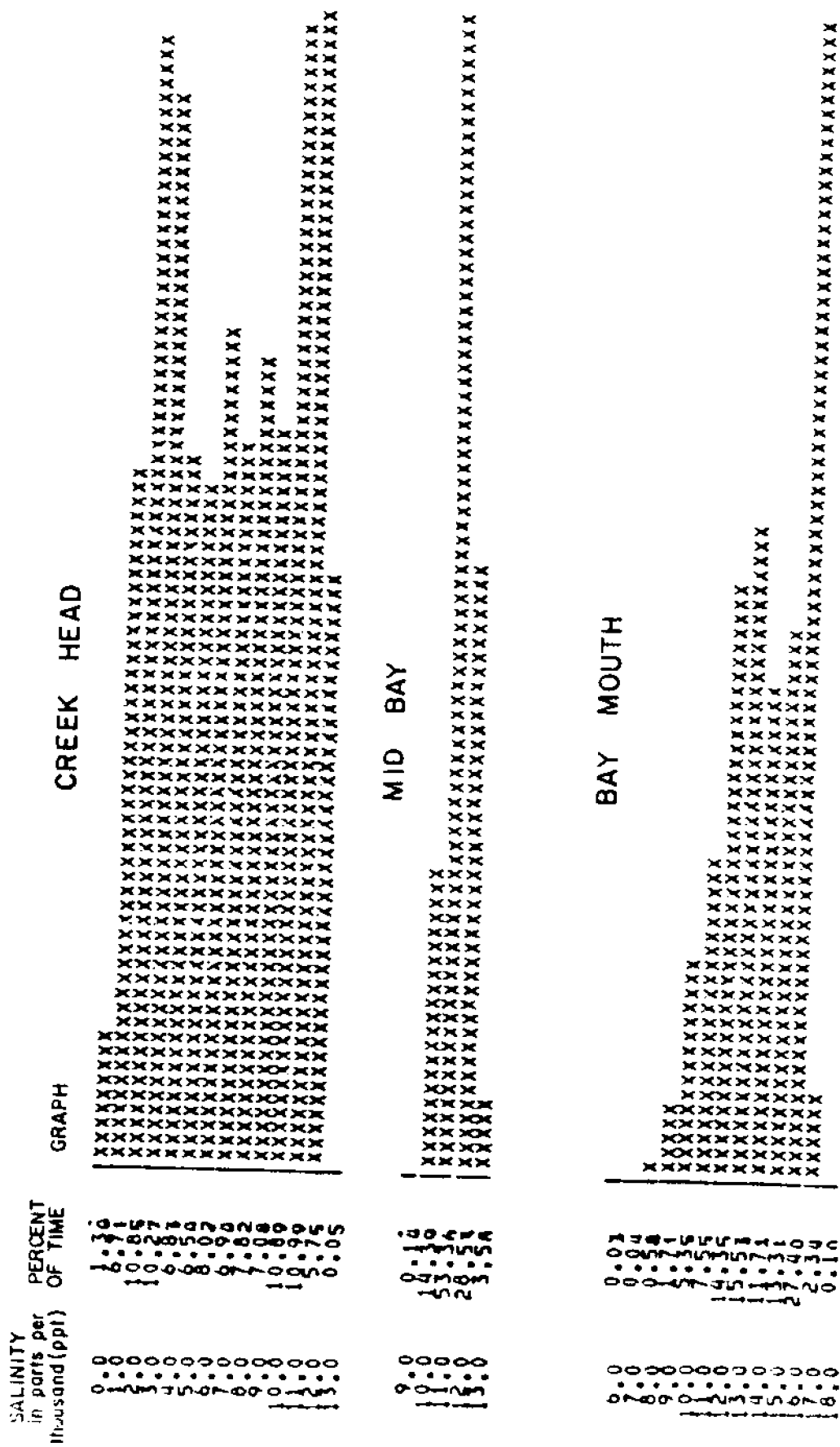


Figure 16. Distribution of salinity in terms of percent of time at the Rose Bay Creek Head, Mid Rose Bay and the Bay Mouth. The range of S is greatest at the tributary Creek Head and least in the middle of the Bay.

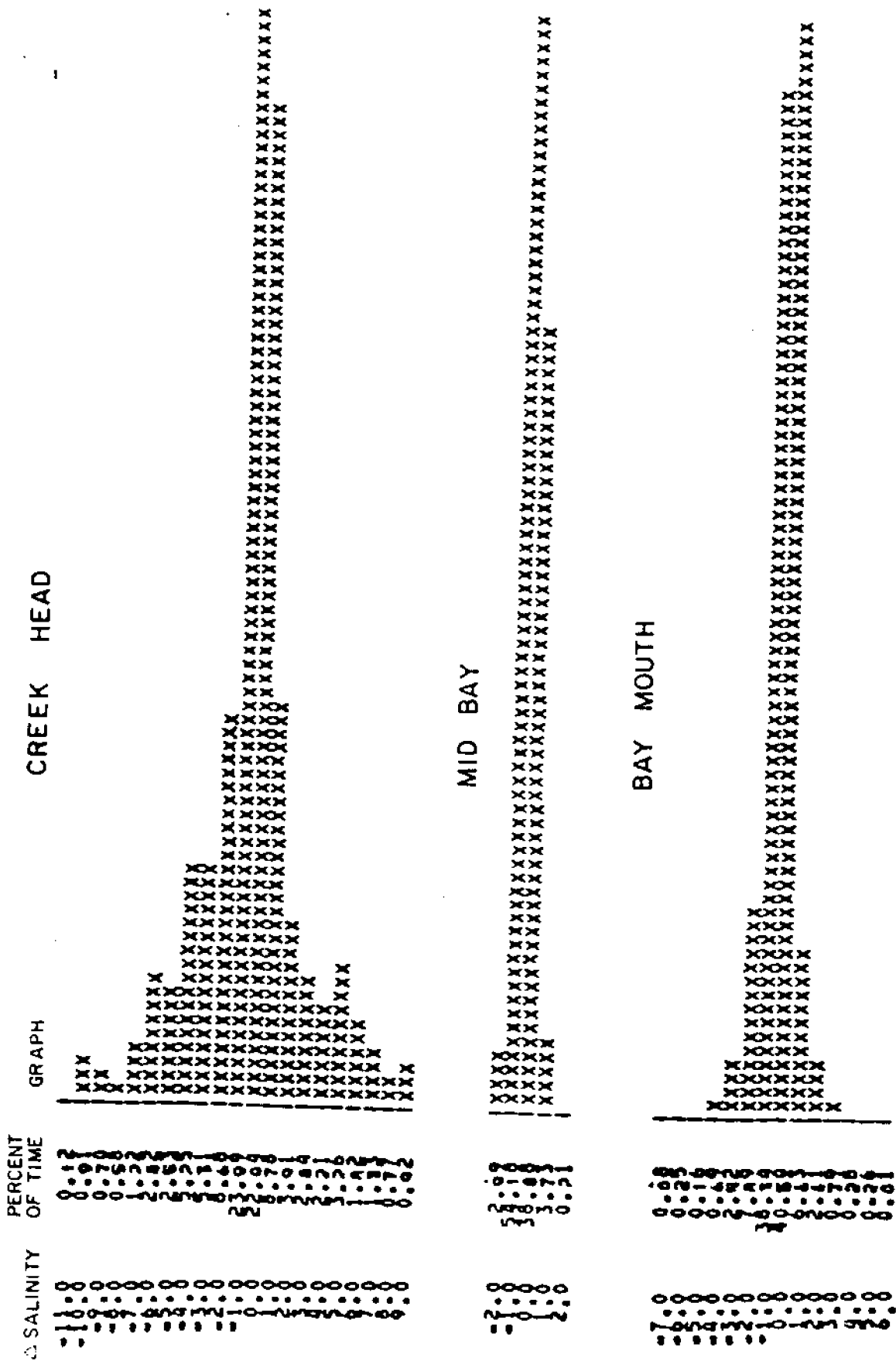


Figure 17. Salinity changes of at least 1 ppt during consecutive 12 hour intervals at the Rose Bay Creek Head, Mid Bay and Bay Mouth. Graphs indicate the incredible decreases and increases in S over half day periods at the Creek Head and Bay Mouth.

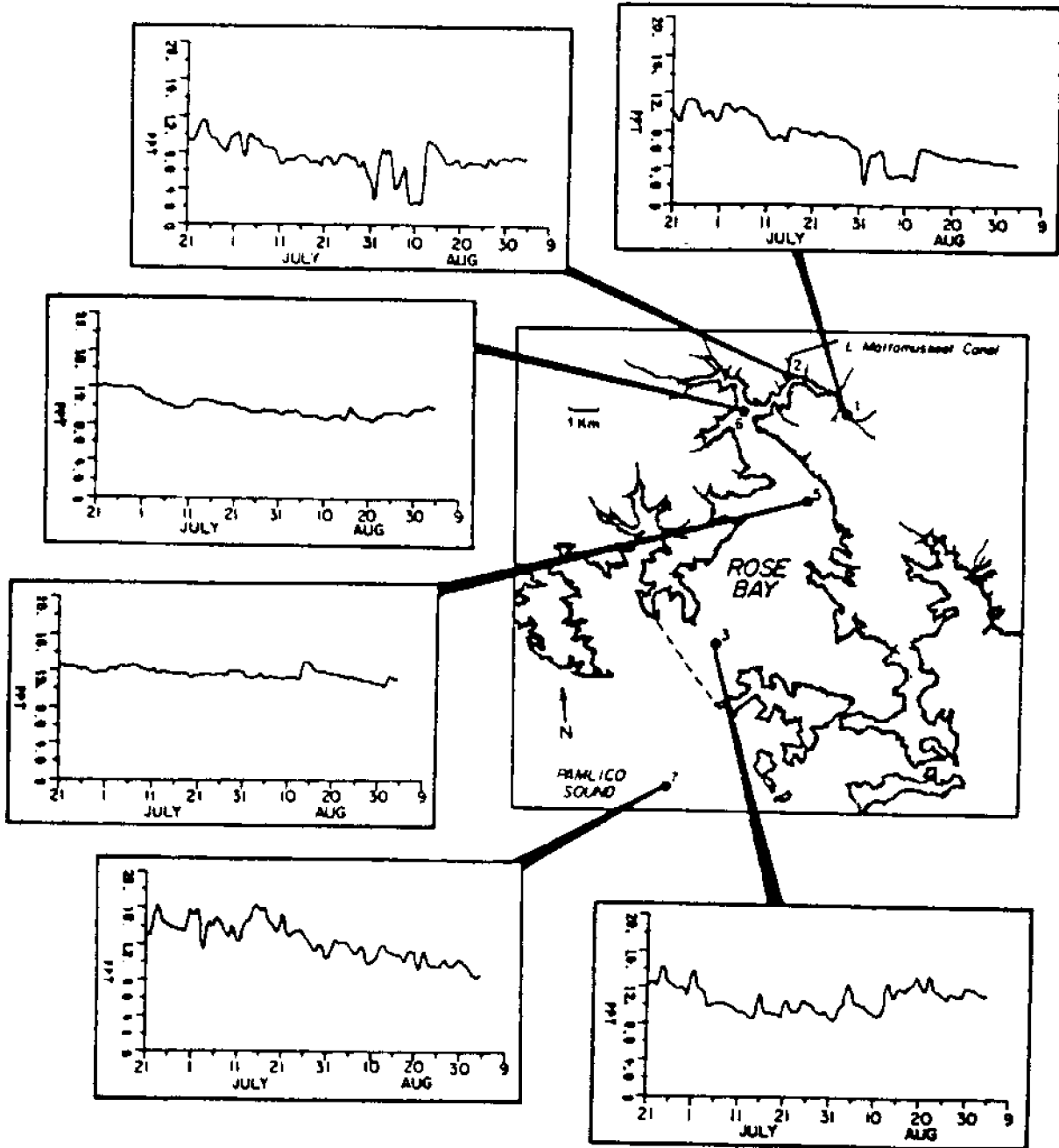


Figure 18. Forty-hour low pass filtered salinity time series throughout the Rose Bay system. Greatest variability is up the creek and at the mouth.

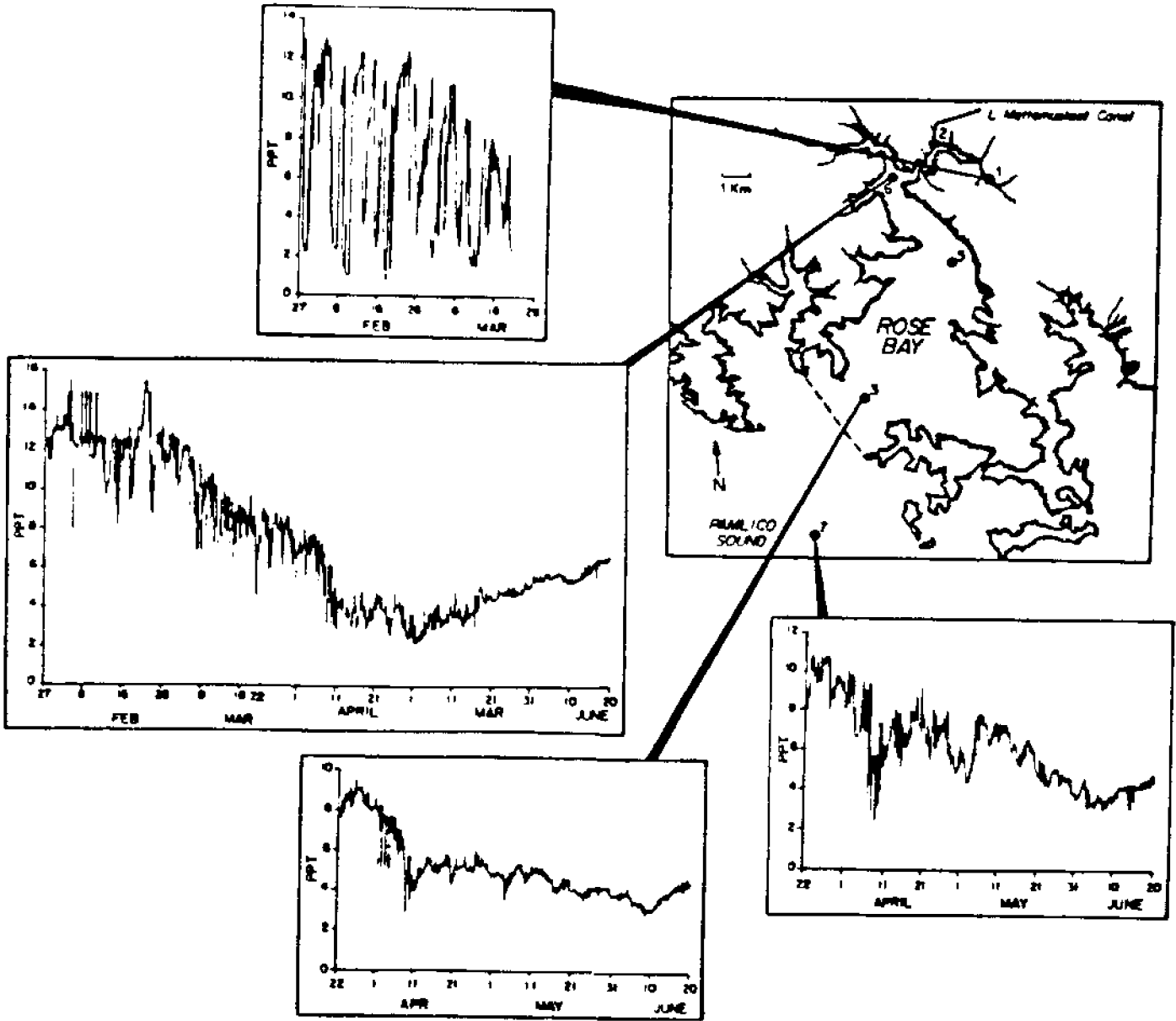


Figure 19. Three hour low pass salinities throughout Rose Bay system. Greatest variability is up the creek and at the mouth.

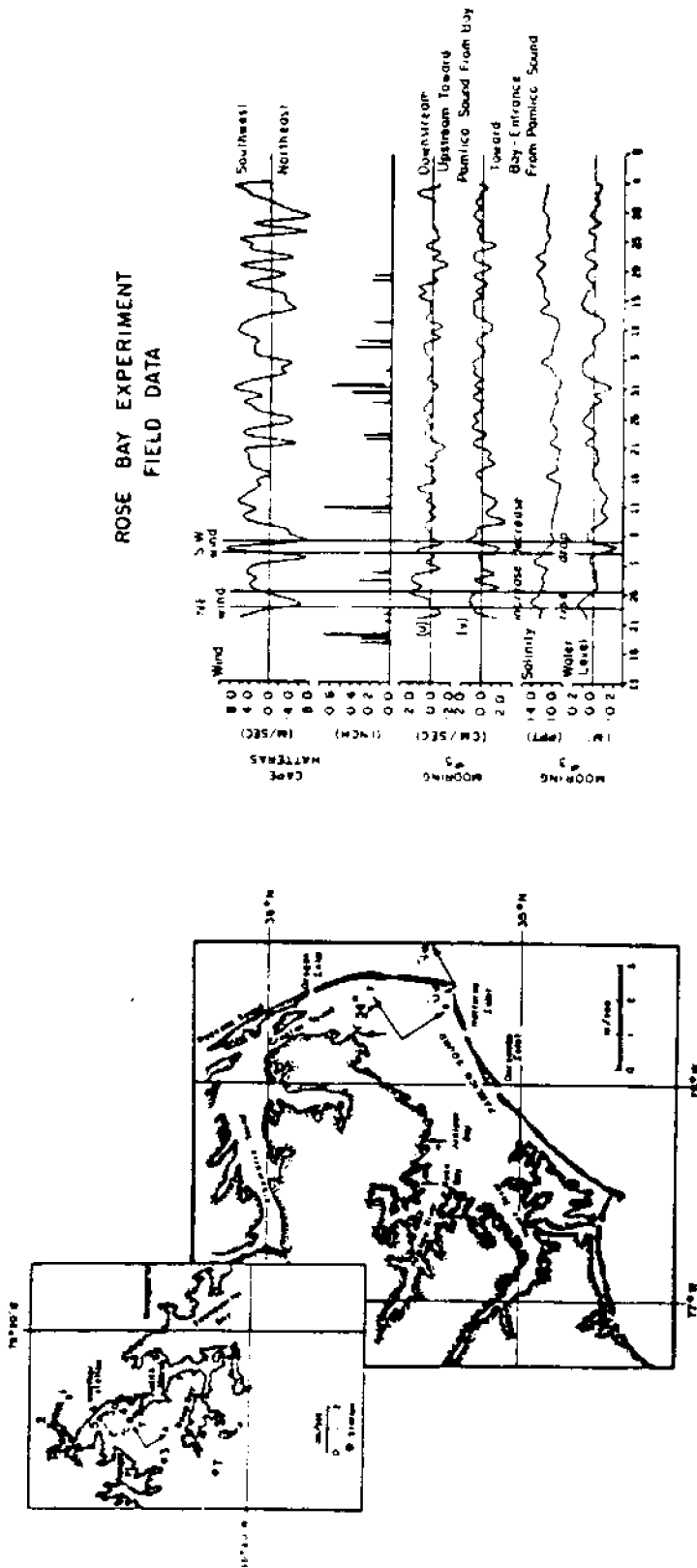


Figure 20. The "Non-Local Forcing Mechanism" at work in Rose Bay (see text for details).

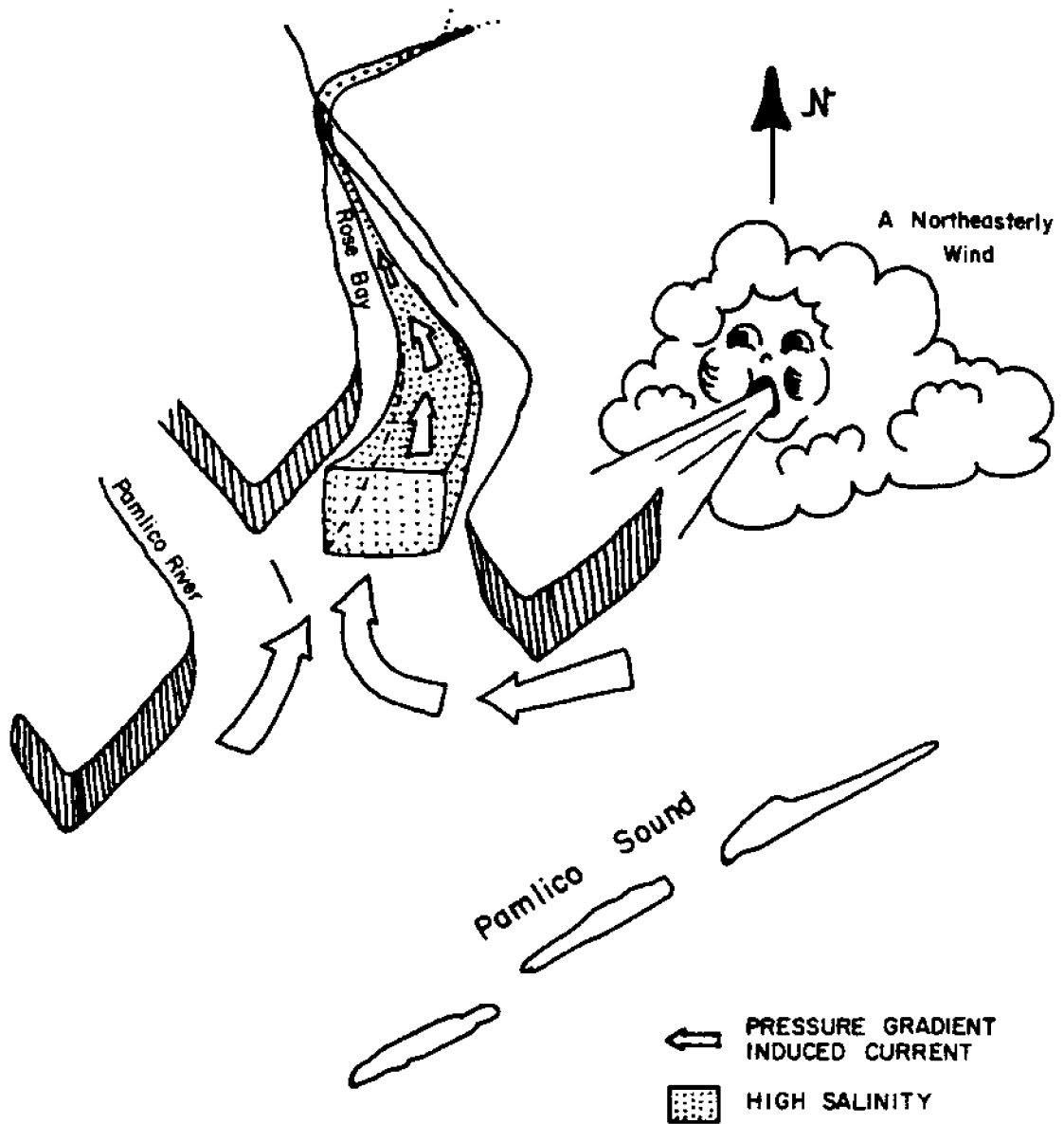


Figure 21. Non-Local Forcing of Rose Bay Mouth shown schematically. (Based on such data as shown in Figure 20; see text for details).

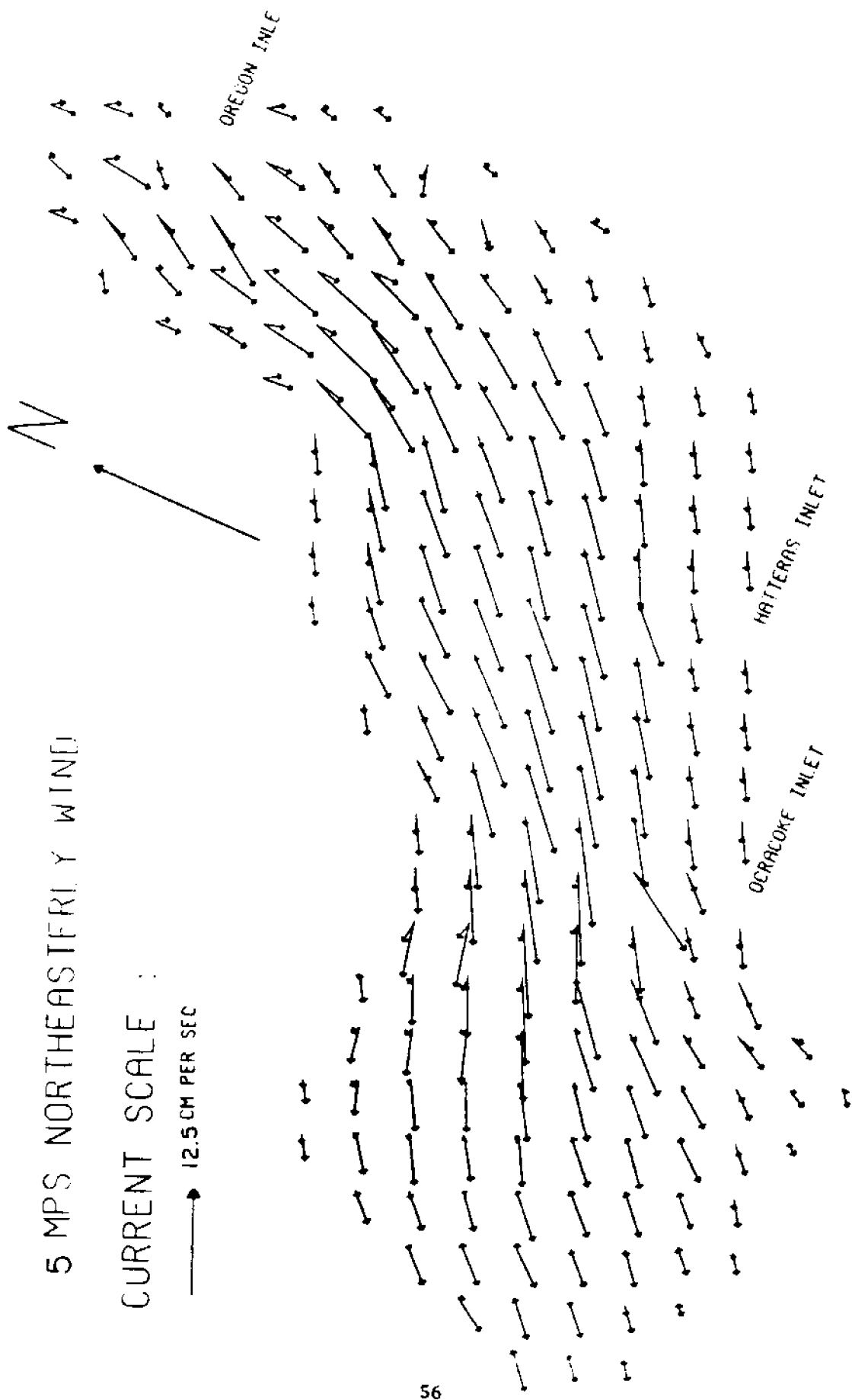


Figure 22. Pamlico Sound surface and bottom layer flows due to a wind directed southwestward.

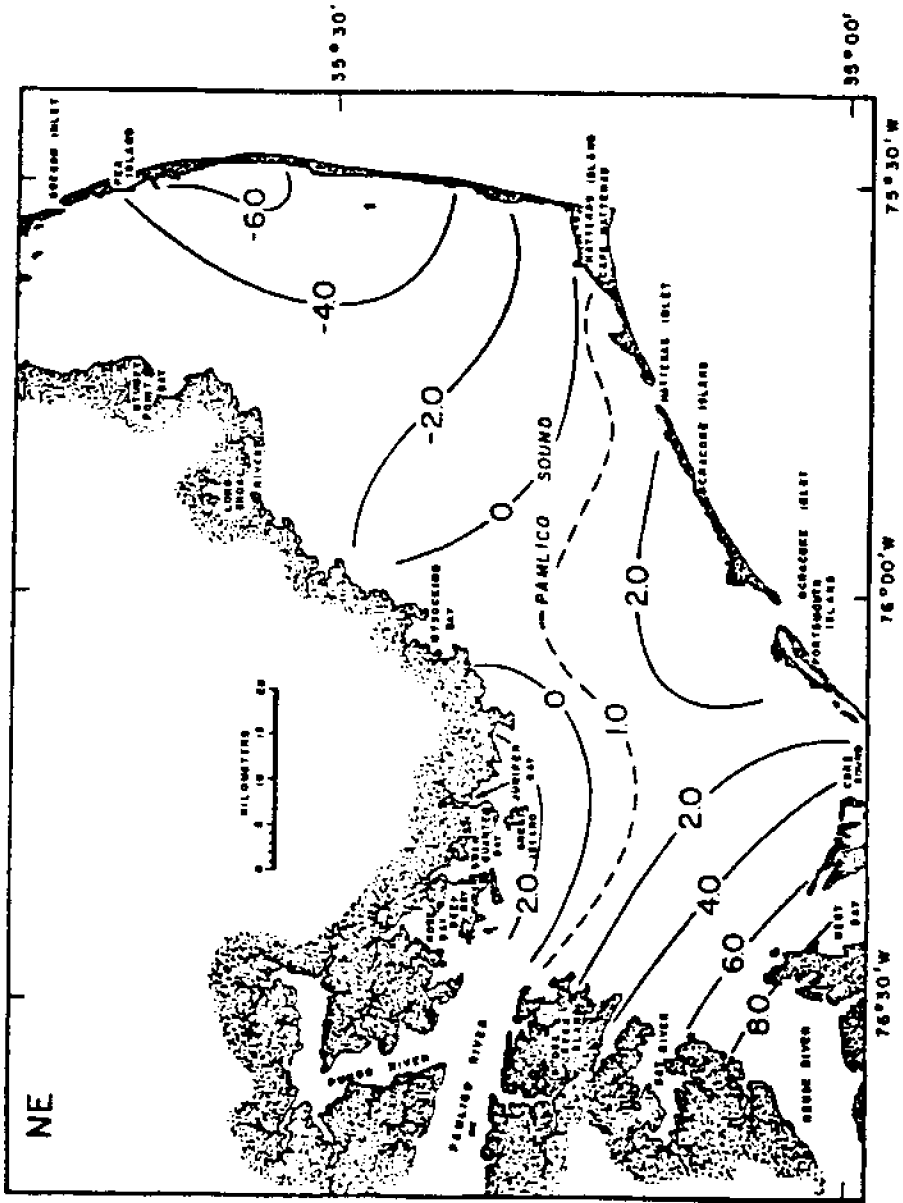


Figure 23. Sea level rise and fall in Pamlico Sound due to a southwestward wind. Note rise of water level at Rose Bay Mouth.

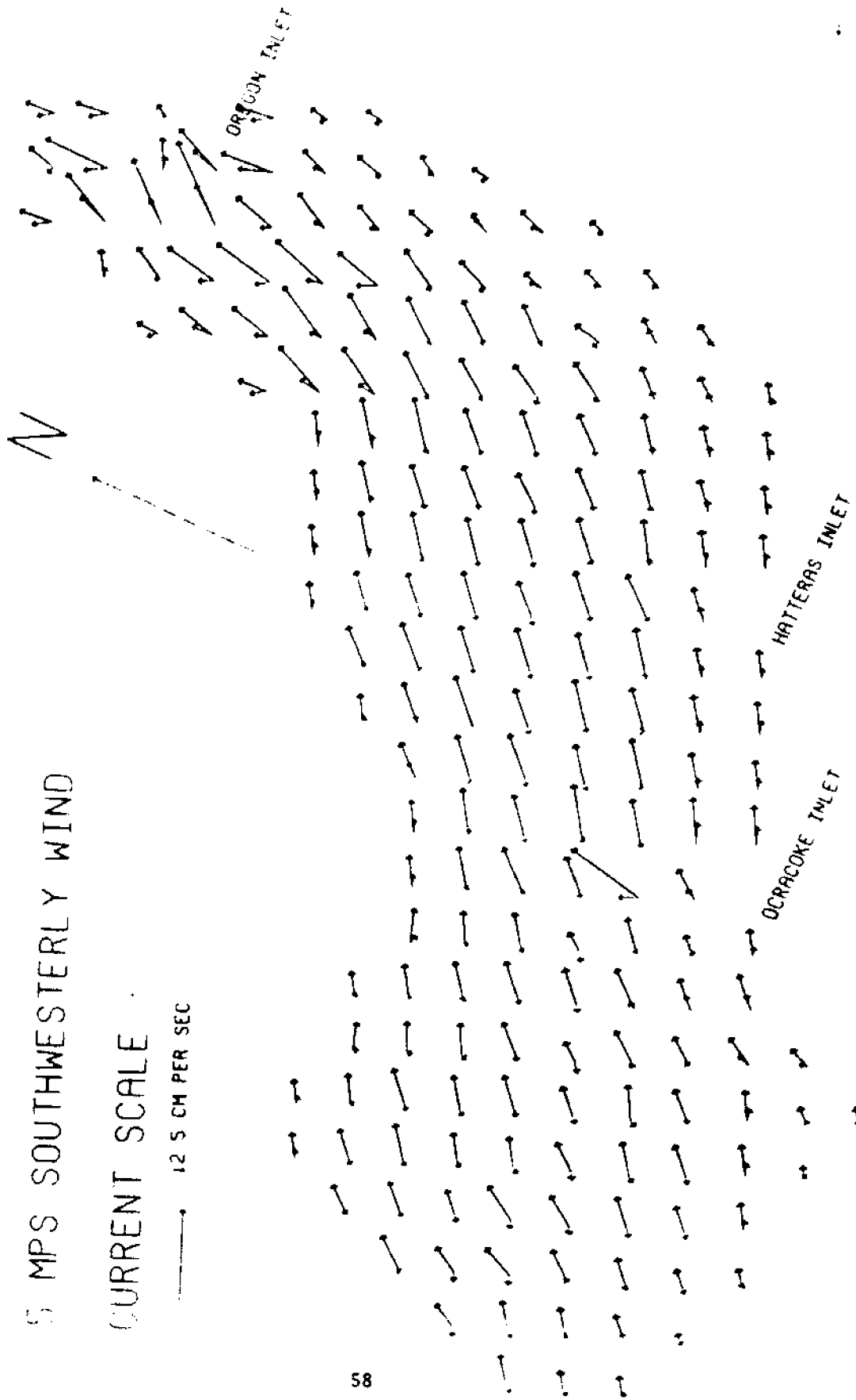


Figure 24. Same as Figure 22, but wind is northeasterly.

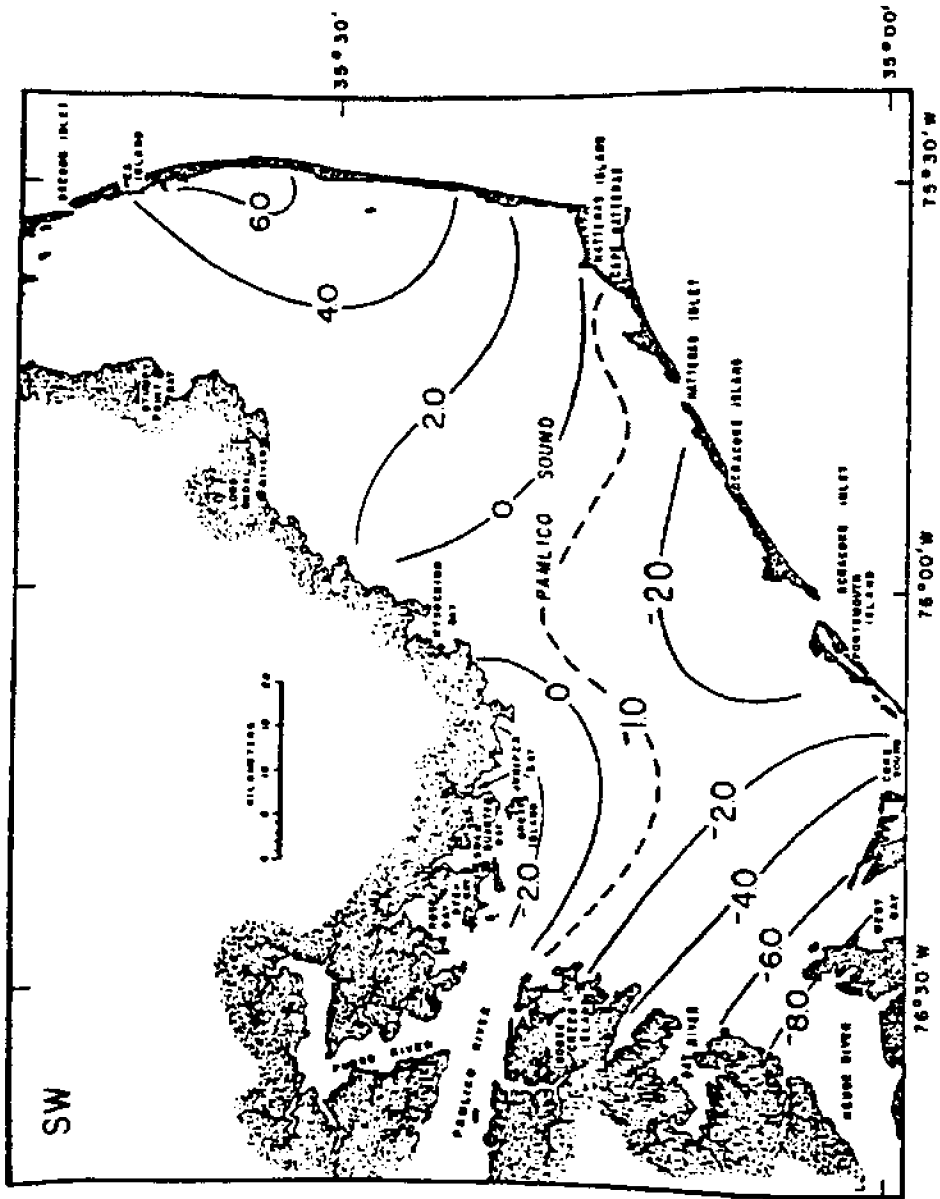


Figure 25. Same as Figure 23 but wind is northeastward. Note drop of water level at mouth of Rose Bay.

SEA LEVEL IN FEET, Demeaned

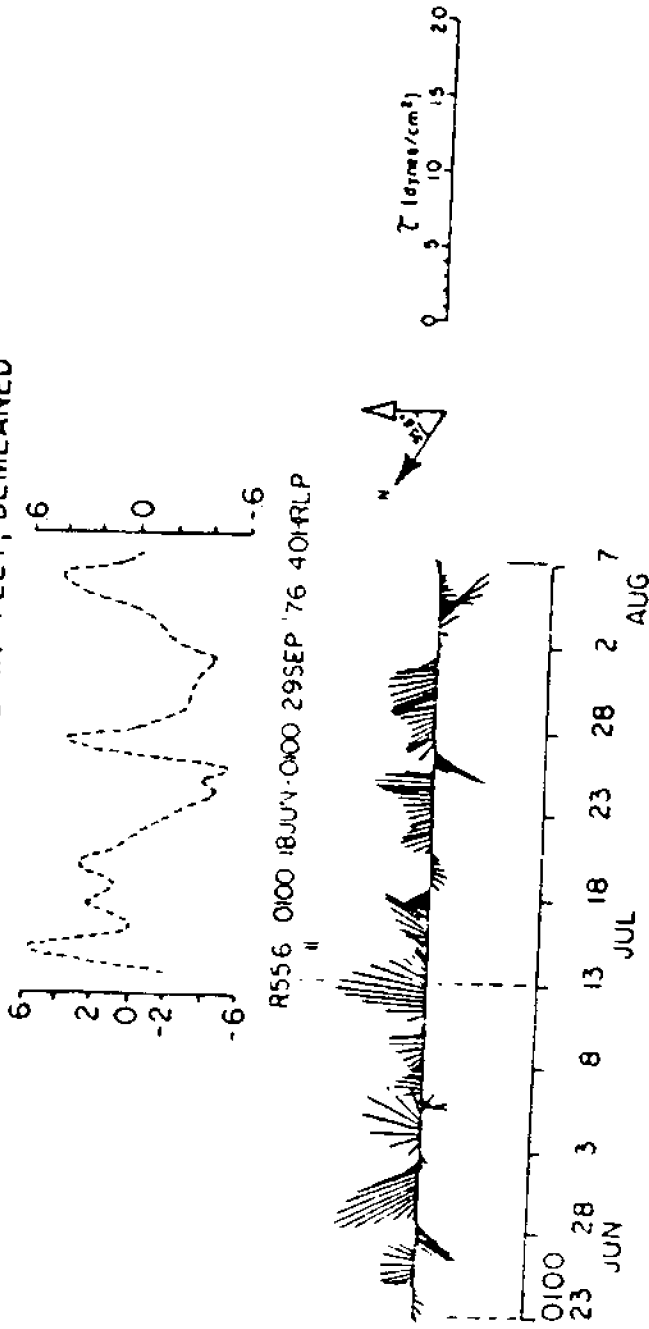


Figure 26. Offshore coastal sea level at Cape Hatteras vs. wind vectors. When wind blows towards northeast, sea level falls, and when wind blows towards southwest, sea level rises.

REFERENCES

- Amein, N. and D.S. Airan. 1976. Mathematical modeling of circulation and hurricane surge in Pamlico Sound, North Carolina. USC Sea Grant College Publication UNC-SG-76-12.
- Chao, S-Y and L.J. Pietrafesa. 1979. The subtidal response of sea level to atmospheric forcing in the Carolina Capes. *J. Phys. Oceanogr.*, 10 (in press).
- Janowitz, G.S. and L.J. Pietrafesa. 1980. A model and observations of time-dependent upwelling over the mid-shelf and slope. *J. Phys. Oceanogr.*, 10, 1574-1583.
- Jarrett, T.J. 1966. A study of the hydrology and hydraulics of Pamlico Sound and their relation to the concentration of substances in the sound. M.S. thesis, North Carolina State University.
- Marshall, N. 1951. Hydrography of North Carolina Marine waters, pp. 1-76. In H.F. Taylor (ed.), *Survey of marine Fisheries of North Carolina*. University of North Carolina, Chapel Hill, N.C.
- Miller, J.M., J.P. Reed and L.J. Pietrafesa. 1984. Patterns, mechanisms and approaches to the study of estuarine dependent fish larvae and juveniles. In: *Mechanisms of Migration in Fishes*, Proceedings of NATO Advanced Research Institute Conference, Acquafredda DiMaratea, Italy, Dec. 1982. Plenum Publishing Corp., 1984, pp. 209-225.
- Pietrafesa, L.J., Sheinn-Yu Chao and Gerald S. Janowitz. The variability of Sea Level in the Carolina Capes, UNC Sea Grant College Publication, UNC-SG-WP-81-11, December 1981.
- Posner, G.S. 1959. Preliminary Oceanographic studies of the positive bar built estuaries of North Carolina, U.S.A., Internal. Oceanogr. Congr. AAS, Washington, D.C.
- Roelofs, E.W. and A.W. Bumpus. 1953. The hydrography of Pamlico Sound. *Bull. Mar. Sci. Gulf and Caribbean*, 3(3): 181-205.
- Smallwood, C.A and M. Amein. 1967. A mathematical model for the hydrology and hydraulics of Pamlico Sound. Proc. Symp. Hydrolo. coastal Waters N.C., Rep. No. 5, Waters Resources Res. Institute of the The University of North Carolina, Raleigh, N.C.
- Weisberg, R.H. and L.J. Pietrafesa. 1983. Kinematics and correlation of the surface wind field in the South Atlantic Bight. *J. Geophys. Res.*, 88(C8): 4593-4610.
- Williams, A.B., G.S. Posner, W.J. Woods and E.E. Deubler, Jr. 1973. A hydrographic atlas of larger North Carolina sounds. Sea Grant Pub. No. UNC-SG-73-02, University of North Carolina, Chapel Hill, N.C.
- Woods, W.J. 1967. Hydrographic studies in Pamlico Sound. Proc. Symp. Hydrolo. Coastal Waters N.C., Rep. No. 5, Water Resources Res. Institute of The University of North Carolina, Raleigh, N.C.

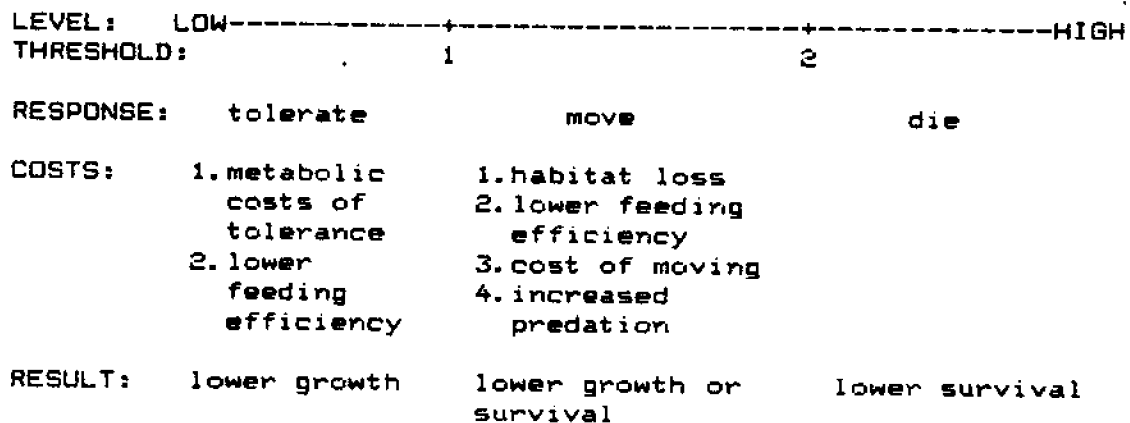
Effects of Freshwater Discharges into Primary Nursery Areas for
Juvenile Fish and Shellfish: Criteria for their Protection

J.M. Miller

General Considerations

Potential negative impacts of perturbations on juvenile fish and shellfish in their primary nursery areas may be conceptualized in 3 steps defined by 2 stress thresholds, of salinity change, for example (Fig. 1). Below threshold #1 the organisms' responses range from no effect to an energetic tax paid for internal physiological regulation. Above threshold #1 organisms must behaviorally regulate their balance by moving to a region of the nursery area which is less perturbed. The price paid is loss of habitat, lower feeding efficiency, the costs of moving and, possibly, increased exposure to predation. All except the last represent losses of growth potential; all can be assessed in terms of lost production. And, besides the direct effects upon the animals of interest, the effects on their food organisms must be considered. At some higher level of stress, threshold #2, the organisms can neither tolerate nor escape, and they die. This level of stress represents a permanent loss of production for that season. The thresholds, thus defined, are arbitrary but useful as a conceptual framework. Thresholds can also be useful in establishing criteria for protecting nursery areas. If thresholds are based on the least tolerant species, they should suffice to protect others. In actuality the effects of impacts will no doubt be a continuum, different for different species.

Figure 1. RESPONSES OF JUVENILE FISH AND SHRIMP TO STRESS



It is also essential to expand on the concept of stress. Stress implies both a perturbation and a response, and as such needs to be defined in biological terms, despite its common definition in terms of the perturbation alone. But the same perturbation, e.g. a decrease in salinity, will have differential impacts on different species or stages of the same species depending on their tolerance. A species' ability to tolerate a perturbation is also a function of its state of health, so the effects of a given potentially stressful perturbation are compound functions of other stresses - e.g., turbidity accompanying runoff, temperature, et al..

The perturbation of interest here is excessive change in salinity which requires energy to maintain the proper internal milieu for physiological processes to proceed. An animal in a hypotonic environment must spend energy to keep excess water from invading its body and keep salts from diffusing out. Conversely, an animal in a hypertonic environment must spend energy to conserve its internal water and to keep excess salts out. The internal salinity of most animals is about 11ppt (parts per thousand), or about 1/3 the concentration of seawater. But not only must an animal spend energy if it is in water with more or less than 11ppt, its ability to regulate (and thus the cost) is a function of the rate of change in environmental salinity. Ability to regulate is also a function of temperature. All evidence suggests that change in salinity is more expensive than sub-optimal constant salinity. An animal which can regulate in a slowly changing salinity may not be able to keep up with a faster

rate of change. Thus the proper quantification of a salinity perturbation includes both the difference between the internal and external salt concentration and a term describing the rate of change. It also seems that a difference of, say 5 ppt, matters whether it is 5ppt above or below the internal salinity, 11ppt. In any case, the significance of the additional energy required to regulate salinity is its effect on growth, since the same energy could be used to grow. High levels of stress cause animals to stop feeding. Furthermore, it seems that there is a minimum amount of growth that must occur during the first summer in the nursery for an animal to be able to survive its first winter. So growth depressions caused by sub-lethal salinities may be ultimately lethal.

The prediction of the effects of accelerated drainage of freshwater into nursery areas requires knowledge of the amount and schedule of salinity change plus an estimate of the effects on the animals. As we have seen, a given amount of freshwater entering an estuary results in a distribution of salinity change, and so has an areal component. The final estimate of the effects of increased freshwater input will be an areal estimate of the various levels of response by the animals times the duration of these responses. The effects of a particular runoff regime will be expressed as the probability of various levels of response by the community. If a generic model of the effects of salinity change can be achieved, the effects of any proposed drainage plan can be estimated with some data on the abundance and kinds of animals in the receiving body of water and the amount and timing

of the freshwater input. The costs of a perturbation will be a direct function of abundance and an inverse function of the species' ability to tolerate change in salinity.

A predictive model will thus need the following inputs and outputs:

1) the amount and schedule of freshwater entering a nursery area from a particular drainage system;

2) the temporal and spatial changes in salinity of the nursery area caused by the freshwater input; and,

3) the distribution and abundance of organisms in the impacted area and the changes in production caused by the various levels of change in the salinity regime.

With the above as a perspective, let us examine what we know about the abundance and responses of animals to salinity change.

The distribution and abundance of animals in nursery areas.

Thanks to the surveys by the NC DMF over the past decade, a great deal is known about the utilization of various nursery areas, particularly those of the Pamlico Sound region. The fauna is largely transitory, and includes: 1) fall- and winter-spawned species which migrate into the nursery areas from offshore; 2) spring- and summer-spawned species which migrate into the nursery areas from inshore (estuarine or near-coastal) spawning areas; and, 3) permanent residents. In addition, some species originating from upstream spawning areas may drift downstream into the nursery areas and there are incidental marine or

freshwater species. The principal species in each category are shown in Table 1. Of the 4 categories, the species in the first generally dominate the biomass of the primary nursery areas designated by the State, and of these spot and croaker are usually found in the greatest numbers from about February to October (Fig 2). Spot juveniles also dominate the production, with seasonal values of up to $7.5 \text{ g m}^{-2} \text{ y}^{-1}$ in Rose Bay. This is equivalent to about 670 pounds (live weight) produced per acre. Production in certain areas of the Bay, in particular regions near the headwaters, may be 10 times as great. Spot are aggregated in the shallow headwaters of the nursery areas early in the season and subsequently disperse by about June. About $1/3$ of the spot production occurs in the shallowest (1.75m) $1/4$ of the Bay. Croaker production is about $1/3$ that of spot and also tracks croaker biomass. But the biomass and production of croaker are even less uniform in Rose Bay than that of spot (Fig. 2). About $1/2$ of the total croaker production occurs in the shallowest $1/4$ of the Bay. Likewise, the seasonal production of both species is unevenly distributed in time. Production rates track biomass, so that the period of peak production occurs in May in most years. The fact that production tracks biomass implies that production is not limited by biomass. The importance of this observation is that a permanent reduction in production in one area or at one time period is not likely to be compensated for by increased production elsewhere. If, on the other hand, the depression of production in one area is a result of emigration, it is possible that the organisms can grow equally

TABLE 1

Offshore Fall- and Winter-Spawned Species

spot, croaker, summer and southern flounder, brown and white shrimp, menhaden, pinfish, striped mullet

Estuarine or Near-Coastal Spring- and Summer-Spawned Species

spotted sea trout, red drum, silver perch, blue crab (also fall), weakfish

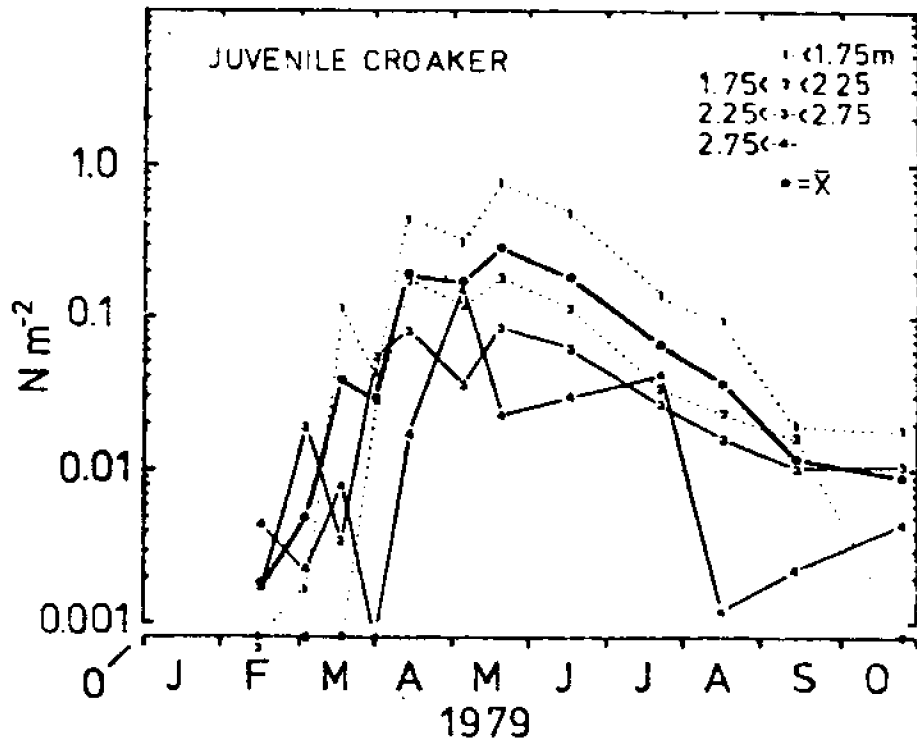
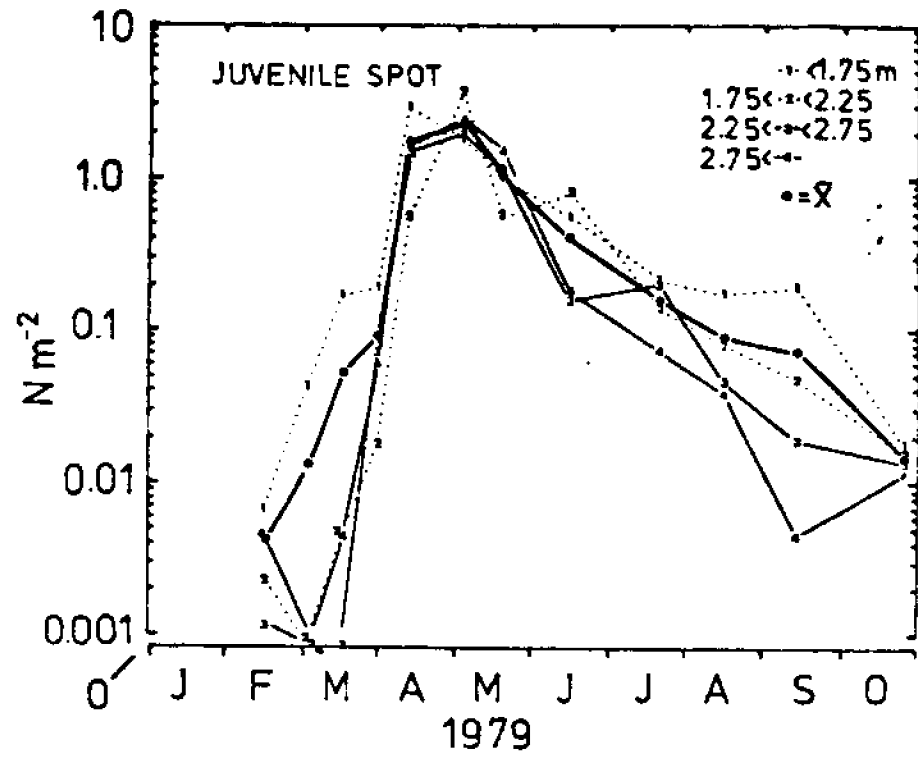
Permanent Residents

bay anchovy, killifish, white catfish, silverside, white perch, gobies

Freshwater Spring- or Summer-Spawned Species

striped bass, alewives, herrings, shad

Figure 2. Abundance and distribution of juvenile spot and croaker in Rose Bay. 1-4 are depth regions of the Bay of approximately equal area.



well in another, because it seems that the carrying capacity is not exceeded anywhere. These observations and generalizations apply to the spot populations in Rose Bay, the only nursery area for which the necessary data are available. The carrying capacity of other nursery areas may indeed be normally reached. Because spot are typically considerably more abundant than any other species (perhaps with the exception of anchovies), it seems reasonable to expect that density-dependent growth would be most likely to occur in that species. But of course it depends on the food supply in relation to the food requirement of a species, and other, more specialized, species may not follow this generalization. We are currently testing this hypothesis in 6 other nursery areas in Pamlico Sound. In any case, other things equal, generalist species are less likely to respond negatively to perturbations than specialist species, of which there are many in nursery areas.

The nursery areas in question are low salinity regions of the estuary, generally peripheral embayments. Average salinities range from about 5 to 20 ppt, and normally fluctuate with freshwater input and wind-forced exchanges of water mass. Species thriving in such areas are adapted to changing salinities. It has been hypothesized that they enjoy some immunity from competition and predation because they are adapted. Certain potential predators and competitors seem to be excluded from the variable environment of nursery areas. Even the adults of some species whose juvenile stages occupy nursery areas are apparently excluded; certainly there are many stenohaline marine

and freshwater species which would prey on the juveniles in either marine or freshwater environments. The point is, there would seem to be a minimum salinity variation necessary for the efficient function of a nursery area. And a trade-off of increased costs of tolerance of the variable environment for less competition and predation seems to have been achieved by a few highly-productive species. In sum, some variation seems necessary (or beneficial); too much seems detrimental. How much is too much and how little is too little? Answers to these questions should be the basis for criteria for protecting nursery areas.

The responses of animals to salinity change.

Metabolic costs

There are few data on the actual costs of salinity tolerance because it is difficult to separate the costs of increased activity which usually accompany a change. On the other hand, routine metabolism may be more relevant to estimating the costs. Juvenile menhaden exhibit the lowest metabolic rate, about 0.32 mg O₂/g/h, at a salinity of 15ppt, which is near the isosmotic level. At 5ppt, the rate is 0.43 - a nearly 35% increase. At 30ppt, the rate is about 0.34, which suggests menhaden have considerably greater costs of tolerating reduced salinity than increased salinity. Juvenile menhaden grew 33% slower at high (28-34ppt) than low (5-10ppt) salinity. The same pattern has

been observed in spotted sea trout, except metabolic costs increased above and below 20ppt, which indicated a higher optimum salinity. Preliminary experiments with juvenile spot acclimated to 33ppt showed about the same metabolic rate, 0.35 mg O₂/g/h. When the salinity was reduced rapidly to near 0 ppt, the metabolic rate fell to about 0.22 over 8h. When the salinity was suddenly increased to 33ppt, the rate increased to 0.35 within about 2h - suggesting a more rapid response to rising salinity. Although the low rate of metabolism might suggest an optimum at 0ppt, juvenile spot die at that salinity. It is likely that their low metabolism at 0ppt represents a metabolic shutdown, not an optimum. But in any case, spot can apparently tolerate low salinity better than either menhaden or spotted sea trout.

To put these data into perspective, 0.10 mg O₂/g/h is equivalent to a daily growth rate of about 1.6%. Since juvenile fish grow at about 3-5% per day, it is clear that the magnitude of salinity-related change in respiration rate represents a significant change in potential growth rate. Unfortunately, the data available do not permit separation of salinity, salinity change, temperature, food, swimming rate and size effects on juvenile fish growth. Nevertheless, it is clear that salinity effects are not insignificant.

Data on brown shrimp show a basically similar pattern. Their metabolic rate is lowest at 15ppt (0.29 mg O₂/g/h); intermediate at 25ppt (0.36); and highest at 5ppt (0.43). Shrimp metabolic rate is increased about 47% with a 10ppt drop in salinity; juvenile menhaden metabolism increases about 33% in response to

the same drop. Recall, these are acclimated rates of metabolism; spot metabolic rate increased about 200% in response to a rapid salinity rise. A fish (or shrimp) exposed to rapidly (say 6h) fluctuating salinity within these same limits could incur up to 8 times the acclimated costs, being kept in a continuous process of metabolic readjustment. Metabolic readjustment to salinity change took 5-12h, depending on the differential, in a variety of estuarine shrimps and fish. Brown shrimp suffer 100% mortality when exposed to 2ppt salinity for 4h.

Movement thresholds and costs

The growth, hence production, of fish varies considerably, but 3-5% per day seems near maximal for juvenile fish in their natural environments with access to abundant food, where they eat about 10% of their weight each day. Small fish grow faster than this; large fish slower. Spot and croaker in Rose Bay grow about 3% per day. About 1% of their body weight in food is required for maintenance, and on this ration fish do not grow. Swimming is expensive; at 3 body lengths/sec fish use about 4 times as much energy as is required for maintenance. At one BL/sec the requirements for swimming and maintenance are about equal. Thus if fish swim at 3 BL/sec they use energy at a rate equal to their normal growth rate. Stated another way, forced swimming may reduce the growth rate to nearly 0. Likewise, energy spent tolerating stress reduces growth potential. Thus, the energetic costs of tolerance or swimming can be measured in reduced growth,

hence lost production. This is our approach. We will attempt to calculate such costs for spot and then revise such estimates according to the information available for other species.

Perez found that spot and croaker responded to changes in salinity of 10 and 5ppt/h, respectively, by increased swimming speed. This can be interpreted as an attempt to behaviorally regulate by an escape response instead of tolerating the change. Thus, 10ppt/h represents a first cut at threshold #1, where a species seems to shift from tolerance to avoidance. If we assume that the swimming speed of avoidance is 3 BL/s (the maximum sustainable), then an estimate of the costs of a 10ppt/h perturbation would be the cost of swimming until a region of the nursery is reached where the rate of change is less - i.e. usually downstream. Given the isopleths of salinity change in the nursery and the size of fish (thus swimming speed) one can calculate the energy cost, thus production lost, of behaviorally regulating. One assumption is critical: the line of travel. If a fish can orient its movements, the distance is a straight line between the origin and the refuge. There is not much evidence for such an ability in small fish, and in fact, there is reason to believe they could not possess such an ability. If they swim randomly, the likelihood of reaching the refuge is small. If the swimming is modelled as an additional diffusion coefficient superimposed on the movement of water, the time is basically that of the advection of water, since diffusion is slow compared to advection in most all cases. Or, they could passively ride currents out of the impacted area. This presents a dilemma.

Freshwater entering a nursery would tend to float rapidly out of the area at the surface. Such movements of water are known to induce upstream flow of bottom water. If the fish swam to the bottom in response to decreasing salinity, which it should to escape, they may be carried passively upstream toward the source of freshwater. On the other hand, if the water is unstratified, all flow is downstream and the fish could just "let go". None of these possible escape strategies has been tested. A more complex, thus less likely, escape scenario can be envisioned whereby the fish learns which way is downstream during colonization or "exploration". It is likely that fish in a typical nursery area learn that deeper is saltier. But the depth gradients in many shallow nursery areas are small. The upshot is that it is hard to envision a general behavioral response that would work in all cases, and thus might be expected to have selective advantage. The speed of response will be determined in a State/Sea Grant-sponsored research effort underway in Broad Creek, and this will contribute greatly to our understanding of the mechanism involved. In the meantime, it seems best to assume that the fish will swim at 3 BL/s for as long as it takes to reach a refuge area by advection. This time interval may in fact be shorter than any of the possibilities discussed above.

The best guess at present as to the costs in terms of lost spot production of a salinity perturbation would seem to be the costs of swimming to a refuge plus the costs of tolerating the (lower rate of) salinity change in the refuge, which would be defined as the region of the nursery described by the (10 ppt/h

change isopleth accompanying the perturbation. For croaker, threshold #1 seems to be 5 ppt/h and the refuge would be defined by the 5ppt/h change isopleth.

But in fact the situation is not this simple. Recall croaker in Rose Bay are more concentrated in the upper, lower salinity, reaches of the Bay where they would appear to be more vulnerable to salinity changes than spot, for example. And Perez's data indicated croaker were more sensitive to salinity changes than spot. Yet the production of croaker catches up in a sense to spot during the course of the year. Peak biomass of croaker is about 1/10 that of spot early in the season. But by the end of the season the biomasses of the two species are about equal. One explanation for the dilemma is that the two species have different salinity optima, and a 5ppt change/h for croaker is equivalent to a 10 ppt change/h. Since Perez tested both species at the same acclimation salinity (12ppt), this cannot be ruled out. This is only one of many possible explanations for the difference between spot and croaker production, but it points out that the quantification of a salinity perturbation needs to include both the acclimation salinity and the rate of change.

We can visualize a nursery as a salinity gradient from low values at the upstream limits (in creeks and at heads of bays) to higher, but still low, salinities downstream. And we can visualize abundance gradients of organisms acclimated to these salinities. Freshwater entering at the head of the nursery would have the greatest impact at the head, but on organisms with presumably lower optima and the percentage decrease in salinity

might be lower since salinity is already low. At the downstream end of the gradient, little change would occur, but it would impact organisms with higher optima. At some intermediate point farther along the gradient the greatest percentage rate of change would occur. Perhaps the best way to generalize across the complex array of animals' tolerances and salinity changes is to consider the percentage change rather than the actual change. The greatest percentage change would occur near the head, the greatest absolute change would be at some intermediate point along the gradient. Such an hypothesis would explain the higher apparent growth and survival of croaker than spot in Rose Bay, despite an indication of greater sensitivity in croaker that Perez found. Our observations in Rose Bay suggest that low numbers of croaker are generally found in waters with <5 ppt average salinity. On the occasions where we have observed salinity drops in response to heavy rains, croaker abundance declined dramatically in regions with former salinities of about 5 ppt and did not recolonize these areas for about a month after. On the other hand, Mattamuskeet Canal near its mouth is a station which frequently exhibits bottom salinities <5 ppt and yet is one of the areas of Rose Bay where spot are most abundant. The Canal is also one of the most dynamic areas of the Bay. For example, on 17 March 1982 rains reduced the surface and bottom salinity to about 1 ppt; one week later the surface salinity was 1 ppt and the bottom salinity was 8.5 ppt. Apparently relatively high salinity water was being advected into the Canal at the bottom. Spot density was $14.9/m^2$, one of the highest densities we have found

anywhere in Rose Bay in 5 years of sampling. Just upstream and downstream of the Canal mouth in Rose Bay Creek, spot abundances were 0.57 and 0.16/m², respectively. A month later the abundance of spot in the Canal was 7/m², still the highest abundance in the vicinity - salinity was 8.5ppt at the bottom and 4.5ppt at the surface. Numbers upstream and downstream had increased to 2.2 and 0.6/m², respectively. This particular data set illustrates how difficult it is to separate the effects of salinity change from the accompanying advection of water (and fish) into an area. It is true, however, that despite periods of intense utilization, these systems of creeks and canals at the heads of the nursery areas are generally less productive than many regions downstream. It would be dangerous to assume that increased perturbation of these creeks and canals, particularly early in the season, would not impact the downstream productivity of the nurseries. It is not known how populations in the creeks and canals interact with the those in the remainder of the nursery. They may be the same, in which case stresses applied at the heads of the systems (even though infrequent) may have biological ripples downstream. This is particularly likely where organisms are advected upstream into canals or creeks. Again, this is most likely early in the season when fish are small and are concentrated at the heads of the nurseries.

1984 was a year which provided a contrast to the above dynamics. During the period 24 May-13 June, salinity was relatively low and stable at 5 stations at the head of Rose Bay. The 5-station means (and SD's) for the dates of 24 May, 31 May

and 13 June were 5.42(1.29), 2.56(1.81) and 5.04(2.78), respectively. Fish abundance did not change appreciably during this time interval. Overall spot abundance was 0.48(0.28) and croaker abundance was 0.20(0.20) for the entire period. These numbers are typical for this time of year in Rose Bay. The higher variability of croaker is mostly due to one station which consistently has a high biomass of croaker, not to intra-station variability. Thus, despite a perturbation which reduced salinity by one half (from 5.42 to 2.56) numbers of fish remained stable. This indicates the salinity did not change rapidly, but also shows that under relatively stable conditions spot and croaker remain at salinities less than 5ppt and incur the costs of tolerance. Their growth rate was about average during this particular time interval.

A Summary: Tolerance vs. Behavioral Regulation

We have seen that significant costs - up to 100% of the normal growth rate - are incurred by shrimp or fish exposed to salinity perturbations in the laboratory. But despite at least crude estimates of these costs, there is still inadequate knowledge of the actual response (i.e. exposure) of either shrimp or fish to particular salinity regimes in the field. Since the costs of both moving and tolerating are clearly significant - and of the same magnitude - until there is clear evidence to the contrary, it seems prudent to assume such costs will be incurred in the course of salinity perturbations of nursery areas.

Furthermore, there are no data available for many species which inhabit these nurseries. There is no evidence to the contrary - only the possibility that organisms may be flushed from the perturbed area under unstratified circumstances. A research effort is currently underway which should answer some of the critical questions.

Criteria to Protect Primary Nursery Areas

Several points are clear from our research in Rose Bay:

- 1) It is change in salinity, not salinity, which is important.

- 2) The criterion of 8-30ppt suggested in the recent DEM Report 84-10: Water Quality Criteria for Primary Nursery Areas in North Carolina does not adequately consider either salinity change or the fact that many important nursery areas are characterized by considerably lower salinities than 8ppt - the lower limit of the proposed salinity range for nurseries. In fact, it is these low salinity nursery areas and the low salinity areas within nursery areas which seem most vulnerable to salinity change.

- 3) Even though shrimp appear to have lower tolerance of salinity change than either spot or croaker, their higher

preferred salinity and later arrival in nursery areas (when salinity is more stable in general) argues that certain other species, such as spot and croaker, may have more stringent nursery area requirements than shrimp. For example, 8ppt as a lower limit would exclude the most important areas of Rose Bay for croaker production and also much of the Bay which is utilized by spot early in the season.

- 4) Perturbations of salinity are episodic, therefore specifying criteria based on mean salinity are virtually useless, unless mean salinity can be related to change over short (e.g. days) time intervals - which it cannot. Criteria must be stated in terms of the probability of certain episodes occurring. Whatever criteria are developed, it must be recognized that they will be occasionally exceeded by natural events. It is the increased probabilities (risks) associated with increased discharges of freshwater into nursery areas which must be assessed and considered in both the criteria developed and the subsequent application of such criteria in decisions to permit additional drainage into nursery areas.
- 5) Although our research has been centered on spot and croaker, there are many other less abundant species which probably are less tolerant to salinity change. Criteria based on these species should be developed to insure their

protection. Special consideration should be given to species which, unlike spot, croaker and shrimp, reside in the surface waters of the nurseries. Surface salinities are more variable and nearby refuges (e.g. depressions in the bottom for demersal species) would appear to be less available.

- 6) The distribution of species is not even within designated primary nursery areas. Nor is the species distribution among different nursery areas the same. Therefore attention must be given to where certain allowable drainages are permitted. Likewise any criteria developed must specify the region of the nursery. Any perturbation can impact up to 100 or more times as many organisms in a nursery area, depending on where and when it occurs.

- 7) The statement in the DEM Report (in #1 above) and in the EMC Information Package that "Standards which provide protection for brown shrimp will generally protect other nursery species." is not adequate. What is the meaning of "generally"? Although it is recognized that criteria will not completely protect any species, the level of protection required must be specified. For example, is a 25% loss of croaker production in a nursery area acceptable? An important finding of our research in Rose Bay is the evidence that permanent losses in one area of the nursery will not be compensated for in some other

area.

- 8) The tolerance levels of salinity cited in the DEM Report and the EMC document should be interpreted with caution. Generally these reflect the literature records of the lowest and highest salinities where a species has ever been found. Salinity is easy to measure, but there is evidence that Calcium, which may be correlated with salinity, is more important than salinity. Especially in low salinity waters, they may be uncoupled. Relatively high levels of Calcium may allow species to inhabit lower salinity waters than would otherwise be possible. And many marine species can be cultured at salinities well below their tolerance limits if adequate Ca is provided. But the freshwaters which lower the salinity in North Carolina nurseries are generally low in Ca. Thus it seems likely that the low salinity tolerance level may be misleading - certainly tolerance of a limit is not synonymous with health, or perhaps even long term survival.

What has been presented here is a conceptual model of the effects of salinity change on spot, croaker and shrimp in their primary nursery areas. Salinity change is probably not the most important potential perturbation, but it is relatively easy to model since salinity is conservative. Likewise, spot, croaker and shrimp are not the most sensitive species in these nursery

areas. They were chosen because they are abundant and relatively easy to study. But even the easiest species and environmental factor do not yield a simple model. The interactions with other factors and species must be considered to be realistic. Until such interactions are understood, any model will be a blunt instrument for its intended purpose of defining and protecting nursery areas. Though we are at the beginning of the effort to develop adequate criteria for nursery areas, and we are currently dealing with an easy factor and tolerant species, we are continuing to improve our predictive capabilities. This should also be recognized. But the ultimate criteria, if they are to be effective, are likely to be more conservative.