PROCEEDINGS

SYMPOSIUM ON HYDROLOGY

OF THE

COASTAL WATERS OF NORTH CAROLINA

May 12, 1967

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Mr. Walton M. Zillgitt, Director, Southeastern Forest Experiment Station, Forest Service, U. S. Department of Agriculture
Purpose

To review and discuss current research and investigations dealing with ground water and estuarine hydrology in the Coastal Region of North Carolina as a basis for intensified work to provide the information and techniques necessary for sound planning, development, and management of the coastal water resources.
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James R. Townsend, Chairman
North Carolina State Board of Water Resources
Raleigh, North Carolina

Research on water problems has accelerated greatly in recent years, and much money is being spent in this field. The Congress, in its wisdom, proposed legislation "to establish water resources research centers at land-grant colleges and State universities, to stimulate water research at other colleges, universities and centers of competence and to promote a more adequate national program of water research."

The idea was warmly received by those on the North Carolina State University campus. A study group, on May 24, 1963, recommended that a Water Resources Research Institute be established at this University. The Congressional proposal became law on July 17, 1964. The Water Resources Research Institute at the Greater University was created by President William C. Friday on July 9, 1964.

We of the Department of Water Resources extend our sincere thanks to the Institute for its outstanding work. Our relationship with the Institute has become so close that we have come to feel that we are a part of you and that you are a part of us.

The Institute has increasingly concerned itself with water resource problems in our State. Your seminar of last year on Estuarine Ecology of the Coastal Waters of North Carolina was most informative. Scientists testified that our tidal marshes are the incubators of great dollar-value marine life. If the marshes are destroyed so will the shrimping and crabbing industries be destroyed.

The recent study of the Water Resources Problems of North Carolina is, along with many others, a fine example of your work. The types of research you are developing are all constructive steps and we offer our congratulations.

Many of you are familiar with the recent report of the Board of Consultants on an Evaluation of Potential Impact of Phosphate Mining on Ground Water Resources of Eastern North Carolina. In the introduction to their recommendations the consultants said:

"We believe that the Coastal Plain of North Carolina is on the threshold of a period of rapid and extensive development of its industrial, mineral, woodland and agricultural resources. The course of this development will depend, to a much larger extent than is generally realized, upon the continued availability of abundant supplies of potable water."

We know that this forum today will advance our knowledge of how to best protect and conserve our potable water. If you read slightly between the lines of the agenda you will note that this theme is being developed.
The roster of today's speakers reads like a Who's Who in the Science of Hydrology. Each is outstanding in his field. We express our thanks to you for the time you are giving us and we promise you that your words will be heeded.

Our luncheon speaker, Mr. William C. Ackermann, will address us on the very broad subject of Water Resources Planning and Management. Mr. Ackermann is Chief of the Illinois State Water Survey and President of the American Geophysical Union. He recently served as Water Plan Director for the preparation of a State Water Plan for the State of Illinois which was submitted to their General Assembly by Governor Kerner on March 10, 1967. I am sure he will be glad to comment on this following his address today.
PRELIMINARY INVESTIGATION OF THE PETROLOGY
OF THE CASTLE HAYNE LIMESTONE

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ABSTRACT

The Castle Hayne Limestone and associated carbonate facies constitute the most important aquifer in eastern North Carolina. The rocks consist mainly of the following seven facies: pelecypod-mold subarkose, with calcite spar cement; sandy, pelecypod-mold biocalcarenite, with calcite spar cement; slightly sandy, phosphatic lithocalcirudite, with micrite matrix; sandy, molluscan-mold biocalcirudite, with pseudospar matrix; biocalcarenite, with micrite matrix; partly silicified, pelletoidal biocalcarenite, with micrite matrix; and biocalcarenite, with some calcite spar cement. All may be divided into a number of subfacies.

Porosity control is due mainly to original skeletal mineralogy and presence or absence of micrite. High-Mg calcite recrystallizes to low-Mg calcite; aragonite usually dissolves and the cavity is later infilled with low-Mg calcite, or rarely, aragonite inverts to low-Mg calcite in the solid state; and low-Mg calcite remains unaffected. All of these carbonates are stable in the normal shallow marine environments in which they originally formed. The sequence given is the order of increased stability in the nonmarine environment. Micrite, if present, eliminates intergrain porosity by infilling as original lime mud.

Porosity, mainly intragrain, is highest in rocks containing the highest frequency of aragonite pelecypods and gastropods. It is moderate, mainly intergrain, in the subarkoses and biocalcarenites that are incipiently cemented. These contain few aragonite fossils. Porosity is lowest in rocks which contain large amounts of micrite (therefore no intergrain porosity) and few aragonite fossils (therefore no intragrain porosity).

Silicification and dolomitization were minor diagenetic processes, and contribute little to the hydrologic properties.

INTRODUCTION

The Castle Hayne Limestone and related carbonate facies constitute the most important aquifer in eastern North Carolina (Figure 1). The unit dips gently to the east below younger strata, and thickens rapidly.

The Castle Hayne Limestone was named by Miller (in Clark et al., 1912, p. 185-197) for carbonate outcrops in the vicinity of Castle Hayne, New Hanover County. LeGrand and Brown (1955) and Brown (1958) gave evidence that it was deposited during the Middle and Late Eocene. LeGrand and Brown (1955, p. 30) redefined the Castle Hayne so it would include
the Trent Formation, a separate unit named by Miller (in Clark, et. al., 1912, p. 174-185), but emphasized that it is a distinctive facies. Recent paleoecologic studies by Lawrence (1966) in the vicinity of Belgrade indicate that channels were cut down into the Castle Hayne, and were filled with an Upper Oligocene oyster-rich fauna.

Included in the Castle Hayne hydrologic unit, besides the various facies of the Castle Hayne and the Upper Oligocene channel deposits, are unnamed Lower Eocene beds found only in the subsurface in Craven, Jones, and Onslow Counties (Brown, 1958), and possibly some Paleocene strata, the Beaufort Formation, also in the subsurface and not known south of Pitt County (Brown, 1958; 1959, p. 12-13).

In the southern part of the outcrop area, the Castle Hayne is underlain by a very porous, molluscan-rich sand, sandstone, and sandy limestone. Miller (in Clark, et. al., 1912, p. 185-197) indicated that the Upper Cretaceous Pee Dee Formation is below the Castle Hayne, although the highly calcareous facies was not recognized. Fallow and Wheeler (1963) proved, with fossil evidence, that the molluscan-rich sandstone and limestone below the basal phosphate-pebble conglomerate of the Castle Hayne is Upper Cretaceous Pee Dee at the abandoned quarry south of Castle Hayne.

The active Superior Stone Company Quarry, two miles northeast of Castle Hayne, has been excavated about 35 feet below the phosphate-pebble conglomerate, and some confusion regarding stratigraphy has arisen because some facies above and below are similar. Recent identifications in our laboratories of pelecypods, echinoids, and foraminifers from lower portions of the quarry indicate that at least the lower part, and probably all of the strata below the phosphate-pebble unconformity represent a highly fossiliferous, calcareous, and porous facies of the Pee Dee Formation. Because the unit has high porosity and permeability it is included here as a portion of the Castle Hayne aquifer system.

The data and conclusions presented here do not represent all of the units listed above. Only those in the outcrop belt are included, and these are the Castle Hayne Limestone and its various facies, the Upper Oligocene beds, and the carbonate-rich facies of the Upper Cretaceous Pee Dee Formation.

GENERAL HYDROLOGY

Hydrologic research has been conducted on the Castle Hayne system by a number of scientists (Brown, 1958, 1959; LeGrand, 1960; Dewiest, Sayre, and Jacob, 1967). Included in these reports are flow patterns, general development of porosity and permeability, water chemistry, stratigraphy, structure, and general petrology.

Regional reports dealing with Coastal Plain Tertiary carbonate aquifers in the southeastern United States, which sometime include North Carolina, have been published recently (Stringfield and LeGrand, 1966; LeGrand and Stringfield, 1966; Stringfield, 1966). Swinnerton (1942) was one of the first to evaluate principles of carbonate hydrology, and since then
there have been numerous symposia and reports on the subject. Most recently, a symposium on limestone hydrology was held in Berkeley in 1965, and the proceedings have been published (Moore, 1966).

One of the major principles stressed by nearly all of these researchers (for example, Stringfield and LeGrand, 1966; LeGrand and Stringfield, 1966), is that solution is greatest in a thin zone just below the water table. Because rise and fall of sea level control water table heights, it becomes apparent that the great vertical changes in sea level during the Pleistocene would have caused water tables, and therefore zones of maximum solution, to migrate vertically. Flushing of original marine pore water from the Castle Hayne system must have occurred numerous times, and been coincident with Pleistocene changes in sea level, also. The flushing extends long distances downdip (Stringfield and LeGrand, 1966).

The water in the Castle Hayne system is, by legal definition (DeWiest, Sayre, and Jacob, 1967, p. 156), "percolating water that filters, oozes, percolates, or flows" through the carbonate, but does not flow in well-defined channels.

All published reports have emphasized the stratigraphy, paleontology, or hydrology, but have not dealt with detailed petrology. Therefore, the diagenetic history of the rocks from initial sedimentation through their present condition is not known. This report is an initial attempt to define the rock types of the Castle Hayne Limestone and related aquifer carbonate facies, and to detail their diagenetic evolution.

Study of thin sections and whole rock specimens or cores is a necessity if one is to correctly evaluate the original character of porous rocks. Many of these rocks are rich in pelecypods and quartz. If the pelecypods are dissolved, only voids, quartz grains, and some calcite cement remain, and the sample would be designated a calcareous sandstone if crushed drill samples were used. In reality, the rock formation was controlled by biologic activities (pelecypods), and diagenetic behavior of the aragonite shells controlled the development of porosity.

METHODS

The Castle Hayne Limestone and its various facies, the Upper Oligocene channel fillings, and the carbonate facies of the Pee Dee Formation were studied in the field, and nearly the entire outcrop belt (Figure 1) has been traversed. Outcrops, both artificial and natural, especially in New Hanover County and along the eastern portion of the outcrop area were studied in particular during several field trips.

One hundred samples were collected, and 41 were made into thin sections and studied with the petrographic microscope. Several samples were stained with alizarin red S to aid in dolomite and low-Mg calcite determinations (Friedman, 1959). Several of these showed the presence of some dolomite, and these were subjected to X-ray diffraction studies, both as polished slabs and powders.
PETROLOGY

Seven distinct carbonate facies have been delineated from the thin sections. None are hybrid and members, but all grade into one another as different parameters (i.e., quartz grains, pelecypod valves, micrite, calcite spar cement, etc.) change ratios. Many, as indicated under particular sections, consist of subtypes that are quite distinct, but share similar origins, diagenetic histories, and hydrologic properties.

Pelecypod-Mold Subarkose, With Calcite Spar Cement

Seven samples fit this category, and all are from the Pee Dee Formation exposed in the Superior Stone Company Quarry near Castle Hayne (Pl. 1, 1-3). The spectrum includes unconsolidated, pelecypod-poor subarkose to those that are completely lithified and have a predominance of pelecypods. In the latter case, the rocks constitute the next category described below. Porosity and permeability vary from high to low depending upon the frequency of dissolved pelecypod valves, and completeness of spar cementation in intergran voids. If there are few pelecypods, the cementation is incipient, and porosity is intergran. If there are many pelecypods, and if they have been dissolved as is the usual case, intergran voids are filled with calcite spar cement, and porosity is intragrain (intrapelecypod valve) (Pl. 1, 2-3). The two types are interbedded, indicating a local source for the calcite cement. In some instances the pelecypod valves have not been affected, and are preserved as original low-Mg calcite skeletal material (Pl. 1, 1). Solution of most valves indicates original aragonite mineralogy of the shell. Echinoid bioclasts and detrital glauconite are found in this facies, also.

Sandy, Pelecypod-Mold Biocalcirudite, With Calcite Spar Cement

Eleven samples were grouped under this facies, all of which were collected from the carbonate phase of the Pee Dee Formation exposed in the Superior Stone Company Quarry near Castle Hayne (Pl. 1, 4-6; Pl. 2, 1). High porosity and permeability are common in this group, and are controlled by frequency of intrapelecypod-mold voids, and the amount of subsequent infilling. Pelecypod valves are occasionally unaffected (Pl. 1, 4; Pl. 2, 1), but most were originally aragonite and have been dissolved. Incomplete intergran calcite spar infilling adds to the porosity (Pl. 1, 5), but this is relatively rare. In some beds, or individual samples, dissolved valves have been completely infilled (Pl. 1, 5). Other minor constituents of this facies are echinoid plates and detrital glauconite.

Slightly Sandy, Phosphatic Lithocalcirudite, With Micrite Matrix

Six samples were thin-sectioned for detailed study. All were collected from the basal portion of the Castle Hayne Limestone in the southern part of the outcrop area where the Castle Hayne lies directly on a solution surface which developed in the Pee Dee Formation. All samples are low in porosity and permeability (Pl. 2, 2-3). This facies contains both phosphate and limestone pebbles, all well-rounded, which may be derived as detrital pebbles from the Pee Dee, or as intraformational clasts. It is possible that the limestone is derived from the Pee Dee, and the phosphate
is intraformational. The small amount of porosity present is due to dissolved molluscan fragments. Other clastic grains are brachiopods, echinoids, foraminifers, bryozoans, bone, ostracodes, and glauconite. The micrite\(^1\) has aggraded to coarser sparry calcite in some parts of the facies.

**Sandy, Molluscan-Mold Biocalcirudite, With Pseudospar Matrix**

Six samples were grouped in this facies, three from the lower Castle Hayne Limestone (Chinquapin and Castle Hayne), one from the Upper Oligocene channel facies (Superior Stone Company Quarry at Belgrade), and two from the Trent facies (Superior Stone Company Quarry at New Bern). They generally display very high porosities and permeabilities, and are similar to the pelecypod-rich facies of the Pee Dee Formation (Pl. 2, 4-6). Pelecypods, and in some areas gastropods, are in various stages of low-Mg calcite infilling of dissolved aragonite valves. A few were low-Mg calcite initially, and they remain unaffected (Pl. 2, 4). Other clastic grains are intraformational limestone lithoclasts, glauconite, echinoids, various phosphates, brachiopods, bryozoans, foraminifers, and occasional ostracodes and oolites. The micrite and pellet matrix has aggraded in many zones to coarse, clear, sparry calcite, or pseudospar (Folk, 1959). This original micrite and pellet matrix is one of the major distinguishing features between this facies and the calcite spar cemented facies of the Pee Dee which has no matrix.

**Biocalcarenite, With Micrite Matrix**

This facies is represented by six samples, which may be divided into two subfacies, one containing mainly bryozoan fragments (Pl. 3, 1), and the other containing mainly echinoid debris (Pl. 3, 2). These are end members, and most samples contain appreciable amounts of both. All samples are from the Castle Hayne Limestone, and generally have low porosities and permeabilities. In many samples the micrite matrix has aggraded to pseudospar. Other grains in this facies are rare and consist of fragments of pelecypods, gastropods, foraminifers, ostracodes, pellets, calcareous algae, brachiopods, glauconite, and quartz. Authigenic dolomite is rarely present.

**Partly Silicified Pelletoidal Biocalcarenite, With Micrite Matrix**

Two samples fit this facies, and both are from beds in the Castle Hayne Limestone. One type (Pl. 3, 3) contains outlines of siliceous sponges, and the other (Pl. 3, 4) contains silicified bioclasts set in a pelletoidal micrite matrix which has remained unaffected. They display low porosity and permeability. Other bioclasts are sponge spicules, ostracodes, echinoderms, bryozoans, foraminifers, and pelecypods.

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\(^1\) Micrite is a contraction of the term microcrystalline calcite. Originally, it was aragonite or calcite ooze or mud, but is now low-Mg calcite. The crystal size is \(< 4 \mu\) (Folk, 1959).
Biocalcarenite, With Some Calcite Spar Cement

Three samples fall into this facies (Pl. 3, 5-6) and all were collected from the Castle Hayne Limestone. Porosity is moderate, original, and therefore intergrain. The grains consist of fragments of echinoids, foraminifers, bryozoans, and some pelecypods, bone, pellets, limestone lithoclasts, and detrital and authigenic glauconite. The latter often fills bryozoan zooecia or pore spaces in echinoid plates. Low-Mg calcite cementation is incipient. There are few aragonite skeletal materials to dissolve in this facies, so there is no local supply for the cement. Some dolomite, mainly in voids, has been identified.

DIAGENESIS

Introduction

Nearly all of the carbonate in the Castle Hayne aquifer is low-Mg calcite, which is the most stable form under meteoric water conditions. It has been shown by a number of researchers that the most common Recent shallow marine carbonate sediments consist of high-Mg calcite and aragonite, and small amounts of low-Mg calcite. This is the order of increasing stability outside the marine environment (Chave, 1952, 1954a, 1954b, 1962; Lowenstam, 1954; Stehli and Hower, 1961; Friedman, 1964; Matthews, 1966). Low-Mg calcite contains less than four percent MgCO$_3$ in solid solution, whereas high-Mg calcite has between four and 30 percent. Aragonite is an orthorhombic metastable polymorph of hexagonal low-Mg calcite. Because shallow marine carbonates are mainly skeletal in origin, it is important to realize original mineralogy of the animals and plants in the environment.

In this study it is evident we are concerned with only a few animals. They are listed below in decreasing order of volumetric importance, followed by common shell mineralogy (Chave, 1962):

- Pelecypods: aragonite, aragonite and low-Mg calcite, low-Mg calcite
- Gastropods: aragonite, aragonite and low-Mg calcite
- Echinoderms: high-Mg calcite
- Bryozoans: aragonite, aragonite and high-Mg calcite
- Foraminifers: low-Mg calcite, high-Mg calcite
- Ostracodes: low-Mg calcite

Bøggild (1930) was one of the first workers to document the diagenetic changes that occur in mollusk shells, and how to recognize the changes. Bathurst (1964, 1966) and Dodd (1966) have more recently applied modern knowledge of Recent marine carbonates to this problem in order to decipher ancient limestones, and have concentrated their efforts on molluscan shells.

In ancient limestones both aragonite and high-Mg calcite are rare. Stehli and Hower (1961) and Friedman (1964) prove that rocks as young as Pleistocene which originally contained large amounts of these minerals now consist mainly of low-Mg calcite. They attribute these changes to
exposure of the marine carbonates to meteoric water. Taft (1967) has performed laboratory experiments in which aragonite conversion to low-Mg calcite takes place in days when placed in pure water.

Aragonite apparently changes to low-Mg calcite in one of two ways. The first, common in conversion of aragonite ooze to micrite, involves solid state inversion (Folk, 1965). Some skeletal fragments may be converted in this manner, also, and this would allow preservation of the original shell texture. The second, and most common among the mollusca, involves solution and formation of moldic porosity (Bathurst, 1964, 1966; Friedman, 1964). These molds may later be infilled with low-Mg calcite which is coarse and clear, but no traces will remain of the original shell texture. This is the process which provides the low-Mg calcite cement needed to lithify a carbonate sediment to a limestone.

Upon subaerial exposure, high-Mg calcite is converted to low-Mg calcite by leaching of the Mg, or solution-deposition on a micro scale (Friedman, 1964). This process does not form moldic porosity, and original textures remain intact.

Diagenesis In The Castle Hayne Aquifer

Calcium Carbonate. Solution of molluscan shells, indicating original aragonite composition, is the most important process in the development of high porosity and permeability. Most shells are either empty, forming perfect molds, or are partly infilled with low-Mg calcite. Few are completely filled. The infilling occurred only after a substantial part of the intergrain voids were filled. An indication that the solution-deposition system is small is shown by interbedded quartz sand with few aragonite pelecypod valves to dissolve and provide bicarbonate which would be deposited as the cement, and well-cemented pelecypod-rich rocks. Most of the molluscan shells were composed of aragonite; few show evidence of original textures. Differential treatment of aragonite valves side by side, some dissolved and others inverted, does not seem reasonable. Solution followed by infilling appears to be the most common type of molluscan shell conversion, not only in the Castle Hayne carbonates, but in all ancient limestones.

Facies containing other skeletal types achieve porosity control in other ways. Echinoids and some bryozoans and foraminifers contribute Mg to the water, but otherwise do not add moldic porosity. They aid in maintaining original porosity, if initially present, because they do not supply much bicarbonate to the system. Evidence of this is seen in the poorly cemented biocalcarenites.

Silicification. Replacement of carbonate, or original precipitation of silica in voids, has been extremely rare. It occurred only in some of the micrite-rich carbonates of the Castle Hayne Limestone, and only if siliceous sponges were available to supply the silica by solution of spicules. Large scale silicification has been reported (LeGrand and Brown, 1955, p. 9), but probably has been attributed to very angular, moldic, sandy limestones. A chemical analysis, or mineralogical analysis would reveal the presence of large quantities of quartz, but it would be present in detrital form.
Silicification, therefore, does not play an important role in the hydrologic properties of the aquifer.

**Dolomitization.** Dolomite was identified in only a few samples, and in very small amounts. The biocalcarenite with micrite matrix and the friable biocalcarenite, both from the Castle Hayne Limestone, were the facies affected. The dolomite infilled some intergrain and intragrain (i.e., bryozoan zooecia) voids. The Mg was probably derived from the echinoid debris as they released the Mg during recrystallization to low-Mg calcite. Brown (1958) reported large amounts of dolomite in well cuttings, but this has not been verified in the outcrop belt.

Dolomitization, it is concluded, played an insignificant role in the development of porosity and permeability.

Porosity

Four types of effective porosity of varying importance are common in the Castle Hayne aquifer. These are given in increasing order of importance:

1. A low frequency of joint and channel solution enlargements. All rocks of the aquifer may be affected.

2. Original intergrain porosity, the pores of which may be partly infilled with calcite cement. This is typical of the pelecypod-mold subarkose facies of the Pee Dee Formation, and the partly-cemented biocalcarenite of the Castle Hayne Limestone.

3. Intragrain porosity, obtained by the solution of aragonite from molluscan shells set in quartz and micrite. This is common in the various facies of the Castle Hayne Limestone and the Upper Oligocene channel beds.

4. Intragrain, coupled with some intergrain, porosity which is found in the sandy, pelecypod-mold bioclastic facies of the Pee Dee Formation. These rocks provide the best effective porosity, and volumetrically are most common in this aquifer. The stages of porosity development are shown diagrammatically in Figure 2. Stages III and IV represent the most common textures found. Stage V is found occasionally, and the first two represent stages formed very early in the history of the rock and are not found. Note that an inversion in the location of the porosity is accomplished between stages I and III.

**CONCLUSIONS**

The following tentative conclusions are reached from this preliminary investigation:

1. The Castle Hayne aquifer, in the outcrop belt, includes a carbonate-rich facies of the Upper Cretaceous Pee Dee Formation, various facies of the Castle Hayne Limestone, and Upper Oligocene channel facies.

2. Seven major facies have been delineated in the aquifer: pelecypod-mold subarkose, with calcite spar cement; sandy, pelecypod-
mold biocalcirudite, with calcite spar cement; slightly sandy, phosphatic lithocalcirudite, with micrite matrix; sandy, molluscan-mold biocalcirudite, with pseudospar matrix; biocalcarenite, with micrite matrix; partly silicified, pelletoidal biocalcarenite, with micrite matrix; and biocalcarenite, with some calcite spar cement.

3. The presence or absence of porosity is controlled by original skeletal mineralogy and micrite. Most of the valves and shells were constructed by pelecypods and gastropods. The most common mineral found in these skeletons in Recent shallow marine waters is aragonite, which is unstable when exposed to meteoric water. Solution of the skeletons occurs after emergence, and low-Mg calcite is precipitated nearby as a cement. The presence of micrite disallows any intergrain porosity.

4. Silicification and dolomitization of the carbonates are minor, and do not contribute to the hydrologic properties of the aquifer.

5. Porosity is achieved four ways, in increasing order of importance: joint and channel enlargements; original intergrain porosity, partly infilled; intragrain porosity, developed in molluscan shells embedded in micrite; and intragrain, with some intergrain, porosity developed in pelecypod-mold rich limestone with initial intergrain porosity (no micrite).

6. Limestones that contain few fossils that were originally aragonite, and large quantities of micrite, have low porosities. Those that have many aragonite fossils, and no micrite, develop high porosities.
Figure 1. Location map showing outcrop pattern of the Castle Hayne Limestone (after Stuckey and Conrad, 1958).

Figure 2. Stages of porosity development of the most typical Castle Hayne aquifer limestone. See text for details.

Stage I. Sedimentation, in shallow marine water, of detrital quartz, aragonite and low-Mg calcite pelecypod valves, an aragonite gastropod shell, and a high-Mg calcite echinoid plate.

Stage II. Emergence of the sediment and exposure to percolating meteoric water. Skeletal aragonite is partially dissolved and precipitated nearby as intergrain low-Mg calcite cement. The high-Mg calcite recrystallizes to low-Mg calcite. Porosity is very high.

Stage III. Complete solution of the skeletal aragonite is accomplished, and the entire sediment is cemented by low-Mg calcite. The porosity is now entirely within the skeletal grains. This stage, and the following one, are the most common.

Stage IV. Low-Mg calcite begins to precipitate within the fossil molds, and porosity is decreased.

Stage V. All original intergrain voids, and secondary intragrain voids have been filled with low-Mg calcite. The rock has no porosity.
ARAGONITE
LOW-MAGNESIUM SKELETAL CALCITE
VOID, WITH OR WITHOUT WATER
QUARTZ SAND
HIGH-MAGNESIUM SKELETAL CALCITE
LOW-MAGNESIUM CALCITE PRECIPITATES

FIGURE 2
Plate 1

Photomicrographs


2. Pelecypod-mold subarkose, with calcite spar cement. A completely dissolved pelecypod valve, originally aragonite, lies parallel to bedding. The valve cavity is dark. Other dark areas represent inter-grain voids and quartz grains at extinction. Porosity is high. Pee Dee Formation, Superior Stone Company Quarry near Castle Hayne. Crossed nicols.


4. Sandy, pelecypod-mold biocalcirudite, with calcite spar cement. The pelecypod valve in the upper portion of the photo is unaffected because it was originally low-Mg calcite. The valve at left-center is empty, because the original aragonite was dissolved. The valve at the bottom has been dissolved and subsequently infilled with low-Mg calcite. Porosity is high. Pee Dee Formation, Superior Stone Company Quarry near Castle Hayne. Plain light.

5. Sandy, pelecypod-mold biocalcirudite, with calcite spar cement. The valve in the upper left has been partially infilled with low-Mg calcite. Another small valve, lower center, has been completely filled. The large valve in the center has only a few crystals which have grown into the void. Note the incompletely filled intergrain space to the upper right. Porosity is very high. Pee Dee Formation, Superior Stone Company Quarry near Castle Hayne. Plain light.

6. Sandy, pelecypod-mold biocalcirudite, with calcite spar cement. Four pelecypod valves are set in low-Mg calcite cement and detrital quartz grains. The valves were originally aragonite, and are in various stages of infilling. Porosity is very high. Pee Dee Formation, Superior Stone Company Quarry near Castle Hayne. Plain light.
Plate 2

Photomicrographs

1. Sandy, pelecypod-mold biocalcirudite, with calcite spar cement. The pelecypod valve in the upper right consists of original low-Mg calcite, as does the one in the lower left. Other valves, initially aragonite, are in various stages of infilling subsequent to solution. Porosity is very high. Pee Dee Formation, Superior Stone Company Quarry near Castle Hayne. Plain light.

2. Slightly sandy, phosphatic calcirudite, with micrite matrix. Three phosphate pebbles are set in micrite and pellets, some of which have recrystallized to pseudospar. Porosity is low. Base of Castle Hayne Limestone, abandoned quarry near Castle Hayne. Plain light.

3. Slightly sandy, phosphatic lithocalcirudite, with micrite matrix. Two pebbles of limestone (intraformational or detrital) are set in micrite and echinoderm bioclastic matrix. Other portions of the sample contain phosphatic pebbles. Porosity is low. Base of Castle Hayne Limestone, Superior Stone Company Quarry near Castle Hayne. Plain light.

4. Sandy, pelecypod biocalcirudite, with pseudospar matrix. Near the top of the photo is a completely infilled low-Mg calcite pelecypod valve, which was originally aragonite. At the base is an original low-Mg calcite, unaltered, pelecypod valve. Porosity is low. Castle Hayne Limestone, near Chinquapin. Plain light.

5. Sandy, pelecypod-mold biocalcirudite, with pelletoidal and pseudospar matrix. Two small pelecypod fragments are located in the upper left portion of the photo, and are completely infilled with low-Mg calcite. The upper right and lower portions of the slide contain partly infilled valve cavities. These were initially aragonite, and were dissolved before low-Mg calcite infilling. Porosity is very high. Trent facies, Castle Hayne Limestone, Superior Stone Company Quarry at New Bern. Plain light.

6. Sandy, pelecypod-mold biocalcirudite, with pseudospar matrix. Two large and completely dissolved pelecypod valves, initially aragonite, are set in detrital quartz, pseudospar, and micrite. Porosity is very high. Castle Hayne Limestone, abandoned quarry near Castle Hayne. Plain light.
Plate 3

Photomicrographs

1. Bryozoan biocalcarenite, with micrite matrix. Two well-preserved bryozoans, with micrite-filled zooecia, are set in a micrite matrix. Poro-
sity is low. Castle Hayne Limestone, abandoned quarry near Castle Hayne. Plain light.

2. Echinoid biocalcarenite, with micrite matrix. Two well-preserved echinoid plates are located in the lower left of the photo, and a bryozoan in the right center. The very porous echinoid bioclasts have lost Mg and have recrystallized to low-Mg calcite, and the pore areas have been infil-
led with low-Mg calcite. White halo zones surrounding bioclasts were
micrite, and have recrystallized to pseudospar. Porosity is low. Castle Hayne Limestone, Superior Stone Company Quarry near Castle Hayne. Plain light.

3. Siliceous sponge-bearing pelletoidal biocalcarenite, with micrite matrix. The white pattern that trends from left to right is a sponge, the light areas representing siliceous spicules. Porosity is low. Castle Hayne Limestone, Maple Hill. Plain light.

4. Partly silicified pelletoidal biocalcarenite, with micrite matrix. Two silicified bryozoans are in the center of the photo, and the other light areas throughout are silicified bioclastics. Porosity is low. Castle Hayne Limestone, Maple Hill. Plain light.

5. Biocalcarenite, with incipient calcite spar cement. Fragments of echinoids and foraminifers are partly cemented by low-Mg calcite. Most of the intergrain zones are empty and show as white areas. Some dark grains represent glauconite. Porosity is moderate. Castle Hayne Limestone, Superior Stone Company Quarry near Castle Hayne. Plain light.

6. Biocalcarenite, with incipient calcite spar cement. Fragments and whole individuals of foraminifers, and echinoids are partly cemented by low-Mg calcite. Many original organic structure voids are filled with glauconite. White areas are intergrain pores that are incompletely filled. Porosity is moderate. Castle Hayne Limestone, Superior Stone Company Quarry near Castle Hayne. Plain light.
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SALT WATER ENCROACHMENT IN THE EASTERN
NORTH CAROLINA COASTAL REGION

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INTRODUCTION

The coastal region of North Carolina is a portion of a broad low-lying plain extending from New England in the North to Georgia and Alabama in the South. The elevation is normally less than 100 feet above sea level and the ground slope is about 3 feet per mile. The eastern margin is characterized by long tidal estuaries. The Coastal Plain in North Carolina is not densely populated and a large part of the land near the coast is swampy (DeWiest et al., 1967).

The physiography and geology of this part of the State are given elsewhere especially in the publications of the U. S. Geological Survey and North Carolina Water Resources Department. The most important formation in this investigation is the Castle Hayne limestone (Eocene) formation which overlies unconformably the Beaufort formation in places or the Pee Dee Formation in some others. At the Lee Creek mine of Texas Gulf Sulphur Company, the thickness of this formation is 230 feet and as a whole it dips gently eastward from its outcrop to southwestern Beaufort County where it is completely covered by the Yorktown formation. "The formation typically consists of very permeable gray to white shell limestones and dolomitic shell limestones interbedded with and underlain by fine to medium-grained calcareous sands and clays." (DeWiest et al., 1967) The Castle Hayne Formation is the main source for any ground-water development in the Coastal region. Its hydraulic conductivity is estimated between 1,000 to 2,500 gpd/ft\(^2\) as compared for example to the Yorktown formation where the hydraulic conductivity is only about 250 gpd/ft\(^2\). (DeWiest et al., 1967)

Due to the recent development of the North Carolina Coastal region, the problem of salt water encroachment in the water bearing formations has become important. In such a vast area with all phases of physiographic and geologic complexities it is difficult to obtain push button theoretical solutions to the problems involved, nor would it be fruitful to conduct a slow extensive research on the present conditions which may change considerably while the research is being conducted. However, there are basic data that should be obtained to better understand the situation and to be able to anticipate any problems that may arise from imposing new conditions. It is needless to emphasize here the need for extensive geologic studies, but the main concern of this paper is to emphasize some important engineering investigations that should be coupled with such geologic work. In addition to these studies, chemical analysis of water pollution problems and pertinent field work and other related investigations should be expanded.
From an engineering point of view the following topics are explained and discussed, but in no way should they be considered as comprehensive:

1. Piezometric maps
2. Study of the leakage problems
3. Physical properties of rocks

Piezometric Maps

From the recent report submitted to the North Carolina Department of Water Resources by R. DeWiest, A. N. Sayre and C. E. Jacob (1967), it was recommended that:

"Inasmuch as there is presently insufficient data to enable us to delineate of the fresh water-salt water contact in the major water-bearing formations, we recommend that this become a prime objective of the Ground Water Division of the Department of Water Resources and that funds be made available for the necessary exploration drilling and testing.

Ground-water investigations should be continued and expanded. Studies of a more detailed nature should be carried forward as rapidly as possible. We recommend the monitoring-well program to be expanded to cover the entire coastal plain on a grid of ten miles or denser." In this respect it is recommended not only to construct contour maps for the Castle Hayne Aquifer, but also for the upper and lower confining beds (Beaufort, Pee Dee and Yorktown for example). These confining beds are not absolutely impervious and definitely there should exist downward and upward leakage under any deviation from the equilibrium condition such as the change in the natural aquifer flow, the change in water pressures by pumping and/or the tidal effects.

Care should be given to the drilling of the observation well in order to determine within a tolerable error the water pressures and to determine exactly what these pressures represent. A method may be developed to use one observation well to determine various values of pressures along the vertical axis in three or more formations coinciding with the axis of the well. If this were found impossible or expensive, separate sets of observation wells should be installed to each distinct soil layer.

The water pressure measurement is relatively simple in soils or rocks of high permeability. However, in soils of low permeability it is not a routine matter. In the latter cases the levels measured at a specific time would represent only a stage in the water movement within the observation well. There are certain approximate methods used (Hvorslev, 1949) to determine the water table level in such cases. These methods generally require bailing water out of the bore hole and then recording 3 or more levels of the rising water at equal time intervals. Such methods can be checked and accordingly modified to suit a certain location. If the bore hole is filled with water and then bailed out successively, then the true water level should lie between a rising and a lowering level. After getting some experience the equations such as those given by Hvorslev.
(1949) may be used directly in other locations or modified according to the results of this procedure.

It is recommended that several piezometric contour maps be constructed for various layers at various times. These maps are invaluable and would assist in the study of the flow and its direction as well as the effects of natural recharge, artificial discharge, tidal effects and even the degree of nonuniformity in the hydraulic properties of the soil and rock media and several other geologic and engineering factors.

**Leakage Problems**

Other than any geologic feature that may exist and be the cause of major leakage that would affect the predominant nature of the flow, the leakage may take place to or from the Castle Hayne formation due to the disturbance of the equilibrium condition within that formation by a natural or artificial condition. The leakage from or into the Castle Hayne is most likely to be derived from the upper or lower confining beds. If the pressures are decreased and the water in one of these beds were brackish, the salt water encroachment would result from two sources: leakage as well as direct encroachment due to the increase in the length of the intruded wedge from the ocean into the main aquifer.

In most of the present theories of leaky aquifers, the semi-pervious confining beds are considered either merely transmitting media for leakage waters to or from the main artesian aquifers, or as transmitting as well as contributing by their storage due to their elasticity to that leakage. In both cases the soil formations are assumed to exhibit no changes with time in their physical properties such as the storativity and hydraulic conductivity. It is to be noted that the first case could not be attained except after the ultimate deformation is reached; a state which requires a theoretical infinite time to develop after deviation from equilibrium takes place. In the second case, water flow is essentially due to change in the pore-water pressures by time. No consideration is presently given to the nature of the change in the coefficient of storage or the hydraulic conductivity due to the gradual change in the porosity. The nature of such changes in the confining beds and their effect on the value of water pressures or hydraulic heads with time due to pressure changes in the main artesian aquifer, were examined by the writer (Kashef, 1966) in order to check the degree of validity of assuming constant soil properties. The problems of determining the rate of leakage and subsidence of the confining bed were also explained considering time-dependent properties. A finite difference equation was given to determine the rate of leakage in terms of the compression index $C_c$, the initial void ratio $E_i$ of the confining bed, the total stress, the initial head, the depth of the layer, the unit weight of the soil material and the magnitudes of the head before and after a time interval $\Delta t$. It has been found that the subsidence of the confining beds due to that leakage also depends on the same factors.

In this respect, it should be emphasized that there is a relation between the leakance or the diffusivity of the soil $C_V$ (known also as the coefficient of consolidation) in the case of time-independent soil physical properties. The relation between the drop in head "s" and time
"t" in the vertical direction y is given by:
\[ \frac{\partial^2 S}{\partial y^2} + \frac{3S}{T} \frac{\partial S}{\partial t} = 0 \]  
(1)

where \( T \) = transmissivity factor = \( kb \)

\[ S = \text{Coefficient of storage} = \frac{n V_w b (\beta + \frac{m_v}{n})}{k} \]  
(2)

\( k \) = the hydraulic conductivity

\( b \) = thickness of formation

\( n \) = average porosity of soil material

\( V_w \) = unit weight of water

\( \beta \) = the compressibility of water or the reciprocal of its bulk modulus

\( m_v \) = vertical compressibility of the soil

If the water compressibility is neglected, then:
\[ \frac{S}{T} = \frac{V_w - m_v}{k} = \frac{1}{C_v} \]  
(3)

and
\[ \frac{\partial^2 S}{\partial y^2} = \frac{1}{C_v} \frac{\partial S}{\partial t} \]  
(4)

On the other hand if \( \beta \) is considered, then:
\[ \frac{S}{T} = \frac{n V_w \beta}{k} + \frac{1}{C_v} \]  
(5)

and
\[ \frac{\partial^2 S}{\partial y^2} = \left( \frac{n V_w \beta}{k} + \frac{1}{C_v} \right) \frac{\partial S}{\partial t} \]  
(6)

Up to date, the ground-water hydrologists have not used the results of laboratory experiments in the study of leakage. The writer recommends that during the drilling program in the North Carolina Coastal Region, undisturbed samples should be taken from such beds as Beaufort, Yorktown and Pee Dee and tested by the consolidation machine. The test results include both factors \( k \) and \( C_v \) as well as \( C_c \) and accordingly the leakage of these aquifers can be studied under various conditions within the Castle Hayne formation as well as the subsidence due to this leakage.

**Physical Properties of Rocks**

It has been noticed that the estimation of the coefficient of storage \( S \) for the Castle Hayne Aquifer in three pumping tests were as follows (DeWiest et al., 1967):

\( S = 0.0008 \) in a test near Aurora run for a period of 28 hours (Dec. 1962)
\[ S = 0.00019 \] in a test in Lee Creek run for a period of 35 days (August-September, 1964)

\[ S = 0.0009 \] in a test in the Coastal plain run for a period of 1 year (1965-1966)

It is observed that in the same formation \( S \) determined from one test is five times as much as that from another test near the same location and in both cases the depth of the formation was the same (b \( \approx \) 300 feet). Although this may be attributed to various reasons but in the writer's belief this discrepancy in the values of \( S \) indicates the existence of cracks, fissures or caverns, that would affect the coefficient of vertical compressibility \( m_v \). It has been stated by J. B. Walsh (1965) that "Measurement of the deformation of rocks under hydrostatic pressure shows that compressibility—the fractional volume decrease per unit of pressure—often is not a constant, as would be expected for an elastic material, but varies with pressure and with the type of test."

Assuming that the results given by DeWiest, Sayre and Jacob (1967) are within reasonable practical limits, that the porosity \( n \) of the Castle Hayne formation is 30%, and that the coefficient of compressibility of water \( \beta = 3.3 \times 10^{-6} \) square inch per pound, then:

In the 35 days test

\[
S = 0.00019 = n \gamma b \beta + \gamma b m_v
= 0.00013 + \frac{62.5}{12 \times 12 \times 12} \times 300 \times 12 \times m_v
= 0.00013 + 130 m_v
\]

Then \( m_v = 0.46 \times 10^{-6} \) square inches per pound and thus the elastic modulus would be \( 2.17 \times 10^6 \) psi.

In the one year test

\[
S = 0.0009 = 0.00013 + 13 m_v
\]

Then \( m_v = 5.92 \times 10^{-6} \) square inches per pound and thus the elastic modulus would be \( 0.169 \times 10^6 \) psi.

Comparing these values with the results obtained by R. P. Miller (1965) on three limestone intact samples (Bedford, Indiana; Ozark Tavernelle, Carthage Missouri and Solenhofen, Bavaria), where the static tangent modulus ranged between \( 3.58 \times 10^6 \) to \( 9.40 \times 10^6 \) psi, it can be concluded that these low approximate values were the result of the presence of cracks in the Castle Hayne Formation. Furthermore in the one year test it is shown that the deformation in the rock is excessive as compared to a porous tuff tested by Miller (1965) where the least static tangent modulus was found to be \( 0.68 \times 10^6 \) psi.
By no means, this discussion implies that the presented procedure is a correct one for determining the coefficient of compressibility of the Castle Hayne formation under various pore water pressure conditions. But, it is presented here to point out the importance of the study of the physical properties of this formation. It is to be noted also that the applied theories for the determination of S and T in this case were developed originally for homogeneous fairly elastic soil formations with no irregularities such as cracks or caverns. It is recommended that such studies are of major importance and a selected bibliography is given at the end of this paper of the most recent work in similar cases. It is further recommended that the compressibilities of the soil formations be recorded in the field to study the effect of the various factors on their behavior.

Salt Water Encroachment Under the Steady State Conditions

In the North Carolina Region, there are many areas where the present situation represents an equilibrium condition. If the salt water encroachment problems are studied in such areas, they would render an explanation of the effects of heavy withdrawal of water in recently highly developed areas such as Aurora, and would create a better ability to formulate sound judgments and reasonable predictions. Furthermore, after collecting enough geologic and engineering data it may be possible to base such predictions on the results of model tests such as the resistance-capacitance models where the initial conditions would be better set on the basis of this information. The problem at present would thus be confined to the location of the interface between fresh and salt water bodies in the Castle Hayne aquifer as well as in the upper confining beds where the pressures are expected to be non-artesian.

It is well established that any minor agitation by water withdrawal or a decrease in the natural flow would cause the intruded salt water body to increase, though not to a dangerous stage except in the event of an overdraft that would create serious problems of fresh water contamination which affect industry, agriculture and domestic usage. Thus, it is of great importance to study the behavior of the intruded salt wedge under various conditions of recharge and water withdrawal. Complex states of flow are amenable to logic analysis once the interface between salt and fresh water bodies is located under various conditions of natural flow. The shape and behavior of such an interface are useful not only in engineering planning, but also in legal, economic, and political considerations. In their recent report, DeMiest, Sayre and Jacob (1967) stated that, "The Board of Water Resources should be empowered to prescribe the criteria to be used and the procedures to be followed to protect fresh-water aquifers from contamination by salty water in coastal areas, especially in the vicinity of tidal estuaries, bays, or other surface or subsurfaces bodies of saline water. Such criteria should provide for maintaining the hydraulic head at or above sea level in all areas where it is known that the Castle Hayne limestone or other productive aquifers are directly connected with brackish water, or where the mantel of less pervious material is so thin that saline water has easy access to those aquifers." Although, there is no general objection to this statement, there should be a basis for the criterion cited that the hydraulic head should be maintained at or above sea level. After further studies such criteria may be enhanced to more
practical ones.

The salt water intrusion problems were recognized more than a century ago (Braithwaite, 1855) and were later analysed theoretically by Ghyben (1889) and his findings, presently known as Ghyben-Herzberg principle, were checked in the field by Herzberg (1901) and Pennink (1905). In Ghyben analysis, the fresh and salt waters are treated as two immiscible fluids separated by a sharp interface. Although both waters mix in a dispersed water belt of various degrees of salinity, the same assumption is still applied in recent investigations as a first approximation and its study is useful in determining the nature of the fresh water losses below sea level. However, Ghyben assumed that the interface, sea level, and the water table all meet at one point contradicting his assumption of static fluids. These assumptions eliminated the actual existence of the seepage surfaces above and below the sea level. Considering the fresh-water movement, it is well established that the Ghyben curve lies above the "exact" interface considered as a distinct surface rather than a dispersed zone.

Hubbert (1940), Glover (1959) and Henry (1959) realized the analogy between the free surface in the seepage through dams and the interface. The surface of seepage is considered either vertical or horizontal. In the most recent viscous model study by Columbus (1965), the water table is assumed to represent the average head along any vertical section within the aquifer. Although in Columbus' analysis, the Ghyben-Herzberg principle is assumed valid and Dupuit's assumptions are adopted, he made use of Henry's (1959) exact solution in his approximate analysis. Almost the same procedure was followed by Rumer and Harleman (1963). In 1967, the author presented a method (Kashef, 1967b) based on the analogy between the interface and the free surface of dams with vertical faces without tail water, a problem that was previously solved by Kashef and McDonald (1967a). Both the confined and unconfined aquifers were analysed. The results compared favorably with Henry's (1959) solution, Muskat's (1937) and the same conclusions concerning the unconfined aquifers reached by Charmsonman (1965) were found to hold true in the writer's method; however, Charmmonman treated the case with a horizontal rather than vertical seepage surface.

Theoretical Results in Artesian Cases:

Referring to Figure 1 and with respect to the shown x and y axes, the following equations resulted:

The length of the intruded wedge $L$ is given by:

$$L = \frac{\alpha k h_o^2}{2\varphi}$$

(7)

where $k =$ hydraulic conductivity in the fresh zone

$h_o =$ the depth of the artesian aquifer

$\varphi =$ rate of flow of the fresh water towards the sea

$\alpha = (\gamma_s - \gamma_f)/\gamma_f$
Fig. 1: Interface in Confined Aquifers

Artesian Aquifer

Total Head Diagram

Interface

$\phi_{y,0} = \frac{\phi_{y,0}}{k}$

$\phi_{x,0} = \frac{\phi_{x,0}}{k}$

$\phi_{y,h} = \frac{\phi_{y,h}}{k}$

$\phi_{x,h} = \frac{\phi_{x,h}}{k}$

$-h_{0}$

$-\Delta h_{0}$

$A$

$-h_{d}$

$-h_{c,0}$

$y = y_{1}$

$y = \frac{y_{1}}{k}$

$\frac{y_{1}}{k}$

$\frac{y}{k}$

$\frac{y+1}{k}$

$\frac{y}{k}$

$\frac{y_{0}}{k}$

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$\frac{y_{1}}$
\( \gamma_s \) = unit weight of the salt water

\( \gamma_f \) = unit weight of the fresh water

Equation 7 was derived "rigorously" without introducing Dupuit's assumption.

The depth of the fresh zone \( h_x \) at any distance \( x \) from the origin (Figure 1) is calculated by:

\[
h_x = h_o \left[ 1 - e^{\frac{-8Lx}{8L^2}} \right] + h_o^2 \left( 1 - \frac{x}{L} \right)
\]

where \( e \) is the base of the natural logarithm.

From Equation 8 the depth of the discharge face \( h_d \) is determined by substituting \( x = L \), then:

\[
h_d = \frac{h_o^2}{2L} \sqrt{\frac{-8L^2}{h_o^2} \left( 1 - \frac{8L^2}{h_o^2} \right)}
\]

When the ratio \( \frac{L}{h_o} \geq 1.0 \), the term \( e^{\frac{-8Lx}{8L^2}} \) or \( e^{\frac{-8L^2}{h_o^2}} \) vanishes and Equation 9 reduces to:

\[
h_d = 0.3535 \frac{L}{h_o} h_o^2
\]

From Equations 7 and 10:

\[
h_d = \frac{0.707}{\alpha k} \gamma
\]

The equivalent equation to equation (10-a) as given by Henry's (1959) rigorous solution for semi-infinite aquifer, was given as:

\[
h_d = \frac{0.741}{\alpha k} \gamma
\]

Also from equations 7 and 8 it follows that:

\[
h_x = \frac{2\pi}{\alpha k} (L - x) + \frac{\alpha^2}{2k^2} \left[ 1 - e^{\frac{-4\pi k x}{\alpha}} \right]
\]

When the ratio \( \frac{L}{h_o} \geq 1.0 \), the term \( e^{\frac{-4\pi k x}{\alpha}} \) can be neglected as compared to unity and Equation 11 is reduced to:

\[
h_x = \sqrt{2 \frac{\alpha}{\pi k} (L - x) + 0.5 \left( \frac{\alpha}{\pi k} \right)^2}
\]
Although Rumer and Harleman (1963) used Dupuit's assumption in their approximate analysis, yet they used at the boundary the result of Henry's solution given by equation (10-b) and they determined the following equation (using the same notations of this paper):

\[ h_x = \sqrt{2 \frac{f}{\alpha k} (L - x) + 0.55 \left( \frac{f}{\alpha k} \right)^2} \]  

(Rumer & Harleman, 1963)

which is very close to equation 12 based on the writer's solution (Kashef, 1967b). Equation 12 can also be considered to be the solution of the semi-infinite case because in this case, \((L-x)\) may be finite but \(x\) is infinite and the exponential term will also vanish in Equation (11). Comparing the writer's method with the semi-infinite case solved rigorously by Henry (1959), it has been found that the maximum difference does not exceed the difference between the results of Equations (10-a) and (10-b) as shown in Figure 2.

Once \(h_x\) is calculated from equation 8 or 11 the total head \(H_x\) at any point distance \(x\) from the origin can be determined from the following equation assuming the \(x-x\) as the datum (upper boundary of the artesian aquifer, Figure 1):

\[ H_x = \xi (x + 1) - h_x \]  

(13)

where \(\xi\) = height of mean sea level above the datum \(x-x\).

The base pressure head \(h_{bx}\) along the upper boundary of the artesian aquifer (the datum) at any point distance \(x\) from the origin is determined by:

\[ h_{bx} = -\frac{3}{4} \frac{h_o^2}{h_x} \left( 1 - \frac{x}{L} \right) - \frac{1}{4} h_x \xi - \xi (x + 1) \]  

(14)

From the already determined values of \(H_x\), \(h_x\), \(h_{bx}\), the velocity potential \(\phi_{x,y}\) at any point \((x,y)\) within the fresh zone is determined by:

\[ \frac{\phi_{x,y}}{k} = -\frac{y^2}{h_x^2} \left( H_x - h_{bx} \right) - h_{bx} \]  

(15)

The basis of equation 15 is that the distribution of the total head diagram is parabolic with a vertical tangent at the upper boundary \(xx\) (Kashef, 1967b). Apparently Equation 15 would be very useful in verifying the field records in areas unaffected by heavy withdrawals.

It is previously mentioned that Dupuit's assumptions were used and the approximate results were found almost the same as given by the present solution. The reason for this, is that a boundary value borrowed from a rigorous solution (Henry, 1959) was introduced in most of these solutions such as those given by Columbus (1965) and Rumer and Harleman (1963). Also, the vertical component of the velocity in the fresh zone is very small, its maximum value being at the interface. This fact can be indicated simply by proving that the difference between \(H_x\) (Equation 13) and \(h_{bx}\) (Equation 14) is negligible:

\[ H_x - h_{bx} = \frac{3}{4h_x} \left[ h_o^2 \left( 1 - \frac{x}{L} \right) - h_x^2 \right] \]
Fig. 2: Comparison Between Various Approaches for the Location of the Interface

Henry's Solution, 1959 (Semi-infinite case)

Proposed Method

\[ \left( \frac{h_x k'}{q} \right)^2 \approx \frac{1}{2} + \frac{2 k'}{q Q} (L-x) \]

Kashef 1967

[Modified Equation for the semi-infinite Case]

\[ \left( \frac{h_x k'}{q} \right)^2 = 0.55 + \frac{2 k'}{q Q} (L-x) \]

Rumer & Harleman, 1963

\[ (L-x) \frac{k'}{q} \]
Applying Equation 8, then:

\[ H_x - h_{bx} = \frac{3}{4h_x} \left( -\frac{h_o}{8L^2} \right)^{\frac{3}{4}} \]

Neglecting the term \( e^{-\frac{8LX}{h_o}} \) and applying Equation 10, then:

\[ H_x - h_{bx} = -\frac{3}{4} \frac{h^2_d}{h_x} \]

The above value would be maximum when \( h_x \) is minimum that is when \( h_x = h_d \). Thus if \( h_x = h_d \) and \( z = .025 \), then:

Maximum difference of \( (H_x - h_{bx}) \) should be equal to \(-0.019 h_d\), that is about 1.9% of the \( h_d \) value.

Conclusions

1. The piezometric contour maps should be drawn for the various geologic formations. Care should be considered in these records especially in the relatively impervious layers where it needs more technical skill.

2. Leakage is an important factor in the North Carolina Coastal aquifers. The available theories are inadequate and they should be improved to be suitable for the available conditions. Soil testing on undisturbed specimens is highly recommended.

3. The physical properties of the Castle Hayne formation should be studied in order to be able to decide whether the Theis, Jacob, and Hantush formulas should be used or not in the evaluation of the effect of pumping. The variation in deformation and absorption with time and pressure are important factors.

4. A method is presented to evaluate the salt water encroachment in the areas unaffected by heavy withdrawals. Such methods should be verified by field records and on that basis the effect of pumping can be appropriately determined.

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Selected Bibliography on Rock Investigations


AN APPLICATION OF THE HIGH RESOLUTION BOOMER SEISMIC
TECHNIQUE TO GROUND WATER PROBLEMS IN THE PAMLICO SOUND AREA

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INTRODUCTION

Seismic geophysical techniques utilize the principle of reflection or
refraction of energy from an interface separating media of different elas-
tic properties. Depending on the nature of the problem at hand the source
of the energy may be high explosives, a heavy weight dropped on the ground
surface, pneumatic guns, gas guns, spark discharge devices, and electro-
mechanical, piezoelectric, and magnetostrictive devices. Each basic tech-
nique has many varieties, sizes, and shapes of systems, and is adaptable to
a range of applications. Generally speaking, the gas gun, pneumatic gun,
weight dropping, and high explosive systems are used where deep penetra-
tion is desired, such as in petroleum exploration. The spark discharge
devices are applicable to problems requiring intermediate penetration and
low resolution, and the magnetostrictive, piezoelectric, and electromechani-
cal devices give higher resolution but limited penetration. A basic part
of any seismic system is a timing mechanism to determine elapsed time between
generation of the signal and reception of the reflected energy. Thus if the
velocities of travel of the energy in the intervening media are known it
becomes a simple arithmetic calculation to determine the depth to the re-
fecting interfaces. A familiar application of this technique is the stan-
dard echo sounder that determines water depths by measuring the elapsed
time between a sound pulse and its echo received after being reflected from
the bottom. The time is converted to depth and is recorded on a strip
chart, giving a continuous record of sea floor topography along the track of
the vessel.

In continuous seismic profiling on water a sound pulse also is
used, but the signal is strong enough and of low enough frequency to
penetrate below the water-sediment interface. Reflections from the various
layers of sediment and rock are received at the surface, and are amplified,
filtered, and recorded on a strip chart to produce a profile of sub-bottom
conditions along the line traversed by the survey vessel (Figure 1).

TYPES OF SYSTEMS

Because of the variety of seismic systems that are available and the
different types of results that are obtained from the various systems, a
choice of system must be made for each particular application or problem.
The commonly used systems for studying bottom and sub-bottom conditions
include the Pinger Probe, the Boomer, and the sparker devices. Each of
these has its own characteristics, summarized briefly below.
Figure 1. Diagram of marine seismic profiling system in operation.
The Pinger Probe uses a piezoelectric type transducer which emits a 6kc or 12kc signal of very short duration. Resolution is very good, allowing definition of layer thicknesses of less than one foot, but penetration is limited to the upper 5 to 10 feet of sediment (Figure 2).

The High Resolution Boomer is a recent development by Edgerton, Germeshausen and Grier, Incorporated. An electromechanical transducer produces a clean, single pulse without secondary cavitation, and a hydrophone is mounted separately to receive the reflected signal. This system obtains penetrations of as much as 200 feet under ideal conditions, and up to 100 feet in the coarse sands and gravels that severely limit the Pinger Probe penetration. Resolutions of 1 foot, even in the near-surface materials, are possible with the High Resolution Boomer. Figure 3 is an example of the type of record obtained with this system showing a buried bedrock surface, the overlying sediment, and the water column along a traverse in Salem Harbor, Massachusetts.

The Standard Boomer electromechanical system does not give good resolution of near-surface layers because of secondary reflections from cavitation collapse and water surface reflections. Every reflecting layer thus appears on the record as three or four parallel lines (Figure 4), and resolution of less than 10 to 20 feet generally is not possible.

Sparker systems utilize multiple underwater electrodes and generate a sound signal by discharging electrical energy to produce an underwater arc explosion. However, in the process a large bubble collapse pulse is generated, making it impossible to obtain a high degree of resolution (Figure 5). High energy sparker systems will achieve penetrations of several thousand feet, and may be of considerable value in offshore petroleum exploration.

THE PAMLICO RIVER SURVEY

In 1966 a proposal was submitted to the North Carolina Board of Science and Technology for a geophysical survey of the Pamlico River. The objective of the proposed survey was to locate buried channels beneath the present river bottom. Such channels, if incised deeply enough into the sub-bottom strata, could provide passageways by means of which surface water, including brackish and saline waters from the estuary, might be introduced into the Castle Hayne formation and into other subsurface aquifers. The survey required maximum resolving power and penetration of as much as 200 to 250 feet, to reach the critical horizons near the mouth of the river. The Edgerton, Germeshausen and Grier, Incorporated High Resolution Boomer was the only system that would meet these specifications, so the survey was contracted to EG&G and was run in August 1966.

The field crew consisted of a geophysicist and an instrument engineer supplied by the contractor to operate and maintain the geophysical equipment, a geological graduate student from North Carolina State University who, using a sextant to determine horizontal angles between landmarks, provided position and location data, and a boat operator for the boat hired at Washington, North Carolina. Two portable generators were mounted on the forward deck of the boat, the power supply and capacitor bank...
Figure 2. 12kc Pinger Probe record over the Hudson River.

Figure 3. High Resolution Boomer record, Salem Harbor, Massachusetts.
Figure 4. Standard Boomer record, Bay of Fundy.

Figure 5. Sparker record, English Channel tunnel survey.
were carried in the aft cockpit, and the portable transistorized amplifier and strip chart recorder were installed in the cabin. The transducer, mounted on a small catamaran, was towed approximately 50 feet astern, and the hydrophone was towed from a rigging on the beam (Figures 6, 7, and 8). While making the survey an average speed of about 5 knots was maintaining, and a total of 90.4 miles of profile was obtained during 4 days of field operation.

Figures 9 and 10 are typical of the records made on this survey. Reverberations or "multiples" generated largely between the river bottom and the water surface introduce complications that create serious problems in interpreting the records. However, the multiples exhibit certain characteristics by means of which they can be identified, so though they tend to confuse the data they do not render it completely unusable.

Accumulations of organic material at and near the bottom attenuate the transmitted signal. As a result, in areas in which organic mats are present sub-bottom reflections are not recorded and the record contains only multiples.

The heavy horizontal lines on the record are time lines representing 0.01 second intervals. At the velocity of sound in water, approximately 5000 feet per second, each 0.01 second line represents 50 feet of one-way travel, or 25 feet of depth on a two-way reflection travel path.

The irregularly spaced vertical lines are fiducial marks mechanically superimposed on the record at the times of position fixes. In this way the geophysical records are synchronized with the forward movement of the boat.

The upper trace on the record represents the water surface, and the first trace below the water surface is produced by energy traveling directly from the transducer to the hydrophone. The first reflected energy comes from the water-sediment interface, which may or may not coincide with the depth to hard bottom as shown on the navigational charts. Commonly the hard bottom appears as a sharper and more continuous reflection slightly below the first bottom.

A change in depth at which the transducer is operating, such as results from porpoising of the catamaran, produces an anomaly on the record. An abrupt change of course also results in a record anomaly, because of the change in geometry of the transducer-hydrophone system during the turn.

The major complication in the seismic records from the Pamlico River survey is the abundance of multiples, tending to mask the genuine reflections. In interpreting these records every attempt has been made to recognize and disregard the multiples, and to use only true reflections for correlations. The possibility of misinterpretation is always present, however, and may influence the reliability of some of the stratigraphic correlations. The paper that follows will present the geologic relationships and stratigraphy as interpreted from the seismic records and subsurface geologic data.
Figure 6. Pamlico River survey boat while surveying the catamaram-mounted transducer is towed astern and the hydrophone is supported by a rigging on the beam.

Figure 7. Power supply and capacitor bank for generating the High Resolution Boomer signal, Pamlico River survey.
Figure 8. Catamaran with the High Resolution Boomer Transducer, Pamlico River survey.

Figure 9. High Resolution Boomer record, Pamlico River survey. 500 watt-second output. Multiples are prominent at the right end of the record and are caused by an organic mat.
Figure 10. High Resolution Boomer record, Pamlico River survey. 500 watt-second output. Broad bands in the left third and near the right end of the record result from abrupt changes of course of the survey boat. A well defined channel is visible near the top of the center portion of the record.
ACKNOWLEDGEMENTS

This project was made possible by a grant from the North Carolina Board of Science and Technology, and this support is gratefully acknowledged. The illustrations used in this discussion, except for the records from the Pamlico River survey and the photographs of the Pamlico River operation, are the property of Edgerton, Germeshausen and Grier, Incorporated, and were used with their permission.
INVESTIGATION OF GEOLOGIC RELATIONSHIPS OF THE SHALLOW AQUIFERS IN THE PAMLICO SOUND AREA

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INTRODUCTION

The paper by Leith and Welby has described the boomer seismic technique and the interpretation of records from boomer investigations. This paper discusses the preliminary results of the investigation. The stretch of the Pamlico River from Blounts Bay to South Creek is reported upon here. Additional records are available and are presently being studied.

The depth of investigation ranged down to about 150 feet. Where conditions were particularly good, reflections were obtained from somewhat greater depths. Where organic material or other low impedance material is present in the river channel, the depth of investigation was less. In addition, the records from below the top of the Castle Hayne Limestone are in general poor. The technique does not provide information about the lithology of the reflecting horizons, although aided by a knowledge of the local section one can draw some reasonable inferences.

Limited well control is available. Most of the well records are gamma-ray logs, and the lithologic logs available do not provide the detailed lithologic descriptions necessary to fix accurately the position of the possible reflector horizons. The gamma-ray logs were used to determine the position of the Yorktown-Pungo River contact and the Pungo River-Castle Hayne contact. In addition, indications of possible reflectors were noted and related to reflections shown by the geophysical records where possible. In some cases recognizable lithologic changes portrayed on the logs can be correlated with reflections shown on the records from the nearby river channel.

Table 1 summarizes the sequence and lithology of the formations being investigated.

<table>
<thead>
<tr>
<th>Age</th>
<th>Formation</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pleistocene and Recent Miocene</td>
<td>Terrace deposits Yorktown</td>
<td>Sand, clays, and gravels</td>
</tr>
<tr>
<td>Miocene</td>
<td>Yorktown</td>
<td>Clay, sand, and shell marl</td>
</tr>
<tr>
<td>Oligocene - possibly present, but thin Eocene</td>
<td>Pungo River</td>
<td>Phosphatic sands, clay, and thin shell layers</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limestone and clay</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Limestone, coquinoïd and well-indurated in the upper layers; possibly some clay-rich layers near top</td>
</tr>
</tbody>
</table>

- 49 -
The geophysical approach permits determination of the character of the upper surfaces of the Pungo River and Castle Hayne formations as well as the disposition of other horizons. When the interpretation is completed, evidence concerning the possibilities of direct connections between the estuary and the Castle Hayne Limestone should be available. Also, the data provided by the study should be useful in considering possible ground water leakage between the Castle Hayne and the estuary. In particular, the study is concerned with the possible existence of Pleistocene channels carved through the Miocene Yorktown Formation down to the Pungo River and Castle Hayne as a consequence of a lowered sea level.

DISCUSSION

Figure 1 illustrates the general location of the area and the lines of section which are illustrated in subsequent figures. Figures 2 and 3 show the configurations of the Castle Hayne and the Pungo River upper surfaces respectively and are based upon those given by Kimery (1965). It was from these maps that the tops marked by the symbols on the sections were taken. Not in all cases is there a reflecting horizon which corresponds directly with the top of each of the formations, although there is often a horizon very near the top.

Figure 4 shows two northerly trending sections from near the mouth of Blounts Bay. The first bottom reflector is shown as a bold line. Lighter weight lines above it are local reflecting horizons in the soft muddy material over it. In each section the Pungo River and the Castle Hayne reflect energy and can be mapped with the boomer. The profile shown toward the northern end of Section II is a diagrammatic representation of the bottom profile taken from the nautical chart. A suggestion of interdigitation of reflecting horizons is shown in this same section.

Figure 5 is a photograph of the record from a short distance west of the mouth of Goose Creek, upstream from the north end of Section I. It shows the erosion of the top of the Castle Hayne, backfilling of the depression by the Pungo River, and subsequent deposition over the Pungo River. The direction of the profile is such that the axis of the channel probably trends in a general northerly direction. This is the only evidence of erosion into the Castle Hayne of the Pungo River that we have found to date. The top of the Pungo River lies between 35 and 40 feet subsea at this point.

The two sections illustrated in Figure 6 indicate the presence of several reflecting horizons above the Pungo River top as mapped in Figure 3. While various circumstances make interpretation of these data difficult, the somewhat bolder line at about 35 feet subsea indicates the presence of a good reflector which can be traced with some confidence into the wells at either end of the section. This same horizon can be traced downstream in the longitudinal profile (LL').

Of particular interest in Figure 7 is the evidence of irregular sedimentation just below the bottom in each section. The preponderance of evidence shows that the reflecting horizons are essentially horizontal as they cross the river. In Section V there is a suggestion of interdigitation of the top of the Pungo River and the reflecting horizons at
Figure 5. Channel cut into Castle Hayne and backfilled with Pungo River sediments. North side of channel between Broad Creek and Upper Goose Creek.
about 75 feet subsea a short distance south of the center of the section. The well at the South end of the section is the North Carolina Department of Water Resources observation well at the Lee Creek mine of Texas Gulf Sulphur Company.

The most easterly of the sections, Section VII, (Figure 8) shows a low stretch in the bottom reflecting horizon overlain by soft, yet reflecting materials. Reflecting horizons beneath the bottom and intersecting it are shown near the north end of the upper part of the figure. Whether the broad depression represents an irregular surface of deposition or whether it represents a minor channel in the river bottom is not clear. Data from greater depths is sparse, but they seem to indicate that there is no channeling below the first reflector. The northern end of the section (lower part of the figure) displays several possible pinchouts in the Yorktown and possibly younger sediments.

The longitudinal section, Section LL' of Figure 9, shows several interesting relationships. The most striking, perhaps, is the pile of sediments and the stratification within the pile about midway between sections II and III. In this region the section crosses diagonally the channel dredged in the river and the adjacent spoil pile. While not shown in detail on Section II a similar relationship exists a short distance north of the center of the section where it crosses the dredged channel. The relationship is shown rather well on the original records, but the scale of the illustrations preclude showing it here.

The lower part of the figure illustrates several pinchouts believed to the present in Yorktown sequence as well as irregularities in the distribution of the bottom reflecting layer.

Although LL' is a composite section built from data compiled from various traverses, its various segments are composed of successive stations on a given traverse; thus while reflecting horizons may be projected from traverse to traverse, within each traverse they may be traced more or less continuously.

The most striking aspect of this section is the generally more gentle gradient of the reflecting horizons compared with the gradient of the Pungo River and Castle Hayne tops as taken from Kimery's maps (Kimery, 1965).

SUMMARY

The work thus far has failed to bring forth any evidence for channels cut through the Miocene beds into the Castle Hayne as the result of lowered sea level during Pleistocene time. In the one instance of a well-defined irregularity on the Castle Hayne surface, the depression has been back-filled by Pungo River sediments, and it represents part of the pre-Miocene erosion surface.

The data indicate the general near-horizontal attitude of the beds in a direction at right angles to the river axis. Also the data seem to support a more gentle eastward dip of the strata than is suggested by the contour maps of the top of the Pungo River and Castle Hayne formations respectively. Possible interdigitations of clay and phosphate-rich units at and
near the boundary of the Pungo River as presently defined are brought out in several of the sections.

ACKNOWLEDGEMENTS

The study has been supported by a grant from the North Carolina Board of Science and Technology. Information concerning wells adjacent to the Pamlico River has been kindly supplied by Mr. P. M. Brown and Mr. J. Miller of the U. S. Geological Survey, Mr. Stephen Conrad of the North Carolina Division of Mineral Resources, and Mr. Harry Peek of the North Carolina Department of Water Resources.

REFERENCE

GROUND WATER PROBLEMS IN THE COASTAL PLAIN RELATED TO HEAVY WITHDRAWALS

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INTRODUCTION

The extensive and prolific ground-water reservoirs of the Coastal Plain region of North Carolina have long been considered a relatively unlimited source of fresh water supply. Although development of the reservoirs has scarcely begun in much of the region, expanding requirements for municipal, industrial and agricultural purposes during recent years have clearly shown that local and regional limitations exist. The effects of large withdrawals at some localities have dramatically emphasized these limitations and related problems.

The general nature of the ground-water reservoirs of the Coastal Plain of North Carolina is fairly well known. The individual water-bearing units consist of sand, shells, limestone or combinations that are separated by beds of silt, clay or sandy clay. Although the individual aquifers may serve as independent reservoirs on a local scale, they comprise a regional aquifer system that extends into the adjacent states. Intensive development or heavy draft on any part of the system affects the entire system to some extent, therefore, efficient development and management of the system must be accomplished on a regional basis.

General Ground-Water Conditions in the Coastal Plain

Precipitation in the Coastal Plain is the source of recharge to the aquifers of the region. Recharge is relatively local, with replenishment of one or more of the principal aquifers occurring throughout most of the region.

Figure 1 shows the general configuration of the composite piezometric surface of the principal aquifers that have been developed in the Coastal Plain as of 1964. The general pattern of ground-water movement is shown by this configuration. The irregularities expressed by the contours reflect the principal areas of artificial and natural discharge. Natural discharge is significant along the lower reaches and estuaries of the rivers. The influence of artificial discharge is most prominent in the Kinston-New Bern area and the Franklin, Virginia area.

The general configuration of the piezometric surface of the principal aquifers in 1966 is shown in Figure 2. The configuration in the central Coastal Plain is considerable different from Figure 1, reflecting the pumping of about 60 MGD at Lee Creek in Beaufort County. Although some change has also occurred in the vicinity of Franklin, Virginia, control was not adequate to show the extent of change.
The general pattern of occurrence of brackish water at relatively shallow depths in the principal aquifers is also shown in Figure 2. The occurrence and distribution of brackish water and potential contamination of the fresh water reservoirs constitute the chief problem of ground-water development in the region. Optimum use of the reservoirs requires limitation of withdrawals in much of the Coastal area.

The only sites of extremely heavy withdrawal presently affecting North Carolina are the Beaufort County and Franklin, Virginia areas. The magnitude and extent of drawdown at these sites are similar, however, one site is relatively far inland and present conditions are the result of a gradual increase in pumpage over a period of 25 years. The other site is adjacent to the coast and conditions were developed in a period of a few months. Some of the aspects of these sites are discussed below.

**Ground Water in the Northern Coastal Plain**

The ground-water resources of the northern part of the Coastal Plain in North Carolina have been developed on a much more limited scale than elsewhere, although use of ground water has expanded during recent years. Individual supplies for rural homes, farms and commercial places do not represent a significant demand, and existing municipal and industrial supplies require only a few million gallons a day for the entire area. However, the effects of withdrawals in southeastern Virginia on ground-water conditions in northeastern North Carolina are extensive and significant, as shown by studies now in progress by Frederic L. Hurd.

**GEOLOGIC FRAMEWORK**

The sedimentary formations of the Coastal Plain in northeastern North Carolina and southeastern Virginia consist predominantly of interbedded sands, marls, clays and limestone. The sedimentary section ranges in thickness from a few feet in the western part of the region to several thousand feet in the eastern part, and in age from Cretaceous to Recent.

Detailed correlation of formations and ages of sediments in North Carolina and Virginia has not yet been satisfactorily accomplished. The sediments are about 900 feet thick at Franklin, Virginia, and the geologic units recognized by the Virginia Division of Mineral Resources are as follows:

<table>
<thead>
<tr>
<th>Unit</th>
<th>Age</th>
<th>Approx. Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chesapeake Group</td>
<td>Miocene</td>
<td>100 feet</td>
</tr>
<tr>
<td>Pamunky Group</td>
<td>Eocene</td>
<td>100 feet</td>
</tr>
<tr>
<td>Potomac Group</td>
<td>Early Cretaceous</td>
<td>700 feet</td>
</tr>
</tbody>
</table>

According to the Virginia Division of Mineral Resources (1966), the 900 feet of sediments at Franklin includes two principal aquifer systems. The thick Cretaceous sands below a depth of about 300 feet comprise a productive artesian system effectively confined by the overlying beds of marl and clay. The near surface sands comprise and aquifer that contains water under both water table and artesian conditions.
In Gates and Hertford County, North Carolina, just south of Franklin, the stratigraphic units recognized by Brown (1959, p. 62-65) in cuttings from wells are as follows:

<table>
<thead>
<tr>
<th>Unit</th>
<th>Age</th>
<th>Approx. Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undiff.</td>
<td>Quaternary</td>
<td>30 - 60 feet</td>
</tr>
<tr>
<td>Yorktown fm.</td>
<td>Late Miocene</td>
<td>25 - 150 feet</td>
</tr>
<tr>
<td>Beaufort fm.</td>
<td>Paleocene</td>
<td>40 - 300 feet</td>
</tr>
<tr>
<td>Pee Dee</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Black Creek</td>
<td>Late Cretaceous</td>
<td>500 - ? feet</td>
</tr>
<tr>
<td>Tuscaloosa</td>
<td></td>
<td></td>
</tr>
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Few water wells in northeastern North Carolina penetrate more than a few hundred feet of the sediments, and few exploratory wells have been drilled. Thus, the nature and extent of the individual aquifers are not known in detail and little is known of the deeper aquifers. However, available data show that northeastern North Carolina and southeastern Virginia are underlain by the same extensive aquifer system.

EFFECTS OF PUMPING AT FRANKLIN, VIRGINIA

Withdrawals of ground water for paper manufacturers began at Franklin, Virginia in 1941, at a rate of about 7 million gallons a day (McGuinness). Pumping continued at that rate until 1954, then was increased to about 25 mgd during the period from 1954 to 1964. Since 1964, withdrawals are reported to have increased to about 40 mgd, largely from the Cretaceous aquifers between depths of 380 and 865 feet. Municipal and industrial use of ground water is also expanding in other parts of southeastern Virginia.

The lowering of artesian pressures since 1942, according to a report by the Virginia Division of Mineral Resources, (Virginia Minerals, 1966), extends 20 miles west, north and east of Franklin, but only 12 miles south. In 1964 the piezometric surface near the well field was 100 feet below sea level, and with increased pumping is expected to be 150 feet below sea level by late 1968. The report predicts that by that time, water levels 20 miles away will have been lowered 10 feet.

Although the above report indicates that the effects of pumping at Franklin did not extend into North Carolina in 1966, hydrographs of several wells in Hertford County of different depths show a continuing decline of the water level throughout the period of record of several years. Hydrographs of four of these wells are shown in Figures 3-6.

Water-level records of the U. S. Geological Survey for the well at Murfreesboro show that the water level was 4.4 feet above land surface in January 1959 and 3.7 feet above land surface in October 1960 (Figure 3). As shown on the hydrograph, the water level has continued to decline into 1965, with a net drop of about 2.5 feet during the 6-year period.

Records of water levels in wells penetrating the deeper Cretaceous aquifer are available for a relatively short time, and neither of these wells is open to the entire thickness of aquifer developed at Franklin.
HYDROGRAPH OF WELL C21 1-1 (U.S.G.S. No. 81), MURFREESBORO, HERTFORD CO., N.C.

FIGURE 3
HYDROGRAPH OF WELL C 19 b-I (1.2 mi. E. of C 20 j-I), HERTFORD COUNTY, N. C.

**ELEV. OF M.P.** - about 20'
**DEPTH** - 167' (rept.).
**DIAM.** - 2''

**OWNER** - LOKIE SUMNER
**LOCATION** - JCT. SR 1306 & 1308

**DECLINE:**
1. SINC MEASUREMENT -1.66' IN 2 yrs.
   8'/yr. (11-24-64 to 12-12-66)
2. SINCE 1953 - 7'' (REPORTED) FOR AN AVERAGE OF .5'/yr.

WELL 16 MI. S. OF FRANKLIN, VA.
M.P. - 4' ABOVE LSD
AQUIFER - ARTESIAN

**PERIOD OF MEASUREMENT - 26 MONTHS**
STARTED - 11-24-64 (-4.84')
LAST MEASURED - 12-12-66 (-6.5')
HYDROGRAPH OF WELL C 20 j-1, (16 mi. S. of Franklin, Va.), HERTFORD COUNTY, N.C.

FIGURE 5

NOTES:
1. WELL ONCE FLOWED WITH A 7' W.L. -1930's (+35' ref. MSL)
2. WELL CEASED FLOWING IN 1943 WHEN W.L. WENT TO LSD (+180' ref. MSL) - JUST 3 YR AFTER UGC STARTED PUMPING
3. W.L. DECLINED TO -3' IN 65 AND DEEP WELL PUMP HAD TO BE INSTALLED - OWNER
4. TOTAL DECLINE RECORDED IN 22 MONTHS (4-24-65 to 12-12-66) - 4.90' ref. MSL
5. LAST W.L. BEING -23.65' ref. MSL

ELEVATION OF MP = 28462' ref. MSL
DEPTH = 500'
DIAM. = 2"
OWNER = CHAS. DeLOATCH
LOCATION = .35 mi. S. JCT. SR 1302 & 1306 NEAR COMO
AQUIFER - CRETACEOUS
RECORER INSTALLED - 12-65 (USGS)
TOTAL REPORTED DECLINE - 58' - 1940 to 1967 - 27 years FOR AN AVERAGE DECLINE OF 2.1'/yr. 1966 DECLINE 2.6'
MP - .37' ABOVE LSD
IT IS EXPECTED THAT DUE TO LOW SCREEN TRANSMISSIBILITY HERE, RECORRED DECLINE LAGS ACTUAL DECLINE.
HYDROGRAPH OF WELL E 20 H, (28 mi. S. of Franklin, Va.), HERTFORD COUNTY, N. C.

FIGURE 6

ELEVATION OF MP - 56' (2.5' above LSD)
DEPTH - 575'
DIAM. - 4-2"
OWNER - R.W. MAGETTE
LOCATION - JCT N.C.56 & SR 1108 (FRAZIERS CROSSROADS)
AQUIFER - CRETACEOUS
DECLINE - 6.45' SINCE OCT. '63 FOR AN AVERAGE OF 2/7 yr.

-5 -4 -3 -2 -1 0 MSL
-1 -2 -3 -4 -5

ELEVATION, IN FEET

0 MSL

OCT. '63
12-13-66

As may be noted in Figures 5 and 6, the water level has declined about 5 feet in well C20j-1 and 3.5 feet in well E20i-1 during a 2-year period of record, and continues at a fairly constant rate.

Although observation wells reflecting water levels in the deep Cretaceous aquifer in North Carolina are scarce, available data shows that magnitude and extent of the effects of heavy pumping are much greater than in the upper aquifers. The profile of water levels from Franklin south to Ahoskie in Figure 7 effectively illustrates present conditions. The map shows the approximate area where the artesian head is now below sea level in the deep aquifers. This area includes a significant part of northeastern North Carolina and is expanding. Of particular significance is the fact that this extensive depression in the piezometric surface intersects the area where the aquifers contain brackish water. Thus, the area has a built-in problem before development of the aquifer has begun in North Carolina.

Ground Water in the Central Coastal Plain

Prior to the beginning of phosphate mining in Beaufort County in 1965, there were no points of really large withdrawals of ground water in North Carolina, and most problems were generally isolated and local. In contrast to conditions in the northern Coastal Plain that developed over a period of many years as withdrawals gradually increased, conditions of heavy draft occurred practically overnight. Also in contrast, are the hydrogeologic environments of the two sites of heavy withdrawals. The Lee Creek site is much less favorably situated with regard to saline water problems.

GENERAL GEOLOGIC CONDITIONS

The general geologic framework of the central coastal area region is fairly well known and has been described in various reports, although work on the details continues. The sedimentary section ranges in age from Cretaceous to Recent and consist of sand, clay, marl, shells, and limestone. Few water wells penetrate the Cretaceous formations in the area of discussion as the overlying Beaufort formation of Paleocene age and the Castle Hayne limestone of Eocene age comprise the most productive aquifer in the State.

The geologic cross sections in Figures 8 and 9 are based largely on exploratory wells and show the geologic conditions on the north and south sides of the Pamlico River. The formation boundaries shown are based on the electrical characteristics and the gross lithology, and are keyed to previously published stratigraphic units recognized in two of the wells.

There are two major aquifers units in the Beaufort County area. The sands of the Black Creek formation constitute the lower aquifer. The upper aquifer includes sands of the Pee Dee and Beaufort formation and the Castle Hayne limestone, and is referred to as the Castle Hayne aquifer. The silt and sandy clays of the upper part of the Black Creek formation and the lower part of the Pee Dee formation serve locally as a confining layer between the aquifers.

The Pungo River formation and Yorktown formation contain water-bearing units in confined and semi-confined state which also serve as minor aquifers in the area.
PIEZOMETRIC PROFILE - FRANKLIN, VA. TO AHOSKIE, N.C. (DEC. 1966)
EFFECTS OF PUMPING AT LEE CREEK

The map in Figure 10 shows the piezometric surface of the Castle Hayne aquifer in the Central Coastal Plain in June 1965, just prior to the beginning of pumping at Lee Creek. The configuration of the contours reflects the nature of the hydrology of the region, with recharge areas in much of the interstream areas, and natural discharge along and in the streams and estuaries. Withdrawal of water from wells at that time was not sufficient to appreciably affect the configuration of the piezometric contours of the region.

The piezometric surface of the Castle Hayne aquifer in the Beaufort County area in January 1967 is shown in Figure 11. The drastic change in local hydrology that has occurred after one and a half years of pumping from the aquifer at the rate of about 60 mgd is shown by the change in the configuration of the contours. The depression resulting from pumping is about 120 feet below sea level in the center, and extends outward many miles from Lee Creek, particularly north, east and south. Figure 12 is a hydrograph of well L15n-2, located in Washington County, more than 25 miles from the center of pumping. The water level in this well has dropped more than 4 feet since the heavy pumping began and is still declining. A decline in water level of more than a foot has caused a well at the Town of Creswell, about 40 miles from the pumping site, to stop flowing.

Problems resulting from large withdrawals and extensive lowering of the artesian head of the Castle Hayne aquifer include the need for pumps where wells previously flowed; the need to replace pumps and enlarge well diameters, and a continuing higher cost for water recovery. The problem of salt-water encroachment into the aquifer from one or more sources is by far the most serious consequence of the lowering of the piezometric head of the Castle Hayne aquifer in this region. As shown in Figure 8, the area in which the head is now below sea level intersects the area in which even the highly permeable limestone part of the aquifer contains brackish water. The water in the lower part of the aquifer is brackish throughout the area of sub-sea artesian head. Thus, certainty of movement of brackish water laterally and upward through the aquifer toward the center of pumping is obvious, even to the non-hydrologist. The board of consultants (1967) concluded that the most immediate and extensive threat of salt-water encroachment, however, is through leakage of brackish water downward from the Pamlico River estuary.

SUMMARY

The two problem areas that have been briefly described represent the first extensive ground-water problems affecting North Carolina. They are indicative of the type and scope of problems to come and effectively demonstrate the need for sound management of our water resources. In northeastern North Carolina the center of heavy pumping is outside the State's control, so that compensating protective measures are required. In the central Coastal Plain, the State can take preventive measures by establishing a management program.
Map showing piezometric surface of the Castle Hayne aquifer June, 1965
Piezometric surface of Castle Hayne aquifer, January 1967
REFERENCES


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This is not an easy place for me to talk about water resources planning and management because of the presence of nationally recognized experts in the field. Among these are Dr. Maynard Hufschmidt who was a member of that elite Harvard Water Group which has revolutionized the subject of water resources planning. We are all trying to fully understand and apply his new technology. I am conscious, too, of your conference chairman who, before coming to Raleigh, was the manager of a program in the U. S. Public Health Service, and was figuratively the manager who wrote the checks which have sustained the most significant water pollution program in the past ten years. I congratulate North Carolina on attracting these and other outstanding experts to work with you in this vital environment.

I intend to speak primarily on water resources planning, in part because this is the necessary prelude to intelligent management of our water resources, but also because I have just recently been involved in the preparation of a water plan for the State of Illinois. I would like to share with you some of our experiences and advocate with all the enthusiasm of a new initiate a similar activity for North Carolina.

Planning has recently become legitimate after what has been a rather checkered career during our generation. Planning seems to have carried a black eye in the past, in part because of its inability to accurately and sensibly anticipate the future. Planning involves the most difficult of all parameters - people - and it is very difficult to predict their future numbers, their distribution, their economic activity, or their desires.

Too much planning has been done by visionaries with impractical ideas instead of by engineers applying established practice. A wise public has often rejected such impractical proposals.

Too much planning has been of the one-shot, package variety, with a lack of follow-through when the plan was not fully and immediately accepted. As a consequence our agency files are literally filled with obsolete, useless plans.

Planning requires constant communication between the public and the government planners. It also requires leadership and education, two qualities for which North Carolina has long been famous.

At the present time the stage is uniquely set for water resources planning, for which we can largely thank the federal government. During the past three years there has been a remarkable series of bills enacted into law. These include the Water Resources Research Act of 1964, the Water Pollution Control Act of 1965, and in the context of our present
discussion -- the Water Resources Planning Act of 1965. In each of these the federal government has gone at least half way in proposing to include or work through state agencies. For example, in the planning act which authorizes the formation of river basin commissions, the state and federal agencies would operate essentially as equal partners. To help insure that the States will be "more equal" the law provides for grants to strengthen planning in the States.

So we are at that moment in the history of water resources planning when the federal government is offering partnership arrangements for working together. At this same moment we are presented with a new technology developed by Dr. Hufschmidt and his associates which shows the way to apply systems analysis which will greatly improve the efficiency over our past efforts.

Truly, this is the time - in fact it may be our last good chance - to tax ourselves and go to work.

Planning is essentially a process through progressive development and management of balancing changing demands with the available resources. The demands are functions of people, and of course this involves uncertainties which become progressively greater as one proceeds outward in time. This risk associated with errors can be minimized by committing actual investments to limited periods in the future, while the really long-range plans serve primarily as distant references which are useful in guiding intermediate decisions.

Our water resources are usually known with greater accuracy than the future demands which will be placed upon them. Nevertheless it can usually be demonstrated that improvement in our resource knowledge is well justified by the resulting improved efficiency of design. The federal agencies involved in resource assessment, such as the U. S. Geological Survey, are competent operators. But do not turn over all of the thinking to them. The States furnish half of the funds for these cooperative programs and should take the responsibility for half of the thinking about what the program should be measuring.

Any State water plan will predictably contain considerations beyond predictions of people and economic activity and an assessment of the resources.

These elements might take the form of chapters on water supply and use, pollution, flood control, navigation, power, land and water management, water-related recreation, and laws. Emphasis will vary from state to state depending upon the degree to which these areas have been identified as problems.

My advice, then, is to prepare a state water plan at the earliest practical moment, and with whatever degree of sophistication is possible. This is the best way to learn what you do know, what you do not know, and to develop some sense of priority for what should be done.

Preparing a plan is also an excellent way for a state to get its coordination in order. Each state is organized in a different way, but
it is typical for the various programs such as research, pollution control, recreation, and others to ignore each other while dealing directly and unilaterally with a special clientele. Preparation of a comprehensive plan requires the painful process of having state agencies work together. This is essential, however, and after a state has learned to coordinate its own efforts it is in a much better position to coordinate the federal and local interests working in that state. Yes, state government can occupy the central coordinating position and thus be a far more useful partner with other levels of government.

Whether a state has organized itself with a central water agency or whether it operates by a committee of agencies, the planning function should be carried out by agencies of state government. Such planning should employ only accepted engineering practice so that an official report can be accepted by the public without any question that it recommends feasible solutions. What I am saying is do not turn the job over to university research people whose ideas may not meet the test of practicality. Universities have their own important functions of training the next generation of practitioners and producing research results which will eventually upgrade practice.

Planning should not only be on a sound and practical basis, but it should be anticipated as a continuing function. Plans, once made, need to be revised and maintained in a current condition as a flexible guide. If viewed in this way the changing needs of people can be incorporated as can the improving technology.

Finally, plans should offer a series of alternative proposals -- each of which is tested for practicality, but each of which is identified with related benefits and costs. It then becomes a public decision to select from among reasonable alternatives. We should avoid a mistake of the past, which is still prevalent today, of presenting one package deal which the public must either accept or reject. Fortunately the new technology of model building and systems analysis with which your Dr. Hufschmidt is closely identified now makes the testing of alternatives feasible. Alternative proposals can be evaluated on an economic basis through the development of functional relations of benefits and costs and utilizing the great capacity of modern computers. The resulting array of alternative choices which can thus be presented to the public represents a considerable advance in the working of the democratic process.
The ecology of estuaries has very recently moved into the forefront of activities by marine scientists and coastal engineers and intense research studies are under way on computers, in experimental laboratories and in the field. These have been stimulated by the fact that most of our large population centers along the coasts have generated increasing demands on the important resource potentials of our estuaries with respect to use in commerce, industry, urban utilities and public recreation. Many conflicting interests have arisen as particular exploitation has proceeded often without regard to consequences to the estuarine environment and their effects on other valid claims on these natural resources.

Modern navigation demands increasing channel depths to be maintained regardless of tidal stage. Growing industry utilizes and modifies the waters withdrawn from and then conveyed back to the estuary. Cities became accustomed to dispose their wastes into these coastal basins, while upland waters were diverted and dammed, thus changing their natural regime. Pressure for new land resulted in indiscriminate filling of large portions of the tidal flats and large structural facilities came to interfere with natural currents.

We are only now becoming aware that such piecemeal exploitation following the convenience of the moment must receive utmost study and care and that an estuary environment represents a complex system of hydrodynamic components interacting often quite delicately with biological, economic and social factors. We are still in the process of defining adequately these hydrodynamic processes, of studying past and present with the aim of producing sufficient criteria for necessary human interference in the estuary behavior with optimal system response. In many cases, however, such information is needed to cope with damage already done, with rectifying past mistakes and with restoring more tolerable conditions, where abuse has become a menace.

Tidal Hydrodynamics

The most powerful forces shaping the estuary life originate - on the surface at least - from the tides, which transport tremendous water masses in regular cycling back and forth from the sea into the estuarine basins. In most of our estuaries, with the exception perhaps of those at the Gulf coast, this tidal motion is responsible for the major currents encountered in the complex channel geometries of the ocean outlets of our large rivers. Hence, our primary concern is with the determination of the tidal stages and of the associated currents throughout the estuary by analytical methods. It can be said with considerable assurance that one way or another the computation of these principal tidal properties poses no major problem since
adequate mathematical models can be established by means of the simplified equations of motion for various estuary geometries. A few observations in nature are required to determine the necessary constants.

a. **Harmonic Solutions** for the basin differential equations of motion are known, where ever the geometry of the tidal channel lends itself to analytical expressions covering the length of the tidal intrusion. Thus, from the simplest case of a uniform channel \( (1), (2) \) to the case of a channel with exponentially decreasing cross-section and, with or without end reflection of the tidal wave, explicit solutions may be developed, which have been given for the Bay of Fundy \( (3a) \), the Delaware estuary \( (3b) \), and others. In addition to the assumption of simplified channel geometry it is necessary to linearize the effect of frictional resistance in the equation of motion and to introduce a constant resistance term \( M \) for the entire estuary which depends on a suitable average value of the maximum tidal velocity \( u_{\text{max}} \), an average hydraulic radius \( R \) and a representative Chezy coefficient \( C_c \). Thus the one-dimensional equation of motion is

\[
\frac{\delta u}{\delta t} + g \frac{\delta y}{\delta x} + g M u = 0 \tag{1}
\]

wherein

\[
M = \frac{8}{3\pi} \frac{u_{\text{max}}}{C_c^2 R} \tag{2}
\]

and the continuity equation is stated as

\[
\frac{\delta (Au)}{\delta x} + b \frac{\delta y}{\delta t} = 0 \tag{3}
\]

The solutions express the variation with distance \( x \) and with time \( t \) of the tidal surface elevation \( y \) and of the tidal velocity \( u \). The limitations of harmonic solutions for the more general case of estuaries with complex geometries are obvious.

b. **Numerical integration methods** for tidal computations must be employed as a rule for most natural conditions, since variations of geometry and in resistance along the channel may be accounted for by suitably dividing the tidal channel into sections, for which these properties are relatively constant. Numerical integration methods employing finite differences of distance \( \Delta x \) and of time \( \Delta t \) in Equations (1) and (3) are then followed in suitable computer programs. Computations of tidal conditions by finite difference methods permit obviously to consider in these equations a number of refinements in addition to those indicated above. Variations of seaward flow from upland or estuary streams as well as of surface stresses exerted by winds may readily be included \( (3c) \).

Even the effects of variable density due to fresh water flow seaward may be accounted for once the intrusion length is known, although normally this influence is negligible in well-mixed estuaries.

Such computer solutions are by now rather numerous for special cases such as San Francisco Bay, Narragansett Bay and more recently for the planned sea level canal in Panama and the Straits of Maracaibo in Venezuela. The last two studies are still in progress at M.I.T. and will be reported on this coming summer. These computer studies have been written without
Figure 1. Comparison of Computer Solution for Time of LW and HW Along Delaware-Prototype (Ref. 3c).

Figure 2. Comparison of Harmonic and of Non-Linear Solution with Experimental Data for HW and LW along Vicksburg Flume (Test No. 4). (Ref. 3c).
linearizing the resistance term in equation (1) and are therefore capable of reproducing the progressive distortions of the tidal wave as it moves into the channel. The refinement of the results is subject only to the limitations of the computer. The great advantage of the computer approach is the availability of the program once it is written for the computation of the effects of any changes in channel geometry, in channel storage or in upland discharge on tidal velocities and elevations, which one may wish to explore for planning purposes. The reliability of the M.I.T. program has been explored under Professor Harleman at M.I.T. for the Tidal Hydraulics Committee of the U. S. Corps of Engineers, by comparing the outputs with a large number of known tidal conditions in U. S. estuaries (3c) as well as with the previous analytical results based on approximate theories.

The results of these computer studies have demonstrated that the non-linear approach can reproduce natural tidal phenomena much more adequately than the harmonic analysis. This is illustrated by Figures (1) and (2) taken as examples from Reference (3c). Figure (1) gives the times of occurrence of low water (LW) and of high water (HW) for the Delaware Estuary over a distance of more than 100 miles from field observations. In the harmonic analysis the interval remains constant between times of LW and HW as indicated by dotted lines, while the solid lines follow the field observations of these tidal stages quite closely since they represent the computer solutions including the non-linear characteristics of the tidal wave progressing upstream. The interval between LW and HW is seen to increase as the wave deforms from 6.21 hours to 7.80 hours.

In Figure (2) the amplitude variations are given as a function of distance in the Vicksburg Tidal Flume (Reference 2) which consists of a rectangular channel connected to a large saltwater basin at Station 0 and is closed at the landward end near Station 320. Hence, the tide is of the co-oscillating type with increasing amplitudes toward the reflecting end. Computations according to harmonic analysis with linear damping are again shown by dotted lines from LW and HW while the non-linear computations are represented by the solid lines with obviously improved agreement with the experimental observations.

These samples taken from a number of such comparisons in Reference (3c) may suffice to illustrate the point to be made here that with steadily expanding computer capacities the numerical integration methods are more adaptable to reproducing natural tidal conditions.

c. Experimental Studies. In addition to the analytical methods in tidal hydrodynamics summarized briefly above, very complex tidal conditions may, of course, be explored by means of hydraulic models, which, in effect, when properly constructed can integrate the tidal performance of very elaborate channel systems in an estuarine region. They are in addition capable of producing information as yet not obtainable by analytical methods, i.e., data on salt-water intrusion, salt-water-fresh water mixing, diffusion of pollutants and shoaling phenomena. Such models are, however, not to be looked upon as easy devices to obtain necessary information for the design of engineering measures in estuaries. They are generally quite expensive to construct and must be operated with considerable expertness. They are usually quite large in order to achieve satisfactory performance with regard to various scaling laws and must be
subjected to extensive verification procedures, for which the basic information must be secured by large-scale field measurements. Once these conditions are satisfied, however, their usefulness is seldom exploited within the time limit originally estimated. New problems are constantly being explored by numerous private and government agencies, which go far beyond the primary purpose contemplated by the principal sponsor. For example, the model of the Hudson estuary at the Waterways Experiment Station in Vicksburg, originally constructed many years ago for shoaling studies in navigation channels, has found continued use for studies of pollution, of tidal effects of the LaGuardia Airport runway extension in the East River, of shoaling in navigation slips, of land fill operations, etc. Similar statements can be made for the San Francisco Bay Model, the models of the Columbia River outlet, of the Savannah River estuary and others. Model experiments, when accompanied by adequate analytical reasoning, can still integrate the various essential environmental factors to a degree of complexity not attainable at present even with the most powerful computer. Their continued use, preceded by careful feasibility studies, is thus assured for the solution of many studies in estuaries, the scope of which is steadily expanding as our understanding of the interaction of the basic physical processes grows.

**Salinity Intrusion Dynamics**

One of the primary reasons for the intensified interest in tidal analysis is the concern with the distribution of salinity both vertically over the depth and longitudinally along the channels carrying fresh water to the sea through the tidal reaches. It has been established that the resulting density variations together with the turbulent mixing processes associated with the tidal flows are the principal factors governing the diffusion of pollutants and the distribution of sedimentation in the estuaries.

**One-Dimensional Aspects**

While these processes are by now well understood reliable mathematical models are available so far only for simple, one-dimensional cases, which furnished however the pertinent general parameters for the correlation of diffusion data in simple experimental channels as well as in more complex estuarine situations in nature. In our studies for the Tidal Hydraulics Committee of the U. S. Army Corps of Engineers (2), (6), the one-dimensional approach proceeded from the conservation of salt equation:

\[
\frac{\partial s}{\partial t} + (u(x,t) - U) \frac{\partial s}{\partial x} = \frac{\partial}{\partial x} \left( \frac{\partial s}{\partial x} \right)
\]

wherein

- \( s \) = local, instantaneous salinity concentration as average for the vertical section
- \( u(x,t) \) = average tidal velocity for any section at \( X \) and at any time \( t \)
- \( U \) = temporal mean fresh water velocity for the section
- \( D_x' \) = local dispersion coefficient including mass transfer by turbulence and mass transfer by internal currents caused by density gradients

If it is assumed that tidal action and fresh water flow remain relatively constant for a period of several days or weeks a quasi-steady state
of salinity distribution should be reached and Equation (4) may be separated into two parts, the first dealing with the periodic translation of the salinity concentration \( s \) by tidal action to and fro:

\[
\frac{\delta s}{\delta t} + u(x,t) \frac{\delta s}{\delta x} = 0 \tag{5}
\]

and the remaining terms stating that any seaward transport of salt is in the average over a tidal cycle compensated by upstream dispersion, hence:

\[
U \frac{\delta s}{\delta x} + \frac{\delta}{\delta x} \left( D \frac{\delta s}{\delta x} \right) = 0 \tag{6}
\]

These equations can be solved for specific cases. Equation (5) may be integrated if the tidal velocity \( u \) is given as a function of \( x \) and \( t \) by tidal analysis, and assuming no effects from density variations. Equation (6) is readily reduced to the form:

\[
\frac{U}{D} \frac{\delta x}{\delta x} = \frac{\delta s}{s} = \ln \frac{s}{s_0} + C_1 \tag{7}
\]

and may be integrated further only by making certain assumptions with regard to the variation of the mean value of \( D \) with distance \( x \) at a given tidal time such as low water slack. A particular solution in agreement with extensive experimental evidence in a rectangular tidal channel has been given in reference (1), (2). While this one-dimensional approach leaves many questions unresolved, it has nevertheless contributed greatly to the correlation of the dispersion characteristics of experimental and natural estuaries with the pertinent tidal conditions and the fresh-water flow regime. It is possible to derive a meaningful "apparent" dispersion coefficient \( D' \) for the seaward end of an estuary by observations of salinity and tidal conditions existing there and to predict changes in its value for changes in tidal amplitude \( a \), in tidal prism \( P_t \), fresh water discharge \( Q_f \) and depth of channel \( h \). This correlation is based on the recognition from harmonic tidal analysis that the magnitude of tidal energy dissipation \( G \) in relation to the gain of potential energy \( J \) by the fresh water passing to the ocean by mixing is responsible for the relative degree of dispersion in the estuary. Referring the dispersion coefficient \( D' \) to the turbulent diffusion coefficient for a shear flow in open channels:

\[
D_0 = 4.5 \frac{u_0 h}{f} \tag{6}
\]

wherein \( u_0 \) = maximum tidal velocity at ocean end
\( f \) = Weisbach - Darcy resistance coefficient.

\[
G = f D' (D_0) = M_0 \left( \frac{P_t}{Q_f} \right) \frac{a}{h} \cdot \frac{1}{\delta \rho / \rho} \tag{8}
\]

wherein \( M_0 \) = characteristic number of estuary geometry roughness and tidal period
\( P_t \) = tidal prism, computed as inflow during flood tide
\( \frac{a}{h} \) = tidal amplitude to depth ratio
\( \frac{\delta \rho}{\rho} \) = relative density difference between fresh and ocean water
\( u_0 \) = maximum tidal velocity at ocean end
FIGURE 3 Correlation of Intrusion Data
Figure 3 reproduced from ref. (6) shows the correlation achieved for all experimental runs in the Vicksburg tidal flume (2) for various tidal amplitudes, fresh water flows, salinities. It is seen that the ratio $D_1/D_0$ may be amplified tenfold with low values of the parameter given in Equation (8) when the fresh water flow is increased or the tidal prism and tidal amplitude are decreased. Hence, increased stratification is indicated. For large values of the parameter the ratio of the dispersion parameter tends to unity as expected for near homogeneous fluids (small density variation), for smaller fresh water flows and large tidal amplitudes, approaching well mixed condition. For the same experimental data the corresponding ratio of a length $B$ to the maximum tidal excursion $2u_0/o$ is given. $B$ is obtained as the length corresponding to the seaward excursion of the maximum or sea salinity from the ocean end of the channel at low tide. It is a fictional but convenient length to be defined from the time of occurrence of minimum mean salinity at the low water slack to the time when full ocean salinity is reached during flood tide. As fresh water flow is increased, the ratio $B/2u_0$ tends toward unity and conversely, this ratio decreases as $u_0$ becomes very small in relation to the tidal flow.

In the same figure field data are shown for two studies of natural estuaries as evaluated from References (4) and (5).

While the Rotterdam data show a similar trend as the experimental data, those at Maracaibo give considerable scatter while exhibiting values of $D_1/D_0$ of the same order as the Rotterdam results. This is due to the fact that all Maracaibo points had to be computed with a constant fresh water flow, since practically no record of this flow exists except for rough estimates. The Rotterdam data, however, are based on reliable flow records together with information on tides and changes in channel geometry. The large difference between these field data and the results from experiments at W.E.S. must be attributed to the fact that appropriate geometric and roughness parameters differ considerably between the two cases, while the essential trends are similar.

Two-Dimensional Features

For a fuller understanding of the mixing processes in the salinity intrusion zones of estuaries, the two-dimensional aspects may be discussed briefly. Figure 4 of Reference (7) gives a typical evaluation of the distribution over relative depth $y/h$ of the time-average horizontal velocity components $\bar{u}$ in terms of mean fresh water velocities $U_f$. The different profiles refer to successive stations from the ocean end near Station 5 to the end of the salinity intrusion near Station 200 in the Vicksburg flume. The velocities $\bar{u}$ are determined by integrating the instantaneous velocities $u$ over a complete tidal cycle, which results in a residual value $\bar{u}$ to be attributed to the effects of the density or salinity gradients. Maximum values of $\bar{u}$ are attained near Stations 40 and 80 where the ratio of $\bar{u}/U_f$ approaches 3.5 near the bottom in the upstream direction, while values near the surface are nearly twice as large in the downstream direction seaward. It is evident that in the average salt water transport in the lower half of the channel sections is landward and of higher concentration until a stagnation zone is reached near Station 160, where the salinity intrusion ends. It is equally clear that sediment settling into the lower half of the sections will be gradually transported upstream as
Figure 4. Time-Average Horizontal Velocity Distribution in Experimental Tidal Channel with Salt Water - Fresh Water Mixing (Ref. (7)).

Figure 5. Instantaneous Salinity and Sediment Distributions in Maracaibo Navigation Channel (Ref. (4)).
long as it is entrained by the turbulent shear flow due to tidal action. The mechanism for the increase in the dispersion coefficient $D_0$ may also be elicited from the flow pattern of Figure 4. Since the velocities are temporal averages of the current it follows from continuity that the net increase in upstream flow between Stations 5 and 40 must result from a net vertical convection downward from the upper portions to the lower portion of the depth. The opposite trend must exist in the upstream section of the channel between Stations 80, 120 and 160. Thus a net circulation of saline water exists within the estuary, contributing to the mixing of fresh and salt water. This circulation proceeds with increasing intensity as stratification and hence vertical and horizontal salinity gradients increase with resulting larger values of the dispersion coefficient $D_0$. The values of the mean vertical velocities are, however, significantly lower than the mean horizontal velocities and their order may approximately be given as $\bar{v} \approx \bar{u} h/L_i$, since the respective cross-sections of flow are proportional to the depth $h$ and the intrusion length $L_i$.

The conditions in actual estuaries in different locations have been generally found to exhibit the same trends as found in the Vicksburg flume experiments. As a typical example, in Figure 5 (from Reference (4) the instantaneous vertical salinity distributions are shown at a Station E-33 near the ocean end of the Maracaibo Navigation channel and at a Station T-46 farther inland. In addition the simultaneous sediment distributions are indicated with respect to relative depth. After the discussion of Figure 4 their analysis leads readily to the important conclusion that the temporal mean velocities $\bar{u}$ which result from the circulation driven by density differences must transport sediment in the upstream direction for deposition near stagnation zones. Thus, sediments approaching the mouth of an estuary are often carried by the entering saline currents into the estuary and lead to shoals, as was shown conclusively by the field studies on the Maracaibo Channel (4).

**Closing Remarks**

The subject "Estuary Hydrodynamics" is clearly one of very much wider scope than could be transmitted in the severely limited presentation for this Symposium. Many engineers and scientists have made valuable contributions to the various phases of this professional field and the literature is extensive. If it appears that this brief review leans too heavily on our own efforts as listed below it may be taken simply as a matter of convenience for the specific task assigned. It is nevertheless hoped that at least the principal trends of present studies have been pointed out sufficiently to clarify the interaction of the various efforts in tidal dynamics, dispersion mechanics and sediment movement in estuaries. Many studies are in progress now in many places which should help to eventually give better quantitative answers for engineering design and planning. However we have reached the state where we can more clearly define the necessary roles of analysis, of basic and model experiments and of minimum field work and thus approach with better expectations of success the many tasks in preserving and improving our estuarine water resources.

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REFERENCES


WATER CURRENT STUDIES IN PAMLICO RIVER ESTUARY

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INTRODUCTION

This paper is intended to present a brief review of the hydrography of the Pamlico River estuary, North Carolina, and to present some results of a dye tracer study during the summer of 1966.

The Pamlico River estuary (Figure 1) runs in an approximate northwest-southeast direction from Washington, North Carolina, to the vicinity of Pamlico Point where it enters Pamlico Sound. The estuary tapers gradually landward from a width of about 3.5 (5.6 km) miles at the mouth. Tidal range averages only seven to nine inches (18 to 23 cm), presumably because of the damping effect of Pamlico Sound on tides. However, wide fluctuations in tidal amplitude are related to changes in wind direction and velocity. The estuary is shallow, averaging 7.5 feet (2.3 m) in the upper portion, 10.5 feet (3.2 m) in the central region and 13 feet (4.0 m) in the lower reaches.

The dye tracer study was made possible by a grant made to Dr. Edward M. Kuenzler, Dr. William J. Woods, and the author by the Water Resources Research Institute (A-014 NC) for a study of water currents and a determination of flushing rates in the Pamlico River estuary.

Dye Tracer Study

Rhodamine B has been shown by Pritchard and Carpenter (1960) to be one of the most sensitive and least expensive tags for measuring mass water movements. It is a fluorescent pigment, relatively resistant to photochemical decay. Rhodamine B fluoresces maximally at 580 millimicrons and has a maximum absorbance at 550 millimicrons. Chlorophyll and its derivatives are likely to be the principal component of the fluorescence background in tracer studies. The background readings caused by plant pigments from 650 to 700 millimicrons may be separated out by appropriate filters. Temperature variations cause serious errors in quantitative work. The fluorescence decreases 2.3 percent per degree centigrade rise and temperature should be monitored continuously while sampling in order to correct for this decreasing sensitivity.

Two major sources of error were encountered in the Rhodamine B dye concentrations measured during this study. Firstly, dye concentrations were not corrected for changes in temperature. Secondly, the primary and secondary filters used were not very suitable for isolating the Rhodamine B dye fluorescence spectra. Dr. Woods checked the fluorescence spectra for the filters used and discovered that both the primary fluorescence and secondary (absorption) filters were only marginally useful. There was no transmission through the latter until 520 millimicrons was attained and reached a plateau at 630 millimicrons. The two primary filters together peaked at
Figure 1. Pamlico River estuary between Washington, North Carolina and Pamlico Light Station locations are shown and referred to in the text.
418 millimicrons and at 550 millimicrons. Rhodamine B. Fluorescent spectra is maximum at 580 millimicrons at a wave-length where primary filters were only transmitting about 25%. Moreover, chlorophyll is excited maximally at about 440 millimicrons which was close to one of the peaks of the primary filters. Also, chlorophyll emits at 650-675 millimicrons, within a range transmitted by the filters used. Consequently, in the field sampling, high background fluorescence prevented quantitatively secure readings of Rhodamine B at low concentrations. Although the background fluorescence usually did not vary more than four to six fluorometer units ($\pm 0.6 \times 10^{-5}$ mg/L) occasionally it would go much higher. For example, readings on one fluorometer reached 10 fluorometer units above background in Durham's Creek, a small tributary. Usually, background readings would increase when sampling toward the headwaters of tributaries. A more suitable filter combination would probably have reduced the high background and increased the reliability at low concentrations (Dr. James H. Carpenter, personal communication).

Movement of the dye was detected in the field with a Turner Model 111 Fluorometer equipped with a flow through cuvette. One fluorometer was mounted on each of two vessels. Power requirements were met satisfactorily with a DC to AC power inverter. Water was pumped to the cuvette through polyethylene tubing that was threaded through a one inch (2.5 cm) pipe to which was attached a small submergible pump. The pump could be lowered to the desired depth, and the water traced while the boat was underway at a speed of eight to ten knots. There was a 30-second lag between the pump and the time that the water reached the cuvette. A time-lag correction was made when the dye concentrations were plotted.

One hundred and fifty pounds of Rhodamine B dye was inserted into the river at station 5 (Figure 1) over a three day period from August 3 to August 5, 1965. The dry powder was mixed with water from the site of insertion (two percent by weight) and pumped into the river at a constant rate. The pump used was a 12 volt electric fuel pump.

**Results** - Reliable estimates of the size and location of the dye patch were possible for the first four days after insertion. Transects were run across and through the patch starting on the last day of insertion, August 5, 1965. By August 9th, the concentrations measured did not exceed $5 \times 10^{-5}$ mg/L anywhere in the river from a location 8 km upstream from the site of insertion to 27 km downstream. On August 9 there was a patch of dye at Core Point on the south shore of the estuary, 7 km below the point of insertion. Also, on August 9, 11 and 12, a large volume of water along the north shore of the river, 14.5 to 27 km below the point of dye release gave a reading of up to 38 fluorometer units above background. A tracer study during a dye release one month earlier showed very high background readings in the same general area. Fluorescence increased continuously from the mouth of the Pungo River (Figure 1) toward its head.

The boundaries of the dye patch are shown in Figure 2. The average net movement of the patch was about 915 m/day (2 tidal cycles) downstream. Assuming a decay of 5 percent per day, the average concentration of the dye patch should have been about $9.6 \times 10^{-5}$ mg/L on August 8. The patch concentrations averaged $4 \times 10^{-5}$ mg/L. Apparently the large areas of apparent dye far downstream were in fact background fluorescence and not introduced Rhodamine B.
Figure 2. Rhodamine B dye location in the Pamlico River estuary on the first four days after insertion, 1966.
A tidal prism model was used to estimate exchange rates and predict half-life of introduced contaminants to compare these with salinity data and Rhodamine B dye concentrations. The model developed by Ketchum (1951) was employed. More realistic models have been developed by Arons and Stommel (1951), Pritchard (1954) and Kent (1958) which take turbulent diffusion processes into account. Nevertheless, the simpler model was considered appropriate to make preliminary comparisons with the rather meager amount of data available.

In Ketchum's model, the estuary is divided into a number of volume segments, each defined by an effective mixing length which is equal to the mean distance covered by the flooding tide. The model assumes that mixing is complete vertically, that steady state conditions exist during the time period that the model is applied (non-variable river flow or tidal prism) and that there are no large lateral differences in salinity. Incomplete vertical mixing can be accounted for in the model by a correction term derived from salinity stratification. When stratification does exist, the model assumes that mixing is limited to the upper layers only and the volumes are computed only to the mixed depth.

Schultz and Simmons (1957) observed that when the flow ratio of a coastal plain estuary (ratio of volume of fresh water inflow during a tidal cycle to the tidal prism) is less than 0.1, the estuary is normally a well mixed type in which vertical salinity differences may be undetectable. During the month preceding the dye insertion in Pamlico River estuary (July 1966), the fresh water inflow averaged $4.2 \times 10^5$ m$^3$/tidal cycle ($9.9$ m$^3$/sec). Assuming an average tidal height of 17.7 cm (a four-month average), the flow ratio was approximately 0.007, and, in fact, the vertical salinity differences were relatively small. Using a stratification parameter $\frac{\Delta S}{S_0}$, where $\Delta S$ is the top to bottom salinity difference and $S_0$ is the sectional mean salinity, the ratio ranged from 0.004 to 0.08 throughout the length of the estuary on August 1, 1966. Therefore, during this period it was assumed that vertical mixing was complete.

Table 1 compares the salinity values predicted by the model to the observed salinities at four locations in Pamlico River (see Figure 1). The source salinity was assumed to be 18 o/oo based on data collected on August 1 by William J. Woods. The calculated salinities averaged between 12 and 26 percent higher than observed for most of the estuary which is reasonably good correspondence. The average fresh water input was approximately $42 \times 10^5$ m$^3$/tidal cycle ($99.1$ m$^3$/sec), a value ten times higher than the very low runoff during July 1966. Therefore, a considerable part of the salinity discrepancy between the observed and calculated results was likely due to accumulated fresh water during periods of high fresh water inflow.

The predicted flushing time, defined as the average length of time for the river water to move through all 61 volume segments of the estuary, is 587 days under these low fresh water flow conditions. Average exchange ratios and half-life values for fresh water in the volume segments in four regions of the estuary are given in Table 2. The exchange ratio is the proportion of the river water (or its continued pollution) within a volume segment, that is lost to the adjacent seaward segment on the ebbing tide. The half-life is the time where half of the river water introduced to a
Table 1. Observed salinities in o/oo in Pamlico River Estuary on August 1, 1966; and salinities calculated from the model. Fresh water inflow was $4.2 \times 10^5$ m$^3$/ tidal cycle (9.9 m$^3$/ sec).

<table>
<thead>
<tr>
<th>Location</th>
<th>Distance from Mouth (km)</th>
<th>Observed Salinity</th>
<th>Calculated Salinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Point</td>
<td>40.2</td>
<td>8.6</td>
<td>8.1</td>
</tr>
<tr>
<td>Rumley Marsh</td>
<td>32.5</td>
<td>9.7</td>
<td>11.7</td>
</tr>
<tr>
<td>Indian Island</td>
<td>21.1</td>
<td>10.7</td>
<td>14.6</td>
</tr>
<tr>
<td>Pamlico Point</td>
<td>1.6</td>
<td>14.3</td>
<td>16.3</td>
</tr>
</tbody>
</table>

Table 2. Average exchange ratios and half-life values estimated for volume segments within sections of the Pamlico River Estuary. Fresh water inflow was $4.2 \times 10^5$ m$^3$/ tidal cycle (9.9 m$^3$/ sec).

<table>
<thead>
<tr>
<th>Section</th>
<th>Length of Section (km)</th>
<th>Number of Volume Segments</th>
<th>Average Exchange Ratio</th>
<th>Half-life/Segment (Tides)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washington to Core Point</td>
<td>22.7</td>
<td>28</td>
<td>.099</td>
<td>6.4</td>
</tr>
<tr>
<td>Core Point to Hickory Point</td>
<td>16.1</td>
<td>13</td>
<td>.056</td>
<td>12.0</td>
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<tr>
<td>Hickory Point to Wades Point</td>
<td>9.0</td>
<td>8</td>
<td>.048</td>
<td>14.0</td>
</tr>
<tr>
<td>Wades Point to Pamlico Point</td>
<td>16.4</td>
<td>12</td>
<td>.042</td>
<td>16.2</td>
</tr>
</tbody>
</table>
volume segment during a tidal cycle has been removed. The predicted flushing time for the section of the estuary in which the dye was released corresponds to an average transport of 213 m per day. The actual net dye movement was about 915 m per day. Therefore the actual flushing time during the period of time may have been considerably less than the predicted value. This seemingly large discrepancy is understandable when one considers that the fresh water inflow may have been underestimated (only an average value for the month preceding the dye insertion was used in the calculation), and vertical mixing was assumed to be complete. More importantly, most of the net seaward movement may have been at the surface in spite of the small amount of stratification observed. Hansen and Rattray (1966) point out that the advective (gravitational) component of salt flux is not necessarily proportional to salinity stratification.

The volume segment model was applied to conditions of normal river flow $42 \times 10^5 m^3/\text{tidal cycle}$, (99.1 m$^3$/sec). These conditions reflect the average fresh water inflow for the year, but, of course, do not imply steady state conditions. However, average river flow data for the month of June 1965 did yield this value. Salinities measured on June 28-29, 1965 are given in Table 3 for the stations indicated in Figure 1. A considerable degree of stratification exists during normal to high water inflow conditions. These values are for a particular time and are not time-mean values over a tidal cycle. A smooth line was drawn through the halocline at the five stations, and the volume segment model was applied, assuming complete mixing of the water column above the estimated halocline. The predicted salinities are given in Table 3. In this case the predicted salinities are 22 to 35 percent lower than those observed. The model does not account for two other transport mechanisms that are of considerable importance; wind and diffusion. Wind has been observed to bring about considerable change in water level in the estuary, and therefore it must be important in salt transport and flushing mechanisms. There is no independent criteria as yet to assess the relative importance of wind stress.

The relative importance of diffusion in upstream salt flux has been determined for several estuaries by Hansen and Rattray (1966). These authors have classified estuaries by two independent parameters when wind stress is not important: a stratification parameter, $\delta S/\delta S_0$ (defined earlier), and a circulation parameter, $U_s/U_f$, where $U_s$ is the longitudinal time-mean velocity at the surface and $U_f$ is the integral velocity (R $\times$ cross sectional area of the estuary).

Application of these parameters to the best available information indicates that net flow reverses with depth, and both advective and diffusion contribute importantly to upstream salt flux. The data suggest that the diffusion fraction of the upstream salt transfer is between 0.1 and 0.5 for hydrographical conditions during July, 1965. Therefore, the discrepancy between the observed and calculated values in the volume segment model application may be due to the diffusive salt flux.

The exchange ratios and predicted half-life values for the higher fresh water inflow conditions are given in Table 4. Under these conditions of greater flow and vertical stratification the number of volume segments is reduced, and the flushing time is estimated to be 65 days for the entire length of the estuary. Several sets of water current measurements
Table 3. Observed "mixed depth" salinities in o/oo in Pamlico River Estuary on July 28-29, 1964, and salinities calculated from the model. Fresh water inflow was $42 \times 10^3$ m$^3$/ tidal cycle (99.1 m$^3$/sec).

<table>
<thead>
<tr>
<th>Station Location</th>
<th>Distance from Mouth (km)</th>
<th>Observed Salinity</th>
<th>Calculated Salinity</th>
</tr>
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<tr>
<td>2</td>
<td>1.6</td>
<td>9.29</td>
<td>6.40</td>
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<tr>
<td>1</td>
<td>17.2</td>
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<tr>
<td>5</td>
<td>48.4</td>
<td>1.42</td>
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</table>

Table 4. Average exchange ratios and half-life values estimated for volume segments within sections of the Pamlico River Estuary. Fresh water inflow was $42 \times 10^3$ m$^3$/ tidal cycle (99.1 m$^3$/sec).

<table>
<thead>
<tr>
<th>Section</th>
<th>Length of Section</th>
<th>Number of Volume Segments</th>
<th>Average Exchange Ratio</th>
<th>Half-life/Segment (Tides)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washington to Bayview</td>
<td>28.0</td>
<td>3</td>
<td>.084</td>
<td>7.9</td>
</tr>
<tr>
<td>Bayview to Hickory Point</td>
<td>10.8</td>
<td>2</td>
<td>.082</td>
<td>8.0</td>
</tr>
<tr>
<td>Hickory Point to Pamlico Point</td>
<td>25.4</td>
<td>5</td>
<td>.073</td>
<td>9.1</td>
</tr>
</tbody>
</table>
in the estuary taken over a tidal cycle clearly demonstrated the existence of a two layer transport system. Moreover, the mean current velocities at the bottom corresponded to the length of the volume segments predicted from the model.

Conclusions

Clearly, the volume segment model of tidal flushing does not accurately fit the hydrographic characteristics of the Pamlico River estuary. Possible reasons for the discrepancies between observed and predicted values have been cited. Better correspondence was shown for model estimates and observed data during higher fresh water inflow conditions. The estimates of exchange ratios, flushing times and half-life values for the volume segments of the estuary are believed to be representative for average fresh water inflow conditions. The attempt to fit the model to the known parameters of fresh water inflow, basin topography and tidal amplitude gave insight into the relative importance of other important parameters.

Exchange ratios between volume segments of the estuary may be estimated and compared with actual tracer substances (dye, fresh water or industrial wastes). This information can be used to help predict the fate of an introduced pollutant during various fresh water inflow and tide conditions. With more complete data, the relative importance of diffusion and wind transport may be assessed and their role in the dynamics of Pamlico River estuary estimated.

REFERENCES


HYDROGRAPHIC STUDIES IN PAMLICO SOUND

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Morehead City, North Carolina

Perhaps I should start by indicating that the given title of this paper is incorrect. Since I am not going to confine my remarks to what are generally considered hydrographic parameters, perhaps the presentation could more accurately be titled, Hydrologic Studies in Pamlico Sound.

Since several people have done similar studies, I think it only right that I mention their work even though it may be familiar to many of those present.

INTRODUCTION

Systematic collection of hydrographic data started with Winslow (1886, 1889), Grave (1904) and Coker (1907) all of whom were primarily concerned with the oyster producing potential of North Carolina estuaries. Seiwell (1927), in addition to seasonal salinity and temperature values, reported on the results of a number of twelve hour sample series at several locations in Pamlico Sound. He also did mechanical analyses of a number of bottom samples. He concluded that lunar tides had (other than near inlets) no effect on the level of water in Pamlico Sound and stated that daily and seasonal variations of salinity in the sound depended on wind direction and velocity. Marshall's (1951) paper was an excellent synthesis of hydrographic data available for North Carolina coastal and inshore waters. Investigators at the Institute of Marine Sciences (formerly the Institute of Fisheries Research) have routinely collected temperature and salinity data in Pamlico Sound since 1948. The work of one of these, Roelofs (Roelofs and Bumpus, 1953) again emphasized the effect of wind and fresh water runoff on horizontal distribution of salinity. In this paper it was estimated that tidal exchange at the inlets would produce a rise and fall of approximately five centimeters over the entire sound. The same authors estimated the flushing time to be five months. Temperature and salinity records from 1948 to June, 1966 were recently summarized by Williams, et al (1967).

Marshall (1951) pointed up the lack of data on chemistry other than salinity and suggested this as an important area of work. My predecessor at the Institute, Dr. Gerald Posner, started this phase of work in 1955 with a series of phosphate and nitrate determinations. As a result of his hydrographic program, Posner (personal communication) estimated the flushing time for Pamlico Sound to be 19 months. I might add here that other informal estimates range down to one month.

The current work in Pamlico Sound started in June, 1963. It was late 1962 when I learned of the phosphate mining operation proposed for the Beaufort-Pamlico County area. Here was an opportunity to study plankton ecology in a natural situation in which there was a possibility of radical change of an important environmental parameter, phosphorous concentration.
In order to establish that a change had occurred it was necessary, of course, to determine chemical, physical and biological conditions which existed before the mining operation began.

Initially I established a series of ten stations (Figure 1) under the impression that the mining operation was to be located in the Pungo River. When I learned of the Lee Creek site, I added the two upriver stations. A one trip a month schedule was maintained for approximately three and one-half years except when prevented by weather or boat lay-up. Vertical salinity and temperature measurements were made at meter intervals and surface and bottom samples were analyzed for dissolved oxygen, plant pigment concentrations, nitrate, nitrite, ammonia and total nitrogen and phosphate and total phosphorous. During the last year of field work, on each cruise, an effort was made to determine dissolved organic nitrogen and phosphorous at two or three stations. Clarke-Bumpus tows were taken at each station using a number 10 net or both a number 2 and number 10. From July, 1965 to October, 1966, periodic measurements of primary production were made using both the LDB (light and dark bottle) (Gaarder and Gran, 1927) and C\textsuperscript{14} (Steeman-Nielsen, 1952) methods. On some of these occasions nitrate-nitrogen, phosphate-phosphorous and a combination of both were added to the bottles in an effort to determine whether any of these components might be limiting photo-synthesis.

**Temperature**

First, let us summarize what is known about temperature and salinity conditions in Pamlico Sound. In any one month it is extremely unusual for surface temperatures over the entire sound and river complex to vary more than three or four degrees centigrade. Exceptions to this generalization occur in June and November when the temperature of water in shallow areas of the sound is changing more rapidly than oceanic water coming in through the inlets. From this we may infer that temperature of water in the major rivers and open sound follow air temperature very closely. On the average, the greatest temperature variations occur in June when the gradient decreases from the rivers to the inlets, and in November when the reverse is true. In general, especially in the open sound, there is very little vertical variation in temperature. Temperatures as low as 2.5°C and as high as 28°C were measured.

**Vertical Salinity Distribution**

In the open sound there is frequently a slight difference (0.50 to 1.00%) between salinity concentrations at the surface and those at the bottom. The higher salinities, of course, are usually at the bottom and most of the increase in salinity seems to occur in the meter of water above the bottom. In 1964 and again in 1966 there were periods when unusually large differences in salinity of surface and bottom water occurred in the open sounds. In 1964 these differences occurred during the spring, summer and fall, and differences up to approximately 6% were noted. A few of the measurements made during this time are presented in Table 1. It seems reasonable to assume that the vertical difference recorded in 1964 are due to freshwater outflow from tributary rivers. This is reasonable because of the widespread occurrence of these differences. If we examine monthly river-flow data, there is apparently no correlation between river flow and the occurrence of salinity stratification. However, if we examine
Figure 1. Map of coastal North Carolina showing location of major estuaries, inlets and sampling stations (●).
Table 1. Selected Salinities, in $Z$, for ten sampling stations in Pamlico Sound and Tributaries.

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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>August 2, 1966</td>
<td>13.70</td>
<td>13.90</td>
<td>15.73</td>
<td>16.84</td>
<td>16.00</td>
<td>16.47</td>
<td>16.85</td>
<td>17.30</td>
<td>8.13</td>
<td>8.84</td>
<td>10.72</td>
<td>10.72</td>
</tr>
</tbody>
</table>
river-flow data on a daily basis, we will find that increased flows in the two rivers (Pamlico and Neuse) in question occurred approximately four to seven weeks prior to occurrence of salinity stratification in the open sound. It would seem on the basis of this, at least during periods of high flow, that a flushing time of one to two months can be estimated for Pamlico Sound. However, it is also apparent, since we are estimating, that a more careful evaluation of data available is necessary. Some measurements obtained during 1966 are also presented in Table 1. It should be emphasized that data presented for both 1964 and 1966 are included here because they are exceptional. Data for 1966 are different from those for 1964 in that over most of the sounds salinity values did not differ much from average. However, the July and August cruise measurements made at Inner Middle (In. Mid.) station and Southwest Light (S.W. Lite) station showed a distinct layering. In fact, bottom salinities given for Southwest Light are the highest salinities that I have measured at this Station. In this set of determinations, the difference stems not from low surface readings but rather from high salinity concentrations at the bottom. The fact that the situation existed only in areas removed from tributary rivers suggests that the occurrence was due to something other than freshwater runoff. If we examine wind records at Hatteras station for July and August, 1966, we find that, although the wind was blowing from the southeast at the time the August 2 samples were taken, it was blowing from the north at speeds up to 23 miles per hour for two days prior to this. For five days prior to that, the wind was blowing from a south or southwesterly direction at velocities up to 25 miles per hour. Seiwell (1927) and Roelofs and Bumpus (1953) have commented on the movement of high-salinity water from Core Sound into Pamlico Sound by strong southwest wind and that winds from the north caused the reverse. These comments are not introduced to add to an understanding of salinity distribution in Pamlico Sound but rather to point out the complexity of the Pamlico Sound system.

**Horizontal Salinity Distribution**

When we consider horizontal distribution of salinity we find, as is to be expected, that there is a much wider range of concentrations. Salinities increase, of course, from the mouths of the rivers to the inlets. I have not made an anchor station in Pamlico Sound but other workers report that there is no daily variation in salinity concentrations (Seiwell, 1927; Roelofs and Bumpus, 1953; Posner, personal communications). Posner (1959) reported a 2% seasonal variation in salinity concentrations. However, as we can see from Table 2, the variation was much greater during the period being discussed here. The greatest variation occurs at the mouth of Pamlico and Neuse Rivers, the smallest on locations closest to the inlets. In general, lowest concentrations occur during spring while highest concentrations occur during winter.

The authors that we have been citing all seem to agree that wind and freshwater runoff are the factors controlling horizontal salinity distribution in Pamlico Sound. With this in mind I have included two figures from Williams et al (1967) showing surface salinity distribution for February (Figure 2) and for July (Figure 3). Let us examine the February distribution first. During this month the prevailing wind would be from the north with velocities in the 15 to 30 mile per hour range approximately 30 percent of the time. Typical contributions for this month from the Roanoke, Pamlico, and Neuse Rivers, given as thousands of cubic feet per second,
Table 2. High and low surface salinity concentrations measured at Pamlico Sound stations from June, 1963 to October, 1966.

<table>
<thead>
<tr>
<th>Station</th>
<th>Salinity %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High</td>
</tr>
<tr>
<td>Neuse Mouth</td>
<td>19.59</td>
</tr>
<tr>
<td>Brant Slue</td>
<td>19.75</td>
</tr>
<tr>
<td>Brant Shoal</td>
<td>21.00</td>
</tr>
<tr>
<td>Brant Shoal N</td>
<td>21.24</td>
</tr>
<tr>
<td>SW Light</td>
<td>22.04</td>
</tr>
<tr>
<td>Inner Middle</td>
<td>20.24</td>
</tr>
<tr>
<td>Pamlico Light</td>
<td>18.68</td>
</tr>
<tr>
<td>Bay River</td>
<td>18.36</td>
</tr>
</tbody>
</table>
Figure 2. February surface isohalines for North Carolina estuaries.
Figure 3. July surface isohalines for North Carolina estuaries.
would be 249, 122 and 144 respectively. We can see that the combination of north winds and high flow from the Roanoke River has pushed low salinity water down into northern Pamlico Sound. The high flow of fresh water from the Neuse River also extends out into the lower portion of the sound and the prevailing north wind has moved some of this low salinity water down into the Core Sound. The picture is somewhat different in Figure 3. In July the wind blows from the southwest about 70 percent of the time with the velocity in the 15 to 30 mile per hour range approximately 30 percent of the time. Typical river flows from the Roanoke, Pamlico and Neuse Rivers, once again in thousands of cubic feet per second, are 151, 7 and 19 respectively. Here the combination of reduced flow from the Roanoke River and the southwest winds have moved higher salinity water up into the northern part of Pamlico Sound. Reduced flow from Neuse River and the prevailing wind have permitted high salinity water to move across the lower part of Pamlico Sound and also change the salinity picture in Core Sound.

While we have a good understanding of temperature and salinity distribution in the Pamlico Sound complex we still cannot give a good estimate of flushing time under all conditions, nor do we as yet, have a full understanding of circulation patterns within the sound. Several projects recently completed or planned for the near future should help in achieving this goal. One of these was the recent completion of a hydrographic atlas by some of the Institute of Marine Sciences faculty members (Williams, et al., 1967). Temperature-salinity data for Pamlico Sound are now in a form that makes analysis possible. Another project contributing to this end was the current study on the Pamlico River last summer described to you earlier by Dr. Horton. During July and August of 1967 another dye tracer study will be attempted in the Neuse River. I hope we can benefit from the mistakes made last summer. A tide cycle station was occupied in June, 1966 at Drum Inlet; in June of this year I plan to occupy a tide cycle station in the Core Creek Canal so that we can have some measure of the volume and quality of water that oscillates back and forth through this canal. As time permits during the summer of 1967 I shall also be following some current drogues especially in a portion of the Sound between the mouth of Neuse River and Brant Island Shoal.

In the time left this afternoon I should like to comment briefly on the distribution of other chemical parameters in the Pamlico Sound Complex.

Dissolved Oxygen

Dissolved oxygen concentrations ranged from approximately four milligrams per liter to eleven milligrams per liter throughout the course of this study. The highest values occurred during periods of cold water and the lower values occurred when the water was warmer. In terms of percent saturation, dissolved oxygen concentrations seldom went below 50 to 60 percent and, especially during winter months, was normally close to 100 percent. Normally there was not much variation in surface dissolved oxygen concentrations throughout the sound on any one cruise. The picture for dissolved oxygen at the bottom is slightly different. Although vertical differences in the open sound were slight, the greatest variation occurring during summer months, there was frequently a vertical difference in concentrations in rivers, particularly the Pamlico River.
In the Pamlico River, during periods of warm water, low oxygen concentrations at the bottom were the rule at the three upstream stations; on occasion oxygen depletion was noted. While vertical differences also occurred in the Neuse River they were not as great nor did they occur as often. In any event, it is probable that anoxic areas are quite local and ephemeral.

**Phosphorous**

The analytic method used to determine phosphate-phosphorous is sensitive to 0.016 ugAt P/liter. During the course of this study, concentrations ranged from below the limit of sensitivity to 1.0 ugAt P/L at the surface and up to 1.5 ugAt P/L at the bottom. Any vertical gradients that were noted usually occurred in the rivers and concentrations were generally higher at the bottom. An exception to the general concentration levels occurred in September, 1965, when concentrations ranging from 1.0 to 2.5 ugAt P/L occurred in the Neuse River and the sounds south of Brant Island Shoal. At the same time higher than normal phosphate-phosphorous concentrations occurred in Pamlico River and the western sound north of Brant Island Shoal although they vary generally below 1.0 ugAt P/L.

The typical range of total phosphorous levels was 1.0 to 2.5 ugAt P/L, but during 1964 consistently high values were recorded at all stations. Concentrations as high as 25 to 30 ugAt P/L were noted. Equally high values were obtained in Bogue Sound during the same period. My only comment at this time is that we have previously noted abnormal salinity distributions over the sound for 1964 and have attributed them to river inflow.

**Nitrogen**

Nitrate-nitrogen concentrations ranged from below the sensitivity of the analytic method (0.10 ugAt N/L) to a "normal" high value of approximately 1.0 ugAt N/L. However, during the period of high phosphorous concentrations noted, similarly high concentrations of nitrate-nitrogen occurred. Distribution was different in that the high concentrations of nitrogen persisted throughout the river-sound system; a high of 10.78 ugAt N/L was recorded at the Inner Middle Station where 0.78 ugAt P/L occurred.

Nitrite-nitrogen concentrations were normally high (up to 0.5 ugAt N/L) for a component usually thought of as ephemeral. Two stations in the Pamlico River (in the vicinity of Bath) did not seem to fit with the other ten. Higher concentrations (up to 3.30 ugAt N/L) persisted at these locations and were always found in conjunction with higher than normal nitrate levels. The high nitrate levels mentioned for September 1965 were not however, accompanied by high nitrite levels.

**Primary Production**

I will not mention primary production levels today except to indicate that nitrogen seems to be a limiting factor most of the time. There are times, however, when both nitrogen and phosphorous are limiting.
REFERENCES


Winslow, F., 1886. Report on the waters of North Carolina with reference to their possibilities for oyster culture, together with results obtained by the surveys directed by the resolution of the General Assembly, ratified March 11, 1885. Raleigh: North Carolina State Printer and Binder.

HYDROLOGY OF SOUNDS AND ESTUARIES IN NORTH CAROLINA

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The estuaries and sounds of coastal North Carolina represent one of the more valuable natural resources in the state. They comprise more than 500 miles of navigable water, into which are discharged an average of about 13 billion gallons of good-quality fresh water per year. Their present and potential value for industry, recreation, sensible waste disposal, etc., are virtually incalculable. The areas surrounding them are virtually undeveloped, and this available space may eventually be one of their more important characteristics. Yet, considering their potential, they have not been adequately studied. To help fill the need for information concerning them, the U. S. Geological Survey in cooperation with the State of North Carolina, initiated a program to investigate the chemical quality of estuarine and sound waters in the early 1950's. This program has continued to the present, and now includes both the general data collection program, and special studies on the lower reaches of the Cape Fear and Chowan Rivers.

For purposes of discussion the estuaries can be separated into two categories (Figure 1): (1) those which essentially open directly into the Atlantic Ocean, and (2) those which empty into the sounds behind the chain of barrier islands known as the Outer Banks. These banks "buffer" the estuaries from the full hydraulic shock of the ocean tides, and as a result, the hydrology of the two types is quite different.

Estuaries Open Directly to the Ocean

Estuaries which open directly into the ocean are hydraulically more dynamic than those which empty into the sounds. The Cape Fear and the Northeast Cape Fear Rivers are the only ones of this type of major importance in North Carolina.

The hydrology of the lower Cape Fear River is dominated by regular lunar tides. Affects of these tides are noticeable for approximately 67 miles upstream from the mouth, where a series of navigation locks impede further upstream movement of the tidal wave. The range of the tide, under typical conditions, decreases progressively upstream. At Cape Fear the mean low-to-high tide range of the ocean is 4.5 feet. At Fort Caswell, which can be considered the mouth of the river, the mean range is 4.1 feet; at Wilmington, North Carolina, approximately 28 miles upstream, mean fluctuation is 3.6 feet; at the U. S. Geological Survey gage near Phoenix, North Carolina, which is almost 42 miles upstream, the range is about 3.4 feet; and at Lock Number 1, 67 miles upstream from the mouth, the tide range is approximately 1 foot (Figure 2). The period of these tides is generally the same as those in the ocean (2 complete cycles in 24 hours and 50 minutes). However, there is normally a progressive

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1 Publication authorized by the Director, U. S. Geological Survey.
Figure 1. Sounds and estuaries of North Carolina.
Figure 2. Upstream decrease in mean annual lunar tide range in Cape Fear River.
time lag as the tide wave moves upstream. For the Cape Fear River this lag amounts to roughly 5 minutes per mile. For example, high slack water normally occurs at Wilmington 2 hours later than at Southport, North Carolina, about 23 miles downstream.

As the tide wave moves upstream into the area where the energy of the incoming tide and the opposing energy of outflowing fresh water become more nearly equal, these spatial, and chronological relationships become more complex. In the stretch of the river between Navassa and Phoenix the fresh water flow becomes as important as ocean tides in determining the flow characteristics of the river. Maximum tide heights may decrease or increase in the upstream direction, and upstream time lags have been observed to vary from near 0 to at least 10 minutes per mile depending upon the relative amount of fresh water inflow. In periods of low fresh water inflow, water levels at the downstream gage (Navassa) will exceed those at the upstream gage immediately after low tide, and will remain higher throughout the time of flood and high tide. During such periods a strong reversal of flow occurs each flood tide throughout the reach. During periods of high fresh water inflow, it takes longer for the incoming tide to raise downstream water levels above those upstream, and the period of reversal of flow will be much shorter. In cases of extreme high flow the gage height at Phoenix may remain higher than that at Navassa throughout the tidal cycle; and, although the river stages are affected by tide levels, the direction of flow may be continuously downstream for several days (Figure 3). Another feature of the dynamic nature of this estuary is reflected by the large amounts of water which move in a relatively narrow channel. Above Wilmington the width of the river does not usually exceed 500-600 feet, yet the total daily movement of water past the Phoenix gage has been observed to vary from 714 million to 4,541 million cubic feet.

An interesting feature of streamflow in this reach of the river is the net downstream flow per tidal cycle. This quantity is determined by subtracting the total upstream flow during a flood tide from the total downstream flow for the next ebb tide. These values have been observed to vary from -50 million cubic feet to around 530 million cubic feet for cycles in which actual reversals of flow occurred (Figure 4).

**Estuaries Discharging Into the Sounds**

Most of the estuaries in North Carolina empty into the sounds behind the Outer Banks. The ocean has access to these bodies of water only through a series of relatively narrow inlets in the banks. As a result, tides which average about 3.6 feet in the ocean off Cape Hatteras, are severely dampened in the sounds and estuaries. The exact mean range of lunar tide in the interior of the sounds and in the estuaries is extremely difficult to obtain due to the overwhelming superimposed effect of wind tides on the water levels. Tide tables published by the Coast and Geodetic Survey list the mean periodic tide range in the Albemarle and Pamlico Sound as less than one-half foot, except near the inlets where it is greater. A USGS operated water-level recorder at New Bern, North Carolina, indicates lunar tides of from 6 to 14 inches. These two observations would seem to be slightly inconsistent, but they do point out the buffering effect of the barrier islands on the hydrology of the waters behind them.
Figure 3. Tide stages, relative to mean sea level, for Cape Fear River near Navassa, North Carolina (34 miles upstream from mouth) and near Phoenix, North Carolina (42 miles upstream from mouth) for a period of low flow (November 1966) and a period of high flow (April 1966).
Figure 4. Net downstream flow per tidal cycle, Cape Fear River near Phoenix, North Carolina for September 15-30, 1966.
Chemical Hydrology

The chemical hydrology of the estuaries is, logically, quite analogous to the physical hydrology. Those estuaries which have direct access to the ocean represent a dynamic, constantly changing equilibrium between tidally driven salt water from the ocean, and inflowing fresh water from upstream. Those which empty into the sounds respond to these same forces; however, the energy of the forces, particularly the tide, does not change as regularly, and usually not with as much intensity, and the patterns of change in chemical quality of the waters are quite different. From the standpoint of chemical quality all of the estuaries, and to a lesser extent the sounds, can be divided into three zones: (1) a zone which is significantly salty all the time, (2) one which may be either fresh or salty, and (3) a zone in which water levels are affected by tide but the water is always fresh (Figure 5).

In the Cape Fear and Northeast Cape Fear Rivers the area affected by salt-water intrusion varies regularly with tides (Figure 6). The salty water moves up the estuary during flood tide in the general shape of the classical salt-water wedge. However, due to turbulence in the river the wedge is not very sharply defined, but is modified to produce a partially mixed condition with the most saline water near the bottom of the channel (Figure 7). The upstream position of the wedge at high tide varies with the relative strength of the forces which control it. Chief among these forces are wind, tide height, and fresh water discharge. In estuaries open to the ocean the dominant force controlling upstream encroachment is fresh-water discharge (Figure 8).

Although the shape of the wedge (i.e., the vertical variation in salinity) will vary somewhat from place to place and time to time; the upstream profiles of maximum chloride concentrations tend to be similar as long as channel geometry doesn't change radically. However, radical changes in the shape of the channel can cause changes in the pattern of salt-water intrusion. Salt water, because of its greater density will "pond" in deep places in the channel, and lie more or less stagnant for long periods while fresher water slides over the top of it. Ledges in the channel will tend to block the upstream progress of the salt-water mass. An example of this is found at a point about 8.5 miles above Wilmington on the Cape Fear River where the channel depth decreases from 31 feet to around 8 feet. Salinity profiles at high tide tend to converge in this area. The shallow depths continue about one mile upstream, then the channel deepens to over 20 feet for the next several miles. Since our investigation started in 1954, salt water is not known to have gone over this natural "dam" in the stream bed. Should severe conditions, such as hurricane winds, force it to do so it would probably require a long period of time or extremely high stream flow to flush the salty water back downstream.

Changes in water quality in the estuaries emptying into the sounds are much more sluggish than in those with direct access to the ocean. These bodies of water react somewhat as if they were lakes with limited access to the sea. This does not imply that streamflow does not affect their hydrology—it does—but not in the same manner or with the same degree of sensitivity. The factors controlling the extent of salt-water encroachment are the same as with the Cape Fear River (winds, lunar tides,
Figure 5. Generalized chemical quality of the sounds and estuaries of North Carolina.
Figure 6. Variation of specific conductance (micromhos at 25°C) and water level for Cape Fear River near Navassa, North Carolina. Water level referred to arbitrary datum 4 feet above mean sea level.
Figure 7. Typical patterns of vertical variation in specific conductance (micromhos at 25°C) in the Cape Fear River. Cross-section (top) taken 29.7 miles upstream from mouth. Upstream profile (bottom) taken on high slack water.
Figure 8. Typical upstream profiles of bottom specific conductance (micromhos at 25°C) for Cape Fear River at high slack tide for various discharges.
and fresh water discharge), but the emphasis here is more on wind than
discharge, with lunar tides playing a more subordinate role. There are
no regular strong reversals of river flow, so the progressive movement
of salt water upstream as discharge decreases is not nearly so noticeable.
Sea-water intrusion is more likely to occur as a rather sudden introduc-
tion of a large mass of water driven upstream by strong wind tides which
may have a duration of a few hours to a few days (Figure 9). Once the
wind tides have subsided, the salt water may, if river discharge is high,
be flushed out rather rapidly. Conversely, if river discharge is low with
respect to the carrying capacity of the channel, downstream flow will be
very sluggish, and the salt water will remain rather passively in place for
long periods of time. Under such conditions it is possible to get signi-
ficant additional upstream movement of saline water by gravitational con-
vection and diffusion.

Our present understanding of the relationships between salt-water
encroachment and the environmental factors which control them are at best
semiquantitative. The investigative program thus far has been aimed pri-
marily at defining those zones which are salty part of the time and fresh
part of the time. This program has been successful in furnishing purely
statistical evaluations of the percent of time many key locations are
affected by salt-water encroachment. However, by its nature it has led
to little real understanding to date of the hydrology of many of the estua-
ries. The weaknesses in the program thus far have been twofold--time and
technique. For the most part, the sampling procedure has been limited to
one or two samples daily at locations near the uppermost extent of encroach-
ment (Figure 10). These samples have been supplemented by occasional boat
studies to determine salinity distribution upstream. The result has been
a somewhat discontinuous record, in which many, or most, of the samples
were fresh water, and gave no indication of the location of salty water.
The time required to achieve significant results by these methods is
extensive; and even then the knowledge gained is mostly empirical. It
has been recognized for a long time that techniques were needed by which
continuous records of water quality at key locations could be collected and
evaluated. The first step in this direction was achieved in 1963 when the
first recorders to continuously monitor temperature and/or specific conduc-
tance on strip charts were installed. These provided much better informa-
tion than had previously been available; but the types of data which could
be collected were limited, and the task of visually scanning and evaluating
the record was inefficient and time consuming. Almost within the past
year this situation has begun to improve. Instrumentation is now available
which will adequately monitor most of the parameters necessary to define
the chemical hydrology of estuarine systems and record the data in such a
form that it can be more easily evaluated.

An example of the new type of instruments is the Honeywell Model W-11
Water Quality Data Collection System. This instrument will record up to
10 variables. Among the possibilities presently available are specific
conductance, temperature, dissolved oxygen, chloride, solar radiation,
wind velocity, wind direction, relative humidity, turbidity, water level,
pH, Eh, and water velocity. New sensors for specific ions are being deve-
loped and improved very rapidly, and this list can be expected to expand
proportionately. The variables are recorded on 16-channel digital tape
in a predetermined sequence. The instrument can be designed to sequence
Figure 9. Typical patterns of salt-water encroachment caused by wind tides in Pasquotank River at Elizabeth City, North Carolina, and near Elizabeth City. The near Elizabeth City location is about 10 river miles upstream.
Figure 10. Locations at which continuous or periodic salinity data are available for sounds and estuaries in North Carolina.
on any desired time schedule. Other models are available which will accept up to 20 variables. The fact that the data are collected on digital tape means that the full range of automatic-data-processing techniques are available for evaluating the data.

Instrumentation of this type will prove to be very helpful in studying the hydrology of streams. Certainly they will make it possible to obtain a more representative picture of the water quality variations in rapidly changing systems such as estuaries. Combined with newer methods for measuring water movement and other environmental factors which control estuaries, they provide us, for the first time, the necessary techniques to gain some real understanding of estuarine hydrology.
HYDROLOGIC IMPLICATIONS OF A DEEPWATER CHANNEL IN
PAMLICO SOUND, NORTH CAROLINA

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Wilmington District, Corps of Engineers
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ABSTRACT

Data on some of the factors which influence tidal flow are tabulated, and the changes that may result if a deepwater channel is provided in Pamlico River and connecting sounds to the ocean are discussed. Additional investigations that would be required if a project were authorized by Congress are enumerated.

SCOPE

This paper considers in a general way the effect that a deepwater channel from the Pamlico River to the ocean would have on the hydrology of the sounds. At this time, six routes, as shown on figure 1, are under consideration, but the best route has not been selected. Furthermore, it has not been determined whether any route would be economically feasible. In any event, detailed studies, including a model study if it were found to be advantageous, will not be made unless the Chief of Engineers makes a favorable recommendation for improvement and Congress authorizes the improvement and provides funds for preconstruction planning. Data cited are taken in part from other investigations as cited and in part from studies by the Corps of Engineers.

DESCRIPTION

Routes under study would either cross Pamlico Sound or Pamlico Sound and Core Sound, which lies to the south. These routes are shown on Figure 1. To the north, Pamlico Sound is connected to Albemarle Sound by Croatan and Roanoke Sounds. Pertinent data on the sounds are given below. Areas and volumes for Currituck Sound are from Taylor, and the same data for the other sounds are from Roelofs and Bumpus.


### TABLE I
Data On Sounds

<table>
<thead>
<tr>
<th>Location</th>
<th>Width (miles)</th>
<th>Length (miles)</th>
<th>Depth (feet)</th>
<th>Average depth (feet)</th>
<th>Area (sq. miles)</th>
<th>Volume (acre-feet)</th>
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</thead>
<tbody>
<tr>
<td>Currituck Sound</td>
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<td>35</td>
<td>14</td>
<td>5.0</td>
<td>160</td>
<td>512,000</td>
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<tr>
<td>Albemarle Sound</td>
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<td></td>
<td></td>
<td>700</td>
<td>5,310,000</td>
</tr>
<tr>
<td>Croatan Sound</td>
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<td>12</td>
<td>19</td>
<td>9.4</td>
<td>46</td>
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<tr>
<td>Roanoke Sound</td>
<td>3</td>
<td>12</td>
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<tr>
<td>Pamlico Sound</td>
<td>30</td>
<td>70</td>
<td>24</td>
<td>12.5</td>
<td>1,675</td>
<td>13,500,000</td>
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<tr>
<td>Core Sound</td>
<td>6</td>
<td>36</td>
<td>9</td>
<td>4.0</td>
<td>92</td>
<td>236,000</td>
</tr>
</tbody>
</table>

Streams. Major streams tributary to the sounds of North Carolina are the Chowan and Roanoke Rivers, flowing into Albemarle Sound, and the Pamlico-Tar and Neuse Rivers, flowing into Pamlico Sound. Since the sounds are interconnected, their outlets cannot be definitely defined. However, Oregon Inlet serves as the principal outlet to the ocean for Albemarle, Currituck, Croatan, and Roanoke Sounds and the northern part of Pamlico Sound. Hatteras and Ocracoke Inlets serve as outlets for Pamlico Sound, and Beaufort Inlet is the principal outlet for Core Sound.

Drainage areas. Drainage areas of streams tributary to the referenced sounds, taken from a publication prepared by the U. S. Geological Survey in cooperation with the North Carolina Department of Water Resources, are tabulated on the next page.

---

### TABLE 2

#### Drainage Area

<table>
<thead>
<tr>
<th>Area</th>
<th>Square Miles</th>
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<tbody>
<tr>
<td><strong>Albemarle Sound</strong></td>
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</tr>
<tr>
<td>Folly Swamp</td>
<td>3</td>
</tr>
<tr>
<td>Pasquotank River</td>
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</tr>
<tr>
<td>Little River</td>
<td>97</td>
</tr>
<tr>
<td>Perquimans River</td>
<td>170</td>
</tr>
<tr>
<td>Yeopin River</td>
<td>46</td>
</tr>
<tr>
<td>Queen Anne Creek</td>
<td>7</td>
</tr>
<tr>
<td>Pembroke Creek</td>
<td>31</td>
</tr>
<tr>
<td>Chowan River</td>
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</tr>
<tr>
<td>Roanoke River</td>
<td>9,666</td>
</tr>
<tr>
<td>Kendricks Creek</td>
<td>25</td>
</tr>
<tr>
<td>Deep Creek</td>
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<tr>
<td>Scuppernong River</td>
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<tr>
<td><strong>Subtotal (Albemarle Sound)</strong></td>
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</tr>
<tr>
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</tr>
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<td>Pamlico River</td>
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<td>Jones Bay</td>
<td>14</td>
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<tr>
<td>Bay River</td>
<td>142</td>
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<tr>
<td>Neuse River</td>
<td>5,598</td>
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<tr>
<td><strong>Subtotal (Pamlico Sound)</strong></td>
<td>10,056</td>
</tr>
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</tbody>
</table>

Drainage areas of streams tabulated do not show the total area draining into the sounds, since some small streams and areas having no well-defined streams, such as Dare County, are not included. Dare County contains 375 square miles. The area not accounted for in the tabulation is roughly estimated at 1,000 square miles draining into Pamlico Sound.

**Runoff.** Average annual runoff for stations listed, taken from U. S. Geological Survey records⁴, on the next page.

---

TABLE 3
Runoff Data

<table>
<thead>
<tr>
<th>Station</th>
<th>Drainage area (sq. miles)</th>
<th>Average runoff (c.f.s.)</th>
<th>Runoff per sq. miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blackwater River near Franklin, Va.</td>
<td>613.0</td>
<td>646.0</td>
<td>1.05</td>
</tr>
<tr>
<td>Nottoway River near Sebrell, Va.</td>
<td>1,451.0</td>
<td>1,296.0</td>
<td>0.89</td>
</tr>
<tr>
<td>Meherrin River at Emporia, Va.</td>
<td>749.0</td>
<td>650.0</td>
<td>0.87</td>
</tr>
<tr>
<td>Roanoke River at Roanoke Rapids, N.C.</td>
<td>8,410.0</td>
<td>8,155.0</td>
<td>0.97</td>
</tr>
<tr>
<td>Tar River at Tarboro, N. C.</td>
<td>2,140.0</td>
<td>2,312.0</td>
<td>1.08</td>
</tr>
<tr>
<td>Neuse River at Kinston, N. C.</td>
<td>2,690.0</td>
<td>2,960.0</td>
<td>1.10</td>
</tr>
<tr>
<td>Ahoskie Creek at Ahoskie, N. C.</td>
<td>64.3</td>
<td>65.5</td>
<td>1.02</td>
</tr>
<tr>
<td>Herring Run near Washington, N. C.</td>
<td>15.0</td>
<td>10.8</td>
<td>0.73</td>
</tr>
<tr>
<td>Swift Creek near Vanceboro, N. C.</td>
<td>182.0</td>
<td>202.0</td>
<td>1.11</td>
</tr>
<tr>
<td>Trent River near Trenton, N. C.</td>
<td>168.0</td>
<td>207.0</td>
<td>1.23</td>
</tr>
</tbody>
</table>

HYDROLOGY

Runoff. Based on the tabulated data, it is estimated that the average flow into Albemarle Sound is 0.95 second-foot and the flow into Pamlico Sound 1.05 second-feet per square mile. These rates of runoff are equivalent to 1.89 and 2.09 acre-feet a day a square mile, respectively. Based on data tabulated above, the flow into Albemarle Sound would total 29,500 acre-feet and the flow into Pamlico Sound 23,100 acre-feet a day. This is equivalent to an annual flow of 10,700,000 acre-feet into Albemarle Sound and 8,450,000 acre-feet into Pamlico Sound, a total of 19,150,000 acre-feet.

Rainfall. Rainfall records for the area in the vicinity of the sounds show that precipitation averages about 48 inches.\(^5\)

Evaporation. Charts show that average annual Class A pan evaporation in the sounds is 50 inches and the average annual lake evaporation is 40 inches. The source of the data states that "freewater evaporation is a good index to potential evapotranspiration, or consumptive use."

Total inflow. If precipitation averages 48 inches and evaporation 40 inches, there is a net gain of 8 inches, or 0.67 foot. The sounds cover 1,290,000 acres. The gain in that case would be 860,000 acre-feet. Adding to this the tributary inflow computed above indicates, roughly, that freshwater inflow totals 20,010,000 acre-feet.

TIDAL DATA

Tidal flow. Available data on the area of inlets at the gorge, maximum rates of flow in cubic feet a second, and total inflow and outflow are tabulated below. Except for the measurements made in April 1950 by Roelofs and Bumpus, the data are from records of the Corps of Engineers. Except for data for 1934, information on the flow through Beaufort Inlet does not indicate whether it is for flood or ebb tide.

TABLE 4
Tidal Flow and Related Data

<table>
<thead>
<tr>
<th>Date</th>
<th>Cross section (sq. ft.) at m.l.w.</th>
<th>Maximum rate of flow (c.f.s.)</th>
<th>Total Flow (acre-ft.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Inflow</td>
<td>Outflow</td>
</tr>
<tr>
<td>Sept. 9, 1931</td>
<td>39,000</td>
<td>134,100</td>
<td>89,200</td>
</tr>
<tr>
<td>Aug. 31, 1932</td>
<td>39,000</td>
<td>129,100</td>
<td>102,700</td>
</tr>
<tr>
<td>Oct. 11, 1932</td>
<td>39,000</td>
<td>126,500</td>
<td>127,300</td>
</tr>
<tr>
<td>Aug. 24, 1937</td>
<td>44,400</td>
<td>180,000</td>
<td>142,000</td>
</tr>
<tr>
<td>Aug. 14, 1939</td>
<td>56,000</td>
<td>152,000</td>
<td>141,000</td>
</tr>
<tr>
<td>Apr. 23, 1950</td>
<td>28,000</td>
<td>28,000</td>
<td>90,000</td>
</tr>
<tr>
<td>Sept. 27, 1965</td>
<td>66,800</td>
<td>292,000</td>
<td>145,800</td>
</tr>
<tr>
<td>Apr. 25, 1950</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr. 27, 1950</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May 25, 1958</td>
<td>82,800</td>
<td>285,000</td>
<td>273,000</td>
</tr>
<tr>
<td>May 25, 1958</td>
<td>45,000</td>
<td>45,000</td>
<td>122,000</td>
</tr>
<tr>
<td>Oct. 14, 1962</td>
<td>94,100</td>
<td>125,000</td>
<td>129,000</td>
</tr>
<tr>
<td>Oct. 14, 1962</td>
<td>74,400</td>
<td>344,000</td>
<td>71,200</td>
</tr>
<tr>
<td>1934</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug. 5, 1935</td>
<td></td>
<td>63,600</td>
<td>47,143</td>
</tr>
</tbody>
</table>

Continued from Table 4

<table>
<thead>
<tr>
<th>Aug. 6, 1935</th>
<th>Oct. 20, 1936</th>
<th>Oct. 21, 1936</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>71,400</td>
<td>39,000</td>
</tr>
<tr>
<td></td>
<td>75,900</td>
<td></td>
</tr>
</tbody>
</table>

Tidal ranges as determined by the U. S. Coast and Geodetic Survey for 1967 are tabulated below.

TABLE 5
Tide Range, In Feet

<table>
<thead>
<tr>
<th>Place</th>
<th>Gorge or Inside Elevations</th>
<th>Ocean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Spring</td>
</tr>
<tr>
<td>Currituck Beach Light</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kitty Hawk</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oregon Inlet</td>
<td>2.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Cape Hatteras</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hatteras Inlet</td>
<td>2.0</td>
<td>2.4</td>
</tr>
<tr>
<td>Ocracoke Inlet</td>
<td>1.9</td>
<td>2.3</td>
</tr>
<tr>
<td>Ocracoke</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Cape Lookout</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Morehead City</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atlantic Beach</td>
<td>2.8</td>
<td>3.4</td>
</tr>
</tbody>
</table>

In 1893, the mean range in the ocean was determined by the Corps of Engineers to be 3.45 feet and the extreme range 4.9 feet\(^7\). The mean range in the throat was determined to be 2.35 feet. The tide ranges at other points in 1893, which were taken on a line to the northwest from the throat and following Wallace Channel, are tabulated below. This is roughly the route of the channel through Ocracoke Inlet, shown on Figure 1.

TABLE 6
Tidal Range in 1893

<table>
<thead>
<tr>
<th>Distance From Gorge (miles)</th>
<th>Mean Range (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.35</td>
</tr>
<tr>
<td>1.5</td>
<td>2.10</td>
</tr>
<tr>
<td>3.0</td>
<td>1.40</td>
</tr>
<tr>
<td>4.8</td>
<td>0.40</td>
</tr>
<tr>
<td>5.7 (Head of Wallace Channel)</td>
<td>0.20</td>
</tr>
<tr>
<td>10.0 (Royal Shoal)</td>
<td>0.10</td>
</tr>
</tbody>
</table>

\(^7\) Tide Tables, High and Low Predictions for 1967, Environmental Science Services Administration, U. S. Coast and Geodetic Survey.

\(^8\) Annual Report of the Chief of Engineers, U. S. Army, for 1894.
The tide range near the heads of seven other channels, from 4.9 to 6.4 miles from the inlet, was the same as at the head of Wallace Channel; that is, 0.2 foot.

No firm data are available on the present tide range in the sounds. U. S. Coast and Geodetic Survey charts carry a notation stating that: "In Pamlico Sound except near the inlets the periodic tide has a mean range less than one-half foot."

**SALINITY**

**Salinity.** Pamlico Sound and the sounds directly connected to it are highly saline, but Albemarle and Currituck Sounds contain relatively fresh water. Information on salinity is in part based on Corps of Engineer findings, but most of it is from reports of others. The average salinity in Pamlico Sound is estimated by Jarrett\(^9\) at 20,000 parts per million, which is about 60 percent of sea water. This estimate appears in general agreement with charts in the "Hydrography of Pamlico Sound." Jarrett also lists data from a Tar-Pamlico River Pollution Survey Report, prepared by the North Carolina Department of Water Resources, Division of Stream Sanitation and Hydrology, which are tabulated below. The tabulated data are converted to percentage of sea water on the basis that sea water has 20,000 parts per million of chlorides. Mile 18.2 is near the upper limit of the deeper channel under consideration, and mile 37.3 is at or near Washington.

**TABLE 7**
Chlorides, In Parts Per Million

<table>
<thead>
<tr>
<th>Distance from mouth</th>
<th>7/30/58</th>
<th>8/8/58</th>
<th>9/9/58</th>
<th>Average per Station (PPM)</th>
<th>Percent sea water</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.9</td>
<td>3,700</td>
<td>5,200</td>
<td>5,100</td>
<td>4,700</td>
<td>23</td>
</tr>
<tr>
<td>12.2</td>
<td>3,200</td>
<td>3,900</td>
<td>4,000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>18.2</td>
<td>3,200</td>
<td>3,300</td>
<td>2,100</td>
<td>3,300</td>
<td>16</td>
</tr>
<tr>
<td>26.9</td>
<td>2,000</td>
<td>2,400</td>
<td>790</td>
<td>1,400</td>
<td>7</td>
</tr>
<tr>
<td>35.3</td>
<td>88</td>
<td>24</td>
<td>190</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Flow at mile 37.3</td>
<td>2,000</td>
<td>3,200</td>
<td>1,200</td>
<td>5,160</td>
<td>-</td>
</tr>
</tbody>
</table>

A report by a Board of Consultants\(^{10}\) states that water sometimes has

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9 A Study of the Hydrology and Hydraulics of Pamlico Sound and Their Relation to the Concentration of Substances in the Sound, unpublished thesis submitted to the Graduate Faculty of North Carolina University at Raleigh, by James Thomas Jarrett.

chlorides of 6,000 to 8,000 parts per million at Washington.

Jarrett also lists data from the referenced paper on the "Hydrography of Pamlico Sound, which shows that in April 1950 the salinity at Ocracoke Inlet was 34,500 parts per million and that it decreased progressively to 21,300 parts per million 5.1 miles from the inlet. Computation by Jarrett show that the mixing length in Pamlico Sound is 5 to 6 miles during maximum flood tides and about one-half of that distance during minimum flood tides. Since tides influence mixing, there appears to be agreement between the finding in 1893 that the tide range in Pamlico Sound decreased to 0.2 foot 5.7 miles from Ocracoke Inlet and the mixing length.

Flushing. In his thesis, Jarrett finds that, based on his computations, the flushing time of Pamlico Sound averages about 3 months. It has been estimated earlier in this paper that the volume of the sounds totals 19,956,000 acre-feet and that the fresh-water inflow averages 20,010,000 acre-feet a year. While there is no direct relationship between the flushing time and fresh-water inflow, the fact that inflow is sufficient to completely fill the sound on an average of once a year indicates that the water would be changed periodically.

ROUTES UNDER CONSIDERATION

Six routes are under consideration in the Pamlico River study, but no determination has yet been made either on the best route or on whether a deep-draft channel would be economically feasible now. Selection of the best channel would be governed by the project that would provide the greatest net benefits, considering tangible, and if pertinent, intangible benefits. Data from preliminary studies of those routes are tabulated below. For estimating purposes, a channel having a depth of 45 feet at mean low water, with a bottom width of 600 feet and 5 to 1 side slopes, is used for the inlet channel; and a channel, 500 feet wide and 40 feet deep, with 3 to 1 side slopes, is used for inside channels. Other depths will be considered in the final report.

TABLE 8
Volume of Excavation

<table>
<thead>
<tr>
<th>Route Via</th>
<th>Miles</th>
<th>Excavation(^1) (cubic yards)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oregon Inlet</td>
<td>95</td>
<td>317,600,000</td>
</tr>
<tr>
<td>Hatteras Inlet</td>
<td>67</td>
<td>222,100,000</td>
</tr>
<tr>
<td>Ocracoke Inlet</td>
<td>51</td>
<td>203,500,000</td>
</tr>
<tr>
<td>Swash Inlet</td>
<td>49</td>
<td>189,600,000</td>
</tr>
<tr>
<td>Beaufort Inlet</td>
<td>63</td>
<td>250,300,000</td>
</tr>
<tr>
<td>(via land cut)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beaufort Inlet</td>
<td>67</td>
<td>237,100,000</td>
</tr>
<tr>
<td>(via AWW)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^1\) Values include 20,650,000 cubic yards in Pamlico River, common to all routes.
The scope of the Pamlico-Tar River study does not permit investigation, beyond the limits discussed herein, of the effects that a deep channel would have on the hydrology of the sound. However, during preconstruction planning, a salinity baseline would be established and the stations on the baseline would be monitored before and after construction of the project. The determination of whether or not the project appears to be engineeringly feasible will be based on available data as summarized below.

Effect of deepwater channel on salinity in sounds and estuary. A channel through the gorge of the dimensions given above would have a minimum area of 37,100 square feet. Based on data tabulated above, Ocracoke Inlet has always had a greater area than this and Oregon Inlet has had greater areas during all measurements except one. Estimates by the Corps of Engineers show that the excavation would increase the cross-section about 9 percent in the Ocracoke Inlet gorge, 3 percent at the mouth of the Pamlico River, and 8 percent in the river at Lee Creek. Because of the large expanse and volume of the sounds and the indications that the influence of the inlet extends only 5 to 7 miles from the gorge, it appears unlikely that minor enlargement of the area in the gorge would appreciably affect the tidal prism or average salinity of the sounds. The data in table 4 show so large a variation in cross-section areas, rates of flow, and tidal volumes at various times when observations were made that they appear to support this finding. The Committee of Tidal Hydraulics, Corps of Engineers states that "Interior navigation channels may either modify to a large degree the regimen of a waterway, as in the case of a tidal river, or make comparatively little change in existing hydraulic conditions, as in the case of a large estuary." If the hydraulic conditions in Pamlico Sound are not appreciably changed, those conditions in Pamlico River should also remain unchanged. Furthermore, the section of the Pamlico River under consideration is estuarine. Near Lee Creek, the cross-section contains about 150,000 square feet. As stated above, excavation would increase the cross-section 3 percent at the mouth of the Pamlico River and 8 percent at Lee Creek.

Effect on salinity in navigation channel. While it is believed that a deepwater channel would have only minor effect on average salinities, it may increase the salinity in the excavated channel. Available data on model studies for the Matagorda Ship Channel in Matagorda Bay, Texas, indicate that salinities in the navigation channel, at depths greater than those in the bay, will be appreciably higher than now occur in the bay system, but salinities outside the navigation channel would not be significantly changed.

Geology. According to available geological data obtained from the Texas Gulf Sulphur Company, relatively impervious strata exist from about 45 feet below mean sea level to 90 feet below. In the vicinity of Lee Creek, the Castle Hayne aquifer is about 150 feet below mean sea level. Above this is a formation, about 65 feet thick, which contains the phosphate ore. A layer of relatively impervious material lies above this.

11 Evaluation of Present State of Knowledge of Factors Affecting Tidal Hydraulics and Related Phenomena, Committee on Tidal Hydraulics, Corps of Engineers, U. S. Army
extending upward to 45 to 50 feet below mean sea level. The present stream-
bed is about 20 feet below mean sea level. If it is deepened to 40 feet,
the cut would barely reach the referenced relatively impervious stratum.

**Pumping and upstream control.** Two other factors that may influence
the effect that a deeper channel in Pamlico River would have are discussed
below. In the first place, the Texas Gulf Sulphur Company is pumping
65,000,000 gallons a day from the Castle Hayne aquifer. The effect of
this operation on water quality is still under study by the Texas Gulf
Sulphur Company and the State. Secondly, the Corps of Engineers is making
a study of water-resources development on the Tar River, where storage
for release during dry periods, for water-quality control, is under con-
sideration. If such reservoirs were constructed, the quality of water in
the Pamlico River would be improved during dry periods.

**Spoil.** One other factor to be considered is the effect on the sounds
of the placement of dredging spoil. At this time, we anticipate that if
dredging were accomplished, spoil in deep water would be placed to a height
of 5 feet above the existing bottom, not less than 1,000 feet from the
channel in piles about one-half mile long and 2,000 feet wide, with open-
ings of 1,000 feet between the spoil deposits. For the Ocracoke Inlet
route, it is estimated that spoil would cover about 15 square miles. Since
Pamlico Sound contains 1,675 square miles, spoil would cover only 0.9 of
1 percent of the area. The dredge spoil to be deposited if the Ocracoke
Inlet route were followed would total 126,000 acre-feet, or less than 1
percent of the volume of Pamlico Sound. Special precautions would be under-
taken during dredging to confine suspended solids until final settlement
occurs.

**Effect of deepwater channel.** Information given above indicates that
a deep channel, if provided, would not greatly affect the tidal prism or
the average salinity in the sounds. Available data indicate that it would
barely cut into the relatively impervious stratum lying above the phos-
phate ore which, in turn, covers the Castle Hayne aquifer. Dredging spoil
would cover a relatively small area and would be spaced to permit circula-
tion of water.

**Post-authorization studies.** If a project is authorized, detailed
studies would be made during preconstruction planning to determine the
effect that it would have on the sounds and ground water. At this time, it
is believed that a model study would be required to determine the effect of
the deep-draft channel under consideration. All interested agencies, Federal
and non-Federal, would be invited to present their views and findings if
such a study were made.

Matters that would be considered in such a study would include:

- Layout of channel
- Structures that would be required to facilitate construction and main-
tenance of the project
- Shoaling pattern
- Location of spoil-disposal areas, best length for spoil banks, and
distance between the banks

- 140 -
Such geological exploration along the construction route as is found necessary
Changes in the tidal prism
Changes in the salinity of the sounds
Changes in salinity in the navigation channel
Changes that the project would have on the regimen of the Pamlico River and the sounds

CONCLUSION

It is concluded that a deepwater channel from Pamlico River to the ocean could be provided without upsetting the regimen of the river or sounds, but that it would be desirable and possibly necessary to make a model study to explore significant aspects of such a project before it is constructed.

ACKNOWLEDGEMENT

Information in this report is taken from published and unpublished reports by many investigators, including the Corps of Engineers. The kindness of those who have made their data available to us in our study and the permission given by the Corps of Engineers to include previously unpublished data are greatly appreciated.
A MATHEMATICAL MODEL FOR THE HYDROLOGY AND HYDRAULICS OF PAMLICO SOUND

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and
Michael Amein
Department of Civil Engineering
North Carolina State University at Raleigh
Raleigh, North Carolina

INTRODUCTION

The startling announcement a few years ago that Lake Erie, one of the mighty Great Lakes, was dying was a terrible reminder of the drastic way in which man can thoughtlessly damage major features of his environment for generations to come. We recall with some remorse that "All the King's Horses and all the King's Men couldn't put Humpty Dumpty together again." It has been estimated that 50 years of heavy expenditure and constant vigilance may restore this lake to the semblance of its state of only twenty years ago. We are also reminded of the Assyrian destruction of the Babylonian irrigation system that has never been repaired.

We could turn our eyes from the visible debauchery of Lake Erie or New York Harbor or even of some of our North Carolina Streams and calculate that the Pamlico Sound and its 1700 square miles of water surface could act as a mighty sewage treatment lagoon and assimilate the wastes of five million people. However, if we did, we would be ignoring the fact that we would be damaging perhaps beyond repair the nursery of multitudes of shell fish and other marine life upon which our diet in the not so distant future may depend. This is not to argue that the waters of the region should not be used beneficially for the people nor that people are not more important than fish. It is to argue, however, that we should gain as much foreknowledge of the results of our actions as is humanly possible.

A powerful tool for predicting the characteristics of the water in streams, estuaries, lakes and other bodies of water, which can be used for the management of water quality is the mass-balance equation used in conjunction with the equations of fluid motion. This system of equations constitutes a mathematical model describing the relationships between causes and effects in the language of mathematics. The mathematical model is essentially complex but can be greatly simplified if the physical circumstances warrant it. The "oxygen sag curve" of Streeter and Phelps (1925) is an example of a simplified version of this model. However, when physical circumstances are complex, the mathematical model must of necessity remain complex if it is faithfully to represent the physical conditions.

The primary advantage of this type of mathematical model is that it depends on a minimum quantity of field data. Mathematical solutions would replace much of the tedious and expensive field measurements. Hydraulic and hydrologic data are very meager for the Pamlico system since there has not been an economic justification for the expenditure of the large sums necessary to collect them. The situation is not likely to change in the near future. A mathematical model based on the mass balance equation
would serve as a valuable guide in preventing the severe pollution of the Sound. Over the past year, several students supported by a Training Grant initiated under the Public Health Service but now under the Water Pollution Control Administration have conducted studies contributing to the formulation of a mathematical model for the flow in the Pamlico Sound. As part of this program, Jarrett (1966) has made estimates of low flow fresh water inputs, has evaluated the eddy dispersion coefficient at several locations in the Sound, and has determined the relative magnitudes of astronomical and wind tides in the Sound by spectral analysis. Other students are working on the computation of unsteady flows through the tidal inlets and on solution of the equations of motion in the Sound.

In the following paragraphs, first a brief physical description of the Sound will be given. Secondly, the mathematical model will be described. Finally the promises and problems of applying it to Pamlico Sound will be delineated.

### PHYSICAL DESCRIPTION OF THE SOUND AND THE BASINS

The Pamlico System (Figure 1) is composed primarily of the Neuse-Trent River system draining some 5600 square miles and the Tar Pamlico River system draining another 4200 square miles to the Pamlico Sound which covers approximately 1675 square miles at a depth of only sixteen feet. The system then drains through Ocracoke and Hatteras Inlets in the Outer Banks to the Atlantic Ocean.

The protection to the Sound provided by the Outer Banks and the shallow depths that prevail make these waters a natural nursery for many types of fish and other marine species. The waters are relatively free of pollution because of the lack of industrial development and low population density. The economic development of the region has been hindered in turn by lack of adequate navigation channels.

The average rainfall of the contributing basins exclusive of the coastal region itself is in excess of 45"/year on the average. Runoff, however, is only about 30% of this amount or about 14"/year. The major runoff occurs in the spring months, minimum runoffs are observed in June and again in October and November.

The dominating feature of the Pamlico Region is the wind. Astronomical tides are of the order of six inches but the winds frequently cause tides far above this value. Hurricane driven tides may be in excess of five feet in some parts of the Sound. Minimum wind influence occurs in the months of June and July. Thus the periods of low wind activity coincide with periods of low flow. Jarrett (1966) has found that the flushing time for the Sound may be of the order of three months. We may expect these circumstances then to be most critical from the pollution standpoint. At virtually all other times, there will be higher freshwater flows, and greater mixing from wind action.

Evaporation data are sparse but from preliminary studies of data gathered at Maysville by the U. S. G. S., it appears that computations may be made with some confidence using the Penman equation. During the summer months evaporation and rainfall are about equal so that the major
sources of fresh water are the inland portions of the drainage basin.

The contribution of swamp water to the Sound has not been fully evaluated. The Southeast Forest Experimental Station at Charleston, South Carolina has obtained some data indicating substantial swamp flows whenever the twenty-four hour rainfalls exceed one inch. However, during May and June, the overflow appears to be small.

DESCRIPTION OF THE MATHEMATICAL MODEL

The mathematical model proposed for this study consists of the equations of conservation of mass and conservation of momentum of the fluid together with the equation of mass-balance for the concentration of a substance transported by the fluid. These equations, written for a unit volume of the fluid in vector notation, are shown on Figure 2 and 3, together with a symbolic representation of the quantities involved.

The first equation expresses the fact that if more fluid enters a given volume than is leaving the given volume in a given time then the density of the fluid must increase. For open bodies of water and a constant density the equation implies that if more water is flowing into an element than is leaving that element, then the water level in the element will be rising.

The second equation expresses the fact that if the forces acting on a given volume of fluid are not balanced, then according to Newton's principle, the fluid will be accelerated. In equation (2), the forces considered are gravity, pressure and friction.

The third equation states that if in a given time, a part of the substances enclosed in a unit fluid volume is carried out by the fluid velocity, a part of the substance is dispersed by some process such as turbulence and if part of the substance disappears from the volume, say by chemical reaction or sedimentation, then the quantity of that substance contained inside that volume will decrease in that time. In a region of finite dimensions, advection moves part of a substance in or out of the region by carrying it beyond the region's boundaries. The effect of dispersion in such a region would be to distribute the substance more evenly within the boundaries of the region. In the mass-balance equation the dispersion and advection are due to the fluid motion, thus it cannot be solved independently of the equations of motion.

The three equations can serve as a mathematical model to predict the motion of the fluid and the fate of a substance transported by it. In the last few years, the advent of the digital computer has made it possible to solve these equations by numerical methods. If the flow conditions and the geometry of the water body are simple, the task is made somewhat easier. Considerable progress in the analysis of estuarine flows has been made in the recent past. For steady flow and simple estuarine geometry, the flow will be uni-directional and the velocity will be inversely proportional to the cross-sectional area. Thus the velocity field, at least on an approximate basis, can be easily determined. The effort will then be directed mainly to the solution of the mass-balance equation which in itself is a formidable task. An excellent example is provided by the study
\[ \frac{\partial \rho}{\partial t} = - (\nabla \cdot \rho \vec{V}) \]  
(1)  
Conservation of Mass

\[ \rho \frac{D\vec{V}}{Dt} = - \nabla p - [\nabla \cdot \tau] + \rho \vec{g} \]  
(2)  
Conservation of Momentum

Figure 2. Equations of Fluid Flow
Figure 3. Mass-balance Equation

\[ \frac{\partial c}{\partial t} = \nabla \cdot \mathbf{E} \cdot \nabla c - \nabla \cdot \mathbf{v} \cdot \nabla c \pm \sum s \]  

(3)
of the Delaware estuary reported by Thomann (1965). As evidence of the continuing progress being made, Dornhelm and Woolhiser (1967) have presented the solution of the three equations for a tidal estuary in which the effects of variable inflow and the variation of water level by tidal action are included. Previous studies had dealt with steady inflow and the tidal action had been averaged over the tidal cycle.

APPLICATION TO PAMLICO SOUND

The third and final objective of this presentation is to explore the problems and to speculate on the promises of applying the mathematical model to Pamlico Sound. The complexity of the flow phenomena in the Sound poses considerable problems for the development of a mathematical model based on the equations of motion and the mass-balance. Let us focus our attention first on the determination of the velocity field which is a necessary step in this effort. Perhaps the most significant aspect of the velocity field is that in contrast to the flow in estuaries, the flow in the Sound is not uni-directional. Thus a two-dimensional approach must be used. It would be instructive to work with a very simple idealized situation which could be the start for the development of more realistic future models. The situation is shown on Figure 4. We have a basin of constant depth with four openings. The basin simulates Pamlico Sound in a rough manner. The two openings on the lower left corner could be the mouths of two river systems, while the three openings on the right represent inlets connecting the basin to the sea while the two openings at the top represent flow from the Albemarle Region. The flow is assumed to be steady and frictional effects are neglected. The equations of motion take the form of Laplace's equation for the stream function $\psi$, that is

$$ \nabla^2 \psi = 0 $$

A coordinate mesh is superimposed on a map of the basin. The values of the stream function are known at all boundary points, because they can be computed from the steady flows through the inlets and outlets. Laplace's equation is solved on a digital computer by a finite difference iterative scheme. The solution would provide values of $\psi$ at all interior points from which the streamlines can be plotted. Knowing $\psi$ values, velocities can be computed. The results of the computation resulting in mapping of the streamlines, as performed by Joe Hammack, are shown on Figure 4.

With the idealized model as a start, more sophisticated models can be developed. For Pamlico Sound there is no dearth of factors which could complicate the problem. At a more advanced stage of development, such a model would simulate the natural conditions, the true geometry, the variability of inflows and outflows and would be a valuable guide in determining the fate of pollutants introduced into the Sound. At the present time, several investigators and public agencies are collecting all kinds of data in the Sound. With the incorporation of these data into the model, a very useful tool for the management of the waters of the Sound can become available.
Figure 4. Streamlines in an Idealized Sound
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Thomann, R. V. (1965), "Recent Results from a Mathematical Model of Water Pollution Control in the Delaware Estuary," Water Resources Research, Volume 1, No. 3.
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