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HYDROGRAPHIC AND ECOLOGICAL EFFECTS OF ENLARGEMENT OF THE CHESA--ETC(U)
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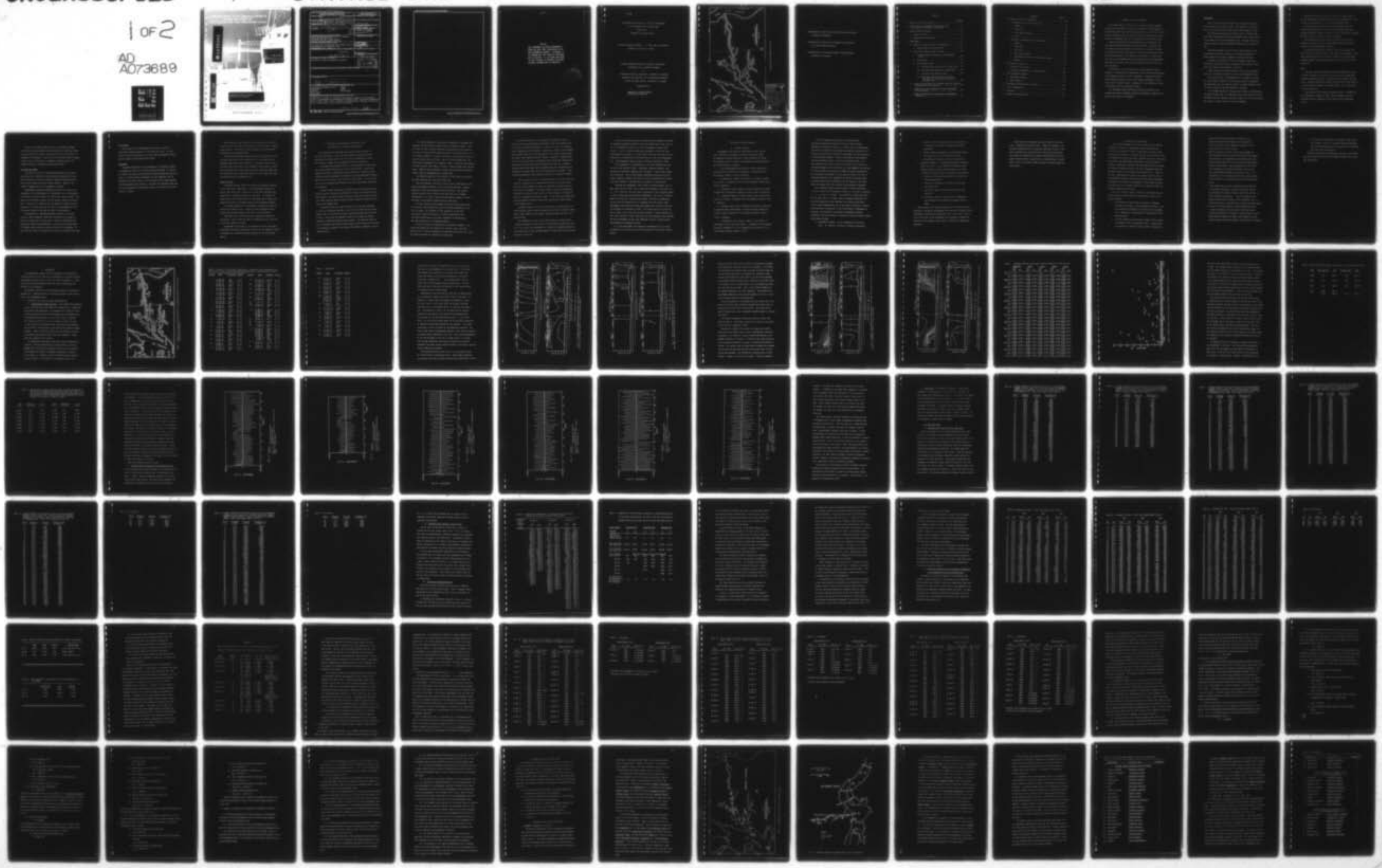

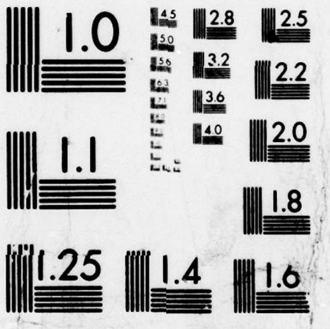
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| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER<br>(6) | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| ~~4. TITLE (and Subtitle)~~ Hydrographic and ecological effects of enlargement ~~of~~ of the Chesapeake and Delaware Canal; ~~final report~~ summary of research findings. | | 5. TYPE OF REPORT & PERIOD COVERED<br>Research rept. |
| | | (9) ~~6. PERFORMING ORG. REPORT~~ NUMBER<br>final rept. |
| 7. AUTHOR(s) | | ~~8. CONTRACT OR GRANT~~ NUMBER(s)<br>(15) DACW61-71-C-0062 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>Natural Resources Institute Univ. of Maryland<br>Chesapeake Biological Lab.<br>Chesapeake Bay Inst. Johns Hopkins<br>College of Marine Studies, U. of Del. | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>U.S. Army Corps of Engineers Philadelphia District<br>Customs House, 2nd & Chestnut Sts.<br>Philadelphia, Pa. 19106 | | ~~12. REPORT DATE~~<br>(11) Sep [redacted]973<br>~~13. NUMBER OF PAGES~~<br>70 |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)<br>(12) 139p. | | 15. SECURITY CLASS. (of this report)<br>Unclassified |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

For public release; distribution unlimited

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

(14) CONTRIB-566

19. KEY WORDS (~~Continue on reverse side if necessary and identify by~~ block number)

Chesapeake and Delaware Canal
Hydrography
Salinity
Tidal flows
Blue Crabs
Fishes
Canals
Fish Ecology

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Primary goal of study is to provide best possible estimate of the ecological effects of enlargement of Chesapeake and Delaware Canal, from control dimensions of 27' x 250' to 35' x 450'. Salinity and flow pattersn, movement of fish and their ecology within the canal were also studied.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

# HYDROGRAPHIC AND ECOLOGICAL EFFECTS OF ENLARGEMENT OF THE CHESAPEAKE AND DELAWARE CANAL

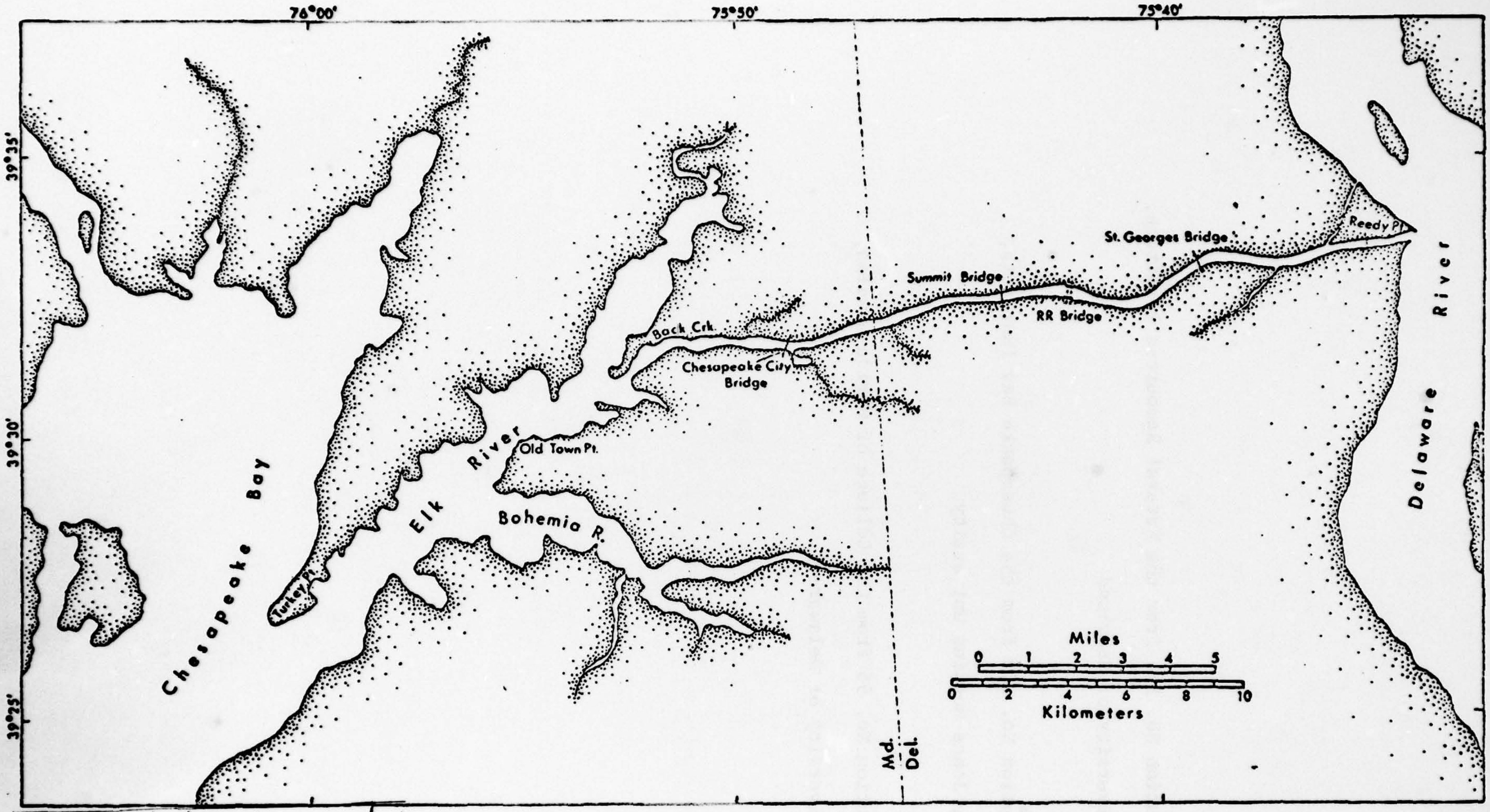
## FINAL REPORT

## SUMMARY OF RESEARCH FINDINGS

TO THE PHILADELPHIA DISTRICT, U. S. ARMY CORPS OF ENGINEERS
CONTRACT NO. DACW 61-71-C-0062

NATURAL RESOURCES INSTITUTE, UNIVERSITY OF MARYLAND
COORDINATOR FOR A COOPERATIVE PROGRAM
BY
CHESAPEAKE BIOLOGICAL LABORATORY, UNIVERSITY OF MARYLAND
CHESAPEAKE BAY INSTITUTE, THE JOHNS HOPKINS UNIVERSITY
COLLEGE OF MARINE STUDIES, UNIVERSITY OF DELAWARE

SEPTEMBER 1973



Chesapeake and Delaware Canal Area

Contribution No. 566 from the Natural Resources Institute,
University of Maryland

Contribution No. 200 from the Chesapeake Bay Institute,
The Johns Hopkins University

Contribution No. 95 from the College of Marine Studies,
University of Delaware

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## A. SUMMARY OF GOALS AND RESULTS

The primary goal of this study is to provide the best possible An estimate of the ecological effects of enlargement of the Chesapeake and Delaware Canal from control dimensions of 27' x 250' to 35' x 450' is given. Serious constraints exist in that the study was initiated late in the process of enlargement and the time available for the study is short.

Specific sub-goals have been identified as the objectives for the research program described. ~~in a later section.~~ These deal with the salinity and flow patterns of the Canal; the value of the Canal as a nursery for fish; the movements of fish in and through the Canal; and the populations of other organisms in the Canal. In each case, the effects of enlargement have been sought and the most advantageous operation of the Canal, from various ecological points of view, has been considered.

Basically all of our studies can be grouped under two major headings: one dealing with hydrographic effects and the other dealing with ecological effects of Canal enlargement. Findings and results are discussed in detail in each of the fourteen appendices, each of which covers a specific study. Highlights of these results are given in Sections D and E of the present report.

The following summary provides the principal results of our research and the most important expected environmental changes in the Canal as the result of enlargement.

## Hydrography

- Flow in the Canal involves rapid and substantial changes in direction and in the volume of flow. Net transport is relatively small in comparison with the large short-term movements of water.
- The long-term average net non-tidal flow will increase from about 900 cfs eastward for the pre-enlargement Canal to about 2450 cfs eastward for the post-enlargement Canal. Average flows may be somewhat larger in spring and somewhat smaller in late summer and fall.
- Increased eastward flow will tend to lower salinity in the Delaware and to increase salinity in the upper Chesapeake Bay. These changes will be small compared to natural variations.
- Salinity in the Canal will be little changed, except that short-term fluctuations will be increased and the region of fresh water will tend to extend farther to the east.
- Tidal velocities and tidal excursion in the post-enlargement Canal will be about 15% higher than in the pre-enlargement Canal.
- Any one water mass, at Chesapeake City for example, will move out of the Canal in about 15% less time than prior to enlargement. The probability that fish eggs and larvae, or other planktonic material, will be carried into the Delaware is increased.
- The standard deviation of the long-term average, including about two-thirds of the cases, for individual tidal cycle values of the net non-tidal flow will increase from about ± 5980 cfs for the pre-enlargement Canal to about ± 14,830 cfs after enlargement.

- About 60% of the tidal cycles will have net eastward flow in the post-enlargement Canal and 40% will have net westward flow. This is about the same partition as in the pre-enlargement flow.

- The average net non-tidal flow in the eastward cycles will increase from about 4425 cfs for the pre-enlargement Canal with a standard deviation of about ± 4315 cfs to about 10,965 with a standard deviation of about ± 10,695 cfs after enlargement.

- The average net non-tidal flow in the westward cycles will increase from about 4130 cfs (± 4095 standard deviation) to about 10,240 cfs (± 10,155 standard deviation).

- The expected maximum net non-tidal flows for one tidal cycle will increase in both directions as the result of enlargement. Eastward maximum flow will rise from about 20,100 cfs to about 48,800. Westward maximum flow will increase from about 15,300 cfs to about 37,900 cfs.

## Fish

- The Canal contains an abundant and diverse population of fish. At least 62 species of fish occur in the Canal and its approaches, including freshwater species, estuarine fish and migrants from the ocean. Seasonal patterns are marked, involving use of this region as a nursery ground, residence or feeding ground. Also, various life history stages occur.

- Many species of fish migrate through the Canal. Striped bass move extensively through the Canal, and this appears to be the principal route of departure for such fish from the Chesapeake system.

- There is no present evidence that the environmental changes in the Canal region resulting from enlargement will adversely affect the adult fish of the region, including their use of the Canal as a passageway for migration. There are untested possibilities of change, however, such as attraction of anadromous migrating fish in the Delaware because of increased outflow from the Canal.

## Fish eggs and larvae

- The Canal is an area of exceptional importance as a hatchery and nursery for striped bass, with principal concentrations in the western portion; of value for alewives, blueback herring and white perch; and of some use for more than 20 species. Spring is the season of highest use, but all seasons are involved.
- Experimental research established the effects of salinity and temperature on the development rate, morphology, rate of development and survival of eggs and larvae of striped bass and white perch. Both species are relatively tolerant but have optimal ranges for development. Results do not indicate that the changes in salinity and temperature in the Canal region as the result of enlargement will have any adverse effects on the eggs or larvae of these species.
- The quantities of suspended sediments observed in the Canal were not, under laboratory conditions, detrimental to the eggs or larvae of striped bass or white perch. There are indications that exceptional loads of such sediments, as could occur from some kinds of dredging, spoil disposal or natural events, can be damaging. No loss from this source is expected as the result of enlarging the Canal.

Flow control

•Flow control may be advantageous when there is threat of exceptional eastward transport of fish eggs and larvae. Any such control devices and operations will have mixed environmental effects, and will require careful design and testing.

Monitoring

.Continued monitoring of any advantageous or deleterious effects of enlarging the Canal is of unusual importance because (1) ecological effects are often subtle and require longer observation than this study, (2) further future enlargement has been suggested, and (3) proposed use of Canal water for waste disposal, power plant purposes and other purposes will require an excellent and continuing data base on the environmental and biological quality of the Canal, and on the effects of change.

•Shear forces of high intensity and low duration were found to injure the eggs and larvae of striped bass and white perch in experimental studies. Such forces are not expected to be significantly detrimental in the enlarged Canal.

•Increased net eastward transport enhances the possibility that fish eggs and larvae may be transported out of the Canal into the Delaware system, where the probability of unfavorable water quality is higher than in the Canal. Such transport is most likely to occur when the western end of the Canal has a water elevation higher than the eastern end for an exceptional period, so that larger than average eastward flow and transport occur.

## Benthic animals

•Macroscopic benthic animals are varied and moderately abundant in the Canal and its approaches. In the Chesapeake approach, 25 species were noted, with a density of at least 865 individuals per square meter. Biomass decreases into the Canal. In Delaware, 22 species occur, with lower density of individuals and of biomass per square meter than in the western Canal or the Chesapeake approach.

•The benthic animals are of considerable importance as food for resident and migratory fish. Usually, the most abundant benthic species were the most abundant food items in fish stomachs.

•Blue crabs occur in the Canal and its approaches during the warm months. Most of them are small or medium-size males, and some of them move through the Canal.

•Enlargement of the Canal is not expected to affect the benthic populations of animals significantly, except for the immediate effects of dredging and a possible eastward extension of some fresh-water species.

## B. EVOLUTION OF THE CHESAPEAKE AND DELAWARE CANAL WITH REMARKS ON BIOLOGICAL CONSEQUENCES

The history of the Chesapeake and Delaware Canal goes back to the late 18th century. Many excellent documents detailing the Canal development have been written, but very little information is available on biotic changes that accompanied the Canal's evolution.

The Delaware and Chesapeake Bays, in close proximity to each other, cut into the middle Atlantic coast of the United States. While their respective mouths are separated by about 130 miles of coastline, their waterways converge northward (Chesapeake Bay) and northwestward (Delaware Bay) so that at one point, they are only 14 miles apart. It is in this area that the Chesapeake and Delaware Canal was constructed, linking the two waterways.

Because of their geographical closeness, the two bays have similar habitats and are occupied by taxonomically similar or ecologically analogous species. The marine fauna are typical mid-Atlantic types, and the less saline upstream portions contain common freshwater fishes that are found in the general area.

Although the idea of a canal linking the two bays was conceived as early as mid-sixteen hundreds, it was not until 1804 that the actual construction of the Canal was started, and then aborted after two years of work. Active work was resumed in 1824 and the Canal was finally completed in 1829 and opened for ship traffic. The Canal was then run by the Chesapeake and Delaware Canal Company, jointly owned by the states of Pennsylvania, Maryland, and Delaware, the Federal Government, and the general public.

The eastern entrance to the Canal was originally at Delaware City, Delaware, two miles north of Reedy Point, the present entrance. Here, the first of three locks was installed, maintaining the water level in the Canal 7.6 feet above the mean low water in the Delaware River. At St. Georges, Delaware, 4.3 miles to the west, a second lock was built to raise the water level by 10 feet. Then, 9.3 miles further west, the Canal reaches Chesapeake City, Maryland. Here, a third lock was required to bring the water level down by 15 feet to reach the same level as Back Creek. Another 4 miles westward, the Canal joins Elk River and finally connects with the Chesapeake Bay at Turkey Point.

The original Canal was 10 feet deep by 36 feet wide on the bottom. The locks were 220 feet long and 25 feet wide.

With the opening of the Canal in 1829, direct interchange of water masses and organisms between the two bays became possible. However, presence of three locks minimized such interchanges, and salinity regimes along the Canal waterway would have been little changed. Consequently, it is safe to assume that substantial changes in biotic structure in the waterway probably did not take place.

The locks would not have impeded some sessile marine forms, such as barnacles, from entering the Canal by attaching themselves to the hulls of ships. The invasion of such organisms, or any other truly marine forms for that matter, would be precluded by the relatively fresh water in the Canal, especially on the Maryland end, which would act as a biological barrier .

In 1919, the Canal was purchased by the Federal Government. The locks were removed and the waterway was converted into a sea-level Canal by 1927. This was enlarged to 12 feet deep by 90 feet wide. Also, the eastern entrance was relocated to Reedy Point.

In the entire history of the Chesapeake and Delaware Canal, no event has had more environmental significance than the conversion into a sea-level, free-flowing waterway, at least in so far as its environmental consequences are concerned. Because the salinity at the Delaware end is higher than that at the Maryland end, the salinity regime along the entire Canal underwent drastic changes. Basically, increased quantities of saline water were transported from Delaware Bay toward Chesapeake Bay, and more fresh water transported the other way. Further, because tidal forces come from two opposing ends and at different time schedules, the water within the Canal was made quite turbulent. These phenomena undoubtedly exert profound influences on biological systems.

Since the water can now flow unobstructedly in the Canal in either direction, organisms can be transported between the two bays either actively by free swimming as nekton or passively by being carried by the current as plankters. This would result in the more westward distribution of estuarine fishes either in their feeding or in using the Canal as a nursery area for their young. At the same time, fishes that are more adapted to fresher waters would extend their ranges farther to the Delaware side.

Anadromous species, such as the striped bass, American shad, and river herrings, which as adults migrate from the sea to rivers to spawn and as young migrate in the opposite direction, might now find a new shorter route.

The turbulence of water in the Canal creates a situation which is highly favorable for the survival of semi-buoyant striped bass eggs. This has lead to the development of a productive spawning ground for the striped bass at the interface between the fresh water and salt water wherever it may occur.

By 1932, five years after the sea-level Canal was opened, the volume of shipping had quickly swelled to over one million tons a year, and the 12' x 90' waterway was found to be far from adequate to handle such traffic. The U. S. Congress thereupon authorized (in 1935) the first enlargement of the Canal, to 27 feet deep by 250 feet wide from the Delaware River to the Elk River, and thence 400 feet wide to the Chesapeake Bay. This enlargement work was begun in 1936 and completed in 1938.

This enlargement of the dimensions of the Canal increased the rate as well as the volume of flows. Turbulence, sediment transport, and transport of planktonic organisms were increased. A new salinity regime was established. All of these changes undoubtedly affected the distribution, spawning, feeding, and survival of both invertebrates and fishes. There were, however, no observations or analyses of these effects.

Following the enlargement, Canal traffic increased sharply, and in 1942, more than 10 million tons of cargo were shipped via the Canal. The 27' x 250' water-way once again became inadequate to meet shipping demands. In 1954, Congress authorized further enlargement; this time to a minimum depth of 35 feet and a minimum bottom width of 450 feet, extending all the way from the Delaware River to Chesapeake Bay near Pooles Island. Enlargement work under this second authorization was started in 1956 and was scheduled for completion in 1969. The target date has not been met due to delays, and at this time the whole project is nearly complete, but for a short section at Reedy Point which has been widened but not deepened. The Canal enlargement has not been completed in order to obtain better understanding of enlargement effects.

It is the hydrographic and ecological consequences of this second enlargement of the Canal that are the focal point of the present investigations.

## C. THE PRESENT RESEARCH PROGRAMS

### 1. Concept and Scope

Enlargement of the Canal was authorized in 1954, and the first substantial enlargement processes were begun in 1963. Environmental concerns expressed in 1970 stimulated the design and implementation of a series of complementary research projects and related studies, including:

1. Field measurements and studies of tides, currents and salinities in the Canal and its approaches. Performed by the Philadelphia District, Corps of Engineers.

2. Construction, testing, and studies in a hydraulic model of the Canal. Performed by the Waterways Experiment Station (WES), Corps of Engineers.

3. Mathematical model studies of water movement in the Canal. Performed by the Waterways Experiment Station, Corps of Engineers.

4. Preliminary design of several types of flow control structures for the Canal. Performed by the Philadelphia District, Corps of Engineers.

5. Hydraulic model tests of possible flow-control structures to determine their effectiveness. Preliminary model studies are presently being conducted by the Waterways Experiment Station, Corps of Engineers.

6. Hydrographic and ecological studies of the effects of enlargement of the Canal (this study). Performed by the Chesapeake Biological Laboratory (U. Md.), Chesapeake Bay Institute (J.H.U.) and College of Marine Studies (U. Del.).

The total program has been highly interdisciplinary. Continuous exchange and interaction has been required among engineers in theoretical and applied fields, physical hydrographers, specialists in hydraulic and mathematical modeling, biologists conducting field surveys and laboratory experiments, and decision-makers in various public agencies. Each has contributed to and depended upon the concurrent efforts of other professional groups. As a brief example, the hydraulic model of the Canal can be useful for estimating changes in net flow and in the time dependent flow pattern; for cross-checking with theoretical models for mutual improvement; for estimating the movements of fish eggs and larvae by the use of simulating particles; for suggesting the effects of various types of possible flow-control structures; and for testing of new ideas which will emerge after this specific study program is completed.

The ecological studies were initiated in October 1970 under a contract between the Philadelphia District of the Corps of Engineers and the University of Maryland. The University is prime contractor for its work, and Dr. L. Eugene Cronin is program coordinator; but the entire program has been conducted as an inter-institutional effort, making complementary use of the special facilities, location, and professional competencies of the Johns Hopkins' Chesapeake Bay Institute; the University of Maryland's Chesapeake Biological Laboratory; and the University of Delaware's College of Marine Studies. This program includes:

1. Hydrographic Program - by the Chesapeake Bay Institute (CBI). Dr. Donald W. Pritchard, Principal Investigator.

   a. Studies of the time variations in the distribution of salinity in the Canal and adjacent estuarine approaches.
   b. Direct current measurements of flow patterns within the Canal and of net flow through the Canal.
   c. Measurements of division of flow at Turkey Point.

2. Ecological Program - by Chesapeake Biological Laboratory (CBL), Dr. Ted S. Y. Koo, Principal Investigator; and Delaware College of Marine Studies (DCMS), Drs. Frank C. Daiber and Victor Lotrich, Co-Principal Investigators.
   a. Analysis of fish eggs and larvae in the Canal and its approaches (CBL).
   b. Effects of environmental variations on fish eggs and larvae (CBL).
   c. Use of the Canal by juvenile and adult fish (CBL and DCMS).
   d. Biological survey in the Canal and its approaches and estimation of the effects of changes (CBL and DCMS).

These projects have variously required one to three years for completion, and special arrangements have been made to extend certain hydrographic observations and analyses until June of 1974. The results of the rest of the hydrographic and ecological research are presented in this Summary Report and in a series of 14 supporting Appendices.

A great amount of assistance has been provided by the Army Corps of Engineers during this study. Thanks are extended to the personnel associated with the Waterways Experiment Station, Vicksburg, Mississippi for their help and concern during the project. Many thanks are extended to the people associated with the Philadelphia District Office, especially Mr. Joseph Phillips, Mr. Mark Wolfe, and Dr. John Burnes, whose assistance and advice aided the study greatly.

## 2. Potentials and Limitations

These studies provide, for a short period of time, detailed information on salinity, temperature, current direction and velocity; net transport of water; relationship of flows to water elevations at the ends of the Canal; the uses of the Canal by fish for spawning and nursery functions; movements of fish in and through the system; year-round benthic populations; specific effects of salinity, temperature, sediment loads and shear fields on the eggs and larvae of important species; and other information about the ecological aspects of the Canal and the changes in it. These are new data, unprecedented in quantity and quality for this site or any comparable situation, and they will greatly assist reasonable evaluation of the effects of enlargement. Several kinds of models are presented in this Summary Report and its Appendices which are original, appropriate and useful.

There are, however, several significant constraints and limitations placed on these studies by circumstances outside of the research program.

1. The studies were made during the process of dredging portions of the Canal to greater depths and widths. This was accepted as preferable to cessation of such dredging, but it complicates interpretations of diverse data from a complex system.
2. The total period of study from the autumn of 1970 through the spring of 1973 is ecologically short. Gross effects can sometimes be learned in such a period, although even

those are not easily quantified in estuaries, but long-term and more subtle impacts may be undetected. They can, however, become enormously important to the future values of the Canal system.

3. Much of the period of study, that between December of 1971 and summer of 1973, involved fresh water flows higher than average in the Susquehanna and Delaware Rivers, and Hurricane AGNES occurred in June of 1972 with many massive effects on the region. These circumstances do not alter basic phenomena or biological principles, but they may have caused unusual patterns of salinity or flow. Such patterns may not be repeated again for many years and some of the results of the aberrations may not have been recognized.
4. Field observations have been centered upon the Canal and its immediate approaches, and could not usually involve the Chesapeake or Delaware systems, their water quality, or their biological populations. Thus, for instance, this report cannot provide estimates of the movements, fate, or long-term success of fish which left the Canal for other waters.
5. It has not yet been possible to obtain simultaneous data on water elevations at the two ends of the Canal and on accurately measured net transport of water through the Canal. These data are essential to some of the estimates and predictions desired from this research, and those must be deferred.

6. Data from final mathematical and hydraulic model studies was recieved so late as to preclude thorough comparisons with direct observations in the Canal and the calculations based upon those observations.

Therefore, substantial and pertinent conclusions can be drawn from this research, but some of the related questions are at this time unanswerable.

## D. HYDROGRAPHY

The hydrographic program (CBI) is responsible for determining salinity patterns in the Canal and its approaches as related to spatial and temporal variations and to effects of Canal enlargement. In addition, water flow and transport within the Canal is determined and related to the enlargement.

The detailed results for the hydrography program are presented in Appendix XIV. Sampling patterns are discussed briefly in each subsection of the hydrography report.

### 1. Salinity in the Canal and upper Chesapeake Bay

a. Distribution in space and time. The salinity data presented cover the period from 13 May 1969 to 14 February 1973. Temperature and salinity were measured at 2-m intervals at 14 stations in the Canal and adjacent areas of the Chesapeake Bay and Delaware River. The measurements were made as near to slack water as possible. Most cruises consisted of two runs through the Canal: one west to east usually at slack before flood (eastward flowing current), and one east to west usually at slack before ebb (westward flowing current). Table 1 lists the cruises with the direction in which the sections were made and which slack they represent. Figure 1 shows the location of the stations.

The temperature and salinity data were drawn on longitudinal sections. Sections representing all observed data are given in Appendix XIV, and some are reproduced here for ease of reference. In discussing the spatial and temporal variations of salinity in the Canal, it is useful to keep in mind the factors influencing the salinity. The salinity in the Delaware River at the

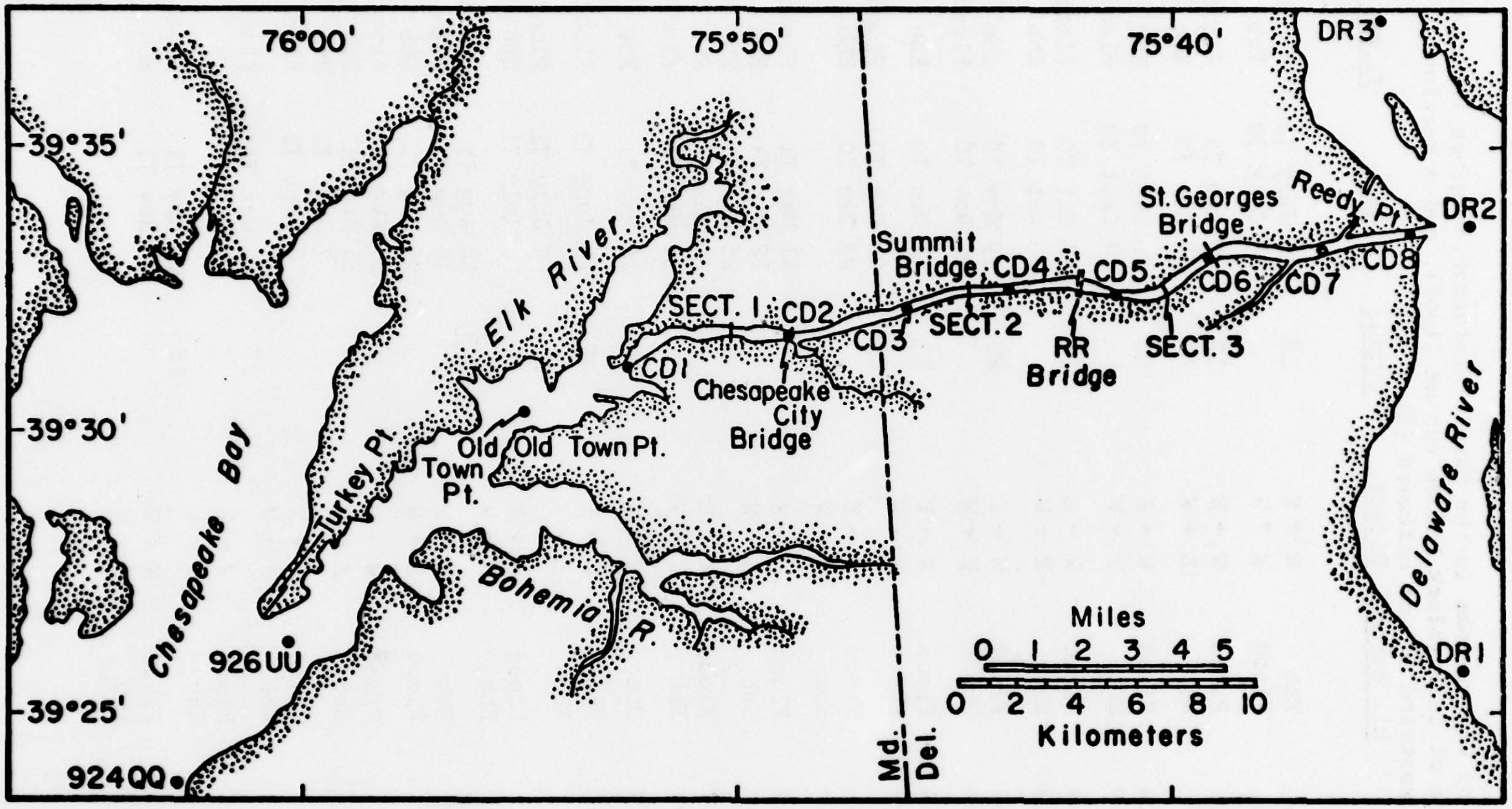


Fig. 1 Chart of C & D Canal showing location of temperature-salinity stations and current meter sections.

Table 1. Summary of CBI cruises in the Canal. Information given includes cruise number, date, stage of tide (slack before ebb or flood), and direction of flow in the Canal, either westward (W) or eastward (E).

| Cruise | Date | Sl. Before | Direct. |
|---|---|---|---|
| 1 | 13 May 69 | Ebb | W → E |
| | 14 May 69 | Flood | E → W |
| 2 | 26 May 69 | Flood | W → E |
| | 27 May 69 | Ebb | E → W |
| 3 | 10 June 69 | Flood | W → E |
| | 11 June 69 | Ebb | E → W |
| 4 | 30 June 69 | Flood | W → E |
| | 1 July 69 | Ebb | E → W |
| 5 | 15 July 69 | Flood | W → E |
| | 16 July 69 | Ebb | E → W |
| 6 | 28 July 69 | Flood | W → E |
| | 29 July 69 | Ebb | E → W |
| 7 | 26 Aug 69 | Flood | W → E |
| | 27 Aug 69 | Ebb | E → W |
| 8 | 8 Sept 69 | Flood | W → E |
| | 9 Sept 69 | Ebb | E → W |
| 9 | 23 Sept 69 | Flood | W → E |
| | 24 Sept 69 | Ebb | E → W |
| 10 | 9 Sept 69 | Ebb | E → W |
| 11 | 4 Nov 69 | Flood | W → E |
| | 5 Nov 69 | Ebb | E → W |
| 12 | 3 Dec 69 | Flood | W → E |
| | 4 Dec 69 | Ebb | E → W |
| 13 | 24 Feb 70 | Ebb | W → E |
| | 25 Feb 70 | Flood | E → W |
| 14 | 18 Mar 70 | Flood | W → E |
| | 19 Mar 70 | Ebb | E → W |
| 15 | 16 Apr 70 | Flood | W → E |
| | 17 Apr 70 | Ebb | E → W |
| 16 | 18 May 70 | Flood | W → E |
| | 19 May 70 | Ebb | E → W |
| 17 | 18 June 70 | Flood | W → E |
| | 19 June 70 | Ebb | E → W |
| 18 | 16 July 70 | Flood | W → E |
| | 17 July 70 | Ebb | E → W |
| 19 | 13 Aug 70 | Flood | W → E |
| | 14 Aug 70 | Ebb | E → W |
| 20 | 16 Sept 70 | Ebb | W → E |
| | 17 Sept 70 | Flood | E → W |
| 21 | 12 Oct 70 | Flood | W → E |
| | 13 Oct 70 | Ebb | E → W |
| 22 | 19 Nov 70 | Ebb | W → E |
| | 21 Nov 70 | Flood | E → W |
| 23 | 1 Dec 70 | Ebb | W → E |
| 23A | 22 Dec 70 | Flood | W → E |
| | 23 Dec 70 | Ebb | E → W |
| A | 11 Mar 71 | Flood | W → E |
| | 12 Mar 71 | Ebb | E → W |
| | 25 Mar 71 | Ebb | E → W |
| | 30 Mar 71 | Ebb | W → E |
| | 31 Mar 71 | Flood | E → W |
| 24 | 26 May 71 | Ebb | W → E |
| 25 | 14 June 71 | Flood | W → E |
| 26 | 7 July 71 | Flood | W → E |
| | 8 July 71 | Ebb | E → W |
| B | 18 Aug 71 | Flood | W → E |
| | 19 Aug 71 | Ebb | E → W |
| | 26 Aug 71 | Ebb | E → W |
| | 27 Aug 71 | Flood | W → E |
| | 31 Aug 71 | Ebb | E → W |
| | 7 Sept 71 | Ebb | E → W |
| | 8 Sept 71 | Flood | W → E |
| 27 | 19 Oct 71 | Flood | W → E |
| | 20 Oct 71 | Ebb | E → W |
| 28 | 16 Nov 71 | Flood | W → E |
| | 17 Nov 71 | Ebb | E → W |

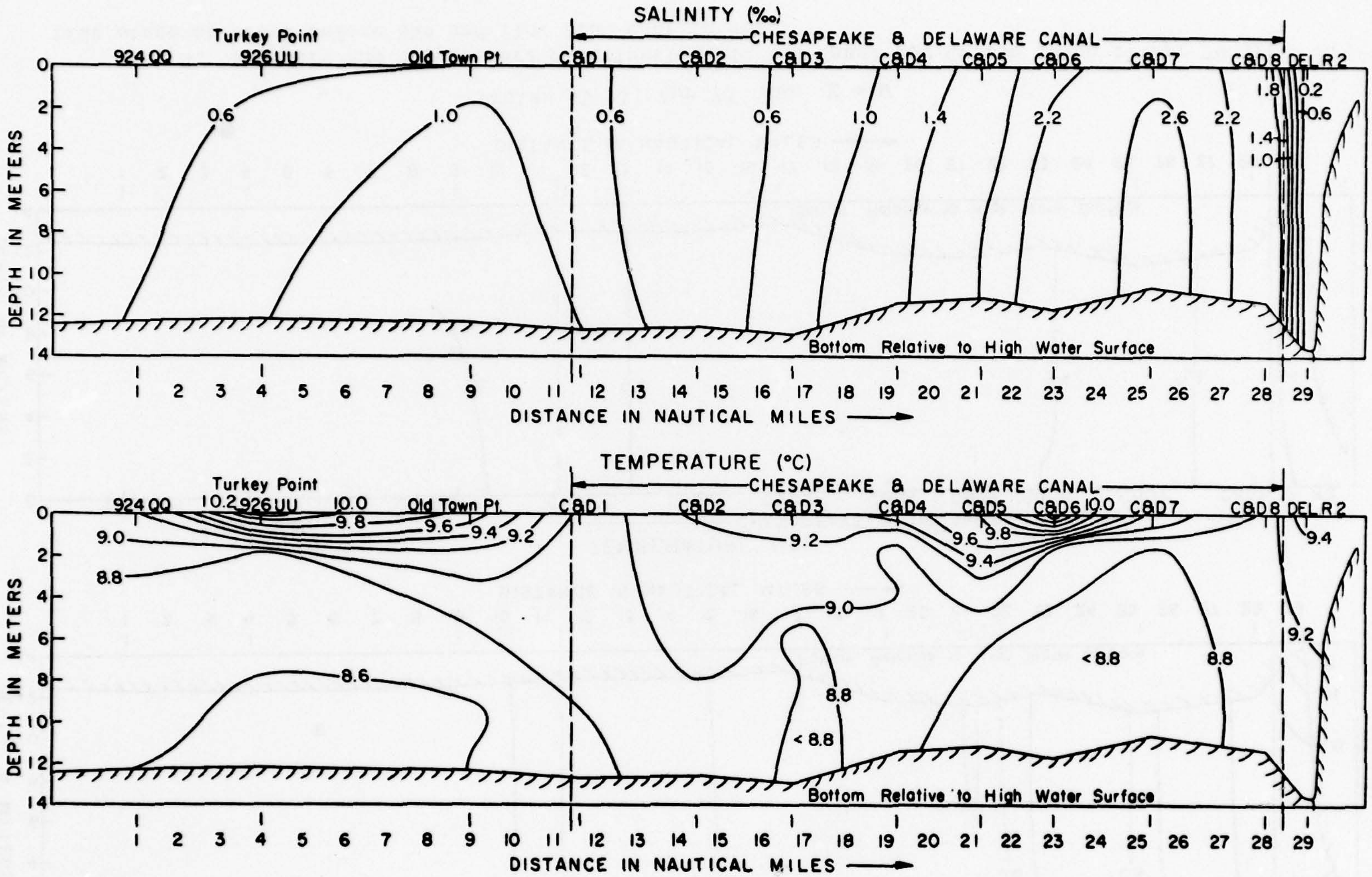
Table 1. *(continued)*

| Cruise | Date | Sl. Before | Direct. |
|---|---|---|---|
| 29 | 14 Dec 71 | Flood | W → E |
| | 15 Dec 71 | Ebb | E → W |
| 30 | 27 Jan 72 | Flood | W → E |
| | 27 Jan 72 | Ebb | E → W |
| 31 | 28 Feb 72 | Flood | W → E |
| | 29 Feb 72 | Ebb | E → W |
| 32 | 28 Mar 72 | Flood | W → E |
| | 29 Mar 72 | Ebb | E → W |
| CDC | 17 Apr 72 | Ebb | E → W |
| | 18 Apr 72 | Flood | W → E |
| | 25 Apr 72 | Flood | W → E |
| | 27 Apr 72 | Ebb | E → W |
| 33 | 31 May 72 | Ebb | W → E |
| | 1 June 72 | Flood | E → W |
| 34 | 11 July 72 | Flood | W → E |
| | 12 July 72 | Ebb | E → W |
| 35 | 8 Aug 72 | Flood | W → E |
| | 9 Aug 72 | Ebb | E → W |
| 36 | 18 Sept 72 | Flood | W → E |
| | 19 Sept 72 | Ebb | E → W |
| 37 | 2 Nov 72 | Flood | W → E |
| | 2 Nov 72 | Ebb | E → W |
| 38 | 5 Dec 72 | Flood | W → E |
| | 6 Dec 72 | Ebb | E → W |
| 39 | 17 Jan 73 | Flood | W → E |
| | 18 Jan 73 | Ebb | E → W |
| 40 | 14 Feb 73 | Flood | W → E |
| | 14 Feb 73 | Ebb | E → W |

junction with the Canal is normally 2 o/oo to 3 o/oo greater than that in the Chesapeake Bay at Turkey Point. If the tidal and nontidal flow conditions in the Canal were uniform over large time periods, the salinity distribution in the Canal would show a gradient from the Chesapeake Bay value at Turkey Point to the Delaware value at Reedy Point. In fact, there are large, short-term fluctuations in the currents which are reflected in the salinity data.

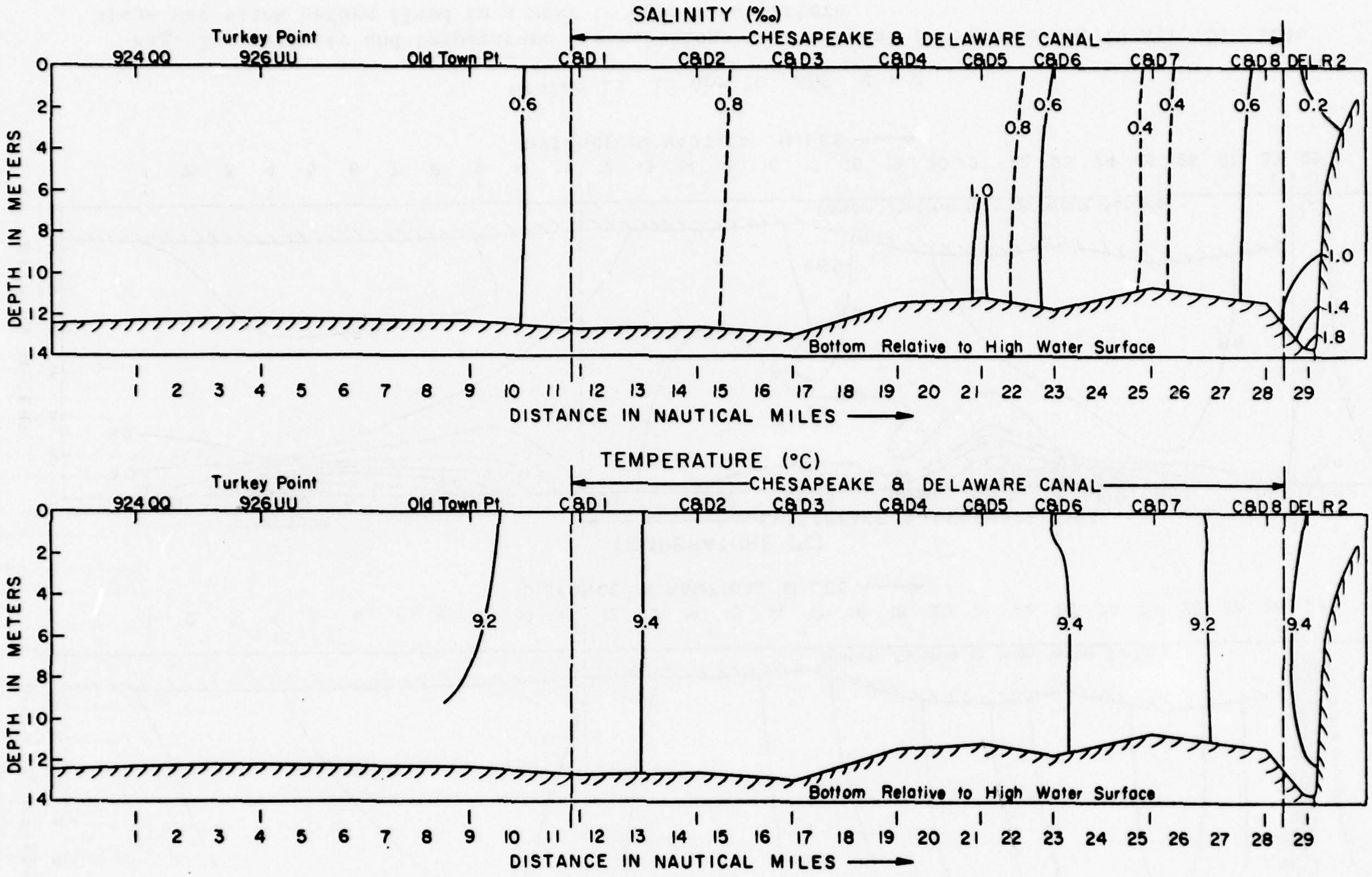
Examination of the sections will show that in general there is an increase in salinity from west to east in the Canal. An example of a large, short-term change in conditions is given in Figs. 2 and 3. On 16 April 1970, the salinity increased from about 0.6 in the western end to 2.6 o/oo near the eastern end. The maximum at C and D 7 is the result of the relation between the tide phases in the Canal and the Delaware River. This feature will be discussed further below. On the 17th of April, the salt water had been swept out of the Canal, indicating an unusually strong flood between the two sections. It is also interesting to note the change in the temperature sections. The rather large vertical temperature gradients of the 16th are replaced by nearly uniform conditions on the 17th. Since the large gradients of the 16th extended all the way to Turkey Point, it is likely that uniform temperature water was not carried into the Canal. Apparently the large currents mixed the water in the Canal, eliminating the temperature gradients.

The maximum noted above near C and D 7 is seen fairly often on sections made at slack before flood. Under normal conditions the westward flow into the Canal at Reedy Point begins about 3 hours



Cruise 15 16 Apr 70 SBF W → E

Fig. 2. Salinity and temperature distributions in the Canal for Cruise 15, 16 Apr 70. Tide stage was slack before flood in a west to east flow pattern.


SALINITY (‰)

TEMPERATURE (°C)

Cruise 15 17 Apr 70 SBE E → W

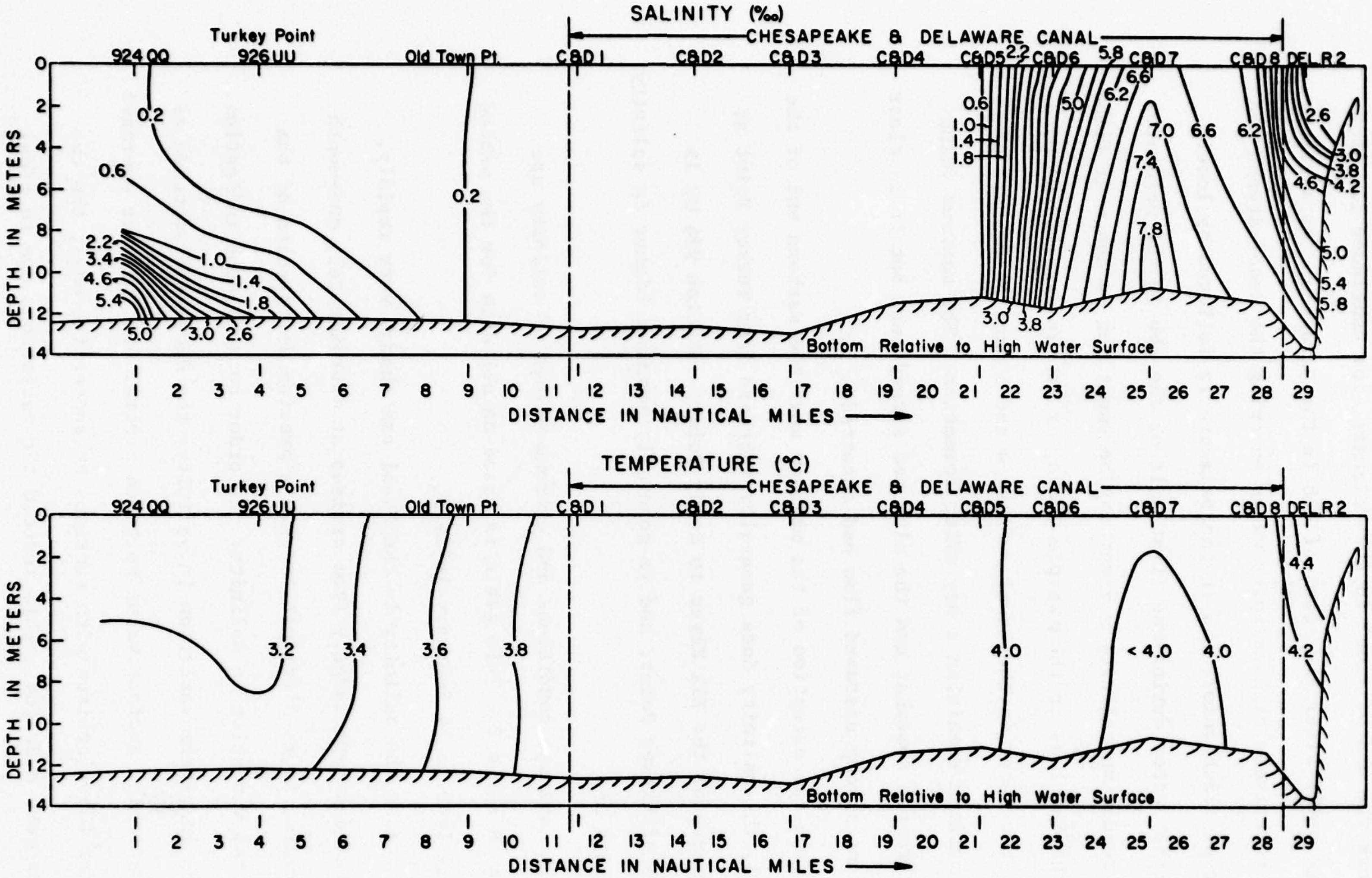
Fig. 3. Salinity and temperature distributions in the Canal for Cruise 15 on 17 Apr 70 with tide stage at slack before ebb and flow from east to west.

before the end of flood in the Delaware, and continues for about three hours after the start of ebb in the Delaware. As a result, the relatively high salinity water entering the Canal around the time of slack before ebb in the Delaware is followed by lower salinity water during the first half of the ebb in the Delaware. The resulting salinity maximum may be swept out on the next flood in the Canal as in the example above, or it may persist and move with the water in the Canal. Figs. 4 and 5 show an example of the maximum remaining a day after formation. The maximum value had dropped somewhat and the slug had spread out, but it is clear that no strong eastward flow had occurred.

With the exception of the maximum near the eastern end of the Canal, the salinity does generally increase from Turkey Point at the mouth of the Elk River to Reedy Point. Station 924 QQ is south of Turkey Point, and is generally somewhat higher in salinity than 926 UU.

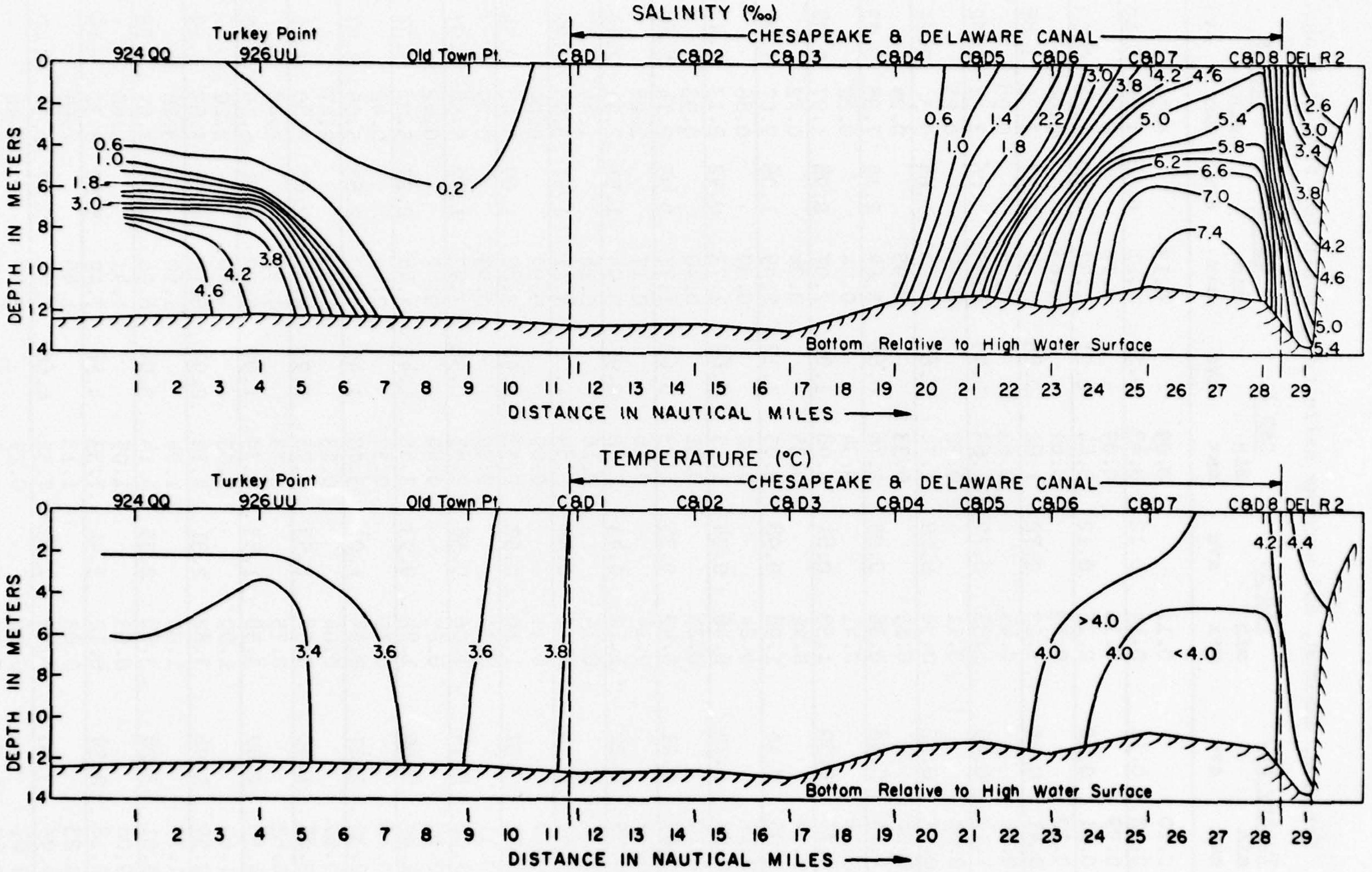
The average conditions and extreme values of salinity are shown in Table 2. This table is based on all data for the period 13 May 1969 to 14 February 14 1973.

Because the salinity in the Canal can change very rapidly, and the data are largely from cruises at approximately one-month intervals, it is difficult to give a precise description of the temporal variation in salinity. In order to give some indication of the long-term variation in salinity, the data were smoothed as follows: the surface value at three central stations was averaged and for those cruises with sections on successive days, the two values were averaged. This reduced the variations due to tidal motions. Figure 6 is a plot of the result. While the smoothed



Cruise 14 18 Mar 70 SBF W → E

Fig. 4. Salinity and temperature distributions in the Canal for Cruise 14 on 18 Mar 70 at tide stage of slack before flood in a west to east flow.



Cruise 14 19 Mar 70 SBE E → W

Fig. 5. Salinity and temperature distributions in the Canal for Cruise 14 on 19 Mar 70 at tide stage of slack before ebb and flow of east to west.

Table 2 Minimum, maximum, and average salinity by month for five stations.

| | | Turkey Pt. | | C&D 1. | | C&D 4. | | C&D 6. | | C&D 8. | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | min max | ave | min max | ave | min max | ave | min max | ave | min max | ave |
| Jan | top | 0.10 | | 0.11 | | 0.09 | | 0.13 | | 0.14 | |
| | | 0.12 | 0.11 | 0.14 | 0.12 | 0.43 | 0.20 | 1.21 | 0.56 | 1.66 | 0.68 |
| | bot | 0.09 | | 0.10 | | 0.09 | | 0.15 | | 0.29 | |
| | | 0.11 | 0.10 | 0.15 | 0.12 | 0.44 | 0.21 | 1.37 | 0.60 | 1.68 | 0.73 |
| Feb | top | 0.13 | | 0.43 | | 0.61 | | 0.65 | | 0.84 | |
| | | 0.41 | 0.25 | 1.23 | 0.72 | 1.62 | 0.88 | 2.24 | 1.17 | 3.33 | 1.86 |
| | bot | 0.13 | | 0.44 | | 0.63 | | 0.65 | | 0.98 | |
| | | 1.13 | 0.49 | 1.33 | 0.72 | 1.63 | 0.90 | 2.55 | 1.26 | 3.31 | 1.92 |
| Mar | top | 0.08 | | 0.11 | | 0.32 | | 0.89 | | 0.25 | |
| | | 0.17 | 0.12 | 0.34 | 0.22 | 1.74 | 0.65 | 4.03 | 1.64 | 5.32 | 2.22 |
| | bot | 0.08 | | 0.15 | | 0.33 | | 0.95 | | 0.24 | |
| | | 4.14 | 0.98 | 0.36 | 0.25 | 1.76 | 0.66 | 5.64 | 2.19 | 7.35 | 2.73 |
| Apr | top | 0.11 | | 0.41 | | 0.34 | | 0.24 | | 0.22 | |
| | | 0.75 | 0.39 | 1.33 | 0.81 | 1.98 | 1.07 | 2.07 | 0.98 | 1.97 | 0.98 |
| | bot | 0.14 | | 0.42 | | 0.35 | | 0.24 | | 0.22 | |
| | | 0.95 | 0.46 | 1.98 | 0.98 | 2.05 | 1.12 | 2.49 | 1.06 | 2.07 | 1.01 |
| May | top | 0.11 | | 0.24 | | 0.32 | | 0.39 | | 0.86 | |
| | | 0.26 | 0.15 | 0.46 | 0.34 | 1.15 | 0.65 | 1.73 | 0.92 | 2.13 | 1.43 |
| | bot | 0.10 | | 0.25 | | 0.31 | | 0.40 | | 0.93 | |
| | | 0.65 | 0.21 | 0.49 | 0.35 | 1.23 | 0.67 | 1.77 | 0.95 | 2.14 | 1.60 |
| Jun | top | 0.12 | | 0.14 | | 0.16 | | 0.17 | | 1.22 | |
| | | 0.55 | 0.22 | 1.12 | 0.43 | 2.82 | 0.97 | 3.94 | 1.51 | 2.91 | 2.14 |
| | bot | 0.11 | | 0.14 | | 0.16 | | 0.24 | | 1.44 | |
| | | 0.59 | 0.24 | 1.15 | 0.44 | 2.89 | 1.01 | 4.11 | 1.57 | 3.05 | 2.22 |
| Jul | top | 0.10 | | 0.11 | | 0.09 | | 0.09 | | 0.09 | |
| | | 0.71 | 0.37 | 1.10 | 0.57 | 2.52 | 0.95 | 3.80 | 1.69 | 5.48 | 2.54 |
| | bot | 0.11 | | 0.11 | | 0.09 | | 0.09 | | 0.09 | |
| | | 2.02 | 0.74 | 1.06 | 0.56 | 2.65 | 0.98 | 3.93 | 1.82 | 5.58 | 2.97 |
| Aug | top | 0.15 | | 0.63 | | 0.49 | | 0.47 | | 0.42 | |
| | | 1.89 | 0.69 | 1.82 | 0.93 | 3.65 | 1.43 | 4.48 | 2.29 | 5.04 | 3.27 |
| | bot | 0.16 | | 0.71 | | 0.50 | | 0.48 | | 0.42 | |
| | | 2.30 | 1.27 | 2.24 | 1.01 | 3.70 | 1.49 | 5.13 | 2.63 | 5.05 | 3.37 |
| Sep | top | 0.61 | | 0.64 | | 0.75 | | 1.05 | | 2.47 | |
| | | 3.05 | 1.40 | 3.58 | 1.53 | 4.75 | 1.93 | 4.37 | 2.67 | 5.80 | 4.16 |
| | bot | 0.63 | | 0.75 | | 0.75 | | 1.23 | | 2.48 | |
| | | 4.56 | 2.02 | 3.58 | 1.53 | 4.79 | 1.97 | 5.39 | 3.01 | 6.15 | 4.53 |
| Oct | top | 1.63 | | 1.00 | | 1.03 | | 1.40 | | 3.20 | |
| | | 2.59 | 1.96 | 3.82 | 2.31 | 4.10 | 2.94 | 6.72 | 4.08 | 7.63 | 5.19 |
| | bot | 1.75 | | 1.01 | | 1.04 | | 1.60 | | 3.16 | |
| | | 5.01 | 3.28 | 3.88 | 2.35 | 4.14 | 3.04 | 6.96 | 4.28 | 7.67 | 5.53 |
| Nov | top | 0.08 | | 0.63 | | 1.05 | | 1.41 | | 1.60 | |
| | | 6.18 | 2.39 | 6.12 | 3.41 | 7.33 | 4.58 | 7.49 | 5.22 | 8.31 | 5.46 |
| | bot | 0.23 | | 0.83 | | 1.13 | | 1.48 | | 1.63 | |
| | | 9.95 | 3.80 | 8.30 | 4.40 | 7.32 | 4.66 | 7.76 | 5.47 | 8.34 | 5.49 |
| Dec | top | 0.07 | | 0.36 | | 0.29 | | 0.58 | | 0.46 | |
| | | 0.49 | 0.24 | 2.58 | 1.11 | 3.38 | 1.33 | 5.47 | 1.83 | 7.79 | 2.17 |
| | bot | 0.07 | | 0.36 | | 0.31 | | 0.59 | | 0.49 | |
| | | 3.06 | 1.01 | 1.85 | 0.84 | 3.71 | 1.37 | 5.89 | 1.93 | 8.45 | 2.33 |

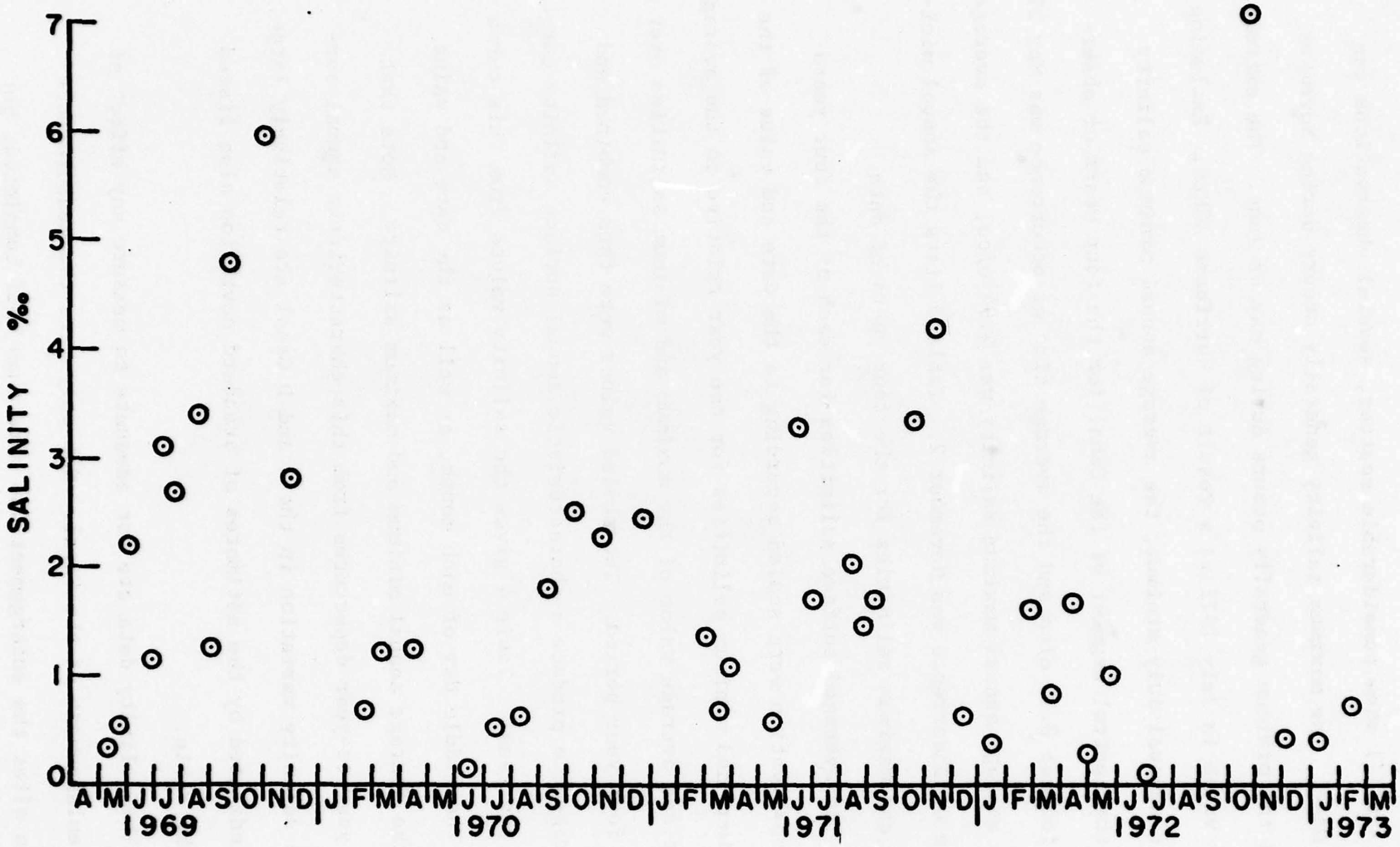


Fig. 6. Surface salinity for central region of Canal, smoothed as described in text.

data still show considerable scatter, several observations can be made. The maximum salinity generally occurs during November and the minimum generally occurs during May or June. The extremely low value in July 1972 is a result of Hurricane AGNES. Excluding this unusual July minimum, the average annual minimum salinity in the central segment of the Canal for the four years of observation was 0.34 o/oo and the average time of occurrence was May 21. The average annual maximum salinity was 4.94 o/oo, and the average time of occurrence was November 2. Table 3 lists the annual minimum and maximum salinities for the four years of data.

The averaged surface salinities for each of the four years of observation were scaled according to the date and value of the maximum and minimum salinities for the year relative to the average time and average value of the maximum and minimum salinities over the four year period. The scaled values were then combined and averaged to produce a characteristic annual surface salinity curve for the Canal. Table 4 gives the salinity values from this curve for the middle day of each month, as well as the date and value of the average annual minimum and maximum salinity. Note that the year-to-year departures from this characteristic annual surface salinity variation in the C and D Canal are relatively large, as indicated by the estimates of standard deviation also listed in the Table.

The salinity data are not adequate to measure any effect of the enlargement of the Canal. Not only were the measurements begun after the enlargement was more than half completed, but three years of data with such large scatter are not sufficient to establish a long-term trend. However, consideration of the

Table 3. Annual minimum and maximum salinities in the Canal for four years.

| Year | Min. Sal (‰) | Date | Max.Sal. (‰) | Date |
|---|---|---|---|---|
| 1969 | 0.33 | May 15 | 5.97 | Nov 6 |
| 1970 | 0.18 | Jun 16 | 2.50 | Oct 12 |
| 1971 | 0.60 | May 20 | 4.20 | Nov 18 |
| 1972 | 0.26<br>(0.08) | May 1<br>(July 6) | 7.10 | Nov 1 |

Table 4. Characteristic annual surface salinity variation and estimated year-to-year standard deviations ( SD ) in the Canal. The SD for the date of the maximum and minimum salinities, and hence in the time sequence of this characteristic annual variation in surface salinity in the Canal, is about ± 25 days.

| Date | Salinity ‰ | SD ‰ | Date | Salinity ‰ | SD ‰ |
|---|---|---|---|---|---|
| 15 Jan | 1.21 | ± 0.70 | 15 Jul | 1.72 | ± 0.83 |
| 14 Feb | 1.21 | ± 0.70 | 15 Aug | 2.26 | ± 0.94 |
| 15 Mar | 1.20 | ± 0.70 | 15 Sept | 2.81 | ± 1.06 |
| 15 Apr | 0.73 | ± 0.46 | 15 Oct | 3.80 | ± 1.28 |
| 15 May | 0.40 | ± 0.29 | 15 Nov | 5.21 | ± 1.59 |
| 21 May | 0.37 | ± 0.27 | 17 Nov | 5.24 | ± 1.60 |
| 15 Jun | 0.80 | ± 0.49 | 15 Dec | 1.40 | ± 0.74 |

factors affecting the salinity sheds some light on the effects of enlargement. The increased flow through the Canal as a result of enlargement will tend to lower the salinity in the Delaware, and to increase the salinity in the upper Chesapeake Bay. These changes will be small compared to the natural year-to-year variation. A detailed analysis of the changes in the salinity distribution in the upper Chesapeake Bay awaits the completion and verification of the real-time model of net flow through the Canal. Since the salinity in the Canal is determined by the salinity in the adjacent areas of the Chesapeake and Delaware, the extremes and general features of the salinity distribution in the Canal will not be much affected by the enlargement. The most noticeable effect will probably be to increase the short-term fluctuations in salinity since the increased velocities will more quickly transport water from either the Delaware or Chesapeake through the Canal. During the spring period of high flow from the Susquehanna River, the Canal is essentially fresh in the western portions, and the increased flow due to enlargement will tend to shift the region of fresh water further to the east.

### 2. Flows and transports within the Canal

a. Time and spatial variations in instantaneous flows. The most obvious and consistent feature of the currents in the Canal is their large variability over a wide range of time scales. Figure 7 shows the measured transports in the Canal for the three study periods. The dotted line represents the instantaneous transport and the solid line the cumulative

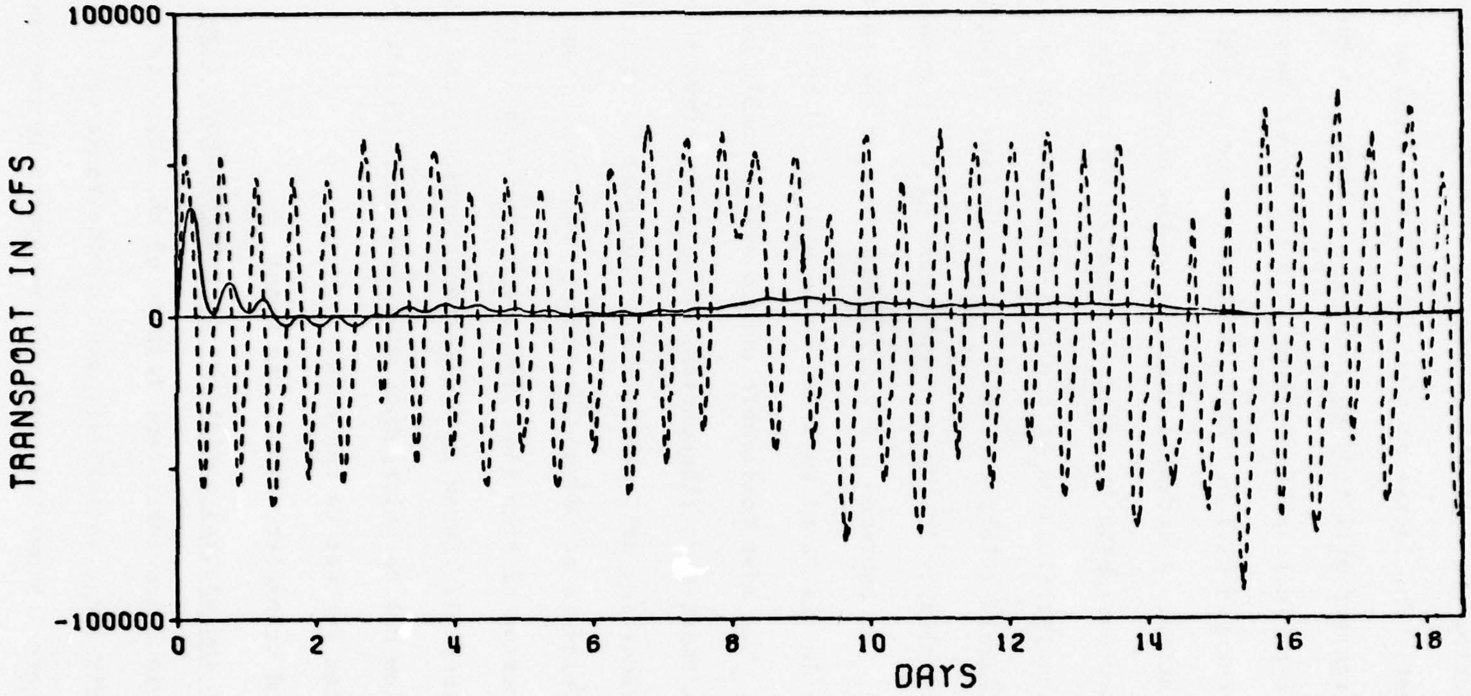


Fig. 7a. Transport

--------- Instantaneous transport

_________ Cumulative average

Based on measurements 1 mile west of Chesapeake City

Begins 1600 12 Mar 71

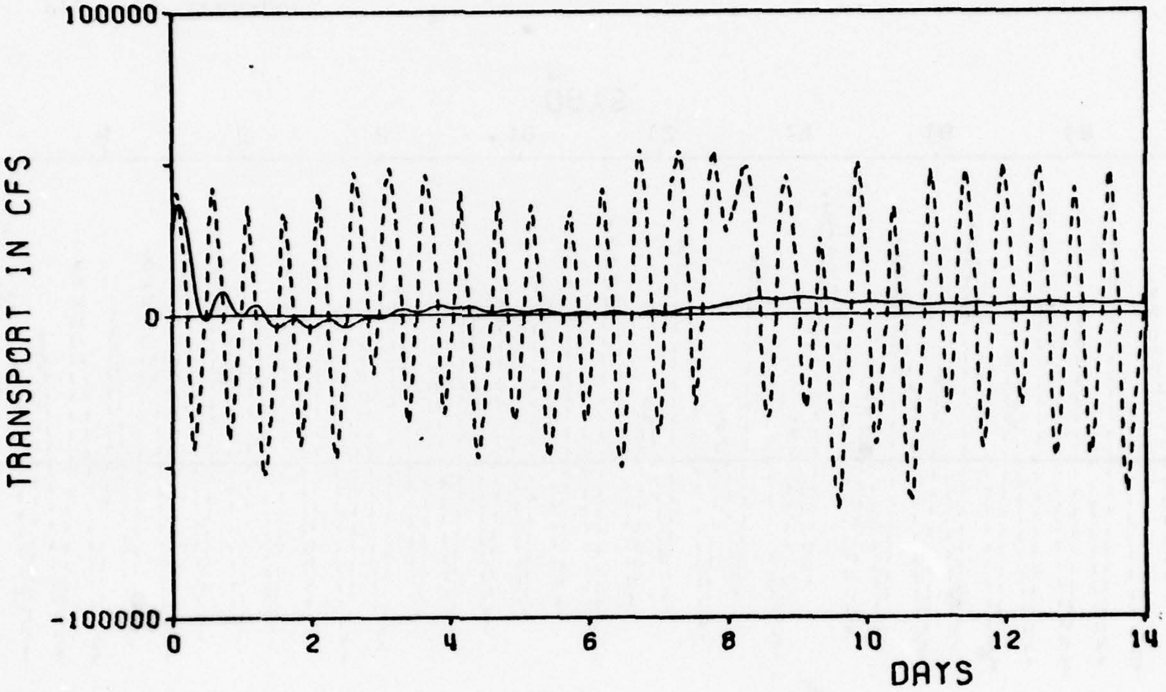


Fig. 7b. Transport

--------- Instantaneous transport

_________ Cumulative average

Based on measurements at Lorewood Grove

Begins 1730 12 Mar 71

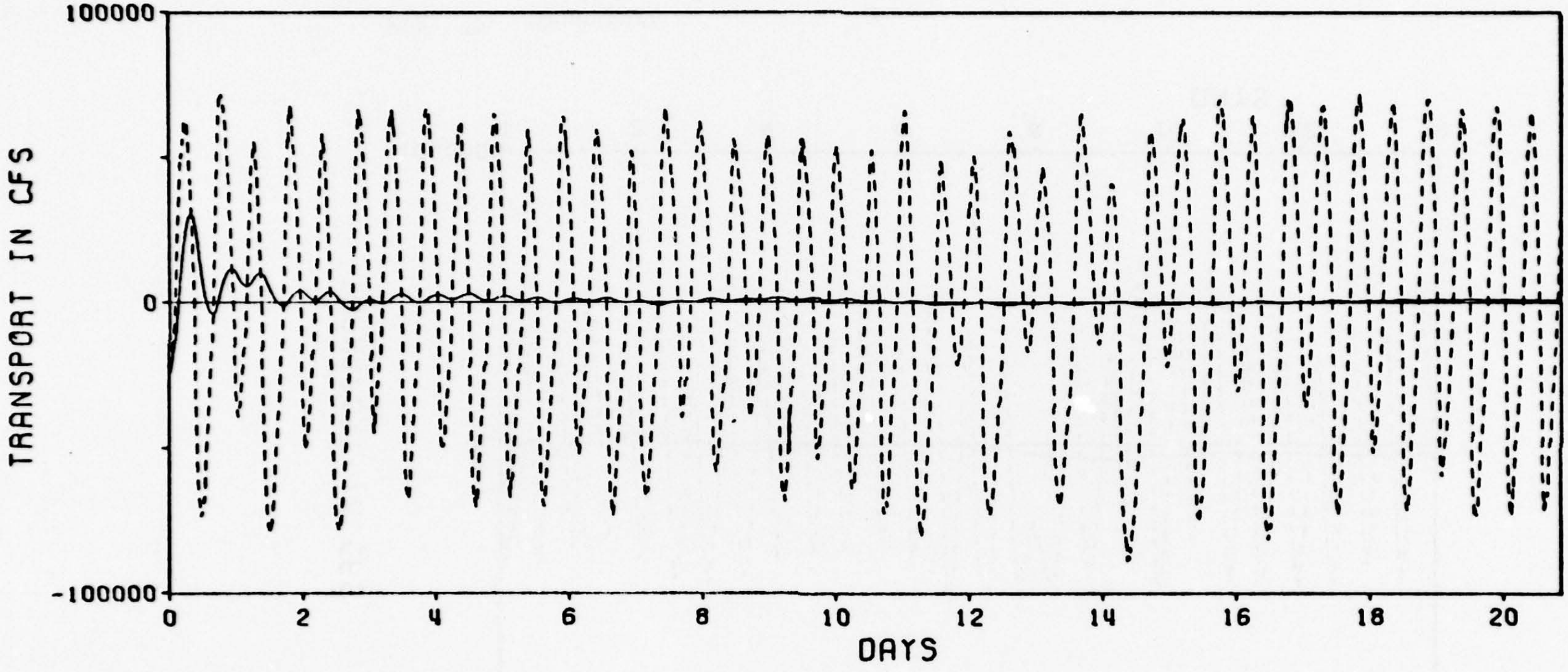


Fig. 7c. Transport
--------- Instantaneous transport
_________ Cumulative average
Based on measurements 1 mile west of Chesapeake City
Begins 1025 17 Aug 71

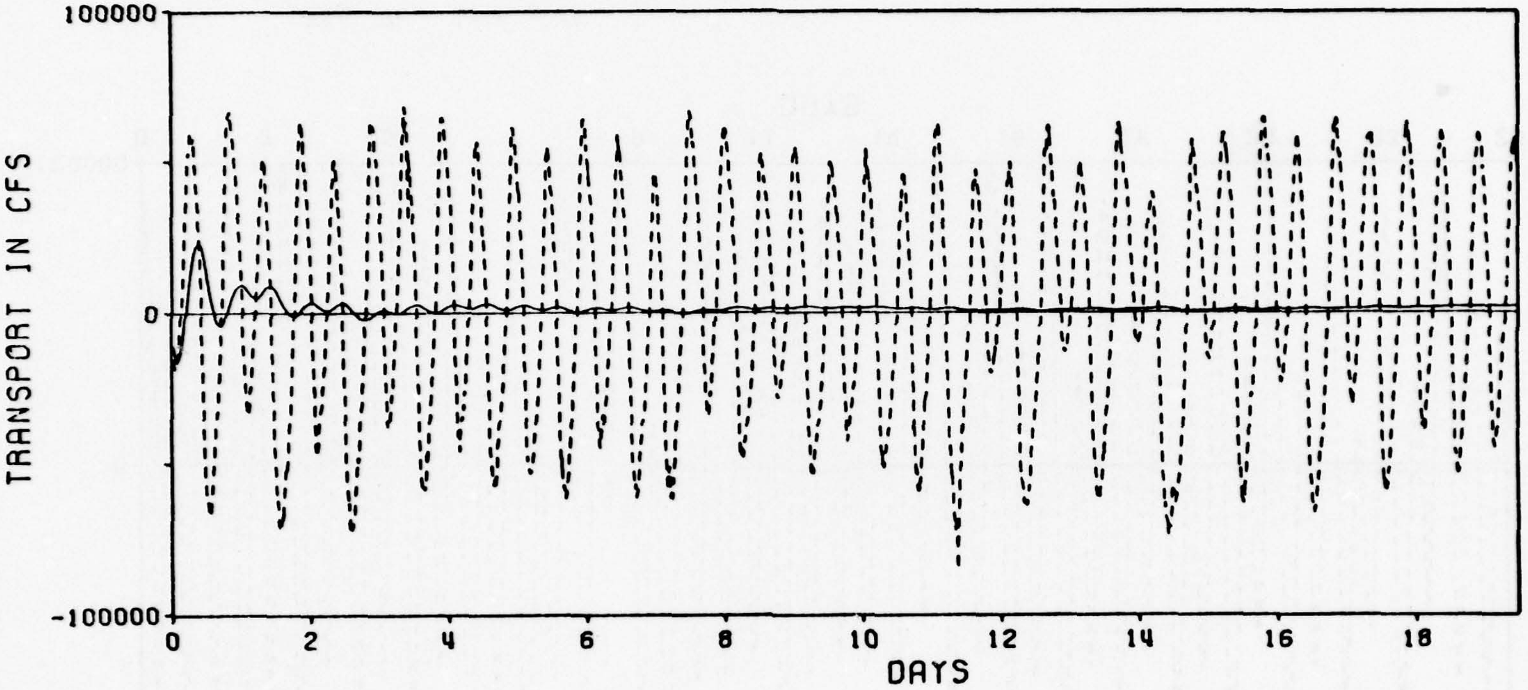


Fig. 7d. Transport
--------- Instantaneous transport
————— Cumulative average
Based on measurements at Summit Bridge
Begins 0900 17 Aug 71

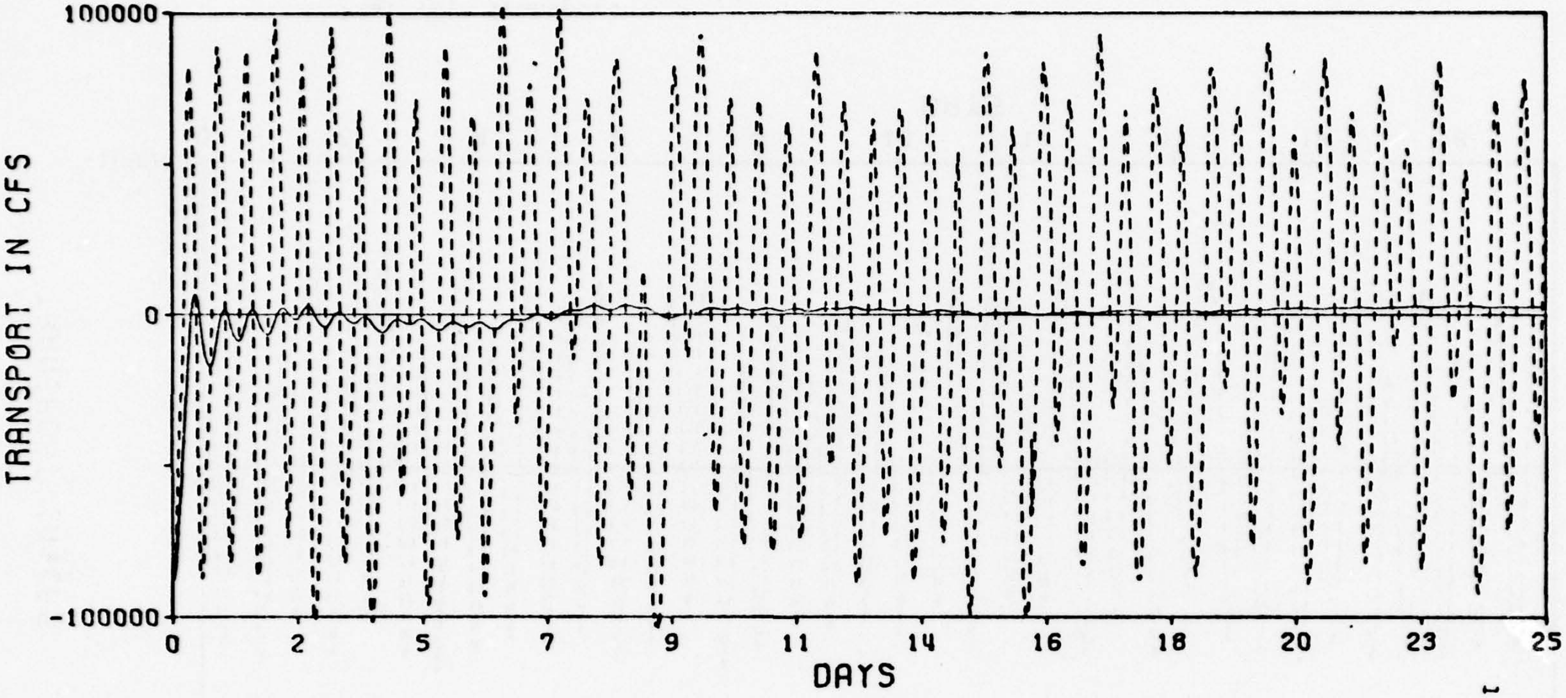


Fig. 7e. Transport

--------- Instantaneous transport

———— Cumulative average

Based on measurements 1 mile west of Chesapeake City

Begins 1100 12 Apr 72

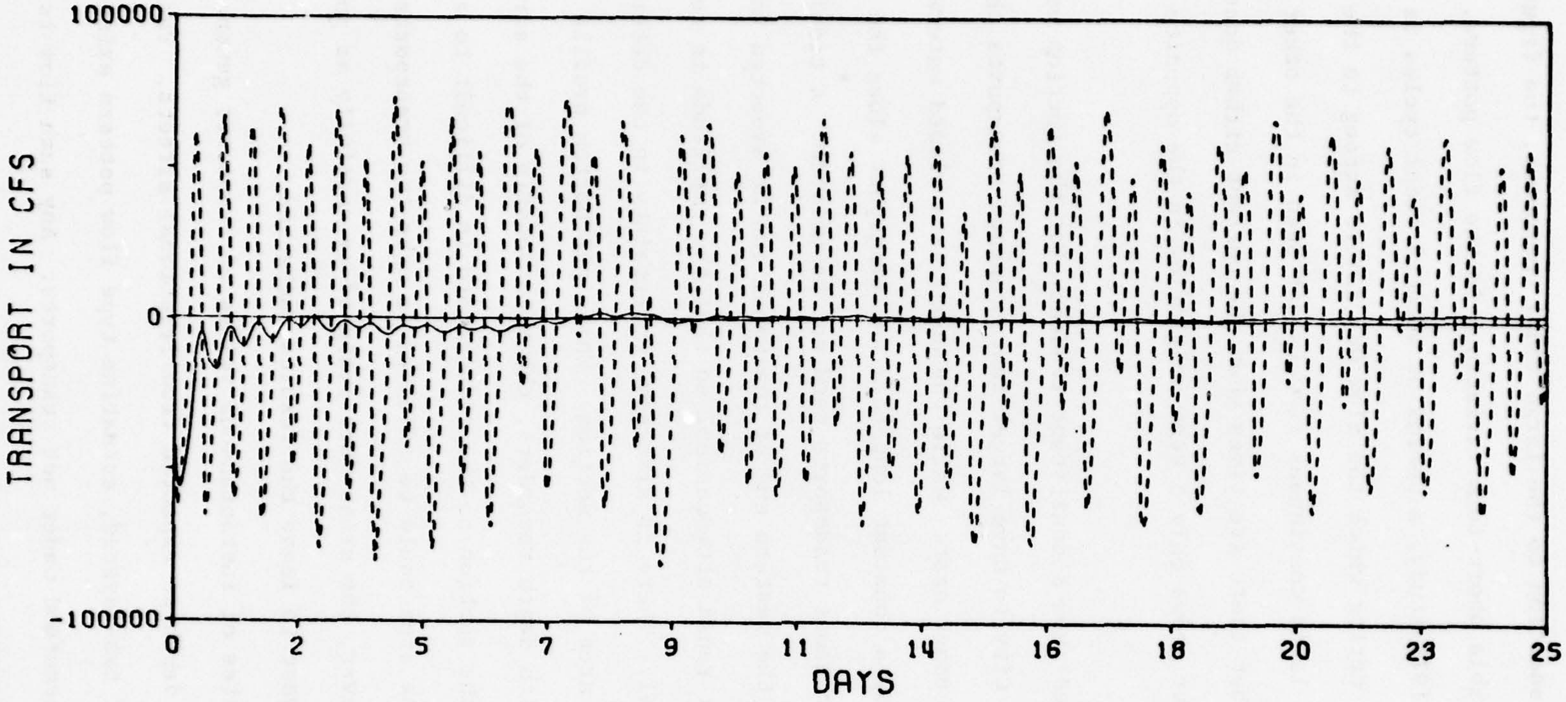


Fig. 7f. Transport
--------- Instantaneous transport
_________ Cumulative average
Based on measurements at Summit Bridge
Begins 0900 12 Apr 72

average. The large tidal component is obvious in all these figures. In addition to the large tidal component, the figures show considerable short-term variations in the flow pattern. In the March 1971 study, a period of about 2 tidal cycles is seen on day 8 during which the flow was always strong to the east. Such a large continuous flow is not seen in the other two studies, but there are times when the current either does not reverse, or shows only a very small flow in the opposite direction.

The figures show a consistent tendency for the section west of Chesapeake City to have larger instantaneous transports than the section farther east. While the Canal is a closed waterway, and should show a constant long-term net transport along the Canal, instantaneous transports need not be uniform. A tidal wave entering the western end of the Canal can be expected to undergo rather rapid attenuation, so that the amplitude is reduced along the Canal. There is also some uncertainty in the determination of the area of the section. While the bottom profile can be measured with depth recorders, the relationship of the surface elevation at the section to the tide record is difficult to assign precisely. The area could be adjusted to make the transports uniform. However, the areas were assigned as carefully as possible, and it seems best to leave the results unchanged.

The estimates of instantaneous values of transport generally decrease with depth as expected from frictional effects. The possibility of two-layered, estuarine type flow pattern exists, and will be discussed under net transports. Any such flow is not apparent in instantaneous values.

b. Tidal flows. As previously mentioned, a large tidal component is the dominant flow characteristic, although it is often modified by meteorological effects. The maximum flow ranges from about 80,000 cfs to about 100,000 cfs. The larger figure was only observed for the section near Chesapeake City during the spring 1972 study. The maximum surface velocities observed were about 4.8 ft/sec (2.8 knots). This is an extreme figure, and a more normal maximum surface value is about 3.7 ft/sec. The velocities obviously decrease with depth, and the maximum velocity at the bottom is usually about 3.0 ft/sec.

c. Net non-tidal flows.

(1) Variations from tidal cycle to tidal cycle.

Tables 5a through 5f list the net transport for each cycle as well as a cumulative average transport to the end of each cycle for each section, for each of the three study periods. The length of the tidal cycles are based on the predicted times of slack water, since the actual slack water times are considerably affected by meteorological conditions. The large short-term variability is very evident in these tables. While the long-term net transports are consistently eastward, shorter periods show transports in either direction. Also, while the long-term net transports are generally between 1,000 and 3,000 cfs, the short-term values can be much larger. The maximum observed single cycle net transport eastward was 42,000 cfs. Values over 20,000 cfs are quite common. The maximum westward net transport was about 30,000

Table 5a. Average transport over predicted tidal cycles and cumulative average to end of each cycle. Positive values are eastward, negative values westward. Based on measurements 1 mile west of Chesapeake City. First cycle begins 1600 12 Mar 71.

| Cycle | Duration (hrs) | Cycle Av. (cfs) | Cumulative Av. (cfs) |
|---|---|---|---|
| 1 | 12.8 | 964. | 964. |
| 2 | 12.4 | 1781. | 1364. |
| 3 | 12.1 | -11824. | -2934. |
| 4 | 12.2 | -3369. | -3041. |
| 5 | 12.3 | -3427. | -3118. |
| 6 | 12.0 | 17500. | 233. |
| 7 | 12.6 | 10529. | 1724. |
| 8 | 11.7 | 10498. | 2782. |
| 9 | 12.9 | -8356. | 1494. |
| 10 | 11.7 | -528. | 1302. |
| 11 | 13.1 | -7219. | 476. |
| 12 | 11.5 | 788. | 500. |
| 13 | 13.5 | -582. | 409. |
| 14 | 11.3 | 12648. | 1215. |
| 15 | 13.7 | 18416. | 2480. |
| 16 | 11.3 | 38423. | 4546. |
| 17 | 13.9 | 11343. | 4992. |
| 18 | 11.4 | 11177. | 5307. |
| 19 | 13.7 | -22438. | 3682. |
| 20 | 11.7 | 4422. | 3717. |
| 21 | 13.4 | -16526. | 2683. |
| 22 | 12.0 | 9614. | 2988. |
| 23 | 12.9 | 4210. | 3043. |
| 24 | 12.2 | 11999. | 3408. |
| 25 | 12.7 | 3210. | 3400. |
| 26 | 12.3 | -2505. | 3175. |
| 27 | 12.5 | -9063. | 2719. |
| 28 | 12.4 | -23319. | 1797. |
| 29 | 12.4 | -21925. | 975. |
| 30 | 12.5 | -30132. | -67. |
| 31 | 12.2 | 766. | -41. |
| 32 | 12.7 | -11429. | -403. |
| 33 | 12.0 | 17178. | 111. |
| 34 | 12.9 | 1007. | 139. |
| 35 | 11.9 | 22157. | 746. |
| 36 | 13.0 | -13876. | 322. |

Table 5b. Average transport over predicted tidal cycles and cumulative average to end of each cycle. Positive values are eastward, negative values westward. Based on measurements at Lorewood Grove. First cycle begins 1730 12 Mar 71.

| Cycle | Duration (hrs) | Cycle Av. (cfs) | Cumulative Av. (cfs) |
|---|---|---|---|
| 1 | 11.3 | -1528. | -1528. |
| 2 | 12.4 | 1382. | -12. |
| 3 | 12.1 | -11128. | -3786. |
| 4 | 12.2 | -4174. | -3884. |
| 5 | 12.3 | -3824. | -3872. |
| 6 | 12.0 | 14922. | -754. |
| 7 | 12.6 | 11028. | 982. |
| 8 | 11.7 | 10278. | 2120. |
| 9 | 12.9 | -7028. | 1048. |
| 10 | 11.7 | -372. | 911. |
| 11 | 13.1 | -5943. | 239. |
| 12 | 11.5 | -44. | 217. |
| 13 | 13.5 | -2031. | 27. |
| 14 | 11.3 | 11473. | 787. |
| 15 | 13.7 | 19462. | 2171. |
| 16 | 11.3 | 38453. | 4273. |
| 17 | 13.9 | 13119. | 4857. |
| 18 | 11.4 | 12405. | 5244. |
| 19 | 13.7 | -20265. | 3741. |
| 20 | 11.7 | 4868. | 3794. |
| 21 | 13.4 | -20358. | 2554. |
| 22 | 12.0 | 8201. | 2803. |
| 23 | 12.9 | 1685. | 2752. |
| 24 | 12.2 | 12289. | 3143. |
| 25 | 12.7 | 3757. | 3168. |
| 26 | 12.3 | -8143. | 2735. |
| 27 | 12.5 | -6990. | 2371. |
| 28 | 12.4 | -26191. | 1355. |

Table 5c. Average transport over predicted tidal cycles and cumulative average to end of each cycle. Positive values are eastward, negative values westward. Based on measurements 1 mile west of Chesapeake City. First cycle begins 1025 17 Aug 71.

| Cycle | Duration (hrs) | Cycle Av. (cfs) | Cumulative Av. (cfs) |
|---|---|---|---|
| 1 | 8.0 | 30416. | 30416. |
| 2 | 14.5 | 1341. | 11679. |
| 3 | 10.5 | 7084. | 10217. |
| 4 | 14.2 | -9548. | 4281. |
| 5 | 10.7 | 2265. | 3909. |
| 6 | 13.9 | -10291. | 1141. |
| 7 | 10.9 | 15217. | 2986. |
| 8 | 13.6 | 2118. | 2863. |
| 9 | 11.3 | 6330. | 3228. |
| 10 | 13.1 | -3108. | 2545. |
| 11 | 11.6 | -5250. | 1858. |
| 12 | 12.7 | -1796. | 1539. |
| 13 | 12.1 | 4305. | 1753. |
| 14 | 12.3 | -12742. | 711. |
| 15 | 12.4 | -924. | 599. |
| 16 | 12.0 | 14834. | 1480. |
| 17 | 12.8 | 150. | 1398. |
| 18 | 11.7 | 10666. | 1893. |
| 19 | 13.2 | -4880. | 1508. |
| 20 | 11.4 | 2521. | 1555. |
| 21 | 13.5 | -8337. | 1034. |
| 22 | 11.2 | -2416. | 888. |
| 23 | 13.8 | -16212. | 57. |
| 24 | 10.9 | 11025. | 470. |
| 25 | 14.3 | -8718. | 40. |
| 26 | 10.6 | 14510. | 520. |
| 27 | 14.5 | -4162. | 315. |
| 28 | 10.5 | 10248. | 620. |
| 29 | 14.5 | -21369. | -274. |
| 30 | 10.5 | 23059. | 393. |
| 31 | 14.3 | -135. | 373. |
| 32 | 10.8 | 16294. | 813. |
| 33 | 13.9 | -5875. | 585. |
| 34 | 11.2 | 17779. | 1045. |
| 35 | 13.4 | 2352. | 1086. |
| 36 | 11.7 | 11049. | 1349. |
| 37 | 12.9 | 3146. | 1399. |
| 38 | 12.1 | 5012. | 1493. |
| 39 | 12.5 | -1898. | 1405. |
| 40 | 12.6 | -2292. | 1310. |
| 41 | 12.0 | -5278. | 1153 |

Table 5d. Average transport over predicted tidal cycles and cumulative average to end of each cycle. Positive values are eastward, negative values westward. Based on measurements made at Summit Bridge. First cycle begins 0900 17 Aug 71.

| Cycle | Duration (hrs) | Cycle Av. (cfs) | Cumulative Av. (cfs) |
|---|---|---|---|
| 1 | 9.4 | 23001. | 23001. |
| 2 | 14.5 | 844. | 9521. |
| 3 | 10.5 | 7846. | 9009. |
| 4 | 14.2 | -8948. | 3720. |
| 5 | 10.7 | 2289. | 3463. |
| 6 | 13.9 | -8379. | 1224. |
| 7 | 1019 | 14731. | 2989. |
| 8 | 13.6 | 2726. | 2953. |
| 9 | 11.3 | 6401. | 3311. |
| 10 | 13.1 | -1378. | 2806. |
| 11 | 11.6 | -4706. | 2160. |
| 12 | 12.7 | -1316. | 1859. |
| 13 | 12.1 | 4591. | 2068. |
| 14 | 12.3 | -11581. | 1083. |
| 15 | 12.4 | 731. | 1059. |
| 16 | 12.0 | 15885. | 1971. |
| 17 | 12.8 | 529. | 1882. |
| 18 | 11.7 | 11517. | 2394. |
| 19 | 13.2 | -3232. | 2076. |
| 20 | 11.4 | 4537. | 2191. |
| 21 | 13.5 | -6706. | 1726. |
| 22 | 11.2 | 1419. | 1713. |
| 23 | 13.8 | -12726. | 1007. |
| 24 | 10.9 | 10742. | 1366. |
| 25 | 14.3 | -5089. | 1065. |
| 26 | 10.6 | 15467. | 1547. |
| 27 | 14.5 | -1392. | 1420. |
| 28 | 10.5 | 8896. | 1648. |
| 29 | 14.5 | -16720. | 904. |
| 30 | 10.5 | 23477. | 1547. |
| 31 | 14.3 | 1185. | 1534. |
| 32 | 10.8 | 15023. | 1905. |
| 33 | 13.9 | -3838. | 1708. |
| 34 | 11.2 | 17665. | 2133. |
| 35 | 13.4 | 2589. | 2147. |
| 36 | 11.7 | 10905. | 2378. |
| 37 | 12.9 | 4570. | 2440. |
| 38 | 12.1 | 5857. | 2527. |
| 39 | 12.5 | 421. | 2473. |

Table 5e. Average transport over predicted tidal cycles and cumulative average to end of each cycle. Positive values are eastward, negative values westward. Based on measurements 1 mile west of Chesapeake City. First cycle begins 1100 12 Apr 73.

| Cycle | Duration (hrs) | Cycle Av. (cfs) | Cumulative Av. (cfs) |
|---|---|---|---|
| 1 | 9.2 | 6580. | 6580. |
| 2 | 13.5 | -1441. | 1862. |
| 3 | 11.2 | 1257. | 1660. |
| 4 | 13.8 | 4698. | 2531. |
| 5 | 10.9 | 5524. | 3092. |
| 6 | 14.1 | -7362. | 1078. |
| 7 | 10.7 | -10424. | -394. |
| 8 | 14.3 | -7059. | -1372. |
| 9 | 10.5 | 1711. | -1069. |
| 10 | 14.4 | -10437. | -2163. |
| 11 | 10.5 | -2522. | -2191. |
| 12 | 14.7 | 6901. | -1288. |
| 13 | 10.5 | 23313. | 369. |
| 14 | 14.4 | 17528. | 1794. |
| 15 | 10.7 | 31447. | 3519. |
| 16 | 14.2 | 4149. | 3565. |
| 17 | 11.1 | -29836. | 1804. |
| 18 | 13.7 | -19846. | 473. |
| 19 | 11.6 | 42337. | 2560. |
| 20 | 13.2 | 3540. | 2613. |
| 21 | 12.1 | 1120. | 2544. |
| 22 | 12.5 | -6874. | 2117. |
| 23 | 12.6 | 10640. | 2496. |
| 24 | 11.9 | 13663. | 2948. |
| 25 | 13.0 | -14922. | 2197. |
| 26 | 11.5 | 246. | 2128. |
| 27 | 13.4 | -3103. | 1915. |
| 28 | 11.2 | -15555. | 1358. |
| 29 | 13.6 | -6761. | 1049. |
| 30 | 10.9 | 5921. | 1194. |
| 31 | 13.8 | -10493. | 778. |
| 32 | 10.7 | 18109. | 1246. |
| 33 | 13.9 | 7822. | 1472. |
| 34 | 10.6 | 17476. | 1879. |
| 35 | 14.0 | -7325. | 1582. |
| 36 | 10.6 | 2901. | 1612. |
| 37 | 14.0 | -2626. | 1483. |
| 38 | 10.6 | 25623. | 2033. |
| 39 | 14.1 | 15174. | 2423. |
| 40 | 10.6 | 14823. | 2683. |
| 41 | 14.0 | -411. | 2598. |
| 42 | 10.8 | 13606. | 2832. |
| 43 | 13.9 | 194. | 2764. |
| 44 | 11.0 | 22688. | 3168. |
| 45 | 13.7 | 3551. | 3178. |
| 46 | 11.3 | 7359. | 3259. |

Table 5e. (continued)

| Cycle | Duration (hrs) | Cycle Av. (cfs) | Cumulative Av. (cfs) |
|---|---|---|---|
| 47 | 13.4 | -14137. | 2850. |
| 48 | 11.7 | 4409. | 2880. |
| 49 | 13.0 | 28446. | 3429. |
| 50 | 12.3 | 8272. | 3526. |

Table 5f. Average transport over predicted tidal cycles and cumulative average to end of each cycle. Positive values are eastward, negative values westward. Based on measurements at Summit Bridge. First cycle begins 0900 12 Apr 72.

| Cycle | Duration (hrs) | Cycle Av. (cfs) | Cumulative Av. (cfs) |
|---|---|---|---|
| 1 | 11.2 | -5153. | -5153. |
| 2 | 13.5 | -1081. | -2952. |
| 3 | 11.2 | 1547. | -1536. |
| 4 | 13.8 | 3413. | -174. |
| 5 | 10.9 | 3874. | 560. |
| 6 | 14.1 | -6438. | -752. |
| 7 | 10.7 | -7830. | -1637. |
| 8 | 14.3 | -5965. | -2259. |
| 9 | 10.5 | 1989. | -1849. |
| 10 | 14.4 | -8426. | -2605. |
| 11 | 10.5 | -1342. | -2508. |
| 12 | 14.7 | 5297. | -1743. |
| 13 | 10.5 | 18511. | -396. |
| 14 | 14.4 | 13939. | 781. |
| 15 | 10.7 | 25837. | 2223. |
| 16 | 14.2 | 2738. | 2260. |
| 17 | 11.1 | -22862. | 948. |
| 18 | 13.7 | -16114. | -92. |
| 19 | 11.6 | 32192. | 1504. |
| 20 | 13.2 | 2587. | 1562. |
| 21 | 12.1 | 1965. | 1581. |
| 22 | 12.5 | -5601. | 1257. |
| 23 | 12.6 | 8759. | 1589. |
| 24 | 11.9 | 11975. | 2007. |
| 25 | 13.0 | -11035. | 1462. |
| 26 | 11.5 | 1150. | 1451. |
| 27 | 13.4 | -2552. | 1289. |
| 28 | 11.2 | -12699. | 846. |
| 29 | 13.6 | -3803. | 670. |
| 30 | 10.9 | 5875. | 824. |
| 31 | 13.8 | -6934. | 549. |
| 32 | 10.7 | 13414. | 895. |
| 33 | 13.9 | 7127. | 1107. |
| 34 | 10.6 | 14079. | 1436. |
| 35 | 14.0 | -6289. | 1188. |
| 36 | 10.6 | 3435. | 1240. |
| 37 | 14.0 | -1634. | 1152. |
| 38 | 10.6 | 20061. | 1581. |
| 39 | 14.1 | 12436. | 1902. |
| 40 | 10.6 | 11759. | 2108. |
| 41 | 14.0 | 737. | 2071. |
| 42 | 10.8 | 10567. | 2250. |
| 43 | 13.9 | 1243. | 2225. |
| 44 | 11.0 | 18958. | 2563. |
| 45 | 13.7 | 3751. | 2593. |
| 46 | 11.3 | 4821. | 2636. |

Table 5f. (continued)

| Cycle | Duration (hrs) | Cycle Av. (cfs) | Cumulative Av. (cfs) |
|---|---|---|---|
| 47 | 13.4 | -9419. | 2353. |
| 48 | 11.7 | 5060. | 2406. |
| 49 | 13.0 | 22841. | 2843. |
| 50 | 12.3 | 6900. | 2924. |

cfs. It is clear from the tables that the single cycle net transport can be quite large and can change rapidly in both magnitude and direction.

### (2) Variations over periods of several days.

The net flow over periods of several days is nearly as variable as that over single tidal cycles. This is not surprising, since the meteorological conditions producing the variations will generally persist for several days. Examination of Table 5 gives an indication of this effect, with periods of eastward flow having a duration of 3 to 5 tidal cycles frequently alternating with periods of westward flow having duration of similar length.

To give a more quantitative indication of the variability over several days, the single cycle net transports were averaged in groups of 5, the averaging "window" being moved one cycle at a time. Table 6 shows the results. It is clear that while the maximum values are smaller than for single cycle averages (about 19,000 cfs as compared to about 40,000 cfs),the smoothed results are still quite variable. These results also clearly show that the net flow can be fairly strong in either direction for periods of several days.

### (3) Variations from month-to-month.

The month-to-month variations are best seen by comparing the results of the three study periods. Table 7 compares several indications of flow conditions at each of the two sections, for each of the three periods.

In examining the information contained in Table 7, it should be noted that the duration of the period over which current velocity data were obtained differed from one study period to another,

Table 6. Transports averaged over 5 tidal cycles (cfs) for cross sections in the Canal for three study periods.

| Starting Date | 12 Mar 73 | | 17 Aug 73 | | 12 Apr 73 | |
|---|---|---|---|---|---|---|
| Starting Time | 1600 | 1730 | 1025 | 0900 | 1100 | 0900 |
| Section | 1 | 3 | 1 | 2 | 1 | 2 |
| | -3175.0 | -3854.4 | 6311.6 | -5006.4 | -3323.6 | 520.0 |
| | 132.2 | -564.4 | -1829.8 | -1269.6 | 535.2 | 263.0 |
| | 1881.8 | 1364.8 | 945.4 | 1507.8 | -1261.4 | -1086.8 |
| | 6346.2 | 5646.0 | -47.8 | 483.8 | -2924.6 | -2589.2 |
| | 5348.8 | 5075.2 | 3127.8 | 3553.6 | -3522.0 | -2874.0 |
| | 5928.6 | 5765.6 | 2053.2 | 2820.2 | -6714.2 | -5334.0 |
| | 984.8 | 1592.6 | 3061.4 | 3554.8 | -5746.2 | -4314.8 |
| | -963.4 | -621.8 | -341.2 | 345.4 | -2281.2 | -1689.4 |
| | -3179.4 | -3083.6 | 96.2 | 718.4 | 3793.2 | 3205.8 |
| | 1021.4 | 616.6 | -3718.2 | -2878.0 | 6956.6 | 5595.8 |
| | 4810.2 | 4583.4 | -3281.4 | -2456.2 | 15333.4 | 12448.4 |
| | 13938.6 | 13462.6 | 735.4 | 1662.0 | 16667.6 | 13264.4 |
| | 16049.6 | 16095.2 | 1124.6 | 2031.0 | 9320.2 | 7632.6 |
| | 18401.4 | 18982.4 | 2396.8 | 3416.2 | 688.4 | 707.6 |
| | 11384.2 | 12634.8 | 3969.2 | 5086.0 | 5650.2 | 4358.2 |
| | 8585.4 | 9716.0 | 4658.2 | 5847.2 | 68.8 | -291.8 |
| | -2404.4 | -2046.2 | 24.0 | 1329.0 | -537.0 | -446.4 |
| | -2750.2 | -3029.8 | -489.2 | 1507.0 | 4055.4 | 3005.8 |
| | -4143.6 | -5173.8 | -5864.8 | -3341.6 | 10152.6 | 7980.4 |
| | 2743.8 | 1337.0 | -2683.8 | -546.8 | 4417.8 | 3937.0 |
| | 2501.4 | 1114.8 | -4931.6 | -2472.0 | 725.4 | 1212.6 |
| | 5305.6 | 3557.8 | -362.2 | 1962.6 | 550.6 | 1049.6 |
| | 1570.2 | 519.6 | -711.4 | 1400.4 | 1304.8 | 1659.4 |
| | -3935.6 | -5055.6 | 4580.6 | 5724.8 | -3934.2 | -2632.2 |
| | -10720.4 | | -1898.2 | 232.4 | -8019.0 | -5787.8 |
| | -17388.8 | | 4457.2 | 5945.6 | -3850.4 | -2405.8 |
| | -16734.6 | | 1528.2 | 3089.2 | -5998.2 | -4022.6 |
| | -17207.8 | | 5619.4 | 6372.2 | -1755.8 | -829.4 |
| | -9108.4 | | 2394.8 | 3825.4 | 2919.6 | 3135.8 |
| | -4522.0 | | 10224.4 | 10702.4 | 7767.0 | 6712.2 |
| | 5935.8 | | 6083.0 | 6524.8 | 5117.8 | 4279.4 |
| | 3007.4 | | 8319.8 | 8468.8 | 7796.6 | 6353.2 |
| | | | 5690.2 | 6378.2 | 3649.6 | 3343.6 |
| | | | 7867.6 | 8317.2 | 7209.8 | 5930.4 |
| | | | 3932.2 | 4868.4 | 6749.4 | 5601.8 |
| | | | 3003.4 | | 11179.0 | 9211.4 |
| | | | -262.0 | | 10516.6 | 8671.8 |
| | | | | | 13763.0 | 11112.0 |
| | | | | | 8677.2 | 7348.4 |
| | | | | | 10180.0 | 8652.8 |
| | | | | | 7925.6 | 7051.2 |
| | | | | | 9479.6 | 7868.0 |
| | | | | | 3931.0 | 3870.8 |
| | | | | | 4774.0 | 4634.2 |
| | | | | | 5925.6 | 5410.8 |
| | | | | | 6869.8 | 6040.6 |

Table 7. Comparison of net non-tidal transports as observed during each of the three study periods, for each of the two cross-sections occupied during each study, and for various averaging periods.

| Study Period | Mar-Apr 1971 | | Aug-Sept 1971 | | Apr-May 1972 | |
|---|---|---|---|---|---|---|
| Section | 1 | 3 | 1 | 2 | 1 | 2 |
| Duration of Observations (Tidal Cycles) | 36 | 28 | 41 | 39 | 50 | 50 |
| Max. Eastward One Cycle Ave. | 38,423 | 38,453 | 23,059 | 23,477 | 42,337 | 32,192 |
| Max. Westward One Cycle Ave | 30,132 | 26,191 | 21,369 | 16,720 | 29,836 | 22,862 |
| Net Transport | *(All net transports given are Eastward)* | | | | | |
| Over: 20 T.C. | 3717 | 3794 | 1555 | 2191 | 2613 | 1562 |
| 28 T.C. | 1797 | 1355 | 620 | 1648 | 1358 | 846 |
| 36 T.C. | 322 | | 1349 | 2378 | 1612 | 1240 |
| 39 T.C. | | | 1405 | 2473 | 2423 | 1902 |
| 41 T.C. | | | 1153 | | 2598 | 2071 |
| 50 T.C. | | | | | 3526 | 2924 |
| % of Total No. of Tidal Cycles with Eastward Net Transport | 56 | 50 | 54 | 67 | 64 | 64 |

and also from one section to the other in a given study period. The shortest period of observation, 28 tidal cycles, was for cross-section 3 during the March-April 1971 study period, while the longest, 50 tidal cycles, was for cross-sections 1 and 2 during the April-May 1972 study period.

Listed in Table 7 are the net non-tidal transports as determined for averaging periods of 20 tidal cycles, 28 tidal cycles, 36 tidal cycles, 39 tidal cycles, 41 tidal cycles, and 50 tidal cycles, for each section and for each study period, to the extent that the duration of observation allowed these averages to be obtained. Note first that there is a difference between the estimates of net transport obtained from the two cross-sections occupied during any study period.

The average difference between estimated net transport for each cross-section (for the same period of averaging for each study period) was 640 cfs. This suggests that estimates of the net transport for any study made using only a single cross-section of the Canal are uncertain by about ± 700 cfs. Any estimates of net transport made by averaging paired (one cross-section compared to the other cross-section) values are uncertain by about ± 500 cfs.

The large variation in the net transport estimates between different cross-sections of the Canal indicates the difficulty in assigning long-term net transport values.

In fact, it seems that a single value for the long-term net transport is rather meaningless. It is possible to assign a characteristic net non-tidal transport for each study period by looking for relative long periods during which the cumulative net transport values are relatively constant for increasing averaging periods. During the March-April 1971 study period, there was an interval from the 14th t.c. through the 25th t.c. when the cumulative average net transport values were quite stable, giving a best estimate for the characteristic net transport for this study period of about 3400 cfs eastward. Similarly, during the August-September 1971 survey, an interval between the 29th and 39th tidal cycles occurred during which the cumulative transport values showed only a small variation, giving an estimate of the characteristic net transport for this study period of about 1900 cfs eastward. The last 20 t.c. of the April-May 1972 survey show cumulative transport values having small variations superimposed on a slow, approximately linear increase. Characteristic net transport for this study period is estimated to be about 3200 cfs eastward.

These estimates of characteristic net transports for each study period support an expected trend: Eastward net transport is larger during the spring than during the late summer. This is due to the difference in discharge of fresh water from the Susquehanna River to the Chesapeake Bay.

An inspection of the extreme one tidal cycle net transport values, both eastward and westward (also listed for each study period in Table 7) does not show any clear trend with time. The fact that these maximum net transport values are larger for the two spring surveys than for the late summer survey may result from the fact that the spring is a period of much more intense meteorological phenomena. These might cause large differences in water level elevation between the two ends of the

Canal than is the case for late summer.

The net transports discussed so far have been sectionally averaged, and hence do not reveal any possible two-layered flow which might occur in response to the longitudinal density gradient through the Canal. The net transports were calculated for each of 3 layers in which current meters were located. Tables 8a - 8c show the results. The frictional effects are quite apparent in the relatively low bottom values. However, there is little or no indication of true two-layered flow for any of the three study periods.

Note that these figures are for transport, and that the area of each of the three layers is different and differ between study periods. Therefore, the mean velocities of each of the three layers must be compared by dividing transport figures by the appropriate areas (Table 9) of the layer. Using these areas, the velocities corresponding to the final net transport were calculated as shown in Table 10.

### (4) Some final comments on the statistical variability in the estimates of the net non-tidal flow.

The large cycle-to-cycle variation in the observed flow imposes a large uncertainty in the estimates of the long-term net non-tidal flow through the Canal from observations made over periods of 50 tidal cycles or less, that is, over periods of the length of the experiments conducted during this study. To appreciate this fact, consider the statistical treatment of the net non-tidal flows as calculated for each tidal cycle, under the following 3 postulates (a-c).

Table 8a. Transport by layer. First cycle begins 1600 12 Mar 71

| | | TOP | | MID | | BOT | |
|---|---|---|---|---|---|---|---|
| Cyc | Dur | Tidal | Cum | Tidal | Cum | Tidal | Cum |
| 1 | 12.8 | 221. | 221. | 679. | 679. | 64. | 64. |
| 2 | 12.4 | 630. | 421. | 872. | 774. | 279. | 170. |
| 3 | 12.1 | -4199. | -1084. | -6342. | -1545. | -1283. | -304. |
| 4 | 12.2 | -894. | -1038. | -2103. | -1683. | -372. | -320. |
| 5 | 12.3 | -932. | -1017. | -2112. | -1768. | -383. | -333. |
| 6 | 12.0 | 6565. | 216. | 9059. | -8. | 1877. | 26. |
| 7 | 12.6 | 4381. | 819. | 4986. | 715. | 1162. | 191. |
| 8 | 11.7 | 3883. | 1188. | 5343. | 1273. | 1272. | 321. |
| 9 | 12.9 | -2773. | 730. | -4701. | 582. | -882. | 182. |
| 10 | 11.7 | 54. | 666. | -638. | 466. | 57. | 170. |
| 11 | 13.1 | -2354. | 373. | -4180. | 16. | -686. | 87. |
| 12 | 11.5 | 341. | 371. | 350. | 42. | 97. | 88. |
| 13 | 13.5 | -356. | 310. | -204. | 21. | -22. | 79. |
| 14 | 11.3 | 5274. | 636. | 5957. | 412. | 1417. | 167. |
| 15 | 13.7 | 7448. | 1137. | 8884. | 1035. | 2083. | 308. |
| 16 | 11.3 | 15323. | 1953. | 18801. | 2056. | 4299. | 537. |
| 17 | 13.9 | 4290. | 2106. | 5651. | 2292. | 1402. | 594. |
| 18 | 11.4 | 4080. | 2207. | 5669. | 2464. | 1428. | 636. |
| 19 | 13.7 | -8134. | 1601. | -11888. | 1623. | -2416. | 458. |
| 20 | 11.7 | 1856. | 1613. | 2042. | 1643. | 524. | 461. |
| 21 | 13.4 | -5982. | 1225. | -8788. | 1110. | -1755. | 347. |
| 22 | 12.0 | 3975. | 1346. | 4667. | 1267. | 972. | 375. |
| 23 | 12.9 | 1436. | 1350. | 1918. | 1296. | 856. | 397. |
| 24 | 12.2 | 4454. | 1477. | 6094. | 1492. | 1451. | 440. |
| 25 | 12.7 | 1024. | 1458. | 1780. | 1504. | 406. | 438. |
| 26 | 12.3 | -1324. | 1352. | -1054. | 1406. | -128. | 417. |
| 27 | 12.5 | -3330. | 1178. | -4637. | 1181. | -1097. | 360. |
| 28 | 12.4 | -4048. | 993. | -16028. | 572. | -3244. | 233. |
| 29 | 12.4 | -5528. | 767. | -13488. | 84. | -2909. | 124. |
| 30 | 12.5 | -11747. | 348. | -15639. | -442. | -2745. | 28. |
| 31 | 12.2 | 756. | 360. | -250. | -436. | 260. | 35. |
| 32 | 12.7 | -4501. | 206. | -6072. | -616. | -855. | 7. |
| 33 | 12.0 | 7290. | 413. | 8053. | -362. | 1835. | 60. |
| 34 | 12.9 | 488. | 415. | 270. | -343. | 250. | 66. |
| 35 | 11.9 | 8587. | 641. | 11333. | -21. | 2237. | 126. |
| 36 | 13.0 | -4993. | 477. | -7371. | -234. | -1425. | 81. |

Table 8b. Transport by layer. First cycle begins 0900 17 Aug 71

| | | TOP | | MID | | BOT | |
|---|---|---|---|---|---|---|---|
| Cyc | Dur | Tidal | Cum | Tidal | Cum | Tidal | Cum |
| 1 | 9.4 | 8017. | 8017. | 12191. | 12191. | 2794. | 2794. |
| 2 | 14.5 | 253. | 3293. | 287. | 4948. | 305. | 1279. |
| 3 | 10.5 | 3098. | 3233. | 3825. | 4605. | 923. | 1170. |
| 4 | 14.2 | -3495. | 1252. | -4412. | 1949. | -1042. | 519. |
| 5 | 10.7 | 1253. | 1252. | 913. | 1763. | 123. | 448. |
| 6 | 13.9 | -2250. | 590. | -5003. | 484. | -1126. | 150. |
| 7 | 10.9 | 5168. | 1188. | 7814. | 1442. | 1750. | 359. |
| 8 | 13.6 | 1439. | 1223. | 949. | 1374. | 338. | 356. |
| 9 | 11.3 | 2422. | 1348. | 3162. | 1560. | 817. | 404. |
| 10 | 13.1 | -97. | 1192. | -1086. | 1274. | -195. | 340. |
| 11 | 11.6 | -1305. | 977. | -2810. | 923. | -592. | 259. |
| 12 | 12.7 | -35. | 889. | -1021. | 755. | -260. | 214. |
| 13 | 12.1 | 1846. | 963. | 2219. | 867. | 526. | 238. |
| 14 | 12.3 | -3553. | 637. | -6336. | 347. | -1691. | 99. |
| 15 | 12.4 | 598. | 634. | 15. | 325. | 118. | 100. |
| 16 | 12.0 | 5734. | 948. | 8227. | 811. | 1924. | 212. |
| 17 | 12.8 | 734. | 935. | -300. | 742. | 95. | 205. |
| 18 | 11.7 | 4138. | 1105. | 5853. | 1014. | 1526. | 275. |
| 19 | 13.2 | -612. | 1008. | -2136. | 835. | -484. | 232. |
| 20 | 11.4 | 1848. | 1047. | 2125. | 896. | 563. | 248. |
| 21 | 13.5 | -1863. | 895. | -3826. | 649. | -1018. | 182. |
| 22 | 11.2 | 827. | 892. | 594. | 647. | -2. | 174. |
| 23 | 13.8 | -3946. | 655. | -7297. | 258. | -1482. | 93. |
| 24 | 10.9 | 3948. | 777. | 5827. | 463. | 967. | 125. |
| 25 | 14.3 | -974. | 695. | -3486. | 280. | -629. | 90. |
| 26 | 10.6 | 5273. | 849. | 8368. | 550. | 1827. | 148. |
| 27 | 14.5 | 208. | 821. | -1580. | 458. | -20. | 141. |
| 28 | 10.5 | 3126. | 891. | 4824. | 591. | 947. | 166. |
| 29 | 14.5 | -4820. | 660. | -9497. | 183. | -2403. | 62. |
| 30 | 10.5 | 8113. | 872. | 12092. | 522. | 3271. | 153. |
| 31 | 14.3 | 1050. | 879. | 37. | 504. | 98. | 151. |
| 32 | 10.8 | 5430. | 1004. | 7595. | 699. | 1998. | 202. |
| 33 | 13.9 | -781. | 943. | -2521. | 588. | -536. | 177. |
| 34 | 11.2 | 6317. | 1086. | 8949. | 811. | 2399. | 236. |
| 35 | 13.4 | 1236. | 1091. | 844. | 812. | 509. | 244. |
| 36 | 11.7 | 4007. | 1167. | 5571. | 937. | 1328. | 273. |
| 37 | 12.9 | 1798. | 1185. | 1852. | 964. | 920. | 291. |
| 38 | 12.1 | 2115. | 1209. | 2719. | 1008. | 1024. | 310. |
| 39 | 12.5 | 471. | 1190. | -151. | 978. | 100. | 304. |

Table 8c. Transport by layer. First cycle begins 0900 12 Apr 72

| | | TOP | | MID | | BOT | |
|---|---|---|---|---|---|---|---|
| Cyc | Dur | Tidal | Cum | Tidal | Cum | Tidal | Cum |
| 1 | 9.2 | 3723. | 3723. | 2465. | 2465. | 393. | 393. |
| 2 | 13.5 | 130. | 1610. | -1283. | 260. | -288. | -8. |
| 3 | 11.2 | 1211. | 1477. | 172. | 231. | -126. | -47. |
| 4 | 13.8 | 3069. | 1933. | 1346. | 551. | 283. | 47. |
| 5 | 10.9 | 3341. | 2197. | 1518. | 732. | 665. | 163. |
| 6 | 14.1 | -2703. | 1253 | -3875. | -156. | -784. | -19. |
| 7 | 10.7 | -4365. | 534. | -4783. | -748. | -1276. | -180. |
| 8 | 14.3 | -2942. | 24. | -3483. | -1149. | -634. | -247. |
| 9 | 10.5 | 1268. | 146. | 507. | -986. | -63. | -229. |
| 10 | 14.4 | -4757. | -427. | -4631. | -1412. | -1049. | -324. |
| 11 | 10.5 | -819. | -457. | -1295. | -1403. | -408. | -331. |
| 12 | 14.7 | 3589. | -55. | 2543. | -1011. | 770. | -222. |
| 13 | 10.5 | 11426. | 718. | 9491. | -304. | 2396. | -45. |
| 14 | 14.4 | 8846. | 1393. | 6790. | 285. | 1891. | 115. |
| 15 | 10.7 | 14840. | 2175. | 13240. | 1039. | 3367. | 305. |
| 16 | 14.2 | 2630. | 2208. | 1072. | 1041. | 448. | 315. |
| 17 | 11.1 | -13475. | 1382. | -13387. | 281. | -2974. | 142. |
| 18 | 13.7 | -8757. | 758. | -8754. | -275. | -2336. | -11. |
| 19 | 11.6 | 21035. | 1769. | 17201. | 597. | 4101. | 194. |
| 20 | 13.2 | 2166. | 1791. | 1174. | 628. | 200. | 195. |
| 21 | 12.1 | 501. | 1731. | 480. | 621. | 140. | 192. |
| 22 | 12.5 | -2821. | 1524. | -3250. | 445. | -802. | 147. |
| 23 | 12.6 | 5349. | 1695. | 4269. | 616. | 1023. | 186. |
| 24 | 11.9 | 6420. | 1886. | 5798. | 825. | 1445. | 237. |
| 25 | 13.0 | -6676. | 1526. | -6587. | 514. | -1660. | 157. |
| 26 | 11.5 | -304. | 1462. | 507. | 514. | 43. | 153. |
| 27 | 13.4 | -1214. | 1352. | -1476. | 432. | -412. | 130. |
| 28 | 11.2 | -6950. | 1088. | -6922. | 198. | -1684. | 72. |
| 29 | 13.6 | -3142. | 927. | -2862. | 82. | -758. | 41. |
| 30 | 10.9 | 2640. | 978. | 2707. | 160. | 574. | 57. |
| 31 | 13.8 | -4191. | 794. | -4981. | -24. | -1321. | 7. |
| 32 | 10.7 | 8542. | 1003. | 7747. | 187. | 1820. | 57. |
| 33 | 13.9 | 3700. | 1096. | 3254. | 292. | 868. | 84. |
| 34 | 10.6 | 8032. | 1272. | 7677. | 480. | 1767. | 127. |
| 35 | 14.0 | -2771. | 1141. | -3741. | 343. | -813. | 97. |
| 36 | 10.6 | 1250. | 1144. | 1355. | 367. | 296. | 101. |
| 37 | 14.0 | -906. | 1081. | -1442. | 312. | -279. | 90. |
| 38 | 10.6 | 12027. | 1331. | 10926. | 554. | 2670. | 149. |
| 39 | 14.1 | 7725. | 1521. | 5875. | 712. | 1574. | 191. |
| 40 | 10.6 | 6515. | 1625. | 6615. | 835. | 1693. | 222. |
| 41 | 14.0 | -249. | 1574. | -219. | 806. | 56. | 218. |
| 42 | 10.8 | 6248. | 1673. | 5803. | 913. | 1555. | 246. |
| 43 | 13.9 | 236. | 1636. | -37. | 888. | -5. | 240. |
| 44 | 11.0 | 10213. | 1810. | 9950. | 1072. | 2525. | 286. |
| 45 | 13.7 | 1477. | 1802. | 1578. | 1085. | 497. | 291. |
| 46 | 11.3 | 3451. | 1834. | 3197. | 1126. | 711. | 300. |
| 47 | 13.4 | -6901. | 1628. | -5842. | 962. | -1394. | 260. |

Table 8c. (continued)

| | | TOP | | MID | | BOT | |
|---|---|---|---|---|---|---|---|
| Cyc | Dur | Tidal | Cum | Tidal | Cum | Tidal | Cum |
| 48 | 11.7 | 1779. | 1631. | 2036. | 983. | 594. | 266. |
| 49 | 13.0 | 12787. | 1871. | 12422. | 1228. | 3237. | 330. |
| 50 | 12.3 | 1542. | 1864. | 2385. | 1251. | 603. | 336. |

Table 9. Areas of the three layers considered in velocity measurements.

| | Top | Mid | Bottom | Section used |
|---|---|---|---|---|
| Mar 71 | 8303 | 11,047 | 3404 | 1 mile west Ches. City |
| Aug 71 | 7541 | 11,651 | 4613 | Summit Bridge |
| Apr 72 | 8306 | 11,047 | 3404 | 1 mile west Ches. City |

Table 10. Net transports of each layer in three cross-sections of the Canal.

| | Top (ft/sec) | Mid | Bottom |
|---|---|---|---|
| Mar 71 | 0.057 | -0.021 | 0.024 |
| Aug 71 | 0.158 | 0.084 | 0.066 |
| Apr 72 | 0.224 | 0.113 | 0.099 |

(a) For any given study period, all individual tidal cycle observations giving an eastward net non-tidal flow represent samples drawn from a distinct population.

(b) For any given study period, all individual tidal cycle observations giving a westward net non-tidal flow represent samples drawn from a distinct population.

(c) For any given study period, all individual tidal cycle observations, regardless of direction, are drawn from a distinct population.

Table 11 gives the statistical data to be discussed in the following paragraphs. In this table, $n_E$ represents the number of individual tidal cycles at each section, during each study period, for which the net non-tidal flow was eastward; $\overline{Q}_E$ is the average of these $n_E$ eastward net non-tidal flow measurements; SD represents the standard deviation of the $n_E$ individual measurements from the average. Likewise, $n_W$ is the number of individual tidal-cycles for which the net non-tidal flow was westward; and $\overline{Q}_W$ is the average of these $n_W$ individual measurements. Further, _n_ is the total number of tidal cycles for which observations are available at each section, during each study period; $\overline{Q}$ is the average net non-tidal flow over all these n tidal periods. Also given in each section of Table 11 are the calculated probable errors of estimate for the listed values of $\overline{Q}_E$, $\overline{Q}_W$, and $\overline{Q}$. Note that these probable errors of estimate do not arise from possible error in the measurements or in the numerical processing of the data, but rather result simply from the high variability in the individual net non-tidal flow observations.

## TABLE 11

Some Statistical Properties of the Net Non-Tidal Flow Estimates from Current Meter Observations in the Chesapeake and Delaware Canal.

| Study Period | Section No. | $n_E$ | $\overline{Q}_E$(cfs) | S.D. (cfs) | Probable Error in Est. $\overline{Q}_E$(cfs) |
|---|---|---|---|---|---|
| Mar-Apr '71 | 1 | 20 | 10,097 | ± 8743 | ± 1353 |
|  | 3 | 14 | 11,341 | ± 8675 | ± 1623 |
| Aug-Sept'71 | 1 | 22 | 8,269 | ± 5968 | ± 878 |
|  | 2 | 26 | 7,266 | ± 5859 | ± 790 |
| Apr-May '72 | 1 | 32 | 10,855 | ± 9502 | ± 1151 |
|  | 2 | 32 | 8,775 | ± 7403 | ± 897 |

|  |  | $n_W$ | $\overline{Q}_W$(cfs) |  | Probable Error in Est. $\overline{Q}_W$(cfs) |
|---|---|---|---|---|---|
| Mar-Apr '71 | 1 | 16 | -11,894 | ± 9266 | ± 1614 |
|  | 3 | 14 | - 8,648 | ± 8574 | ± 1604 |
| Aug-Sept'71 | 1 | 19 | - 7,130 | ± 6349 | ± 1009 |
|  | 2 | 13 | - 7,218 | ± 5463 | ± 1064 |
| Apr-May'72 | 1 | 18 | - 9,683 | ± 7007 | ± 1146 |
|  | 2 | 18 | - 7,629 | ± 5255 | ± 860 |

|  |  | n | $\overline{Q}$ (cfs) |  | Probable Error in Est. $\overline{Q}$ (cfs) |
|---|---|---|---|---|---|
| Mar-Apr '71 | 1 | 36 | 323 | ± 14143 | ± 1612 |
|  | 3 | 28 | 1,347 | ± 13201 | ± 1714 |
| Aug-Sept'71 | 1 | 41 | 1,133 | ± 9836 | ± 1049 |
|  | 2 | 39 | 2,438 | ± 8914 | ± 975 |
| Apr-May '72 | 1 | 50 | 3,461 | ± 13140 | ± 1266 |
|  | 2 | 50 | 2,870 | ± 10345 | ± 997 |

Note that the standard deviations for $Q_E$ and $Q_W$ are just about equal in magnitude to the mean values, while the values of the probable error of estimate is on the order of 10% of the mean values. However, for the average non-tidal flow over each of the periods of estimate, $\overline{Q}$, the magnitude of the standard deviation is from four to ten times the average values. Further, the probable error of estimate is of the same order as the average value $\overline{Q}$, supporting the argument that very little confidence can be placed on the differences between the estimates of $\overline{Q}$ for the different study periods.

If we treat the data from all sections and all study periods as being drawn from the same population, then we have a total recore of 244 tidal cycles. Of these, 146 tidal cycles had an eastward net non-tidal flow, with an average magnitude of 9313 cfs, a SD of ± 9082 cfs, and a probable error of estimate of ± 509 cfs. There were 98 tidal cycles with a westward net tidal flow, with an average magnitude of 8617 cfs, a SD of ± 8625 cfs, and a standard error of estimate of ± 591 cfs. The average net non-tidal flow over the full 244 tidal cycles is 2080 cfs (eastward) with a SD of ± 12,591 cfs and a probable error of estimate of ± 545 cfs.

It is seen that by combining the study periods the uncertainty in the estimate of the long-term net non-tidal flow is reduced.

These statistics re-emphasize the fact that the important feature of the net non-tidal flow through the Canal is its large variability, with the long-term average being of lesser importance.

3. Predicted distribution of transport times for specific water parcels in the Canal.

The large temporal fluctuations in net transport previously described make the value of the long-term net transport rather unimportant for some considerations. If an organism is subjected to lethal conditions for a short time, the average conditions over a much longer time are not significant. One of the important biological concerns is the transport of fish eggs and larvae from the Canal into the Delaware River. In order to arrive at a more meaningful indication of transport from this standpoint, the transport data were used to calculate the time required for a parcel marked at Chesapeake City to leave the Canal either into the Delaware or into the Chesapeake. For this purpose, the Elk River was considered a part of the Canal, and Turkey Point the western end of the Canal. Table 12 (a-f) lists the results of this calculation.

### 4. Comparison of pre-enlargement and post-enlargement flow conditions.

The large majority of data on the flow through the Canal and on the salinity distribution were taken during the construction period for Canal enlargement. The only direct observations of current velocities in the Canal made prior to the construction period were those obtained by Wicker (1939) during a 1938 study of the then recently completed 27-ft deep, 250-ft wide Canal. Some salinity measurements from the Canal and its approaches have been made over the years, but no systematic investigation of the seasonal variation in the distribution of salinity over the length of the Canal was made prior to the studies reported here. Since the dredging of the final short segment of the Canal at its eastern end has not yet been completed, no observational data is available for post-enlargement conditions.

What we essentially have is an intensive set of measurements made during the transitional period of Canal enlargement, which must be interpreted to estimate the probable changes which will occur in the flow conditions between the period prior to start of Canal enlargement and the period after completion of enlargement of the Canal to the new project

Table 12a. Time required for parcel marked at Chesapeake City to leave Canal, based on data at 1 mile west Chesapeake City Bridge.

| SLACK BEFORE FLOOD | | | SLACK BEFORE EBB | | |
|---|---|---|---|---|---|
| Date | St. Time | Time Out/hrs | Date | St. Time | Time Out/hrs |
| 12 Mar 71 | 1600 | 177.7 Del. | 12 Mar 71 | 2218 | 179.3 Del. |
| 13 Mar 71 | 0448 | 164.2 " | 13 Mar 71 | 1054 | 153.7 " |
| | 1712 | 152.2 " | | 2242 | 55.2 " |
| 14 Mar 71 | 0518 | 51.5 " | 14 Mar 71 | 1136 | 39.0 " |
| | 1730 | 39.2 " | | 2306 | 16.2 " |
| 15 Mar 71 | 0548 | 110.7 " | 15 Mar 71 | 1218 | 111.7 " |
| | 1748 | 112. " | | 2336 | 101.7 " |
| 16 Mar 71 | 0624 | 38.2 " | 16 Mar 71 | 1300 | 91.7 " |
| | 1806 | 70.5 " | 17 Mar 71 | 0012 | 75.8 " |
| 17 Mar 71 | 0700 | 56.2 " | | 1342 | 60.8 " |
| | 1842 | 32.0 " | 18 Mar 71 | 0048 | 46.2 " |
| 18 Mar 71 | 0748 | 19.2 " | | 1436 | 31.7 " |
| | 1918 | 16.5 " | 19 Mar 71 | 0136 | 20.0 " |
| 19 Mar 71 | 0848 | 11.0 " | | 1536 | 13.7 " |
| | 2006 | 160.0 Ches. | 20 Mar 71 | 0230 | 20.2 " |
| 20 Mar 71 | 0948 | 145.5 " | | 1636 | 157.8 Ches. |
| | 2106 | 128.3 " | 21 Mar 71 | 0336 | 134.7 " |
| 21 Mar 71 | 1100 | 127.3 " | | 1736 | 134.2 " |
| | 2224 | 113.2 " | 22 Mar 71 | 0442 | 119.2 " |
| 22 Mar 71 | 1206 | 101.3 " | | 1836 | 30.7 Del. |
| | 2348 | 86.8 " | 23 Mar 71 | 0600 | 92.2 " |
| 23 Mar 71 | 1312 | 72.5 " | | 1924 | 79.8 " |
| 24 Mar 71 | 0112 | 52.0 " | 24 Mar 71 | 0712 | 52.8 " |
| | 1406 | 45.7 " | | 2006 | 41.8 " |
| 25 Mar 71 | 0218 | 33.3 " | 25 Mar 71 | 0824 | 27.7 " |
| | 1500 | 47.3 " | | 2048 | 27.2 " |
| 26 Mar 71 | 0318 | -4.3 miles* | 26 Mar 71 | 0936 | -5.6 miles* |
| | 1578 | 1.7 miles* | | 2124 | -1.6 miles* |

Table 12a. *(continued)*

| SLACK BEFORE FLOOD | | | SLACK BEFORE EBB | | |
|---|---|---|---|---|---|
| Date | St. Time | Time Out/hrs | Date | St. Time | Time Out/hrs |
| 27 Mar 71 | 0412 | 0.3 miles* | 27 Mar 71 | 1036 | 53.2 |
| | 1636 | 1.3 miles* | | 2206 | 31.3 |
| 28 Mar 71 | 0506 | -3.5 miles* | 28 Mar 71 | 1136 | 1.3 miles* |
| | 1718 | -4.7 miles* | | 2248 | 1.8 miles* |
| 29 Mar 71 | 0600 | -4.1 miles* | 29 Mar 71 | 1236 | -5.3 miles* |

* Distance from Chesapeake City Bridge at end of study.

Positive value indicates eastward movement.

Table 12b. Time required for parcel marked at Chesapeake City to leave Canal, based on data at 1 mile west Chesapeake City Bridge.

| SLACK BEFORE FLOOD | | | SLACK BEFORE EBB | | |
|---|---|---|---|---|---|
| Date | St. Time | Time Out/hrs | Date | St. Time | Time Out/hrs |
| 17 Aug 71 | | | 17 Aug 71 | 0900 | 216.8 |
| | 1254 | 212.0 Del. | | 1824 | 405.7 |
| 18 Aug 71 | 0212 | 197.5 " | 18 Aug 71 | 0854 | 366.5 |
| | 1400 | 384.0 " | | 1924 | 354.3 |
| 19 Aug 71 | 0300 | 294.5 " | 19 Aug 71 | 0936 | 165.7 |
| | 1500 | 332.7 " | | 2018 | 44.5 |
| 20 Aug 71 | 0342 | 146.0 " | 20 Aug 71 | 1012 | 137.7 |
| | 1554 | 306.3 " | | 2106 | 126.0 |
| 21 Aug 71 | 0418 | 316.7 " | 21 Aug 71 | 1042 | 286.8 |
| | 1636 | 279.0 " | | 2200 | 272.0 |
| 22 Aug 71 | 0454 | 264.8 " | 22 Aug 71 | 1106 | 260.2 |
| | 1718 | 78.5 " | | 2242 | 246.2 |
| 23 Aug 71 | 0524 | 188.5 " | 23 Aug 71 | 1124 | 258.0 |
| | 1754 | 52.5 " | | 2330 | 218.7 |
| 24 Aug 71 | 0548 | 16.3 " | 24 Aug 71 | 1148 | 205.7 |
| | 1830 | 199.3 " | 25 Aug 71 | 0012 | 218.0 |
| 25 Aug 71 | 0600 | 187.3 " | | 1212 | 205.7 |
| | 1906 | 222.8 " | 26 Aug 71 | 0100 | 191.2 |
| 26 Aug 71 | 0624 | 209.8 " | | 1242 | 179.2 |
| | 1942 | 196.0 " | 27 Aug 71 | 0154 | 164.3 |
| 27 Aug 71 | 0648 | 183.5 " | | 1318 | 127.5 |
| | 2030 | 143.7 " | 28 Aug 71 | 0248 | 63.3 |
| 28 Aug 71 | 0724 | 107.8 " | | 1400 | 125.2 |
| | 2118 | 41.3 " | 29 Aug 71 | 0348 | 85.8 |
| 29 Aug 71 | 0806 | 82.0 " | | 1442 | 114.7 |
| | 2218 | 64.2 " | 30 Aug 71 | 0500 | 98.3 |
| 30 Aug 71 | 0854 | 93.7 " | | 1536 | 96.7 |

Table 12b. *(continued)*

| SLACK BEFORE FLOOD | | | SLACK BEFORE EBB | | |
|---|---|---|---|---|---|
| Date | St. Time | Time Out/hrs | Date | St. Time | Time Out/hrs |
| 30 Aug 71 | 2324 | 14.8 Del. | 31 Aug 71 | 0606 | 32.5 |
| 31 Aug 71 | 1000 | 52.0 " | | 1636 | 59.8 |
| 1 Sept 71 | 0024 | 51.3 " | 1 Sept 71 | 0706 | 54.2 |
| | 1112 | 75.3 " | | 1736 | 42.3 |
| 2 Sept 71 | 0118 | 49.3 " | 2 Sept 71 | 0754 | 41.8 |
| | 1236 | 7.6 miles* | | 1842 | 30.0 |
| 3 Sept 71 | 0212 | 7.9 miles* | 3 Sept 71 | 0836 | 7.2 miles* |
| | 1354 | 5.9 miles* | | 1946 | 6.9 miles* |
| 4 Sept 71 | 0254 | 5.0 miles* | 4 Sept 71 | 0912 | 1.0 miles* |
| | 1500 | 5.7 miles* | | 2054 | 1.2 miles* |

* Distance from Chesapeake City Bridge at end of study.

Positive value indicates eastward movement.

Table 12c. Time required for parcel marked at Chesapeake City to leave Canal, based on data at 1 mile west Chesapeake City Bridge.

| SLACK BEFORE FLOOD | | | | SLACK BEFORE EBB | | | |
|---|---|---|---|---|---|---|---|
| Date | St. Time | Time Out/hrs | | Date | St. Time | Time Out/hrs | |
| | | | | 12 Apr 72 | 0900 | 295. | Del. |
| 12 Apr 72 | 1434 | 174.3 | Del. | | 2015 | 283.3 | " |
| 13 Apr 72 | 0313 | 161.0 | " | 13 Apr 72 | 0944 | 174.0 | " |
| | 1522 | 149.3 | " | | 2057 | 148.3 | " |
| 14 Apr 72 | 0407 | 136.0 | " | 14 Apr 72 | 1047 | 245.0 | " |
| | 1609 | 127.3 | " | | 2142 | 234.0 | " |
| 15 Apr 72 | 0501 | 111.0 | " | 15 Apr 72 | 1147 | 109.7 | " |
| | 1655 | 100.0 | " | | 2228 | 97.3 | " |
| 16 Apr 72 | 0556 | 65.7 | " | 16 Apr 72 | 1246 | 80.7 | " |
| | 1744 | 68.3 | " | | 2318 | 70.3 | " |
| 17 Apr 72 | 0652 | 40.0 | " | 17 Apr 72 | 1343 | 48.0 | " |
| | 1839 | 29.3 | " | 18 Apr 72 | 0012 | 37.7 | " |
| 18 Apr 72 | 0751 | 14.0 | " | | 1440 | 29.3 | " |
| | 1947 | 23.3 | " | 19 Apr 72 | 0110 | 23.7 | " |
| 19 Apr 72 | 0852 | 12.0 | " | | 1535 | 122.0 | " |
| | 2105 | 288.7 | " | 20 Apr 72 | 0216 | 307.0 | " |
| 20 Apr 72 | 0953 | 274.3 | " | | 1627 | 316.7 | " |
| | 2221 | 275.7 | " | 21 Apr 72 | 0330 | 256.7 | " |
| 21 Apr 72 | 1052 | 14.0 | " | | 1714 | 60.7 | " |
| | 2328 | 64.3 | " | 22 Apr 72 | 0449 | 248.0 | " |
| 22 Apr 72 | 1148 | 225.0 | " | | 1757 | 234.0 | " |
| 23 Apr 72 | 0027 | 212.3 | " | 23 Apr 72 | 0605 | 229.3 | " |
| | 1240 | 229.3 | " | | 1835 | 208.3 | " |
| 24 Apr 72 | 0118 | 16.7 | " | 24 Apr 72 | 0713 | 204.7 | " |
| | 1328 | 190.7 | " | | 1910 | 218.0 | " |
| 25 Apr 72 | 0204 | 175.0 | " | 25 Apr 72 | 0812 | 172.7 | " |
| | 1414 | 163.3 | " | | 1943 | 168.0 | " |

Table 12c. *(continued)*

| SLACK BEFORE FLOOD | | | SLACK BEFORE EBB | | |
|---|---|---|---|---|---|
| Date | St. Time | Time Out/hrs | Date | St. Time | Time Out/hrs |
| 26 Apr 72 | 0246 | 137.7 Del. | 26 Apr 72 | 0904 | 147.0 Del. |
| | 1456 | 126.0 " | | 2015 | 133.3 " |
| 27 Apr 72 | 0325 | 53.3 " | 27 Apr 72 | 0951 | 107.0 " |
| | 1535 | 99.3 " | | 2046 | 97.0 " |
| 28 Apr 72 | 0401 | 28.3 " | 28 Apr 72 | 1034 | 81.0 " |
| | 1609 | 74.7 " | | 2117 | 84.7 " |
| 29 Apr 72 | 0435 | 14.3 " | 29 Apr 72 | 1113 | 72.7 " |
| | 1635 | 74.3 " | | 2150 | 95.3 " |
| 30 Apr 72 | 0506 | 39.7 " | 30 Apr 72 | 1151 | 56.0 " |
| | 1655 | 42.0 " | | 2224 | 46.0 " |
| 1 May 72 | 0537 | 15.0 " | 1 May 72 | 1226 | 31.7 " |
| | 1717 | 49.3 " | | 2300 | 62.7 " |
| 2 May 72 | 0609 | 38.0 " | 2 May 72 | 1303 | 57.3 " |
| | 1747 | 65.3 " | | 2341 | 71.3 " |
| 3 May 72 | 0645 | 36.0 " | 3 May 72 | 1340 | 57.7 " |
| | 1827 | 50.7 " | 4 May 72 | 0027 | 5.4 miles* |
| 4 May 72 | 0726 | 28.3 | | 1420 | 5.1 miles* |
| | 1918 | 0.8 miles* | 5 May 72 | 0119 | -1.1 miles* |
| 5 May 72 | 0812 | 4.3 miles* | | 1502 | -3.0 miles* |
| | 2021 | -2.6 miles* | 6 May 72 | 0220 | -2.9 miles* |
| 6 May 72 | 0902 | 4.9 miles* | | 1546 | 0.0 miles* |
| | 2134 | 4.5 miles* | 7 May 72 | 0330 | -1.7 miles* |

* Distance from Chesapeake City Bridge at end of study.
Positive value indicates eastward movement.

dimensions. We had intended to determine the pre-enlargement and post-enlargement flow conditions using a numerical model of the dynamic processes in the Canal and its approaches. However, such a model required adjustment and verification using observed currents in the Canal and water surface elevation records from the two ends of the Canal. While the current measurements were adequate for such adjustment and verification of the model, the tide gage records at either Reedy Point or Courthouse Point were incomplete for all of the three study periods.

A less precise but probably still useful estimate of the changes in the flow conditions in the Canal due to enlargement can be made by combining our results with some of those obtained using the hydraulic model of the Canal by personnel of the Waterways Experimental Station, Vicksburg, Mississippi. The procedure involves the following sequential set of arguments (1-8):

(1) Although a segment of the C and D Canal just west of Reedy Point is uncompleted, the high tidal velocities which occur in this stretch, due to the reduction in resistance to the flow over the remaining length of the Canal, has resulted in considerable scouring of this segment. Consequently, the cross-sectional area in this segment is considerably greater than that for the old 27-ft x 250-ft channel dimensions. The flow conditions in the Canal at present are probably much closer to those which will occur after completion of enlargement than is implied by the one test of present conditions using the hydraulic model at WES. Our best present estimate is that about 75% of the total effect in flow conditions which will occur as a result of Canal enlargement has already occurred.

(2) The model tests at WES confirm expected results that the net non-tidal flow through the Canal is strongly dependent upon the difference in water surface elevation between Reedy Point at the eastern end of the

Canal and Courthouse Point near the western end of the Canal. The tests conducted with the new 35-ft by 450-ft channel dimensions indicate a linear relationship between the net non-tidal flow, $\overline{Q}$, and the average difference in water surface elevation between the two ends of the Canal, $\overline{\Delta h}$ (Courthouse Point MTL minus Reedy Point MTL), which passes through the origin $\overline{Q} = 0$, $\overline{h} = 0$. The relationship is given approximately by

$$\overline{Q} = 30{,}500\,\overline{\Delta h}$$

with $\overline{Q}$ given in cfs and $\overline{\Delta h}$ in feet.

(3) The somewhat non-linear relationship between $\overline{Q}$ and $\overline{\Delta h}$ as indicated by the WES model studies for the old 27-ft x 250-ft Canal, which fails to pass through the origin, is difficult to explain on theoretical grounds. Particularly troublesome is the positive head difference of about +0.16 ft for $\overline{Q} = 0$. Part of this zero net-flow head difference can be explained in terms of the density (or salinity) gradient through the Canal. The normal difference in salinity between Reedy Point and Courthouse Point is slightly over 2 o/oo, corresponding to a density difference of approximately $1.6 \times 10^{-3}$ g/cm$^3$. This density difference could account for a head difference of at most 0.06 ft. A density-related head difference of 0.16 ft would require a salinity difference through the Canal of about 7.9 o/oo, a difference seldom observed.

It should be noted that the two model tests made for the 27-ft by 250-ft Canal, under conditions of zero salinity in the Elk River, do suggest a linear relationship between $\overline{Q}$ and $\overline{\Delta h}$ which passes through the point $Q = 0$, $h = 0$. We consider that the most suitable flow relationship to use for the pre-enlargement Canal is

$$\overline{Q} = 12{,}300\,\overline{\Delta h}\ .$$

(4) It is our present estimate that the flow conditions measured in the Canal represent about 75% of the total change from pre-enlargement to post-enlargement conditions. The relationship between net non-tidal flow through the Canal and head difference between Canal ends for the present velocity study is:

$$\overline{Q} = 25{,}900\ \overline{\Delta h}$$

(5) The present estimates of the non-tidal flow (and variation) are obtained by analysis of the individual net non-tidal flow for each tidal cycle for each of the cross sections during the three study periods. On this basis, the following values (a-i) describe the flow conditions in the presently incomplete Canal. Positive flows are eastward and negative flows are westward.

(a) Long-term average net non-tidal flow:

$\overline{Q} = +2080$ cfs

(b) SD of individual tidal cycle values of $\overline{Q}$ from long-term average

SD = $\pm$ 12,591 cfs

(c) Probable error (PE) of estimate of $\overline{Q}$

$PE_{\overline{Q}} = \pm 545$ cfs

(d) Of the individual tidal cycle values, 60% are directed eastward, with a long-term average value:

$\overline{Q}_E = +9313$ cfs

(e) SD of individual values of $\overline{Q}_E$ from long-term average value

SD = $\pm$ 9082 cfs

(f) PE of estimate of $\overline{Q}_E$

$PE = \pm 509$ cfs

(g) Of the individual tidal cycles, 40% are directed westward with a long-term average.

$\overline{Q}_W = - 8697$ cfs

(h) SD of individual values of $\overline{Q}_W$ from long-term average

$SD = \pm 8625$ cfs

(i) PE of estimate of $\overline{Q}_W = \pm 591$ cfs.

(6) On the vasis of the relationship:

$$\overline{Q} = 25{,}900\ \overline{\Delta h}$$

selected as our estimate for the flow conditions for the <u>present</u> <u>incomplete</u> <u>Canal</u>, the head difference between Courthouse Point and Reedy Point, corresponding to the long-term average value of $\overline{Q}$ of +2080 cfs, is $\overline{\Delta h} = +0.080$ ft. This value is considerably smaller than the value previously obtained from analysis of tide gage records, and suggests that there may be an error in the leveling between the gages at the two ends of the Canal by as much as 0.15 ft.

(7) Using the relationship:

$$\overline{Q} = 12{,}300\overline{\Delta h}$$

as representative of flow conditions in the <u>old</u> 27-ft by 250-ft Canal, the following values (a-h) describe the flow conditions assuming a head difference between the two ends of the Canal of + 0.08 ft.

(a) Long-term average net non-tidal flow:

$\overline{Q} = +988$ cfs

(b) SD of individual tidal cycle values of $\overline{Q}$ from long-term average

SD = ± 5980 cfs

(c) Long-term average of eastward flow

$\overline{Q}_E = +4423$

(d) SD of long-term average of eastward flow

SD = ± 4313 cfs

(e) Long-term average of westward flow

$\overline{Q}_W = -4130$ cfs

(f) SD of long-term average of westward flow

SD = ± 4096 cfs

(g) Maximum predicted eastward non-tidal flow

$(\overline{Q}_E)$ max = + 20,100 cfs

(h) Maximum predicted westward flow

$(\overline{Q}_W)$ max = - 15,300 cfs

The last two numbers are the expected maximum net non-tidal eastward and westward flows for a single tidal cycle.

(8) By a similar approach, the following estimates (a-h) of the long-term average net non-tidal flow, and of the other statistical parameters of the flow, for flow conditions characteristic of the post-enlargement Canal, are made:

(a) Long-term average net non-tidal flow

$\overline{Q} = +2450$ cfs

(b) SD of individual tidal cycle values of $\overline{Q}$ from long-term average

SD = ± 14,827 cfs

(c) Long-term average of eastward flow

$\overline{Q}_E = +10{,}967$ cfs

(d) SD of long-term average of eastward flow

SD = ± 10,695 cfs

(e) Long-term average of westward flow

$\bar{Q}_W$ = -10,242 cfs

(f) SD of long-term average of westward flow

SD = ± 10,157 cfs

(g) Maximum predicted eastward non-tidal flow

$(\bar{Q}_E)$ max = + 49,800 cfs

(h) Maximum predicted westward flow

$(\bar{Q}_W)$ max = - 37,900 cfs.

Probable (standard) errors cannot be calculated for some of the statistical parameters in items 7 and 8 without having estimates of sample size.

5. Summary of probable post-enlargement environmental conditions.

The following summarizes the expected changes in environmental conditions in the post-enlargement Canal from those which probably existed in the pre-enlargement Canal.

(1) The tidal velocities in the post-enlargement Canal will be about 15% larger than the tidal velocities in the pre-enlargement Canal.

(2) About 60% of the individual tidal cycle values of the net non-tidal flow will be directed eastward, and about 40% westward, in the post-enlargement Canal. T his partition is the same as existed for the pre-enlargement Canal.

(3) The long-term average net non-tidal flow will increase from about +990 cfs (i.e., eastward) for the pre-enlargement Canal to about +2450 cfs for the post-enlargement Canal. There is some evidence that these average values will be somewhat larger in spring, and somewhat smaller in late summer and fall.

(4) The standard deviation of the individual tidal cycle values of the net non-tidal flow from the long-term average will increase in magnitude from about ± 5980 cfs for the pre-enlargement Canal to about ± 14,830 cfs for the post-enlargement Canal.

(5) The 60% of the individual tidal cycles which have an eastward directed net non-tidal flow will have an increase in the average eastward net non-tidal flow from a value of about + 4425 cfs for the pre-enlargement Canal to about + 10,965 cfs for the post-enlargement Canal.

(6) The standard deviation of the individual eastward directed net non-tidal flows from the average of the eastward directed net non-tidal flows will increase in magnitude from a value of about ± 4315 cfs for the pre-enlargement Canal to about ± 10,695 cfs for the post-enlargement Canal.

(7) The 40% of the individual tidal cycles which have a westward directed net non-tidal flow will have an increase in the average westward net non-tidal flow from a value of about -4130 cfs for the pre-enlargement Canal to about -10,240 cfs.

(8) The standard deviation of the individual westward directed net non-tidal flows from the average of the westward directed net non-tidal flows will increase in magnitude from about ± 4095 cfs for the pre-enlargement Canal to about ± 10,155 cfs for the post-enlargement Canal.

(9) The expected maximum eastward directed net non-tidal flow for a single tidal cycle will increase from about +20,100 cfs for the pre-enlargement Canal to about +49,800 cfs for the post-enlargement Canal.

(10) The expected maximum westward directed net non-tidal flow for a single tidal cycle will increase in magnitude from about -15,300 cfs for the pre-enlargement Canal to about -37,900 cfs for the post-enlargement Canal.

(11) The ratio of the various parameters of the net non-tidal flow (i.e., the average, the standard deviation, and the maximum values) for post-enlargement to pre-enlargement conditions of about 2.48 is about 15% larger than the ratio of the post-enlargement cross-sectional area to the pre-enlargement cross-sectional area of 2.20. Hence the tidal velocities and the tidal excursions for the post-enlargement Canal will be only about 15% greater than those for the pre-enlargement Canal.

(12) The transport times required for the center of mass of specific water parcels from an initial position (say, Chesapeake City) to leave the Canal and enter either the Delaware estuary or the upper Chesapeake Bay will be about 15% less for the post enlargement Canal than for the pre-enlargement Canal. Hence there will be a corresponding increase in the probability that a particular water parcel will be transported out of the Canal into the Delaware River,in a time period which is less than some critical biological time period, for post-enlargement conditions as compared to pre-enlargement conditions.

(13) The slight changes in the salinity in the Canal and its approaches for post-enlargement conditions as compared to pre-enlargement conditions will be too small to have biological consequences.

(14) The salinities in the upper Chesapeake Bay will be somewhat higher for the post-enlargement Canal than for the pre-enlargement Canal. The size of such a change in the salinities and the biological consequences of the change will require further analysis.

## E. ECOLOGICAL EFFECTS OF ENLARGEMENT

The Chesapeake and Delaware Canal area serves as a habitat for a variety of freshwater, estuarine and marine species for either all or part of their life cycle. To determine what kinds of aquatic organisms and communities utilize this man-made habitat and to estimate what possible effects enlargement of the Canal might impose upon the biota, an ecological program, through CBL and DCMS, was initiated. Basically, the ecological program was designed to measure the following (1-5):

(1) to survey the benthic community for species composition and biomass both spatially and temporally,

(2) to survey the distribution and abundance of fish eggs and larvae in the Canal and its approaches,

(3) to study the effect of salinity, suspended sediment, and flow on fish eggs and larvae common to the Canal,

(4) to determine fish movements through the Canal,

(5) to determine the distribution and abundance of fish in the Canal.

### 1. Biological uses of the Canal system

a. <u>Benthos</u> (Appendices III and IV)

The benthic investigation of the Chesapeake and Delaware Canal system included the approaches from the upper Chesapeake Bay and from the Delaware River, as well as the Canal proper (Figs. 8 and 9). The "upper Chesapeake Bay approach" includes the area from approximately 8 miles south of Turkey Point to Welch Point, a total of 13 miles, and includes the Bohemia and

Elk Rivers. The "Canal proper" refers to the area from Welch Point to Reedy Point, a stretch of 14 miles. The "Delaware River approach" refers to an area from Reedy Island to a point 3 miles north of Pea Patch Island, a total of 14 miles.

In the Delaware River approach and the Delaware side of the Canal proper, a total of 22 benthic invertebrate species were collected. However, 6 species made up over 90% of the numerical total. These were the hydrozoan *Garveia franciscana*, the oligochaete worm *Limnodrilus* sp., the polychaete worm *Scolecolepides viridis*, the isopod crustaceans *Chiridotea almyra* and *Cyathura polita*, and the amphipod crustacean *Gammarus daiberi*. The bottom sediments varied from large gravel to sands and silts, dependent on the station location. Water temperatures ranged from near 0 C (32 F) in winter to 27 C (80.6 F) in midsummer. Salinity varied from 0.1 to 8.0 o/oo with the highest salinity attained in late summer.

In the upper Chesapeake Bay approach and in the Maryland portion of the Canal proper, a total of 25 species of benthic invertebrates were collected. Eight of these species made up over 90% of the fauna numerically. These included the oligochaete worm *Limnodrilus* sp., the polychaete worm *Scolepides viridis,* the amphipod crustacean *Leptochierus plumulosus*, the isopod crustacean *Chiridotea almyra*, the molluscan snail *Hydrobia* sp., and the insect larvae *Chironomus attenuatus*, *Procladius* sp., and *Coelotanypus scapularis*. In this western approach to the Canal, the salinity varied between 0.15 and 2.6 o/oo. The water temperature ranged from 5 to 28.9 C (41.0 to 84.0 F). Samples of the fauna were taken from varied water depths and predominantly sand and silt sediment types.

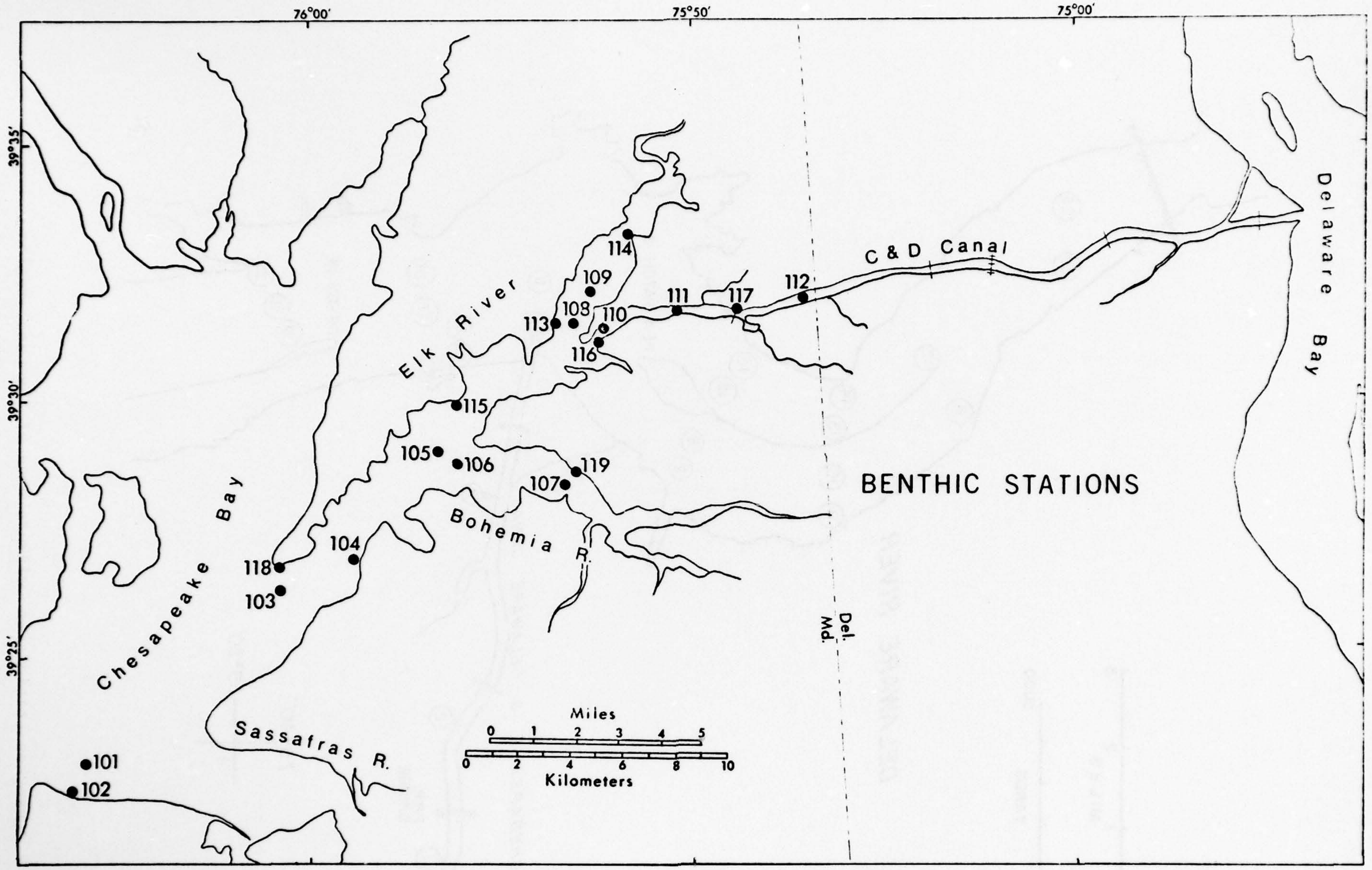


Fig. 8. Maryland benthos stations in the Canal region

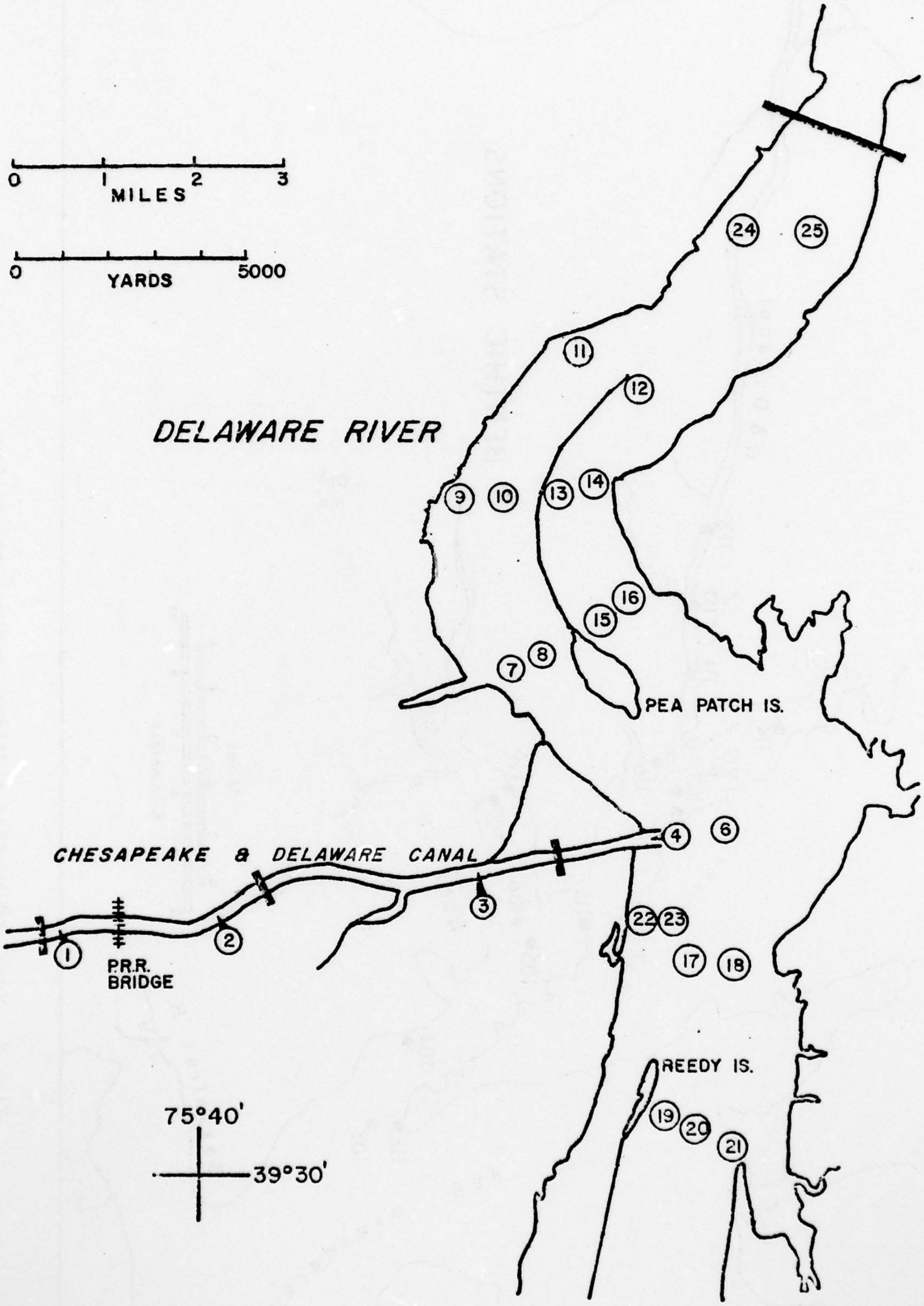


Fig. 9. Benthos stations in Delaware area of the Canal region.

In the Canal proper, no additional species of benthic invertebrates were found but the most common inhabitants were the isopod crustacean Chiridotea almyra, and the polychaete worm Scolecolepides viridis. The numbers of S. viridis decreased eastward through the Canal, while the numbers of C. almyra were highest in the center of the Canal and decreased both eastward and westward. The distribution pattern of the former is apparently in response to a salinity gradient. The crustacean Gammarus daiberi, while very abundant at the Delaware River approach stations, decreased westward through the Canal proper and was almost entirely absent from the Chesapeake Bay approach. The crustacean Leptochierus plumulosus, although the second most abundant benthic invertebrate collected in the Chesapeake Bay approaches, was not collected in the Canal proper and was never collected from the Delaware River approach stations. Rangia cuneata, a clam, was also abundant in the Chesapeake but only 5 living specimens were collected from the Delaware River and eastern portion of the Canal proper although shells of dead specimens were fairly common.

At the Chesapeake Bay approach, an average density of 1,416 individual benthic specimens were collected per $m^2$ of bottom material. The extremely high density of one species of snail, Hydrobia, at two stations, found only during one sampling period, accounts for this high value. If this species is excluded, a lower and more realistic average standing crop of 865 individuals/$m^2$ was found. A decreasing biomass from 1.19 g/$m^2$ to 0.76 g/$m^2$ was found progressing from the Chesapeake approaches to the Canal proper.

In the Delaware River approach and Delaware portion of the Canal proper, the biomass of organisms was somewhat less but indicated a similar gradient pattern. At stations outside the Canal, values averaged 0.542 g/m$^2$ and in the Canal proper the average values were 0.038 g/m$^2$. The density of individuals averaged 228 per m$^2$.

In comparison with other documented areas of the Chesapeake and Delaware Bays, the C and D Canal system is less productive in terms of number of species of benthic invertebrates and number of specimens. An adjacent downbay area of the Chesapeake Bay yielded 66 species whereas this study included only 35 species of benthos. The decrease may be attributed to the comparatively low salinity and the seasonal changes from fresh or near fresh to 2.5 o/oo at the Chesapeake approach to the Canal and near 8 o/oo at the Delaware approach. Change in numbers of species and specimens in either direction was probably due to change in salinity and the tolerance of species to the salinity gradient. Also, the lack of firm bottom and shell substrates limited the diversity of species found in this area.

The benthic fauna of the Canal study area were found to be of considerable importance as food items for resident and migratory fish species occurring in the Canal area. Stomach analysis of major species of fish sampled in all portions of the study area showed a relationship between density of benthic organisms found in the bottom and number of items found in the stomachs. Usually the most abundant benthic species were found to be the most abundant food items found in the stomachs analyzed.

Table 13. A list of fishes caught in the C and D Canal study.

| | COMMON NAME | SCIENTIFIC NAME | OCCURRENCE[1/] |
|---|---|---|---|
| | **Species caught throughout the Canal region** | | |
| 1. | Atlantic menhaden | *Brevoortia tyrannus* | M |
| 2. | Atlantic needlefish | *Strongylura marina* | M |
| 3. | Bluefish | *Pomatomus saltatrix* | M |
| 4. | Silver perch | *Bairdiella chrysura* | M |
| 5. | Weakfish | *Cynoscion regalis* | M |
| 6. | Spot | *Leiostomus xanthurus* | M |
| 7. | Atlantic croaker | *Micropogon undulatus* | M |
| 8. | Black drum | *Pogonias cromis* | M |
| 9. | Carp (scaled) | *Cyprinus carpio* | F |
| 10. | Golden shiner | *Notemigonus crysoleucas* | F |
| 11. | White catfish | *Ictalurus catus* | F |
| 12. | Brown bullhead | *Ictalurus nebulosus* | F |
| 13. | Channel catfish | *Ictalurus punctatus* | F |
| 14. | Yellow perch | *Perca flavescens* | F |
| 15. | Naked goby | *Gobiosoma bosci* | F |
| 16. | Bay anchovy | *Anchoa mitchilli* | E |
| 17. | Northern pipefish | *Syngnathus fuscus* | E |
| 18. | White perch | *Morone americana* | E |
| 19. | Hogchoker | *Trinectes maculatus* | E |
| 20. | Blueback herring | *Alosa aestivalis* | A |
| 21. | Hickory shad | *Alosa mediocris* | A |
| 22. | Alewife | *Alosa pseudoharengus* | A |

The amphipod Gammarus daiberi was the most abundant benthic species found in the Delaware River approach and Delaware end of the Canal proper and was the most abundant food item found in fish stomachs analyzed from these areas. In the upper Chesapeake Bay approach and Maryland end of the Canal proper, the annelid worm Scolecolepides viridis was the most abundant species found in the sediment and was the most abundant form found in fish stomachs analyzed in these areas. Two exceptions were the hydrozoan Garveia franciscana and the oligochaete Limnodrilus sp. which were abundant in the Delaware River and upper Chesapeake Bay approaches, respectively, but quite rare in the stomachs analyzed.

b. Adult Fish (Appendices VI, VII, VIII, and IX)

The Canal and its approaches from the Delaware and Chesapeake Bays play various roles in the life cycles of the different species found there. Fifty-two species of fishes, both juvenile and adult, were found in the Canal region during the 30 months of the study. Other species were present, but they were not obtained with the gear used.

Table 13 lists 25 species that were caught in both the Delaware portion and Maryland portion of the C and D Canal region during the present study, 9 species caught only in Delaware waters of the Canal, and 18 species caught only in Maryland waters of the Canal. Many species of fish reside in the Canal but were not collected. The region of the C and D Canal is typically estuarine in nature, having marine, freshwater, estuarine and diadromous species in the area. The total number of 52 fish species encountered in the 30-month study is approximately one-fourth of the fish species known to occur in the Chesapeake system.

Table 13. (Continued)

| COMMON NAME | SCIENTIFIC NAME | OCCURRENCE[1/] |
|---|---|---|
| 23. Gizzard shad | Dorosoma cepedianum | A |
| 24. Striped bass | Morone saxatilis | A |
| 25. American eel | Anguilla rostrata | C |
| **Species caught only in Delaware portion of the Canal region** | | |
| 1. Sea lamprey | Petromyzon marinus | M |
| 2. Northern searobin | Prionotus carolinus | M |
| 3. Speckled trout | Cynoscion nebulosus | M |
| 4. Atlantic sturgeon | Acipenser oxyrhynchus | F |
| 5. Silvery minnow | Hybognathus nuchalis | F |
| 6. Common shiner | Notropis cornutus | F |
| 7. Bluegill | Lepomis macrochirus | F |
| 8. Atlantic silverside | Menidia menidia | E |
| 9. American shad | Alosa sapidissima | A |
| **Species caught only in Maryland portion of the Canal region** | | |
| 1. Atlantic herring | Clupea harengus harengus | M |
| 2. Black sea bass | Centropristis striata | M |
| 3. Butterfish | Peprilus triacanthus | M |
| 4. Harvest fish | Peprilus alepidotus | M |
| 5. Goldfish | Carassius auratus | F |
| 6. Johnny darter | Etheostoma nigrum | F |
| 7. Largemouth bass | Micropterus salmoides | F |

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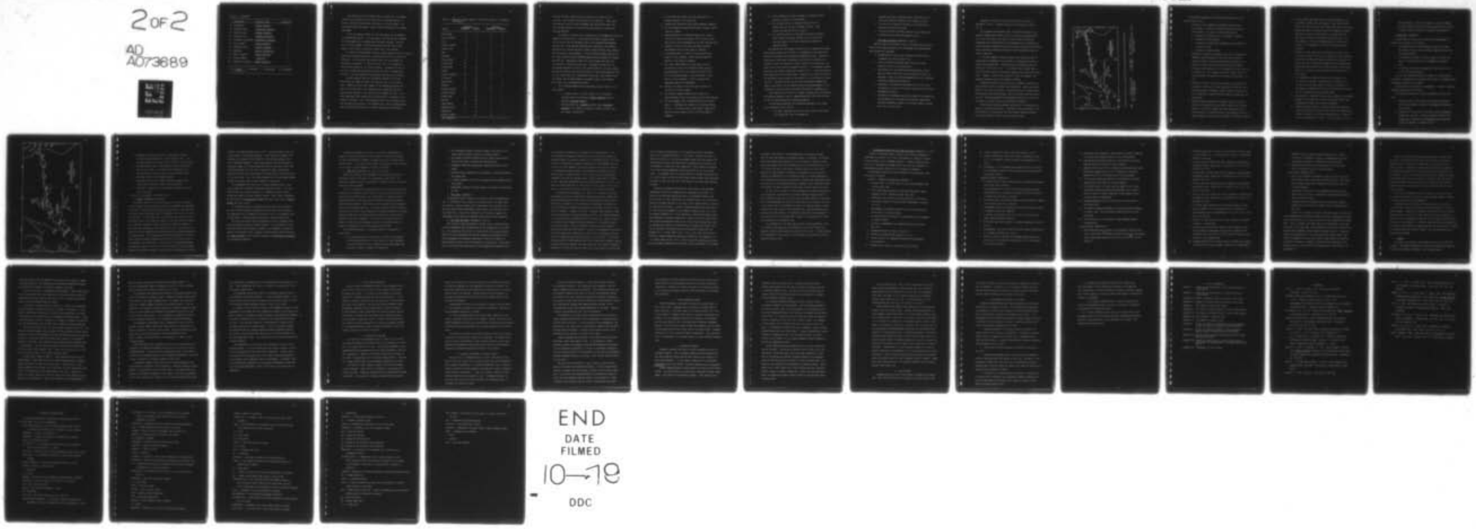

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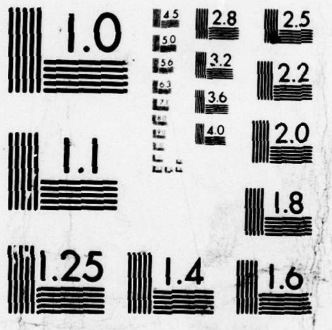

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Table 13. (Continued)

| | COMMON NAME | SCIENTIFIC NAME | OCCURRENCE[1/] |
|---|---|---|---|
| 8. | Pumpkinseed | *Lepomis gibbosus* | F |
| 9. | Smallmouth bass | *Micropterus dolomieui* | F |
| 10. | Spottail shiner | *Notropis hudsonius* | F |
| 11. | Striped blenny | *Chasmodes bosquianus* | F |
| 12. | Threespine stickleback | *Gasterosteus aculeatus* | F |
| 13. | White crappie | *Pomoxis annularis* | F |
| 14. | Banded killifish | *Fundulus diaphanus* | E |
| 15. | Mummichog | *Fundulus heteroclitus* | E |
| 16. | Rough silverside | *Membras martinica* | E |
| 17. | Oyster toadfish | *Opsanus tau* | E |
| 18. | Tidewater silverside | *Menidia beryllina* | E |

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[1/] M = marine, E = estuarine, C = catadromous, F = freshwater, A = anadromous.

Even though there are 9 species that are caught only in Delaware portion and 18 species that are caught only in Maryland portion, it does not mean that those species are unique to the area caught. All the species listed are known to occur in both the Delaware and Maryland watersheds.

Of all the species listed, only the sea lamprey can be regarded as an undesirable species. But here again, this fish has been recorded in the Chesapeake Bay, including Havre de Grace, Maryland. The fact that it was not caught in the Maryland portion of the C and D Canal region is most likely a chance miss rather than a true absence.

At specific periods during the year, certain migratory species (Table 14) became very abundant and made up a significant part of the overall fish population. In the spring, striped bass moved into and through the Canal area for spawning. At that time (May), up to 75 kilograms per mile tow were present at the stations sampled. Throughout the rest of the year, striped bass biomass was usually less than 5 kilograms per mile tow. The other important spring migrant species was the alewife.

Juvenile weakfish and spot are dominant species in the Canal area during the summer and early fall when they use it as a nursery area. Weakfish are much more abundant in the Delaware approaches and part of the Canal than in the Chesapeake side, suggesting that this species gains entrance to the Canal from the Delaware end only. A multiple regression model showed that the distribution of weakfish is correlated to salinity. Up to 100 kilograms per mile tow of juvenile weakfish per month were present in the Delaware area. Spot are approximately evenly distributed throughout the system, indicating that they enter

Table 14. Ranking of fishes caught in the C and D Survey as to abundance and biomass.

| Species | Maryland Abundance | Maryland Biomass | Delaware Abundance | Delaware Biomass |
|---|---|---|---|---|
| White perch | 1 | 1 | 1 | 1 |
| Brown bullhead | 5 | 2 | 11 | * |
| Carp | 17 | 3 | * | * |
| Channel catfish | 4 | 4 | 8 | 6 |
| American eel | 8 | 5 | 9 | 7 |
| Spot | 9 | 6 | 4 | 8 |
| Hogchoker | 3 | 7 | 7 | 5 |
| White catfish | 16 | 8 | 14 | * |
| Striped bass | 12 | 9 | 3 | 3 |
| Gizzard shad | 11 | 10 | * | * |
| Alewife | 7 | 11 | 5 | 4 |
| Atlantic menhaden | 10 | 12 | 10 | * |
| Bay anchovy | 2 | 13 | 6 | * |
| Yellow perch | 13 | 14 | * | * |
| Weakfish | 6 | 15 | 2 | 2 |
| Blueback herring | 14 | 16 | 12 | * |
| Spottail shiner | * | 17 | * | * |
| Hickory shad | * | 18 | * | * |
| Goldfish | * | 19 | * | * |
| Johnny darter | 15 | 20 | * | * |
| Largemouth bass | * | 21 | * | * |
| Pumpkinseed | * | 22 | * | * |
| Atlantic croaker | * | 23 | 13 | * |

*Not rankable.

the area from both sides since they spawn only in waters of high salinity. Spot biomass was lower than that of weakfish. Other important species, such as Atlantic menhaden, also utilize the Canal area for a nursery ground, but these species were usually not caught with the gear employed.

One species, the white perch, dominated all fish populations (Table 14) sampled in the Canal area. The average total monthly biomass figure for 18 stations was 170 kilograms and at times exceeded 380 kilograms per mile tow. Other species contributing to the bulk of the resident populations are channel and white catfish, brown bullhead, carp, American eel, bay anchovy, and hogchoker. The total monthly biomass figures for all other resident species combined generally never exceeded 75 kilograms per mile tow. Approximately 80% of the total biomass came from the Maryland part of the Canal study area. The probable reasons for the much higher abundance of fish on the Maryland side are: (1) most resident species are found in lower salinity water; (2) the Maryland approach area to the C and D Canal has a considerably larger and a more diverse drainage system; and (3) water quality is probably lower in the Delaware River than in the Chesapeake tributaries.

The following summarizes the information on adult fishes in the Canal region:

1. In Delaware waters, the most abundant of the 33 species collected were the white perch (Morone americana) and the weakfish (Cynoscion regalis).
2. The striped bass (M. saxatilis) and the spot (Leiostomus xanthurus) were caught in significant numbers in spring and late summer, respectively.

3. Of the above four fishes, only the white perch is a resident species in the Canal area.
4. Striped bass utilize the Canal during spawning migration.
5. The two sciaenids, weakfish and Atlantic croaker, use the area as a nursery.
6. Stomach analysis of six species suggest that invertebrates are a primary food source, but the Canal contributes little to the maintenance of the fish captured there.
7. Abundance of fish in the study was highly variable and declined over the three years of sampling.
8. In Maryland waters, a total of 41 fish species were caught by otter trawling. Beach seining yielded 23 species, 2 not caught by trawling.
9. The C and D Canal region as a fish habitat can be evaluated not only by the relatively large number of species present, but by the varieties of fish lives. Of the 59 species present, 24 are freshwater, 12 are marine, 16 are estuarine. Six of the species are anadromous and one is catadromous.
10. Various life stages of fish from eggs to adults can be found in the Canal region.
11. The young of resident species use the Canal as a nursery ground as well as the young of many marine species.
12. The most abundant fish in Maryland waters is the white perch. It dominates the catches at all stations during the year. The total weight of white perch caught nearly equals the total weight of all of the other species combined.

13. Three catfishes (the brown bullhead, the channel catfish, and white catfish) are also abundant.
14. The smallest catches are generally made during the colder months of the year (December to March). Best catches are made from April to August.
15. The sampling stations in the upper Elk River and Bohemia River yielded the largest catches, and stations in the artificial part of the Canal consistently yielded the smallest catches.

Data gained from fish tagging indicate that all resident and anadromous species present use the Canal as a passageway in both directions between the Delaware River and upper Chesapeake Bay areas. Striped bass utilizing the Canal make an important contribution to the sport and commercial catch from Maryland to Maine. Hickory shad and American shad were the only other species recaptured outside of the Chesapeake-Delaware Bays area, with hickory shad moving to North Carolina rivers and American shad migrating up the Atlantic Coast. Recaptures for these three principal anadromous species show that fish return to use the Canal on succeeding years. Resident species use the Canal for movements between the areas at each end, with the freshwater ones moving predominately to the Maryland end for less saline water when necessitated by spawning, etc.

Other species such as Atlantic sturgeon, American eels, the herrings, and Atlantic menhaden, were not tagged during this study, but are known to use the Canal during their migratory movements.

The following summarizes the information obtained in the tagging study completed by DCMS and CBL:

1. The upper Chesapeake Bay and the C and D Canal is the source for striped bass found in Delaware Bay.

2. Striped bass found in Delaware waters contribute to the sport and commercial fisheries from Virginia to Maine.
3. The Canal is an important waterway in the migrations of American shad and hickory shad.
4. The Canal is used by resident species to move between the Delaware River and upper Chesapeake Bay area.

## C. Fish eggs and larvae (Appendices I and II)

Specific goals of the present study of the production and distribution of fish eggs and larvae in the Chesapeake and Delaware Canal area included the following:

1. Determination of the species utilizing the Canal area as a spawning site and/or nursery area.
2. Precise location of spawning areas within the system, especially those of the striped bass.
3. Determination of the production and distribution of fish eggs and larvae within the C and D system with respect to geography, season, and physical parameters of the environment, especially temperature and salinity.
4. Assessment of the possible importance of the C and D area to production of each of the several species within the entire Chesapeake Bay region.
5. Integration of knowledge gained from studies of the production and distribution of fish eggs and larvae with hydrographic information hopefully leading to an optimal scheme of management for the C and D area.

Summaries of the work on fish eggs and larvae are found in Appendices I and II. Sampling stations for the study are shown in Fig. 10.

The Chesapeake and Delaware Canal, an artificial system, is an important spawning and nursery area for a variety of estuarine fish. All of the fish species that spawn in other estuarine systems of Chesapeake Bay and Delaware Bay are represented with the exception of those fish species associated with high salinity and oyster bar habitats. Typical estuarine anadromous species are well represented in egg and larvae collections.

As in most temperate estuarine systems, most spawning occurs in spring when the temperature of the water is increasing from winter to summer water temperatures. High densities of striped bass eggs and larvae are found in the Canal. It is evident that the Canal area is one of the most important striped bass spawning areas along the Atlantic Coast. Indeed, it may be more important to both the Delaware and Maryland fisheries than we can presently estimate.

Summertime spawning in the Canal area is primarily restricted to forage fishes such as the anchovy and silversides. During the summer and fall, the Canal is primarily a nursery area for the juveniles produced during the spring and summer, both in the Canal area and from the two bays. High phytoplankton and zooplankton production in the Canal area appears to supply food for the larvae and juveniles.

Other typical estuarine spawners (white perch, the herrings, and shad) use the Canal intensively. Production of eggs and larvae in the Canal during the spring period for these species compares favorably with other estuarine systems along the Atlantic Coast.

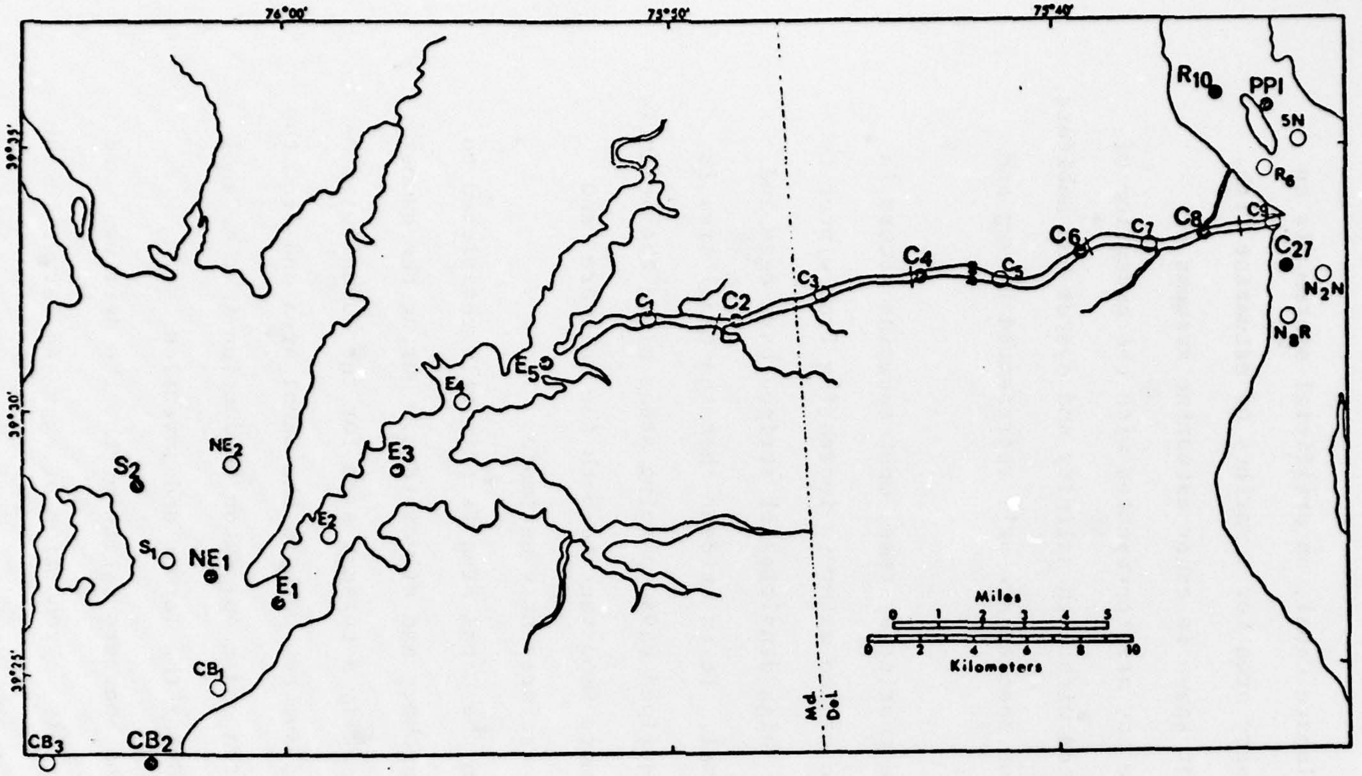

Figure 10. Location of fish egg and larvae stations during 1971 sampling year.

Key

S = Susquehanna River
NE = Northeast River
CB = Chesapeake Bay
E = Elk River
C = C&D Canal
PPI = Pea Patch I .
C27, R10 etc correspond to navigation buoys.

The following summarizes the information obtained in the fish eggs and larvae study:

1. The area of the Chesapeake and Delaware Canal fits well the concept of a common low-salinity estuarine nursery for larval fishes. The concept includes these points:
    a. reduction of competition in a low-diversity community
    b. abundance of food organisms
    c. occurrence of higher water temperature than in down-bay or coastal waters
    d. presence of fewer predators.
2. Although the striped bass appears to be the only numerically important species collected in the actual area covered by transect stations, the larvae and juveniles of more than 20 species of fishes have been recovered from Canal samples.
3. Although strong seasonality in the abundance of a given species is evident, as in all temperate estuaries, young fishes (of various species) are present in the Canal area throughout the year.
4. The months of April, May, and June appear to be particularly important in this area as these three months effectively cover the peak periods of abundance of eggs, larvae, and juveniles of all numerically important species except the naked goby and bay anchovy.
5. Important species spawning in freshwater found in the Canal area are the striped bass, white perch, alewife, and blueback herring. All but the striped bass spawn upstream in freshwater portions of tributaries and this is reflected in the far greater numbers of larvae taken than eggs of the latter 3 species.

6. No yellow perch eggs were taken (as might be expected), and the numbers of white perch and *Alosa* sp. eggs taken no doubt reflect the fact that those eggs captured have been carried downstream from areas of spawning, and do not adequately represent production of eggs of these species in the upper bay area.
7. The larvae of Alosa sp., white perch and yellow perch, show peak captures in the more freshwater portions of the Canal transect (the Chesapeake Bay, Elk River, and western Canal stations).
8. Important species spawning in estuarine waters found in the Canal area include the bay anchovy, naked goby, and silversides. Silverside and naked goby eggs are demersal and attached, but anchovy eggs are an important component of the ichthyoplankton during warm water months in more saline portions of the Chesapeake Bay. No anchovy eggs were taken in the sample from the Canal itself.
9. Our information on atherinid larvae is very meager due to the paucity of specimens recovered from our samples, but it is likely that the Canal samples, taken in mid-channel, do not provide an adequate picture of the utilization of the Canal area as a nursery area for silverside larvae.
10. The presence of naked goby and bay anchovy larvae is an excellent example of the concept of a common low salinity nursery area geographically remote from the area of spawning.
11. Important species spawning in marine waters whose larvae and juveniles are found in the Canal area include the American eel, Atlantic menhaden, and the three sciaenid species. Catches of juvenile sciaenids are too meager to justify more than noting

their occurrence. American eel elvers and Atlantic menhaden juveniles apparently utilize the Canal primarily as an access to upriver areas, and perhaps as access to Chesapeake Bay.

### D. Blue Crabs (Appendix V)

The objectives of the blue crab studies in the Chesapeake and Delaware Canal project are as follows:

1. to describe the blue crab population in the C and D Canal and adjacent areas in terms of density, population structure, and general behavior;
2. to determine the extent to which the Canal is used by blue crabs in migrations between the Chesapeake and Delaware Bays;
3. to determine what effect enlargement of the Canal will have on the blue crab population.

The blue crab program involved two studies: (1) a survey effort to describe the population on a seasonal basis, and (2) a tagging program to document migrations in the region.

Information for this species is in Appendix V. Figure 11 shows the sampling stations used in the study.

The following summarizes the results obtained in the blue crab study:

1. Crabs are found in the entire area during the warm months of the year; during cold months, they apparently migrate out of the region.
2. Densities of crabs caught in the region varied considerably between 1971 and 1972. Densities were much lower in 1972, perhaps due to salinities and temperatures that were lower during this period, as compared to 1971.

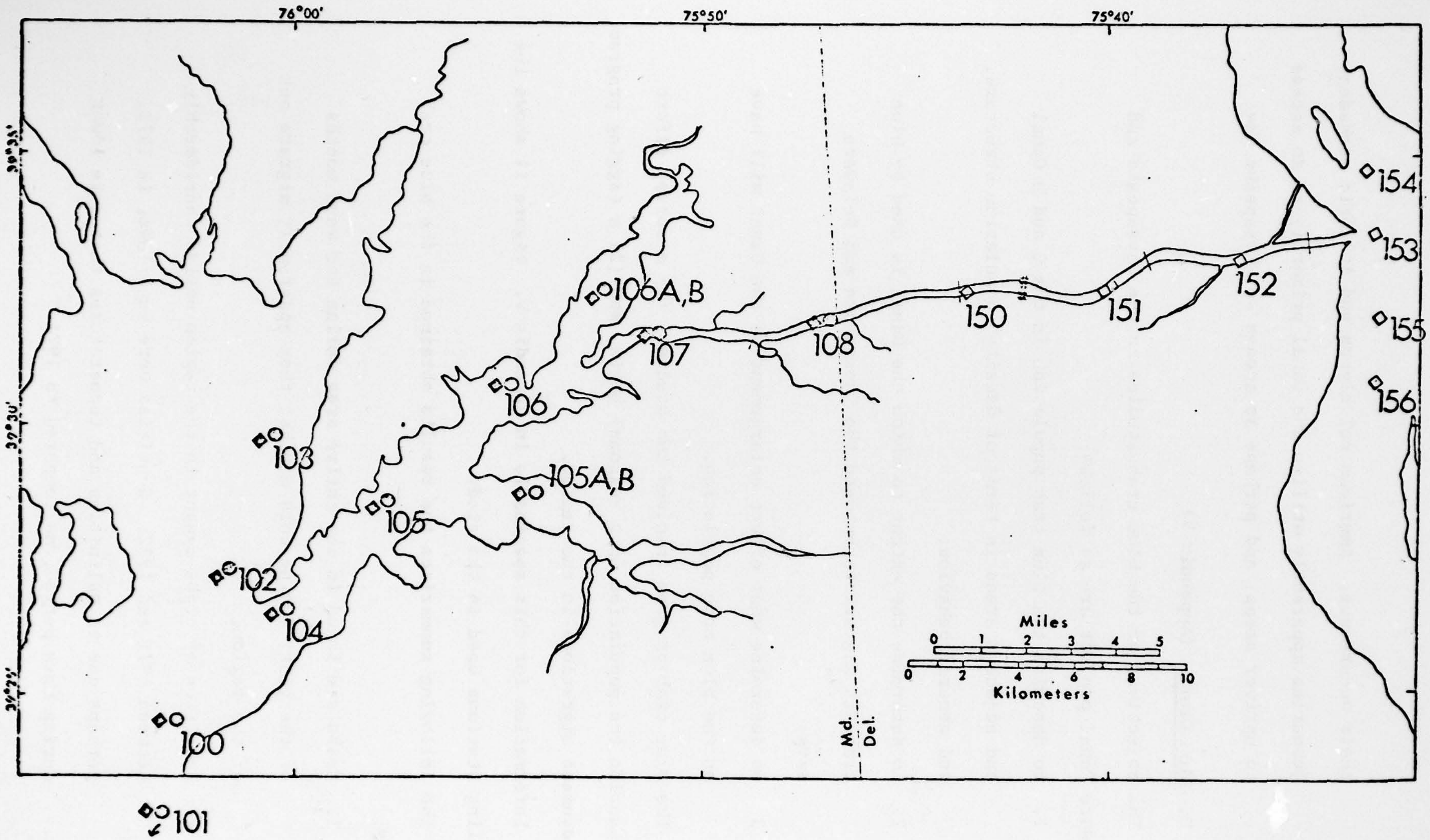

Fig. 11. Blue Crab sampling stations in the Canal area.

3. Population structure consists of a predominance of small and medium-sized individuals ( 120-mm carapace width). The Elk River seemed to be a particularly favorable nursery ground.
4. An approximately three-to-one male/female ratio was measured for all size classes. An exception was noted during June 1972 when density values as well as the male/female ratios were lower than in other sampling periods.
5. Preliminary results from tagging experiments suggest that crabs do pass through the Canal in both directions.
6. Direction of movement may be influenced by direction of water flow in the Canal.

## 2. Effects of Enlargement on Biological Uses

### a. Benthos (Appendices III and IV)

The benthic fauna of the Delaware approach to the Canal exhibited major differences from the benthic fauna of the Chesapeake Bay approaches to the Canal. Whether these differences existed prior to the opening of a sea-level Canal or developed after the opening of the Canal is a matter of conjecture. The important point is that after forty-six years these differences exist, even though the Canal is a sea-level Canal and theoretically provides unlimited transport between the different communities which have been maintained at both ends of the Canal. The physical conditions in the two approaches are different and allow different abundances of various species. The major physical differences noted in this study which affect the benthic organisms were salinity, bottom type, stability of conditions, and water quality. Salinity for the Chesapeake approach was generally between 0.5 and 2.0 o/oo, while salinities in the Delaware approach were generally between 0.3 and 8.0 o/oo and hydrographic studies indicate an average difference of 2.5 o/oo. Salinity tended to vary over a wider range in the Delaware approach. Tidal amplitude is greater and currents are stronger and more variable in the Delaware approach than in the Chesapeake approach. Bottom type showed no consistent pattern of difference except in the Canal proper where the bottom type is fine sand. Following dredging, the fine sand is replaced by poorly sorted silts. Apparently the silts are then scoured by current action, leaving fine sand as the bottom type. Thus, the bottom sediments of the Canal proper undergo substantial changes where and when dredging is carried out.

The hydrographic data show that a salinity gradient exists in the Canal proper with the salinity increasing from west to east. It is very probable that this salinity gradient is an important factor in determining distribution of various benthic species. This is well illustrated by the decline in _Scolecolepides viridis_ from west to east and of _Gammarus daiberi_ from east to west.

It is predicted that the enlargement of the Canal will not change the total salinity gradient through the Canal and that the salinities in the approaches will be changed by less than 0.5 o/oo. It is possible that a displacement of existing salinity patterns to the east could occur.

The other factor which must be considered is that of increased flows of water through the Canal in either direction. It is possible that this large flow could cause substantial changes in the abundance of sensitive species in the affected area. Examples of species which could be affected are _Gammarus daiberi_ in the Delaware approaches and _Leptochierus plumulosus_ in the Chesapeake approach.

Following enlargement of the Canal, the benthic communities are expected to maintain themselves in their present structure with perhaps a slight displacement of abundance eastward as long as an extreme event does not occur. If an extreme event occurs, which causes a large displacement of water to either approach, an effect is possible.

b. Adult fish (Appendices VI, VII, VIII, and IV)

There is no evidence that enlargement of the Canal will have any deleterious effect on its usage as a passageway by adult fish. The increase in current velocity is predicted to increase at most by 20% which should not affect movements.

There is a predicted three-fold increase in net flow from the present condition with occasional greater surges of lower salinity water from the Canal into the Delaware River. This could produce a condition where an anadromous species in the Delaware which follows a decreasing salinity gradient would encounter a low salinity water mass which leads through the Canal to the Chesapeake Bay area. At present, American shad and herrings now move past the Canal and up Delaware Bay spawning northward of the Canal. Changed response could increase numbers of individuals of these species spawning in the upper Chesapeake. If this occurs, assuming that water quality is better in the Chesapeake area than in the Delaware area, an increase in population size of these species would result.

The following summarizes the possible effects of enlargement on adult fishes:

1. The anticipated change of flow rate as a result of enlargement is relatively small and it is not expected to affect migration of fishes through the Canal, because fish are good swimmers and are quick to adapt to changed flow conditions.

2. The anticipated change in salinity regime in the Canal is not large enough to affect brackish or estuarine species.
3. The change in salinity patterns will not affect marine species which use the Canal as nursery and feeding ground.
4. Freshwater fishes may redistribute themselves within the Canal region.
5. Unstable bottom conditions are not conducive to benthos production for ground fish.
6. A reduced abundance of fish can be expected in the enlarged Canal area proper.
7. Enlargement increases the water volume in the Canal for production of fish.

c. <u>Blue crabs</u> (Appendix V)

Two potential areas of impact of the Canal on blue crab populations are: 1) alterations in the character of the Elk River which might affect its value as a nursery ground, and 2) alterations in the flow pattern of the Canal which affect recruitment of small crabs to the Elk River from the Delaware Bay. There is no evidence in the results to suggest that enlargement of the Canal will adversely affect the blue crab population.

d. <u>Fish eggs and larvae</u> (Appendices I and II)

This study was largely prompted by concern over the possible effects of Canal enlargement upon the production of the striped bass in the upper bay. The discussion that follows is concerned only with purely hydraulic effects of Canal enlargement and does not consider the possibility that Canal enlargement and subsequent expansion of Canal use by ships will lead to pollution effects upon the production of striped bass. There seems to be little doubt that construction of the Chesapeake and Delaware Canal has benefited the production of striped bass in Chesapeake Bay. The Canal provided a favorable alternative to the historical and destroyed spawning grounds in the lower reaches of the Susquehanna River. The Canal has been a sufficiently favorable alternative that this manmade area may be one of the more important spawning and nursery areas for this species. As a spawning and nursery ground, the Chesapeake and Delaware Canal is highly atypical, perhaps unique, in that within the same circumscribed geographic area eggs are spawned, hatch, and the early growth of larvae occurs. Typically,striped bass eggs are spawned upstream in a river. The eggs are carried downstream by the current and early growth of the larvae occurs in low salinity estuarine conditions at the mouth of the river.

The prime question prompting this study, i.e., whether or not Canal enlargement will lead to significantly greater advection of striped bass eggs and larvae from the Canal into the Delaware River estuary cannot be definitively answered until our knowledge of hydrographic conditions in the Canal during the critical time period (the last week in April to early June) is improved. A number of factors: consistent peak captures of eggs, limited observations of presumed spawning activity, and limited information on the distribution of breeding adults in the Canal area, strongly point to the conclusion that spawning occurs predominantly in the western portion of the Canal itself. There is no doubt, based on the strong agreement between the results for 1971 and 1972, as well as the remarkable consistency of the data within each sampling year, that by far the greatest concentrations of striped bass eggs and young larvae are in the Canal. The remarkable consistency of rank-abundance data for all numerically important species recovered from Canal samples, and particularly the very strong concordances exhibited by striped bass egg and larvae data, might justify the conclusion that the eggs and young larvae of the striped bass remain essentially where they are spawned and hatch - in the Canal - and that the Canal in essence is acting as a 14-mile-long manmade nursery for this species, and that advection of eggs and larvae into the Delaware River estuary is not as important as feared (note that especially in 1972 hydraulic conditions in the Canal closely approached those anticipated for the full 35-foot Canal). The apparent shift in the distribution of larger striped bass larvae from the Canal into the Elk River might further support this conclusion (although it might also mean that those larvae in the Canal were advected eastward).

Conflicting evidence provided by Mr. Thomas Hill of the Waterways Experimental Station at Vicksburg may be introduced at this time. In a series of dye injection experiments made in the hydraulic model of the 27-foot Canal, Mr. Hill injected dye at Courthouse Point, in the Elk River beyond the westward entrance to the Canal, and at Summit Bridge, in the central portion of the Canal. He used a simulated difference in elevation of 0.7 feet from the Chesapeake to the Delaware (Delaware lower), over twice the average difference of 0.3 feet reported by Pritchard and Cronin (1971). This difference in elevation resulted in a model net flow of 7,000 $ft^3$/sec, seven times the average net flow for the 27-foot Canal and more than twice the estimated net flow for the 35-foot Canal (Pritchard and Cronin, 1971). The dye injected at Courthouse Point was essentially flushed into the Delaware in 4 - 6 tidal cycles (ca 50 - 75 h in real time) while the dye injected at Summit Bridge was essentially flushed into the Delaware in 1.5 - 2.0 tidal cycles (ca 19 - 25 h). While it could be argued that the head and net transport conditions were extreme, and the maintenance of a constant difference in elevation of the Chesapeake over the Delaware is unreal over any long time period, the question remains: how unreal? The critical period for striped bass production vis-a-vis hydraulic conditions in the Canal would appear from data presented herein to be about April 20 to June 1, by which time most of the larvae (the eggs hatch in ca 48 h) would probably be large enough to physically or behaviorally avoid advection. Factors that probably must be considered include (1) average discharge of the Susquehanna River during this period,(2) average tidal conditions during this period, and (3) prevailing weather, especially wind, conditions during this period, and their interactions and effect on flows through the Canal.

The fact that the effects of Canal enlargement on salinity distribution in the upper bay are expected to be minimal during the spring period of high freshwater runoff, the fact that larvae of these species are more abundant in the Chesapeake Bay and Elk River portions of the transect area than in the Canal itself, the widepread occurrence of spawning grounds of these species within and outside of the Chesapeake Bay, and the apparently high production of these species are sufficient indication that enlargement of the Canal will effect no demonstrable changes in the populations of freshwater spawners in the upper bay area.

The enlargement of the Canal might actually enhance production of the bay anchovy in the upper bay by extending the area of low salinity (as opposed to fresh) water during the summer and fall months. It seems unlikely that enlargement of the Canal will cause changes in populations of marine species using the Canal.

e. Environmental Effects on Fish Eggs and Larvae (Appendices X - XIII)

Laboratory work under present contract was originally designed for determining the effects, due to Canal enlargement, of changes in salinity, of water movement, and of suspended sediment. Studies of general water quality and temperature were added because they were also important in understanding possible effects due to the present enlargement.

The following summarizes the major findings of the laboratory study on fish eggs and larvae:

Salinity - Temperature Experiments (APPENDIX X).

1. Salinity from 0 to 10 ppt does not alter the development rate of white perch eggs.
2. White perch eggs incubated at 0 ppt had significantly larger diameters than at salinities higher than 2 ppt.
3. Temperature has no effect on the egg diameter of white perch.
4. The optimum temperature for white perch development is between 11 to 16 C.
5. Development of striped bass eggs at 0.5 ppt was significantly better than at 2.5 ppt or higher.
6. The percent hatch and survival of striped bass was not dependent on salinity levels.
7. The rate of development for striped bass eggs was best from 16 to 22 C.
8. Striped bass hatch was best at 19 and 22 C.
9. Survival of larvae was best between 16 to 23 C.
10. Neither salinity nor temperature affected the egg diameter of striped bass.
11. Salinity had no effect on striped bass larval length.

12. Maximal striped bass larval length was observed at 21.5 C.
13. Deformed striped bass larvae were found at temperatures above 24.5 C. The deformity commonly observed was pugheadness of the larvae.
14. Enlargement of the Chesapeake and Delaware Canal will not result in a significant change in salinity patterns for either striped bass or white perch.

Suspended Sediment (APPENDIX XI).

1. The percent hatch of white perch eggs was not affected by sediment levels from 50 to 5,250 ppm.
2. The development rate of white perch eggs incubated at sediment concentration over 1,500 ppm was inhibited so that there would be a possible hatching delay of one day.
3. The percent hatch of striped bass eggs was not affected by sediment levels ranging from 20 to 2,300 ppm.
4. Developmental rates of striped bass eggs were significantly lower at sediment levels over 1,500 ppm.
5. A sediment layer greater than 1.2 mm over the top of a white perch caused 100 percent mortality.
6. White perch eggs were resistant to sediment blanketing of 0.45 mm or less.
7. Developmental rates of white perch eggs were lowered significantly at a sediment thickness over 0.8 mm.
8. Levels of 1,626 or 5,380 ppm of suspended sediment resulted in white perch larval mortality ranging from 27.3 to 29.3 percent for a one-day exposure.

9. White perch larvae exposed to seston levels of 1,626 to 5,380 ppm for two days had mortality rates of 22.6 to 62.0 percent.
10. The $LD_{50}$ for white perch larvae was 11,642.4 ppm for a one-day exposure and 2,679.5 ppm for a two-day exposure.
11. Sediment levels from 1,557 to 5,210 ppm caused striped bass larval mortalities ranging from 20.0 to 27.3 percent for a one-day exposure and 38.7 to 66.0 percent for a two-day exposure.
12. The $LD_{50}$ for striped bass larvae was 7,845.8 ppm for a one-day exposure and 3,411.0 ppm for a two-day exposure.
13. The sediment load in the Canal does not appear to be a factor influencing striped bass hatch and subsequent larval survival. However, effects of chronic exposures to high sediment concentrations need to be determined.
14. Suspended sediment levels in the Canal are not detrimental to white perch hatch.
15. The amount of deposited sediment, resulting from either dredging or natural input, can significantly affect the hatch of white perch eggs.
16. Larval white perch are resistant to high suspended sediment concentrations.

Water Movement (APPENDIX XII).

1. White perch eggs were resistant to low-intensity long-term shear until a shear force ($\bar{\tau}$) between 0.20 and 0.50 dynes/$cm^2$ was applied. Larval white perch mortality was low (35%) even at $\bar{\tau}$'s of 0.88 dynes/$cm^2$.

2. Striped bass eggs were resistant to low-intensity long-term shear up to 0.88 dynes/cm$^2$. At 0.88 dynes/cm$^2$, there was a 100 percent mortality of the eggs.
3. The $LD_{50}$ values for white perch eggs, exposed to high-intensity, low-duration shear, ranged from 1.7 dynes/cm$^2$ for 1 min to 0.88 dynes/cm$^2$ for 5 min.
4. The $LD_{50}$ value for white perch larvae, exposed to high-intensity, low-duration shear, ranged from 1.63 dynes/cm$^2$ for 1 min to 0.90 dynes/cm$^2$ for 4 min.
5. The $LD_{50}$ values for striped bass eggs, exposed to high-intensity low-duration shear, ranged from 2.1 dynes/cm$^2$ for 1 min to 1.04 dynes/cm$^2$ for 4 min.
6. The $LD_{50}$ values for striped bass larvae, exposed to high-intensity, low-duration shear, ranged from 3.4 dynes/cm$^2$ for 1 min to 1.25 dynes/cm$^2$ for 4 min.
7. The average shear generated by water moving through the Canal at about 45,000 cfs is 13.8 dynes/cm$^2$ which is effective in a lethal boundary layer of approximately 0.2 cm ($2.2 \times 10^{-4}$ of the total Canal volume).
8. Mortality of eggs and larvae due to water movement in the Canal is probably insignificant.
9. A typical cargo ship moving through the Canal against a water flow of 40,000 cfs generated a shear of 78.9 dynes/cm$^2$ which translates into a kill area of 4.20 m$^3$ (based on the $LD_{50}$ 1-min value of 2.1 for striped bass).
10. Shipping during the two intensive weeks of striped bass spawning could kill 284,722 eggs (assuming a water flow of approximately

40,000 cfs for this period and egg densities of 10 - 20 $m^3$). The loss to the commercial fishery is approximately 2,847 fish and probably represents a nondetectable yearly mortality.

11. Pelagic eggs and larvae may be carried out of the Canal and into the Delaware River due to water movement.

Water Quality (APPENDIX XIII).

1. Acute static bioassays, performed on eggs and larvae of striped bass and white perch using water collected from the C and D Canal area, showed no significant differences in mortality rates for a two-day exposure.
2. One station, located in an area immediately upstream from the eastern end of the Canal, consistently displayed higher mortality rates than other stations.
3. Sediments from the Chesapeake end of the Canal have elemental compositions very similar to sediments from the Delaware end of the Canal.

Based on the information collected from three years of study, there is no indication that detrimental changes in salinity, temperature, sediment load or water quality in the Canal will occur as the consequence of enlargement. There is, however, one factor that may be detrimental to fish eggs and larvae in the Canal area. Water movement out of the Canal and into the Delaware River frequently occurs during the spawning season. If eggs and larvae are transported out of the Canal and up the Delaware River, they would be developing in an area which receives large amounts of industrial and domestic effluents. Transport of eggs and larvae downstream in the Delaware River may allow survival rates comparable to those rates in the Chesapeake Bay.

Damage is most likely when water containing eggs or larvae leaves the Canal at the Delaware end and mixes with Delaware River water at either the end of an ebb or at the beginning of a flood tide in the Delaware system. Consequently, pelagic eggs and larvae would generally be transported upstream into the Delaware River where water quality is questionable. While static 48-hour bioassays did not indicate any significant mortalities due to water quality in the Canal area, one station, located immediately above the Canal at the Delaware end, did display consistently higher test mortalities of eggs and larvae than the other stations tested.

Of the major environmental factors studied, only water quality in the Delaware River and its relation to water movement remains a question in regard to effects of Canal enlargement.

The problem of water movement and water quality may be solved by future work that relates water surface elevation differences to net non-tidal transport. Prediction of transport for the period of time in which spawning activity occurs in the Canal would allow better estimation of effects to the fish populations using the Canal and permit efficient modification of such transports. In addition, some estimate of the probability of transport either upstream or downstream from the Canal would be of benefit in estimating possible ecological damage to the fish populations and in minimizing such damage.

### f. Summary

The coastal environment is extraordinary, exacting, and difficult to study. Man typically inhabits the coast and, unfortunately, dumps his wastes in this dynamic environment. Man transports goods along the coastal zones and modifies the natural coastal systems to improve his shipping ability. Only recently has man seriously examined the damage he has done and is doing to the coastal systems of the world.

Insult to the coast is commonplace and increasing. Cronin (1967) points out that one-third of the total population of the United States lives and works near the coastal zone and that seven of the ten largest metropolitan areas in the world border estuarine systems.

The estuary, or coastal zone, is subject to a variety of environmental impacts generally classified as physical, chemical, or biological. Of the physical pollutants, modification of river flow and modification of basins are important to any discussion of the Chesapeake and Delaware Canal. Cronin (1967) describes a canal as a change in the "shape" of estuaries and predicts that noticeable effects will include biotic exchanges and range extensions.

Aron and Smith (1971) point out that biological equilibrium has not been observed in three important canal systems, the Erie, Welland, and Suez Canals. Biological effects of the opening of the Erie and Welland Canals were observed primarily in the Great Lakes and included major changes in the population dynamics of the fish. Major changes in fish populations were observed after a long time-lag. The Erie Canal was opened in 1819 and the Welland Canal was first used in 1829 (Hatcher, 1945). Part of the time-lag may be a function of the use of locks in the Welland and Erie Canals.

The Suez Canal, opened in 1869, is a link between the Red Sea and the Mediterranean. Faunal composition of the eastern Mediterranean is impoverished; the fauna of the Red Sea is much richer. Although there is some exchange between the two faunas in the Suez area, the major Lessepsian migration is from the Red Sea to the Mediterranean (Por, 1971). There are a variety of reasons cited by Por (1971) as to why the major migration pattern seemed to be unidirectional. Again, fish invasion of the Mediterranean by

Red Sea species is significant enough to have economic impact. In this case, the economic impact is beneficial since 11 of the 24 invading Red Sea species are commercially valuable (Por, 1971).

The Chesapeake and Delaware Canal connects two estuarine systems whose faunas (and floras) are roughly similar. However, the Canal joins an area of low salinity (the upper Chesapeake Bay) to a segment of an estuarine system with slightly higher salinities (the Delaware River). It is the hallmark of the successful estuarine organism to tolerate euryhaline conditions, so a link between the Delaware and Chesapeake Bays will not have an acute effect salinity-wise. (It is important to remember that toleration of adversion conditions is not equatable to normal functioning.)

The Chesapeake and Delaware Canal is comparable in age to the Erie, Welland, and Suez Canals, having been first opened as a locked canal in 1829 and converted a sea-level canal in 1927. Since the opening the Canal, there have not been any documented effects attributable to the Canal. Indeed, two factors point to its importance, at least, to the Maryland fishery.

Dovel and Edmunds (1971) suggest that the C and D Canal serves as an alternate for striped bass spawning activity that at one time was in the Susquehanna River. The shift from the Susquehanna to the C and D did not visibly hurt the spawning ability of the striped bass population. The C and D Canal is actually an incubation chamber 18 miles long.

In addition, opening of the Canal may have given striped bass from the Delaware an alternative site for spawning. Migration through the Canal appears to be directional (Koo and Wilson, 1972). Chittenden (1971) commented that striped bass spawning in the Delaware River may be nonexistent. The Elk River population of striped bass is also quite distinct from other river populations of striped bass in the Chesapeake Bay area (Morgan et al., 1973). This distinctness may be due to a mixing of the gene pools of Elk and Delaware striped bass.

The Chesapeake and Delaware Canal is an extremely important asset to the Chesapeake and Delaware fisheries. It must be managed properly. Cooperation between the Army Corps of Engineers and scientific groups is vital for determining proper management policies of the C and D Canal.

In summary, the best present estimate of the biological effects of Canal enlargement is that there will be no significant changes in the benthic community, except for a possible eastward increase in some species and numbers. No significant detrimental effect is expected on fish populations utilizing the Canal. Fish eggs and larvae will be detrimentally affected only by transport upstream in the Delaware River. There is no present evidence that predicted salinity changes, possible increased suspended sediment, ship traffic, and increased water movement due to Canal enlargement will have any appreciable effect. The spawning area may be shifted eastward and increased slightly.

The possibility of an unusually large transport of water in either direction exists. It is not thought that this unusual transport of water will occur frequently or have disastrous consequences. However, since the magnitude of the unusual event is not known, continued monitoring of water movement and the important biota is recommended. At present, there is no evidence that completion of the widening and deepening of the Canal will have serious detrimental effects on the fauna of the Canal and its approaches.

## F. FLOW CONTROL STRUCTURES

The most direct environmental effect of the enlargement of the Canal from 27 x 250 ft to 35 x 450 ft is the change of flow, both of volume and in rate. As a result of flow changes, the salinity regime will be modified and aquatic lives may be affected. If the changes in salinity and effects upon the biota are to such an extent that they are unacceptable, then the flow could be restored to pre-enlargement conditions by the installation of control structures. We are informed by Corps of Engineers that such structures could be constructed in various forms and designs from completely blocking locks to partial, adjustable "walls." However, such structures are very expensive and they themselves may cause new ecological problems. It is therefore imperative that the merits and demerits of any flow control structure be carefully evaluated.

### 1. Evaluation of the need

As a result of the enlargement from 27 x 250 ft to 35 x 450 ft, the long-term average net non-tidal flow may be increased by a factor of 2.5 in volume, and by 15% in rate. The relative frequency of flow Delaware-bound and Chesapeake-bound will remain unchanged, at 60% and 40%, respectively. Change in the salinity regime will be slight in the Canal, the approaches, and in the upper Chesapeake Bay. There may be a slight eastward shift of the freshwater boundary in the Canal.

The effects of these changes on aquatic lives would be minimal in most instances. There will be no hindrance to the migration of fishes and crabs. Planktonic organisms will be transported 15% faster than before. This means that striped bass eggs and newly hatched larvae can be moved out of the Canal and into the Delaware more rapidly. The precise consequence of this happening is difficult to predict, but unless the organisms are moved northward into Delaware River, no serious adverse effects are expected. Careful monitoring of the movement of fish eggs and larvae and their survival rates is needed after the completion of enlargement.

Depending upon the size of the increase of salinity and area extent, it is not possible to predict all biological consequences. Here again, post-enlargement monitoring is needed.

It is our considered opinion that under normal conditions a flow control structure in the Canal is not needed. However, in case of catastrophic happenings where the flow may drastically deviate from the expected and aquatic lives are threatened, then a control measure may be of great value.

We therefore recommend that design and model testing of flow control structures be initiated and carried out by engineers. We further recommend that actual construction of such structure should not occur unless pending post-enlargement studies indicate that they are of substantial importance in protecting biological resources of the region.

### 2. Ecological requirement of control efforts

When and if it is deemed desirable to build a flow control structure in the C and D Canal, such a structure must take into consideration some ecological requirements. Of foremost importance, such a structure should not obstruct the free movement and migration of aquatic organisms, either actively or passively. A lock, for instance, would be an undesirable structure from this point of view. A blocking structure in the Canal will create still water and reduce the turbulence which is favorable for striped bass eggs.

From an ecological standpoint, a flow control device should not be a permanent structure. Flow conditions vary seasonally, and biological phenomena are even more seasonal. A flow control structure can be beneficial during certain times of the year and detrimental during other parts of the year, and should therefore be flexible in operation. For instance, a short-term control structure may prove beneficial during April and May when striped bass spawning reaches the peak, if the increased flow at that time becomes detrimental to the spawn. However, a similar flow reduction in fall may be detrimental.

The operation of any flow control structure would not be useful unless salinity and tide levels can be monitored on a continuing basis at both ends of the Canal. Adequate modeling of the hydrographic characteristics of the Canal based on substantially improved tide recording stations would be necessary. Control of the structure would then be monitored by tide stations at the ends of the Canal.

Properly designed and installed, a flow control device can divert disastrous effects upon aquatic lives. It can prevent or correct excessive, harmful interchange of Delaware and Chesapeake water masses if such conditions are imminent. At times of catastrophic happenings which may radically alter the flow patterns in the Canal and consequently threaten ecological balance in the area, a flow control structure could be very useful.

Any flow control structure (a lock, a groin, or an inflatable device) will create some undesirable effects. It will usually either obstruct or impede the free migration of fishes or other aquatic organisms. It may delay the spawning migration of striped bass, American shad, and other anadromous species simply by the presence of a large structure in the migration path of fishes. Modification of a normal flow pattern by a control structure could have serious effects on all trophic levels by altering normal patterns of salinity and possibly temperature. Addition of a control structure to the Canal may create a more unstable environment than what would be present in post-enlargement conditions.

## G. CANAL MANAGEMENT PROGRAM

Periodic dredging is required to maintain the desired depth in the C and D Canal. Dredging entails the removal and deposition of bottom material. As has been shown by our various studies, the C and D Canal region (1) supports many species of aquatic invertebrates and fishes, (2) is an important pathway between Delaware and Chesapeake Bays for many species of fish including several important anadromous species, (3) is the site of heavy striped bass spawning, and (4) serves as the nursery for more than twenty species of marine fishes. Dredging activities could have serious ecological consequences. Such activities should be conducted so as to prevent effects on those valuable biological uses.

### 1. Maintenance dredging

Dredging a waterway will result in three phenomena that have an ecological bearing. First, dredging releases nutrient materials that have been trapped in bottom mud and these materials may actually stimulate photosynthesis. In this regard, dredging can be ecologically beneficial, rather than harmful. Excessive dredging can be ecologically detrimental.

Second, dredging removes bottom materials and thus disrupts benthic habitat. The Canal bottom is, in most areas, comprised of sands, which harbor many species of invertebrate animals. These animals are an important source of food for fish. Dredging not only physically removes these animals with the sand, but alters the bottom structure in replacing sand with silt. Not until the silt is scoured away by current action and the bottom returns to sand condition, can rehabitation of benthic community occur.

By carefully scheduling dredging activites, adverse effects on the benthic community can be minimized. Most invertebrate animals do not live more than a year, and their breeding season normally occurs when water temperature rises in the spring, with highest activity starting in June. It is important that the young life stages be protected as much as possible so that they have a chance to grow. The cropping of adult forms is not as harmful since they are going to die in any event. The abundance of adults also varies seasonally, being the least numerous during the cold, winter months. During the period from January through May dredging will have the least adverse effect on benthic animals, and the months of June through September should be avoided to protect the spawning and young.

Third, dredging increases sediment load in the water column and creates turbidity. The effect of sediment load on fishes is not well understood. Schubel and Wang (1973) and Morgan (Appendix XI) found that up to 2300 ppm and 5250 ppm suspended sediment had no observed effect on hatching success of striped bass and white perch eggs, respectively, but seemed to have prolonged the incubation period. Seston loads in the C and D Canal have at times reached more than 2,000 ppm. Further research is needed, especially on longer term exposure experiments, to determine the upper tolerant limits of fish eggs and larvae to seston loads.

We have found that the C and D Canal, specifically in the Back Creek section and extending to Summit Bridge area, is an important spawning area for the striped bass, and that most of the spawning takes place from April to May, which coincides with the breeding season of most benthos in the Canal. It would be wise to avoid dredging during this period in this section of the Canal.

High turbidity also impedes light penetration, thus reducing the euphotic zone in the water column. Reduced light penetration due to heavy sediment load has been known to kill off aquatic vegetation such as the widgeon grass. Since the C and D Canal is devoid of high aquatics, the creation of turbidity due to dredging poses no threat in that regard. As regards the reduction of euphotic zone, no gross effects on the phytoplankton following dredging operations are anticipated since reduction in light penetration is a temporary phenomenon. Avoidance of dredging during spring and summer as noted above has merit also in regard to possible effects on primary production, since it is during this period that the euphotic zone is normally much reduced due to natural conditions. Characteristic of some estuarine systems is the loss of primary production (and subsequent loss to the food chain) due to light-limitation. Usually, reduced light penetration occurs in the upstream areas of estuaries where silt from freshwater runoff is present. Dredging in these areas may add to the suspended sediment load and further decrease light penetration.

## 2. Spoil disposal

Dredged material from the C and D Canal is disposed of on nearby land. This practice has merits over disposal in water column in that it minimizes the spread of spoil and reduces the potential of resettlement of sediments. Therefore, it is of ecological benefit that the disposed solid material be retained in the basin as much as feasible, but that nutrient materials are returned to the Canal.

## H. ENVIRONMENTAL MONITORING OF THE CANAL

Important unresolved questions remain concerning the subtle long-term impacts of enlarging the Canal. Such impacts may be beneficial or detrimental to various human interests, but they could not be adequately detected and evaluated in the period of this study. It is recommended that the following observations be made to provide accurate information on the occurrence or absence of significant effects and assist toward optimal management of the Canal.

1. Physical parameters of the water should be monitored on a regular basis in the Canal and its approaches. Parameters of interest include salinity, temperature, dissolved oxygen, suspended solids, flow rate and direction. Automatic instrumentation, properly installed and supervised, can be of value.

2. Tide stations should be properly maintained at both ends of the Canal.

3. Striped bass spawning activity and egg and larval abundance should be monitored during the spring of each year. Variation in time and amount of spawn from year-to-year can be correlated to physical parameter data to better assess the value of the Canal for striped bass spawning and the effects of change.

4. The survey of juvenile and adult fish should be continued on a seasonal basis to determine any significant changes in species composition and population structures, since these may reveal or foreshadow ecological perturbations.

5. The benthic fauna provides food for fish, constitutes a major food source of the overwintering waterfowl of the upper Bay area, and provides a valuable indicator of important biological changes. Since slight changes in salinity may affect some species, continued monitoring is recommended.

It is further recommended that a review of monitoring and results be developed each year, and that it be subject to discussion and evaluation by interested parties.

It is further recommended that there be an annual review of new knowledge resulting from monitoring, research, engineering experience and other sources pertinent to the hydrography and ecology of the Chesapeake and Delaware Canal.

## I. A LIST OF APPENDICES

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| Appendix I. | Production and distribution of fish eggs and larvae in C and D Canal. |
| Appendix II. | Production and distribution of striped bass eggs in C and D Canal. |
| Appendix III. | Benthos of Maryland waters in and near C and D Canal. |
| Appendix IV. | Benthos of Delaware waters in and near C and D Canal. |
| Appendix V. | Blue crabs in C and D Canal region. |
| Appendix VI. | Fish survey in Maryland portion of C and D Canal region. |
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| Appendix X. | Effects of salinity and temperature on the development of eggs and larvae of striped bass and white perch. |
| Appendix XI. | Effects of suspended sediments on the development of eggs and larvae of striped bass and white perch. |
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| Appendix XIII. | Effects of water quality in C and D Canal region on the survival of eggs and larvae of striped bass and white perch. |
| Appendix XIV. | Hydrography of C and D Canal. |

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## K. GLOSSARY AND ABBREVIATIONS

The following definitions cover terms and abbreviations used in the final report and all of the appendices.

acute static bioassays -- tests using non-flowing water systems to determine the lethality of a toxicant to a test organism

amphipod -- an order of crustaceans

anadromous -- species that migrate to freshwater for spawning.

annelid -- referring to worms

arc sin $\sqrt{P}$ -- a statistical transformation used to normalize data that falls between 0 and 100%

atherinid -- referring to the family Atherinidae, mainly forage fishes

beach seine -- a net primarily designed for shallow-water inshore sampling

benthic (benthos) -- organisms inhabiting the bodies of water

biomass -- amount of living matter

-- centigrade

ca -- about

carapace - shield-like plate covering the cephalothorax of decapods

catadromous -- species migration to saltwater for spawning

cfs -- cubic feet per second

chorion -- the outermost membrane of an egg

cm -- centimeter

cod of net -- the inner baglike part of a trawl net

control ranked development -- an arbitrary ranking system used in determining the rate of embryonic and larval development of fishes correlation -- in statistics, the determination of the relationship of two variables (the variables are usually interdependent or co-vary)

crustacean -- referring to the class Crustacea, phylum Arthropoda

$\Delta h$ -- average difference in water surface elevation

decapod -- order of crustacea including crabs, crayfish, etc.

demersal -- bottom-dwelling, attached to the bottom

df -- degrees of freedom

diadromous -- migratory between fresh and salt water

dynes/cm$^2$ -- dynes per square centimeter

edometer -- a depth recorder

elvers -- young eel

estuarine -- referring to waters where freshwater and saltwater meet

euryhaline -- ability to withstand large variations in dissolved salts

F -- a statistical distribution, determined by two values for degrees of freedom used in testing hypothesis

fork length -- the distance from the nose of a fish to the fork in the tail

freshwater - water with little salt content

ft -- feet (foot)

ft/sec -- feet per second

ft$^3$/sec -- cubic feet per second

g/cm$^3$ -- grams per cubic centimeter

g/m$^2$ -- grams per square meter

gastrula -- early embryonic stage of animals

h -- hour(s)

hydrozoan -- referring to a class of the phylum Coelenterata isopod -- order of crustaceans

laminar flow -- streamline flow in a viscous fluid near a solid boundary

$LD_{50}$ -- the lethal dose of any material that will kill 50% of the test population in a given time period

m -- meter

$m^2$-- square meter

$m^3$-- cubic meter

marine -- water with high salt content

min -- minute

mg/l -- milligrams per liter

mm -- millimeter

molluscan -- referring to members of the phylum Mollusca

morula -- loose spherical group of cells during early stages of segmentation in embryos

MS -- mean square

$\underline{n}$ -- number of tidal cycles for which observations are available

$n_E$ -- number of individual tidal cycles at each section

Newtonian fluid -- any fluid that behaves according to Newton's law of viscosity which states that the shear force per unit area is proportional to the negative of the local velocity gradient

nitex -- a tradmark for nylon monofilament screening

non-parametric -- non-distribution dependent statistics

non-tidal flow -- water movement after tidal movement has been accounted for in a system

oligochaete -- referring to one of the annelid classes of worms

otter trawl -- a net towed from a vessel that fishes the bottom p -- probability

parametric -- distribution dependent statistics

PE -- probable (standard) error

pelagic -- pertaining to open waters of the sea and lakes

polychaete -- referring to one of the annelid classes

ppm -- parts per million

ppt -- parts per thousand

$\bar{Q}$ -- average net non-tidal flow

$\bar{Q}_E$ -- average of net non-tidal flows (eastward)

$\bar{Q}_W$ -- average of net non-tidal flows (westward)

Regression -- in statistics, the dependence of a variable on an independent variable

Reynolds number -- a combination of four factors (density of the fluid, average velocity fluid viscosity, diameter of the system) that determines if the flow of a viscous fluid is laminar or turbulent

sciaenid -- referring to the family Sciaenidae, marine and freshwater drums

SD -- standard deviation

seston -- suspended material

shear -- a stress resulting from force that causes parts of a body to slide relative to each other

SNK -- Student Newman Keuls test. Used for comparing means in statistical testing such as in analysis of variance

SS -- sums of squares

$\bar{\tau}$ -- average shear force

t.c. -- tidal cycle

total length -- the distance from the nose of a fish to the end of the tail

TPX -- trademark for polymethylpentene

trawl net -- a net towed from a vessel

tubificid -- referring to the genus Tubifex, small freshwater worms

Zapon -- tradename for an adhesive

′ -- feet

% -- percent

o/oo -- parts per thousand