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Present and historical environmental survey of the Poquoson River, York County, Virginia and the Warwick River; Newport News, Virginia : with special reference to biotic communities and the effects of alum discharge

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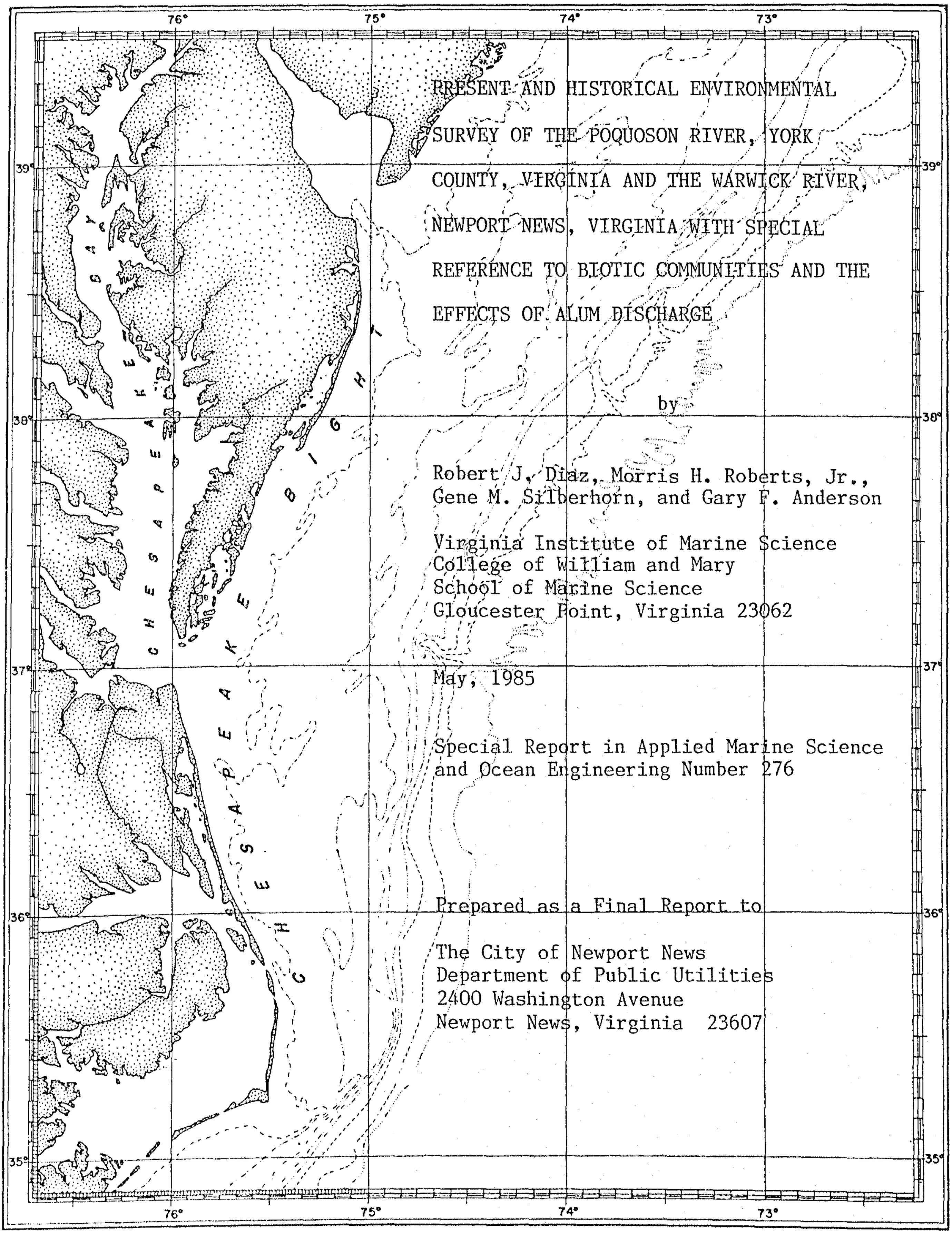

PRESENT AND HISTORICAL ENVIRONMENTAL SURVEY OF THE POQUOSON RIVER, YORK COUNTY, VIRGINIA AND THE WARWICK RIVER, NEWPORT NEWS, VIRGINIA WITH SPECIAL REFERENCE TO BIOTIC COMMUNITIES AND THE EFFECTS OF ALUM DISCHARGE

by

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and Ocean Engineering Number 276

Prepared as a Final Report to

The City of Newport News
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INTRODUCTION

The City of Newport News, VA operates two water treatment plants, one located near the dam for Harwood's Mill Reservoir, and the other along the Newport News City Reservoir at Lee Hall. As part of the treatment process in each location, the water is treated with alum, aluminum sulfate, to facilitate precipitation of solids, and allowed to settle. The settleable solids are subsequently discharged from the settling tanks at the two plants into the upper reaches of the Poquoson and Warwick Rivers respectively. Both plants discharge alum sludge only intermittently at about 6 week intervals. The plants differ, however, in the amount of alum sludge discharged, the Lee Hall plant discharging about three times as much material as does the Harwood's Mill plant. In addition at each plant there are rapid sand and mixed media filters, and the backwash water from these is also discharged into the two rivers. The plant discharge, while occasionally containing small amounts of filter matrix material (anthracite coal and quartz sand), consists primarily of alum sludge.

Aluminum is a naturally occurring element in the matrix of clay minerals such as kaolinite which are characteristic of sediments in the coastal plain of Virginia. The addition of alum sludge to a natural system such as the Poquoson or Warwick River can be expected to produce enrichment of bottom sediments with aluminum, probably in the form of aluminum hydroxide. This enrichment can be quantitatively demonstrated by measuring aluminum as a ratio to another element in the substrate which will be conservative, an element such as silicon. By measuring the Al:Si ratio at varying distances downstream of the discharge point and at increasing depths in the sediment, one can then map in the receiving stream the apparent extent of aluminum enrichment resulting from the practice of discharging alum sludge from water treatment plants.

While it is not possible to determine the exact rate of alum sludge accumulation in the sediments, it is possible to determine an approximate average rate of total sediment accumulation at a site using the naturally occurring levels of ^{137}cesium activity. Data on sediment accumulation rates and aluminum enrichment can then be compared to evaluate in a crude way the resuspension and redistribution of sediments and aluminum within the creek systems.

Alum (or aluminum sulfate) and aluminum hydroxide are quite insoluble in water unless the solution is rather strongly acidic (pH 4 or less). When solubilized, aluminum is toxic like most other heavy metals, but as a solid such as aluminum sulfate or an aluminum hydroxide complex, it is quite non-toxic (Burrows, 1977; Driscoll, et al., 1980; Lamb and Bailey, 1981). Since waters in the Poquoson River and Warwick River are not acidic (customarily pH = 7.5 to 8.0), it is not expected that the aluminum would be in solution, and therefore, little or no toxicity is to be expected. There are two situations, however, in which toxicity could develop: first, rainfall in the area is often acidic, sufficiently to solubilize aluminum hydroxide if the receiving water has a low buffering capacity (which is not considered likely); second, pH of pore water could be low enough to solubilize alum.

An additional source of impact from alum sludge discharges on the benthic community would be mediated by changes in the substrate particle size distribution resulting from sedimentation. Considering the potential for resultant impacts on the benthic community, it is important to evaluate the condition of the fauna associated with sediments in these two rivers receiving alum sludge to ascertain whether any impact has in fact occurred.

Submerged benthic invertebrate communities have historically been useful in evaluating environmental impacts. The life history characteristics of the species inhabiting the benthos are such that they tend to be good long-term integrators of effects of natural physical parameters and pollutants (Boesch, 1977; Diaz, 1977). Low salinity environments like the Poquoson and Warwick Rivers typically have communities which are naturally low in species. This makes an evaluation of changes resulting from pollutants more difficult to detect than in areas with more diverse communities (Roberts, et al., 1975). Nevertheless, pollutant effects on benthic communities are recognizable in low salinity habitats when of sufficient magnitude.

Benthic and planktonic algal communities are important components of shallow water estuarine systems which fix solar energy as biomass which in turn serves as the energy source for other organisms within the system. Benthic algae are especially important on intertidal and shallow subtidal bottoms because of their high year-round productivity, fast turnover, and value as a food source (Diaz et al., 1982). It is essential that the algae, whether benthic or planktonic, receive sufficient light to maintain high production levels. Light is a critical parameter limiting production of the benthic algae community in shallow submerged areas (Van Raalte and Valiela, 1976; Sullivan and Daiber, 1975; Diaz et al., 1982). The depth to which phytoplankton can photosynthesize is similarly controlled by available light. Any activity by man such as the discharge of alum sludge has the potential to reduce significantly the amount of light available to these algal communities and thereby to reduce the productivity of the system receiving the discharge.

Algal communities may also be negatively impacted by chemical pollutants, causing changes in community size and productivity. Ionic aluminum is known to be toxic to those unicellular algae which have been tested (Foy and Gerloff, 1972; Helliwell et al., 1983). Since large amounts of ionic aluminum can exist only under acid conditions which are unlikely to occur in estuarine environments, one might predict that there is little potential for an adverse effect of alum sludge based on chemical toxicity, but rather that most impacts would result from the effect of suspended particulates on light availability.

Marsh communities adjacent to tidal creeks may also be affected by man's activities. There is potential for deposition of alum sludge on the surface of the marshes fringing the receiving stream which could change the root environment though no direct chemical toxicity from alum sludge is expected. Nevertheless, there could be changes in species composition, total marsh area, and plant production.

OBJECTIVES

The objectives of this study were:

1. to determine the areal extent of discharged materials within each of the rivers using the aluminum:silicon ratio as an indicator;
2. to evaluate the benthic invertebrate communities within each of the rivers;
3. to determine whether there are differences in the productivity of the benthic algal and planktonic communities which can be attributed to the discharge of alum sludge in each river;
4. to evaluate the condition of the marsh communities in each river near the filtration plant;
5. to review historical biological data for the Poquoson and Warwick Rivers and to relate the biological communities within these two systems to communities in subestuaries not receiving alum sludge discharges;
6. to evaluate the probable sediment yield from the drainage areas of the two reservoirs in the absence of a dam using the STORM model;
7. to identify mitigation alternatives and evaluate their ecological implications.

MATERIALS AND METHODS

Study Site Description

Harwood's Mill, Poquoson River

The Harwood's Mill Water Filtration Plant is located on U.S. Route 17 alongside the dam forming the Harwood's Mill Reservoir in the headwaters of the Poquoson River, VA. Water from the reservoir is treated with alum to sediment the particulates, and the sludge is periodically discharged into the Poquoson River just upstream from the U.S. Route 17 bridge. At this point, the stream is narrow, approximately 20 ft wide, and quite shallow, ranging from 46-76 cm (18-30 inches) at the deepest point. The substrate of the creek is extremely soft, and of a light brown to off white color on the surface with rust colored sediments in some areas. About 50-60 cm down in the sediment, a more solid substrate is encountered which will support a man's weight.

Downstream of the U.S. Route 17 bridge, the stream is unusually straight for 0.25 miles, suggesting channelization by man, perhaps at some time when changes were made in the road bridge. Thereafter, the stream assumes a more usual sinuous configuration, winding through marshes which fill the drainage area. At several points the stream lies against an upland bank rising rapidly to the 25 ft contour on the southern bank. In most such locations, there are one or more houses, but the stream is decidedly nonresidential in character in the upper reaches. The stream remains narrow for about a mile, before broadening and becoming very shallow. The substrate continues to be extremely soft downstream to about mile 1.7, whereafter the channel gradually deepens to 7 ft at 3.1 miles downstream.

From the point at which the stream is conspicuously wider below mile 1.5, the shoreline assumes a distinctly light to moderate residential character. Many of the houses are of recent construction. Very few property owners have made any effort to build bulkheads or otherwise greatly modify the shoreline. Most lots have been left wooded, with lawns generally not reaching to the shore. A few open piers and one boat house have been built in the wider and deeper reach below mile 1.3. There are still some narrow fringing marshes along much of the downstream area.

Lee Hall, Warwick River

The Lee Hall Water Filtration Plant is located overlooking Newport News Reservoir at about 20 ft above sealevel. Alum sludge is discharged from this plant into a ravine at about the 10 ft contour. The discharge has cut into the forest floor forming a typical (except for the suspended solids load) forest stream extending down the ravine to U.S. Route 60 where it joins a stream which receives, on rare occasion, overflow from the spillway of the dam forming the reservoir and land runoff from the adjacent area. The combined flow forming the headwaters of the Warwick River, passes under U.S. Route 60 into an initially forested bottom land. At mile 0.3 from the discharge, the stream, about 10-15 ft wide, flows into a marshland, at which point it widens to perhaps 20 ft. From here to the mouth, the river meanders through broad marshes along most of its length until it discharges into the James River at Menchville near the James River Sewage Treatment Plant. The western bank of the river is bordered by the Fort Eustis Transportation Center, with little development of any kind along the river.

At one point where the stream approaches the uplands, there are some multifamily housing units for base personnel, but there are no shoreline modifications and the bank remains wooded. At about mile 2.5, there is a landing, pier, parking and picnic area associated with the Officer's Club. These are the only developments on the western bank.

On the eastern bank, the shoreline is marsh or upland in character with residential development in several areas. The further downstream, the more development there is along the eastern shoreline. Nevertheless, the river retains an essentially undeveloped character downstream to at least mile 5.5.

Station Locations

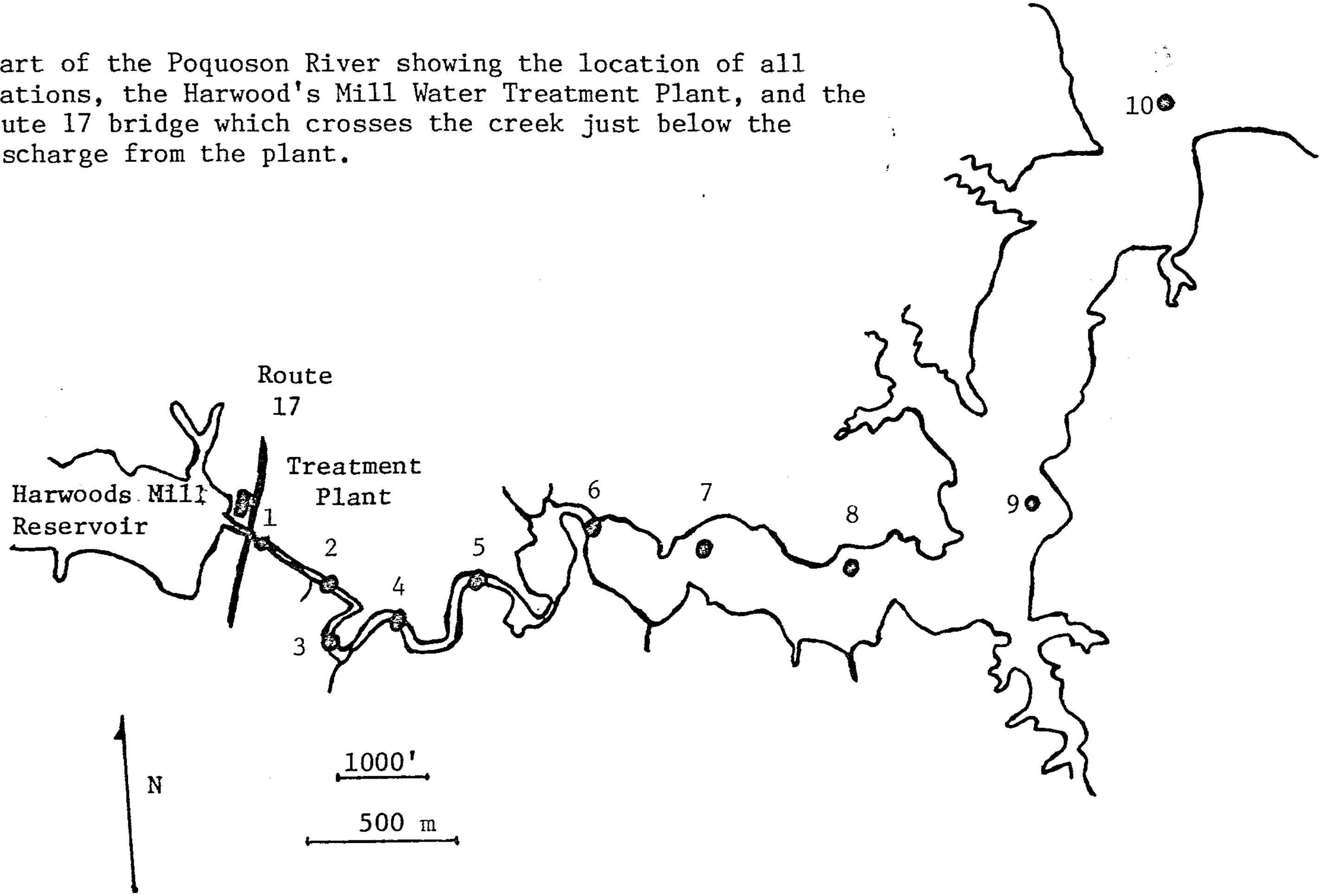
Poquoson River

Ten stations were established in the Poquoson River covering a distance of 3.1 miles downstream from the discharge from Harwood's Mill Water Filtration Plant (Figure 1). Five stations were located in the first mile, three between Mile 1 and 2, and two at slightly greater separations. The close placement of stations in the upriver area was a feature of the sampling design aimed at providing greater resolution of physical and biological features at locations close to the discharge points than at more remote locations.

Warwick River

Eleven stations were established on the Warwick River, spanning the area from 0.1 miles below the discharge to mile 5.4 (Figure 2). Station 1 was located upstream from the confluence of the stream carrying the

Figure 1. Chart of the Poquoson River showing the location of all stations, the Harwood's Mill Water Treatment Plant, and the Route 17 bridge which crosses the creek just below the discharge from the plant.



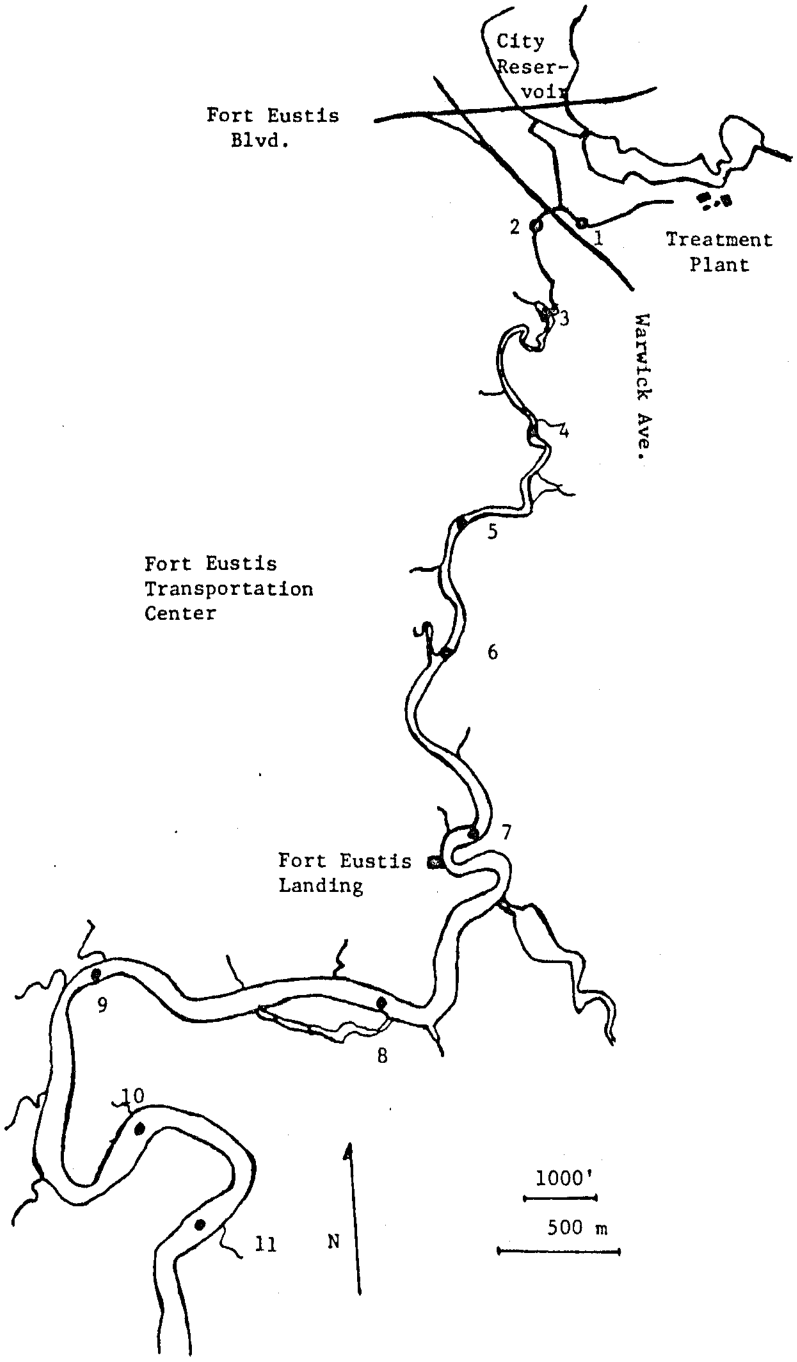


Figure 2. Chart of the Warwick River showing the location of all stations, the Lee Hall Water Treatement Plant, and the Route 60 bridge which crossess the creek about 0.15 miles below the discharge from the plant.

discharge from the plant and that draining the spillway area. Station 2 was located just downstream of the bridge crossing Route 60. While no major construction on the bridge/culvert was in progress during the study, work had been in progress in the recent past, and construction will continue in the area as Route 60 is widened from 2 to 4 lanes. Both stations were located in wooded sites, well shaded in the summer months. Stations 3 through 11 were located downstream in the region fringed by broad marshes extending from mile 0.3 to mile 5.4. As in the Poquoson River, stations were established closer together in the upstream areas than in the downstream areas.

Physical Parameter Cores

We collected core samples from Stations 1 through 10 in the Poquoson River on 24 February 1984, and from Stations 1 through 9 and Station 11 in the Warwick River on 16 March 1984. An additional set of cores was taken from the Poquoson River in April for x-ray analysis. At each station, a 10 cm diameter core, ranging from 0.7 to 0.9 m in length (except at Warwick River Station 1, at which only a 0.25 m core could be procured), was collected. The core tube was inserted into the substrate manually until only a small portion remained above the sediment surface, hermetically plugged, and withdrawn by hand. Insertion of the core was accomplished as slowly as possible to minimize compaction of the core. Compaction of the sediment ranged from 5 to 10 cm and was greatest at stations with muddy substrates. Once withdrawn, the bottom end of the core was capped before withdrawal from the water. Cores were placed in as upright a position as possible during transport to the laboratory at Gloucester Point so as to minimize disturbance of the cores.

Each long core was cut into 33 cm sections and the ends capped. These sections were then placed on top of a sheet of 35.5 x 28.0 cm x-ray film and x-rayed with a Torr cabinet x-ray machine. Kodak AA Industrial X-ray film was used. The exposure time ranged from 3 to 4 minutes at 70 kV. After x-raying, the sediments were extruded from the core tube and subsampled for Al:Si and grain size analyses. Samples were removed at centimeter intervals for the first 3 cm, and then at three centimeter intervals to the bottom of the cores.

Sediment samples from each station were analyzed for percent sand and silt-clay following the wet sieving procedure of Folk (1974). To present the grain-size data from the long cores, sediment descripters developed by Udden-Wentworth (Pettijohn, 1957) were used (Figure 3).

To analyze sediment subsamples for aluminum and silicon, each sample was mixed with a spatula, and 0.8-1.1 g of sediment (wet weight) was placed in a beaker. Larger subsamples were necessary for sections of cores which contained a large proportion of sand or charcoal in order to obtain sufficient silt/clay. The sediment was suspended in 50 ml of a 1:15 Tween 20:distilled water solution. The Tween 20 was added not only as a dispersing agent but also to prevent cracking of the sediment cake as it dried on the filters. The sediment suspension was passed through a 100 um stainless steel sieve to remove all coarse sand and organic debris which would otherwise have prevented formation of a uniform sediment cake. The resulting suspension of fine particles was filtered onto preweighed 0.45 um metricel filters and washed with 25 ml of the Tween 20 solution. The cake and filter were then dried and weighed.

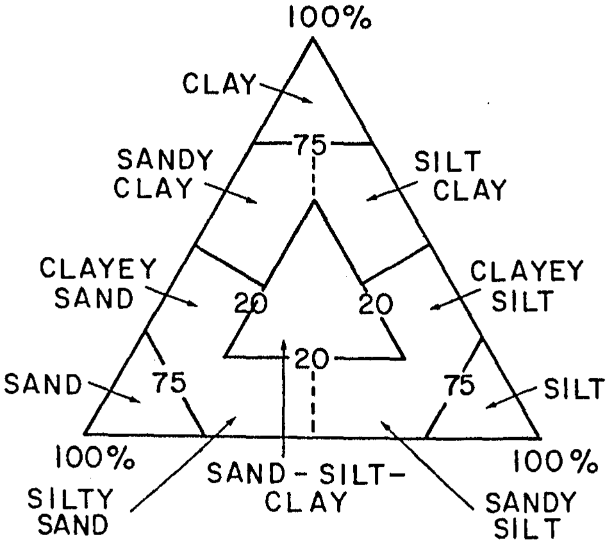


Figure 3. Sediment descripters used in the characterization of cores from the Poquoson and Warwick Rivers, after Pettijohn (1957).

Since clay and silt sediments contain both aluminum and silicon, it was necessary to determine the ratio of these two elements in sediments which had not been enriched by the addition of aluminum sludge. Therefore a sediment sample was obtained from the York River about 400 yds from the Institute's beach at a station known as the plankton buoy station. Sediments at this site consist of silts and clays with little or no sand. In addition, samples of finely ground kaolinite and montmorillonite, common clay minerals of the coastal plain of Virginia were obtained. The York River sediments and the samples of clay minerals were processed for analysis in the same manner as the samples from the two rivers.

The sample cake was analyzed by x-ray dispersive spectroscopy using a PGT Model 342 Spectroscope with a Si(Li) detector. The amplified signal at each wavelength was analyzed by a PGT System 4 computer. Samples were placed in the sample chamber, air was evacuated, and x-rays were passed through the sample. Each element absorbs and re-emits (fluoresces) x-rays at particular wavelengths. The x-ray energy emitted is measured and plotted against wavelength. The areas under peaks on the curve representing aluminum and silicon were determined by computer analysis of the spectrum and the ratio was calculated automatically.

Radionuclide Analysis Methods

Subsamples from the same cores used for the Al:Si ratio analyses were used to determine the activity of ^{137}Cs. Each 2 or 3 cm thick core section was dried, pulverized, and stored in a plastic bag. The sediment samples were subsequently counted for ^{137}Cs using an Ortec Model 7450 Multichannel Analyzer and a Model GEM-15200 P-type Germanium Detector. The detector was shielded with 6 inches of lead on the bottom and sides, and 4 inches of lead on top. The detection system was calibrated using a standard ^{137}Cs source to determine the energy region of the ^{137}Cs peak. Each sample in a 250 ml plastic beaker was placed on top of the detector and counted for 10 hr.

The background activity level within the ^{137}Cs energy peak was determined by eight consecutive 10 hr counts starting 17 December 1984. The average counts per hour (cph) and 95% confidence interval for all eight 10 hr counting periods was 46.6 ± 6.0 [range: 42.9-51.6 cph]. All background counts fell within the grand mean ± 95% confidence interval. Each sediment sample count was corrected by subtracting the mean background count.

Biological Parameter Cores

On 17 May 1984 we sampled Stations 1-10 in the Poquoson River, and on 21 May 1984, Stations 1-10 in the Warwick River for the benthic invertebrate community. At each Station, five 5-cm diameter cores were collected to a depth of 10 cm for a total area sampled of 126 cm^2. Each core was subdivided into the top 5 cm and the bottom 5 cm to examine the vertical distribution of organisms. Each section of core was placed in a plastic bag and preserved with 10% formalin (stained with rose bengal). In the laboratory, samples were washed onto a 0.5 mm sieve and the residue sorted under a dissecting microscope to remove all organisms. So few organisms were obtained in the deep sediment fraction, that the samples were recombined with the top fraction of the core for analysis. All organisms were identified to the lowest possible taxonomic level. A sample of surface sediment was also examined to determine whether the grain size had changed since the March collection.

Primary Production and Related Measurements

Phytoplankton Community

Primary production of the phytoplankton community in the Poquoson River was measured on 5 and 6 March 1984, and again on 18 and 19 June 1984. In each case, the first day corresponded to the day before an alum sludge discharge, and the second to a day of alum sludge discharge from the Harwood's Mill Water Treatment Plant respectively. The phytoplankton productivity in the Warwick River was measured on 22 March and 21 June. Only single measurements were made in this case because the alum sludge discharged from the Lee Hall Water Treatment Plant is continuously present in the receiving water despite the infrequency of discharge. The failure of the aluminum hydroxide to settle completely in the receiving water possibly reflects the absence of salt in the water.

Primary production was measured in situ using the ^{14}C-uptake method. Four 23.8 ml scintillation vials were filled with aliquots of the phytoplankton community and inoculated with $NaH^{14}CO_2$. Two of the vials were wrapped with aluminum foil to darken them. All four vials, two light and two dark, were placed in a holder suspended 12 inches below the water surface and incubated for 2 to 4 hours. After incubation, two 5-ml samples were withdrawn from each incubation vial and placed in a vial containing 2 ml glacial acetic acid and dimethyl sulfoxide (DMSO) to fix the sample and drive off any unconsumed inorganic carbon label. Upon returning to the laboratory, the samples were evaporated to dryness, redissolved in 2 ml of water to which 10 ml Aquasol II was added as a scintillation medium. The activity of fixed carbon in the samples was then counted using a Beckman LS150 Liquid Scintillation Counter. In a few cases in which there were large amounts of insoluble suspended material (principally alum sludge), an internal standard was added and the samples were recounted to correct for quenching by the suspended material. In addition, a sample of the $NaH^{14}CO_3$ stock solution was placed in a vial containing 2 ml 0.1 N NaOH to which was added 10 ml Aquasol II. This sample was then counted to verify the amount of activity added to the incubation vials.

When the samples were collected for the ^{14}C analysis, a sample was also collected for carbonate alkalinity determination, which is necessary to determine the total amount of carbon available for photosynthesis. The alkalinity was determined by the method of Strickland and Parson (1972), using a computerized calculation procedure available at the Virginia Institute of Marine Science.

Samples were also collected for chlorophyll a analysis. A 5 or 10 ml subsample was filtered onto a 0.8 um glass fiber filter. The sample on the filter was placed in a darkened test tube containing 8 ml of a DMSO:acetone:water:diethyl amine (DEA) mixture (45:45:9:1), and allowed to extract for 24 hours at room temperature. The resultant extract was analyzed for chlorophyll a and phaeophytin by fluorometry (Strickland and Parsons, 1972; Burnison, 1980).

Benthic Algal Community

Primary production of the benthic algal communities at the same two stations in each river were measured at the same time as the phytoplankton productivity. A modified "dark and light bottle" procedure was employed (Rizzo, 1977). Four 1-liter plexiglas chambers, two light and two dark, were inserted into the substrate at each station at a shallow depth but deep enough that they would not be emersed during the incubation period. Samples were taken with a 10 ml syringe and fixed with Winkler reagents in order to determine the initial oxygen concentration in each chamber. After a 2 to 4 hr incubation period, each chamber was again sampled to determine the final oxygen concentration. The samples were titrated in the usual manner with sodium thiosulfate and starch indicator, except that a syringe buret was used to dispense the reducing agent. Net production and respiration were calculated directly from the measured oxygen concentrations in each chamber, and gross production was calculated as the algebraic sum of net production and respiration.

Two sediment cores were collected adjacent to the location of the incubation chambers to measure the benthic chlorophyll a concentrations at the time of the productivity measurements. In addition, when the long cores for sedimentological analyses and again when the benthic invertebrate samples were collected from the Warwick River, a series of short 2.5 cm diameter cores were collected at many stations. The top 1 cm of these cores was analyzed for chlorophyll content as an indication of the condition of the benthic algal community. The top 1 cm from the 2.5 cm diameter cores was extruded into an Ehrlenmeyer flask. Each sample was extracted overnight at room temperature in the dark with DMSO:acetone:water:DEA (45:45:9:1). Each extract was diluted as necessary and analyzed for chlorophyll a with a Turner Fluorometer. The chlorophyll content, uncorrected for phaeophytin, is expressed as mg/m^2.

Evaluation of Tidal Marshes

In order to facilitate the task of assessing the present plant community structure of the marshes in the two rivers, recent aerial imagery was sought from the Institute's Remote Sensing Archives. Unfortunately, suitable imagery of the site was not available. Therefore both marshes were examined visually by walking through the marshes in July and again in October 1984 specifically to determine whether any changes had occurred within the plant community structure since the 1973 inventory. Notes of species observed and estimates of coverage were made and compared to the prior inventories of the marshes in each area.

STORM Model

The hydrologic simulation model STORM (US Army Corps of Engineers, 1976) was used to estimate runoff quantity and quality from the watersheds draining into the Lee Hall and Harwood's Mill water supply reservoirs. The model was run first with existing (1984) land uses in each sub-basin, and again with land use configurations representing typical residential and agricultural development in the absence of reservoirs.

Model Calibration

The VIMS version of STORM is a copy of the program used in the area-wide Hampton Roads Water Quality Management (208) Project (Hampton Roads Water Quality Agency, 1978). In the present study, the model was run using the coefficient method of flow quantity and quality accounting. No storage or treatment options were chosen, and since snowfall is relatively insignificant on an annual scale, snow melt computations were not made. The options selected for the present modeling work were identical to those used in the 208 study, and are described in detail in Volume 5 of the Hampton Roads Water Quality Management Plan (Hampton Roads Water Quality Agency, 1978).

During the 208 Study, land uses on the Peninsula and Southside Hampton Roads were divided into eleven categories for the purpose of basin modeling with STORM. Calibration of the model for each land use was accomplished by comparing STORM simulations with actual field data from watersheds having characteristics thought to be typical of each of the eleven categories. The model parameters were then adjusted to provide the best least-squares fit with the field data. Once the best fit was achieved, the model was considered to be calibrated with respect to land use categories, and could then be applied to any watershed for which land use areas are known. The calibrated model coefficients for each land use are provided in detail in Volume 5, Chapter 5.3a of the 208 Plan (Hampton Roads Water Quality Agency, 1978).

In a comparison of annual loadings for each land use category derived from the unmodified calibrated STORM model with actual data reported from areas with similar land uses, the STORM loadings for nitrogen, phosphorus, and 5-day biochemical oxygen demand (BOD_5) were above the range of literature values reported for forest and row-crop agriculture (Table 1-4). The pollutant accumulation rates for these parameters were therefore adjusted downward to bring them into line with the values reported in the literature. These tables contain the final adjusted loading rates (column 1) used during all subsequent STORM simulations for the water supply watersheds.

Application to the Reservoir Watersheds

The information needed to apply the STORM model to the study watersheds can be divided into two general types: 1) land use (the fraction of watershed in each of eleven categories), and 2) basin morphology (i.e.

watershed area, average slope, soil types, etc.). Data of both types, collected for over 120 watersheds on the Peninsula and Southside Hampton Roads during the 208 project, were used as input in the simulations for the two reservoirs. During the model runs, basin morphology parameters were held constant for each reservoir, while land use parameters were changed to simulate various development scenarios.

Basin morphology parameters were scaled appropriately for the catchments draining into each reservoir. Total watershed and reservoir areas were determined from 1:24,000 U.S.G.S. topographic maps. Since the purpose of the basin modeling study was to project watershed loadings in the absence of reservoirs, the total area (watershed + reservoir) was used for input to STORM. Therefore, the outflow points of the model simulation (the point for which pollutant loads are calculated) were located at the spillway of each reservoir. Basin morphology parameters input to the model are reported in Table 5.

Land Use Data

In addition to present day land use, alternate land use patterns were input to the model to simulate loadings that might have occurred had development been unrestricted in the watersheds. The two types of growth that would most likely have occurred in these watersheds in the absence of reservoirs are residential development or row-crop agriculture. The percentages used to reflect development are intended to represent what conditions might have been in the watersheds in the absence of reservoirs assuming land development was unrestricted. The data for these development scenarios, including the existing (1984) land use case, were provided by the Department of Public Utilities of the City of Newport News. In addition, a

Table 1. A comparison of annual suspended solids loads calculated by STORM with values reported in the literature.

Land Use	STORM (HRWQA, 1978)	Grizzard & Brown (1979)	NVPDC (1979)	Anderson et al. (1982) Ware River	Anderson et al. (1982) Lynnhaven Bay
Residential	105.8	14-118	40-200	106	30-89
Commercial	132.2	22-52	480	ND*	170-185
Industrial	132.2	350-1000	320-440	ND	ND
Forested	66.9	3-250	20-100	112	ND
Agriculture					
Row Crop	185.1	144-706	900-1500	134	ND
Pasture	158.6	41-502	20-100	ND	ND

* ND = Non-detectable

Table 2. A comparison of annual BOD loads calculated by STORM with values reported in the literature.

Land Use	STORM (HRWQA, 1978)	Grizzard & Brown (1979)	NVPDC (1979)	Anderson et al. (1982) Ware River	Anderson et al. (1982) Lynnhaven Bay
Residential	30.5	4-9	19-36	8	6-13
Commercial	36.4	6-12	97-206	ND*	43-63
Industrial	33.1	ND	111-145	ND	ND
Forested	6.6	0.86-160	6	5	ND
Agriculture					
Row Crop	18.6	112-590	29	5-6	ND
Pasture	78.6	-	15	ND	ND

* ND = Non-detectable

Table 3. A comparison of annual total nitrogen loads calculated by STORM with values reported in the literature.

Land Use	STORM (HRWQA, 1978)	Grizzard & Brown (1979)	NVPDC (1979)	Anderson et al. (1982) Ware River	Anderson et al. (1982) Lynnhaven Bay
Residential	11.9	0.9-1.9	3.1-11.4	3	1-3
Commercial	14.9	1.1-3.1	13-24	ND*	8-18
Industrial	14.9	1.7-12.5	10-12	ND	ND
Forested	3.3	0.2-0.8	2.4	1.2	ND
Agriculture					
Row Crop	9.3	2.4-6.3	9-13	0.7-1.2	ND
Pasture	9.9	1.7-5.1	9	ND	ND

* ND = Non-detectable

Table 4. A comparison of annual total phosphorus loads calculated by STORM with values reported in the literature.

Land Use	STORM (HRWQA, 1978)	Grizzard & Brown (1979)	NVPDC (1979)	Anderson et al. (1982) Ware River	Anderson et al. (1982) Lynnhaven Bay
Residential	1.2	0.2 -0.9	0.2-1.2	0.4	0.25-0.50
Commercial	1.7	0.2 -0.8	1.6-2.7	ND*	1.6 -2.7
Industrial	1.7	0.8 -3.6	1.2-1.4	ND	ND
Forested	0.33	0.03-0.12	0.1	0.2	ND
Agriculture					
Row Crop	1.26	0.5 -1.7	1.1-2.3	0.4-0.6	ND
Pasture	1.95	0.2 -1.4	0.3	ND	ND

* ND = Non-detectable

Table 5. Basin morphology parameters for the Lee Hall and Harwoods Mill water supply reservoirs.

	Lee Hall Reservoir	Harwoods Mill Reservoir
Watershed area (acres)	9884	5922
Reservoir area (acres)	316	278
Total area (acres)	10200	6200
Outfall elevation (ft above sea level)	10	10
Maximum watershed elevation (ft above sea level)	65	65
Maximum stream length (ft)	24000	24000
Average slope	0.23 %	0.23 %
Time oc concentration (hrs)	1.5	1.5

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simulation was made in which each watershed was left 100% forested in order to estimate background loadings from the two watersheds under pristine land use conditions.

Rainfall Data

Model runs were conducted to define watershed pollutant loadings for a typical year. The rainfall data from 1957 was used to represent typical conditions because the annual total and the monthly distribution of rainfall for that year most closely approximated the long term (35 yr) average. These rainfall data were measured at Langley AFB. The procedure used for the selection of this particular precipitation record is detailed in Volume 5, Section 5.3c of the 208 Report (Hampton Roads Water Quality Agency, 1978).

RESULTS AND DISCUSSION

Poquoson River

X-Ray Stratigraphy

X-rays of the long cores from the Poquoson River revealed a combination of processes affecting sediment stratigraphy with physical processes dominating at Stations 1 to 5 and biological processes dominating at Stations 6 to 10 (Figure 4). The biogenic structures present in the top 10 cm of the core from Station 6, were predominantly worm tubes, probably formed by *Nereis succinea*. These burrows appeared to be active when the core was taken. At Station 7 there were biogenic structures, worm burrows and shells, scattered throughout the central portion of the core (at 20 to 60 cm). All these features were relict, representing past organismic activity. Station 9 had biogenic structures evident to a depth of 55 cm, all of which were relict, except the small active worm burrows present at the surface. Station 10 had burrows in the upper 25 cm and below 65 cm in the core. The core from Station 8 was structureless to a depth of 40 cm, and no data are available below this depth.

Physical laminations were the dominant features from Stations 2, 3, 4, and 5 indicating the variable episodic nature of the flow at these stations. Organic detritus was abundant at Stations 1 and 4, as represented in Figure 4 by the irregular stippling.

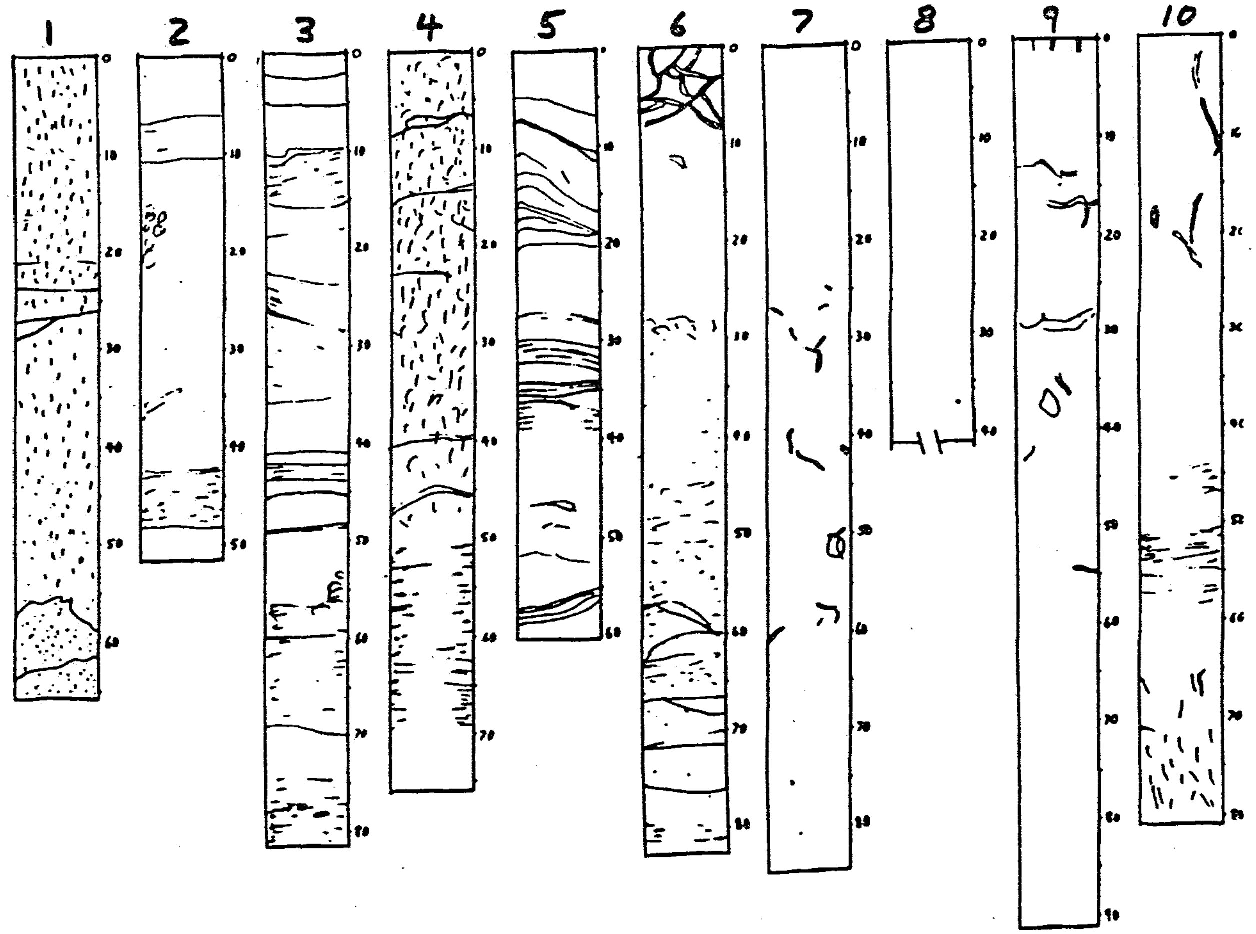

Figure 4. Schematic diagrams of x-ray cores from the Poquoson River. Horizontal or tilted lines indicate physical lamination within cores resulting from sediment bedding. Areas that are dotted tended to have high detritus content. Featureless areas were uniform layers of one type of sediment.

The lack of biogenic structures at Stations 1, 2, 3, 4, and 5 is related to the transitional nature of the habitat and episodic nature of flow. The lack of any physical structure at Station 8 was related to the uniform grain size of the sediment. The recent and relict biogenic structures at Stations 6, 7, 9, and 10 indicate the presence of well developed estuarine benthic communities. This type of biogenic structure is characteristic of mesohaline habitats in both the James River and the Chesapeake Bay (Schaffner and Diaz, 1982; Nilsen et al. 1980).

Al:Si Ratios

The average Al:Si ratios for the clay minerals analyzed to define the background Al:Si ratio were 0.179 (s.d.=0.003, n=3) for montmorillonite and 0.555 (s.d.=0.006, n=3) for kaolinite. The average ratio for a York River sediment sample was 0.176 (s.d.=0.009, n=6). Based on these observations, a value of 0.2 would seem a reasonable background Al:Si ratio.

Since the background aluminum:silicon ratio must ultimately depend on the mixture of clay minerals which make up the substrate, a better estimate could be made if the clay mineral composition of the sediments was known. No attempt was made to determine directly what minerals and proportions of minerals were present in the locations studied. Hathaway (1972) presented maps representing the abundance of various clay minerals on subaqueous bottoms along the coast of the eastern United States including the Chesapeake Bay. The principle clay minerals reported were kaolinite, illite and montmorillonite. The scale of the distribution maps was too small to determine with any certainty the clay mineral content in either of the rivers under study. Some further insight can be gained from Feuillet and

Fleisher (1980) who reported that kaolinite and illite are especially abundant in low salinity systems (0-5 ^{o}/oo), occurring in about equal proportions, whereas montmorillonite is low in abundance in such low salinity waters. It seems likely then that these two minerals represent the principle components of the sediments in the study area. Illite and montmorillonite are very similar in content of aluminum and silicon (Grim, 1953), so the Al:Si ratio measured by us for montmorillonite probably represents that of illite reasonably well.

Based on the Al:Si ratio measurements for the clay minerals, the background ratio would be expected to lie between 0.18 and 0.56. The ratio for York River sediments is at the low end of this range, suggesting that aluminum-rich kaolinite was not contributing greatly to the ratio. The York River sampling site lies in 20 ^{o}/oo water where the abundance of kaolinite is reduced and that of illite and montmorillonite increased (Feuillet and Fleisher, 1980). Therefore one might expect a somewhat lower ratio at the York River site than in the freshwater-estuarine transition zone of either the Poquoson or Warwick Rivers.

An Al:Si ratio of 0.2 was finally selected as the maximum ratio for uncontaminated sediments. This value is most appropriate for the mesohaline portion of the Poquoson River site. A case could be made for a higher background ratio in the oligohaline and freshwater areas of the Poquoson and Warwick Rivers, but the ratio for uncontaminated natural sediments could not be greater than 0.5.

In the Poquoson River, the aluminum:silicon ratios were high only at the most upstream stations (Table 6), with the highest observed ratio being

Table 6. Aluminum:Silicon Ratios for sediments in cores collected in the Poquoson River, VA in March 1984.

Depth of Sample (1) (cm)	Station									
	1	2	3	4	5	6	7	8	9	10
0-1	0.932	0.488	0.604	0.411	0.408	0.233	0.203	0.175	0.168	0.190
5-6	0.510	0.479	0.460	0.350	0.342	0.246	0.206	0.173	0.158	0.195
11-12	0.206	0.421	0.449	0.290	0.268	0.227	0.204	0.200	0.167	0.197
20-21	0.214	0.392	0.364	0.326	0.249	0.209	0.172	0.172	0.147	0.204
26-27		2.163*								
29-30	0.326		0.303	0.444	0.293	0.205	0.144	0.144	0.149	0.203
41-42	0.500	0.235	0.166	0.429	0.181	0.151	0.142	0.147	0.150	0.212
50-51	0.307	0.207	0.172	0.239	0.182	0.149	0.134	0.146	0.150	0.209
59-60	0.269	0.158	0.181	0.246	0.164	0.154	0.116	0.141	0.155	0.217
62-63	0.406									
71-72		0.145	0.155	0.202	0.160	0.153	0.121	0.137	0.164	0.203
76-77				0.191						
80-81			0.158		0.166	0.151	0.128	0.133	0.167	0.203
85-86							0.132			
89-90								0.142	0.183	0.203
92-93									0.160	0.201

(1) Sample depths are uncorrected for compaction

* This datum may be artifactual since the counts for Silicon were unusually low

0.93 in the surface sediment at Station 1 (A higher value, observed at 26-27 cm in the core from Station 2, is believed to be spurious since the peak for silicon was unusually small, while that for Al was comparable to that for samples with much lower ratios). At Station 1, the Al:Si ratio suggests two subsurface lenses of elevated Al, one at 41-42 cm, and another at 62-63 cm (or below, since this depth was the bottom of the core).

At Station 2, the sediments were only slightly enriched from the surface of the core to 50 cm, and below that depth were at extremely low background levels. As mentioned above, the high ratio of 2.16 observed at 26-27 cm in the core from Station 2 is thought to be an artifact. If one omits that sample from consideration, the degree of enrichment decreases monotonically with depth; there are no subsurface lenses of enriched sediment at this station.

At Stations 4 through 6, the surface sediments were very slightly enriched with aluminum, overlying unenriched sediments beginning at depths ranging from 10 to 70 cm. All other cores revealed no enrichment with Al with the possible exception of the bottom of the core from Station 10 (depths below 30 cm), but the degree of enrichment was almost trivial, and may simply reflect a mineral sediment with a slightly higher Al:Si ratio than sediments found elsewhere in the Poquoson. Indeed, the "enriched" sediments at Station 10 are barely higher than background levels for the Warwick River, while most samples from cores at Stations 5-9 had Al:Si ratios below those observed for kaolinite and montmorillonite clays and sediments from the York River which were analyzed to determine background ratios for unenriched sediments.

In summary, aluminum enrichment in the Poquoson River was only slight and restricted to Stations 1 to 6. Further, enrichment was observed at depths greater than 30 cm core depth only at Stations 1, 2 and 4.

Sediment Particle Size

Surface sediments in the Poquoson River were muddy at all stations except 1 and 10 (Table 7). Quartz sand occurred at all stations except Stations 7, 8, and 9 which were primarily silt. The entire 93 cm length of the core from Station 10 was fine sand. From Stations 1 to 6 the sand layers were interspersed with silt and clay. Water content of surface sediments was lowest at Station 1 (16.5 %) and highest at Station 9 (92.9 %). Surface sediments did not change between the February and June collections (Table 7 and 8).

Sediments were most heterogenous with respect to depth in the cores at the upstream stations (Stations 1 to 6). The sediment at the bottom of the cores does not appear to be relict terrigenous sediment. The interbedding of sands and silts at the first six stations indicates fluctuating flow conditions. Stations 7, 8, and 9 are located in broad stretches of the Poquoson that are not subject to strong currents. Station 10, while in a broad section of the Poquoson, is close to the mouth and subject to strong wind or tidal currents.

There was no evidence of coal or powdered activated carbon (PAC) particles from the treatment plant in any core. Coal and PAC particles were found in the Warwick River (see below) and Broad Creek (Diaz and Roberts, 1984). Cores from many stations in the Poquoson River, especially Stations 1 and 4, had a high detrital content throughout most of their length. The surface sediments from Stations 2 and 3 also had high detrital content.

Table 7. Sediment type from Poquoson River cores, March 1984. Sand (SA), Silty Sand (SISA), Clayey Sand (CLSA), Silt (SI), Sandy Silt (SASI), Clay (CL), Clayey Silt (CLSI), and Sandy Clay (SACL).

	Station									
Layer (cm)	1	2	3	4	5	6	7	8	9	10
0-1	SA	SI	SI	SI	SI	SI	SI	SI	SI	SISA
1-2	SA	SI	SI	SISA	SI	SI	SI	SI	SI	SISA
2-3	SA	SI	SI	SI	SI	SI	SI	SI	SI	SISA
5-6	SA	SI	SI	SI	SI	SI	SI	SI	SI	SISA
8-9	SA	SI	SI	SASI	SI	SI	SI	SI	SI	SISA
11-12	SA	SI	SI	SASI	SI	SI	SI	SI	SI	SISA
14-15	SISA	SASI	SISA	SI	SI	SI	SI	SI	SI	SISA
17-18	SA	SA	SISA	SI	SI	SI	SI	SI	SI	SA
20-21	SA	SI	SI	SISA	SI	SASI	SI	SI	SI	SA
23-24	SA	SI	SI	SISA	SI	SASI	SI	SI	SI	SA
26-27	SA	SI	SI	SI	SI	SA	SI	SI	SI	SA
29-30	SA	SA	SI	SI	SI	SA	SI	SI	SI	SA
32-33	SA	SA	SASI	SI	SASI	SISA	SI	SI	SI	SA
35-36	SA	SA	SI	SI	SASI	SASI	SI	SI	SI	SA
38-39	SI	SISA	SI	SI	SI	SI	SI	SI	SI	SA
41-42	SISA	SI	CLSI	SI	SASI	SASI	SI	SI	SI	SA
44-45	SISA	SI	SI	SI	SI	SISA	SI	SI	SI	SA
47-48	SISA	SI	SI	SI	SI	SISA	SI	SI	SI	SA
50-51	SISA	SI	SI	SI	SASI	CLSA	SI	SI	SI	SA
53-54	CL	SISA	SI	SI	SI	SISA	SI	SI	SI	SA
56-57	SA	SISA	SI	SI	SI	SASI	SI	SI	SI	SA
59-60	CL	SA	SA	SI	SASI	CLSI	SI	SI	SI	SA
62-63	CL	SI	SISA	SI	SASI	SI	SI	SI	SI	SA
65-66		SI	SI	SASI	SISA	SI	SI	SI	SI	SA
68-69		SI	SI	SA	SISA	SI	SI	SI	SI	SA
71-72		SI	SISA	SA	SISA	SI	CLSI	SI	SI	SA
72-73		SI	SI	SI	SISA	SI	SI	SI	SI	SA
74-75		SI	SI	SI	SISA	SI	SI	SI	SI	SA
77-78		SI	SI	SI	SA	SI	SI	SI	SI	SA
80-81			CL		SA	CL	SI	SI	SI	SISA
83-84						SI	CL	SI	SI	SISA
86-87						SI		SI	SI	SISA
89-90								CLSI	SI	SISA
91-92									SI	SISA
92-93									SI	SISA

Table 8. Surface sediment type from biological collections, May, 1984.

River	Station	% Sand	% Silt+Clay	Type
Poquoson	1	96	4	Sand
	2	18	82	Silt
	3	4	96	Silt
	4	15	85	Silt
	5	3	97	Silt
	6	4	96	Silt
	7	2	98	Silt
	8	2	98	Silt
	9	3	97	Silt
	10	45	55	Silty Sand
Warwick	1	5	95	Silt
	2	90	10	Sand
	3	72	28	Silty Sand
	4	68	32	Silty Sand
	5	7	93	Silt
	6	2	98	Silt
	7	4	96	Silt
	8	3	97	Silt
	9	1	99	Silt
	10	2	98	Silt
	11	1	99	Silt

Relationships among Sediments-Stratigraphy-Al:Si Ratio

When the stratigraphic and Al:Si ratio data are compared, there were no clear relationships between stratigraphic features and the amount of aluminum present (Figure 5). Transitions from high ratios to low ratios did not occur at lamination points in the cores. High and moderate levels of Al:Si ratio were also not associated with any particular type of sediment. The highest ratios were found at the upstream stations where the sediments were sandy at some stations, silty at others.

Background Al:Si ratios were observed in all cores except Station 1. Background levels were reached at varying depths in the cores. The deepest penetration of elevated Al:Si ratio was 71 cm at Station 4. From Station 4 downstream to Station 7, elevated Al:Si ratios penetrated to progressively shallower depths in the cores. At Stations 8, 9, and 10, measurements of Al:Si from all stations were at or very near background levels.

Radionuclide Distribution

The major sources of ^{137}Cs in marine sediments of the coastal plain of Virginia are fallout from atmospheric testing of nuclear weapons in the late 1950's and early 1960's and discharge from the Surry Nuclear Reactor. The input from atmospheric weapons testing reached a peak in 1963; there was a major release of ^{137}Cs from the Surry Nuclear Reactor in 1975 (Cutshall et al., 1981). The Surry Reactor peak should be more evident in the Warwick River sediments than the Poquoson River sediments due to its closer proximity to the source; indeed, the Poquoson River may be too distant from the reactor to have received any ^{137}Cs from the 1975 release. Fallout from

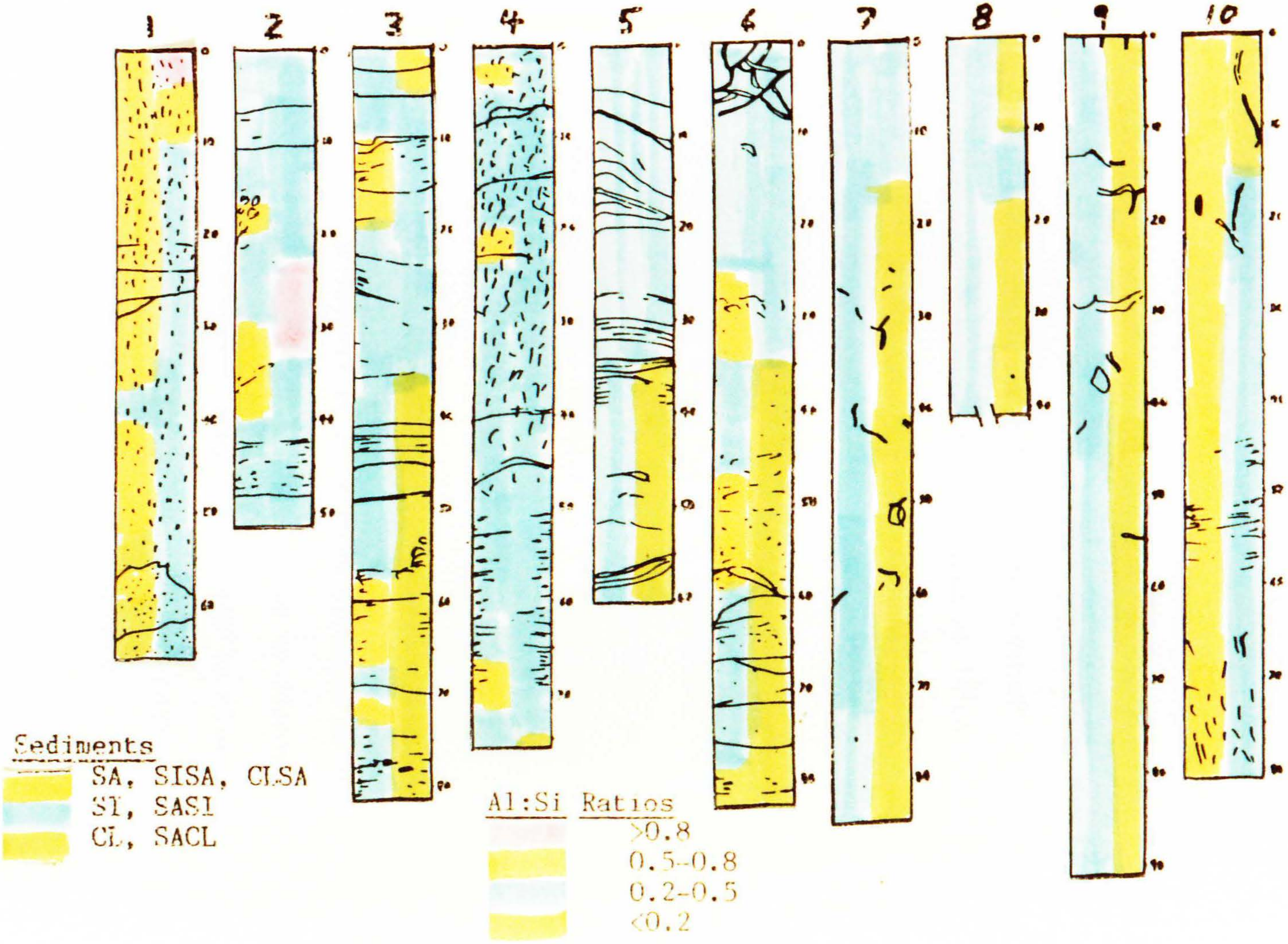

Figure 5. Comparison of sediment particle type, stratigraphy, and Al:Si ratios in the Poquoson River. Left side of the core diagram is colored to indicate the sediment particle type. The right side of the core diagram is colored to represent specific ranges of Al:Si ratio.

atmospheric testing should have been the same for both study sites, with the size of the watershed determining the total quantity of ^{137}Cs received.

Nine of the ten cores from the Poquoson River were analyzed for ^{137}Cs activity. The net activity of ^{137}Cs measured in each core section standardized on a per gram dry weight basis is contained in Table 9. Cores from Stations 1, 2, 3, and 6 did not exhibit a distribution of ^{137}Cs which could be interpreted. Of the remaining stations, Station 8 and 9 appear to be erosional because the ^{137}Cs activity was greatest at the surface, decreasing to zero with depth. The profiles of ^{137}Cs at Stations 4, 5, and 7 all have a single peak. If this peak is interpreted to be the 1963 fallout period, then the average accumulation rages at these stations were 1.4, 1.1, and 0.8 cm/yr respectively.

There appears to be a trend toward a decreasing rate of sediment accumulation as one progresses downstream. At Station 10, the farthest downstream station, the distribution of ^{137}Cs indicates deep resuspension with the radioactivity spread throughout the majority of the core (Table 9).

Primary Production

Phytoplankton productivity at Station 1, based on ^{14}C- uptake, was extremely low (<2 mg C/m^3/h) on the day prior to discharge of the alum sludge both during the winter sampling and the late spring sampling (Table 10). In both cases, the low productivity corresponded to a low standing crop of algae as indicated by chlorophyll a concentrations at or below 1.1 mg/m^3 (Table 10). At the downstream station, production prior to the discharge was several times higher during the winter and late spring. On the day of the sludge discharge in both March and June, the production

Table 9. Net activity for ^{137}Cs (net counts/g dry sediment/hr) in cores collected in the Poquoson River, VA in March 1984. Zero values indicate that the true value was less than one 95% confidence interval from zero (see Materials and Methods for full explanation).

Depth of Sample (1) (cm)	Station 1	2	3	4	5	6	7	8	9	10
0–1	*							0.021	0.013	0.000
3–4					0.000					
5–6		0.009					0.007	0.016		0.005
8–9		0.018		0.016					0.013	0.005
11–12				0.016	0.015	0.014		0.012		0.006
14–15									0.010	0.002
17–18					0.016	0.023	0.011			0.001
20–21			0.002	0.017						
23–24			0.000	0.025	0.019	0.040	0.008		0.009	0.003
26–27										0.002
29–30				0.026				0.000		0.004
32–33									0.000	
35–36				0.022	0.007		0.000	0.000		0.003
38–39		0.001				0.005				0.004
41–42		0.000	0.000	0.024	0.000			0.000		0.003
44–45						0.000	0.001			
47–48				0.016				0.000	0.000	
50–51		0.000			0.000					0.004
53–54			0.000	0.004		0.000		0.000		
56–57							0.000			
59–60			0.000	0.008					0.000	
62–63										0.005
65–66				0.005	0.000	0.000				
68–69							0.000			
71–72			0.001	0.004				0.000		0.001
74–75										
77–78					0.000	0.000	0.000		0.000	0.001
80–81										
83–84									0.000	
86–87										0.000
89–90								0.000		
92–93									0.001	0.000

* Short core; not counted

Table 10. Plankton Productivity, Chlorophyll Concentration, and Assimilation Ratio in the Poquoson and Warwick Rivers during March and June, 1984.

Date	Carbon Uptake (mg C/m^3/h)		Chlorophyll a Concentration (mg chlor a/m^3)		Assimilation Ratio (mg C/h/mg chlor a)	
	POQUOSON RIVER					
	Sta. 1	Sta. 6	Sta. 1	Sta. 6	Sta. 1	Sta. 6
3-05-84	1.4	18.9	0.85	8.7	1.6	2.4
3-06-84	10.4	30.5	3.7	8.5	2.8	3.6
6-18-84	< 0.1	40.1	1.1	12.6	<0.1	3.2
6-19-84	11.7	88.7	62.9	15.8	0.2	5.6
	WARWICK RIVER					
	Sta. 3	Sta. 6	Sta. 3	Sta. 6	Sta. 3	Sta. 6
3-22-84	6.1	53.6	3.7	12.4	1.6	4.3
6-21-84	3.1	85.3	25.5	16.9	0.1	5.0

measured at Station 1 was increased 10-fold corresponding to a large increase in standing crop (4-fold in March and 57-fold in June). The dramatic increases in standing crop and corresponding though lesser increases in primary production assuredly reflect the standing crop of algal material in the sludge derived originally from the reservoir. No such differences in standing crop were apparent at Station 6, and although there was a small increase in production on the day of discharge in both winter and late spring, these differences are considered to be insignificant.

Few productivity studies have been conducted specifically in habitats like the Poquoson River. Stross and Stottlemyer (1965) studied primary production at 22 stations in the Patuxent River, MD. The salinity at their most upstream station ranged from 1 to 10 o/oo, and at a mid-subestuary station the salinity was approximately 15 o/oo, conditions comparable to Stations 1 and 6 on the Poquoson River. At the low salinity station, the standing crop of phytoplankton expressed in terms of chlorophyll _a_ was markedly higher than at Poquoson River Station 1 in both March and June (Table 11). The standing crop at Station 6 on the Patuxent and Station 6 on the Poquoson were nearly the same in March, and not greatly different for June.

Phytoplankton productivity in the Patuxent River in March was distinctly higher at the nearly freshwater station (Station 22) than at the comparable station (Station 1) in the Poquoson River (Table 11). At Station 6 in each river, production was quite similar, with higher production in June in the Poquoson than in the Patuxent, which corresponds to higher standing crop (Table 11).

Table 11. Comparison of phytoplankton productivity and standing crop (expressed as chlorophyll a concentration) in the Poquoson and Warwick Rivers to that at stations with similar salinity regimes in the Patuxent River, MD (Stross and Stottlemeyer, 1965).

	Freshwater				Moderate Salinity	
	Poquoson Station 1	Warwick Station 3	Warwick Station 6	Patuxent Station 22	Poquoson Station 6	Patuxent Station 6
Carbon Uptake (mg $C/m^3/h$)						
March	1.4	6.1	53.6	2.	18.9	18.
				2.	30.5	30.
June	<0.1	3.1	85.3	35	40.1	20.
				148	88.7	30.
Chlorophyll Concentration (mg chlor a/m^3)						
March	0.85	3.7	12.4	10	8.7	8
				5	8.5	8
June	1.1	25.5	16.9	10	12.6	6
				33	15.8	-

An alternate way to examine algal responses to a toxicant is to evaluate the assimilation ratio; i.e. the ratio of production to standing crop expressed as chlorophyll *a* concentration. The assimilation ratio adjusts the production for the amount of plankton biomass present, allowing, in a sense, an evaluation of the physiological condition of the plankton. Plankton stressed by a pollutant will exhibit a lower assimilation ratio than algae not so stressed.

In March, the assimilation ratio calculated for Station 1 was slightly low on the day preceeding a sludge discharge (Table 10) but within the expected range (Flemer, 1970). In June, however, the assimilation ratio was strongly depressed at Station 1 before the alum sludge discharge, and increased only slightly on the day of the sludge discharge despite the large increase in chlorophyll a concentration. The assimilation ratio at Station 6 was in the expected range, indicating no adverse effects on the plankton from any source.

The interpretation of the depressed assimilation ratios at Station 1 is not simple. While it might be argued on the basis of the assimilation ratio that the phytoplankton are impacted by the alum sludge, there was no depression of assimilation ratio for the algae entering the system with the alum sludge discharge in March, and in June there was even a slight increase in the assimilation ratio on the day of discharge. The improved assimilation ratio following the addition of algal material which had been in contact with alum sludge for some time argues against the observed impact being exclusively the result of alum sludge. One might speculate that some alternate pollutant may be involved; one possible candidate would be a substance associated with run-off from US Route 17, although this cannot be proven by the data at hand.

Benthic algal production can be expressed both as gross production (total production uncorrected for respiration) and net production (production corrected for respiration). In March, gross production was extremely low, reflecting the low light availability on both sampling days which were heavily overcast with occasional light to heavy rain (Table 12). Despite the poor conditions, it is clear that gross production was increased at both stations on the day of sludge discharge. This is thought to be an artifact of increased light availability; this cannot be substantiated due to a malfunction of the light meter. In June, the gross production at Station 1 was again very low. A severe interference with the Winkler oxygen determinations by the aluminum hydroxide in the sludge precluded measuring gross or net production during the June discharge.

In March, gross production was slightly higher at Station 6 than at Station 1, while respiration was much higher at Station 6. As a result, net production at Station 1 was higher than at Station 6, though in both cases, net production was negative (Table 12). During the discharge on the second sampling day in March, gross production and respiration were both markedly increased at Station 1 and 6. In contrast, the June gross production, respiration, and net production at Stations 1 and 6 were nearly the same on the day preceeding the sludge discharge. No comparison is possible for the day of discharge because of some material in the effluent (aluminum hydroxide?) which interfered with the Winkler oxygen method. Net production in June was positive at both stations. The lack of any difference in net production between the two stations results directly from the similarity in

Table 12. Benthic Algal Production at Upstream and Downstream Stations on the Poquoson and Warwick Rivers, VA during March and June.

Station Location	Date	Gross Production (mg $C/m^2/h$)	Respiration (mg $C/m^2/h$)	Net Production (mg $C/m^2/h$)
Poquoson				
Sta. 1	5 Mar 84	2.8	8.2	-5.4
	6 Mar 84	38	67	-29
	18 Jun 84	104	29	75
	19 Jun 84	*	*	*
Sta 6	5 Mar 84	10	76	-66
	6 Mar 84	88	102	-14
	18 Jun 84	103	23	79
	19 Jun 84	147	21	126
Warwick				
Sta 3	22 Mar 84	127	69	58
	21 Jun 84	*	*	*
Sta 6	22 Mar 84	78	78	0
	21 Jun 84	404	160	244

* No samples from benthic incubation chambers were analyzable due to interference (see text).

gross production and respiration at the two stations. Thus there is no evidence of any impact of the alum sludge discharge on the benthic algal community as measured by primary production rate during June, although there was a difference in March.

Gross production of benthic microalgae in salt marshes in Delaware is reported to range between 10-68 mg C/m^2/h (Gallagher and Daiber, 1974) and in Georgia, from 20 to 110 mg C/m^2/h (Pomeroy, 1959). For mudflats adjacent to marshes, gross production has been reported to range between 12 and 58 mg C/m^2/h in Georgia (Williams, 1962) and 16 to 21 mg C/m^2/h in Delaware (Gallagher and Daiber, 1974). Pomeroy (1960) reported gross production ranging from 65-190 mg C/m^2/h for a subtidal area near a turtle grass bed. Other researchers have provided support to the adequacy of these range estimates (Marshall, et al. 1971; Bunt et al., 1972; Gargas, 1970). By comparison, the gross production at Station 1 on the Poquoson was low, but certainly not outside the range of values observed in other shallow subtidal mudflats adjacent to marshes. Gross production at Station 6 is at the high end of previously observed production rates at similar latitudes, but again within the expected range.

The concentration of chlorophyll a in the sediments at Station 1 was 2.0 to 18.5 mg/m^2 in both March and June (Table 13). At Station 6, the chlorophyll concentration was 21.8 to 27.4 mg/m^2. The concentrations observed at Station 1, in a nearly freshwater habitat, are low in comparison to data from a similar habitat in the James River, at which the sediment chlorophyll was 50 to 60 mg/m^2 (Rizzo, personal communication). The observed concentrations fall at the low end of the range of chlorophyll concentrations reported for intertidal mud flats in saline waters. The data

Table 13. Sediment Chlorophyll Concentrations in mg/m^2 (uncorrected for phaeophytin) at Stations in Poquoson and Warwick Rivers during Productivity Measurements.

Date	Poquoson River Station 1	Poquoson River Station 6	Warwick River Station 3	Warwick River Station 6
3-5-84	2.0	27.4		
3-6-84	18.5	21.8		
3-22-84			28.5	10.1
6-18-84	ns	ns		
6-19-84	7.2	26.1		
6-21-84			3.5	31.9

ns = no sample

for the more saline Station 6 are comparable to data for similar subtidal habitats reported by Bunt et al. (1972) and Rizzo (1977).

Benthic Invertebrate Communities

From the Poquoson River, a total of 26 taxa were found at ten stations (Table 14). The most abundant taxa were amphipods, followed by polychaetes and oligochaetes (Table 15). Faunal diversity was high with five amphipod, eight polychaete and two oligochaete species present. The fauna from the Poquoson River was composed almost entirely of marine species. Only five of the 26 taxa were of freshwater origin. The salinities at all stations were high enough to reduce the occurrence of freshwater species. Nevertheless, at Station 10 one plecopteran larva was collected. These insects as a group are not very salt tolerant and the occurrence of a plecopteran at this station with a salinity of 18 o/oo is highly unusual. Despite this anomaly, it does not appear from a consideration of the benthic fauna that the salinities in the Poquoson ever drop to 0 o/oo long enough for salt-tolerant freshwater species to invade even at Stations 1 to 5.

The stations with the lowest diversity were Stations 1, 2, 3, 4, and 5, all in the low salinity area of the Poquoson. A total of 5 taxa were observed at these stations (Table 16). At Station 3, no organisms were found in any core. Stations 1 and 2 each had only one species represented. The salinity at these 5 stations, between 2 to 8 o/oo (Table 17), should be high enough to support a more diverse fauna, particularly at Station 5. At similar salinities in the James River (Diaz, 1977), York River (Boesch, 1977) and Broad Creek (Diaz and Roberts, 1984) systems a greater number of species was observed. It must be kept in mind,

Table 14. Species list for Poquoson River benthic collections, May 1984

Scientific Names	Common Names	Origin
Nemertea		
Lineus (?) spp.	Ribbon Worm	M*
Annelida		
Oligochaeta		
Tubificoides spp.	Bloodworms	M
Tubificoides heterochaetus	Bloodworms	M
Polychaeta		
Streblospio benedicti		M
Polydora ligni		M
Eteone heteropoda		M
Nereis succinea	Sand Worm	M
Scoloplos robustus	Rag Worm	M
Glycera dibranchiata	Bloodworm	M
Heteromastus filiformis		M
Diopatra cuprea	Tube Worm	M
Arthropoda		
Ostracoda		
Ostracod spp.	Seed Shrimp	M
Copdpods		
Harpacticoid spp.	copepods	F+M
Isopoda		
Edotea triloba	Sea Roach	M
Amphipoda		
Gammarus spp.	Scud	F
Gammarus fasciatus	Scud	F
Gammarus daiberi	Scud	F
Erichsonella spp.	Scud	M
Corophium spp.	Scud	M
Decapoda		
Libinia dubia	Spider Crab	M
Acarina		
Hydracarinids	Water Mite	F
Insecta		
Plecopterans	Nerve Wings	F

Table 14. Species list for Poquoson River benthic collections, May 1984 (con't)

Scientific Names	Common Names	Origin
Mollusca		
Gastropoda		
Retusa canaliculata	Snail	M
Sayella fusca	Snail	M
Pyramidella spp.	Snail	M
Bivalvia		
Mulinia lateralis	Coot Clam	M

* M - Species of marine origin
F - Species of freshwater origin

Table 15. Abundance data for benthic species collected from the Poquoson River in May 1984.

Station	Species	Core Number 1	2	3	4	5	Total
1	Harpacticoids	6	0	0	0	0	6
2	*Mulinia lateralis*	0	0	0	1	0	1
3				No Animals			
4	Hydracarinid	1	0	0	0	0	1
	Tubificoides spp.	1	1	2	30	2	36
5	Ostracods	0	1	0	0	0	1
	Tubificoides spp.	18	18	5	13	2	56
	Tubificoides heterochaetus	0	0	0	1	0	1
6	Ostracods	0	0	0	0	1	1
	Hydracarinid	1	0	0	0	0	1
	Gammarus fasciatus	6	10	2	5	0	23
	Gammarus spp.	0	1	0	0	2	3
	Tubificoides spp.	0	1	0	1	0	2
	Tubificoides heterochaetus	0	0	3	1	0	4
	Nereis succinea	0	1	0	0	0	1
	Streblospio benedicti	1	0	3	0	1	5
	Eteone heteropoda	1	0	0	0	1	2
7	*Gammarus fasciatus*	10	9	8	0	8	35
	Gammarus spp.	1	0	0	3	0	4
	Erichsonella spp.	0	0	0	0	1	1
	Tubificoides spp.	1	1	3	0	0	5
	Streblospio benedicti	0	1	0	1	8	10
	Nereis succinea	1	0	0	1	0	2
	Scoloplos robustus	0	0	0	2	0	2
	Glycera dibranchiata	0	0	0	1	0	1
8	*Lineus* (?) spp.	0	0	1	0	0	1
	Gammarus fasciatus	23	25	31	17	9	105
	Gammarus spp.	0	1	1	2	9	13
	Tubificoides spp.	2	0	1	0	1	4
	Eteone heteropoda	2	0	0	0	0	2
	Heteromastus filiformis	0	1	0	0	1	2
	Streblospio benedicti	10	5	15	6	3	39
	Mulinia lateralis	1	0	0	0	0	1

Table 15. Abundance data for benthic species collected from the Poquoson River in May 1984 (con't).

Station	Species	Core Number 1	2	3	4	5	Total
9	*Lineus* (?) spp.	1	0	0	0	0	1
	Gammarus fasciatus	38	43	42	4	21	148
	Gammarus spp.	0	7	0	5	2	14
	Corophium spp.	0	0	1	0	0	1
	Tubificoides spp.	1	1	1	0	0	3
	Streblospio benedicti	30	16	8	13	39	106
	Nereis succinea	0	1	0	1	0	2
	Heteromastus filiformis	0	0	0	2	1	3
	Eteone heteropoda	1	0	1	0	0	2
	Scoloplos robustus	1	0	1	0	0	2
	Glycera dibranchiata	1	0	0	0	0	1
	Mulinia lateralis	1	0	0	0	0	1
	Pyramidella spp.	0	1	0	0	0	1
10	*Gammarus fasciatus*	20	15	2	14	12	63
	Gammarus duebeni	0	0	0	1	2	3
	Gammarus spp.	3	0	0	1	0	4
	Edotea triloba	1	0	0	0	3	4
	Libinia dubia	1	0	0	0	0	1
	Plecopteran	1	0	0	0	0	1
	Tubificoides spp.	12	0	3	1	0	16
	Diopatra cuprea	1	0	0	0	0	1
	Polydora ligni	3	0	0	0	2	5
	Streblospio benedicti	4	6	16	12	16	54
	Eteone heteropoda	1	1	0	0	0	2
	Scoloplos robustus	0	1	3	1	1	6
	Glycera dibranchiata	0	0	0	0	1	1
	Heteromastus filiformis	2	1	2	0	0	5
	Retusa canaliculata	0	0	0	1	0	1
	Sayella fusca	1	0	0	0	0	1
	Mulinia lateralis	0	1	0	0	0	1

Table 16. A comparison of numbers of benthic infaunal species and total abundance in various muddy habitats, freshwater/oligohaline (0.5-5 ^{o}/oo) and mesohaline (5-18 ^{o}/oo).

Study Area	Species Numbers [area sampled (m^2)]	Abundance/m^2	Source
<u>Tidal Freshwater/Oligohaline</u>			
Susquehanna Flats, MD	--	2114	Diaz, 1982
James River, VA	6-15 [0.1]	481-5982	Diaz, 1977
James River, VA	3-14 [0.1]	63-7940	Jordan et al., 1976
Poquoson River, VA	5 [0.05]	0-6438	This study
Warwick River, VA	13 [0.1]	111-17980	This study
<u>Mesohaline</u>			
James River, VA	12-18 [0.1]	1124-1693	Diaz, 1977
Upper Chesapeake Bay	13-20 [1.2 to 6.5]	882-3828	Holland, et al., 1971
Kent Island	--	6258	Diaz, 1982
Warwick/James River, VA	40 [0.2]	243-3425	Diaz & Boesch, 1976
Poquoson River, VA	24 [0.05]	4551-31660	This study

Table 17. Salinity distribution and distance from discharge at sampling sites in the Poquoson and Warwick River, VA, during February/March, 1984.

	Poquoson River		Warwick River	
Station No	Distance from Discharge (mi)	Salinity ($^{o}/oo$)	Distance from Discharge (mi)	Salinity ($^{o}/oo$)
1	0.01	2	0.09	0
2	0.21	2	0.15	0
3	0.30	2	0.30	0
4	0.51	5	1.20	0
5	0.82	8	1.48	0
6	1.34	14	1.81	0
7	1.69	15	2.43	0
8	1.91	18	3.18	0
9	2.37	15	4.07	0
10	3.12	18	4.80	-
11	-	-	5.43	1

however, that comparisons of species numbers between studied using different gear, and hence different sampling area, are at best only qualitative. The relationship between number of species collected and sampling area is directly proportional. The total abundance of benthic invertebrates ranged from 0 to 6438 /m^2. While the zero abundance value from Station 3 is unusual, the abundances at all other stations were within the normal range.

From Station 6 downstream to Station 10, the fauna was that which is characteristic of a mesohaline (5 to 18 o/oo) estuary. Species number (24 taxa) and abundance (4551-31660/m^2) were comparable to those reported in other tidal freshwater, oligohaline and mesohaline muddy habitats around the Chesapeake Bay (Table 16) (Diaz, 1977; Boesch, 1977; Diaz and Boesch, 1976; Holland et al., 1977; Mountford et al., 1977).

The mean abundance for all stations in the Poquoson River without regard to salinity was 9140/m^2. It is especially noteworthy that the amphipod fauna was more abundant in the Poquoson River than at most stations sampled in the studies mentioned in the previous paragraph. Amphipods are important food items for many fishes and their high abundance is indicative of a habitat that has a high resource value to fishes. Considering the high sensitivity of amphipods to heavy metals and organic toxicants, the presence of an abundance of amphipods lends support to the conclusion that toxic substances are not a problem in the Poquoson River.

Polychaetes were also dominant in the fauna from Stations 6 to 10, with *Streblospio benedicti* the most abundant species. Five other species (Table 15) occurred at most of these stations, but none were very abundant. Most of these species are known to be tolerant of organic enrichment and are very opportunistic in their life histories (Richardson, 1971; Boesch et al., 1976; Grassle and Grassle, 1974; Holland et al., 1977). *Streblospio benedicti* has been found to be the most abundant polychaete in many studies around the Bay, in particular Broad Creek (Diaz and Roberts, 1984), the Elizabeth River (Schaffner and Diaz, 1982), the lower Warwick River (Diaz and Boesch, 1976), and the lower Chesapeake Bay (Nilsen et al., 1980).

Diopatra cuprea was the only polychaete species at these stations that is not considered to be opportunistic. The occurrence of *Diopatra cuprea* at Station 10 gives some indication that environmental conditions at this station have not fluctuated widely since this species became established. *Diopatra* is a tube building species which does not do well in unstable environments.

Thus, the benthic communities in the lower Poquoson River were typical in species diversity and abundance for similar estuarine environments (Diaz, 1977; Mountford et al., 1977; Holland et al., 1977). The communities present at Stations 1, 2, 3, 4, and 5 have lower species richness and, at some stations, abundance than would be expected for similar low salinity transition environments. This may reflect an effect from the alum sludge discharge, though it cannot be determined conclusively from the data whether the effect stems from sedimentation, paucity of food (benthic algae), or a chemical toxicity effect stemming from highway runoff.

Tidal Marshes

The tidal marshes of York County were inventoried in 1973 utilizing aerial imagery and extensive ground truth data sampling. An attempt was made at that time to determine plant community patterns from imagery alone, but resolution varied from location to location to such an extent that it was necessary to verify all determinations by field examination.

The portion of the Poquoson River receiving the discharge from the Harwood's Mill Water Treatment Plant passes through a marsh which can be classified as a brackish water mixed type 12 marsh (Silberhorn, et al., 1974). The marsh is the single largest marsh unit in the Poquoson River system, covering 56 acres (22.4 hectares) (Table 18, Figure 6) (Silberhorn et al., 1974; Silberhorn, 1974). The Harwood's Mill marsh consisted of six plant communities in 1973, with the Saltmeadow (*Spartina patens* and *Distichlis spicata*) and Saltbush (*Iva fructescens* and *Baccharis halimifolia*) communities covering 75% of the marsh. Saltmarsh Cordgrass (*Spartina alterniflora*) and Big Cordgrass (*Spartina cynosuroides*) covered 20% of the marsh, principally along open water channels.

It was noted during the 1973 field survey that the marsh was impacted in several areas near the upland border by fill material including solid waste such as pieces of concrete, asphalt, brush, and tree stumps. The marsh area along the U.S. Route 17 causeway is also impacted by a linear mud wave formation caused by the causeway itself. Compression of the elevated highway has elevated the marsh surface to several feet above normal. This alteration has allowed upland species such as loblolly pine, red maple, and sweet gum to invade the former marsh habitat.

Based on visual observations during walks through the Harwood's Mill marsh in summer and fall of 1984, the plant communities appear to have remained unchanged. The only discernible differences found were in areas of the marsh that were previously filled with solid waste and other materials. These areas are now overgrown with "weedy" upland vegetation and reed grass

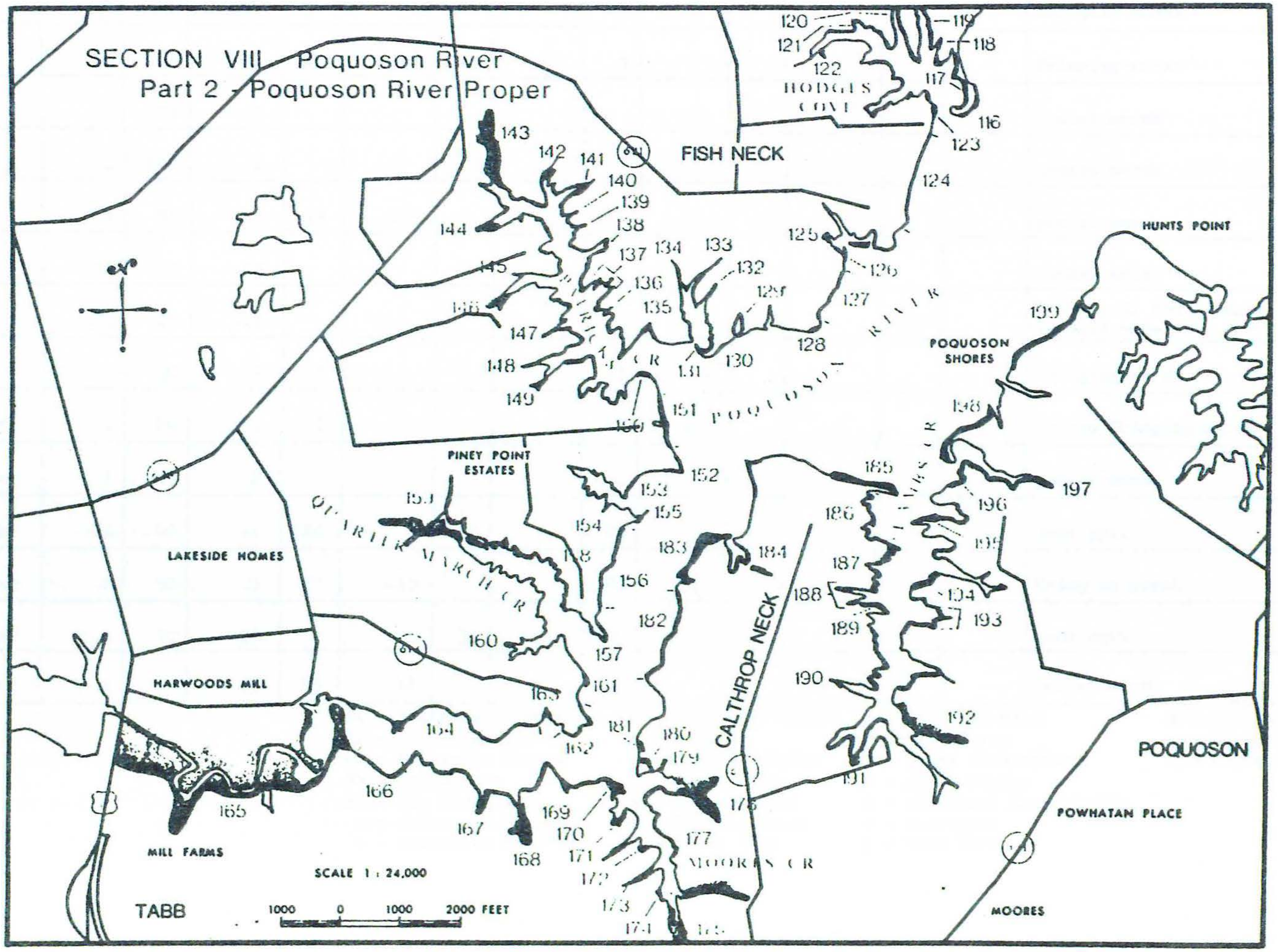

Figure 6. Map of the Poquoson River showing the areal extent of all marsh types from the Route 17 Bridge to the mouth of the river (copied from Silberhorn1974).

Section VIII. Poquoson River. Part 2. Poquoson River Proper

#	Place Name	Acres	Sa %	 Acres	Jr %	 Acres	Md %	 Acres	Sb %	 Acres	Sc %	 Acres	Other %	 Acres	Observations	Marsh Type
116	Hodges Cove	.5	70	.35			15		15						fringing marsh	I
117	Hodges Cove	.8	60	.48	20	.16	15	.12	5						fringing marsh	I
118	Hodges Cove	.3	100	.3											pocket marsh	I
119	Hodges Cove	1	100	1											pocket marsh	I
120	Hodges Cove	1	85	.85	15	.15									pocket marsh	I
121	Hodges Cove	.25	100	.25											pocket marsh	I
122	Upper End Hodges Cove	.25	70	.17									d 20		much spoil and dredged channel in this area	I
123	Mouth Hodges Cove	.7	90	.63	5				5						fringing marsh	I
124	Poquoson River	1.2	80	1	5				15	.2					narrow fringing marsh	I
125	Poquoson River	1	100	1											pocket marsh	I
126	Poquoson River	.25	40	.1	20		20		20						sand spit	XII
127	Poquoson River	.6	50	.3	25	.15			25	.15					fringing marsh	I
128	Poquoson River	.5	50	.25			30	.15	20	.1					sand spit	I
129	Poquoson River	.5	50	.25	25	.12			10				d 15		pocket marsh	I

Sa = Saltmarsh Cordgrass
Jr = Black Needlerush
Md = Saltgrass Meadow
Sb = Saltbushes
Sc = Big Cordgrass
a = Saltmarsh Bulrush
b = Saltmarsh Fleabane
c = Saltmarsh Aster
d = Cattail
e = Marsh Hibiscus
f = Water Hemp
g = Switch Grass
h = Foxtail Grass
i = Arrow Arum
j = Pickerel Weed
k = Reed Grass
l = Olney Threesquare
m = Marsh Mallow
n = Saltmarsh Loosestrife
o = Smartweed
p = Wild Rice
q = Sea Lavender
r = Marsh Pink
s = Saltwort

Table 18. Listing of the marshes along the Poquoson River as shown in Figure 6 (from Silberhorn, 1974).

Section VIII. Poquoson River. Part 2. Poquoson River Proper.

#	Place Name	Acres	Sa %	Sa Acres	Jr %	Jr Acres	Md %	Md Acres	Sb %	Sb Acres	Sc %	Sc Acres	Other %	Other Acres	Observations	Marsh Type
130	Near Patricks Creek	.25	60	.15	40	.1									fringing marsh	I
131	Near Patricks Creek	.25	50	.12	50	.12									fringing marsh	I
132	Near Patricks Creek	.25	100	.25											pocket marsh	I
133	Near Patricks Creek	1	100	1											pocket marsh	I
134	Near Patricks Creek	2	95	1.9									d 5	.1	pocket marsh	I
135	Near Patricks Creek	.5	40	.2	60	.3									pocket marsh	XII
136	Patricks Creek	.25	100	.25											pocket marsh	I
137	Patricks Creek	1	100	1											3 pocket marshes	I
138	Patricks Creek	1.5	100	1.5											pocket marsh	I
139	Patricks Creek	.25	100	.25											pocket marsh	I
140	Patricks Creek	.25	100	.25											pocket marsh	I
141	Patricks Creek	1.5	100	1.5											pocket marsh	I
142	Patricks Creek	1.5	100	1.5											pocket marsh	I
143	Patricks Creek	5.5	95	5.2	5	.3									extensive pocket marsh	I

Sa = Saltmarsh Cordgrass
Jr = Black Needlerush
Md = Saltgrass Meadow
Sb = Saltbushes
Sc = Big Cordgrass
a = Saltmarsh Bulrush
b = Saltmarsh Fleebane
c = Saltmarsh Aster
d = Cattail
e = Marsh Hibiscus
f = Water Hemp
g = Switch Grass
h = Foxtail Grass
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Table 18. Listing of the marshes along the Poquoson River as shown in Figure 6 (from Silberhorn, 1974) (con't).

Section VIII. Poquoson River. Part 2. Poquoson River Proper.

#	Place Name	Acres	Sa %	Sa Acres	Jr %	Jr Acres	Md %	Md Acres	Sb %	Sb Acres	Sc %	Sc Acres	Other %	Other Acres	Observations	Marsh Type
144	Patricks Creek	2.5	95	2.4					5	.1					pocket marsh	I
145	Patricks Creek	.25	80	.2									d 20		pocket marsh	I
146	Patricks Creek	2.5	100	2.5											pocket marsh	I
147	Patricks Creek	1	90	.9									e 10	.1	pocket marsh	I
148	Patricks Creek	.25	80	.2	5				15						pocket marsh	I
149	Patricks Creek	1	90	.9					5				d 5		pocket marsh	I
150	Patricks Creek	.25	60	.15	20				20						fringing marsh	I
151	Poquoson River	1.2	40	.5	40	.5			20	.2					fringing marsh	XII
152	Poquoson River	1	70	.7	20	.2			10	.1					spit	I
153	Poquoson River	.25	60	.15	40	.1									fringing marsh	I
154	Poquoson River	.25	70	.17	20				10						pocket marsh	I
155	Poquoson River	.75	20	.15	80	.6									spit	III
156	Poquoson River	1.2	60	.7	40	.5									narrow fringing marsh	I
157	Mouth Quarter March Creek	.75	45	.34	35	.26	10		5						spit	XII

Sa = Saltmarsh Cordgrass
Jr = Black Needlerush
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Sc = Big Cordgrass
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b = Saltmarsh Fleabane
c = Saltmarsh Aster
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Table 18. Listing of the marshes along the Poquoson River as shown in Figure 6 (from Silberhorn, 1974) (con't)

Section VIII. Poquoson River. Part 2. Poquoson River Proper.

#	Place Name	Acres	Sa %	Sa Acres	Jr %	Jr Acres	Md %	Md Acres	Sb %	Sb Acres	Sc %	Sc Acres	Other %	Other Acres	Observations	Marsh Type
158	Quarter March Creek	2.5	80	2.0	20	.5									fringing marsh	I
159	Quarter March Creek	8.2	70	5.7	5	.4	15	1.2	10	.82					large pocket marsh	I
160	Quarter March Creek	.5	90	.45			10								fringing marsh, cove marsh	I
161	Quarter March Creek	.25	60	.15	40	.1									fringing marsh	I
162	Upper Poquoson River	.5	60	.3	35	.2			5						fringing marsh	I
163	Upper Poquoson River	1.5	85	1.3	5				10	.2					pocket marsh	I
164	Upper Poquoson River	2.3	75	1.7	25	.6									extensive fringing marsh	I
165	Harwood Mill Marsh	56	10	5.6	5	2.8	40	22.4	35	19.6	10	5.6			k, extensive pocket marsh	XII
166	Upper Poquoson River	.33	100	.33											fringing marsh	I
167	Upper Poquoson River	2.6	75	2					10	.3			d,e 15	.3	pocket marsh	I
168	Upper Poquoson River	2	90	1.8									d,e 10	.2	pocket marsh	I
169	Upper Poquoson River	.75	90	.7	5				5						pocket marsh	I
170	Moores Creek	.33	70	.23	25	.1			5						spit	I
171	Moores Creek	.5	95	.5					5						pocket marsh	I

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b = Saltmarsh Fleabane
c = Saltmarsh Aster
d = Cattail
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g = Switch Grass
h = Foxtail Grass
i = Arrow Arum
j = Pickerel Weed
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Table 18. Listing of the marshes along the Poquoson River as shown in Figure 6 (from Silberhorn, 1974) (con't).

Section VIII. Poquoson River. Part 2. Poquoson River Proper.

#	Place Name	Acres	Sa		Jr		Md		Sb		Sc		Other		Observations	Marsh Type
			%	Acres	%	Acres	%	Acres	%	Acres	%	Acres	%	Acres		
172	Moores Creek	1.5	100	1.5											e, pocket marsh	I
173	Moores Creek	1.5	90	1.35									d 10	.15	pocket marsh	I
174	Moores Creek	.5	100	.5											pocket marsh	I
175	Moores Creek	4	90	3.6					10	.4					pocket marsh	I
176	Moores Creek	3	80	2.4			15	.45	5	.15						I
177	Moores Creek	.25	80	.2	10						10				fringing marsh	I
178	Moores Creek	5	90	4.5	5	.25			5	.25					pocket marsh	I
179	Moores Creek	.75	80	.6	20	.15									pocket marsh	I
180	Moores Creek	.5	10		30	.15	50	.25	10						spoil on marsh	I
181	Moores Creek	.5	95	.47					5						spoil and dredged channels	I
182	Calthrop Neck	1	95	.95					5						Jr, fill behind marsh narrow fringing marsh	I
183	Calthrop Neck	3.5	85	3	10	.3			5	.2					mainly fringing marsh erosion where Sa has been mowed	I
184	Calthrop Neck	.33	100	.33											cove marsh, fringe	I
185	Calthrop Neck	1.3	90	1.2	5				5						fringing marsh	I

Sa = Saltmarsh Cordgrass
Jr = Black Needlerush
Md = Saltgrass Meadow
Sb = Saltbushes
Sc = Big Cordgrass
a = Saltmarsh Bulrush
b = Saltmarsh Fleabane
c = Saltmarsh Aster
d = Cattail
e = Marsh Hibiscus
f = Water Hemp
g = Switch Grass
h = Foxtail Grass
i = Arrow Arum
j = Pickerel Weed
k = Reed Grass
l = Olney Threesquare
m = Marsh Mallow
n = Saltmarsh Loosestrife
o = Smartweed
p = Wild Rice
q = Sea Lavender
r = Marsh Pink
s = Saltwort

Table 18. Listing of the marshes along the Poquoson River as shown in Figure 6 (from Silberhorn, 1974) (con't).

Section VIII. Poquoson River. Part 2. Poquoson River Proper.

#	Place Name	Acres	Sa		Jr		Md		Sb		Sc		Other		Observations	Marsh Type
			%	Acres	%	Acres	%	Acres	%	Acres	%	Acres	%	Acres		
186	Lambs Creek	.6	75	45	20	.12			5						fringing marsh	I
187	Lambs Creek	.25	75	.2	20				5							I
188	Lambs Creek	.5	95	.47					5						2 small pocket marshes	I
189	Lambs Creek	.5	85	.42	15				5						fringing marsh	I
190	Lambs Creek	.25	85	.2					5				k 5			I
191	Lambs Creek	.25	100	.25												I
192	Lambs Creek	2.5	95	2.4					5	.1						I
193	Lambs Creek	.75	100	.75											2 small pocket marshes	I
194	Lambs Creek	.6	50	.3	15	.1	30	.2	5						fringing marsh	I
195	Lambs Creek	.25	85	.2	10				5						fringing marsh, spoil	I
196	Lambs Creek	.75	90	.67			5		5						fringing marsh	I
197	Lambs Creek	2	100	2											pocket marsh	I
198	Poquoson Shores	1	60	.6			30	.3	10	.1					fringing marsh	I
199	Poquoson Shores	1	85	.85			10	.1	5						fringing marsh	I

Sa = Saltmarsh Cordgrass
Jr = Black Needlerush
Md = Saltgrass Meadow
Sb = Saltbushes
Sc - Big Cordgrass
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Table 18. Listing of the marshes along the Poquoson River as shown in Figure 6 (from Silberhorn, 1974) (con't).

(Phragmites australis), formerly present only in trace amounts. These changes are unrelated to the discharge of alum sludge into the system.

The marsh proper is still dominated by saltmeadow grass and saltbush communities which occur above mean high water and are flooded only by spring tides and storm surges. The intertidal community, dominated by saltmarsh cordgrass is largely restricted to the area along the main channel of the marsh system. These community types are typical of the upper reaches of tidal waterways in this salinity regime.

STORM Model

In order to maintain good water quality, the City of Newport News employs various methods to restrict development in the reservoir watershed, including the purchase of land tracts in the basin. The land use percentages used in the STORM simulations for that portion of the Poquoson River watershed draining into the Harwood's Mill water supply reservoir are listed in Table 19. The land use scenarios tested for this reservoir included development that would have been in place by 1984 in the absence of management in addition to the 'ultimate' development of the watershed. Ultimate development can be thought of as that which would exist after all available land has been used. These land use data were provided by the Department of Public Utilities, City of Newport News.

Under the existing land use, the majority of the watershed is forested. Much of this land is in City or Federal ownership, and is managed through the implementation of best management practices (BMP's) so as to minimize non-point source loadings to the reservoir. In the case of unrestricted residential or agricultural development in the absence of the reservoir, on

Table 19. Land use percentages used in STORM model simulations of existing and hypothetical development of the Harwoods Mill watershed.

Land Use Category	Existing (1984)	1984		Ultimate	
		Agric.	Resid.	Agric.	Resid.
Residential	14.9	24.2	44.4	24.2	44.3
Commercial	8.2	10.8	11.6	16.9	25.8
Industrial	3.7	5.8	6.0	12.0	25.4
Forested	73.2	27.9	21.9	4.5	4.5
Agriculture					
Row Crop	0	20.9	11.0	28.3	0
Pasture	0	10.4	5.1	14.1	0
	100	100	100	100	100

the other hand, one would expect that only minimal implementation of BMP's would occur. We do not take into account the effect of best management practices in any of these simulations, however, because very little data exist to characterize BMP effectiveness in reducing runoff pollutant loads. Therefore, the loadings that are estimated for existing conditions are probably higher than the actual loads (by as much as 30%), and can therefore be thought of as representing 'worst case' loadings under present day conditions.

The STORM model cannot simulate the processes occurring in the reservoir itself, such as the settling out of solids or the uptake of nutrients by plants. Thus the calculations by STORM represent the pollutant transport out of the watershed as if no reservoir was in place. The present day watershed is smaller by 278 acres (the size of the reservoir) than it would have been if the reservoir were not in place. For the sake of comparison among the various land use scenarios, the larger watershed size was used in all four simulations with STORM.

Results of the simulations using these land use percentages are shown in Table 20. Unlike the results from the Lee Hall reservoir, the predominantly residential use of the watershed yielded the highest loadings for all pollutant constituents, except for suspended solids, which had highest loadings in the agricultural scenario. As expected, the 100% forested configuration yielded the lowest loadings. As in the case of the Lee Hall watershed, the loadings in the 'ultimate' development scenario were roughly double those estimated under the existing land use. The loadings projected for an assumed unrestricted development prior to 1984 (columns 4 and 5) are almost the same magnitude as the 'ultimate' loadings, indicating

Table 20. Annual pollutant loadings (lbs/year) for various land development activities in the Harwoods Mill Reservoir watershed.

Water Quality Constituent	Existing (1984)	100 % Forested	1984		Ultimate	
			Agric.	Resid.	Agric.	Resid.
Suspended Solids	495,183	409,783	751,130	695,862	877,339	728,510
BOD_5	84,395	41,187	168,277	168,305	211,704	195,898
Total Nitrogen	37,023	20,509	57,349	62,733	70,440	80,969
Total Phosphorus	3,839	2,071	6,957	6,985	8,762	8,620
Fecal Coliform ($\times 10^9$ cells)	229,765	1,028	489,356	591,164	641,066	784,062

that a substantial portion (over 60%) of the increase in loadings due to development would have taken place by 1984 in the absence of the reservoir.

Although the STORM model does not simulate improvements in runoff quality due to reservoir processes, a simple method is available for predicting the efficiency of the reservoir for trapping suspended solids based on the size characteristics of the basin. This is a function known as the Brune Curve (Brune, 1953), which relates sediment trapping to the volume of the reservoir and the area of the watershed draining into it. The range of trapping efficiency, expressed as percent of inflowing mass retained by the reservoir, predicted for the two reservoirs under study, is shown in Figure 7. In these calculations, mean depths of 2.5 ft and 12.5 ft were used to predict the lower and upper limits, respectively. These mean depths are probably less than the true mean depth, and therefore illustrate that these two reservoirs are likely to be efficient sediment traps. As can be seen in the figure, both reservoirs are predicted to trap not less than 70% of the inflowing sediment, indicating that a substantial portion of the watershed loadings never reach the estuarine receiving waters.

Warwick River

X-Ray Stratigraphy

X-rays of the long cores from the Warwick River revealed the dominance of physical processes over biological processes in producing the observed stratigraphy at all stations except 11 (Figure 8). At the top (0 to 18 cm) and bottom (80 to 114 cm) of the core from Station 11 there were worm burrows probably made by several different species of oligochaetes (*Limnodrilus* spp.). The center of this core did not have any prominent

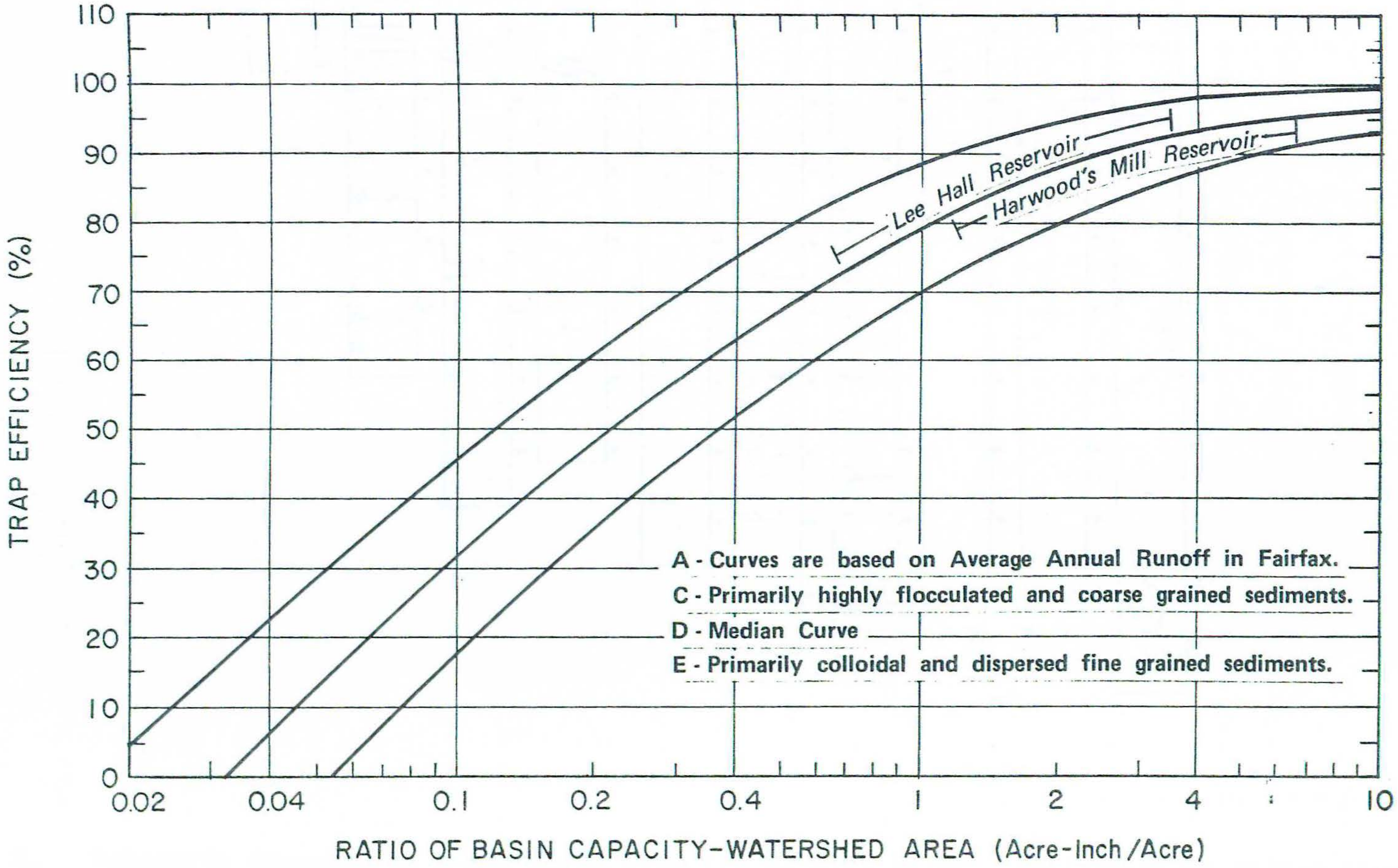

Figure 7. The relationship between pond volume (acre-inches), inflow area (acres), and sediment trapping efficiency (%) of reservoirs (from Brune, 1953).

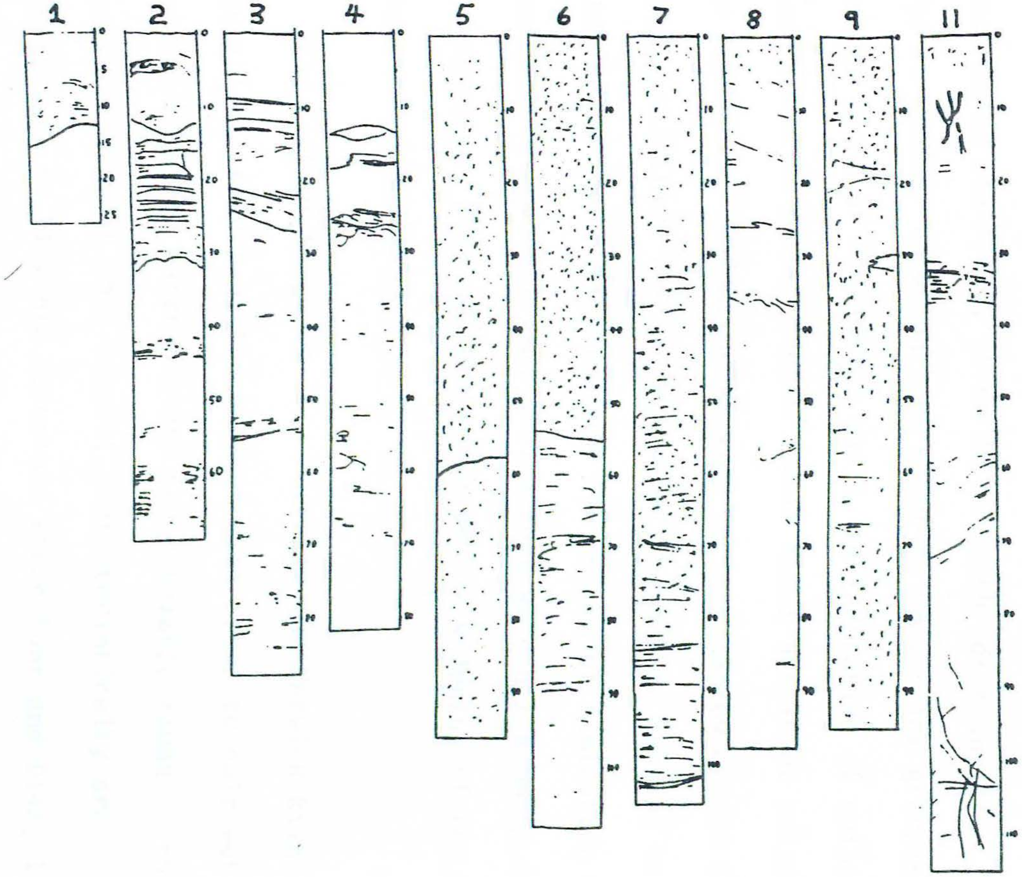

Figure 8. Schematic diagrams of x-ray cores from the Warwick River. Horizontal or tilted lines indicate physical lamination within cores resulting from sediment bedding. Areas that are dotted tended to have high detritus content. Featureless areas were uniform layers of one type of sediment.

biogenic structure. The burrows at the surface could have been active when the core was taken, but those at the bottom were definitely relict.

X-rays of the cores from Stations 5, 6, 7, 9, and the top of 8 all indicated a fairly high organic or detritus content in the sediments. This is shown in Figure 8 by irregular stippling. The other obvious feature in many cores is physical lamination caused by interbedding of sand and silt (such as at Station 2, 10 to 30 cm depth) or transition from one sediment type to another (Station 1 at about 15 cm). The grouping of laminations, such as found at Stations 2 and 3, is indicative of episodic flow events. These could be either sudden runoff after a rain or pulsed discharge from the reservoir. Since the Warwick is very narrow around Stations 2 and 3, stream velocities will be relatively high here leading to sediment sorting into laminations. At Station 4 the degree of lamination was intermediate. From Station 5 downstream, laminations were not a major feature of the stratigraphy. This pattern reflects the widening of the Warwick as one progresses downstream.

The lack of biogenic structures in the Warwick River is related to the transitional nature of the habitat from fresh to salt water and to episodic flow events. The eurytopic and opportunistic fauna of the Warwick, described below in this report, characteristically are not major contributors to biogenic structure (Schaffner and Diaz, 1982). It is therefore very probable that a well developed advanced successional stage benthic community never existed in this section of the Warwick River for as far back in time as is represented in the sample cores. The presence of worm burrows at Station 11 is the only exception. The oligochaetes that formed these burrows can be major reworkers of sediment.

Al:Si Ratios

In the Warwick River, the distribution of aluminum enriched sediments differs only in degree from that in the Poquoson River. At Station 1, the upper 13 cm of the core was a loose floc consisting largely of alum sludge, resulting in high Al:Si ratios. Below that was a dense clay layer which could be cored only to 25 cm with a background Al:Si ratio (Table 21).

At Station 2, the upper 16-17 cm was slightly enriched with a ratio of 0.2 to 0.5, overlying a more highly enriched lens from 18 to 30 cm. The ratios in the sediments from 30 cm down indicated only slight enrichment. The upper sediment layer with only slight enrichment is thought to result from introduction of uncontaminated silt-size particles during the construction in progress on US Route 60, involving widening the highway to four lanes with construction of a new bridge/culvert.

At Stations 3 and 4, the surface 5-15 cm was moderately enriched with aluminum. Below that the sediments were slightly enriched to a depth of 55 to 70 cm. At the core bottom, sediments with background Al:Si ratios were observed. Sediments from Stations 5 through 11 were slightly enriched with aluminum to depths of 45 cm or more down to at least 110 cm at Station 6. Only at Stations 5 and 11 were sediments with background Al:Si ratios observed. Thus some degree of aluminum enrichment was observed much farther downstream in the Warwick River (5.4 miles) than in the Poquoson River (1.3 miles). This difference reflects the difference in total discharge of alum sludge discharge, with the Lee Hall plant discharging about three times as much alum sludge into the Warwick River as does the Harwood's Mill plant into the Poquoson River.

Table 21. Aluminum:Silicon Ratios for sediments in cores collected in the Warwick River, VA in March 1984.

Depth of Sample (cm)	Station 1	2	3	4	5	6	7	8	9	11
0-1	1.810	0.286	0.510	0.759	0.423	0.328	0.392	0.350	0.347	0.221
5-6	1.097	0.336	0.569	0.699	0.433	0.334	0.387	0.338	0.350	0.231
11-12	0.927	0.251	0.433	0.714	0.433	0.454	0.369	0.331	0.357	0.229
20-21		0.580	0.383	0.328	0.467	0.430	0.380	0.280	0.349	0.221
23-24	0.275									
29-30		1.649	0.378	0.257	0.445	0.414	0.376	0.265	0.337	0.227
41-42		0.272	0.344	0.216	0.443	0.386	0.342	0.298	0.317	0.202
50-51		0.264	0.304	0.206	0.476	0.393	0.328	0.288	0.340	0.156
59-60		0.246	0.293		0.255	0.362	0.322	0.299	0.329	0.201
61-62				0.144						
65-66		0.248								
71-72			0.280	0.206	0.167	0.347	0.309	0.301	0.333	0.195
76-77				0.179						
80-81			0.179		0.154	0.301	0.339	0.319	0.232	0.167
89-90					0.155	0.316	0.323	0.261	0.218	0.202
95-96					0.170			0.302	0.213	
98-99						0.277	0.305			
101-102										0.163
107-108						0.301				
110-111										0.163

Sediment Particle Size

Surface sediments at the Warwick River stations were primarily muddy (Table 22). Quartz sand was only found above trace amounts at Stations 2, 3, and 4. Water content of the surface sediments was high, ranging from 31.0 to 80.3 %. Sediments did not change between the March and June collections (Tables 22 and 8).

Sediments were most heterogeneous, with respect to depth in the cores, at the most upstream stations in the Warwick (Stations 1, 2, 3, and 4). Station 1 was the only station to have terrigenous clay, starting at 14 cm and continuing to the bottom of the core. This indicates a soil base of a terrestrial type as opposed to one of recent aquatic origin. The clays found at the downstream Warwick River stations were all recent marine deposits and not terrigenous.

Most sand size particles in the top 14 cm of the core from Station 1 were anthracite coal rather than quartz. Anthracite coal forms part of the water filtration matrix, which is the presumed source of the particles found. At Station 2, very few of the sand sized particles near the core surface were coal, and below 6 cm, no coal particles were apparent.

Stations 2 through 4 were predominantly sandy over the entire length. There was a great deal of lamination and interbedding of the sand with silty sand. This can be seen in the x-rays of the cores (Figure 8). The interbedding of the sediments results from changing flow patterns or episodic discharges of fresh water. The source of the sediments may also be a factor. Downstream of Station 4 there does not appear to be any major sand deposit.

Table 22. Sediment type from Warwick River cores, March 1984. Sand (SA), Silty Sand (SISA), Clayey Sand (CLSA), Silt (SI), Sandy Silt (SASI), Clay (CL), Clayey Silt (CLSI), and Sandy Clay (SACL).

	Stations									
Layer (cm)	1	2	3	4	5	6	7	8	9	11
0–1	SI	SA	SISA	SISA	SI	SI	SI	SI	SI	SI
1–2	SA	SA	SASI	SISA	SI	SASI	SI	SI	SI	SI
2–3	SA	SA	SASI	SISA	SI	SI	SI	SI	SI	SI
5–6	SA	SA	SASI	SISA	SI	SI	SI	SI	SI	SI
8–9	SA	SA	SA	SI	SI	SI	SI	SI	SI	SI
11–12	SISA	SISA	SISA	SI	SI	SI	SI	SI	SI	SI
14–15	CL	SASI	SISA	SASI	SI	SI	SI	SASI	SI	SI
17–18	CL	SASI	SISA	SASI	SI	SI	SI	SA	SI	SI
20–21	CL	SASI	SA	SA	SI	SI	SI	SACL	SI	SI
23–24	CL	SASI	SISA	SA	SI	SI	SI	CLSI	SI	SI
26–27		SASI	SA	SA	SI	SI	SI	CLSI	SI	SI
29–30		SI	SA	SA	SI	SI	SI	CLSI	SI	SI
32–33		SISA	SA	SA	SI	SI	SI	SI	SI	SI
35–36		SA	SA	SA	SI	SI	SI	SI	SI	SI
38–39		SA	SA	SASI	SI	SI	SI	SI	SI	CLSI
41–42		SA	SA	SISA	SI	SI	SI	SI	SI	CLSI
44–45		SISA	SA	SISA	SI	SI	SI	CL	SI	CLSI
47–48		SA	SISA	SA	SI	SI	SI	CL	SI	SI
50–51		SA	SISA	SISA	SI	SI	SI	CL	SI	CL
53–54		SA	SISA	SA	SI	SI	SI	SI	CLSI	CL
56–57		SA	SISA	SA	SI	SI	SI	CL	CLSI	SI
59–60		SISA	SA	SISA	SI	SASI	SI	CLSI	CLSI	SI
62–63		SISA	SA	SISA	CLSI	SASI	SI	CL	SI	CL
65–66		SA	SA	SISA	CL	SI	SI	CL	SI	CL
68–69			SA	SA	CL	SI	SI	CL	SI	CL
71–72			SISA	SASI	SI	SI	SI	CL	SI	CL
74–75			SA	SA	SI	SI	SI	CL	SI	CL
77–78			SA	SISA	CLSI	SI	SI	CL	SI	CL
80–81			SISA	SA	SI	SI	SI	CL	SI	CL
83–84			SISA		SI	SI	SI	CL	SI	CL
86–87			SISA		SI	CL	SI	CL	CLSI	CL
89–90					SI	CL	SI	CL	CLSI	CL
92–93					CLSI	SI	SI	CL	SI	CL
94–95					CLSI	SI	SI	CL	SI	CL
95–96					CLSI	SI	SI	CL		CL
98–99						CL	SI			CL
101–102						CL				CL
104–105						CL				CL
107–108						CL				CL
110–111										CL

Between Stations 4 and 5, a major change in the sediment stratigraphy occurs. Beginning at Station 5 sediments are primarily silt for the entire length of the core (Table 22). This pattern is characteristic of all downstream stations. In addition, there were substantial amounts of marine clays in the bottom portions of cores from Stations 8 and 11. At the downstream stations, sandy sediments occurred only at three locations in cores from Stations 6 and 8. It appears that sand entering the Warwick River from its source is not transported downstream more than 1.2-1.5 miles. The lack of sand at the downstream stations may indicate a limited sand supply for the system.

Relationships among Sediment-Stratigraphy-Al:Si Ratio

When the stratigraphy and Al:Si ratio data were compared, there were some clear relationships (Figure 9). The transition from high and moderately high Al:Si ratios to low ratios always occurred at or near a major lamination associated with a change in sediment type. At Station 1, sediments change from sand to clay very abruptly at 15 cm, and the Al:Si ratio drops abruptly from about 1.0 in the sandy sediments to 0.3 in the clay. At Stations 2, 3, and 4 the changes in Al:Si ratio occur at transitions from sandy to silty sediments.

Background Al:Si ratios (<0.2) were apparent near the bottom of cores from Stations 2, 4, and 5 and over most of the length of the core from Station 11. From Stations 5 to 11, there does not appear to be any relationship between stratigraphy, sediment type, and Al:Si ratio, nor does the decline of the Al:Si ratio to background levels seem to be related to

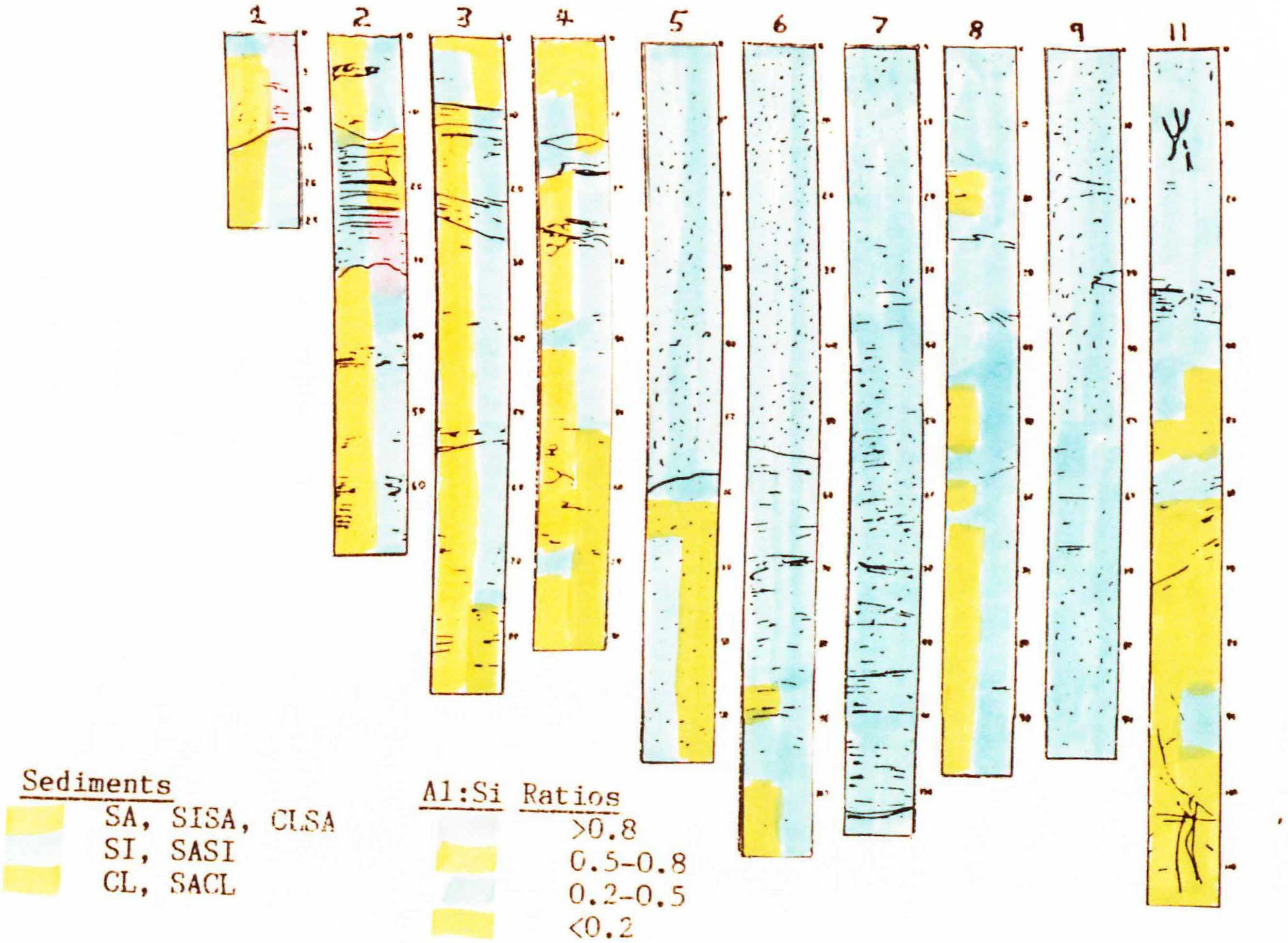

Figure 9. Comparison of sediment particle type, stratigraphy, and Al:Si ratios in cores from the Warwick River. Left side of the core diagram is colored to indicate the sediment particle type. The right side of the core diagram is colored to represent specific ranges of Al:Si ratio.

any stratigraphic feature. The lack of relationship is also apparent in the bottoms of the cores from Stations 3 and 4.

From Stations 1 to 4, the type of sediment varied with depth in the core. From Stations 5 to 11, sediment type was less variable, and tended to be silty, with the exception of the bottoms of cores from Stations 6, 8, and 11. The Al:Si ratio was not consistently high for any particular sediment type.

Radionuclide Distribution

Data for ^{137}Cs net activity standardized on a per gram dry weight basis for the Warwick River cores is shown in Table 23. Cores from Stations 1, 3, and 4 were not suitable for determination of accumulation rates, either because they were too short or too sandy. Station 7 had the only core that had a distinct peak of ^{137}Cs. The peak was observed at about 50 cm. If this represents the 1963 fallout peak, then the average sediment accumulation rate was 2.4 cm/yr. On the other hand, if this peak represents the 1975 peak resulting from the Surry Nuclear Reactor release, the accumulation rate was 5.6 cm/yr. Since there is a relatively high activity of ^{137}Cs at the surface of the core from Station 7, indicative of resuspension and redistribution, the lower average sediment accumulation rate seems more probable. The cores from Stations 2, 5, 6, 9, and 11 all strongly indicate resuspension with the profile of ^{137}Cs activity spread evenly deep within the cores. The core from Station 8 had a ^{137}Cs profile indicative of an erosional area with higher levels of activity near the sediment surface than below.

Table 23. Net activity for ^{137}Cs (net counts/g dry sediment/hr) in cores collected in the Warwick River, VA in March 1984. Zero values indicate that the true value was less than one 95 % confidence interval from zero (see Materials and Methods for full explanation).

Depth of Sample (1) (cm)	Station									
	1	2	3	4	5	6	7	8	9	11
0–1	*	0.000	**	**		0.005	0.023	0.021	0.013	0.022
3–4									0.020	
5–6									0.025	
8–9					0.017				0.015	
11–12		0.002			0.021			0.013	0.019	
14–15							0.027		0.018	
17–18						0.008			0.024	0.029
20–21		0.004			0.015				0.012	
23–24								0.000	0.022	
26–27					0.020				0.020	
29–30		0.004							0.021	
32–33							0.043		0.010	
35–36						0.010		0.000	0.029	0.021
38–39		0.000								
41–42					0.019				0.027	
44–45			0.000						0.032	
47–48		0.001			0.014	0.006		0.001	0.016	
50–51							0.052		0.027	0.000
53–54					0.020					
56–57		0.000							0.024	
59–60								0.000	0.015	
62–63									0.024	
65–66		0.000			0.000				0.025	0.000
68–69							0.016		0.027	
71–72						0.005		0.002	0.013	
74–75									0.025	
77–78					0.000				0.029	
80–81					0.000				0.028	0.002
83–84								0.003	0.016	
86–87					0.000	0.010	0.014		0.033	
89–90										
92–93									0.039	
95–96								0.000		0.008
98–99						0.005	0.006			
110–111										0.000

* Short core; not counted

** Samples from this core too sandy to count except as noted

None of the cores demonstrated the bimodal distribution of ^{137}Cs expected in the "ideal" core similar to that found in the nearby James River (Cutshall et al., 1981). The apparent bimodal distribution observed in the core from Station 11 probably does not represent the Surry Reactor-weapons testing fallout combination since the activity of the fallout peak, which would occur deeper in the core, should be about twice that of the Surry Reactor peak.

Primary Production

At Station 3 on the Warwick River, primary production by the phytoplankton was depressed corresponding to a depressed standing crop (Table 10). In June, primary production was essentially unchanged from that in March despite the nearly 10-fold increase in apparent standing crop. At Station 6 both primary productivity and standing crop were more consistent and higher at both sampling times than at Station 3.

Primary production by the phytoplankton at Station 3 on the Warwick River in March was similar to production reported by Stross and Stottlemyer (1965) for Station 22 on the Patuxent River, MD (Table 11). In June, this was not true, with production at Warwick River Station 3 much depressed, and that at Patuxent River Station 22 greatly elevated. Primary production at Warwick River Station 6, in contrast, was markedly higher than at Station 3 in both March and June, and also was higher than that reported for the Patuxent River Station 22 in March, though not June, despite the fact that Warwick River Station 6 is also located in freshwater.

Standing crop, expressed as chlorophyll a concentration, was dramatically increased at Warwick River Station 3 in June compared to March.

At Station 6, the chlorophyll concentration was essentially the same in the two sampling months and comparable to Patuxent River Station 22 (Table 11).

The assimilation ratio for the communities at Station 3 was within a normal range though low in March, but severely depressed in June. The explanation of this observation is not clear. Light penetration at this station was limited to the upper few centimeters of the water column. With the devise used to hold the incubation vials, the phytoplankton community was below the level of the sludge plume, thus causing serious underestimation of the productivity of the community had it been incubated in sunlight at the water surface. On the other hand, the community of algae was collected as close to the surface as possible, but nevertheless was severely contaminated with the underlying sludge layer, probably leading to underestimation of the chlorophyll a content of the surface layer. If the chlorophyll a concentration were underestimated, the assimilation ratio would then be lower.

Aside from errors and uncertainties associated with the sampling and incubation procedure, the primary point which needs to be clearly understood is that the high sediment load in the upper reaches of the Warwick represents a severe, albeit non-toxic, limitation to primary production by the phytoplankton. At best, the primary producers are restricted to the upper 5 to 10 centimeters of the water column for production. This condition only gradually improves as one progresses downstream. The sludge plume is readily apparent at Station 6 at least in the channel, and is recognizable to Station 7 and perhaps beyond.

Gross production of the benthic algal community at both Stations 3 and

6 was low in March, approximating the respiration rate (Table 12). As a result, net production was essentially zero. In June, interference by alum sludge in the Winkler determination of oxygen concentration prevented an estimate of gross or net production at Station 3 (though some slight amount of titrable iodine was present in the light chamber samples, indicating that photosynthesis was going on). At Station 6, gross production was an order of magnitude higher in June than in March and net production was positive.

Gross and net production of the benthic algae in the Warwick River were generally comparable to the production observed in the Poquoson River (Table 12), and were within the normal range for freshwater/oligohaline environments, as discussed previously. There did not appear to be any impact of the sludge discharge on the light availability or resultant productivity of the benthic algal community at the downstream station.

Sediment chlorophyll concentrations at Stations 3 and 6 on the Warwick River (Table 13) were within a normal range in March. In June, sediment chlorophyll at Station 3 was dramatically reduced, probably because of low light availability. There was no such limitation evident at Station 6.

Another approach to evaluating the impact of the alum sludge plume on the benthic algal community is measurement of the standing crop of the benthic algae based on chlorophyll _a_ concentration over the length of the River. In March, the concentration of chlorophyll _a_ in the sediment was homogeneous from Station 3 to 5, increasing slightly at Stations 6 and 7, and increasing further at Stations 9 and 11 (Table 24). This suggests some impact of the alum sludge plume on the development of the benthic algal community. In May a second series of samples was analyzed in which the increase in chlorophyll concentration with distance downstream was much less

Table 24. Sediment chlorophyll concentrations (uncorrected for phaeophytin) at sampling sites in the Warwick River, VA, during March and May, 1984.

Station No	Chlorophyll a Concentration (mg chlor a/m^2) March	May
1	-	33
2	-	39
3	29	23
4	32	36
5	15	57
6	64	66
7	51	51
8	-	49
9	138	54
10	-	49
11	187	-

pronounced. There is no clear indication why this should be so, unless the downstream extent of the plume was greater in May than March. We have no evidence to corroborate such a speculation. We should note that the chlorophyll concentration measured at Stations 3 and 6 during the productivity experiments was lower than in the samples from the same stations described above which were collected on separate sampling trips and therefore at slightly different locations.

Benthic Invertebrate Communities

A total of 13 benthic taxa were collected at the 11 Warwick River stations sampled for benthos (Table 16, 25). The most abundant taxa were harpacticoid copepods, followed by *Limnodrilus* spp., cladocerans, and *Tubificoides heterochaetus* (Table 26).

Faunal diversity was low at all stations with the fewest species occurring at the upstream stations. Very low diversity and species richness are characteristic of low salinity-tidal freshwater transitional habitats. For example, in the James River transition from freshwater to the estuarine zone, the area between the Chickahominy River and Hogg Island, 14 taxa were reported by Diaz (1977). In a more intensive study of the same reach of the James River, Jordan et al. (1976) reported a total of 20 taxa. In an environmental evaluation of Broad Creek, a tributary of the Elizabeth River which also has a water treatment plant at its headwaters, a total of 11 benthic taxa were reported from low salinity-tidal freshwater transitional habitats (Diaz and Roberts, 1984) (a total of 17 benthic taxa were reported for Broad Creek when all stations are considered). As one would expect in a low salinity system (<1 o/oo at all stations, Table 17), the fauna was composed mainly of salt tolerant freshwater forms (Table 25). Only four of

Table 25. Species list for Warwick River benthic collections, May 1984

Scientific Names	Common Names	Origin
Turbellaria		
Acoels	Flatworm	F*
Annelida		
Oligochaeta		
Limnodrillus spp.	Bloodworm	F
Tubificoides spp.	Bloodworm	M
Tubificoides heterochaetus	Bloodworm	M
Arthropoda		
Copepoda		
Calanoid spp.	Copepods	F
Harpacticoid spp.	Copepods	F+M
Brachiopoda		
Cladocean spp.	Water Flea	F
Ostracoda		
Ostracod spp.	Seed Shrimp	F
Amphipoda		
Gammarus spp.	Scud	F
Gammarus fasciatus	Scud	F
Corophium spp.	Scud	M
Insecta		
Chironomids	Non-biting midge larva	F
Acarina		
Hydracarinids	Water Mite	F
Mollusca		
Bivalvia		
Macoma spp.	Mud Clam	M

* F - Species of freshwater origin
M - Species of marine origin

Table 26. Abundance data for benthic species collected from the Warwick River in May 1984.

Station	Species	Core Number					Total
		1	2	3	4	5	
1	Harpacticoids	1	0	3	3	0	7
	Cladocerans	1	0	3	0	0	4
2	Harpacticoids	4	38	3	94	13	152
	Cladocerans	1	8	1	14	2	26
3	Harpacticoids	3	95	2	0	2	102
	Cladocerans	0	7	2	0	0	9
	Calanoids	0	3	0	1	0	4
	Chironomids	0	2	0	0	1	3
	Limnodrilus spp.	0	0	1	1	1	3
4	Harpacticoids	5	3	1	2	3	14
	Cladocerans	0	1	0	0	0	1
5	Harpacticoids	1	0	0	0	0	1
	Cladocerans	0	0	0	0	1	1
	Gammarus fasciatus	0	0	0	0	1	1
	Limnodrilus spp.	2	2	3	0	1	8
6	Chironomids	2	1	1	4	2	10
	Limnodrilus spp.	0	0	1	1	1	3
7	Harpacticoids	3	0	1	1	9	14
	Ostracods	1	3	0	0	0	4
	Chironomids	1	0	0	0	1	2
	Gammarus spp.	0	0	1	0	1	2
8	Harpacticoids	0	2	3	1	2	8
	Calanoids	0	0	0	1	0	1
	Chironomids	0	0	0	1	1	2
	Gammarus spp	2	2	0	0	1	5
	Corophium spp	0	1	0	0	0	1
	Tubificoides spp.	0	1	0	0	0	1
	Tubificoides heterochaetus	3	2	2	0	5	12
9	Harpacticoids	15	2	0	1	0	18
	Gammarus fasciatus	3	0	0	0	1	4
	Acoels	2	0	0	0	0	2
	Limnodrilus spp.	15	8	1	1	2	27
	Tubificoides spp.	0	2	0	0	0	2

Table 26. Abundance data for benthic species collected from the Warwick River in May 1984 (con't).

Station	Species	Core Number					Total
		1	2	3	4	5	
10	Harpacticoids	1	3	8	20	2	34
	Cladocerans	1	0	0	0	0	1
	Gammarus fasciatus	0	0	1	0	0	1
	Gammarus spp.	0	1	0	1	0	2
	Limnodrilus spp.	0	12	1	1	2	16
	Tubificoides heterochaetus	1	0	0	1	6	8
	Macoma spp.	0	0	0	2	0	2
11	Harpacticoids	15	14	0	4	3	36
	Hydracarinid	0	0	1	0	0	1
	Gammarus fasciatus	1	0	3	0	0	4
	Limnodrilus spp.	11	10	6	0	1	28
	Tubificoides heterochaetus	0	4	12	4	1	21
	Macoma spp.	0	2	1	0	1	4

the 13 taxa were of marine origin. Further down the Warwick at the mouth, the benthic communities are dominated by marine and estuarine endemic species (Diaz and Boesch, 1976). The two dominant species, *Tubificoides* spp. and *Macoma* spp., found by Diaz and Boesch (1976) near the mouth of the Warwick were also found at Stations 8, 9, 10, and 11 of this study. This is an indication that salinities at these stations are at times higher than those observed during our study. Conversely, based on the fauna it does not appear that salt ever intrudes up river beyond Station 7. From Stations 1 to 6, there were only freshwater species present.

A characteristic of the fauna that inhabits tidal freshwater or transitional and fluctuating low salinity habitats is that they are very eurytopic and tolerant of extreme environmental conditions. The more sensitive freshwater and marine species are excluded from these habitats (Boesch, 1977; Diaz, 1977; Jordan and Sutton, 1984). As a group, oligochaetes have the greatest ability to invade these transitional areas. In the Warwick River, the dominant taxa were, as expected, oligochaetes. The freshwater genus, *Limnodrilus*, was dominant at Stations 5, 9, 10, and 11. This genus is the most widely distributed and contains the most cosmopolitan oligochaete species in the world (Brinkhurst and Jamieson, 1971). *Limnodrilus* spp. have the broadest tolerances for organic enrichment, sediment type, water quality, and salinity of all oligochaetes (Brinkhurst and Cook, 1974; Diaz, 1980). The other two dominant oligochaetes at Stations 8, 10 and 11 were in the genus *Tubificoides*. They are also very hardy species that have an opportunistic life history similar to *Limnodrilus* spp., but are true estuarine endemics (Diaz, 1980).

Harpacticoid copepods and cladocerans were the only taxa to have widespread occurrence at Stations 1 to 5. Other species that occurred at these stations were in low abundance and found at only one or two of these stations. Overall, the communities at Stations 1 through 6 were very poor in species, except Stations 3 and 5. While the stations further downstream were more speciose, no polychaete species were collected at any station. This was the result of the low salinity in this reach of the Warwick. At salinities of 1 $^{o}/oo$ or less in the James River, only a single polychaete species has been collected (Diaz, 1977; Jordan et al., 1976), and under a similar salinity regime in Broad Creek, only two polychaete species were observed (Diaz and Roberts, 1984).

In summary, the benthic communities were of low species diversity and abundance, but well within the ranges reported for other low salinity fluctuating environments (Diaz, 1977; Tenore, 1972; Jordan et al., 1976). The species present have life histories which are consistent with the low salinity fluctuating conditions encountered in the portion of the Warwick River studied. All the dominant species were opportunistic and very eurytopic. The physical harshness of the environment with respect to low salinity and tidal freshwater conditions is the major limiting factor in the development or lack of development of the benthic communities. Past surveys in the Warwick River indicated well developed benthic communities in the mesohaline salinities found near the mouth of the River (Diaz and Boesch, 1976).

Tidal Marshes

The Warwick River from the U.S. Route 60 bridge to Stony Run Branch flows through an extensive tidal marsh system totaling 123.8 acres (49.5 hectares; Figure 10, Table 27) (Moore, 1977). The tidal marshes within the

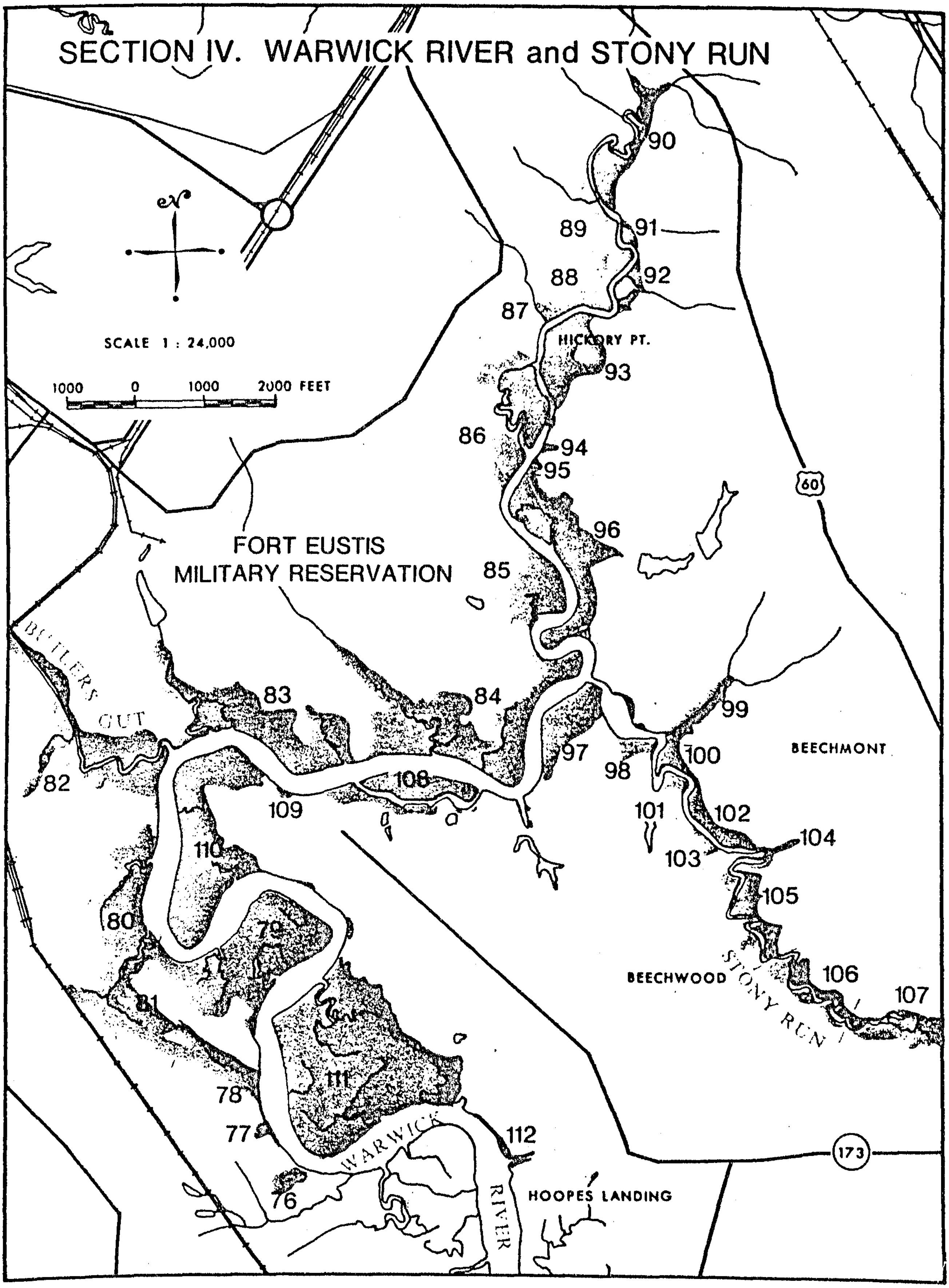

Figure 10. Map of the Warwick River showing the areal extent of all marsh types from the headwaters near the Route 60 bridge to Hoops Landing (copied from Moore, 1977).

Section IV. Warwick River and Stony Run

Marsh Location	Total Acres		Saltmarsh Cordgrass	Saltmeadow Grasses	Black Needlerush	Saltbushes	Big Cordgrass	Saltmarsh Bulrush	Water Hemp	Cattails	Marsh Hibiscus	Marsh Mallow	Reed Grass	Olney Threesquare	Common Threesquare	Sea Oxeye	Water Dock	Saltmarsh Loosestrife	Sea Lavender	Saltmarsh Fleabane	Saltmarsh Aster	Pickerelweed-Arrow Arum	Smartweed	Giant Bulrush	Cardinal Flower	Other	Observations	Marsh Type
Warwick River	2.6	%	70	-	10	-	20	-		-																	Pocket marsh; dominated by saltmarsh cordgrass with big cordgrass along upland; berm partially across front of marsh.	I
		acres	1.8	-	0.3	-	0.5	-		-																		
Warwick River	0.90	%	30	-	25		45	-		-	-			-													Pocket marsh; dike across front has been broken through allowing tidal flushing to interior.	XII
		acres	0.27	-	0.22		0.40	-		-	-			-														
Warwick River	8.3	%	25	10	20	-	40	2		-	-			3													Pocket marsh; dominated by big cordgrass and saltmarsh cordgrass; interior portions grade to high marsh mixed with trees.	XII
		acres	2.1	0.8	1.7	-	3.3	0.2		-	-			0.3														
Warwick River	45.5	%	45	5	35	5	10	-	-	-	-			-													Saltbushes form ridge along river's edge; interior of marsh a mixture of needlerush, cordgrass and meadow areas.	XII
		acres	20.5	2.3	15.9	2.3	4.6	-	-	-	-			-														
Warwick River	33.6	%	20	5	35	5	35	-	-	-	-		-	-													Broad creek marsh; extends back around upland areas; dominated by big cordgrass and needlerush areas; saltmarsh cordgrass along creek channels.	XII
		acres	6.7	1.7	11.8	1.7	11.8	-	-	-	-		-	-														
Warwick River	10.3	%	5	-	85	2	3	-		3	-		-	2													Interior section of creek marsh; almost completely black needlerush which grades to uplands; pocket of cattails..	III
		acres	0.5	-	8.8	0.2	0.3	-		0.3	-		-	0.2														
Butlers Gut	32.0	%	25	5	25	15	30	-		-	-		-	-													Disturbed area near mouth that is overgrown with saltbushes; berm of saltbushes parallels dredged creek channel; connects with Milstead Island Creek.	XII
		acres	8.0	1.6	8.0	4.8	9.6	-		-	-		-	-														
Warwick River	39.9	%	50	-	20	-	30	-	-	-	-						-										Broad creek marsh extends back to several pocket areas that are mostly needlerush; remainder of marsh dominated by cordgrass.	I
		acres	20.0	-	8.0	-	12.0	-	-	-	-						-											

a = Saltmarsh Fimbristylis
b = Swamp Milkweed
c = Wild Rice
d = Jewel Weed
e = Mock Bishop-weed
f = Water Parsnip
g = Water Hemlock
h = Marsh Pennywort
i = Arrowhead
j = Cutgrass

Table 27. Listing of the marshes along the Warwick River as shown in Figure 10 (from Moore, 1974).

Section IV. Warwick River and Stoney Run

#	Marsh Location	Total Acres		Saltmarsh Cordgrass	Saltmeadow Grasses	Black Needlerush	Saltbushes	Big Cordgrass	Saltmarsh Bulrush	Water Hemp	Cattails	Marsh Hibiscus	Marsh Mallow	Reed Grass	Olney Threesquare	Common Threesquare	Sea Oxeye	Water Dock	Saltmarsh Loosestrife	Sea Lavender	Saltmarsh Fleabane	Saltmarsh Aster	Pickerelweed-Arrow Arum	Smartweed	Giant Bulrush	Cardinal Flower	Other	Observations	Marsh Type
84	Warwick River	54.2	%	30	5	20	3	40	1	-	-	1																Extensive creek marsh; mostly a mixture of saltmarsh cordgrass and big cordgrass areas with large stands of needlerush.	XII
			acres	16.3	2.7	10.8	1.6	21.7	0.5	-	-	0.5																	
85	Warwick River	13.0	%	85	-			15	-	-	-	-							-					-		-	i,-	Creek marsh dominated by saltmarsh cordgrass with scattered big cordgrass; cattails along upland edge.	I
			acres	11.0	-			2.0	-	-	-	-							-					-		-	i,-		
86	Warwick River	24.9	%	65	-			5	-	5	-	5	-			5			10		-			5		-	i,- j,-	Creek marsh dominated by saltmarsh cordgrass; other species scattered throughout.	I
			acres	16.2	-			1.2	-	1.2	-	1.2	-			1.2			2.5		-			1.2			i,- j,-		
87	Warwick River	0.80	%	65				10		-	5	10	5			-		-	-		-			5		-	i,- j,- e,-	Pocket marsh dominated by saltmarsh cordgrass; other species scattered throughout.	I
			acres	0.52				0.08		-	0.04	0.08	0.04			-		-	-		-			0.04		-	i,- j,- e,-		
88	Warwick River	6.2	%	45				-		-	-	10	5			10		-	25		-	-	-	-		-	i,- j,- f,- e,-	Creek marsh; mixture of freshwater and brackish species.	XII
			acres	2.8				-		-	-	0.6	0.3			0.6		-	1.6		-	-	-	-		-	i,- j,0.3 f,- e,-		
89	Warwick River	11.3	%	35			15			-	5	10	10			-		-	20		-		-	-	-	-	j,5 i,- f,- e,- b,- g,-	Berm with saltbushes along channel edge; interior of marsh largely saltmarsh cordgrass mixed with freshwater species.	XII
			acres	4.0			1.7			-	0.6	1.1	1.1			-		-	2.3		-		-	-	-	-	j,0.6 i,- f,- g,- e,- b,-		
90	Warwick River	17.8	%	10			35			-	5	10	5			-		-	10		-	-		-	-	-	b,- h,10 i,- j,15	Creek marsh at head of river; dominated by saltbushes with other species scattered throughout.	XII
			acres	1.8			6.2			-	0.9	1.8	0.9			-		-	1.8		-	-		-	-	-	b,- h,1.8 i,- j,2.7		
91	Warwick River	1.3	%	45			5	20		15		5	-			-		-	5		-		-	-		-	j,5 i,- f,-	Creek marsh section; berm with saltbushes along channel edge; interior mostly saltmarsh cordgrass and big cordgrass.	XII
			acres	0.6			0.1	0.3		0.2		0.1	-			-		-	0.1		-		-	-		-	j,0.1 i,- f,-		

a = Saltmarsh Fimbristylis
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h = Marsh Pennywort
i = Arrowhead
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Table 27. Listing of the marshes along the Warwick River as shown in Figure 10 (from Moore, 1974) (con't).

Section IV. Warwick River and Stony Run

#	Marsh Location	Total Acres		Saltmarsh Cordgrass	Saltmeadow Grasses	Black Needlerush	Saltbushes	Big Cordgrass	Saltmarsh Bulrush	Water Hemp	Cattails	Marsh Hibiscus	Marsh Mallow	Reed Grass	Olney Threesquare	Common Threesquare	Sea Oxeye	Water Dock	Saltmarsh Loosestrife	Sea Lavender	Saltmarsh Fleabane	Saltmarsh Aster	Pickerelweed-Arrow Arum	Smartweed	Giant Bulrush	Cardinal Flower	Other	Observations	Marsh Type
92	Warwick River	3.7	%	45			-	-		-		5	5			10				30			-			-	i,- j,5	Creek marsh section; dominated by saltmarsh cordgrass with abundant loosestrife.	XII
			acres	1.7			-	-		-		0.2	0.2			0.4				1.1			-			-	i,- j,0.2		
93	Warwick River	14.7	%	45	-	-	5	-		-	5	10	5			5				25				-		-	b,- i,- j,-	Creek marsh dominated by saltmarsh cordgrass and loosestrife extends back around upland to area dominated by hibiscus.	XII
			acres	6.6	-	-	0.7	-		-	0.7	1.5	0.7			0.7				3.7				-		-	b,- i,- j,-		
94	Warwick River	0.60	%	65	-			10		5	10	5	5			-										-		Small pocket marsh dominated by saltmarsh cordgrass; cattails and big cordgrass abundant in interior.	I
			acres	0.39	-			0.06		0.03	0.06	0.03	0.03			-										-			
95	Warwick River	0.05	%	45		-		5		-	5	10	30			-			5							-	b,- i,-	Pocket marsh; interior area mostly hibiscus and marsh mallow; cordgrasses dominate lower portion.	XII
			acres	0.22		-		0.02		-	0.02	0.05	0.15			-			0.02							-	b,- i,-		
96	Warwick River	29.5	%	55	-			30	-	5	-	-	-			-			5					5		-	i,-	Extensive creek marsh dominated by cordgrass and big cordgrass; water hemp scattered throughout	I
			acres	16.2	-			8.8	-	1.5	-	-	-			-			1.5					1.5		-	i,-		
97	Warwick River	11.5	%	75	5			15	-	-	-	-	-	5	-				-					-				Creek marsh along both Stony Run and Warwick River; interior section partially filled; reed grasses along upland.	I
			acres	8.6	0.6			1.7	-	-	-	-	-	0.6	-				-					-					
98	Stony Run	3.1	%	80	-			15	-	-	-	-	5						-									Creek marsh dominated by saltmarsh cordgrass with stands of big cordgrass; hibiscus and mallow scattered throughout.	I
			acres	2.5	-			0.5	-	-	-	-	0.2						-										
99	Stony Run	5.6	%	55	5	-	-	35	-	-	-	5	-	-		-			-					-	-			Pocket marsh dominated by big cordgrass and saltmarsh cordgrass; scattered hibiscus with patches of reed grass.	I
			acres	3.1	0.3	-	-	2.0	-	-	-	0.3	-	-		-			-					-	-				

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100	Stony Run	1.9	%	45		-		40	-			10	5			-			-				-					Creek marsh section dominated by saltmarsh cordgrass and big cordgrass; hibiscus and mallow scattered throughout.	XII
			acres	0.9		-		0.8	-			0.2	0.1			-			-				-						
101	Stony Run	1.8	%	65	-			30	-	-		-	5	-					-									Creek marsh dominated by saltmarsh cordgrass; big cordgrass along upland; hibiscus and mallow scattered throughout.	I
			acres	1.2	-			0.5	-	-		-	0.1	-					-										
102	Stony Run	5.0	%	65	-	-	-	30		-	-	-	5						-				-	-				Creek marsh dominated by a mixture of saltmarsh cordgrass and big cordgrass; interior section along upland has been filled.	I
			acres	3.2	-	-	-	1.5		-	-	-	0.2						-				-	-					
103	Stony Run	1.9	%	80		-		20		-	-	-	-						-									Creek marsh dominated by saltmarsh cordgrass; marsh has been dredged in several places to provide small boat slips.	I
			acres	1.5		-		0.4		-	-	-	-						-										
104	Stony Run	20	%	40				60	-	-	-	-	-											-				Branch of creek where main channel has been altered by highway construction; marsh extends to pocket area above road.	V
			acres	0.8				1.2	-	-	-	-	-											-					
105	Stony Run	13.0	%	20				35		-	-	25	-			10							10	-	-		c,-	Creek marsh section; saltmarsh and big cordgrass as well as hibiscus are most abundant; pickerelweed and threesquare in upstream portion only.	XII
			acres	2.6				4.6		-	-	3.2	-			1.3							1.3	-	-		c,-		
106	Stony Run	10.3	%	25				40		-		35				-							-	-	-		c,-	Creek marsh section; includes mixture of brackish and freshwater species.	XII
			acres	2.6				4.1		-		3.6				-							-	-	-		c,-		
107	Stony Run	9.5	%	-				-		-	5	15	-			5							20	5			c,50	Upstream portion of creek; freshwater species, especially wild rice, dominate.	XI
			acres	-				-		-	0.5	1.4	-			0.5							1.9	0.5			c,4.8		

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Section IV. Warwick River and Stony Run

Marsh Location	Total Acres		Saltmarsh Cordgrass	Saltmeadow Grasses	Black Needlerush	Saltbushes	Big Cordgrass	Saltmarsh Bulrush	Water Hemp	Cattails	Marsh Hibiscus	Marsh Mallow	Reed Grass	Olney Threesquare	Common Threesquare	Sea Oxeye	Water Dock	Saltmarsh Loosestrife	Sea Lavender	Saltmarsh Fleabane	Saltmarsh Aster	Pickerelweed-Arrow Arum	Smartweed	Giant Bulrush	Cardinal Flower	Other	Observations	Marsh Type
Warwick River	16.5	%	50	-	5		35	-	-	-	-	5	-					5							-		Creek marsh with wide channel extending across marsh; open to river at both ends.	I
		acres	8.2	-	0.8		5.8	-	-	-	-	0.8	-					0.8							-			
Warwick River	0.50	%	95				5	-	-		-																Small pocket marsh dominated by saltmarsh cordgrass; big cordgrass along upland edge.	I
		acres	0.48				0.02	-	-		-																	
Warwick River	48.3	%	35	5	30	-	30	-	-	-	-	-		-				-									Extensive creek marsh; dominated by big cordgrass and saltmarsh cordgrass; several large areas of needlerush.	XII
		acres	16.9	2.4	14.5	-	14.5	-	-	-	-	-		-				-										
Warwick River	98.4	%	30	20	15	5	30	-	-	-	-	-		-													Extensive creek marsh; large areas of meadow grasses, big cordgrass, saltmarsh cordgrass and black needlerush.	XII
		acres	29.5	19.7	14.8	4.9	29.5	-	-	-	-	-		-														
Hoopes Landing	2.0	%	10	35	30	10	15	-		-				-													Includes area of high marsh fringe along river; extends back to pocket marsh area dominated by needlerush.	XII
		acres	0.2	0.7	0.6	0.2	0.3	-		-				-														
Total Section IV	582.9	%	38	6	17	4	25	-	-	-	3	1	-	-	1		-	3		-	-	1	1			b,- c,1	e,- f,- g,- h,- i,- j,1	
		acres	220.5	32.8	96.2	24.4	144.1	0.7	2.9	2.5	15.9	4.8	0.6	0.5	4.7		-	15.4		-	-	3.2	3.2			b,- c,4.8	e,- f,- g,- h,1.8 i,- j,3.9	

a = Saltmarsh Fimbristylis
b = Swamp Milkweed
c = Wild Rice
d = Jewel Weed
e = Mock Bishop-weed
f = Water Parsnip
g = Water Hemlock
h = Marsh Pennywort
i = Arrowhead
j = Cutgrass

Table 27. Listing of the marshes along the Warwick River as shown in Figure 10 (from Moore, 1974) (con't)

City of Newport News were inventoried in 1976 utilizing a mixture of aerial photography and ground-truth observation to aid in interpretation of the imagery. Based on these methods, marshes number 85 through 96 on the upper reaches of the Warwick River were classified as Brackish Water Mixed Type 12 and Saltmarsh Cordgrass Community Type 1 (Table 27; Moore, 1977; Silberhorn et al., 1974).

The marshes, when reexamined in July and October 1984, were found to be unchanged since the inventory. In Marsh 90, closest to Route 60, the tidal marsh vegetation grades into swamp/bottomland hardwood forest consisting of black gum, red maple, and sweet gum. These tree dominated wetlands were judged to be only marginally tidal. This is a normal habitat type for this type of stream and location. There was no evidence of an adverse impact on the salt marshes or bottomland forest from the discharge of alum sludge into the Warwick River.

STORM Model

Land use percentages used in the STORM simulations for the portion of the Warwick River watershed draining into the Lee Hall water supply reservoir are listed in Table 28. Land use under present day conditions and predicted land use had residential or agricultural intensive development been allowed to take place in the absence of the reservoir are considered. The term 'ultimate' is used to describe the final land use percentages assuming that all available land has been developed.

The results of the model runs for these land use scenarios in the Lee Hall reservoir watershed are presented in Table 29. In addition, a simulation was made for comparison in which the basin was left undeveloped

Table 28. Land use percentages used in STORM model simulations of existing and hypothetical development of the Lee Hall watershed.

Land Use Category	Existing (1984)	Ultimate Agric.	Ultimate Resid.
Residential	14.5	25.4	43.4
Commercial	3.5	2.2	4.8
Industrial	2.0	11.0	9.5
Forested	77.8	26.6	27.6
Agriculture			
Row Crop	1.5	23.2	10.0
Pasture	0.5	11.6	4.7
	100	100	100

Table 29. Annual pollutant loadings (lbs/year) for various land development activities in the Lee Hall Reservoir watershed.

Water Quality Constituent	Existing (1974)	100 % Forested	Ultimate	
			Agric.	Resid.
Suspended Solids	787,276	668,770	1,246,861	1,102,940
BOD_5	124,330	67,217	278,206	259,145
Total Nitrogen	54,089	33,473	93,069	97,567
Total Phosphorus	5,622	3,378	11,454	10,801
Fecal Coliform ($x10^9$ cells)	290,801	1,687	755,656	870,576

(100% forested). The loading data are expressed in units of lbs/yr based on the 12 month simulation using the 1957 rainfall sequence. These can be thought of as average annual loads, and can be directly compared, for example, with the annual load from a point source when such loads are expressed in similar units.

In general, the predominantly agricultural use of the watershed yielded the highest loadings for all pollutant constituents, except for fecal coliforms which had the highest loadings in the residential scenario. As expected, the 100% forested configuration yielded the lowest loadings. Comparing the loadings projected for residential and agricultural development with those from the existing or 100% forested land use scenarios, it is estimated that loadings for the watershed would be roughly double the present day loadings for all constituents if growth in the past were not restricted.

HISTORICAL DEPTHS

Poquoson River

In 1868 the U.S. Coast Survey conducted a bathymetric survey of the Poquoson River, recorded as Boat Sheet Number 446, Registration Number 977. The Boat Sheet does not include the most upstream reach from the present day Harwood's Mill dam to Station 6 of the present study. That portion of the Boat Sheet from the survey which includes at least part of the present study area is reproduced here as Figure 11. Comparing the 1984 Navigational Chart (Number 12238) to the 1868 Boat Sheet, the depths appear to be essentially unchanged over this 124 year period. There are apparent major changes in the shorelines, however; for example Moore's Creek is not shown on the 1868 Boat Chart.

While the 1868 Boat Chart does not include the most upstream area of the present study, there is no reason to believe that this area had a greater depth at that time. At the most upstream depth surveyed in 1868, the depth ranged from 1 to 2 ft, very similar to the depths found today. For the portion of the chart covering the lower half of the present study, the maximum depth was 7-8 ft, at a point near our Station 10.

Warwick River

Surveys of the lower end of the Warwick River below the present study area date back to 1871. Unfortunately, it was not until 1946 that the U.S. Coast and Geodetic Survey conducted a hydrographic survey of the upper

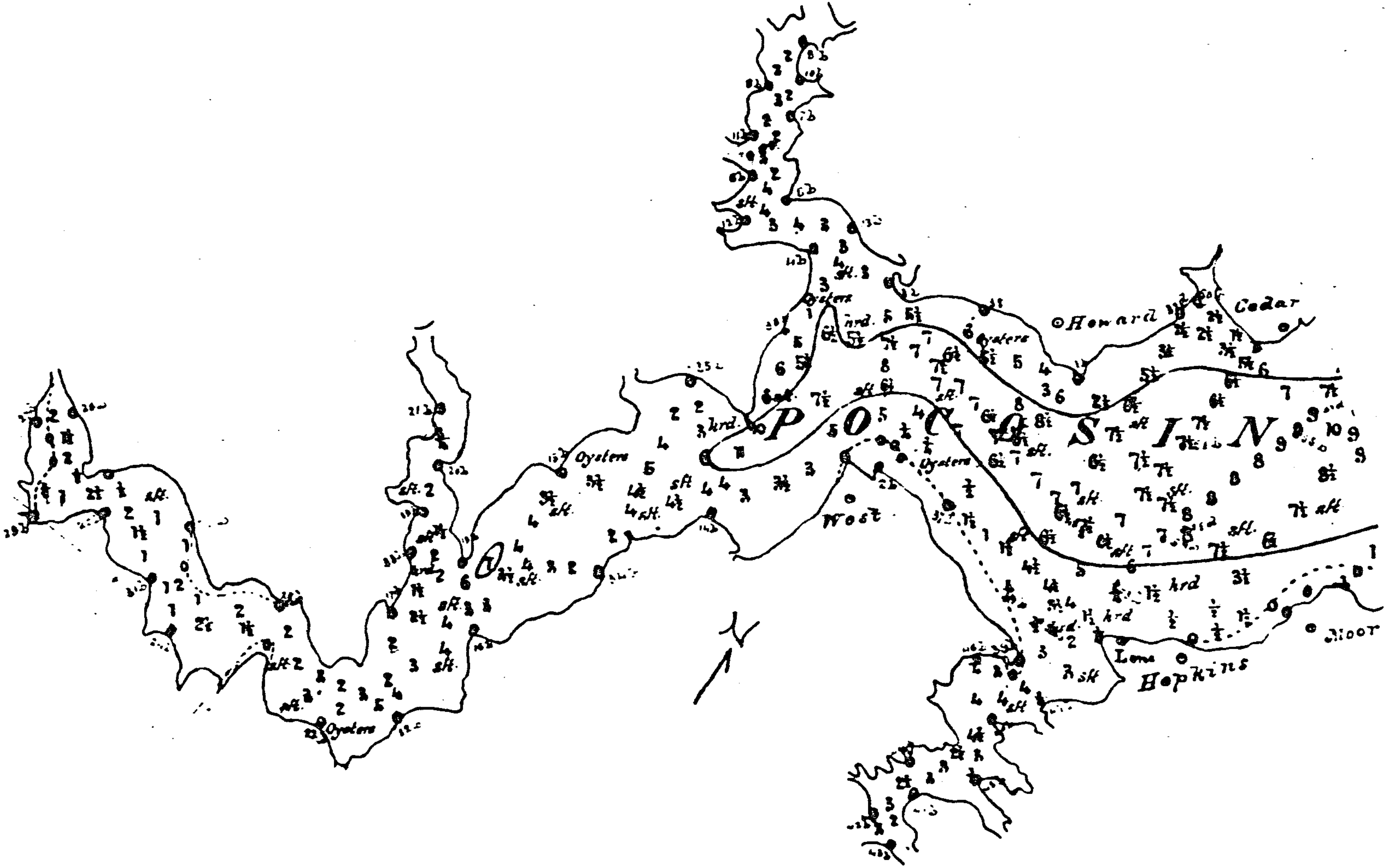

Figure 11. Reproduction of the 1868 U.S. Coastal Survey Boat Sheet for the Poquoson River showing the depths at mean low water (in feet).

reaches of the Warwick River. The survey was recorded as number 7160 of the lower James River. The Boat Sheet of the survey is reproduced here as Figure 12. When a current navigational chart is compared to the 1946 survey, it appears that the depths used on the 1984 Navigational Chart (Number 12248) are the same as those on the 1946 boat sheet.

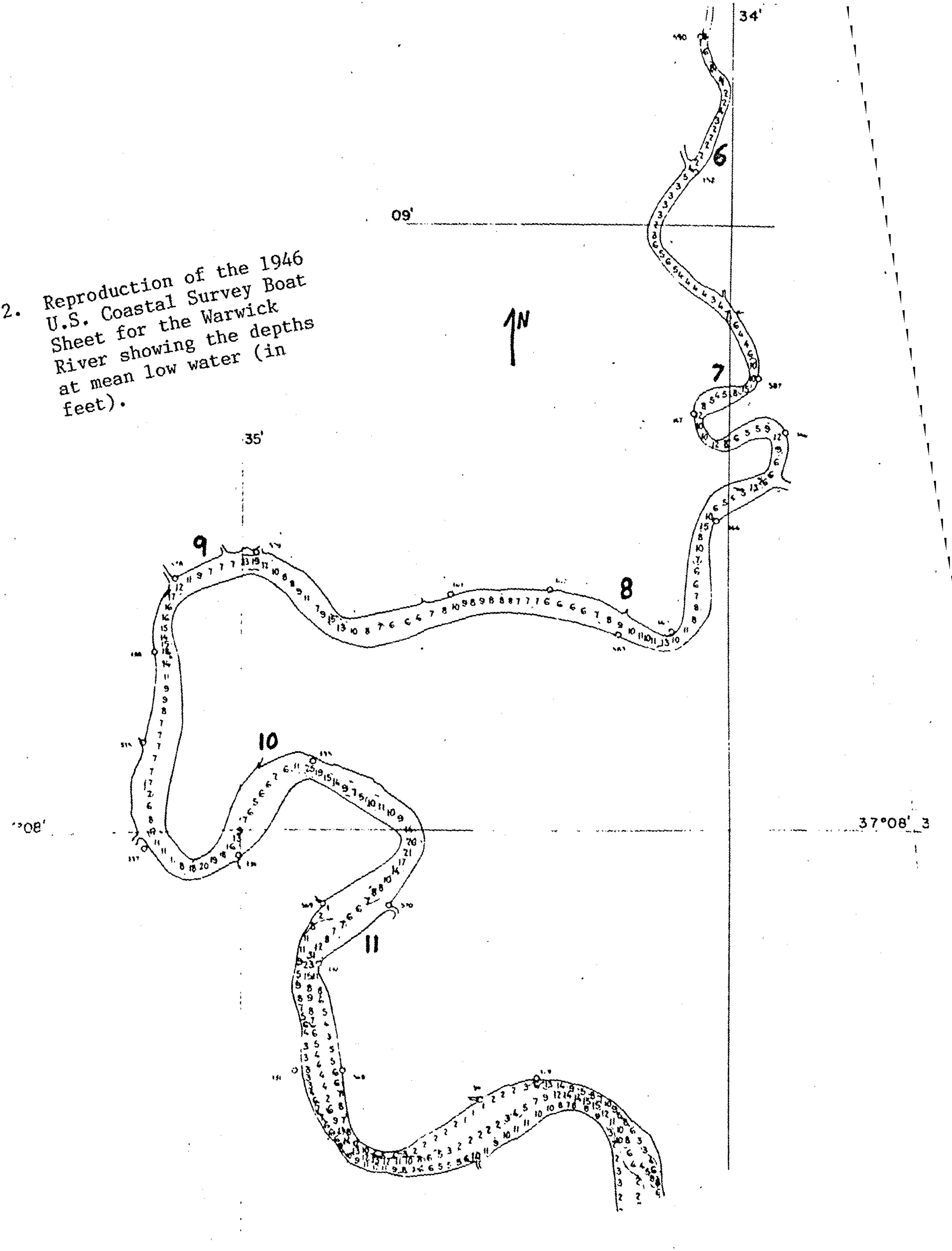

Figure 12. Reproduction of the 1946 U.S. Coastal Survey Boat Sheet for the Warwick River showing the depths at mean low water (in feet).

HISTORICAL REVIEW OF PUBLISHED LITERATURE

Poquoson River

The Poquoson River is a small tributary system off the Chesapeake Bay to which little scientific attention has ever been given. The marsh survey previously discussed represents the only published account of environmental conditions in the Poquoson River.

There do not appear to be any municipal discharges of any kind into the Poquoson other than that from Harwood's Mill Water Treatment Plant. However, Air Products and Chemical, Inc. has a discharge into Bennett Creek which is a part of the Poquoson River system.

Warwick River

The Warwick River is a tributary of the James River; consequently there are a number of environmental studies of the lower James River which have included stations located near or in the mouth of the Warwick River. The Warwick, however, is very long and narrow, and consequently no environmental survey has ever been conducted over the entire length of the river with the exception of the marsh inventory (Moore, 1977).

The only benthic study conducted in the Warwick River was that of Diaz and Boesch (1976). They were evaluating the environmental effects of constructing a sewage effluent discharge line and diffuser. None of their stations were located far from the mouth of the Warwick River, and many were in the James River proper.

There are several industrial and municipal discharges on the Warwick River. Bendix Corporation, located about one mile upstream from the mouth, is the primary industrial discharger. The major municipal dischargers are the Lee Hall Water Filtration Plant located at the head, and James River Sewage Treat Plant operated by the Hampton Roads Sanitation District Commission, and Newport News City Farm, both located at the mouth of the Warwick River (Diaz, 1977).

CONCLUSIONS

1. There are obvious reductions in primary production for both phytoplankton and benthic algae at the most upstream stations studied in each river. These effects are largely attributable to the effects of alum sludge on light transmission in the water column. The low productivity, in turn, leads to a low standing crop of algae. No toxic impact of alum sludge is evident since the assimilation ratios determined are within a normal range for this habitat type.

2. Marshes associated with the upstream areas of both rivers are typical for freshwater-estuarine transition zones. There are no obvious impacts on marsh flora attributable to the water filtration plants, although there are effects related to Route 17 crossing the Poquoson River.

3. Alum sludge enrichment is evident in both rivers. In the Poquoson, measurable enrichment is limited to one and a half miles downstream of the discharge point. In the Warwick, enrichment was evident over the entire 5.5 miles studied, though at the most downstream station, the Al:Si ratio was reduced almost to background level. This difference in the two rivers is thought to reflect the difference in amount of alum sludge discharged, with three times as much discharged into the Warwick as is discharged into the Poquoson. Greatest enrichment was observed in the upper portions of cores, generally declining uniformly with depth, although subsurface lenses of enriched material were sometimes observed.

4. Stratigraphic analysis of the cores indicates no major changes in the benthic communities over the depositional period represented by the cores. The absence of biogenic structure in the Warwick River cores is typical of freshwater transition communities. The absence of biogenic structure observed in the Poquoson River cores from the upstream, nearly freshwater locations, is typical of this transitional habitat. At the more saline downstream stations, typical biogenic structure is observed.

5. The benthic communities in the Poquoson River seem to be depressed at the first four or five stations. Considering the salinity at these stations, a more diverse fauna was expected; however, the impact cannot be conclusively attributed to any specific cause. From Station 6 to 10, communities were diverse and very representative of mesohaline estuarine habitats.

6. The benthic communities in the Warwick River were of low diversity which is not surprising for the tidal freshwater transition zone. However, the communities at Stations 1, 2, 4, and 6 were of lower diversity than the other stations.

7. Runoff loads were computed using the mathematical model STORM (Storage, Treatment, Overflow, Runoff Model) for the two watersheds draining into the Harwood's Mill and Lee Hall Water Supply Reservoirs. The model was used in order to compare pollutant loads under conditions of hypothetical unrestricted development of the watersheds with the present day (1984) land use. The model predicts that unrestricted residential or agricultural development would result in a doubling of

the annual runoff loading of suspended solids, BOD_5, nitrogen, and phosphorus for both watersheds.

8. A simple nomograph (Brune, 1953) was applied to estimate the efficiency of the two reservoirs in trapping runoff-borne sediments. From the nomograph, we estimate that 72% and 78% of the inflowing suspended sediment is trapped in the Lee Hall and Harwood's Mill Reservoirs respectively.

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GLOSSARY

Alkalinity	a measure of the amount of each of several bases in water; in the present study, only the alkalinity due to carbon dioxide and its reaction products with water were measured, i.e. we measured the carbonate alkalinity; used as a measure of the total amount of carbon available for photosynthesis.
Bathymetric	pertaining to depth of a body of water.
Benthic	pertaining to the bottom of a water body; often used to describe organisms associated with the bottom.
Biogenic Structure	biologically produced structures in sediments which remain after an organism dies (e.g. tubes, shells, etc.) or biologically produced disturbances of sedimentary laminations.
Bioturbation	disturbance of the benthic sediments by the normal life activities of the biological community; includes redistribution of sediments by burrowing through or ingesting sediments, burrow formation, deposit feeding on the surface with deposition of feces.
^{14}C-uptake Method	a method to measure the net production of phytoplankton based on the measured uptake of radiolabelled carbon after a specified incubation period; this method cannot measure gross production, nor can it measure net production under low light conditions when net production may be less than zero.
Detritus	particles of dead organic material of various sizes and degrees of decomposition.
Estuarine Endemic	refers to species which are found only at estuarine salinities, typically 0.5 to 18 o/oo.
Eurytopic	tolerant of a wide range of environmental conditions as defined by various parameters such as salinity, sediment type, temperature, etc.
Mesohaline	refers to water with a salinity between 5 and 18 o/oo or used in reference to organisms living in a water within this salinity range.

Opportunistic	pertaining to organisms with a life style which allows rapid invasion of an environment with available resources (space, food, etc.).
Plankton	organisms which are free-floating in the water column, including both plant-like forms (phytoplankton) and animal forms (zooplankton).
Productivity	a measure of the amount of energy fixed as hydrocarbons by algae through the process of photosynthesis.
Gross	the total amount of carbon fixed in a specified time interval.
Net	the total amount of carbon fixed less the amount consumed during the specified time interval by the process of respiration; this is the amount of fixed carbon available as increased biomass.
Salinity (o/oo)	the salt content of the water in grams of salt/kilogram of water, expressed as parts/thousand.
Scintillation Medium	a solution containing a substance which emits a light pulse when bombarded by a beta particle from an isotope such as radioactive carbon; the light pulses can be counted electronically as a measure of the number of radioactive disintegrations occurring.
Stratigraphy	description of the structure of a sediment column.
Terrigenous	pertaining to origination from land; in the context of the present report, refers to sediments which have been exposed to air for extended periods, and not subject until recently if at all to aquatic erosion and redeposition.