CHESAPEAKE BAY LOW FLOW STRATEGY STUDY

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SUSQUEHANNA RIVER BASIN COMMISSION

The Susquehanna River Basin Commission was created as an independent agency by a federal-interstate compact* among the states of Maryland, New York, Commonwealth of Pennsylvania, and the federal government. In creating the Commission, the Congress and state legislatures formally recognized the water resources of the Susquehanna River Basin as a regional asset vested with local, state, and national interests for which all the parties share responsibility. As the single federal-interstate water resources agency with basinwide authority, the Commission's goal is to effect coordinated planning, conservation, management, utilization, development and control of basin water resources among the government and private sectors.

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CHESAPEAKE BAY LOW FLOW STRATEGY STUDY

Final Report

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EXECUTIVE SUMMARY

The purpose of this study is to develop a general strategy to study and manage the impacts of low freshwater inflows, and reductions of low freshwater inflows, from the Susquehanna River on the salinity distribution, water quality, available habitat, and living resources of the Chesapeake Bay.

The goals of the Chesapeake Bay Program (CBP) include restoration and protection of the living resources, their habitats, and ecological relationships. One of the objectives of the bay program is to maintain low freshwater flow regimes.

The Susquehanna River Basin Commission (SRBC) has a mission to bring about coordinated planning and management of the water resources of the Susquehanna basin. The goals of the commission include preventing reduction of freshwater inflows into the Chesapeake Bay. The commission's Comprehensive Plan provides guidelines and criteria to prevent adverse impacts on the historic quantity and quality of flow into the Chesapeake Bay, and requires compensation for consumptive uses. The commission's consumptive use compensation regulation requires new consumptive users to replace their consumptive use under specified low flow conditions. One of the purposes of the consumptive use regulation is to protect the bay, but it has not been determined whether the current regulation adequately protects the bay. Commission staff is presently conducting studies that may lead to changes in the regulation.

Significant growth in the Susquehanna basin, and in other bay tributaries, has resulted in increased demand on the resources of the Susquehanna basin and the bay, and may be contributing to the decline of the bay's living resources. These increases in consumptive uses and diversions from the Susquehanna basin may aggravate the decline in the bay's resources and make it more difficult to accomplish the CBP goals.

To manage the water resources of the Susquehanna basin, the commission needs to know what effects management actions have on the bay, and to determine what actions are necessary to meet the needs of the bay and the goals of the CBP. The effects of low freshwater inflows and reductions of natural flows on the salinity distribution, water quality, available habitat and living resources of the bay need to be quantified. The benefits of increased low flow, and maintenance of low flow, to the bay also need to be quantified.

The effects of low flows and reduction in low flows on the bay are not well documented or understood. This report will provide a strategy for studying and managing these effects.

The report describes the hydrology of the Susquehanna basin, and the effects of consumptive uses and diversions and hydropower operations on Susquehanna flows.

To develop the strategy, relevant literature regarding the effects of Susquehanna flows on salinity, water quality, living resources, water supply, commercial, recreational and aesthetic uses of the bay was reviewed and summarized. Literature regarding the effects of the Chesapeake and Delaware Canal (C&D Canal) on the bay also was reviewed and summarized. Then a survey was conducted to determine the extent of agreement on the important issues that need to be addressed, and to obtain feedback regarding those issues. A workshop was held to address the issues and to develop a final strategy.

The literature indicates potentially significant impacts of low flows and consumptive uses on salinity, water quality and living resources, and confirms the need for further study. The impacts identified in the literature are summarized in section 3.4.

The major recommendations resulting from the study are:

- Flow management should be based on an acceptable level of impact on all significantly impacted uses and resources in the Chesapeake Bay.
- The goals of flow management for the Chesapeake Bay should be to maintain tolerable salinity conditions for all uses at all times.
- The effects of low flows and consumptive uses on the salinity, water quality and living resources of the Chesapeake Bay need to be considered. The effect of changes in salinity on water supply, commercial, recreational and aesthetic uses also need to be considered.
- Evaluation and mitigation of the effects of consumptive uses on the bay is the important problem to address at this time. Augmentation of low flows should be considered at a later time.
- The strategy should focus on the effects of consumptive uses on salinity and living resources.
- The strategy for addressing the effect of consumptive uses should be iterative. The first iteration should be a problem assessment which should include:

    * Analysis of historical data to determine effects of low flows on salinity and living resources;
    * Use of existing watershed models to determine the effect of certain flow scenarios on the salinity in the bay.
    * Evaluation by experts of the effect of changes in salinity on the ecosystem and individual species.
    * Economic analysis to determine whether additional studies are appropriate.

- The first iteration also should investigate what areas of the bay are impacted by consumptive uses and diversions.
- Additional studies of the effects of hydropower operations and the effects of the C&D Canal on the bay should be conducted.
- The studies should be coordinated through the CBP. All interested agencies should be invited to participate. The studies should be coordinated with ongoing studies of consumptive use in the Susquehanna basin.
- Existing monitoring programs will provide useful data for future analyses of the effects of low flows and consumptive uses and should be continued.

1.0. INTRODUCTION

1.1. Purpose of Study

The purpose of this study is to develop a general strategy to study and manage the impacts of low freshwater inflows from the Susquehanna River on the salinity distribution, water quality, available habitat, and living resources of the Chesapeake Bay.

1.2. The Chesapeake Bay Program

The CBP is a multilevel, interagency program involving various federal agencies, the state of Maryland, the Commonwealths of Virginia and Pennsylvania, and the District of Columbia. The organization of the CBP is described elsewhere (U.S. Environmental Protection Agency (US EPA), 1995)

In 1976, the CBP began an extensive study to determine the reasons for declining water quality and living resources of the Chesapeake Bay. This study (US EPA, 1983) concluded the decline was caused by increased input of pollutants to the bay. The increased input of pollutants (nutrients and toxics) caused increased anoxia, and the decline of important living resources such as submerged aquatic vegetation (SAV), shellfish, and finfish. The decline of the living resources, especially the shellfish and finfish, resulted in significant adverse economic and social impacts.

An agreement was signed in 1987 committing the participants to a cooperative program to reverse the decline of the bay and restore the bay's water quality and living resources. The participants developed a number of goals and objectives to fulfill the agreement. The goals, adopted in 1987, and reaffirmed in 1992, include:

- Provide for the restoration and protection of the living resources, their habitats, and ecological relationships; and
- Reduce and control point and nonpoint sources of pollution to attain the water quality condition necessary to support the living resources of the Chesapeake Bay and its tributaries.

The objectives under the first goal include:

- Restore, enhance, protect, and manage submerged aquatic vegetation;
- Maintain freshwater flow regimes necessary to sustain estuarine habitats, including, where appropriate, establishing minimum instream flows;
- Develop baywide fisheries management programs; and
- Develop programs to protect and restore the finfish and shellfish stocks of the bay, especially the freshwater and estuarine spawners.

Discussion of the second goal in the 1987 agreement makes it clear that the improvement and maintenance of water quality, particularly the dissolved oxygen concentrations in the bay and its tributaries, are critical to enhancing the living resources of the bay.

In 1988, the CBP adopted a Comprehensive Research Plan (Chesapeake Executive Council, 1988) that includes the following research needs related to the effects of freshwater inflow on living resources:

- Explore the relationship between freshwater inflow and the trophic structure of living resources of the bay system; and
- Determine the baywide circulation dynamics and stratification under a variety of freshwater inflow conditions.

The Chesapeake Bay Program has focused on the water quality and living resource restoration goals, including major efforts to reduce the pollutant inputs to the bay. The goal of maintaining freshwater flow regimes has not been given a priority for implementation to date.

1.3. The Susquehanna River Basin Commission

1.3.1. Structure and mission

The SRBC was formed under the Susquehanna Compact (SRBC, 1972) to coordinate the water resources programs of signatory members and to manage the water and related land resources of the Susquehanna basin. The partners in the commission are the federal government, the Commonwealth of Pennsylvania, and the states of New York and Maryland. The commission is comprised of one representative from each of the partners. Commission programs are conducted by a multidisciplinary staff under the direction of the commissioners and the executive director.

The commission's mandated mission is to bring about coordinated planning and management of the water resources of the basin. The commission's jurisdiction is the entire Susquehanna watershed, from its headwaters near Cooperstown, N.Y., to the railroad bridge at Havre de Grace, Md. The Compact (SRBC, 1972) furnishes the commission with broad powers to manage the water resources of the Susquehanna basin, including the power to review and approve certain projects, and to establish regulations necessary to implement the Compact. The duties of the commission are described in more detail in the Compact (SRBC, 1972).

The six major program areas of the commission are: flood plain management and protection; water supply; water quality; watershed protection and management; recreation, fish, and wildlife; and cultural, visual, and other amenities. The commission has adopted a Comprehensive Plan (SRBC, 1987) that includes objectives and goals for each major program area and related guidelines for planning and project review.

1.3.2. Goals, guidelines, and criteria

The objective of the water supply program is to fulfill the needs of the people of the basin for water.

The goals of the water supply program include:

- To establish an equitable system for the allocation of water for various uses, including protection of the receiving waters of the Chesapeake Bay;
- To acquire and manage water supply storage;
- To prevent reduction of low flows into the Chesapeake Bay, including development of policies for reducing future consumptive uses; and

- To implement the recommendations of the U.S. Army Corps of Engineers' (Corps of Engineers) Chesapeake Bay Study pertaining to water supply.

Goals of the recreation fish and wildlife program include:

- To generally improve fish and wildlife habitat related to the water resources of the basin;
- To restore migratory fish resources (American shad, hickory shad, blueback herring, alewife, striped bass, and American eel);
- To incorporate the evaluation of the effects of withdrawals and consumptive uses on instream uses in all water resource activities; and
- To evaluate the effects of withdrawals and consumptive use on recreation, fish, and wildlife resources.

The guidelines and criteria include:

- The development and use of water resources shall be planned and managed to assure that the historic quantity and quality of flow into the Chesapeake Bay are not adversely affected; and
- Compensation shall be required for consumptive uses.

1.3.3. Consumptive use compensation regulation

The commission has adopted a consumptive use compensation regulation (18 CFR §803.42). The regulation requires certain new consumptive uses coming on-line after the effective date of the Compact (January 23, 1971) to replace their consumptive use whenever the natural flow is less than the 7-day, 10-year low flow (Q7-10) plus the amount of the consumptive use. Alternatives to replacement of consumptive uses such as cessation of consumptive use during low flow (less than Q7-10) or payment of a consumptive use fee to the commission are also allowed. Pre-compact consumptive uses are grandfathered under the present regulation. Diversions are generally treated in the same manner as consumptive uses under the regulation. However, for the purposes of this study, they will be considered individually.

One of the purposes of the regulation is to protect the Chesapeake Bay, but it is not clear whether the existing regulation adequately protects the bay. The commission staff is presently conducting studies that may lead to revision of the regulation.

To provide consumptive use water compensation, the commission has acquired storage in two Corps of Engineers reservoir, and has participated in studies of the feasibility of acquiring storage in other Corps of Engineers reservoirs.

1.4. Physical Description of the Chesapeake Bay

Figure 1.1. shows the major tributaries and other physical features of the Chesapeake Bay.

The Chesapeake Bay begins at Havre de Grace, Md., and runs due south until it enters the Atlantic Ocean near Norfolk, Va. The bay varies from 4 to 30 miles in width, and is about 200 miles long (Corps of Engineers, 1984a). It is the largest estuary in the United States, with a surface area of

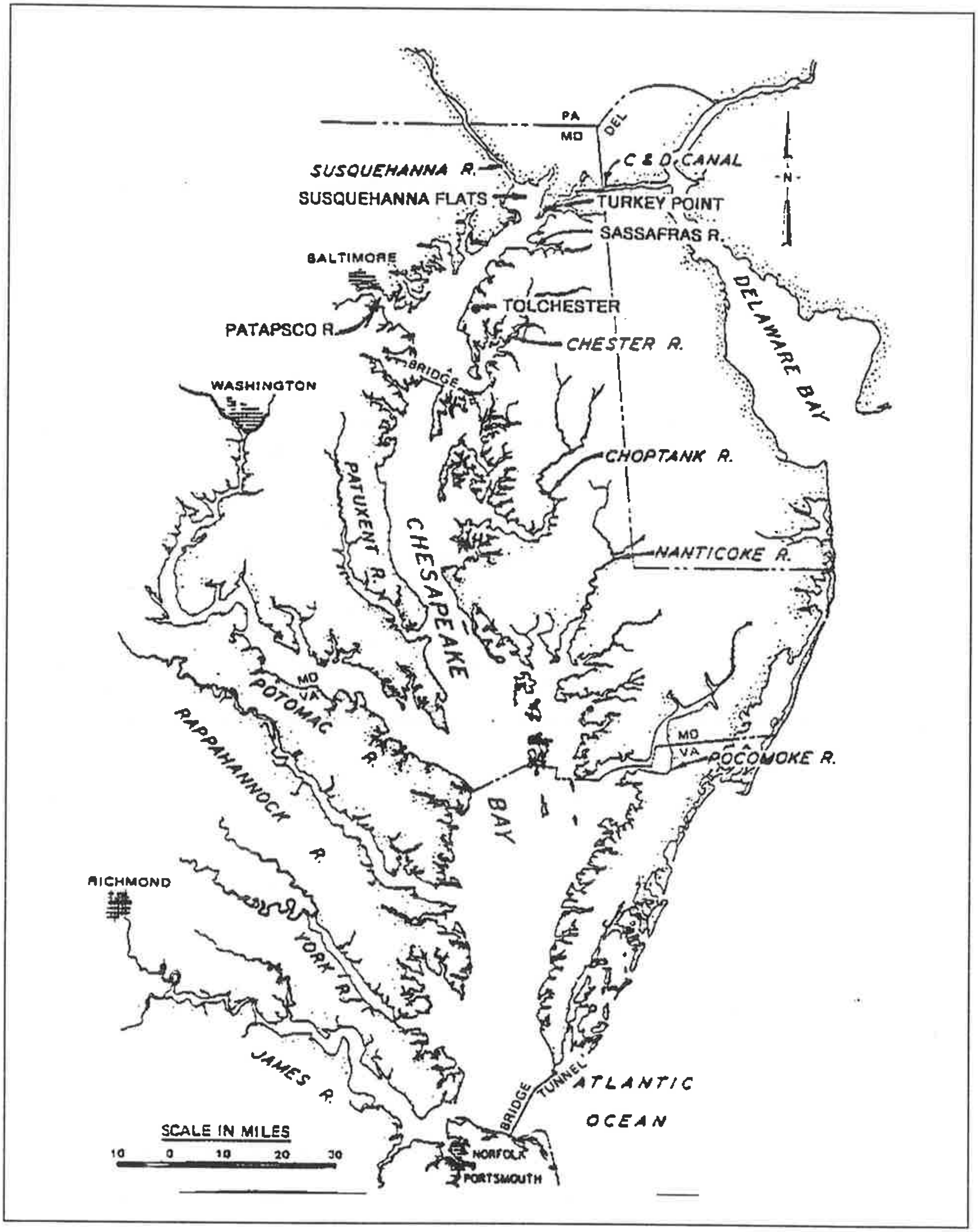

Figure 1.1. Map Showing the Chesapeake Bay With Its Major Tributaries

about 4,400 square miles. However, it is very shallow; the average depth is only about 28 feet, and about two thirds of the bay is less than 18 feet deep.

The typical cross section for most of the bay is a deep central channel with shallow water on the sides. This central channel begins just upstream from the Bay Bridge at Annapolis, Md. Just downstream from the mouth of the Susquehanna River there is a shallow area called the Susquehanna flats. The flats extend downstream to Spesutie Island and Turkey Point. Just downstream from Turkey Point, the Elk River enters from the east side. The C&D Canal begins on the Elk River near Town Point, and runs approximately due east until it enters the Delaware River estuary.

Other major rivers that drain into the Chesapeake Bay include the Potomac, which drains most of Maryland and part of Virginia, and the Rappahannock, York and James Rivers, which drain the rest of Virginia west of the bay. Smaller tributaries that enter the bay from the east side include the Northeast River, the Sassafras River, the Choptank River, and the Nanticoke River.

1.5. The Susquehanna River Basin

1.5.1. Basin description

Figure 1.2. shows the Susquehanna River Basin.

The Susquehanna River begins near Cooperstown in east central New York state. The major tributaries include the Chemung River, West Branch Susquehanna River, and the Juniata River. The commission has defined six subbasins that are used for planning purposes. The six subbasins are shown in Figure 1.2.

The total length of the main stem is about 450 miles. The basin drains 27,510 square miles. About 76 percent of the drainage area is in Pennsylvania, about 23 percent in New York, and about 1 percent in Maryland. At Harrisburg, the river is about a mile wide.

The head-of-tide on the Susquehanna River is near the north end of Robert Island, about 3 miles downstream from Conowingo Dam, and 6 miles upstream from the mouth.

1.5.2. Population, land use, and industry

In 1970, the estimated population of the basin was 3.53 million; in 1990 the estimated population of the basin was 3.85 million. The projected population in 2020 is 4.7 million (SRBC, 1987).

There are major population centers in the vicinity of Binghamton, Corning, and Elmira in southern New York, and in the vicinity of Scranton, Wilkes-Barre, Williamsport, Altoona, Lancaster, York, and Harrisburg in Pennsylvania. The location of these population centers is shown in Figure 1.2.

The changes in distribution of population are more important than the total population. While some counties within the basin have lost population since 1970, all the subbasins shown in Figure 1.2 have experienced increasing populations. Major population growth areas are located south and east of the mountains, which includes the Harrisburg, Lancaster, Carlisle, and York standard

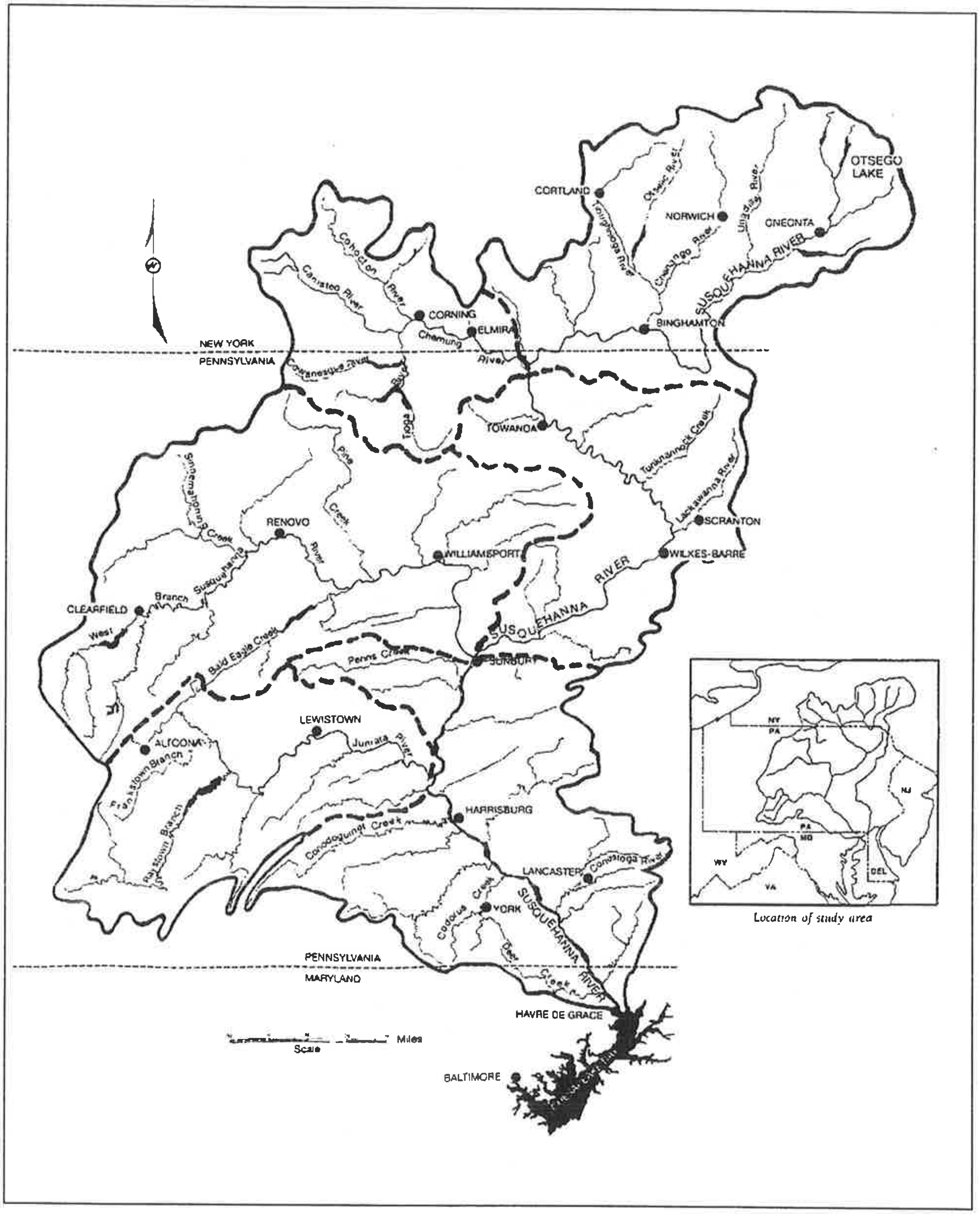

Figure 1.2. Map Showing the Susquehanna River Basin and Its Six Subbasins

metropolitan statistical areas. There is another growth area in the vicinity of State College. These areas have experienced about 12 percent growth per decade since 1970.

Approximately 62 percent of the basin is forested, 36 percent is in agricultural land, and 2.0 percent is in urban and developed land uses.

The basin has a varied manufacturing and service industrial base. Agriculture also is an important industry.

1.5.3. Reservoirs

There are 12 major reservoirs in the Susquehanna basin. The location of these reservoirs is shown in Figure 1.2, and certain statistics for these reservoirs are shown in Table 1.1. In addition, there are a large number of smaller reservoirs owned by state and local governments, public water supply utilities, and other private parties such as electric utilities.

Table 1.1. Statistics for Major Reservoirs in the Susquehanna River Basin

Reservoir	Drainage Area	Conservation Storage	Water Supply Storage	Flood Control Storage	Total Storage
	square miles	acre-feet			
East Sidney	102	1,700		31,800	33,500
Whitney Point	255	5,000		81,500	86,500
Almond	56	1,100		12,900	14,000
Arkport	31	0		7,950	7,950
Tioga-Hammond	402	18,350		106,650	125,000
Cowanesque	298	7,000	25,600	56,400	89,000
Bush	226	1,740		73,260	75,000
Stevenson	243	2,300		73,500	75,800
Curwensville	365	4,180	5,360	114,660	124,200
Raystown	960	514,000		248,000	762,000
Indian Rock	94	0		28,000	28,000
Sayre	339	6,300		92,700	99,000
Stillwater	36.8	86	257	11,657	12,000
Total	**3,042.8**	**561,756**	**31,217**	**938,977**	**1,531,950**

As is apparent from the table, most of the storage available is allocated to flood control, in accordance with the basin's long history of flooding. The total amount of storage available in these reservoirs is about 0.96 inch of runoff, or about 5 percent of the average annual runoff from the entire basin. The drainage area controlled is about 11 percent of the drainage area of the basin.

1.5.4 Power generation facilities

As of 1986, there were a total of 13 thermal and 8 hydropower generation plants in the basin. Since that time, several small cogeneration plants have been developed. The adoption of thermal discharge regulations for power plants has resulted in the installation of cooling towers at a number of these power plants. Cooling towers reduce the amount of water withdrawn, but increase the amount of consumptive use.

The power utilities have constructed five hydropower generation plants on the lower river, downstream from Harrisburg. Pertinent statistics regarding these reservoirs are shown in Table 1.2. One important aspect of these plants is the small amount of storage available. As a result:

- The power plants operate in run-of-river mode on a weekly average basis;
- There is insufficient storage to affect flood flows in excess of the maximum plant flow rate; and
- There is very limited capability to provide water supply storage.

Table 1.2. Statistics for Hydropower Plants on the Lower Susquehanna River

Hydropower Plants	Maximum Plant Discharge	Drainage Area	Storage	
	cfs	square miles	acre-feet	inches
York Haven	16,000	25,000	8,000	0.006
Safe Harbor	105,000	26,100	143,306	0.103
Holtwood	32,000	26,800	46,592	0.033
Conowingo	80,000	27,000	310,000	0.215
Muddy Run	Not relevant	Not relevant	60,000	0.042

1.6. Reasons for Study

During the last 30 years, there has been significant growth in the Chesapeake Bay and the Susquehanna basins. Growth has been very strong along the corridor from Philadelphia, Pa., to Baltimore, Md., and Washington, DC. There also has been substantial population growth in the corridor from Philadelphia to Harrisburg and Carlisle. This increased population needs various services, including water supply and electric power.

Historically, the growth has been accompanied by increased consumptive use and diversion in the bay watersheds, particularly the Susquehanna basin. It is expected that consumptive use and diversions will continue to increase as growth continues. The following is evidence of this continuing trend:

- Baltimore is presently planning to expand its water supply service area into Harford, Baltimore, Carroll, and Howard Counties.
- Cecil County has submitted an application to divert 7 mgd at the Perryville intake to serve Elkton, Md.
- New Castle County, Delaware, has received temporary approval to purchase up to 4 mgd from the Chester Water Authority, which is being withdrawn from the Susquehanna basin. Chester Water Authority has submitted a new application to make that approval permanent, and to increase the quantity to 6 mgd.
- In the past, proposals have been made to withdraw water from the Susquehanna River to serve a large part of southern Pennsylvania and part of northern Maryland. Also, proposals

- In the past, proposals have been made to withdraw water from the Susquehanna River to serve a large part of southern Pennsylvania and part of northern Maryland. Also, proposals have been made to withdraw water from the upper Susquehanna basin to serve New York City. These proposals may reappear as the demand for water supply increases.
- Coatesville Water Authority and Chester Water Authority continue to meet growing demands by diverting water from the Susquehanna basin.

Growth pressures have increased the demand for freshwater, and also increased the demands on the resources of the Chesapeake Bay Basin, particularly the bay itself. While the demands are increasing, the living resources populations have been declining, which may be evidence the increased demands are a factor contributing to this decline. Increased demand on the water resources of the Susquehanna basin will further reduce flows to the bay, potentially aggravating the decline in bay resources, and making it more difficult to meet the restoration goals of the CBP. The attainment of the other goals of the CBP may depend on maintaining freshwater inflows from the Susquehanna River (Corps of Engineers, 1984a).

The CBP and SRBC have similar goals for protecting the bay, and therefore need to work together to determine how to manage the low freshwater inflows to accomplish the goals of both programs. The Susquehanna River is the largest single source of freshwater inflow to the bay. To satisfy the CBP goal of maintaining freshwater flow regimes, the Susquehanna River flows need to be maintained.

To manage the water resources of the Susquehanna basin, the commission needs to know what the effects of management actions are on the bay. The commission needs to determine what management actions are necessary to meet the needs of the Chesapeake Bay and to meet the living resource and water quality goals of the CBP. Management actions may include releases of water from upstream reservoirs, or cessation of consumptive uses or diversions, during critical low flow periods.

To accomplish the goals of the Chesapeake Bay Agreement, the commission's Comprehensive Plan, and the commission's consumptive use compensation regulation, the effects of low freshwater inflows and reductions of natural low flows from the Susquehanna River on the salinity distribution, water quality, available habitat, and living resources of the Chesapeake Bay need to be quantified. Also, the benefits of increased low flow for the multiple uses, including the living resources of the bay, need to be quantified. The ultimate goal is to establish a target freshwater inflow regime that will protect the Chesapeake Bay and its living resources. A flow regime should be developed that will balance the needs of the bay with the needs of the people and industry within the Susquehanna basin.

At present, the effects of decreased flows on the bay are not well documented or understood. Previous studies have shown natural droughts and future consumptive uses are expected to have a significant impact on living resources (Corps of Engineers, 1984a, 1984b). These studies have not provided sufficient information to quantify impacts of natural low flows or consumptive uses, or the benefits of increased low flows to the bay, or to develop specific flow recommendations for protection of the bay. These previous studies recommend additional studies to quantify the effects of natural low flow, and the effects of consumptive uses and diversions, on the salinity, water quality, habitat availability, and living resources of the bay. Recent studies have shown there is no consensus regarding whether low flows or reductions in low flows affect the Chesapeake Bay, and what the nature of the effect is.

At present, there is no clear strategy for studying and managing the effects of natural low flows, and reductions of natural low flows, on the Chesapeake Bay, or for establishing a target flow regime.

The purpose of this project is to establish that strategy. The strategy will include a rationale for further study of the effects of low flows, and reductions in low flows, on the bay, with the ultimate objective of developing flow management guidelines, particularly for the Susquehanna River.

1.7. Study Procedure

The study procedure includes the following steps.

Develop Susquehanna River hydrology

Susquehanna River hydrology was developed for the purpose of demonstrating the occurrence of high and low flows, and the variability in the Susquehanna River flows. To assess the magnitude and timing of potential impacts on the bay, estimates of current consumptive uses and diversions were developed and compared to Susquehanna River flows.

Literature review

Selected literature, pertinent to the problem, was identified, reviewed, and summarized. The literature includes both studies specific to the Chesapeake Bay and studies conducted elsewhere. The scope of the literature review was limited.

Survey

From the literature review, certain key issues were identified, and a survey was prepared and distributed to various interested parties.

The purposes of the survey were:

- To determine whether there is agreement regarding what issues need to be addressed;
- To determine the extent of agreement regarding these issues among various interested parties;
- To obtain feedback regarding these issues; and
- To clarify some points in the literature review.

Draft strategy

From the literature review and survey, the critical issues needed to be included in the strategy were identified and formed into a draft strategy.

Workshop

A workshop was held to further discuss the issues identified, and to refine the strategy. The purpose was to obtain agreement on a strategy to determine impacts of low flows on the Chesapeake Bay and develop guidelines for managing Susquehanna River flows, considering the effects on the Chesapeake Bay.

Final report and final strategy

Following the workshop, this final report, including the strategy developed at the workshop, was prepared.

1.8. Definitions

1.8.1. High flow, low flow, drought flow

For the purpose of this study, a high flow is defined as *"a flow that exceeds the mean monthly flow for each month."* A low flow is defined as *"a flow less than the mean monthly flow during a month."* A drought flow is defined as *"a low flow that occurs very infrequently, based either on the annual averages or the monthly averages."*

Please note that, with these definitions, flows less than the monthly average are considered low flows, even if they occur during the season when flows are normally high. As a result, a low flow event may occur during the high flow period.

These definitions are somewhat unsatisfactory, because low flows should be defined in terms of impacts on the salinity, water quality, living resources, and other uses of the bay. Since we do not know how the bay responds to different levels of flow during different seasons of the year, and cannot define impacts of natural flow variations or of changes in natural flows, there is no basis for specifically defining low flows in those terms.

While flow impacts cannot be defined specifically, the following general definitions of flow ranges are proposed for consideration as a conceptual framework for defining effects of flow.

The effects of flows on salinity suggest that the entire flow range can be divided into three parts:

- High flow range, where reduced salinities have a significant adverse affect on certain species;
- Normal range, where salinity changes have no adverse affect on any of the species; and
- Low flow range, where increased salinities have a significant adverse affect on certain species.

Based on the scientific consensus regarding effects of flows on low dissolved oxygen (anoxia) (Harding and others, 1992) and the modeling data (Cerco and Cole, 1994a; C. Cerco, oral communication), the flow range can similarly be divided into three parts, based on effects of flows on anoxia:

- High flow range, where anoxia is increased as a result of increased stratification and high nutrient transport;
- Normal flow range, where anoxia tends to be reduced as a result of reduced stratification and nutrient availability; and
- Low flows that tend to increase the anoxia by increasing residence time.

This interpretation of the effects of low flows on anoxia is controversial, and will be discussed in section 3.4.2.

From the viewpoint of effects on water supply, a low flow range can be defined as the range where there is a significant effect of increased salinity on water supply.

Based on these definitions, the high flow, normal flow, and low flow ranges can be defined as follows:

- The **high flow range** in which either anoxia is increased or salinity is reduced, causing a significant adverse impact on the living resources;
- The **normal flow range** in which neither the increased anoxia nor changes in the salinity cause adverse impacts on the living resources; and
- The **low flow range** in which either anoxia is increased due to increased residence time or the salinity is increased, causing a significant adverse impact on the living resources, or increased salinity has a significant effect on water supply.

These definitions should be considered as a refinement of the definitions given previously.

Although this study is intended to focus on the effects of low flows on the bay, both high and low flows are important, because of the interrelationship between flow and anoxia, which will be discussed subsequently. Some consideration needs to be given to the entire flow range in developing this strategy.

1.8.2. Water withdrawal, consumptive use, and diversions

- Water withdrawal is the total amount of water used in and from the basin, regardless of whether it is returned to the basin.
- Consumptive use is the loss of water from a ground-water or surface water source through a manmade conveyance system due to transpiration by vegetation, incorporation into products during their manufacture, evaporation, or any other process by which the water withdrawn is not returned to the waters of the basin undiminished in quantity (18 CFR §803.3).
- Diversions are withdrawals that result in exporting water to other river basins.

1.8.3. Natural flows

Natural flows are defined as flows that would occur in the absence of any anthropogenic effects such as land use, reservoir operations, consumptive use, and diversions. As a practical matter, for the purpose of this study, natural flows will be assumed to be identical to the observed flows at any location during the period of record. Whether the flow record should be adjusted to account for anthropogenic effects will be discussed later.

1.8.4 Salinity zones

The literature shows a number of different salinity classification schemes have been used to describe the occurrence of different plant and animal species. The following is a summary of some of the classifications found in the literature.

Venice System (Anonymous, 1959)

Tidal Fresh Water	0.0 ppt to 0.5 ppt.
Oligohaline	0.5 ppt to 5.0 ppt.
Mesohaline	5.0 ppt to 18.0 ppt.
Polyhaline	18.0 ppt to 30.0 ppt.
Euhaline	over 30.0 ppt.

Stone and others (1994)

Tidal Fresh	0.0 ppt to 0.5 ppt
Mixing	0.5 ppt to 25.0 ppt
Sea Water	over 25 ppt

Bulger and others (1993)

Zone 1	0.0 ppt to 4.0 ppt
Zone 2	2.0 ppt to 14.0 ppt
Zone 3	11.0 ppt to 18.0 ppt
Zone 4	16.0 ppt to 27.0 ppt
Zone 5	Greater than 24.0 ppt

Phytoplankton (Corps of Engineers, 1984e)

Tidal Fresh	0.0 ppt to 5.0 ppt
Oligohaline/Low Mesohaline	3.0 ppt to 10.0 ppt
Mesohaline	8.0 ppt to 15.0 ppt
Polyhaline	13.0 ppt to bay mouth

Benthic Organisms (Corps of Engineers, 1984e)

Freshwater	
Estuarine Endemic	2.0 ppt to 11.0 ppt
Euryhaline opportunistic	8.0 ppt to 17.0 ppt
Euryhaline marine	17.0 ppt to 27.0 ppt
Stenohaline marine	Greater than 25.0 ppt

Emergent Aquatic Vegetation (Corps of Engineers, 1984e)

Coastal fresh marsh	0.0 ppt to 5.0 ppt
Coastal brackish marsh	5.0 ppt to bay mouth
Brackish irregularly flooded marsh	10.0 ppt to bay mouth

The salinity zones used in Stone and others (1994) are very wide and heavily favor species that occur in the more saline portions of the bay.

Bulger and others (1993) developed the salinity zones shown, based on field data for the salinity ranges of 316 species/life stages in the Chesapeake Bay/Delaware Bay area. The zones were defined by statistical (principal components) analysis.

The Venice system was crafted from the observation, judgment, and experience of scientists of the day (Anonymous, 1959). No objective criteria for the zone boundaries are reported.

Since the Venice classification system is widely applied in describing patterns of distribution of estuarine organisms, and since it was used in the Corps of Engineers' study (Corps of Engineers, 1984b, 1984e), that system will generally be used in this report, unless it is specifically stated that another system is being used.

2.0. SUSQUEHANNA RIVER HYDROLOGY

2.1. Natural Flows

The Susquehanna River has highly variable flows. The historical maximum recorded daily flow at the mouth of the river is about 1.1 million cfs, or about 600 times the historical daily low flow of about 1,900 cfs.

The Susquehanna River is the most flood-prone basin in the United States. Shank (1972) lists seven major floods at Harrisburg between 1784 and 1972. Other major floods occurred in 1975 and 1996. The January 1996 flood was the second largest peak flow entering the bay. Historically, significant floods have been experienced about every 20 years, and there have been many minor floods. The floods in 1993 and 1994 were minor from the viewpoint of magnitude of peak flows, even though the volume and duration of high flows were much larger than usual.

The average monthly flows show considerable variability, as seen in Figure 2.1. Note the typical annual cycle of high flows in the spring and low flows in the fall. While that pattern is typical, high flows can occur as the result of heavy rainfall at any time of the year. Note that:

- The average monthly flow ranges from about 82,000 cfs in April to about 12,500 cfs in August;
- The lowest average monthly flow for April is about 23,800 cfs, and the highest mean monthly is about 214,000 cfs;
- The lowest average monthly flow for August is about 3,850 cfs, and the highest average monthly flow for August is about 42,000 cfs; and
- Although the lowest mean average monthly flow occurs in August, the lowest minimum average monthly flow occurs in September; September, October and November have lower minimum monthly flows than August.

The Susquehanna River low flows can occur at any time. Droughts occur less frequently, but may occur as an isolated year, or may occur as a series of consecutive years of low flows. The two worst droughts in the Susquehanna basin occurred during the period 1930-32 and 1963-66. The CBP has determined that the period 1959-68 was a dry period; the period 1969-78 was a wet period; and the period 1979-88 was an average period (Cerco and Cole, 1994a). Within the latter average flow period, the year 1984 was considered a wet year, 1985 was considered a dry year, and 1986 was considered a normal year, for modeling purposes (Cerco and Cole, 1994a).

2.2. Water Uses, Consumptive Uses and Diversions

Total water withdrawal in the Susquehanna basin is presently estimated at about 4,930 mgd (7,640 cfs).

Most of the water withdrawn is returned to the Susquehanna basin and, therefore, does not affect the amount of water reaching the bay. However, part of the water is used consumptively or diverted out of the basin. Consumptive uses and diversions reduce the amount of water reaching the bay, and therefore impact the bay.

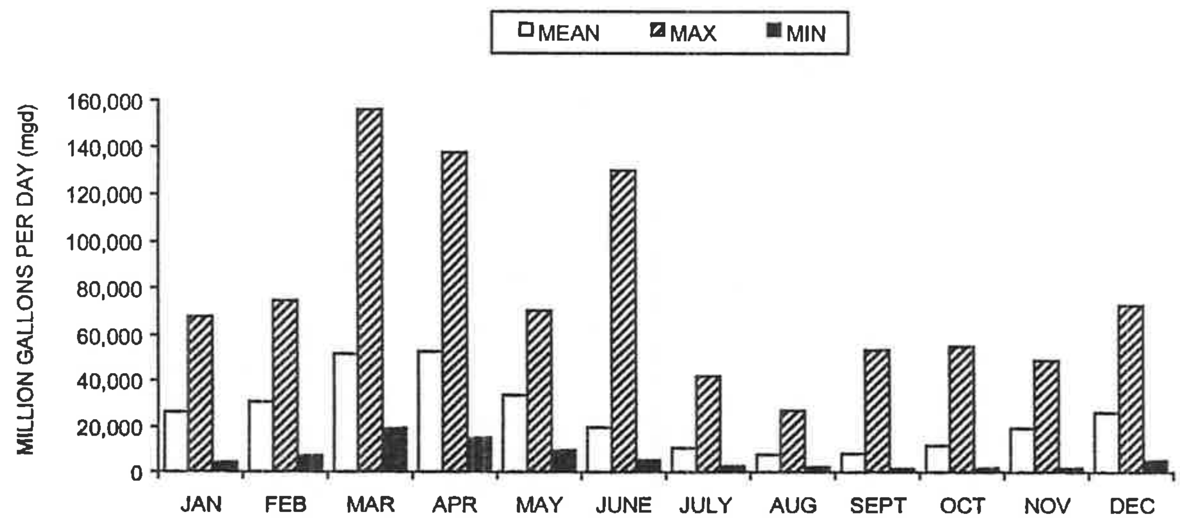

Figure 2.1. Susquehanna River Mean Maximum and Minimum Average Monthly Inflows to the Bay

Estimated existing consumptive uses and maximum diversions for each month of the year are shown in Figure 2.2. The consumptive uses are presently estimated as 256 mgd on an average annual basis. Consumptive uses are expected to increase by 152 mgd by the year 2020.

The existing maximum out-of-basin diversions are estimated as 388 mgd. For the purposes of this study, the diversions are assumed to be constant year-round. The estimated diversion for the city of Baltimore is 250 mgd, and the total permitted diversion for the city of Chester, Pa., is 60 mgd. These two diversions account for about 80 percent of the total allowable diversions from the Susquehanna basin.

Historically, Baltimore and Chester have not used the full amount of the allowable diversion. Chester is presently diverting about 36 mgd (annual average), and about 44 mgd on a peak day. The Chester diversion is expected to increase in the future, and there are proposals for other diversions pending.

Baltimore historically has diverted water only occasionally, averaging about 7 mgd annually, with peak day uses averaging about 100 mgd. The Baltimore withdrawal is expected to increase in the near future, as the service area is expanded to counties around Baltimore. The planned expansion will increase peak day withdrawals to 250 mgd. The city of Baltimore is presently conducting a study to determine the timing of their withdrawals.

2.3. Combination of Low Flows and Consumptive Uses and Diversions

While the effects of low flows and the effects of consumptive uses and diversions each need to be considered, the effect of consumptive uses and diversions on the bay will be greatest when the consumptive uses and diversions occur at times of low flow.

2.4. Hydrologic Relationships Between the Susquehanna River and the Chesapeake Bay

Drainage areas for the major tributaries of the Chesapeake Bay are shown in Table 2.1. The total drainage area of the bay is 64,100 square miles. The Susquehanna drainage comprises 43 percent of the total drainage area, and about 80 percent of the total drainage area upstream from the mouth of the Potomac River.

Table 2.1. Chesapeake Bay Drainage Areas
(Corps of Engineers, 1984c)

Stream Name	Drainage Area square miles
Susquehanna River	27,510
Western Shore above Potomac River	2,443
Potomac River	14,217
Rappahannock River	2,885
York River	2,857
James River	10,187
Eastern Shore	4,061
Total	**64,160**

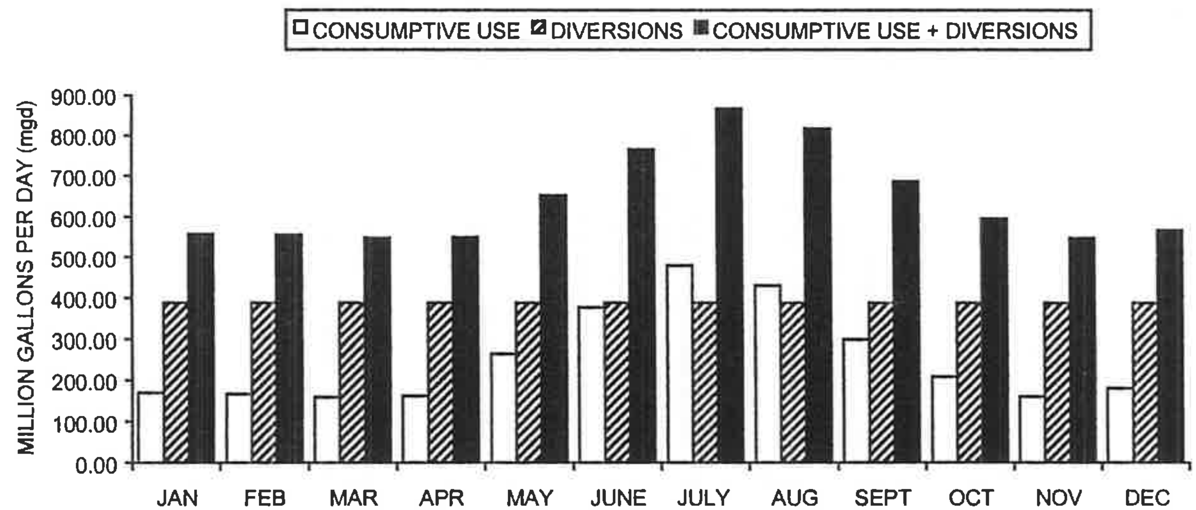

Figure 2.2. Consumptive Uses and Permitted Diversions By Month

The Susquehanna River provides about 50 percent of the total freshwater inflow to the Chesapeake Bay, and at least 80 percent of the total freshwater inflow above the mouth of the Potomac River. These numbers indicate that the Susquehanna River flows, whether high or low, can be expected to have a significant effect on the salinity distribution and on the processes that involve the mixing of fresh water and salt water. The salinity distribution affects the water quality and the living resources of the bay.

USGS data shows, during 1995, the Susquehanna River contributed only about 25 percent of the freshwater inflow to the bay as of the end of August. This demonstrates the Susquehanna River contribution to the bay is highly variable, and low flows in different tributaries to the bay do not coincide.

The effects of high flows on the water quality in the Chesapeake Bay have been reasonably well documented. The effects of the 1972 flood have been documented by Davis (1975). The floods in the spring of 1993 and 1994 adversely impacted the Chesapeake Bay (Blankenship, May 1993; September 1994) due to the large volume of freshwater inflow over an extended period of time.

The effects of low flows on the Chesapeake Bay are not well documented.

The sum of present consumptive uses and maximum diversions in the Susquehanna basin is about 2.5 percent of the average annual Susquehanna flow into the Chesapeake Bay. Existing consumptive uses and permitted diversions are not expected to significantly affect the average annual flows reaching the Chesapeake Bay.

The sum of present consumptive use and diversions in the Susquehanna basin is shown as a percentage of the estimated maximum, mean, and minimum monthly flows at the mouth of the Susquehanna River in Figure 2.3. The seasonal pattern of these percentages is important in determining the impact on the bay. The present consumptive uses and diversions are less than 10 percent of the minimum monthly flows for the months of February through May. Present consumptive use and diversions are a small percentage of the monthly average flow for the months of January through June. The present consumptive use and diversions amount to about 10 percent of the historical monthly mean flow during the months of July, August, and September, and more than 30 percent of the minimum monthly flow during the months of July through October. The conclusion is that present consumptive uses and diversions:

- Have little impact on flows reaching the bay during the months of February through May;
- Have little impact on flows greater than or equal to the average flow during the months of October through June;
- Have significant impact on flows less than or equal to the average flows during the months of July, August, and September; and
- Have a significant impact on low monthly flows during the months of June through January.

2.5. Effects of Hydropower Operations

Five hydropower facilities are located on the lower Susquehanna River (Table 1.2), and modify flow and water quality inputs to the bay. These power facilities generally operate in peak mode during low flow conditions. The most important facility, from the standpoint of the bay, is the Conowingo power plant, which is the furthermost downstream facility. This plant is located about three miles

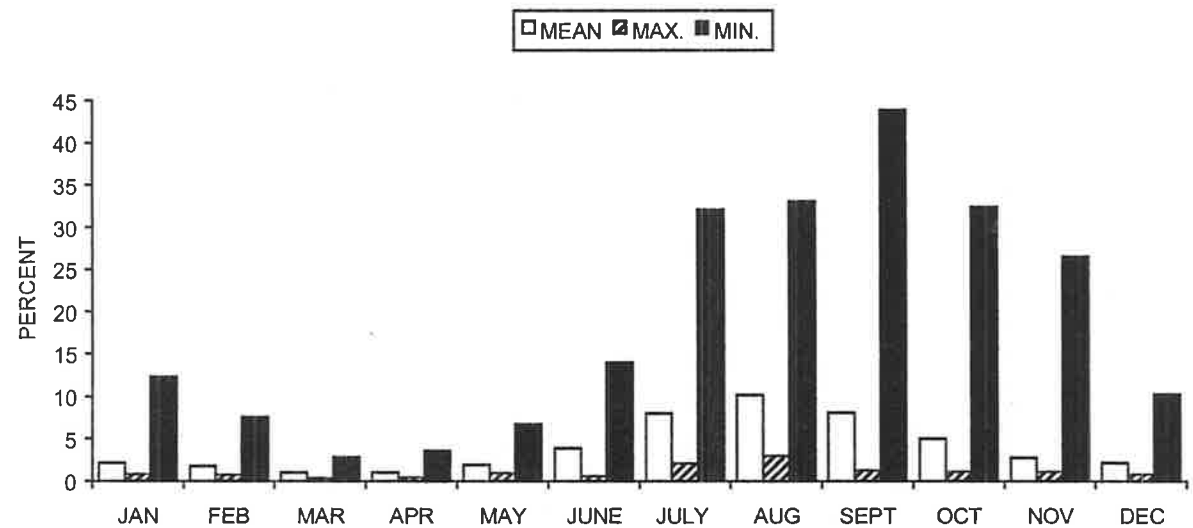

Figure 2.3. Consumptive Use and Permitted Diversions, Percent of Natural Flow

upstream from the head-of-tide. The Conowingo plant, essentially, controls the flow and pollutants reaching the bay on a short-term basis.

Conowingo operates with a daily and weekly peaking cycle when flows are less than about 45,000 cfs. Over a weekly time scale, the total river flow is released, but the flows will vary on hourly or daily time scales, depending on the amount of natural flow and the minimum releases required, according to a schedule developed by an interagency committee and approved by the State of Maryland. In general, Conowingo is required to make minimum releases at all times of the year. Recently, the State of Maryland and the Federal Energy Regulatory Commission (FERC) have agreed to allow Conowingo to shut down for intermittent periods when natural flow is less than 5,650 cfs during the October-November time period to facilitate passage of juvenile fish (R. St. Pierre, USFWS, oral communication).

The peaking operation will affect the amount of fresh water reaching the tidal freshwater zone, and may affect the water quality input to that zone on an hourly or daily basis. It is expected that those flow and quality fluctuations will be damped out over a short distance. The fluctuations in flows can be observed as far as Turkey Point (W. Boicourt, HPEL, oral communication), but are not expected to significantly affect salinities. Stevenson (letter to J.E. McSparran, August 7, 1995; oral communication with Roman Jesien) is concerned nutrient concentration fluctuations in the Susquehanna River flats may be caused by the peaking operation, and may adversely affect SAV.

3.0. LITERATURE REVIEW

3.1. Previous Studies of Chesapeake Bay

3.1.1. United States Environmental Protection Agency and the United States Army Corps of Engineers studies

Environmental problems of the Chesapeake Bay and its tributaries were investigated by the US EPA in a comprehensive study initiated in 1975. Final research findings and recommended remedial strategies were published by US EPA (CBP, 1983). The US EPA study was designed to determine the reasons for the decline of the Chesapeake Bay water quality and living resources, and addresses water quality issues. The US EPA report addresses issues related to flow only in the context of water quality.

The Corps of Engineers conducted a major study between 1967 and 1984. The purpose of the study (Corps of Engineers, 1984a, 1984b) was to conduct a comprehensive investigation of the entire bay region so that the most beneficial uses could be made of its resources. The major objectives of the study were:

- To assess the existing physical, chemical, biological, economic, and environmental conditions of the bay;
- To project the future water resource needs of the bay region to the year 2020; and
- To formulate and recommend solutions to priority problems using the hydraulic model.

The level of detail for the study was generally framework, which is equivalent to reconnaissance level in the current Corps lexicon (Noel Beegle, Corps of Engineers, oral communication).

The Corps of Engineers study included an Existing Conditions Report (Corps of Engineers, 1973), a Future Conditions Report (Corps of Engineers, 1978), and reports on two substudies conducted, one of which was the Low Freshwater Inflow Study. The Low Freshwater Inflow Study is the part of the overall study most relevant to this study, and will be discussed in depth.

The Chesapeake Bay Existing Conditions Report (Corps of Engineers, 1973) included a description of the existing physical, economical, recreational, social, biological, and environmental condition of the bay. This was the first published report to furnish a comprehensive survey of the entire bay region, and treat the Chesapeake Bay as a single entity (Corps of Engineers, 1984a).

The Chesapeake Bay Future Conditions Report (Corps of Engineers 1983a, 1984b) projected water resource needs to the year 2020. Problems and conflicts were identified that could result from uncontrolled growth and use of the bay's resources.

One of the most pressing problems identified was the effect of low flow and consumptive uses and diversions on the bay (Corps of Engineers, 1984a). While there have been previous studies related to this problem, there have been no previous comprehensive studies of the interrelationships among the bay's resources, problems, and solutions.

The Corps reports (1984a, 1984b) describe the physical characteristics and living resources of the Chesapeake Bay. There is a description of the bay's physical features, tidal characteristics, non-tidal circulation, salinity patterns, and biological productivity. The natural resources of the bay watershed also are described.

The Corps of Engineers study (1984a, 1984b) showed the effects of low flows and reductions of low flows on the Chesapeake Bay. The study evaluated effects of four flow scenarios on salinities in the Chesapeake Bay, and considered the effects of increased salinities resulting from natural drought and increased consumptive use on various uses of the Chesapeake Bay. The study showed significant effects of drought conditions and increased consumptive use on the living resources of the bay.

The Corps of Engineers study (1984b) evaluated several methods for minimizing these impacts, including storage requirements to maintain base drought salinities. However, there is insufficient information available in the study to allow determination of target flows. The need to establish target flows was recognized in that study, and also noted in subsequent studies by the Corps of Engineers. A recent study of storage reallocation was unsuccessful, because of the inability to define the benefits of increased low flows to the Chesapeake Bay.

3.1.2. Low Freshwater Inflow Study: Overview and process

The Corps of Engineers Low Freshwater Inflow Study is the most important previous study of the effect of low flows on the Chesapeake Bay.

The following problems and needs related to low flows were identified (Corps of Engineers 1984a, 1984b).

- Increased consumptive uses and diversions out of the watershed may increase salinity.
- Increased salinity may adversely affect the bay ecosystem; change the location of commercial fishing areas; and affect industries that require low salinity water for cooling and process water.
- Reduced flows may affect bay water quality, which will adversely affect the bay ecology, increase costs of water treatment, adversely affect commercial fisheries, adversely affect recreation uses, and increase corrosion of structures in the water.
- Increased navigation use may adversely affect the bay through channel maintenance and dredging projects in the bay.
- Potential future growth of noxious weeds (e.g., Eurasian milfoil, water chestnut, sea lettuce) may adversely affect navigation, recreation, fish and wildlife, water quality, and public health.

The study objectives were (Corps of Engineers, 1984a, 1984b):

- To provide better understanding of the relationship between salinities in the bay and the magnitude of freshwater inflow from its tributaries;
- To define the socio-economic and environmental impacts of both short- and long-term reductions of freshwater inflow; and
- To identify promising alternative solutions to the problems caused by reduction in freshwater inflow.

The study procedure included:

- Projection of water supply demands and consumptive uses to the year 2020;
- Determination of the effect of flows on salinity using a physical hydraulic model of the bay;
- Assessment of impacts on living resources;
- Assessment of effects on other uses such as water supply, commercial fishing, sport fishing, water contact recreation, and rare and endangered species; and
- Formulation and evaluation of plans to mitigate the effects of low flows on the bay.

The Corps of Engineers study was based on estimated withdrawals and projected year 2020 consumptive uses, which now are considered to be too high.

3.1.3. Models available

There are three models of the Chesapeake Bay that will be useful for the purpose of studying effects of low flows on the Chesapeake Bay. The first model has been developed by the Corps of Engineers for the CBP (Cerco and Cole, 1994a). The second is the model of the upper bay (above Annapolis) developed by Wang (1992). The third is a model of the upper bay also developed by the Corps of Engineers (Hsieh, Johnson, and Richards, 1993; Hsieh and Richards, in preparation).

3.1.3.1. Chesapeake Bay Program model

The CBP has developed two models: a hydrologic and water quality model of the watershed above and below the fall lines; and a three-dimensional hydrodynamic and water quality model of the entire Chesapeake Bay.

Detailed discussion of the watershed model is beyond the scope of the present study. The model is designed to simulate the loadings of various constituents reaching the bay. The watershed model will need to be used to generate below-fall-line inflows to the bay (L. Linker, CBP, oral communication) for use in evaluating effects of flows on the bay. The model also may need to be used to evaluate effects of variable flows and changes in flows on the water quality constituents reaching the bay.

The second model is a three-dimensional hydrodynamic and water quality model of the Chesapeake Bay developed by the Corps of Engineers for the CBP (Cerco and Cole, 1994a). The capabilities of the model include:

- Simulation of responses of water quality and sediment processes to point and nonpoint source control actions;
- Performance of short-term (annual) and long-term (decades) simulations;
- Determination of effect of spring runoff events on summer anoxia;
- Simulation of lateral water quality variations;
- Determination of bay response to area-specific management activities;
- Determination of response time of the bay to management actions;
- Evaluation of the frequency of critical water quality events; and
- Evaluation of historical changes in anoxia.

The characteristics of the hydrodynamic and water quality models are described by Cerco and Cole (1994a). There are separate coupled models for the water column and for the sediments. The hydrodynamic model computes three-dimensional velocities, surface elevation, vertical viscosity and diffusivity, temperature, salinity, and density. The water quality model includes 22 state variables, including salinity.

The hydrodynamic model operates on a 5-minute time step, but the 5-minute values were averaged to tidal cycle values. The water quality model operates on a tidal cycle (about 12 hr.) time step. The model realistically represents the following time scales: tidal average hydrodynamics; daily meteorology; biweekly fall-line loads; and monthly direct loads. The model is capable of representing processes at these time scales, but there is limited field data for comparison with model results. Therefore, the Modeling Subcommittee recommends that the existing model should not be used to represent time scales less than one month (L. Linker, CBP, oral communication).

The model considers four types of loads: fall-line loads; below fall-line loads; point source loads; and atmospheric loads. Carbon, nitrogen, and phosphorous were the only constituents treated as mass loads at the fall lines. Algae, dissolved oxygen, and silica inputs were treated using concentration boundary conditions.

Models were developed and calibrated for the James, York, Rappahannock, Potomac, and Patuxent Estuaries. There is no model for the Susquehanna River. However, the upper limit of the model is the head-of-tide on the Susquehanna River.

The hydrodynamic and water quality model described by Cerco and Cole (1994a) is being modified to provide increased spatial and temporal resolution in the main bay and the major tributaries other than the Susquehanna River. The following living resources components also will be added to the improved model (Science and Technical Advisory Committee, 1994):

SAV;
Phytoplankton;
Zooplankton; and
Benthos.

The hydrodynamic and water quality model is expected to be ready for the 1997 reevaluation of the CBP Goals. The availability of the living resources components is uncertain. Higher trophic levels, e.g., finfish, will not be added until after 1997 (R. Jesien, notes from Living Resources and Water Quality Modeling Workshop, July 12-13, 1995).

Model calibration results are presented by Cerco and Cole, (1994a, 1994b).

Cerco and Cole (1994a) note that operation of Conowingo Dam imposes high frequency, almost daily, fluctuations in the inflow to the bay that are especially noticeable during low flow periods. The effect of these fluctuations on the bay has not been studied, and they are probably damped out quickly in the bay (C. Cerco, oral communication).

The model calibration showed there are differences in sediment-water column nutrient fluxes in salt water, compared to fresh water. This implies low flows and changes in flows may affect sediment-water nutrient fluxes, and thus affect water quality and living resources. Higher nitrification and denitrification rates and phosphorous sorption coefficients were applied in fresh water, compared to salt water. Experiments by others showed ammonia release from sediment in fresh water was less than from the same sediment in sea water.

The watershed model provided daily fall-line loads for seven major tributaries. These daily loads were summarized to obtain biweekly loads for input to the water quality model.

The Susquehanna River annual loads are summarized in Table 3.1.

Table 3.1. Susquehanna River Annual Loads

Year	Carbon	Nitrogen	Phosphorous
	kg/d		
1984	787,811	240,516	11,760
1985	293,608	134,674	6,239
1986	416,029	172,379	8,229

Obviously, the loads are much less in the dry and average years (1985 and 1986), compared to the wet year (1984). Interestingly, the loads in the dry year are only slightly less than the loads in the average year.

For the purpose of evaluating water quality scenarios, hydrodynamics were run for each of three years: 1984, which is considered a typical wet year; 1985, which is considered a typical dry year; and 1986, which is considered a typical average year. Flow data for each model cell were averaged in zones to represent transport processes. There is a total of nine zones, and the first four zones are upstream of the Potomac River.

Model output data were aggregated by seasons as follows:

- Season 1, Julian day 1 to 60, which is the onset of the spring bloom (approximately January 1 to March 1);
- Season 2, Julian day 61 to 150, which is the duration of the spring bloom (approximately March 1 to May 31);
- Season 3, Julian day 151 to 270, beginning of the anoxic period to the fall overturn (approximately June 1 to end of September); and
- Season 4, Julian day 271 to 365 (approximately October 1 to the end of December).

Then a simulation was made for the 30-year period 1959-88. Based on the annual average Susquehanna River flows, the period was divided into wet, dry, and average years as follows:

1959-68, dry;
1969-78, wet; and
1979-88, average.

The hydrodynamics were determined for each period based on the corresponding calibration years. Point source loads were estimated by 5-year periods. Below fall-line loads were represented as a power function developed from output from the watershed model. Daily fall-line loads were computed from regression equations. Nitrogen loading was strongly correlated to hydrology. The nitrogen loading was low in dry years and high in wet years. Total phosphorous loading peaked in 1972, and then declined.

The model output shows the wet years had the lowest dissolved oxygen and the largest anoxic volume. The study indicates this is due to increased stratification, rather than to increased loading during the wet years. Dry years also exhibited more anoxia than average years, due to weak circulation. There is little correlation between anoxia and phosphorous load, but there is a correlation between anoxia and nitrogen loads from the previous year.

3.1.3.2. Other models

The Corps of Engineers (Wang, 1992) has developed a hydrodynamic model of the upper part of the bay, defined as the portion of the bay upstream from the Chesapeake Bay Bridge at Annapolis. The model was based on an earlier version of the CBP model, but includes three key refinements important to studies of the effects of low flows: it models a smaller area; it has finer spatial resolution in the area modeled; and it includes the C&D Canal as a time varying input. Although Wang (1992) describes the model as time varying, it appears that the flow inputs are constant. This model includes sediment transport, but does not include the sophisticated modeling of other water quality constituents found in the CBP model.

The Corps of Engineers (Hsieh, Johnson and Richards, 1993; Hsieh and Richards, in preparation) also has developed a model of the upper bay, which includes the Delaware Bay and the C&D Canal. Only the area upstream from Annapolis is modeled. This model also has higher resolution than the CBP model. It appears to be a refinement of the model used by Wang (1992), in that it includes finer resolution in the modeled area, and includes the C&D Canal as a time-varying input. This model includes salinity, but does not include any water quality constituents.

3.1.4. Other pertinent studies of the Chesapeake Bay

Schubel and Pritchard (1986) characterize the variation in flow pattern of the Susquehanna River, and describe the effects of these variations on the upper Chesapeake Bay, which is defined as the section of the bay from the mouth of the Susquehanna River to just above the mouth of the Potomac River. Variations in the Susquehanna River flows are closely coupled to: circulation; stratification; salinity; sediment transport and distribution; nutrient transport; and dissolved oxygen concentrations in the bay.

Wang (1992) used a three-dimensional numerical model of the upper bay to study the effects of Susquehanna River flows on the circulation in the bay and the dispersion of pollutants discharged from the dredge disposal area at Hart-Miller Island (HMI). The upper bay is defined for this study as the area upstream from the Chesapeake Bay Bridge at Annapolis, and includes the C&D Canal to the Delaware Bay end. The upstream boundary appears to be the head-of-tide on the Susquehanna River.

Smith and others (1992) and Harding and others (1992) summarize the current state of knowledge regarding the effect of flows on dissolved oxygen.

Stone and others (1994) summarize information on the distribution (spatial and temporal) and abundance of 61 fish and invertebrates in 22 mid-Atlantic estuaries. Funderburk and others (1991) and Batiuk and others (1992) summarize the current state of knowledge regarding habitat requirements of important species in the bay. Various other papers describe aspects of the ecosystem related to the response to flows.

Cooper (1995) has reconstructed a 2,000-year-old history of sedimentation, eutrophication, anoxia, and diatom community structure over time.

3.2. Chesapeake Bay Ecosystem

3.2.1. Introduction

To understand how Susquehanna River flows and how changes in those flows affect the ecosystem, it is necessary to understand the ecosystem, and to understand which species may be affected, and how those species may be affected. The purpose of this section is to summarize the literature regarding the ecosystem and its components and the habitat requirements of those species.

The Corps of Engineers study (1984e) includes a lot of detailed information regarding the living resources in the bay and their habitat requirements. An overview of the functioning of the ecosystem is provided. Also, each of the following major groups of flora and fauna in the bay are discussed:

- Phytoplankton;
- SAV;
- Emergent Aquatic Vegetation (EAV);
- Zooplankton;
- Benthic organisms;
- Fish; and
- Wildlife.

A discussion of each component, its importance to the bay, physical description, and factors that control abundance and distribution are included. The interactions between these groups are discussed with the help of trophic diagrams and species interactions matrices (Corps of Engineers, 1984e).

Table 3.2. shows a list of scientific and common names for important species.

Stone and others (1994) summarize information on the spatial and temporal distribution and the abundance of 61 fish and invertebrates in 22 mid-Atlantic estuaries. The information is organized based on three salinity zones: tidal fresh (0.0-0.5 ppt); mixing (0.5-25 ppt); and sea water (>25 ppt). Of the fish and invertebrate groups presented, 50 occurred in Chesapeake Bay, 19 of which occurred in the tidal freshwater portion.

Table 3.3. shows a summary of fish abundance in the Chesapeake Bay extracted from Stone and others (1994).

Table 3.2. Scientific and Common Names of Important Species

Submerged Aquatic Vegetation	
Ceratophyllum demersum	Hornwort
Chara sp.	Stoneworts
Elodea candensis	Common Elodea
Heteranthera dubia	Water stargrass (Mud plantain)
Hydrilla verticillata	Hydrilla
Myriophyllum spicatum	Water milfoil
Najas sp.	Waterweeds
Najas guadalupensis	Southern naiad
Najas flexis	Bushy pondweed
Najas minor	*Naiad* (no common name)
Naias gracillima	*Naiad* (no common name)
Potamogeton amplifolis	Bigleaf pondweed
Potamogeton amplifolis	Crisp pondweed
Potamogeton gramineus	Variable pondweed
Potamogeton nodosus	Longleaf pondweed
Potamogeton diversifolius	Sailseed pondweed
Potamogeton pectinatus	Sago pondweed
Potamogeton perfoliatus	Redhead grass
Ruppia maritima	Widgeon grass
Vallisneria americana	Wild celery
Zannichela palustris	Horned pondweed
Emergent Vegetation	
Pontederia cordata	Pickerel weed
Scirpus olneyii	Olney three-square
Spartina alterniflora	Marsh cordgrass
Spartina cynosuroides	Big cordgrass
Spartina pectinata	Meadow cordgrass
Spartina patens	Salt meadow grass
Zizannia aquatica	Wild rice
Fish	
Anguilla rostrata	American eel
Alosa aestivalis	Blueback herring
Cyprinodon variegatus	Sheepshead minnow
Fundulus sp.	Killifishes
Gobiosama sp.	Gobies
Ictalurus punctatus	Channel catfish
Syngnathus fascus	Northern pipefish
Trinectes maculatus	Hogchocker

Table 3.3. Fish Occurring in the Tidal Freshwater Portion of the Chesapeake Bay (Stone and others, 1994)

Species	Life Stages				
	Adult	Spawning	Juvenile	Larvae	Eggs
Spot			C		
Atlantic menhaden			HA		
American eel			C		
Atlantic croaker			R		
Silversides (sp)	A	A	A	A	A
White perch	A	A	A	A	A
Killifishes (sp)	A	A	A	A	A
Bay anchovy	A		HA		
Striped bass	C	C	C	C	C
Hogchocker	C		C	R	
Channel catfish	C	C	C	C	C
Alewife	C	C	C	C	C
Yellow perch	C	C	C	C	C
Blueback herring	C	C	C	C	C
Blue crab	C		C		C
North pipefish	R		R		
Sheepshead minnow	R	R	R	R	R
American shad	R	R	R	R	R
Gobies (sp)	R		R	A	
Total Number	15	10	19	12	10

HA - Highly abundant   A - Abundant   C - Common   R - Rare

Funderburk and others (1991) present information on the life histories, ecological roles, habitat requirements, and special concerns for 31 (14 aquatic) target species, including plants, shellfish, finfish, waterfowl and colonial wading birds, and raptors. The target species were chosen for their commercial, recreational, and ecological importance. It was intended that the target species would represent all major trophic levels and aquatic habitat types in the Chesapeake Bay. Summaries of the aquatic species are presented below.

Species presented in Stone and others (1994) and discussed in detail in Funderburk and others (1991), are shown in bold type in Table 3.3. Fishes not included in Funderburk and others (1991) as key Chesapeake Bay species, but are considered by Stone and others (1994) to be important in the bay and are common in abundance or greater are:

- American eel, which has a wide salinity tolerance;
- Three groups of forage fishes (silversides, killifishes, hogchocker), which also have wide salinity tolerance; and
- Channel catfish, which is considered a freshwater species.

The primary objective of the SAV technical synthesis (Batiuk and others, 1992) was to establish the quantitative levels of relevant water quality parameters necessary to support continued survival, propagation, and restoration of SAV. Secondary objectives were:

- To establish regional SAV distribution, density, and species diversity targets for the Chesapeake Bay and its tributaries;
- To document the baywide applicability of habitat requirements developed through the studies in the synthesis; and
- To assess the applicability of mid-channel monitoring data for evaluating the water quality in adjacent shallow water habitats.

Batiuk and others (1992) selected four study areas to develop specific relationships between SAV survival and water quality (e.g., Upper Chesapeake Bay, Potomac River from Washington, DC, Choptank River, York River). SAV distribution restoration targets, approached from a baywide and regional perspective, were produced through a series of geographical overlays delineating actual and potential SAV habitat. A tiered set of SAV distribution restoration targets for areas previously vegetated between 1971 and 1990 (Tier I), and for 1-meter (Tier II) and 2-meter (Tier III) water depths were established to provide management agencies with quantitative measures of progress in SAV restoration in response to the implementation of Chesapeake Bay restoration strategies.

3.2.2. Food chain description

The Corps of Engineers (1984e) describes the classic food chain model in which phytoplankton converts inorganic carbon to organic matter using solar energy. The phytoplankton is consumed by zooplankton, which, in turn, are consumed by fish. This model is still valid, although it has been found to be oversimplified. It has been determined there is a microbial loop that involves very small phytoplankton, protozoan grazers, and bacteria that fix carbon and consume and recycle minerals in parallel with the zooplankton. (Azam and others, 1983).

3.2.3. Phytoplankton

Phytoplankton (Corps of Engineers, 1984e) are important in the bay, because they fix energy from the sun into plant biomass (primary production), forming the basis of the estuarine food chain or web. Production by net plankton (>10 μm) is important in the spring and fall, when blooms of large diatoms occur. During summer, large dinoflagellates occasionally grow to form thick algal patches or blooms in bay surface waters. Blooms of certain dinoflagellate species discolor the water, forming red or brown tides.

Phytoplankton depend on nutrients such as nitrogen and phosphorous for growth. Nutrient concentrations are controlled by riverine input and wind mixing (Corps of Engineers, 1984e). During summer, nutrient availability is closely linked to recycling by grazers and bacteria (Glibert and others, 1992). Phytoplankton production is usually maximum in summer, even though nutrient concentrations are typically very low (Malone and others, 1988; Fisher and others 1992). Recent research (e.g., Malone and others, 1988; Fisher and others, 1992) provides extensive data on patterns of nutrient and productivity relationships. Sellner and others (1987), White and Roman (1992b), and Kemp and others (1992) provide a lot of detailed information regarding predator prey relationships and energy flows between the trophic levels.

Phytoplankton distribution is limited vertically in the bay, due to light attenuation with depth. The euphotic (lighted) zone is generally shallow in the northern bay and deeper in the south. Light usually penetrates deeper in the winter when plankton standing stocks are low.

Water temperature affects the type of phytoplankton species present and the physiological rates such as growth and respiration of individual cells.

3.2.4. Zooplankton

Zooplankton are important to ecosystem function because they are a link between phytoplankton production and fish. However, the link between primary (phytoplankton) production and zooplankton may be less direct and more temporally variable than previously thought, due to existence of the microbial loop (White and Roman, 1992a, 1992b).

The Corps of Engineers (1984e) classifies zooplankton as either carnivorous or herbivorous, but recent studies show that many species of crustacean zooplankton are omnivorous, and feed on both algae and other zooplankton. This fact greatly complicates efforts to model energy flow in aquatic systems (e.g., White and Roman, 1992a).

3.2.5. Submerged aquatic vegetation (SAV)

The ecological role of SAV is complex. SAV are important to the bay for a number of reasons, including habitat, substrate stabilization, food source, and source of detritus. The plants serve as a food source and a habitat and nursery area for many invertebrates and vertebrates. SAV also contributes to primary production, nutrient absorption, and dissolved oxygen production.

SAV are found in the fresh, oligohaline, mesohaline, and polyhaline waters of the Chesapeake Bay. Maximum depth of SAV is about 3 meters, although in clearer waters, SAV occur at greater depths.

A wealth of scientific studies from around the world has established the importance of light availability as the major environmental factor controlling SAV distribution, growth, and survival (Corps of Engineers, 1984e; Funderburk and others, 1991; Batiuk and others, 1992). Other controlling factors for SAV include salinity; water quality parameters such as herbicides; turbidity; nutrient enrichment; presence and density of epiphytes; water velocity; critical bed size; proximity to seed beds; and grazing by animals such as waterfowl and rays (Corps of Engineers, 1984e). Nutrients are important because they indirectly contribute to light attenuation by stimulating growth of phytoplankton within the water column, and epiphytes on SAV leaves.

Batiuk and others (1992) used the primary environmental factors associated with growth of SAV to formulate SAV habitat requirements: light attenuation coefficient; chlorophyll a; total suspended solids (TSS); dissolved inorganic nitrogen (DIN); and dissolved inorganic phosphorus (DIP). The following SAV habitat requirements are applied as median values over the April-October critical life period for the Tidal Fresh (<0.5 ppt), Oligohaline (0.5-5 ppt), and Mesohaline (5-18 ppt) salinity regimes. Polyhaline (>18 ppt) regime habitat requirements are applied as median values from combined March-May and September-November data. (See Table 3.4.)

Table 3.4. Habitat Requirements for Submerged Aquatic Vegetation

	Tidal Fresh	Oligohaline	Mesohaline	Polyhaline
Light attenuation coefficient (m^{-1})	<2	<2	<1.5	<1.5
TSS (mg/l)	<15	<15	<15	<15
Chl a	<15	<15	<15	<15
DIN (mg/l)	—	—	<0.15	<0.15
DIP (mg/l)	<0.02	0.02	<0.01	<0.02
Critical life period (month)	4-10	4-10	4-10	3-11

Although wild celery and sago pondweed are listed by Funderburk and others (1991) as occurring in the tidal fresh zone, Batiuk and others (1992) indicate these species are much more widely distributed in the bay, and occur in the oligohaline and mesohaline (5-18 ppt) portions.

Funderburk and others (1991) determined habitat requirements for five dominant species of SAV, representing four salinity regimes. A description of the range and distribution of the five species is presented for the following salinity zones:

- Tidal fresh-oligohaline—wild celery (*Vallisneria americana*) and sago pondweed (*Potamogeton pectinatus*);
- Mesohaline—sago pondweed, redhead grass (*P. perfoliatus*) and widgeon grass (*Ruppia maritima*); and
- Polyhaline—widgeon grass and eelgrass (*Zostera marina*).

SAV were more prevalent in the past than at present. The baywide decline of SAV has been attributed to reduced light availability from excessive water turbidity and biofouling of the plants caused by excessive loadings of nutrients and sediments from the watershed. The CBP is devoting a lot of effort to the restoration of SAV.

The 1990 SAV distribution data (Batiuk and others, 1992) indicate current SAV abundance (24,393 HA) is 53 percent of the Tier I target and only 10 percent of the Tier III target. These estimates provide a baseline for assessing the success of nutrient and sediment reduction strategies for the Chesapeake Bay.

Batiuk and others (1992) provide detailed regional information to identify species distribution. The plant distribution along the main stem of the bay from the mouth of the Susquehanna River (CB1) to the mouth of the bay (CB8) is summarized in Table 3.5. Historical and present SAV species occurrence in each of the 45 Chesapeake Bay Program segments (including 29 segments that occur from the mouth of the Susquehanna River to the Potomac River), along with references documenting the occurrence are provided. Figure 3.1 shows the location of these segments.

Table 3.5. Submerged Aquatic Vegetation Occurrence in Chesapeake Bay Segment
(Batiuk and others, 1992)

SAV Species (published salinity tolerance - ppt)	Occurrence in Chesapeake Bay Program Segment*									
	CB1	CB2	CB3	CB4	CB5	CB6	CB7	CB8	ET2	ET3
Ceratophyllum demersum (<6)	X	X	X	X					X	X
Chara sp	X	X	X						X	X
Elodea canadensis (<10)	X	X	X	X					X	X
Heteranthera dubia	X	X							X	X
Hydrilla verticillata (<6)	X	X	X						X	X
Myriophyllum spicatum (<10)	X	X	X	X					X	X
Najas sp.	X	X	X						X	X
Najas flexis	X									
Najas gracillima	X								X	X
Najas guadalupensis (<10)	X	X	X						X	X
Najas minor	X									
Potamogeton amplifolius	X									
Potamogeton crispus		X	X						X	X
Potamogeton gramineus	X									
Potamogeton nodosus	X									
Potamogeton diversifolius	X								X	
Potamogeton. pectinatus (<9)	X	X	X	X	X		X		X	X
Potamogeton perfoliatus (<20)	X	X	X	X					X	X
Ruppia maritima ("widest salinity tolerance of all SAV in CB")		X	X	X	X	X	X	X	X	X
Vallisneria americana (<13)	X	X	X	X					X	X
Zannichelia palustris (<20)	X	X	X	X	X		X		X	X
Zostera marina (10-35)			X	X	X	X	X	X		
Total Number of Species	19	14	14	9	4	2	4	2	16	15

* See Figure 3.1.

Salinity Regimes

Segment CB1: Tidal fresh (<0.5 ppt)
Segment CB2: Oligohaline (0.5-5 ppt)
Segment CB3: Mesohaline (5.0-18.0 ppt)
Segment CB4: Mesohaline
Segment CB5: Mesohaline
Segment CB6: Polyhaline (18.0-30.0 ppt)
Segment CB7: Polyhaline
Segment CB8: Polyhaline
Segment ET2: Oligohaline
Segment ET3: Oligohaline

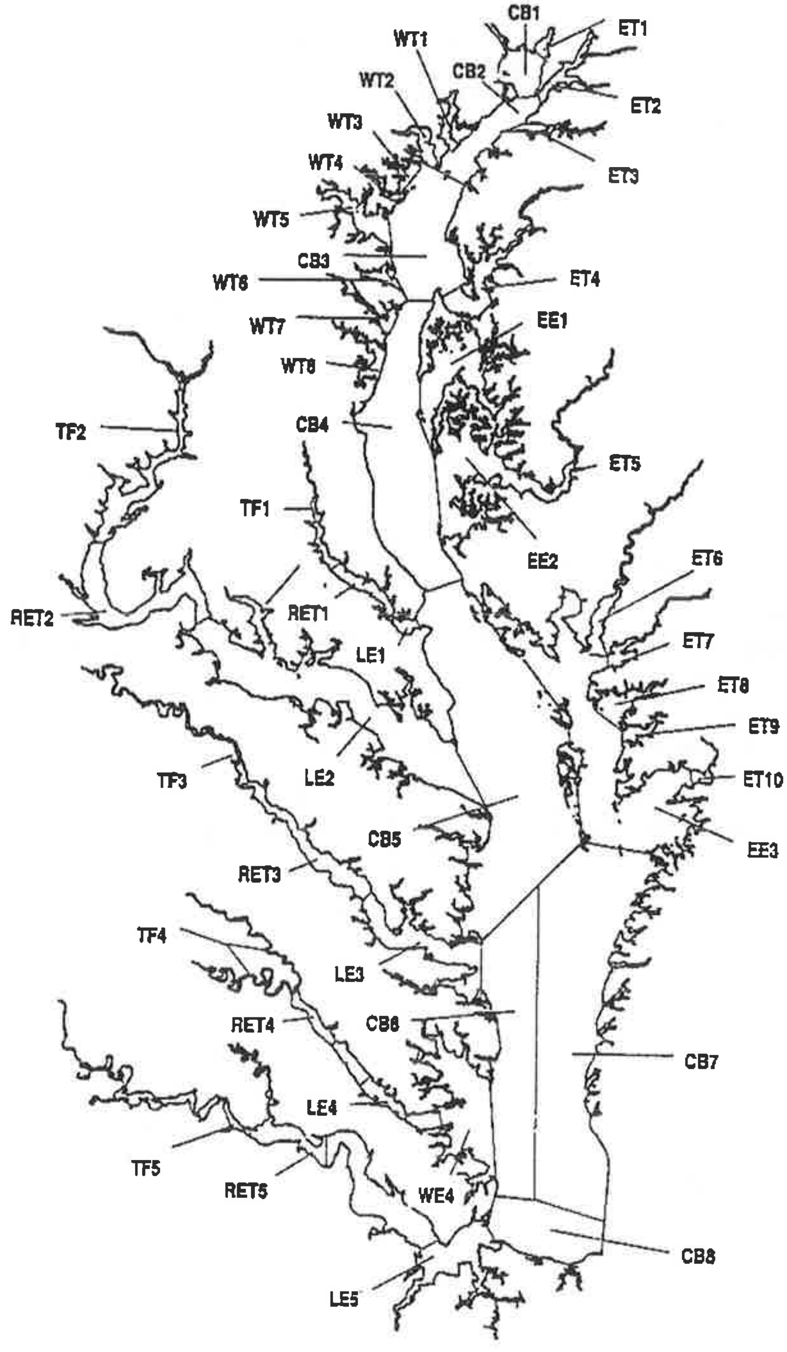

Figure 3.1. Map Showing Chesapeake Bay Program Segments (Batiuk and others, 1992)

3.2.6. Emergent aquatic vegetation (tidal wetlands)

The Chesapeake Bay tidal wetlands comprise one of the great tidal wetland systems in the United States (Corps of Engineers, 1984a). The dominant species of marsh plants (emergent aquatic vegetation or EAV) depends upon the level of salinity, and frequency and duration of flooding. Wetlands are divided into three categories, based on salinity (Corps of Engineers 1984e):

- Coastal Fresh Marsh (0 ppt to 5 ppt);
- Coastal Brackish Marsh (5 ppt to bay mouth); and
- Brackish irregularly flooded marsh (10 ppt to bay mouth).

EAVs are primary producers, and are used directly as food by a variety of organisms, although the freshwater marsh species are primarily used indirectly. The major pathway through which marsh-derived energy enters the estuarine trophic web is detritus-based food chains (Corps of Engineers, 1984e).

Wetlands are valued as habitat and food sources for a large number of aquatic and terrestrial organisms, as a source of detritus and nutrients, and in erosion control. Fish utilize the marsh for spawning, as a nursery, and/or as adult feeding area, depending on the species. Freshwater marshes tend to be a more important direct food source to waterfowl and animals such as muskrats than brackish water marshes (Corps of Engineers, 1984e).

Neither the Corps of Engineers (1984e), Funderburk and others (1991), nor Batiuk and others (1992) give data regarding the habitat requirements for EAV.

Marshes consist of many species of tall grasses and grass-like plants. The number of plant species in the coastal marshes declines as the salinity of the water increases (McCormick and Somes, 1981). Tiner (1987) presented a general scheme for mapping vegetation in the Chesapeake Bay region, and elsewhere, by the US Fish and Wildlife Service. The mapping scheme was summarized by Stevenson and Pendleton (1993) and consisted of the following representative plant species in coastal marshes:

Wetland Zone	Salinity Range (ppt)	Venice Salinity Class	Typical Species
High salinity	>5	Meso- and poly-haline	Marsh cordgrass Salt meadow grass
Low salinity	0.5-5.0	Oligohaline	Olney three-square Big cordgrass
Tidal fresh	<0.5	Tidal fresh	Pickerel weed Wild rice

In general, low and high salinity emergent plants have a wide salinity tolerance, but marsh cordgrass generally disappears at salinities less than about 2 ppt (Stribling, 1994).

3.2.7. Benthic organisms

Benthic organisms represent a major component of the estuarine ecosystem (Corps of Engineers, 1984e). Benthos are comprised of primarily invertebrate organisms that live in association with the substrate. Benthos have important ecological roles in: controlling water quality; nutrient recycling; trophic dynamics and energetics as an important food source; and affecting the flux of sediment and contaminants (CBP, 1993).

The Corps of Engineers (1984e) classified benthic organisms into five groups according to whether they live on or above the substrate (epifauna), or burrow into the substrate (infauna), and whether they feed on particles in the sediment (deposit feeders) or particles suspended in the water column (suspension feeders).

The distribution and abundance of benthic species are primarily controlled (CBP, 1993) by salinity, and secondarily by sediment type and dissolved oxygen concentration. In the polyhaline lower bay, infaunal deposit feeders are the dominant functional group, and suspension feeders are of secondary importance. In other parts of the bay, the dominant benthic organisms are the suspension feeders.

There are more than 300 macrobenthic infaunal species in the bay. Representative species include (CBP, 1993):

Tidal freshwater zone:	Midge larvae (*Chironimids, Chaoborids*) Oligachaete worms (*Limnodrilus*) Clams (*Corbicula*)
Transitional (0.5-5 ppt):	Polychaete worms (*Marenzelleria*) Clam (*Rangia*) Crustaceans (*Leptocheirus, Cyathura, Gammarus*)
Mesohaline (5-20 ppt):	Polychaete worms (*Marenzelleria, Heteromastus, Nereis, Streblospio, Eteone, Paraprionospio, Glycinde*) Clams (*Mya, Rangia, Macoma, Mulinia, Gemma*) Crustaceans (*Leptocheirus, Cyathura, Monoculodes*) Nemertean worm (*Carinoma*)
Polyhaline: (20-35 ppt)	Polychaete worms (*Asychis, Chaetopterus, Clymenella, Diopatra, Loimia, Macroclymene, Nephtys, Notomastus, Pseudeurythoe, Spiochaetopterus*) Clams (*Ensis, Mercenaria, Tellina*) Mud Shrimp (*Upogebia*) Anemone (*Cerianthus*)

Macrobenthic production in the Chesapeake Bay is moderate to high, but varies markedly among regions and habitats (CBP, 1993). Tidal fresh and transitional habitats are the most productive. The deep mesohaline portions of the main stem and Potomac River are least productive habitats, because of the annual occurrence of low dissolved oxygen in the summer.

In general, benthic community biomass, numbers of individuals, and species diversity increase with salinity from 0 to 30 ppt (CBP, 1993). However, three problem areas have been identified:

- The central main stem due to low dissolved oxygen;
- Portions of Baltimore harbor probably due to toxics in the sediments;
- Tidal freshwater regions possibly due to sensitivity to ephemeral runoff events.

The seasonal and spatial distribution of the benthic organisms is primarily mediated by physical factors of the environment (i.e., salinity, substrate type, dissolved oxygen, and temperature). Also, predators exert a controlling effect on the population densities of many organisms.

The most important benthic organisms are oysters, soft shell clam, hard clam and blue crab.

3.2.7.1. Oysters

Oysters are an important component of the ecosystem for two reasons (Funderburk and others, 1991): their ability to remove sediment by filtering water and producing pseudofeces; and their ability to stabilize soft shifting substrates and provide hard substrate for a variety of other organisms. Oyster reefs increase biodiversity in the area by providing habitat for a variety of organisms that, in turn, provide an energy source for higher trophic levels. Reefs with many live oysters seem to remain free of sediment for reasons not clear, but may include effects of water pumping and vigorous shell clapping by resident oysters. Oysters filter particles in the water from 0.2 μm, and selectively ingest 20-30 μm organisms.

Consumption of phytoplankton by benthic suspension feeders such as oysters has been considered an important removal mechanism for phytoplankton. Newell (1988) shows the abundance of American oysters in the bay has been so drastically reduced that they are no longer an important removal mechanism for phytoplankton. There is considerable effort underway to restore oyster populations.

One of the factors in the reduction of oyster populations has been the encroachment by the diseases MSX and dermo. Some people believe this increase in disease, and the subsequent decline of oyster populations, is at least partly related to freshwater inflow.

Adult oysters are immobile, but release eggs and sperm into the water where external fertilization occurs. Temperature increase stimulates natural spawning, which takes place from 18 to 20^{O}C and above. Spawning duration is poorly understood; apparently some oysters will release all their eggs at once, some will release periodically, and some will continually release over a long period. Fertilized eggs develop into ciliated veliger larvae within 24 hours, and larvae are free-swimming for 2 to 3 weeks before settlement.

Salinities less than 20 ppt seem to protect oysters from disease, and predation by snails and starfish is almost nonexistent at salinities greater than 5 ppt. Significant decrease in abundance is typically observed in salinity less than 5 ppt. The most deleterious salinities are low salinities associated with high freshwater inflow over a number of weeks. Salinities of 7.5 ppt or greater are necessary for gametogenesis and spawning to be even moderately successful. Optimum salinity and salinity range for development of oyster eggs into larvae are influenced by the salinity experienced by parents during gametogenesis. Oysters born in low salinity (<10 ppt) may depend on influx and settlement of nearly full-grown larvae from higher salinity areas. Larvae will grow well at about 12.5 ppt salinity and higher, whereas spat and adults should grow slowly from about 7 to 12 ppt, and normally from 12 ppt to 27 ppt. Mortality in oysters subjected to fresh water and low salinity typically increases with increasing temperature.

Funderburk and others (1991) present tables for habitat requirements for the various oyster life stages. The critical life period is June-August. Also, tables are presented that list the toxicity of selected compounds.

3.2.7.2. Soft shell clam

The soft shell clam occurs along the Atlantic coast in marine and intertidal estuarine waters to 200 miles (Funderburk and others, 1991). Also known as the steamer or mannose, the soft shell clam is found in the shallow, sandy, mesohaline portions of the Chesapeake Bay. The clam is restricted by salinity, sediment type, anoxia, and predation. Because of salinity requirements, the Patapsco River is the upstream limit in the bay. High salinity areas typically have more predators during longer periods of the year. Predators eradicate clams in soft sediments; therefore, only sandy areas contain clams. Population levels have declined since harvest began in 1953, and there has been no significant harvest in Virginia since 1968.

This organism comprises a major component of filter-feeding benthic fauna of the mesohaline Chesapeake Bay. The soft shell clam filter feeds on microscopic algae, flagellated cells and diatoms in the 5-50 μm range, which indicates it is important in removing particles from the water. Rejected particles are ejected as pseudofeces.

The soft shell clam spawns twice per year, during autumn and spring, at 12-15^{O}C. During spawning, gametes are expelled externally. Eggs develop into trochophore larvae within a day, and become veliger larvae in two more days. The veligers metamorphose into juvenile clams in about one to three weeks, and commercial size is reached within two years.

The lower summer salinity limit is 8 ppt, and there is apparently no upper salinity limit. There is no lower temperature limit in the Chesapeake Bay, but warm temperatures decrease tolerance to low salinity.

3.2.7.3. Hard clam

The hard clam also is known as the quahog or cherrystone clam. Within the Chesapeake Bay, the distribution is limited by salinity, and it is not abundant below 18 ppt (Funderburk and others, 1991). The life cycle is typical of other venerid bivalves and includes a pelagic larval phase and relatively sedentary benthic juvenile and adult stages. The hard clam is an important member of the suspension feeding infauna, which is important in processes such as benthic-pelagic-coupling; grazing of primary production; transfer of carbon and nitrogen to benthic food chains; through excretion, and rapid recycling of particulate nitrogen as ammonium. The major food for hard clams is planktonic microalgae.

Hard clam spawning takes place in May, when temperatures rise above 23^{O}C. Younger life stages have narrower temperature tolerances for survival than adults. Normal egg development takes place in 20 ppt to 35 ppt water (optimum 27 ppt), and high mortality occurs in low salinity water (<12 ppt).

Dissolved oxygen is not usually a limiting factor. All life stages exhibit marked tolerance to low dissolved oxygen The minimum dissolved oxygen required for normal development is about 0.5 mg/l. Heavy sediment loads have negative effects on growth and survival, although clams usually can tolerate ambient concentrations of suspended materials.

3.2.7.4. Blue crab

The original geographic distribution of the blue crab was from Nova Scotia to northern Argentina. Along the coasts of the United States, the blue crab is most abundant from Texas to New Jersey. After mating, mature females migrate to the lower bay in late summer and fall. Some females overwinter in the deeper basins of the lower bay, where they are joined in the spring by more females whose migration was interrupted by cold weather in the fall. Hatching occurs near the mouth of the bay in summer, and larvae are exported to the continental shelf where development occurs. The number of post-larvae that return to repopulate the bay each year is greatly influenced by weather conditions on the shelf during the planktonic larval period. Post-larvae that do make it back settle in the lower bay to metamorphose to the juvenile crab stage. Juvenile crabs spread throughout the bay and its tributaries during the fall and the following spring. SAV beds and shallow near-shore areas are important nursery, molting, and foraging habitats.

Larval and post-larval stages, while part of the plankton, are preyed upon by a variety of small fish and gelatinous zooplankton. After settlement, larvae are prey to a variety of fish and crustaceans that feed in the nursery areas. American eels are major predators on blue crabs, and striped bass also consume large numbers of juvenile crabs. Blue crabs can be scavengers or voracious predators that may be responsible for controlling populations of some bivalves and fish.

Blue crabs generally avoid areas with low dissolved oxygen (<33 percent saturation). Blue crabs inhabit all regions of the bay from the high salinity region at the mouth to tidal fresh waters, but are most abundant in waters of intermediate salinity. Larval blue crabs are much less tolerant of low salinity, and must be in salinities greater than 20 ppt to survive.

3.2.8. Finfish

Fish are important components of the Chesapeake Bay fauna (Corps of Engineers, 1984e). Fish inhabit nearly every habitat in the bay, and collectively consume at all trophic levels.

Fish population sizes are a basic concern in the Chesapeake Bay. Population size can be considered in terms of numbers (population size) or weight (biomass). Population growth of any particular species of fish depends on birthrate, survival rate, growth rate, immigration from outside the bay, emigration from the bay, natural death, loss as prey for other animals, and harvest. These factors, in turn, depend upon physical factors such as salinity, temperature, precipitation, water quality, availability of suitable spawning habitat, and biological factors such as crowding, competition pressure of predators, fishing pressure, and food availability.

There are 287 species of fish reported within the Chesapeake Bay drainage area below the fall-line. Most abundant are the grazers (menhaden), consumers of zooplankton (anchovies and silversides), and consumers of bottom invertebrates (hogchocker and white perch). Some are generalized predators (striped bass), and others live mainly on molluscs (drums, rays), fishes (bluefish), or crustaceans (oyster toadfish) (Corps of Engineers, 1984e).

The fish fauna may be divided into four ecological groups based upon salinity and migration patterns: diadromous species; estuarine species; marine species; and freshwater species (Corps of Engineers, 1984e).

The Corps of Engineers (1984e) selected the following as study species:

- Forage Fish: bay anchovy and silversides;
- Menhaden;
- Alosids: American shad and alewife;
- Demersal Fish: croaker and spot; and
- Pelagic fish: striped bass, white perch and yellow perch.

Funderburk and others (1991) include habitat requirements for the following fish species:

- Atlantic menhaden;
- Bay anchovy;
- American shad and hickory shad;
- Alewife and Blueback Herring;
- Spot;
- White Perch;
- Striped bass; and
- Yellow Perch.

The following is a summary of the life history, predator-prey relationships, and habitat information provided by Funderburk and others (1991).

3.2.8.1. Atlantic menhaden

Atlantic menhaden occur in coastal waters and estuaries of eastern United States and Canada, from Nova Scotia to Florida. The Chesapeake Bay is an important nursery for juvenile menhaden, where they occupy almost the entire bay and its tributaries, from above Baltimore to the mouth of the bay.

Menhaden spawn in coastal waters over most of the continental shelf. Larval menhaden enter the Chesapeake Bay in early summer and move into lower salinity waters in estuarine tributaries. Juvenile menhaden remain in the bay until fall, when most migrate southward, and winter offshore south of Cape Hatteras.

Larval menhaden graze on phytoplankton and suspended detritus. Juveniles and adults are primarily herbivores, but may feed on zooplankton. Menhaden are seasonally very important components of estuarine fish assemblages. Given the large numbers, individually high growth rates, filtering and feeding capacity, and seasonal movements, they consume and redistribute significant amounts of energy and materials on an annual basis.

Menhaden can withstand substantial variations in salinity ranging from almost fresh (3.5 ppt) to full strength sea water, and juveniles can withstand sudden shifts in salinity. Menhaden periodically suffer high mortalities during summer months in small coves when large numbers of fish exhaust the available oxygen supply. Also, rapid mortality occurred when temperatures rose above 33°C.

3.2.8.2. Bay anchovy

The bay anchovy is the most abundant fish in the Chesapeake Bay, and is reported to have the largest biomass of any estuarine fish found along the United States South Atlantic and Gulf Coasts. Bay anchovy occurs along the Atlantic Coast from Maine to the Yucatan Peninsula, including the Florida keys.

All life stages are found in the Chesapeake Bay. Spawning is widespread and occurs from May to September, with peak spawning in July. The species is a batch spawner; individual females spawn at least 50 times each season. Spawning occurs in water depth less than 20 m, in salinities from 0 ppt to 32 ppt. Peak spawning in the Chesapeake Bay apparently occurs at 13 ppt to 15 ppt and at average surface water temperatures from 26°C to 28°C. Eggs have been collected in most areas of the bay and its tributaries. The larval and juvenile stages may be completed in 2.5 months, and some Chesapeake Bay young-of-the-year may mature by late summer, although most apparently overwinter before maturing the following year. Adults live up to 3 years.

Bay anchovy is a major consumer of zooplankton, and is important in diets of commercially and recreationally important predatory fish, including striped bass, bluefish, weakfish, and summer flounder. The limiting dissolved oxygen for viability and productivity of bay anchovy in the Chesapeake Bay is less than 3 mg/l. Eggs have been found over the entire salinity range from 0 ppt to 32 ppt, but the highest densities of eggs were found at salinities in the range from 13 ppt to 15 ppt in the upper Chesapeake Bay, and at 17 ppt to 23 ppt in the polyhaline lower bay. Bay anchovies often live in turbid water, and may be attracted to high turbidities. Suspended-sediment concentrations greater than 250 mg/l cause a reduction in food ingestion by copepods, a primary food of bay anchovy. Eggs have been collected from 9°C to 31°C, and the preferred temperature appears to be 13°C to 30°C. Adults tolerate a wide range of temperatures in all seasons in the Chesapeake Bay. Structure and substrate do not appear to be important for the pelagic bay anchovy, as bay anchovies have been collected over a variety of substrates, including sand, mud, sea grass, oyster shell, and hard bottoms of beaches in surf zones.

3.2.8.3. American shad and hickory shad

American shad range from Labrador to the St. Johns River, Florida. Hickory shad have historically occurred along the east coast of North America from the Bay of Fundy, Canada, to the Tomoka River, Florida; but now the specie is probably restricted to waters from New York southward, and is viewed as a more southern species than American shad.

After spawning, hickory shad return to ocean waters, and there is evidence that their distribution and movements are similar to American shad. Collections of juvenile hickory shad are sparse, but it is believed most young fish leave water and brackish habitats in early summer, and migrate to estuarine nursery areas at an earlier age than other anadromous alosids. The egg, larvae, and early juvenile life history stages are critical for both American shad and hickory shad. The critical time period is between April and July.

Both species live most of their life at sea, and spawn in fresh water. Spawning activity for American shad occurs at approximately 16-19°C in fresh water, in areas dominated by extensive flats, over sand or rocky shallows, and mouths of larger tributary streams. Hickory shad ascend spawning rivers in early spring, when water temperatures reach 12-13^{O}C. Peak spawning occurs when temperatures reach 15-19^{O}C. In the Chesapeake Bay, hickory shad spawning runs typically precede American shad runs. The spawning period for these species begins in mid-March and extends into mid-April.

Specific hickory shad spawning sites in the Chesapeake Bay are not well documented. Apparently, hickory shad spawn near Conowingo Dam, as evidenced by numbers collected at the fish lift. During the early 1970s, numbers of hickory shad were greater than American shad in the fish lift, but decreased drastically in 1975, and have remained depressed until 1988, at which time numbers have been increasing annually at a very low rate, about 10 percent of American shad numbers (Susquehanna River Anadromous Fish Restoration Report, 1992). Deer Creek is another spawning area (R. St. Pierre, U.S. Fish & Wildlife Service, oral communication).

American shad eggs are semi-demersal and pelagic; the optimum hatching conditions are 17^{O}C and 7.5 ppt salinity. Juveniles complete metamorphosis in 21 to 28 days, and subadults leave the bay by late fall. Hickory shad populations are at very low levels, and very little is known of their life history, but is presumed to be similar to American shad. Hickory shad eggs are slightly adhesive and semi-demersal in slow-moving water.

Juvenile American shad consume plankton. Adults do not feed extensively (if at all) during freshwater spawning migration. Eggs are found in 0 ppt to 1 ppt salinity, and can withstand transfers from fresh water to 5 ppt to 30 ppt salinity. However, 100 percent mortality was observed when fish were taken from 30 ppt to fresh water. Juveniles appear to be very tolerant of a wide range of salinities, and this tolerance begins in early life. Dissolved oxygen levels are critical, as dissolved oxygen concentrations less than 3.0 mg/l have been observed to block adult and juvenile migrations. Suspended-sediment concentrations exceeding 1,000 mg/l did not affect hatching success; however, concentrations of 100 mg/l reduced larval survival. The optimum current velocity for larvae and juvenile American shad is in the range from 6 to 30 cm/s. American Shad spawning habitats and egg incubation success was maximized at water velocities ranging from 30 cm/s to 90 cm/s.

3.2.8.4. Alewife and blueback herring

The distribution of alewife and blueback herring is similar, although blueback herring occur further south than alewife. Alewife range from Newfoundland to South Carolina; blueback herring range from Nova Scotia to northern Florida. Alewife spawning occurs in natal streams at about 10-18^{O}C (March through May). Blueback herring spawn later than alewife, and the optimum spawning activity occurs at about 21^{O}C to 25^{O}C. Alewife favor slow-moving sections of streams or coastal ponds and lakes for spawning, whereas blueback herring prefers spawning areas where flows are relatively swift, and tend to avoid low-velocity areas. Spawning activity for both species occurs from 0 ppt to 6 ppt salinity.

Juvenile alewife and blueback herring remain in tidal freshwater areas in spring and early summer. As water temperature decreases, alewives move downstream, then tend to move to brackish areas about one month earlier than blueback herring. Some remain in deep estuarine waters through the winter. Downstream migration occurs near the bottom during the day and at the surface at night.

Subadult and adult alewife and blueback herring are typically found in southern New Jersey waters between December and April. Juvenile alewife and blueback herring consume plankton. Adults do not feed extensively (if at all) during upstream spawning migration. Alewife juveniles often coexist with juvenile blueback herring and shad in nursery areas.

Decreasing herring stocks coincided with increasing gizzard shad populations above Conowingo Dam. Alewife are excellent ion regulators, and are quite tolerant of wide salinity changes.

3.2.8.5. Spot

Spot range from Massachusetts Bay, south along the Atlantic Ocean, to Florida and into the Gulf of Mexico, over the depth range from less than 1 m to 130 m. The specie occurs throughout all tributaries and the main stem of the Chesapeake Bay, and over all depths and substrates. Adults are found in the Chesapeake Bay from April through late fall. Decreasing temperatures trigger seaward migration.

Spawning occurs in late September through May, with peak activity in December and January, in moderately-deep areas along the western Atlantic continental shelf from North Carolina to Florida. In the Chesapeake Bay, larvae have been collected as early as April in the southern portion of the bay. Fish reach sexual maturity near the end of their second year, or early in their third year.

Throughout most of their range, spot repeatedly are among the most abundant demersal fish species during late spring through late fall. Their high densities, along with their high rate of growth, suggest spot have a large impact on their prey populations, and are an important food source for other species. Spot have been found over a wide range of salinities from freshwater up to 60 ppt. They also have been found in areas of low dissolved oxygen concentrations, less than 2 mg/l, but are most abundant when dissolved oxygen exceeds 4 mg/l. Spot are extremely tolerant of high levels of suspended and deposited sediments. This may be related to feeding behavior, as spot have shown a preference for muddy sediments, and are well-adapted for feeding in such habitats.

3.2.8.6. White perch

White perch are endemic in Atlantic coastal waters from Nova Scotia to South Carolina, and are most abundant between the Hudson River and the Chesapeake Bay. White perch migrate from lower estuaries to fresh water to spawn. Chesapeake Bay white perch spend their entire lives in the bay, migrating up into tidal fresh and slightly brackish waters of the tributaries each spring to spawn. Adult white perch overwinter in the downstream portion of tributaries and in deeper saline waters throughout the bay, usually at depths greater than 6 m to 12 m, in areas with salinities in the teens and water temperatures between 0 and 5^{O}C.

Spawning takes place from March through early June, with peak activity occurring in April and May. The optimal spawning temperature range is 12 to 14^{O}C. Spawning occurs in riverine and tidal fresh water, as well as brackish water up to about 4.2 ppt salinity. The optimal salinity range is between 0 and 1.5 ppt. Most spawning occurs in fresh water over fine gravel or sand. Nursery areas are the inshore zones of estuaries and creeks, somewhat downstream of the spawning areas.

Larval white perch consume zooplankton, and are prey for juvenile white perch and other species. Subadult and adult white perch are benthic predators. The minimum dissolved oxygen is 5.0 mg/l for all life stages The optimal salinity range for eggs is 0 to 2 ppt. The optimal salinity range for larvae and juveniles is less than 1.5 ppt and less than 3 ppt, respectively, although both life stages have been found in salinities as high as 13 ppt. Adults have been found in salinities between 5 ppt and 18 ppt. Optimal hatching occurs at 12^{O}C to 14^{O}C. The temperature preference for adults depends on acclimation temperatures and latitude of the population. Suspended-sediment concentrations in the range between 100 mg/l and 500 mg/l delay hatch of white perch eggs by 4 to 6 hours, and continuous exposure of white perch eggs to suspended-sediment concentrations of 1,000 mg/l reduces hatching success. Deposition of sediment on white perch eggs appears to be more important than suspended-sediment concentration. Covering white perch eggs with a 1.1 mm sediment layer resulted in 100 percent mortality. Larvae are more sensitive to suspended sediment than adults. White perch prefer areas with mud, sand, and clay bottoms with little or no cover. Young-of-the-year prefer inshore zones of estuaries and creeks, generally somewhat downstream from spawning areas. White perch overwinter in deeper channels, usually at depths between 12 m and 18 m.

3.2.8.7. Striped bass

Striped bass range from the St. Lawrence River in Canada to the St. Johns River, Florida, and along the Gulf of Mexico coast. The principle spawning and nursery areas are the Chesapeake Bay, Hudson River, and Roanoke River. Seasonal movement and location of the fish are related to age, sex, degree of maturity, and natal river. Generally, sexually immature fish remain in the natal estuary until about age 2. After age 2, the majority of females, and some males, leave the estuary and undertake seasonal coastal migrations. Overwintering occurs in deeper water of the Chesapeake Bay and its tributaries. Striped bass that overwinter in Maryland waters of the Chesapeake Bay are smaller than 22 inches (559 mm). Fish overwintering in tributaries tend to be smaller than fish overwintering in the main stem.

Spawning takes place between early to mid-April and the end of May, primarily in the tidal freshwater areas, just above the salt wedge. Spawning activity is triggered by a rise in water temperatures (11-24^{O}C). The optimal spawning temperature, in the Chesapeake Bay, is between 14^{O}C and 19^{O}C. Larvae move in-shore, and spend the summer and early fall in shoal waters less than 6 feet deep. As juveniles grow, they move progressively down river into higher salinity areas.

Striped bass larvae feed on copepods and cladocerans. Juveniles are flexible in food habits and consume insect larvae, polychaetes, and larval fish. Adults typically eat other fish. Low salinities enhanced survival of striped bass eggs in hatcheries, although most striped bass spawning occurs in tidal fresh water. Low salinities increase growth and survival of larvae. Optimal salinities for growth and survival of larvae ranged from 3 ppt to 7 ppt. Concentrations of suspended sediment greater than 1,000 mg/l reduced hatching of striped bass eggs. Temperature less than 12^{O}C is considered lethal to striped bass eggs and larvae. Optimal temperatures for larvae range from 18^{O}C to 21^{O}C.

3.2.8.8. Yellow perch

Yellow perch range from South Carolina north to Nova Scotia, west through the southern Hudson Bay region, and south to the northern half of the Mississippi River drainage. In Maryland, yellow perch historically have been reported in all tributaries to the Chesapeake Bay and the Youghiogheny River. There has been an absence of spawning in several lower western shore Chesapeake Bay tributaries over the past several years.

Adults migrate from downstream stretches of tidal waters to spawning areas in less saline upper reaches in mid-February though March. Spawning generally takes place in mid-March. Optimal spawning temperature is 7.8^{O}C to 12.2^{O}C. Yellow perch remain in their natal river systems. Downstream dispersal of juveniles also occurs. Egg deposition occurs in upstream areas, generally in places with large amounts of organic debris.

Larvae consume copepods and cladocerans. Adults consume fish and insects. Larvae can tolerate temperatures in the range 10^{O}C to 30^{O}C. For adults, the physiologically optimal temperature is 24.7^{O}C. For adults, the minimum suitable dissolved oxygen is 5 mg/l, and lethal dissolved oxygen is 0.2 mg/l in winter and 1.5 mg/l during summer. The optimal salinity range for reproduction is between 0 ppt and 2 ppt. For juveniles, the salinity tolerance ranges from 0 ppt to 13 ppt salinity. Suspended-sediment concentrations greater than 1,000 mg/l may affect hatching success. Fry generally prefer current velocities less than 2.5 cm/s, and adults prefer velocities greater than 5 cm/s. Current velocities exceeding 25 cm/s can destroy egg strands.

3.2.9. Wildlife

Marine birds, waterfowl, amphibians, reptiles, and mammals are included in this category (Corps of Engineers, 1984e). These animals are all important to the productivity and ecological balance of the bay, serving as both predator and prey. The distribution and abundance of the wildlife of the Chesapeake Bay are generally a function of available food, cover, and breeding areas. SAV and EAV serve as food, cover, and/or breeding areas to a variety of organisms up and down the food web, and thus are a controlling factor in the distribution and abundance of wildlife. For example, the distribution of the canvasback duck is dependent on the Baltic clam and the SAV wild celery. Wildlife study species consist of three duck species: mallard, black duck, and canvasback (Corps of Engineers, 1984b).

3.3. Effects of Susquehanna River Flows on Chesapeake Bay

3.3.1. Hydrologic relationships

Hydrologic relationships between the Susquehanna River and the Chesapeake Bay are described in section 2.4.

3.3.2. Effects of Susquehanna River flows on circulation and salinity

Clark (1981) states the importance of both the quantity and quality of freshwater inflows in maintaining the integrity of estuaries.

Klein and others (1981)

- Describe the importance of the quantity and timing of freshwater inflow in determining the circulation patterns and distribution of salinity in the Chesapeake Bay.
- Note the importance of salinity to the living resources of the bay.
- Note the importance of circulation in determining the water quality distribution and the resulting exposure of organisms to toxics and nutrients.

The effects of low flows and changes in low flows on circulation and salinity are described by the Corps of Engineers (1984b), by Schubel and Pritchard (1986), and Wang (1992).

The Corps of Engineers (1984b) and Schubel and Pritchard (1986) note the existence of a salt front at the transition from river to estuary. This transition zone also is a zone of maximum turbidity, which has a high concentration of fine-grained suspended sediments. These suspended sediments limit the depth of light penetration and, therefore, the amount of photosynthesis in that transition zone. The location of this salt front depends on Susquehanna River flows. The salt front marks the boundary of the two-layer circulation typical of most of the bay.

Schubel and Pritchard (1986) show the salinity distribution for the following three periods with 10-day average flows as shown:

- April 11, 1968 1.5 times long-term average flow
- June 28, 1969 0.8 times long-term average flow
- October 24, 1968 0.2 times long-term average flow

Their study shows significant changes in the salinity distribution for these periods. The zone of maximum salinity gradient shifts about 40 km between the first two cases, but shifts only about 10 km between the second and third cases. For the first case, the upstream limit of the zone of maximum salinity gradient is about the Newtown-Hanesville area. For the second case, the upstream limit of the zone of maximum salinity gradient is about the mouth of the Sassafras River. The salinity gradient also is more compressed for the latter two cases. The salinities at Turkey Point increase from 0 ppt for the first case to 2 ppt (surface) and 5 ppt (bottom) for the second case. The salinities at the same point increase to about 4 ppt at all depths for the third case.

The authors also show the position of 1 ppt and 5 ppt salinities for the period June 10 to September 30, 1972, which shows a rapid recovery of normal salinity after the Agnes flood.

The Corps of Engineers (1984b) investigated four scenarios using a physical model (Corps of Engineers, 1984f).

- Base Average: Long-term average freshwater inflow to the bay;
- Base Drought: Freshwater inflows that occurred in the years 1963-66;
- Future Average: Base average reduced by incremental consumptive losses expected between 1965 and 2020; and
- Future Drought: Base drought freshwater inflows reduced by incremental consumptive losses expected between 1965 and 2020.

The Corps (1984a, 1984b) reports summarize salinity changes in the entire bay for these scenarios. In general, consumptive uses cause an increase in salinities in the bay, but the magnitude and time variation in salinity depend on location and hydrodynamic conditions. The salinities during the base drought scenario are as much as 5 ppt higher than long-term average salinity. Salinities increased by a maximum of 2 ppt to 4 ppt due to consumptive uses of water. Isohaline maps show increased penetration of higher salinities for the latter three scenarios. The lines of equal salinity are located much further upstream in the futures test, than for the base test.

The salinities at three locations most impacted by the Susquehanna River flows for each of the four scenarios are summarized in Table 3.6. The locations are: the mouth of the Susquehanna

River; Spesutie Island/Turkey Point; and just upstream from the mouth of the Potomac River. The table shows the average seasonal salinity for each scenario at the surface and at depth at each location. These values were read from the isohaline maps prepared from the model output (Corps of Engineers, 1984d) and, therefore, the accuracy and resolution are limited. The data in this table are plotted in Figures 3.3. through 3.5.

The salinity data show that at the mouth of the Susquehanna River:

- Surface salinities are less than or equal to 0.5 ppt (500 mg/l) for all seasons and all scenarios;
- Surface salinities in a future drought are about 0.5 ppt during the summer and fall;
- For some scenarios, surface salinities may exceed the drinking water standard (0.25 ppt);
- Salinities at 10-ft depth are less than or equal to 0.5 ppt for base and future average conditions and all seasons;
- Salinities at 10-ft depth are greater than 1.0 ppt for base drought and future drought scenarios and all seasons; and
- Salinities at 10-ft depth reach 5-6 ppt for some base drought and future drought scenarios and seasons.

The salinity data at Spesutie Island/Turkey Point show:

- Base Average and Future Average surface salinities are less than or equal to 0.5 ppt for spring, summer and winter, and about 1 ppt for fall.
- Base Drought and Future Drought surface salinities increase to between 1.0 ppt and 5.0 ppt during summer and fall.

The salinity data at the mouth of the Potomac River show:

- Surface salinities are in the range 12 ppt to 22 ppt, depending on scenario and season;
- Base Average surface salinities increase from 12 ppt to 16 ppt between seasons;
- Base Drought salinities increase from 15 ppt to 20 ppt across seasons;
- Future Drought salinities increase from 17 ppt to 22 ppt across season;
- Salinities increase about 3 ppt between base average and base drought;
- Maximum salinities occur during fall and winter under base drought and future drought scenarios;
- Base and Future Drought salinities are constant or increase between summer and fall.
- Salinities increase across all scenarios within season; and
- Salinities increase across season from summer to fall, but decline slightly in winter.

These data show that the effect of Susquehanna River flows on salinity extends to the mouth of the Potomac. The data also appear to show that the effects of salinity changes need to be considered in all seasons, with the possible exception of spring.

Table 3.6. Comparison of Salinities at Selected Locations
(Corps of Engineers, 1984d)

Location	Base Average	Future Average	Base Drought	Future Drought
Spring Surface				
Mouth of Susquehanna River	<0.5	<0.5	<0.5	<0.5
Spesutie Island/Turkey Point	<0.5	<0.5	<0.5	<0.5
Upstream Mouth of Potomac River	12	13	15	17
Summer Surface				
Mouth of Susquehanna River	<0.5	<0.5	<0.5	0.5
Spesutie Island/Turkey Point	0.5	0.5	2	5
Upstream Mouth of Potomac River	14	15	17	18
Fall Surface				
Mouth of Susquehanna River	<0.5	<0.5	0.5	0.5
Spesutie Island/Turkey Point	1	1	4	5
Upstream Mouth of Potomac River	17	19	20	21
Winter Surface				
Mouth of Susquehanna River	<0.5	<0.5	<0.5	<0.5
Spesutie Island/Turkey Point	0.5	0.5	1	2
Upstream Mouth of Potomac River	16	17	20	22
Spring 10-ft depth				
Mouth of Susquehanna River	<0.5	<0.5	<0.5	<0.5
Spesutie Island/Turkey Point	<0.5	<0.5	0.5	0.5
Upstream Mouth of Potomac River	13	14	17	18
Summer 10 ft depth				
Mouth of Susquehanna River	<0.5	<0.5	<3	<3
Spesutie Island/Turkey Point	0.5	1	3	5
Upstream Mouth of Potomac River	15	16	18	19
Fall 10-ft depth				
Mouth of Susquehanna River	<2	<3	<5.0	<7.0
Spesutie Island/Turkey Point	2	2	5	7
Upstream Mouth of Potomac River	18	19	20	22
Winter 10-ft depth				
Mouth of Susquehanna River	<1	<1	<1	<1.0
Spesutie Island/Turkey Point	1	1	1	3
Upstream Mouth of Potomac River	17	18	21	22
Spring 20-ft depth				
Mouth of Susquehanna River				
Spesutie Island/Turkey Point				
Upstream Mouth of Potomac River	15	17	19	20
Summer 20 ft depth				
Mouth of Susquehanna River				
Spesutie Island/Turkey Point				
Upstream Mouth of Potomac River	16	18	19	20
Fall 20-ft depth				
Mouth of Susquehanna River				
Spesutie Island/Turkey Point				
Upstream Mouth of Potomac River	19	21	21	23
Winter 20-ft depth				
Mouth of Susquehanna River				
Spesutie Island/Turkey Point				
Upstream Mouth of Potomac River	19	20	21	23

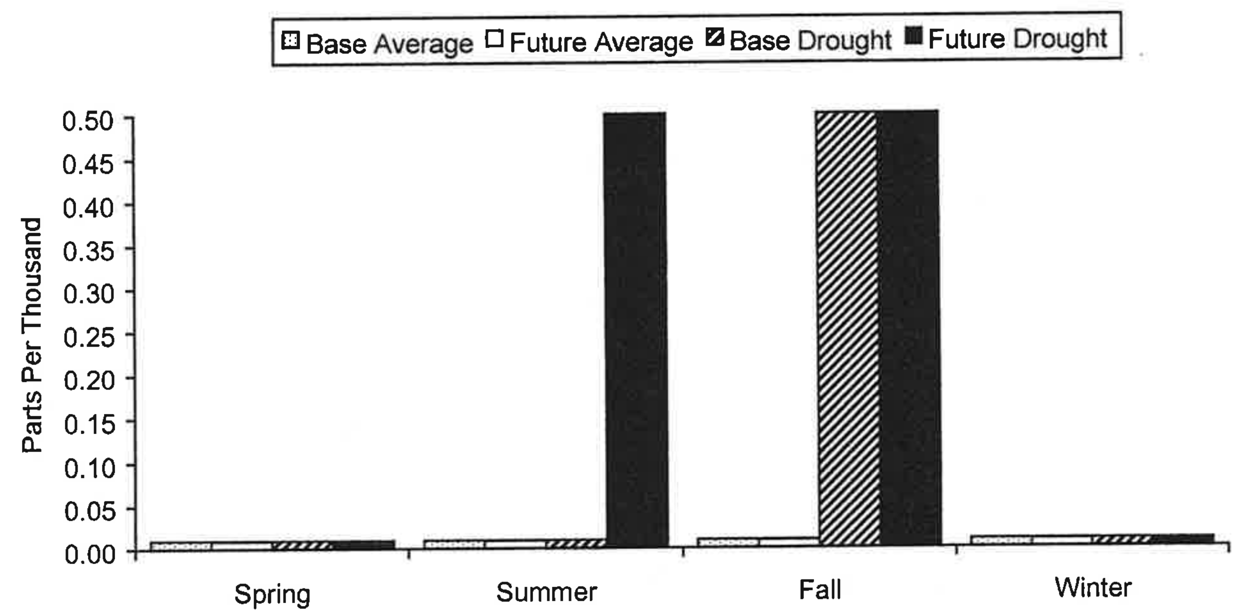

Figure 3.2. Surface Salinity at Mouth of Susquehanna River

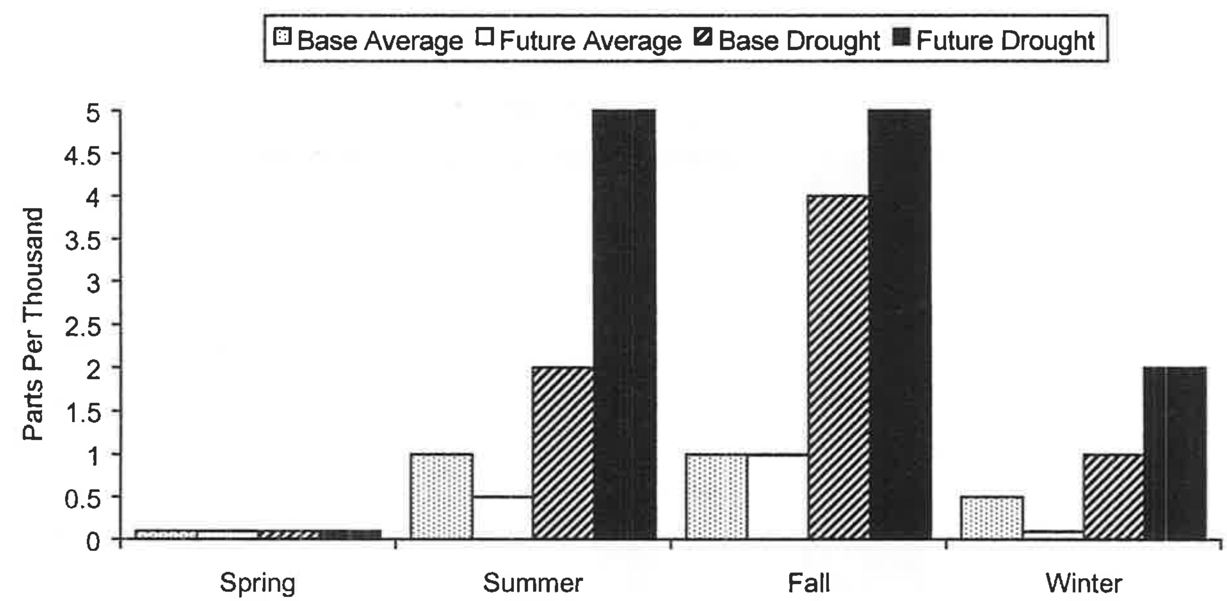

Figure 3.3. Surface Salinity at Spesutie Island/Turkey Point

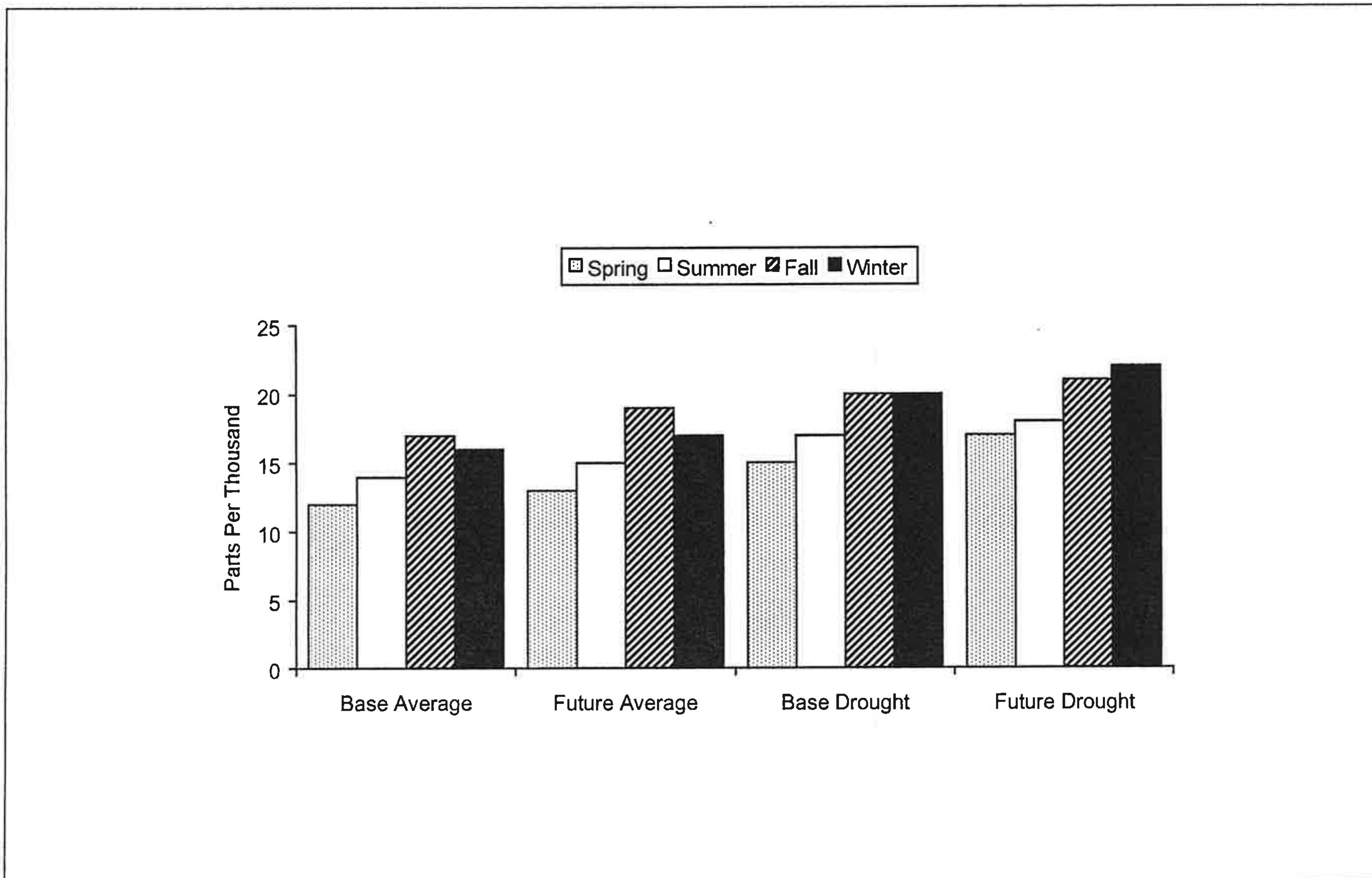

Figure 3.4. Surface Salinity at Mouth of Potomac River by Scenario

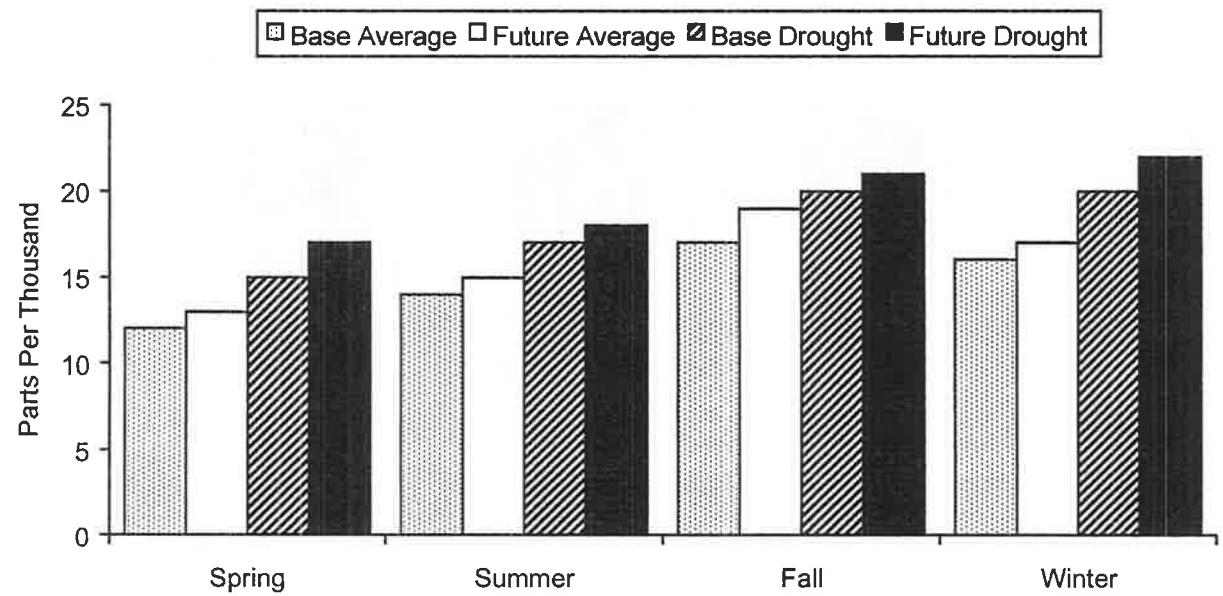

Figure 3.5. Surface Salinity at Mouth of Potomac River by Season

The reduced flows for the base drought, future average, and future drought scenarios result in upstream movement (translation) of the isohalines, compared to the base average scenario, and an increase in the salinity at a point. The maximum translation of isohalines and the maximum increase in salinity are compared in Table 3.7. The table was prepared from a summary in the Corps' report (Corps of Engineers, 1984d).

Table 3.7. Summary of Changes in Salinity
(Corps of Engineers, 1984d)

Case	Maximum Translation of Isohaline		Maximum Increase in Salinities	
	Upper Bay	Middle Bay	Upper Bay	Middle Bay
	miles		ppt	
Base Average vs. Base Drought	25	70	3.8	3.5
Base Average vs. Future Average	15	30	2.8	2.7
Base Drought vs. Future Drought	15	50	3.8	2.6
Base Average vs. Future Drought	35	80	6.5	4.9

These data show:

- Base average versus base drought shows larger maximum translation of isohalines in both upper bay and middle bay, compared to either base average versus future average or base drought versus future drought. This indicates drought conditions have greater effect on isohaline location than consumptive uses.
- Base average versus base drought shows larger maximum increases in salinity than base average versus future average in the upper bay and middle bay, which leads to the same conclusion.
- Base average versus base drought, compared to base drought versus future drought, shows about the same increase in maximum salinity in the upper bay, but less increase in the middle bay. Thus, there are differences between the effect of changes in flows between the upper bay and the middle bay.
- Comparison of maximum translation of isohalines shows changes in flow have more effect in the middle bay than in the upper bay.
- Comparison of maximum increase in salinity shows the same or greater increases in the upper bay than in the middle bay.
- Largest maximum translation of isohalines occurs in the middle bay, rather than the upper bay.
- Larger maximum increases in salinities occur in the upper bay, compared to middle bay.
- There are differences in the response of the upper bay and the middle bay.
- There are differences in the response of the maximum translation of isohaline and the maximum increase in salinity.
- The effect of drought is greater than the effect of consumptive uses, even at the very high level of consumptive use assumed in the Corps study.

The Corps of Engineers study did not attempt to evaluate effects of high flows on salinity, or effects of either high flows or low flows on water quality.

Schubel and Pritchard (1986) show:

- Increased river discharge causes the leading edge of salt water to move seaward and compresses the frontal zone, i.e., the longitudinal gradient of salinity is increased. The vertical stratification indicated by the vertical gradient of salinity also is strengthened. As the river flow decreases, the salt water rebounds quickly, but the rebound is more rapid in the lower layer than in the upper layer. That increases the stratification during periods immediately following the time of peak flow. The time for recovery is not well documented, but is relatively short, certainly less than a week, and perhaps as short as a few tidal cycles, in the bay upstream from Annapolis.
- The salinity distribution is significantly different for periods with flows 1.5 times the average, 0.8 times the average, and 0.2 times the average.
- There are substantial shifts (40 km; 24 mi.) in the location of the zone of maximum salinity gradient between the first two cases, but less significant shifts (10 km; 6 mi.) between the second and third cases. The salinity gradient also is more compressed for the latter two cases than for the first case.
- The salinity at Turkey Point increases from 0 ppt to 2 ppt (surface) and 5 ppt (bottom) between the first two cases. The salinities are about 4 ppt at all depths for the third case.
- A relatively rapid recovery (about three months) to normal salinity following the 1972 (Agnes) flood
- The Susquehanna River is crucial to flushing the Baltimore Harbor and other small tributaries to the upper bay.

Wang (1992) assumed three Susquehanna River flows to model the effects of different flow rates on circulation and salinity patterns. These flows are considered representative of different seasons. The seasons and Susquehanna River flows are:

• Spring (March, April, May)	40,818 cfs
• Summer (May, June, July)	9,378 cfs
• Fall (August, September, October)	16,687 cfs

Wang (1992) divided the upper bay into three zones, based on circulation patterns at these three flows:

- Northern zone, from the Susquehanna River to the Bush River;
- Middle zone, from Bush River to North Point-Swan Point (just downstream from Back River); and
- Southern zone, remainder of the upper bay, as defined previously.

The circulation and salinity patterns are affected by dynamic processes, the coastal geometry, and bottom topography

In the northern zone, the velocity is mainly downstream, and is driven by the Susquehanna River. The salinity is zero during the wet season, and increases to about 2 ppt during the low flow season.

The middle zone is characterized by a transition to a much wider basin on the western side. Most of the area is shallow, with a depth of about 4 meters (13 ft), except in the ship channel along the eastern shore, where the depth is 15 meters (50 ft). The velocity, magnitude and direction, and the salinity are very different in this zone, compared to the northern zone. The non-tidal velocity in the eastern shore south of Poole's Island is concentrated in a narrow band, with speeds approximately 15 cm/s to 20 (0.5-0.65 ft/sec). The velocity turns to the west in the vicinity of Swan Point to the vicinity of HMI, where part of the water turns south and part turns back toward Poole's Island, thus forming a gyre. The salinity in this zone shows considerable spatial and temporal variability.

In the southern zone, the main stem of the bay is generally wider than in the upper two zones, but then narrows significantly in the vicinity of the Bay Bridge. The average flow in the southern zone is greater than in the upper two zones, possibly due to saltwater intrusion. The ship channel is located in the center of the bay, and has a wider cross section. The shape of the isohaline near the Bay Bridge indicates saltwater intrusion from the lower bay.

The effect of the Susquehanna River on both velocity and salinity is strongest in the spring. The 1 ppt isohaline is pushed south of HMI. During the summer, the salt water was pushed further north, to the vicinity of the Bush River. There is still a high velocity band in the middle zone along the eastern shore, probably due to the ship channel. During the fall, the strong saltwater intrusion creates a very strong salinity gradient in the middle zone.

The gyre circulation is considered to be unusual for several reasons that are described. Wang (1992) concludes it is a result of the topography combined with normal dynamic effects. The gyre is very important for understanding the dispersion of HMI effluent.

3.3.3. Effects of Susquehanna River flows on water quality

3.3.3.1. Sediment transport and distribution

Schubel and Pritchard (1986) describe the effects of Susquehanna River flows on the sediment distribution in the bay. The geological responses of the upper bay are tightly coupled with fluctuations in discharge of the Susquehanna River from the mouth to about Tolchester. The responses are modulated, but still important downstream from Tolchester. Some of the Susquehanna River sediment is transported at least as far as the mouth of the Potomac River.

Approximately 70 percent of the Susquehanna River sediment load is deposited in the upper 45 km (28 mi.) of the bay. Variations in flow rate cause differences in the suspended-sediment distribution.

There are two distinctive distributions of sediment transport within the upper 35 km to 45 km of the bay. The first is characteristic of the spring freshet and other brief periods of high flow. The second is characteristic of periods of low to moderate flow. The net transport of water and sediment is downstream at all depths for locations upstream of the salinity front, but the net transport changes with depth downstream of the salinity front.

This suggests changes in flow rates, and particularly changes in low flow, affect the circulation and the distribution of sediment.

The authors discuss the distribution of sediment during high flows and during periods of low to moderate flows. During periods of low to moderate flows, there is a zone of maximum sediment concentration that coincides with the maximum salinity gradient.

3.3.3.2 Dissolved oxygen

Schubel and Pritchard (1986) note there is a zone of low dissolved oxygen that typically occurs in the deep trench between the Bay Bridge and the mouth of the Potomac River.

Schubel and Pritchard (1986) state the timing and duration of the period of low flow in the spring have a major impact on the initiation of low oxygen conditions in the upper bay. If the annual high flows occur in late winter and early spring, and lower than average flows occur in April and May, the onset of low oxygen conditions occurs later than normal. If the high river discharge extends into late April and May, the onset of low oxygen conditions will likely occur earlier than normal. The intensity of the anoxia event is likely to depend on the accumulated freshwater inflow during the period from early spring to midsummer and, in part, to whether there are higher than normal flows in May, June, or July.

Schubel and Pritchard (1986) note the end of the anoxia period is associated with weakening of the vertical stratification, which normally occurs in September, but can occur in late August or be delayed until early October. The timing of the end of the anoxia event can occur prior to or later than the time of reversal of the temperature gradient, depending on the river flow. If the discharge of the Susquehanna River during the summer months is significantly below normal, the vertical density stratification can be reduced such that a wind event can result in an early end of the stratification. Significantly higher than normal flow in August and September can result in delaying complete mixing into October. This suggests low flows improve dissolved oxygen conditions in the upper bay during summer.

Subsequent studies have shown high flows, particularly the spring runoff events, have a significant effect on the salinity and water quality, particularly dissolved oxygen, in the mesohaline region of the Chesapeake Bay (Smith and others, 1992). This region is generally defined as the portion of the bay between the Bay Bridge and the mouth of the Potomac River. The high flows carry increased loadings of pollutants, especially nutrients, which fuel primary production. The high flows also cause stratification in this part of the bay. The stratification prevents vertical mixing, and the combined effect is to reduce dissolved oxygen in the bottom layer.

Smith and others (1992) conclude:

- Oxygen depletion is a spring/summer phenomenon linked to the annual spring inflow of fresh water. Nutrient input, vertical stratification, and gravitational circulation are all highly coupled to river flow.
- Stratification increases with increased freshwater (due to decreased vertical mixing). Decreased vertical mixing lessens the input of oxygen-rich surface water into the bottom layer. The net result is a decrease in the concentration of dissolved oxygen in the bottom water. Increased spring stratification is still evident as stronger summer stratification. Vertical

mixing is more important than horizontal transport in reaerating bottom water in the deep channel of the mesohaline.

- Spring phytoplankton biomass maximum is fueled by riverine delivered nutrients, which the Susquehanna River dominates. Increased river flow increases phytoplankton biomass and deposition and decomposition of organic matter into bottom waters, and, consequently, increases the oxygen depletion. The typical summer peak in primary production is driven by recycled nutrients, much of which is derived from decomposition of the spring bloom. Sediment nitrogen regeneration is higher than normal, because oxygen depletion in bottom waters reduces biological nitrogen removal due to nitrification/denitrification processes. Sediment sulfur chemistry in the middle bay helps maintain bottom water anoxia in the absence of strong turbulent mixing.
- Interannual variability in sediment metabolism and nutrient recycling processes are directly related to recent past nutrient loading from the watershed. Reductions in nutrient inputs should result in significant decreases in benthic oxygen consumption and nutrient regeneration, since sediments are not a vast storage of labile organic matter.
- The Chesapeake Bay is naturally susceptible to depletion of oxygen in the bottom layer. However, the anoxia problem has increased in recent years, due to increased nutrient loadings, and possibly to changes in the flow regime, leading to higher flows.

The scientific consensus is (Harding and others, 1992):

- The Chesapeake Bay has always experienced oxygen depletion in the deep channel of the mesohaline region; however, the extent and severity of this depletion have probably increased over the past several centuries, and particularly so over the past 100 years.
- The volume of water experiencing oxygen depletion is largely determined by the spring flow of the Susquehanna River and the intensity of the vertical density stratification during the summer. There are natural and large year-to-year climatic variations. Since the Susquehanna River delivers the bulk of the springtime fresh water and nutrients (particularly nitrogen), an unequivocal separation between the effects of vertical density stratification and nutrient enrichment on the level of oxygen depletion of the bottom waters is difficult to achieve.
- The annual cycle of phytoplankton production is characterized by a spring biomass maximum, supported by riverine nutrient input, and a summer productivity maximum supported by internal nutrient recycling.
- Oxygen depletion in the bottom waters inhibits the loss of nitrogen through nitrification-denitrification processes and exacerbates summer primary production, which, in turn, increases oxygen depletion.
- Effects of oxygen depletion on living resources are highly species-specific and complex. Therefore, it will be difficult to predict future scenarios.
- Nutrient reduction and oxygen depletion are not linearly related, hence a 40 percent nutrient reduction will not result in an increase in dissolved oxygen of the bottom waters to 40 percent saturation. Rather, a small

increase from the present value less than 0.5 mg/l to 1-2 mg/l might be realistic, and could have major ecological ramifications.

- The responses of the bay to a modest increase in dissolved oxygen concentrations of bottom water are many. Functioning benthic communities can exist at oxygen concentrations between 1 mg/l to 2 mg/l. Because of the hypsographic characteristic of the bay (a central deep paleochannel and broad flanks), decreasing the volume of severely oxygen-depleted water will result in a large increase in benthic habitat for animals (mobile and sessile) and a similar increase in the area of sediments for coupled nitrification/denitrification.
- The goal of restoring dissolved oxygen concentrations to the bottom waters of mesohaline Chesapeake Bay must be based on what is realistic, given the natural and historical propensity of the deep channel for seasonal oxygen depletion. Furthermore, evaluating the severity of oxygen depletion should be based on the effects on living resources. Finally, our understanding of processes controlling oxygen dynamics has progressed to the level of realizing the existence of complex physical, biological, and geochemical feedback loops.

It is not clear from the information presented by Smith and others (1992) and Harding and others (1992) what effect the high flows in the spring have on the upper bay, defined as head-of-tide to the Bay Bridge, and what effect low flows in the spring will have on this reach. In the spring of 1995, the inflows to the bay were below normal. Monitoring data showed areas in the upper bay were more oxygen-starved than in previous years, when the flow was high. However, conditions in the middle bay were better than in the previous high flow years (Blankenship, July-August 1995). This appears to confirm that conditions in the middle bay will be improved if spring flows are reduced, but that the upper bay will experience higher primary productivity and lower dissolved oxygen.

In general, the low flows in the summer and early fall are expected to facilitate vertical mixing and improve dissolved oxygen in the middle bay. However, the effect on the upper bay is again uncertain. The results of the water quality modeling (Cerco and Cole, 1994a; C. Cerco, oral communication) show low flows have two opposite effects; one beneficial to dissolved oxygen, and one detrimental. The beneficial effect is a reduction in stratification, and therefore anoxia. The detrimental effect is an increase in residence time, which potentially increases anoxia.

Cerco and Cole (1994a) note the present consensus is anoxic volume is strongly linked to runoff from the Susquehanna River, and year-to-year variations in anoxic volume associated with variations in runoff prevent detection of trends in the historical record.

3.3.3.3. Pollutant dispersion

Wang (1992) used the mathematical model and the same flows as described previously to show that the upper bay flow conditions, particularly the Susquehanna River flows, significantly affect flow dispersion at HMI. The lateral dispersion of effluent increases with decreasing Susquehanna River flows. At the lowest flow, the effluent spreads across the bay and into the Chester River. Also, the gyre circulation is stronger at higher flows than at lower flows. At the higher Susquehanna River flows, the transverse concentration gradient is increased; at lower flows, the transverse gradient is more uniform.

3.3.4. Effects on living resources

3.3.4.1. Corps of Engineers assessment methodology

To assess the effects of reduced freshwater inflows on the biota of the Chesapeake Bay, key species were selected based on groupings of the dominant species by salinity and season. From a list of approximately 2,650 species identified as occurring in the Chesapeake Bay in the Existing Conditions report, 167 study species were selected based on the following criteria:

- Sensitivity to salinity;
- Sensitivity to other factors such as circulation, temperature, food and substrate;
- Affected by biological interactions;
- Represent key trophic links;
- Perform key ecosystem processes;
- Commercially or recreationally important species;
- Threatened or endangered species; and
- Availability of data.

These species were further screened to obtain a final list consisting of 57 species and associations. This final list included 7 phytoplankton, 3 EAV, 5 SAV, 10 zooplankton, 19 benthic invertebrates, 10 fish, and 3 waterfowl. Determination of the final list included special consideration of factors that could be affected by low freshwater inflow (e.g., first and second items from above). Species and their typical salinity ranges are presented. Although 57 species represent only 3 percent of the total Chesapeake Bay biota, the study species include the major organisms in the estuary. In addition, the species are representative of various salinity zones and estuarine habitats, and can serve as models for other species with similar requirements. Thus, impacts of low freshwater inflows can be assessed (Corps of Engineers, 1984e) in a specific manner for the study species and, to a certain extent, extrapolated for the entire Chesapeake Bay ecosystem.

The effects of changes in salinity on living resources were evaluated using an assessment methodology developed by the study Steering Committee, the U.S. Fish and Wildlife Service, the Corps of Engineers, and Western Ecosystem Technology Inc.

The assessment methodology included the following steps:

- Selection of the representative species, shown in Table 3.8.
- The potential habitat for each of these species was mapped for each inflow scenario, considering salinity tolerance, substrate, depth and critical seasons.
- A Biota Evaluation Panel was formed to determine how the changes in habitat would affect the populations of the species for each scenario, considering species interaction, recovery time, recruitment and recolonization (U.S. Fish and Wildlife Service, 1983).

Table 3.8. Species Used in Corps of Engineer's Study
(Corps of Engineers, 1984a)

Phytoplankton Associations	
Winter/Spring	
Cyclotella meneghiniana/Melosira granulata tidal freshwater association	
Asterionella japonica/Skeletonema costatum dominated mesohaline association	
Katodinium rotundatum/Skeletonema costatum oligohaline, low mesohaline association	
Nitschia pungens atlantica/Skeletonema costatum/Chaetoceros spp. dominated polyhaline association	
Summer/Fall	
Anacystis/Microcystis tidal freshwater association	
Gymnodinium spp./Prorocentrum minimum dominated oligohaline, low mesohaline associations	
Gymnodinium/Chaetoceros/Skeletonema dominated high mesohaline polyhaline association	
Submerged Aquatic Vegetation	
Ceratophyllum dermersum	hornwort
Potamogeton	pondweeds
Ruppia maritime	widgeon grass
Zanichellia palustris	horned pondweed
Zostera marina	eelgrass
Emergent Aquatic Vegetation Associations	
Tidal Freshwater Associations	
Juncus roemerianus	dominant, brackish tidal marsh
Spartina spp	dominant, brackish tidal marsh
Zooplankton	
Cnidaria	
Chrysaora quinquecirrha	sea nettle
Crustacea	
Acartia clausi	copepod
Acartia tonsa	copepod
Bosmina longirostris	cladoceran
Eurytemora affinis	copepod
Evadne tergestina	cladoceran
Podon polyphemoides	cladoceran
Scottolana canadensis	copepod
Ctenopora	
Mnemiopsis leidyi	ctenophore
Rotifera	
Brachionus calcyiflorus	rotifer

Table 3.8. Species Used in Corps of Engineer's Study—Continued
(Corps of Engineers, 1984a)

Benthos	
Annelida	
Limnodrilus hoffmeisteri	oligachaete worm
Heteromastus filiformis	polychaete worm
Pectinaria gouldii	polychaete worm
Scolecolepides virdis	polychaete worm
Streblospio benedicti	polychaete worm
Mollusca	
Urasalpinx cinerea	oyster drill
Crassostrea virginica	oyster
Macoma balthica	Baltic clam
Mercenaria mercenaria	hard clam
Mulinia lateralis	coot clam
Mya arenaria	soft clam
Rangia cuneata	brackish clam
Crustacea	
Ampelisca abdita	amphipod
Balanus improvisus	barnacle
Callinectes sapidus	blue crab
Cyathura polita	isopod
Gammarus daiberi	amphipod
Leptocheirus plumulosus	amphipod
Palaemonetes pugio	grass shrimp
Fish	
Alosa sapidissima	American shad
Alosa pseudoharengus	alewife
Brevoortia tyrannus	menhaden
Anchoa mitchilli	bay anchovy
Leiostomus xanthurus	spot
Menidia menidia	Atlantic silverside
Micropogon undulatus	Atlantic croaker
Morone saxatilis	striped bass
Morone americana	white perch
Perca flavescens	yellow perch
Wildlife (Birds)	
Anas platyrhynchos	mallard
Anas rubripes	black duck
Aythya valisineria	canvasback

3.3.4.2. Corps of Engineers assessment of impacts

The impact assessment led to the following conclusions (Corps of Engineers, 1984a, 1984b):

- Changes in habitat due to long-term average increases in consumptive losses are small, but the impacts can be significant.
- Large reductions in the population of oysters, soft clams, and brackish water clam may be expected with long-term decreases in freshwater inflow.
- Much larger losses are expected during both base and future drought events.
- The following species are affected: anadromous fish, low salinity SAV, soft clams, brackish water clam, and oysters.
- Certain species will be affected by reduction in food supply (e.g., ducks) or increases in predation or disease (oysters).
- Small, rapidly growing organisms such as plankton would be expected to repopulate areas rather quickly.
- It could take a decade, or longer, for SAV and some benthic organisms to recover from the effect of drought.
- Oyster mortalities due to effects of disease are expected to be 80 percent under future drought conditions. This may be an explanation for declining oyster populations and increased penetration of diseases during low flow periods in the early 1980s.
- The acreage of low salinity varieties of SAV may be significantly reduced by inflows, and some species could be totally eliminated.
- Reductions in SAV and brackish water clam are expected to result in reductions of canvasback duck populations.
- The density of sea nettles would increase, which could have an adverse effect on aesthetics.

The panel also considered impacts of salinity changes in specific zones of the estuary. These zones were defined according to the Venice system, described in section 1.8.4.

As freshwater inflows decrease and salinities increase, these zones move further upstream, and the size of the lower salinity areas is compressed. For example, under the Future Drought Condition, the areas of the oligohaline and tidal freshwater zones are reduced by approximately 80 and 50 percent, respectively. The large loss in the oligohaline zone is one of the most significant impacts of reduced freshwater inflow. The general tendency is for nutrients and detrital material to concentrate at the saltwater/freshwater interface. During spring and summer, the low salinity areas experience significant growth of plankton, which is a major source of food for important species of juvenile fish. Many important species depend on the low salinity waters. The oligohaline zone is important in the life histories of a wide spectrum of organisms, and it also is important in overall ecosystem function. Because of the importance of the oligohaline zone, it is imperative to protect and, if possible, enhance that zone under all conditions of freshwater inflow.

The Biota Evaluation Panel determined the net adverse impact on the ecosystem resulting from decreased freshwater inflow would be small under Future Average conditions, moderate under Base Drought conditions, and moderate to large under Future Drought conditions.

The Corps of Engineers (1984a) concludes large increases in salinities during a drought, or less dramatic increases over a long period of time, produce significant adverse impacts on many of the aquatic species. Increased salinities could contaminate the water supplies for the municipalities and industries along the shores of the bay.

The estimated magnitude of environmental impacts is summarized in Table 3.9.

3.3.4.3. Effects of flows on phytoplankton

Harding (1994) synthesized about 40 years (1950-90) of data on phytoplankton abundance in Chesapeake Bay, assessing the contributory effects of light penetration, nutrient availability, and Susquehanna River flow. Interannual variation in the timing, position, and magnitude of the winter-spring phytoplankton bloom in the bay was correlated to variation in the freshwater flow of the Susquehanna River. The author concludes:

- Seasonal and interannual variation in the flow from the Susquehanna River could explain differences in the pattern of phytoplankton abundance during winter-spring shown in the report. When there is low winter-spring nutrient loading (associated with persistent drought conditions and below-average Susquehanna River flow), low biomass and production are seen from the phytoplankton. Interannual variations in the winter-spring bloom do not seem to be affected by river flow events earlier than 4 months before onset of the bloom. Significant reductions in nutrient inputs from the watershed can be expected to elicit fairly rapid decreases in the abundance of phytoplankton.
- There is an interplay between light and nutrients regulating phytoplankton abundance in the bay. Light limitation of phytoplankton growth in the oligohaline portion of the bay is linked to higher flows from the Susquehanna River and delivery of suspended particles.

Harding (1994) concludes the relationship of freshwater flow from the Susquehanna River to the accumulation of phytoplankton biomass in the Chesapeake Bay is complex. While it is difficult to separate variability from trends, there is a general understanding the two are linked. It is important to focus on understanding the relationship between nutrient inputs delivered, in excess of that needed to produce the winter-spring bloom, with the specific Susquehanna River flow conditions. Further study of historical and recent data should attempt to generate a conceptual model of flow, nutrient, light and phytoplankton relations, and phytoplankton abundance.

3.3.5. Social and economic impacts

The estimated magnitude of social impacts is summarized in Table 3.10.

The estimated economic impacts are shown in Table 3.11.

The commercial fishing industry will incur most of the anticipated economic losses. The annual losses associated with a long-term decrease in average flows is estimated at $15 million (1980 dollars), while the Future Drought condition would result in losses in excess of $300 million

Table 3.9. ***Summary of Environmental Impacts***
(Corps of Engineers, 1984a)

Environmental Category Account	Impact Criteria	Magnitude of Adverse Impacts			Extent of Effects		
		Future Average	Base Drought	Future Drought	Local	Regional	National
Aquatic Resources							
Tidal Fresh Phyto.	habitat loss	—	VL	VL	X		
Mesohaline Phyto.	habitat loss	M	L	L	X		
Prorocentrum minimum	habitat loss	—	M	L	X		
Ceratophyllum demersum and other low salinity SAV	habitat loss	S	L	L	X	X	
Tidal Fresh Marsh	habitat loss	S	M	L	X		
Brachionus calcyiflorus	habitat loss	—	L	L	X		
Eurytemora affinis	habitat loss	—	L	L	X		
Scottolana Canadensis	habitat loss	—	VL	VL	X		
Bosmina longirostris	habitat loss	—	VL	VL	X		
Limnodrilus hoffmeisteri	habitat loss	—	L	VL	X		
Oyster (MSX & Dermo.)	habitat loss	L	VL	VL	X	X	X
Macoma balthica	habitat loss	M	L	L	X		
Soft Clam	habitat loss	L	VL	VL	X		
Shad	habitat loss	—	M	L	X	X	X
Alewife	habitat loss	—	M	M	X		
White perch	habitat loss	—	M	M	X		
Striped bass	habitat loss	—	M	L	X	X	X
Yellow perch	habitat loss	M	M	M	X		
Canvasback	habitat loss	M	L	L	X	X	X
Ecosystem	net adverse effect	S	M	M-L	X	X	X
Aesthetics							
Water quality	poor flushing in subestuaries	—	M	M	X		
Canvas back	few ducks	—	S	S	X		
Boat-docking facilities	collapsing boat docks	S	M	M	X		
Sea nettle	effect on recreationists	—	S	S	X		
Rare And Endangered Species	habitat loss	—	M	M	X	X	X

LEGEND: — Insignificant S Small M Medium L Large VL Very Large

Table 3.10. ***Summary of Social Impacts***
(Corps of Engineers, 1984a)

Social Category Account	Impact Criteria	Magnitude of Adverse Impacts			Extent of Effects		
		Future Average	Base Drought	Future Drought	Local	Regional	National
Health & Safety							
Sea nettle	effect on swimmers	—	—	S	X		
Public water systems	effect of salt on public health	—	—	—	X		
Recreation Experience							
Sport fishing	loss of preferred species	—	S	M	X	X	
Waterfowl hunting	population loss of favored waterfowl	S	M	L	X	X	
Swimming and water-skiing	increased densities loss sea nettle	—	M	M	X		
Boating	effect of borers	—	S	S	X	X	
Traditions							
Chesapeake Bay watermen	loss of oysters	M	L	VL	X	X	X

LEGEND: — Insignificant S Small M Medium L Large VL Very Large

Table 3.11. Summary of Economic Impacts
(Corps of Engineers, 1984a)

Economic Category Account	Impact Criteria	Magnitude of Adverse Impacts			Extent of Effects		
		Future Average	Base Drought	Future Drought	Local	Regional	National
Commercial Fisheries							
Oysters	lost harvest values	L	L	VL	X	X	X
Striped bass	lost harvest values	S	M	L	X	X	
Shad	lost harvest values	S	M	L	X	X	
Soft clam	lost harvest values	L	VL	VL	X	X	
Recreation							
Swimming (Sea nettle)	reduced expenditures	—	—	—	X		
Boating (*Teredo & Bankia*)	reduced expenditures	M	EX	EX	X	X	
Waterfowl hunting (Canvasback and other ducks)	reduced expenditures	—	S	S	X	X	
Sportfishing	reduced expenditures	—	—	—	X	X	
Bay Water Users							
Municipal	increased treatment costs	—	—	—	X		
Industrial	increased treatment costs	—	—	—	X		
Power	increased treatment costs	—	—	—	X		

LEGEND: — Insignificant S Small M Medium L Large VL Very Large EX Extreme

(1980 dollars). Future Average conditions would have negligible impacts on borers (*Teredo* and *Bankia*), but would increase the number of boating slips affected by borers by 15 percent, or 1,600 slips. Base Drought conditions could cause infestation of nearly 12,000 additional slips (120 percent increase), while 18,000 more slips would be affected under Future Drought conditions, compared to Base Average. Although drought events are a temporary phenomena, the ability of these borers to move rapidly into new habitats highlight possible economic significance.

3.3.6. Historical effects of flows

Cooper (1995) used stratigraphic records preserved in the sediments of the mesohaline Chesapeake Bay to reconstruct a 2,000-year history of sedimentation, eutrophication, anoxia, and diatom community structure over time. Cores were obtained from four sites located on a transect across the bay between the Choptank River and Plum Point, Md. This paper covers the results for diatoms, pollen, and biogenic silica. Other paleoecological indicators used include total and organic carbon, total sulfur, acid-soluble iron, and estimated degree of pyritization of iron.

Study results show changes in diatom community structure continued into the 20th century, coincident with urbanization and industrialization of the watershed. The species diversity continued to decline. The numbers and relative abundance of marine benthic species declined, while planktonic brackish and freshwater diatom species increased. These changes suggest increased freshwater input, possibly large runoff events. The changes confirm the results of other studies of the decline of the Chesapeake Bay.

The study has limited immediate application to the study of effects of low flows, particularly because it is showing effects of high flows, and because of the long time period considered. However, the data collected and techniques used may be helpful in future studies of the historical effects of low flows.

3.4. Summary of Impacts of Flows

3.4.1. Effects of flows on circulation and salinity

- Freshwater inflow quantity and timing are important to:

    * Determine circulation patterns (Klein and others, 1981; Schubel and Pritchard, 1986; Wang, 1992); and
    * Determine salinity distribution (Klein and others, 1981; Schubel and Pritchard, 1986; Corps of Engineers, 1984a, 1984b; Wang, 1992);

- High flows cause the isohalines to move downstream, which decreases salinity (Schubel and Pritchard, 1986; Wang, 1992);
- Low flows cause the isohalines to move upstream, which increases salinity throughout the bay (Corps of Engineers, 1984b; Schubel and Pritchard, 1986; Wang, 1992);
- Consumptive uses affect isohalines similarly to low flows (Corps of Engineers, 1984b);
- Consumptive uses and diversions increase the effect of low flows on salinities (Corps of Engineers, 1984b);

- The size of the tidal fresh and oligohaline zones is reduced during low flow events, and as a result of consumptive uses (Corps of Engineers, 1984b);
- High flows and low flows result in different distributions of sediment in the upper bay (Schubel and Pritchard, 1986); and
- The sediment deposition is closely related to the Susquehanna River flow as far south as Tolchester Beach (Schubel and Pritchard, 1986).

3.4.2. Effects of flows on water quality

- The magnitude, timing, and duration of high flows, particularly during the spring, have a significant effect on the development of anoxic conditions (low dissolved oxygen) in the mesohaline zone between the Bay Bridge and the mouth of the Potomac (Schubel and Pritchard, 1986; Smith and others, 1992; Harding and others, 1992);
- The intensity of the anoxia event is likely to depend on the accumulated freshwater inflow during the period from early spring to midsummer and, in part, to whether there are higher than normal flows in May, June, or July (Schubel and Pritchard, 1986);
- Reductions in high flows during the spring period are expected to significantly improve dissolved oxygen in the deep trench (Harding and others, 1992);
- Reductions in high flows during the spring may have an adverse effect on water quality in the upper bay (Blankenship, July–August 1995);
- The Chesapeake Bay has always experienced oxygen depletion in the deep channel; the extent and severity have probably increased over the past several centuries, and particularly the last 100 years (Smith and others, 1992; Harding and others, 1992);
- Stratification increases with increased freshwater input during the spring freshet (Smith and others, 1992; Harding and others, 1992);
- Increased stratification causes anoxic conditions in the deep trench during the period from the spring freshet until the fall turnover (Smith and others, 1992; Harding and others, 1992);
- The anoxic condition is caused by increased nutrient inputs and by the magnitude of the flow (Smith and others, 1992; Harding and others, 1992);
- The timing of the fall turnover depends on the timing and magnitude of the fall flow (Schubel and Pritchard, 1986);
- Low flows in the summer and fall are expected to decrease the anoxic condition in the deep trench (Harding and others, 1992);
- The volume of water experiencing oxygen depletion is largely determined by the spring flow of the Susquehanna River and the intensity of the vertical density stratification during the summer (Harding and others, 1992);
- The understanding of processes controlling oxygen dynamics has progressed to the level of realizing the existence of complex physical, biological, and geochemical feedback loops (Harding and others, 1992);
- The Corps of Engineers' study (1984a, 1984b) did not evaluate effects of low flows on water quality; and
- Susquehanna River flows affect the dispersion of pollutant discharges from the HMI dredge disposal area, and low flows may cause pollutants from HMI to enter the Chester River on the eastern shore (Wang, 1992).

The scientific consensus (Harding and others, 1992) is low flows in the spring, summer, and early fall are expected to facilitate vertical mixing and improve dissolved oxygen in the middle bay. This scientific consensus may be incomplete for the following reasons:

- The consensus is based on effects in the middle bay, but the effects on the upper bay are poorly understood;
- The effects of low flows are not well understood;
- Recent data confirms low flows in the spring will decrease anoxia in the middle bay, but may have adverse effects on water quality in the upper bay (Blankenship, July–August 1995);
- There is some evidence from the water quality modeling studies (Cerco and Cole, 1994a; C. Cerco oral communication) that low flows have both beneficial and detrimental effects on dissolved oxygen:

  * The beneficial effect is a reduction in stratification and, therefore, anoxia;
  * The detrimental effect is an increase in residence time, which potentially increases anoxia; and
  * The relationship between anoxia and residence time is not well understood.

This argument is controversial, and needs further evaluation.

3.4.3. Effects of flows on living resources

- Circulation patterns determine exposure of organisms to toxics and nutrients (Klein and others, 1981);
- The changes in salinity due to low flows and consumptive uses are expected to have significant adverse impacts (Corps of Engineers, 1984b) on salinity intolerant SAV, oysters, soft clams, brackish water clams, and anadromous fishes;
- Salinity is very important in describing suitable conditions for survival of many organisms (Corps of Engineers, 1984b);
- The oligohaline zone is very important, and needs to be protected (Corps of Engineers, 1984b);
- The improvement of water quality, particularly reduction of anoxic conditions, is very important to the restoration of the living resources; and
- Small improvements in bottom dissolved oxygen could have significant positive ecological impacts (Harding and others, 1992).

3.4.4. Effects of flows on water supply

- The water supply for the City of Havre de Grace, Md., may be affected by high salinity under some conditions (Corps of Engineers, 1984b). Havre de Grace water supply has been affected by high salinity twice in the last decade (Roger Wagoner, City of Havre de Grace, oral communication; Nancy Reilman, Maryland Department of the Environment (MDE), oral communication). The problem has been caused by low flows aggravated by strong winds out of the south (Roger Wagoner, City of Havre de Grace, oral communication; Nancy Reilman; MDE, oral communication).
- There have not been any major droughts in the last decade, so there is reason to be concerned about the effects of very low flows over extended periods of time on the salinity.

- Increasing salinity was observed at Havre de Grace during the summer of 1995, a low flow period, but the salinity did not increase enough to cause any problem for Havre de Grace.

3.4.5. Economic impacts of low flows and consumptive uses

- Most of the economic losses will be incurred by the commercial fishing industry.
- Estimated annual losses associated with long-term decrease in flow are $15 million (1980 dollars).
- Losses resulting from future drought are estimated in excess of $300 million (1980 dollars).
- Additional losses are due to increased infestation by borers.

3.5. Effects of Chesapeake and Delaware Canal

The C&D Canal connects the northern end of the Chesapeake Bay with the Delaware Bay. The eastern end is at Reedy Point, Delaware, about 41 miles downstream from Philadelphia. At the western end, the canal enters the Chesapeake Bay via Back Creek and Elk River. The canal is about 14 miles long, and is entirely at sea level (Boyd and others, 1973).

In 1953, Congress authorized enlargement of the canal from the existing 27-ft depth and 250-ft width to 35-ft depth and 450-ft width. This enlargement was nearly complete in 1972, except for the last few miles at the eastern end (Boyd and others, 1973). Concerns regarding the environmental impact of the enlargement resulted in a study by the Philadelphia District of the Corps of Engineers, with assistance from other parties.

The Corps of Engineers (1984b) notes the C&D Canal affects salinity in the upper bay. However, they state further work is necessary to determine the magnitude of the effect.

Pritchard and Gardner (1974) note the salinity generally increases from west to east through the canal, with a normal salinity difference of about 2 ppt. The salinity ranges from essentially fresh in the western end, during the period of high flow from the Susquehanna River, to about 8 ppt in the Delaware Bay end during low flow conditions. Currents are basically tidal, though there may be a net non-tidal flow due to differences in mean water level elevations and salinity between the two ends. There also are large variations caused by meteorological conditions. As a result, the average condition is hard to determine, and for many purposes, is less important than the short-term fluctuations (Pritchard and Gardner, 1974).

The most definite result of the study by Pritchard and Gardner (1974) is any long-term average conditions in the canal are usually marked by large, short-term fluctuations. The best estimate for the long-term average transport is 988 cfs before enlargement, and 2,450 cfs after enlargement, both toward the Delaware Bay. The large variability of the net transport is shown by the standard deviation of individual tidal cycle averages from the mean: ±5,980 cfs before enlargement; ±14,827 cfs after enlargement.

Boyd and others (1973) used a physical model to study the effects of the enlargement of the canal. They concluded:

- Enlargement of the canal caused a net increase in flow of 4.8 times for a mean head differential. For the enlarged canal, net flows of as much as 40,000 cfs eastward and 25,000 cfs westward can be expected.
- The net discharge and salinity characteristics within the canal were very sensitive to minor changes in the mean tidal level at each end of the canal, regardless of the size of the canal.
- Small changes in head difference can significantly affect the tide, duration and magnitude of current velocities, salinities, and direction and volume of net discharge.
- Salinities in the Chesapeake Bay in the vicinity of Turkey Point vary from fresh water during the rainy season to as much as 9.0 ppt after extended periods of low tributary flow. Mean value is about 1.3 ppt. Mixing is excellent in this area, and there is no density stratification.
- The flow conditions at the Delaware Bay end of the canal, and adjacent waters, are very complex and dynamic, and can have great influence on net discharge and flow direction in the canal.
- Meteorological conditions have a great influence on the conditions in the canal.
- When the salinity at the eastern end of the canal is appreciably greater than the salinity at the western end, there is a net discharge to the west, if the tide level difference is small. This is caused by a longitudinal salinity gradient. The salinity gradient has a significant influence on rate and direction of net flow for small head differences.
- Salinity characteristics in the Delaware Bay and upper Chesapeake Bay, in the vicinity of the canal, are significantly influenced by net tidal discharge through the canal.
- Net discharges for comparable head differences were increased when the salinity at the western end was reduced to zero and conditions resulted in net eastward flow. The fresh water from the Elk River reduces the source salinity at the eastern end of the canal, which reduces the salinity differential in the canal, which reduces the salinity generated pressure gradient flow in the westward direction.
- Completion of the enlargement is expected to increase net flow towards the Delaware Bay about 2.5 times.
- Increased efficiency of a larger canal will greatly influence tides in the Elk River, the canal, and the adjacent reaches of the Delaware Bay.
- Large westward net flow will increase salinities in the Elk River, but the effect of large eastward net flows on salinity in the Chesapeake Bay and Elk River could not be determined.

Hsieh and Richards (in preparation) describe simulations to determine the net transport through the canal for various forcing conditions over two (spring and fall) seasonal periods, and to study the impact of deepening the canal from 35 ft to 40 ft. Twenty-four simulations were conducted with a wide range of boundary conditions and geometries, including combinations of freshwater inflow, tide, and salinity boundary conditions. The low flow, medium flow, and high flow conditions were determined statistically.

Average flow and salinity patterns were determined for four sets of extreme simulated seasonal flow and transport conditions: 1964, the lowest low flow year; 1977, the highest low flow year; 1985, the lowest high flow year; and 1972, the highest high flow year.

The simulations showed the following:

- For the low flow base period, relatively weak residual circulation was found in the middle Chesapeake Bay (which appears to confirm Wang's (1992) results), and the net transport in the canal was westward, due to the low flows. The 2 ppt isohaline penetrates to the entrance of the Sassafras River.

- For the high flow base period, stronger residual flows were found in the upper Chesapeake, due to higher freshwater flows. The 2 ppt isohaline was pushed to the mouth of the Chester River, and a very fresh region formed in the upper Chesapeake.
- For 1964, flow and salt transport was from the Delaware to the Chesapeake. Average circulation in the upper Chesapeake was weak. The 2 ppt isohaline was restricted to the Susquehanna flats and lower Susquehanna River;
- For 1977, there was a strong down-bay flow in the Chesapeake, which caused flow and transport from the Chesapeake to the Delaware. The 2 ppt isohaline was pushed to Poole's Island.
- For 1972, the historical spring high flow year, most of the freshwater was pushed to the lower Chesapeake Bay.
- For 1985, the average river flows were small, but there was eastward transport through the canal. This indicates westward transport is unlikely during the spring. The 2 ppt isohaline occurred near HMI.
- The effect of the deepening was considered minor overall, but was greater than under higher flow conditions, compared to lower flow conditions.
- The net transport of flow and salt is primarily dependent on the total amount and relative strength of the freshwater inflows in the two river basins.

While these previous studies have helped to understand the effect of the C&D Canal on the Chesapeake Bay, it appears that additional work is necessary to understand the effect of the canal and the interrelationship with Susquehanna River flows.

3.6. Chesapeake Bay Data Sets Related to Impacts of Low Flows

Jacobs and others (1988) describe both current and historical data sets available for the bay. That inventory includes descriptions of 826 data sets. Heasley and others (1989) describe current water quality, biological, living resource, and physiochemical monitoring programs in the Chesapeake Bay. Updated data inventories are being prepared, but were not available for this study.

These inventories were used to develop Tables 3.12 and 3.13 showing the data sets that are expected to be relevant to the study of the effects of low flows and reduction in low flows from the Susquehanna River on the Chesapeake Bay. The criteria used in selecting relevant data sets from these compilations were:

- Include data for upper or middle bay;
- Cover a broad geographic area, rather than focus on specific locations;
- Include salinity, water quality or living resources data;
- Have reasonably long period of record.

Table 3.12. ***Selected Historical Data Sets***
(Jacobs and others, 1988)

Ref. No.	Title	Collecting Party
2	Toxicants in the Chesapeake Bay Water Column, 1968-81	CBP
10	Water Quality Data for the Chesapeake Bay and Its Tributaries, 1949-63	CBI
14	Nutrient Cruises of the Upper Chesapeake Bay, 1964-66	CBI
66	Blue Crab Recruitment in Maryland Waters	MDNR
68	Weakfish Population Data in Maryland Portion of Chesapeake Bay	MDNR
71	Fishery Landings Data for the Chesapeake Bay and Offshore Areas	MDNR
112	Distribution of Submerged Aquatic Vegetation in the Chesapeake Bay and Tributaries	MDNR
122	Tissue and Community Structure Data on Chesapeake Bay Biota	MDHMH
123	Biomonitoring Data From the Maryland Portion of the Chesapeake Bay and Its Tributaries, 1974-86	MDHMH/MDE
124	Water Quality Data From the Main Stem of the Chesapeake Bay, 1984-86	MDHMH/MDE
125	Water Quality Data from the Main Stem of the Chesapeake Bay, 1964-present	MDHMH/MDE
126	Supplementary Water Quality Data From Chesapeake Bay Tributaries: 1964-Present	MDHMH/MDE
166	Water Quality of Upper Chesapeake Bay, Chesapeake and Delaware Canal, Elk River and Choptank River, 1983-85	MDNR
225	Juvenile Finfish Index File for the Chesapeake Bay	CBP
226	Chesapeake Bay Fisheries Landing Data	CBP
227	Maryland Fisheries Statistics	CBP
236	US EPA Chesapeake Bay Freshwater Inflow Data	CBP
313	Examination of Tidal Flats in Maryland, Virginia and North Carolina, 1977-81	VIMS
329	Juvenile Blue Crab Survey Database for Maryland and Virginia, 1956-present	VIMS
398	Trends in Distribution and Abundance of Submerged Aquatic Vegetation in Maryland, 1971-81	MDNR
587	Survey of Hard Clams in the Chesapeake Bay, 1967-73	VIMS
588	Survey of Soft Clams in the Chesapeake Bay, 1967-70	VIMS
693	Survey of Submerged Aquatic Vegetation Eastern Chesapeake Bay and Adjacent Tributaries, Maryland, 1976-81	CBP (NC)
739	Environmental Data for the Chesapeake Bay, 1949-1980	CBI
752	Water Quality Conditions in the Chesapeake Bay, 1970-72	CBP
755	Chesapeake Bay Oceanographic and Water Quality Data, 1949-82	CBI
771	Environmental Data for Chesapeake and Delaware Canal, 1955-76	CBI
778	Environmental Data for the Elk River, Maryland, 1955-80	CBI
792	Environmental Data for Northeast River, Maryland, 1955-76	CBI
810	Environmental Data for Susquehanna River Maryland, 1955-77	CBI

Table 3.13. ***Selected Current Data Sets***
(Heasley and others, 1989)

Title	Collecting Party
Maryland Chesapeake Bay Water Quality Monitoring Program: Main Stem Chemical/Physical Component, June 1984-?	MDE
Maryland Chesapeake Bay Water Quality Monitoring Program: Tributary Chemical/Physical Component, July 1984-?	MDE
Maryland Chesapeake Bay Water Quality Monitoring Program: Benthic Organism Component, July 1984-?	MDE
Maryland Non-Tidal Benthic Macroinvertebrate Monitoring Program, 1980-?	MDE
Chesapeake Bay Submerged Aquatic Vegetation Aerial Survey, 1984-?	CBP
Maryland Submerged Aquatic Vegetation Ground Survey Program, 1971-?	MDNR
Maryland Oyster Spat and Condition Index Program, 1939-?	MDNR
Maryland Blue Crab Monitoring Program, May 1975-?	MDNR
Maryland Yellow Perch Population Survey, December 1986-?	MDNR
Maryland Juvenile River Herring Survey, June 1983-?	MDNR
Maryland Estuarine Juvenile Finfish Survey, 1954-?	MDNR

The MDE Water Quality Inventory (MDE, undated) describes data sets that have been collected by MDE under the long-term ambient monitoring and estuarine monitoring programs.

The long-term ambient monitoring program includes water quality, benthic macroinvertebrate, fish tissue, and phytoplankton sampling to provide information on trends in water quality. The program originally began in the 1970s. Recently, sampling frequency and methodology of these programs have been changed. The program includes phytoplankton sampling at 20 stations in the main stem bay and certain tributaries.

The estuarine monitoring program includes the following monitoring programs initiated in 1984.

Program	Description
Chesapeake Bay Main Stem Tributary Program	Water quality sampling at 22 main stem bay and 55 tributary stations twice a month between March and October and once a month at other times of year. Sampling sites include a Susquehanna River input station, which appears to be at the head-of-tide, and main stem stations at the mouth of the Susquehanna River and at Spesutie Island/Turkey Point.
Chesapeake Bay Sediment Toxicant Monitoring Program	Surface sediment samples are collected at each of 22 main stem and 37 tributary stations once a year since 1984.
Chesapeake Bay Benthic Program	Benthic biota samples are collected up to 10 times a year, at up to 70 stations in the main stem and tributaries. Water quality data collected at the same time.
Chesapeake Bay Plankton Program	Phytoplankton and zooplankton samples and physical and chemical data are collected at 14 stations in the main stem and tributaries at monthly or semimonthly frequencies.
Chesapeake Bay River Input Program	Susquehanna River and other locations are monitored for flow, sediment, and nutrient concentrations during storm and base flow conditions.
Chesapeake Bay Living Resources Program	Samples collected from stations in the Choptank River and the upper bay are analyzed for water quality constituents, phytoplankton, zooplankton, and fish larvae to investigate the relationship between habitat quality and abundance of selected species.

3.7. Related Studies in Other Estuaries

3.7.1. National Symposium on Freshwater Inflow to Estuaries

Studies of effects of freshwater inflows in other estuaries are discussed by Grubb (1981), Browder and Moore (1981), and Rozengurt and Haydock (1981).

Grubb (1981) describes planning for freshwater inflow to estuaries in Texas. Studies have shown the freshwater needs of estuarine ecosystems are not static annual needs. A range of quantities of inflow is apparently both realistic and desirable for an estuarine ecosystem, because extended periods of inflow conditions that are consistently above or below the maintenance level of the ecosystem can lead to a degraded estuarine environment, loss of important nursery areas for fish species, and a reduction in the potential for assimilation of organic and nutritive wastes. For example, the productivity of Texas estuaries severely declined during historical drought events, and began to take on characteristics of marine lagoons. When flows are too high, fisheries production is lowered.

Browder and Moore (1981) describe the following types of studies performed up to that time in various estuaries:

- Growth rate and mortality laboratory studies;
- Field studies of frequency and abundance of certain organisms at various salinities and temperatures;
- Statistical studies of estuarine food chains; and
- Statistical studies of relationships between landings and prior salinities or river discharges.

They state a number of findings from those studies, including:

- Certain synergistic effects of salinity and temperature have been established; and
- Significant relationships between fishery yields and freshwater flow have been demonstrated by correlation/regression analysis for a number of estuaries and species. The correlations have been positive for some estuaries and negative in others, positive for some species and negative for others.

Browder and Moore (1981) summarize scientific studies in estuaries along the coast of the Gulf of Mexico (Florida, Louisiana, and Texas) relating to the problem.

Land use changes have changed the time distribution of inflows to the estuary in southern Florida. Also, the following have been noted in the Appalachicola Bay system:

- Effects of land use changes result in changing the timing of flows, which are discussed.
- Variations in abundance of different trophic groups are related to annual fluctuation in river flow. Atlantic croaker, spot and benthic-feeding fish reach maximum abundance in years of high flow.
- Correlations have been developed between oyster and crab harvests and river flow. For the period 1957-77, oyster harvests were negatively correlated with annual river flow, and annual blue crab harvests were positively correlated with annual river flow.
- Studies show salinity fluctuations may be beneficial.

Extensive studies have been conducted relating fishery production to freshwater flows in the Mississippi Delta.

The various Texas estuaries that have been studied seem more similar to the Chesapeake Bay, than the other locations discussed. The problems have similar sources (operations of dams, consumptive uses, and diversions), and these estuaries all have large freshwater inflow volumes relative to estuary volume. Some simple models have been used to try to estimate flow requirements for the Trinity-San Jacinto, Matagorda, and Guadalupe River Basins.

Browder and Moore (1981) propose an energy flow model to show the effects of freshwater inflow to estuaries on fishery production. The flow of fresh water into estuaries may influence fishery production, either directly or indirectly, in at least five ways: transport of nutrients; transport of detritus; transport and deposition of sediments; reduction of salinity; and mixing and transport of water masses. The authors discuss the implications of this energy diagram. One concern is nonlinear effects of freshwater flow on mixing, or the potential importance of mixing conditions to the survival and growth of juvenile and sessile organisms, are often ignored.

Browder and Moore (1981) propose interdisciplinary studies to develop production functions relating fish production to freshwater inflow under varying circumstances Such a model will incorporate hydrologic and hydrodynamic concepts. Such studies should include the following elements:

- Monitoring freshwater flow rates;
- Measurement of vertical profiles of salinity, temperature, oxygen, current direction and velocity;
- Measurement of detrital biomass and decomposition rates;
- Mapping isohalines and quantification of area between isohalines periodically during the nursery period;
- Mapping and quantification of potentially productive habitat at different tidal levels; and
- Monitoring fishery yield and effort.

Relationships that should be explored are:

- Productive habitat as a function of flow during the nursery season;
- Stratification versus freshwater flow;
- Fishery production versus productive area;
- Fishery production versus area of marsh;
- Detrital decomposition versus stratification;
- Recruitment versus currents during post-larval periods; and
- Fishery production versus water quality.

Rozengurt and Haydock (1981) state each river/estuary system has a natural limit beyond which water supply activities change the ecological balance and geomorphological regime between the river, the delta, and the contiguous seas. The author's experience, and published results of effects of water development elsewhere, show no more than 25 to 30 percent of the natural outflow can be diverted without disastrous ecological consequences. The early warning signs of excessive withdrawal are apparent in the reduced productivity of fish and wildlife resources, changed biological structure of plankton, benthos, and fish communities, increased salinity intrusion, and increased effects of pollution loads. This is confirmed by experience with the San Francisco Bay.

Rozengurt and Haydock (1981) present procedures for calculating water and salt balances and methods for regulating flow and salt regimes, based on experiences with streams in Russia. The solution is based on the principal correlation between components of the water and salinity balance and the influence of particular water consumers on the environment.

There appears to be a number of problems with the approach suggested by Rozengurt and Haydock (1981).

- The procedures for computing allowable withdrawals are unclear, and the references given are to Russian journals. Efforts to contact the senior author to clarify the procedure were unsuccessful.
- The author's comments appear to be most applicable to estuaries that are already greatly stressed by withdrawals, etc. That is the case with the San Francisco estuary, but it is probably not the case for the upper Chesapeake. Conversely, the goal should be to manage the withdrawal of fresh water to prevent these impacts from occurring.
- The procedure appears to consider only one average annual withdrawal value, and does not consider the time pattern of flow or the time pattern of diversion.

Clark (1981) recommends that the 25 percent allowable diversion be verified for American estuaries. We are not aware of any studies that have used this methodology for American estuaries.

3.7.2. Current studies

Several telephone contacts were made to determine the status of studies conducted in other estuaries. Two ongoing studies were identified, one in the San Francisco Bay Delta Estuary, and one in the Appalachicola estuary.

3.7.2.1. San Francisco Bay Delta Estuary Study

In December 1994, representatives of state and federal governments and urban, agricultural, and environmental interests agreed to the implementation of a San Francisco Bay-. Delta protection plan based on certain principles ("Principles," 1994). The agreement is to be in force for three years ("Press Release").

The Agreement includes ("Principles," 1994; "Press Release," 1994):

- Final water quality standards for the bay/delta issued by US EPA under the Clean Water Act;
- U.S. Fish and Wildlife Service designation of critical habitat for delta smelt, which is considered threatened;
- The final biological opinion will contain recommendations on flows through the estuary to ensure appropriate habitat for delta smelt and transport flows for juvenile fish;
- Budget of $10 million per year for the three years to conduct additional studies, which are to be determined later;
- Budget of $180 million for modifications to existing facilities; and
- Institutional arrangements for further discussion and resolution of the problem.

The federal agencies describe the agreement as including the following standards ("Press Release," 1994):

- Salinity criteria for Suisun Bay, which is the nursery area;
- Survival targets for young migrating chinook salmon;

- Salinity criteria to protect fish spawning grounds on the lower San Joaquin River; and
- Descriptive criteria for maintaining Suisun Bay marsh tidal wetlands.

A more recent report (CALFED, 1995) describes the agreement as including the following provisions:

- Springtime water export limits expressed as a percentage of delta inflow;
- Regulation of the salinity gradient in the Suisun Bay;
- Specified springtime flows on the lower San Joaquin River to benefit chinook salmon;
- Intermittent closure of the Delta Cross Channel gates to reduce entrainment of fish;
- Reconcile operational flexibility with compliance with the federal Endangered Species Act through real-time monitoring of aquatic species;
- Improve conditions through measures not directly related to Delta outflow (e.g., screening diversions, waste discharge control, habitat restoration). These measures are budgeted at $60 million per year, over three years.
- Establish joint federal state (CALFED Bay-Delta Program) process to develop a comprehensive balanced plan that addresses long-term solutions to problems related to fish and wildlife, water supply reliability, vulnerability of existing structures to natural disasters, and water quality.

Fullerton (1995) discusses the agreement in some detail, and particularly describes the institutional and political context.

Fullerton (1995) describes the rationale for the standards.

- Delta outflow standards are well developed. The goal is to provide optimum conditions for the ecosystem at an acceptable cost to water withdrawal users. There is strong scientific evidence to indicate spring delta outflow is correlated with biological health.
- There is little information to determine the timing of pumping of water for export. This is partly due to competing theories of how water flows affect biology. The first theory is net flows of water are the dominant factors affecting biology; the second theory is tidal effects are the dominant factor. These result in different standards. There is no basis for determining the validity of either theory.

Fullerton (1995) discusses short-term and long-term solutions to the problem.

Fullerton (1995) describes the following aspects of the agreement in detail:

- Estuarine habitat standard;
- Delta import/export relationship;
- San Joaquin fall salmon run standards;
- Operational flexibility and adaptive management;
- Improved monitoring; and
- Endangered species.

In all cases, the standards are considered to be less than ideal from an ecosystem viewpoint; nevertheless, they are improvements over existing conditions where there are no standards.

The ongoing process is described by CALFED (1995).

The development of the estuarine standard is described by Schubel (1991, 1993).

3.7.2.2. Appalachicola Estuary Study

Ted Hoehn, Florida Department of Fish and Game, provided the following information (oral communication).

The Corps of Engineers has proposed several actions that would impact flows in the Appalachicola-Flint-Chattahoochee River Watershed, which will affect the states of Georgia, Alabama, and Florida. The actions included modification of the operation of several reservoirs on the watershed. The states of Florida and Alabama both objected to these actions.

Studies are underway to determine the impact on the estuary and living resources. The management philosophy among the living resources parties is to maintain the normal flow regime. They are most concerned with manipulation of low flows, because high flows cannot be controlled. The studies include hydrologic analysis, designed to determine the natural flow regime. A salinity model has been developed by the Northwest Florida Water District. The model does not include living resources components. Synthesis of long records of data regarding the biota is underway. These data are showing shifts in trophic indexes and species composition from saline to fresh water species. They also are seeing effects of floods and droughts on species community types for long periods after the occurrence of the flood or drought. Landings data have been compared to flow, but has been inconclusive. The effect of low flow on freshwater marshes also is being studied.

The next decision point comes in 1996. The parties may then return to court.

4.0. SURVEY REGARDING LOW FLOW IMPACT ISSUES

4.1. Survey Purpose

The original study plan included interviews with selected parties to obtain input regarding issues. After conducting the literature review, preparing a list of people to be interviewed, and preparing a list of questions that needed to be addressed in the interviews, the study team concluded a survey would be more useful and cost-effective than interviews.

The purposes of the survey were:

- To determine whether there is agreement regarding issues that need to be addressed;
- To determine the extent of agreement regarding these issues among various interested parties;
- To obtain feedback regarding these issues; and
- To clarify some points in the literature review.

4.2. Survey Procedures

A list of questions was developed based on the literature review and comments made by the study Steering Committee. A list of people who should receive the questionnaire was developed. Comparison of the two lists showed certain questions needed to be targeted to certain interests.

The survey package included a cover letter, a brief summary of the study, a brief summary of the Corps of Engineer's study (1984a, 1984b), a brief discussion of the Susquehanna River hydrology and consumptive uses, and the appropriate survey forms.

To target certain interests, three sets of questions were developed. The first set was addressed to all parties. The second set included separate survey forms directed to certain groups. These separate survey forms were developed for the following groups:

- Baltimore District Corps of Engineers
- Living resource agencies and researchers, including:
    - Maryland fisheries agencies
    - U.S. Fish & Wildlife Service, NOAA/NMFS
    - Living Resources Subcommittee members
    - Biota Evaluation Panel members
    - Researchers
- State water resource agencies (Pa. Department of Environmental Protection (Pa. DEP); Md. Water Resources Administration (Md. WRA))
- Maryland Department of the Environment (MDE)
- Corps of Engineers Waterways Experiment Station

The complete set of questions is included in Appendix A. The list of people to whom the questionnaire was sent is attached in Appendix B (page 175). Sixty-four questionnaires were sent.

Twenty-seven questionnaires were returned in time to be included in the interpretation. MDE staff furnished one combined response for four people, so the actual response was about 50 percent. A list of those who responded is shown in Appendix C (page 183). Note 16 of the respondents represented living resource interests.

The summary tabulation of responses is included with the list of questions in Appendix A (page 153).

4.3. Summary of Responses

4.3.1. Main questionnaire

Question 1 was designed to determine whether there is agreement on the issues that need to be addressed. There is general agreement the following issues need to be addressed:

- Whether the bay is affected by natural low flows or consumptive uses and diversions or both;
- Which resources and uses are affected;
- Which part of the Chesapeake Bay is affected;
- The time of year that effects occur;
- Significance of factors other than salinity;
- Purposes of flow management;
- Goals of flow management;
- Effects of tributaries other than the Susquehanna River*;
- Effects of C&D Canal on the Chesapeake Bay *;
- Effects of Baltimore withdrawal from the Susquehanna River;
- Whether existing data are adequate to develop low flow management plans*;
- Necessary additional studies; and
- The appropriate time scale for evaluating impacts.

While the majority agreed with the need to address all issues, a significant number of people dissented or had no opinion regarding the issues marked with asterisks.

The following significant comments were received regarding these issues. The author's response is shown for each comment.

Comment	Response
Describe how resources and uses are affected.	Expect to cover in the report; not clear whether the comment is seeking whether impacts are positive or negative, or asking for description of process.
Describe how each part of CB is affected.	Expect to cover in the report.
Assume that part of bay that is affected is above the Bay Bridge.	Needs further discussion.
Time of year should be limited to seasons at most.	Needs further discussion.
Mention other tributaries, C&D Canal, and Baltimore withdrawal as factors, but limit scope of effort.	Agree for purposes of developing strategy.
May not be able to address effects of other tributaries and effects of C&D Canal in detail, but some generic consideration is necessary. Displacement in main stem relates to other tributaries and C&D Canal.	Agree.
Note whether effects are positive or negative.	Agree.
Describe effect of all tributaries.	For purpose of defining strategy will present reasons for/against considering all major tributaries.
Factors other than salinity are minimal.	Needs further discussion.
Existing data satisfactory.	Needs further discussion.
Minimal additional studies necessary.	Needs further discussion.
Effects of Baltimore withdrawal should not be the objective.	Asking only whether it needs to be considered.
Need to include Chester withdrawal along with Baltimore.	Agree. It has been included in diversion calculations.

In addition to these issues, a number of additional issues were identified by the respondents. These issues, and a response to them, are as follows:

Issues	Response
Authority and mechanism to regulate.	Will include in final report.
Effect of lower Susquehanna River impoundments.	See discussion section 2.5.
Other consumptive uses including effects of evaporation from the lower Susquehanna River impoundments.	Evaporation from reservoirs can be included in consumptive use calculations.
Economic effect on Pa., Md., Va.	Will be considered.
Effect of flow on other water quality problems (e.g., nutrient input, stratification, low DO).	Will be considered.
Effects of low flow on Susquehanna River.	Not relevant to this study

Question 2 was intended to determine whether there is agreement Susquehanna River low flows affect the salinity in the bay. Most people agreed, but there was one disagreement, and three respondents had no opinion. Comments included:

- High flows affect the flats, the lower bay, and probably Delaware Bay; and
- Low flows affect the bay only in limited areas; and low flows affect only the upper bay.

In general, the agreement appears satisfactory, and the issue does not need further discussion. However, the issue of what areas are affected needs further discussion.

Question 3 was designed to elicit opinions regarding the importance of natural low flows, consumptive uses, diversions, and interactions on salinity. In general, all respondents agreed all of these have an effect. Interactions among all factors received the most votes.

Comments received and responses are:

Comments	Response
Concern for effects of power plant peaking discharges.	Relevant only if there is an impact of peaking operation in the study area.
Have observed high variation in nutrient concentrations in Susquehanna River flats, possibly related to Conowingo peaking operation.	Need to consider further.
Need to decide base conditions, use natural flow regime to measure impact of man-induced changes.	Needs further discussion.
C&D Canal also affects salinity.	Will include in final report

Question 4 was designed to determine the extent of agreement on whether natural low flows affect certain resources and uses. The responses indicate general agreement dissolved oxygen, phytoplankton, zooplankton, submerged aquatic vegetation (SAV), shellfish and finfish are significantly affected, although there are some dissenting votes. A majority of respondents thinks the following resources and uses are significantly affected, but there is more disagreement and uncertainty regarding significance: temperature; emergent aquatic vegetation (EAV); municipal and industrial water supply; recreation; and commercial. There is no consensus regarding significance of effects on aesthetic uses.

Some respondents mentioned the following water quality resources on which low flows may have a potential significant affect: nutrient inputs; sediment inputs; toxic inputs; alkalinity; and dissolved inorganic carbon (DIC) availability. The following shellfish species are mentioned as being affected: oligohaline species, in general; oysters; oyster diseases; rangia; clams; macoma; and mya (soft shell clam). The following finfish species are mentioned as being affected: anadromous (all life stages); and juvenile and larvae life stages.

The following comments were made regarding municipal and industrial water supply: effect of flows on salinity at Havre de Grace may someday need to be addressed; and effects on water supply are insignificant, except during a severe drought. In response to the latter comment, the question did not say anything about the conditions, so the response is interpreted to mean water supply may be affected under severe drought conditions. Since Havre de Grace has had two occurrences of high salinity since 1985, and there was no truly severe drought condition during the period, it appears more consideration of this problem is necessary.

Fishing is the only commercial use mentioned in the comments.

Comments and responses are:

Comment	Response
Need to carefully define area affected.	Agree, but area affected needs more discussion.
Effects on water quality, zooplankton, habitat, municipal and industrial water supply, recreation, commercial and esthetic uses more pronounced during several consecutive years of natural low flow.	Agree. Will consider effects of consecutive years in the strategy.
Historically, living resources and habitats prospered despite (or because of) natural low flow occurrences.	Depends on how you read the historical record.
Could affect all resources and uses, but only in limited areas near mouth of Susquehanna River.	Agree with first part, but point was to evaluate whether some resources and uses are considered more affected than others. Area affected needs more discussion.

The purpose of **Question 5** was to elicit opinions regarding the effects of consumptive uses and diversions on the same resources and uses as Question 4. In general, there is consensus the same resources and uses are significantly affected, and there is the same disagreement regarding certain uses and resources. In particular, there is less agreement regarding the significance of effects on water supply.

In general, the same uses and resources were mentioned in the comments as in question 4. However, the issue of dilution of waste discharges, including heated discharges, was mentioned. Also, distribution of clams and crabs in the upper and middle bay was mentioned as a possible effect. There appears to be a disagreement regarding the life stages affected, which may depend on which species are being considered. Jellyfish and recreational fishing also are mentioned as possibly being impacted.

Comments and responses are:

Comment	Response
Need to define area affected.	Agree, but area needs more discussion.
Alone or in combination with natural low flows; depends on amount and duration.	Agree. Data regarding present magnitude were provided.
Need to see data for volume of flow.	Data were provided.
Depends on magnitude of consumptive uses and diversions.	Agree, but need to determine what magnitude is significant
Could affect all resources and uses, but only in limited areas near mouth of Susquehanna River.	Agree with first part, but area affected needs further discussion.

Question 6 was intended to obtain comments on what parts of the bay are affected by natural low flows. As noted, responses to several previous questions mentioned this issue. Several possible areas were included in the question. The tidal fresh and low salinity zones received the most votes, but there was strong support for the Susquehanna River flats and the reach from head-of-tide to mouth of the Potomac River as the affected reaches. One comment was that studies should concentrate on the Susquehanna River flats, because of the significant impacts on SAV in that area.

Other areas mentioned in the comments include: lower bay; C&D Canal; Delaware Bay; head-of-tide to the Bay Bridge (Annapolis); whole bay if flow approaches the 1960's level; and area affected by isohaline displacement, but not the entire bay. It appears this issue needs more discussion.

Question 7 was designed to obtain the same information as question 6, but with regard to the effects of consumptive uses and diversions. The response was very similar, but fewer respondents indicated the reach from head-of-tide to the mouth of the Potomac River. It was noted impacts depend on the magnitude of consumptive uses and diversions, and that seems reasonable. Another comment was that the impacted area is from the head-of-tide to the Bay Bridge at Annapolis.

Question 8 was designed to obtain opinions regarding the season of the year during which natural low flows affect the bay. Most respondents indicated summer and fall, but a significant number indicated spring and a few voted for winter.

Comments and responses are:

Comment	Response
Prolonged multiyear drought has greater impact on salinity in late summer.	Need to consider multiyear effects.
Low flows in spring have positive effect.	Low flows in spring are expected to have positive effect on dissolved oxygen. Recent data questions that hypothesis (*Bay Journal*, July-August 1995). Multiseason salinity effects uncertain.

Question 9 was designed to evaluate seasonal effects of consumptive uses and diversions. The response was basically the same as for question 8, but with more concern for the effect during the winter. Comments include:

- Concern for effects of Baltimore withdrawal on flows during all seasons; and
- Consumptive uses and diversions may affect all seasons but in different degrees.

Both comments are valid. Baltimore is currently conducting a study to determine the timing of withdrawals from the Susquehanna River.

Question 10 was designed to elicit opinions regarding the importance of certain factors other than those covered in previous questions. Responses indicate current pattern, nutrient availability, and biological interactions are significant factors in assessing effects of low freshwater inflows on the bay. There was no agreement regarding the significance of pH or carbon dioxide. One comment was to add stratification to current pattern, and that was intended to be implied by the question. There also is a general comment that impacts depend on antecedent conditions in the bay, and factor needs to be considered. Another general comment was that the primary concern is effects of dissolved oxygen. Without disagreeing with the concern for dissolved oxygen, this question was intended to address other potential factors. There also were a number of expressions of uncertainty regarding the significance of these factors.

Question 11 requested opinions regarding the importance of the same factors in assessing effects of consumptive uses and diversions. The response was essentially the same, and the comments were similar.

Question 12 asked whether certain components of the bay ecology were affected by low flows and reductions in low flows. The majority believes sediment inputs, pollution inputs, dispersion of pollutants, nutrient inputs, nutrient transport and fate, and transport of nonmotile organisms, are significantly affected. However, a large group questions the significance of the impact on sediment inputs, dispersion of pollutants, and non-motile organism transport.

Comments and responses are:

Comment	Response
Sediment inputs not a concern until Conowingo reaches equilibrium.	Relevance to low flow problems unclear.
Pollution inputs: Point sources insignificant because they are independent of flow; only nonpoint sources (nutrients) significant.	Needs further discussion.
Dispersion of pollutants affected only near mouth of Susquehanna River.	Needs further discussion.
Uncertain about significance of effects of sediment inputs due to effects of power dams.	Relevance not clear.

Question 13 asked whether flow management should be based on an acceptable level of impact on certain resources and uses. The question was designed to accomplish two purposes: determine whether flow management could be based on an acceptable level of impact; and which uses should be considered in establishing that level. The responses to the question indicate the concept of basing flow management on an acceptable level of impact is satisfactory, and most respondents agree the following uses should be considered: SAV; EAV; shellfish; finfish; waterfowl; municipal and industrial water supply and recreation. A significant minority indicates recreation is unimportant. A few respondents disagree with the majority opinion regarding the other uses listed.

The only comment was that flow management should be based on all potential impacts. The study team suggests flow management should be based on all significant impacts, insofar as those can be estimated. The difference appears to be semantic, and there appears to be basic agreement on the issue.

Question 14 was designed to seek opinions on whether there is a need to manage low flows for certain purposes. Most respondents agree there is a need to manage Susquehanna River low flows to replace consumptive uses, maintain appropriate seasonal salinity patterns, prevent degradation of inflow water quality, and prevent degradation of bay water quality. The largest number say Susquehanna River low flows should not be managed to augment low flows, but an equal number of respondents have no opinion on the issue, and almost as many believe there is a need.

Comments and responses include:

Comment	Response
Augment low flows only in most dire circumstances.	Agree, but purpose of study should be to determine what those circumstances are.
Augment low flows only in special cases.	Same response.
Susquehanna River management should be used to correct water quality problems only in limited fashion.	Question was intended to ask whether flow quantity should be used to prevent degradation of bay water quality, where water quality degradation was related to flow. This comment seems to address a different issue.
Maintain appropriate salinity patterns and prevent inflow water quality degradation only related to man-generated impacts.	Needs further discussion.
Biota can handle natural low flow conditions.	Needs further discussion.
Need to establish historical salinity cycle. (CRC Symposium, June 1994)	Need to consider further.
Control consumptive uses/diversions, rather than replace. Wait for study results to answer whether there is a need.	Need to consider further.

Question 15 was designed to elicit opinions regarding appropriate goals for managing effects of natural low flows. Respondents were asked to select one of the following goals or propose a different goal:

- Management of effects of natural low flows is unnecessary because it is sufficient to maintain the natural flow regime;
- Maintain salinity levels experienced during a repeat of the 1960s drought;
- Maintain tolerable salinity levels for certain species in critical areas at all times;
- Maintain tolerable salinity levels for certain species in critical area at critical times;
- Maintain tolerable salinity levels for certain species in critical areas some percentage of time.

Approximately half of the respondents selected the first goal, but almost as many selected either goal 3, 4, or 5. No one selected goal 2. The only additional goal proposed was to eliminate the peaking operation at Conowingo. One person did not respond to the question.

Question 16 asked a similar question regarding goals for managing effects of consumptive uses and diversions. The following alternative goals were provided:

- Specify some maximum level of flow reduction;
- Maintain salinity levels experienced during a repeat of the 1960s drought;
- Maintain tolerable salinity levels in critical areas at all times;

- Maintain tolerable salinity levels for certain species in critical areas at critical times; and
- Maintain tolerable salinity levels in critical areas some percentage of time.

The largest single number of respondents selected the first goal, but approximately 60 percent of the respondents favored one of the other goals provided. One respondent proposed the goal should be to prevent degradation of water quality and maintain natural flow patterns. Another goal proposed was to maintain tolerable water quality conditions (e.g., dissolved oxygen) in primary impact areas at all times.

One comment received was that a salinity goal is unrealistic because it is operationally difficult to accomplish. The same person suggested a more realistic goal is to try to maintain the seasonal hydrograph, or establish a release scheme to release a certain volume over a certain period of time. Without disagreeing with the comment, it appears the determination of the release volume is a key sticking point. A salinity target, presumably based on some acceptable level of impact on the bay and its resources, is one way to establish the release volume. In effect, that was what was done in the San Francisco Bay agreement, as discussed in section 3.6.2.1, but those procedures may not be applicable to the Susquehanna River and Chesapeake Bay.

Another comment was that maintaining tolerable salinity levels may be a goal, but some surrogate measure may be necessary to achieve that goal.

Question 17 asked whether protection of species in the tidal fresh and low salinity zones against changes in salinity was the most important aspect of low freshwater flow management. About 60 percent of the respondents agreed with the idea, but the remainder were equally divided between NO and NO OPINION. Those that responded NO were asked what they thought was the most important aspect. The following were proposed:

- Water supply for human use;
- Maintain salinity up to 15 ppt;
- No single most important factor; need to consider temperature, DO, fish in reservoir tailwaters, increased dilution of pollution, effect on Havre de Grace water supply intake;
- Nutrient cycle in bay and overall productivity and habitat quality;
- Impact in mesohaline region (DO and oyster disease) are as important; and
- High flows have more impact than low flows; some change in salinity is normal, and biota can adapt.

The following comments were made:

- Salinity may be on a long period cycle; and
- Do not worry about mild responses down bay, concentrate on strong response in tidal freshwater area.

It appears there is no consensus that any aspect is most important.

Question 18 asked whether there was a need to maintain a specific size of the low salinity zone during low flow periods. The response was almost equally divided between YES and NO, but almost as many had NO OPINION.

Question 19 asked whether there is need to develop a target low freshwater flow regime for the Susquehanna River. About 67 percent said YES, most of the other respondents had NO OPINION. One respondent said the natural flow pattern should be maintained whenever possible.

Question 20 asked whether low flows in other tributary watersheds will affect the salinity in the bay. Most responded YES, but there were a few NO and NO OPINION responses. One comment was that only major tributaries should be considered, and that was the intent of the question. Another comment was that low flows in other watersheds will have a marginal effect if the Susquehanna River provides 50 percent of the freshwater in the bay above the Potomac River. Since the Susquehanna River provides 50 percent of the total freshwater inflow to the bay, and at least 80 percent of the total inflow above the mouth of the Potomac River, the conclusion that low flows in other watersheds will have a marginal impact needs to be reevaluated. Another comment was that the effect of other tributaries will be local. The comment may be valid, but it is not clear what is considered local, or whether that affects the need to consider those tributaries. The latter two comments may reflect confusion regarding which tributaries were meant in the question.

Question 21 asked whether studies of effects of low flows, consumptive uses, and diversions should include all the tributaries to the bay. Again, the question should have said all the main tributaries. Again, most of the respondents answered YES, but there were more dissents than for the previous question. The only significant comment received was that the studies should concentrate on the area above the Bay Bridge.

Approximately half of the respondents agreed further study of the effect of the C&D Canal on the Chesapeake Bay (**Question 22**) is necessary. There were three dissents, and the remainder had NO OPINION.

About half of the respondents agreed that withdrawal of water from the Susquehanna River for the City of Baltimore will affect salinity and living resources (**Question 23**), with only two dissents. Almost 66 percent of the respondents agreed that the effect of the Baltimore withdrawal needs further study (**Question 24**), with only one dissent.

Comments and responses are:

Comments	Response
Water reenters bay as sewage.	True, but it reenters about 35 miles downstream from where it is withdrawn.
Baltimore withdrawal is affecting salinity and living resources.	Possibly, but not aware of any evidence.
Baltimore withdrawal has effect as cumulative withdrawal.	Agree, if cumulative withdrawal means cumulative consumptive use and diversion.
If large enough.	Agree.

About 75 percent of the respondents agreed that the recovery time of the species following a low flow period is important in managing low freshwater flows (**Question 25**).

Question 26 and 27 were designed to elicit opinions regarding the need for additional studies of the effect of low flows, consumptive uses and diversions on the living resources of the bay. About 40 percent said additional studies are necessary, and a like number had NO OPINION. About 20 percent thought the problem has been adequately studied.

The largest number of respondents agreed the following suggested studies were necessary, with a few dissents, and a larger number (in most cases) of NO OPINION.

- Basic data collection and analysis;
- Physical/biological process studies;
- Modeling studies using the 3-D model;
- Living resource impact field studies;
- Flow management studies;
- Watershed hydrology studies; and
- Literature review and synthesis.

Physical and biological process studies seemed to be the greatest concern, but that may be due to the interests of those who responded.

The following additional studies were proposed by the respondents:

- Investigate impacts of dissolved oxygen and nutrients that were not studied previously;
- Zonal extent, duration, and specific physical studies on target species;
- Determine relationship of flow and salinity; and
- Include recent studies of role of flow in bay's nutrient and oxygen dynamics, phytoplankton production, and fate and effect of toxics.

The following comments were received:

- Need to concentrate on biological impact measurement;
- Basic data collection and analysis and living resource impact studies may be necessary, but they should be limited and targeted;
- Question how much literature review is necessary;
- Look at importance of additional watershed hydrology studies from risk analysis viewpoint; and
- Watershed hydrology studies probably unnecessary, should have adequate data.

Question 28 asked whether future studies should be designed to evaluate impacts of natural low flow, rather than determining how to satisfy preset salinity conditions. Approximately half the respondents agreed this was necessary, but approximately 20 percent disagreed, and the remainder had NO OPINION.

Question 29 asked the same question with regard to effects of consumptive uses and diversions. Approximately 67 percent agreed, with only a few dissents.

Question 30 asked whether increased salinities will significantly increase the effect of wood borers on marine facilities. About 40 percent of the respondents said YES, a couple of people said NO, and about 60 percent had NO OPINION. One respondent commented borers will have an increased effect only if salinity is at a constant high level.

4.3.2. Living resources questionnaire

Sixteen responses were received to this part of the survey.

Questions 1 and 2 were designed to elicit opinions regarding the relative importance of salinity and water quality to the survivability and reproduction of the following resources: SAV; EAV; shellfish; finfish; and waterfowl. The responses varied a little, but about 75 percent believe salinity is either critical or important to the first four groups of resources. One person felt salinity was unimportant to these groups. The remainder had NO OPINION. About 60 percent felt salinity was critical or important to waterfowl. About 90 percent felt water quality is critical or important to SAV, shellfish, and finfish. Ten people felt water quality is critical or important to EAV, but 50 percent felt water quality is important to waterfowl. Two people felt water quality was unimportant to EAV, and the rest had NO OPINION regarding all five groups of resources.

A few people commented these questions should have been more specific with regard to individual species or water quality constituents. Those kinds of questions were addressed in the main survey.

Question 3 asked about evidence of the need to maintain the size of the low salinity zone. Five people said such evidence exists, one said NO, and the rest did not know whether such evidence is available. One person cited the Corps of Engineers' study for evidence of that need. Recognizing the Corps of Engineers' study was very extensive, we have not been able to find actual evidence of this need in that study.

Question 4 asked whether there were any historical data showing effects of low flows on living resources. The intent of the question was to obtain specific references to sources of data Seven people responded such data were available, and three responded the data were not available. Several respondents suggested the Corps of Engineers' study as a source of data, but again, we have not been able to find that data. Another person cited U.S. Fish and Wildlife Service (USFWS) instream flow studies as a source of such data. The first author is familiar with the USFWS Instream Flow Incremental Methodology (IFIM), and it does not address salinity issues. Another comment noted data are available more for freshwater streams than for estuaries, which confirms our understanding. Another comment cited the historical distribution of oysters above the Bay Bridge since the last ice age, as shown by fossil shells. The respondent indicates less beaver dams and more urbanization allow for more spring runoff, which reduces salinities and increases oyster mortality. Another comment suggested checking with Maryland fisheries staff. Another source suggested was Richard Lacoutre, ANS-ERC. One person mentioned intense monitoring in 1993 in the Susquehanna River flats. Due to time and cost limitations we were not able to follow up on these suggestions.

Question 5 asked whether the respondents agreed all species in the following groups can adapt to small changes over short or long periods of time: SAV; EAV; shellfish; finfish; and waterfowl. Approximately 75 percent agreed in all cases. There were a few dissents, and a number with NO OPINION.

Comments received on this question indicate the question was too generally worded, and questioned how small and how short, and whether all species in the group could adapt. The question was deliberately worded to be very general. Another person said most species in the bay are present because they are adaptable. Another person cites the tolerable salinity ranges for oysters, and appears to be saying species can adapt to small changes, provided salinity remains within their tolerable range. It appears there is a need to address the issue with more specifics.

Question 6 asked what is the appropriate time scale for addressing impacts of low flows on living resources. Seven people said short term (days to weeks); 13 said medium term (weeks to months) and 12 said long term (years). It appears there is a need to address these impacts on multiple time scales. One respondent suggested it depends on the time of year, and the life stages present at the time. Another person suggested it depends on the degree of low flow.

Question 7 asked whether the three-dimensional model of the Chesapeake Bay (including the living resources components presently being developed) is the best way to evaluate impacts of low flows and changes in low flows. Six people agreed, but two disagreed, and eight had NO OPINION. One person said we need to understand the basic biology and ecology in addition to using the model. Another person suggested looking at impacts of 1960's drought. We are not aware of any existing analyses regarding living resource impacts during the 1960's drought.

Question 8 asked whether the three-dimensional model will be adequate for modeling effects on all species that will be significantly impacted. Two people responded YES, two people NO, five were UNSURE, and seven had NO OPINION. One person suggested the 1985-87 hydrology should be evaluated further. Stevenson states the SAV modeling is currently very crude, and doubts the model could ever be useful. These responses suggest the capabilities of the model are not well understood. They also suggest additional model development may be necessary to use the model to study the living resource impacts.

Question 9 asked whether the procedure used in the Corps of Engineers' study was adequate for determining low freshwater impacts. One person answered YES, three answered NO, and ten had NO OPINION. Comments included:

- Need to look at effects of low flows on dissolved oxygen, and nutrient dynamics;
- Many questions were unresolved in the work performed by the Biota Evaluation Panel, including scales of response for several organisms.

Several people were unfamiliar with the methodology, despite the fact a brief summary of the Corps' study was included in the information packet transmitted with the questionnaires.

Question 10 asked whether it was appropriate to average salinities over 90-day periods to evaluate impacts of living resources, and whether the seasons used in the Corps' study were appropriate. Four people said seasonal averaging was satisfactory, but eight people said it was not satisfactory, and three had no opinion. Seven people said the seasons used in the Corps of Engineers' study were appropriate, six said NO, and two had NO OPINION. Again, it appears the whole question of time scale needs to be considered carefully.

Comments include:

- More specific data preferable;
- Need to evaluate impact within season;
- Time scale for averaging salinities should be monthly during the period from late winter through summer, but longer term averaging satisfactory for rest of the year;
- The bay is too dynamic for seasonal averaging to be satisfactory; seasonal averaging was necessary in the Corps of Engineers study due to the inadequacies of the physical model; we have more sophisticated tools available today;
- Droughts and floods stress the bay. Averaging parameters over season removes the variability from the life cycles equation. The model should show wet, dry, and average years or average monthly flows;
- Shorter period, e.g., 2 weeks or a month;
- Treat time as a continuous variable;
- Key season is June 1 to September 30;
- Cannot study effect of Susquehanna River low flows until the peaking operation of the power dams is eliminated; and
- Seasonal averaging was used in the Corps of Engineers study because of the inadequacies of the physical model.

4.3.3. State water resources agencies questionnaire

Only five responses were received from state water resource agencies, four from Pa. Department of Environmental Resources (now Department of Environmental Protection (DEP)) and one from Md. WRA.

Question 1 in this part of the survey asked whether the methodology used in the Corps of Engineers' study to evaluate water supply, recreation, commercial, economic and social impacts was satisfactory for the purpose of developing management plans. Most of the respondents indicated NO OPINION, with a few NO responses, and even fewer YES responses. The conclusion is the Corps' methodology and conclusions need to be considered very carefully.

Question 2 asked whether a predictive relationship was needed between salinity and low freshwater inflows. Two people responded YES, one NO, and two NO OPINION. No one had any suggestions regarding the development of such a relationship. One comment was the three-dimensional model of the bay could be used to evaluate salinity and water quality effects, but the respondent was not clear how to handle the living resources impacts.

Question 3 asked whether future studies should be designed to develop curves of impact versus flow. Two people agreed, one disagreed, and two had no opinion.

Question 4 asked whether the three-dimensional model of the bay (including the living resources components presently being developed) was the best way to evaluate impact of low flows. Two people said YES, one with reservations, and three people had NO OPINION. It appears, again, use of the model needs to be considered carefully.

4.3.4. Maryland Department of the Environment questionnaire

MDE provided one consolidated response for the four people who received the survey.

Questions 1 and 2 in this part of the survey were designed to elicit opinions regarding the relative importance of salinity and water quality to the survivability and reproduction of the following resources: SAV; EAV; shellfish; finfish; and waterfowl. MDE feels salinity is critical for SAV, EAV, and shellfish, and important for finfish and waterfowl. MDE believes water quality is critical for these species.

In response to the **Question 3**, MDE believes there is no evidence of the need to maintain the size of the low salinity zone.

In response to the **Question 4**, MDE believes the appropriate time scale for addressing impacts of low flows on living resources is short term (days to weeks) and medium term (weeks to months). Long term (years) is considered unimportant.

MDE does not have an opinion regarding whether the procedures used in the Corps of Engineers' study was adequate to evaluate biological, water supply, recreation, commercial, economic, or social impacts (**Questions 5 and 6**).

MDE agrees all species in the following groups can adapt to small changes in salinity over short or long periods of time: SAV; EAV; shellfish; finfish; waterfowl (**Question 7**).

MDE does not believe the three-dimensional model presently under development will be adequate for modeling effects of low flows on all the species that will be significantly impacted (**Question 8).** They comment the model is designed to deal with average conditions, and does not perform well at extremes. Also, only a few species are modeled (**Question 9**).

MDE agrees a predictive relationship between salinity and low freshwater inflows is needed to develop flow management plans. But, they have no suggestions as to how to develop such a relationship (**Question 10**). They also agree future studies should be designed to develop additional points on curves of impact versus flow (**Question 11**). They do not believe it is appropriate to average salinities over seasons to evaluate impacts (**Question 12**).

4.3.5. Baltimore District Corps of Engineers questionnaire

While two responses were received from the Corps of Engineers staff, one respondent deferred to the other one on all except one question in this part of the survey.

Question 1 noted the Corps of Engineers study effectively defined the problem in terms of impacts on salinity and the resultant impacts on habitat, and asked whether there were other ways to define the problem. In response, the Corps staff noted water quality related impacts were not studied.

Question 2 asked whether there was historical data showing effects of low flows on living resources. The Corps staff said they were not aware of any useful hard data. However, they suggested looking at long-term oyster harvest data to see what it shows.

Question 3 asked about the recommendation in the Corps' report for a comprehensive water supply and drought management study to optimize the use of existing water supplies and minimize reduction in freshwater inflows. The response was that this was never developed beyond the general recommendation.

Question 4 asked whether the methodology used to evaluate water supply, recreation, commercial, economic, and social impacts was adequate for the purpose of developing management plans. The response was that the original study was equivalent to a reconnaissance level study, and a feasibility level study would be necessary as the next stage in developing management plans.

Question 5 asked whether the salinity data developed using the physical model were analyzed in any greater detail than seasonal aggregation and interseasonal comparison. The response was that no additional analysis has been done. (See Appendix D, Chapter III, p. D-28 of the Low Freshwater Inflow Study report.)

In response to **Question 6**, the Corps staff indicated the physical model data sets can be used to a limited degree for the following purposes:

- Improve understanding of the salinity response to different flow conditions;
- To facilitate design of future studies; and
- To develop interim management guidelines.

The Corps staff suggested the following additional studies would be desirable:

- Expanded testing of different inflow scenarios to define the salinity inflow regime under a broad range of hydrologic conditions;
- Expanded analysis of impacts of low flows on biological resources;
- Limited analysis of effects of C&D Canal on upper bay salinities under drought level conditions in the Susquehanna River; and
- Consider water quality impacts of drought level flows.

The Corps staff agrees a predictive relationship between freshwater flows and salinity needs to be developed, and they have proposals regarding how to develop such a relationship. They also agree future studies should be designed to develop additional points on curves of impact versus flow. They believe the three-dimensional model of the bay is the best way to evaluate impacts, including living resource impacts. However, they are not sure the model will be adequate for this purpose. They comment the model is more sophisticated and specific in modeling salinity and water quality changes and relationships. The implication is the model is not as sophisticated in modeling living resources.

4.3.6. Waterways Experiment Station questionnaire

A letter was sent to Donald Robey, Chief, Environmental Processes and Effects Division of the Environmental Laboratory, asking for a response to certain questions. The original letter is included in Appendix A (page 171). Dr. Carl Cerco responded by telephone call to the first author July 28, 1995. The following is a summary of the original questions and the telephone discussion.

1. Dr. Cerco said high frequency fluctuations in flow rate were noticed in the hydrograph at Conowingo. He did not look for any effects on the bay, but expects the effect is damped out very quickly.

2. Dr. Cerco confirmed the upper boundary of the model is the head-of-tide on the Susquehanna River.

3. Dr. Cerco said the most important thing that they have learned during development and application of the model is that low flows have two opposite effects, one beneficial to DO, and the other detrimental. The beneficial effect is the low flows reduce the stratification, and therefore the anoxia. The detrimental effect is low flows increase residence time, which potentially reduces DO. It is necessary to run specific scenarios to evaluate the beneficial and detrimental effects.

4. Dr. Cerco said the model runs on a 5-minute time step, and they can print output at that interval. Seasonal averaging was used in the water quality studies because of limited field data for comparison. The salinity and temperature output at 5-minute intervals seem valid; chlorophyll and some others do not. Valid scenario comparisons can be made at whatever time interval we would specify. The author suggested a 2-week averaging period, and he said that seems reasonable.

5. Dr. Cerco said the model can be used to test alternative hypotheses regarding the appropriate time scale.

6. Dr. Cerco says the model can be used to evaluate short-term impacts (say 2-4 weeks) of Susquehanna River flows and water quality on the bay salinity, water quality, and living resources.

7. Dr. Cerco does not think there is any problem with using the model to evaluate short-term impacts. The physics is highly accurate on any time scale. There is not anything in the model or the output that would limit its use for any time period.

8. Dr. Cerco said the model is satisfactory for extreme conditions because extreme conditions are used in the calibration, and therefore it can be used to model extreme years. It is satisfactory for other than average conditions.

9. Dr. Cerco said it is feasible to use existing model-generated salinity or water quality time series for the calibration period; the 30-year simulation; or 10-year simulation to understand salinity/water quality evolution at different locations in years with different Susquehanna River flows. The 3-year calibration period represents different flow conditions. The hydrodynamic simulation for the 3-year calibration period was used in the 30-year simulations based on classification of years. Therefore, the 30-year simulations will show the same hydrodynamics, depending on year classification, as for the three calibration years. He thinks 30-year hydrodynamic simulations would be necessary to evaluate effects of low flows.

10. Johnson (Waterways Experiment Station, Tech Report HL-91-7) has done a short-term comparison of salinity and temperature data in his report on the calibration of the model.

11. From Dr. Cerco's viewpoint, there is no technical reason for running either long records or specific test years. We should try to make optimal use of what has been done already. The model-generated salinity and water quality data for 1985 (dry year) and 1986 (average year) should be compared. Different flows could be run for these years, and the salinity and water quality comparisons made. The hydrodynamics and water quality model(s) are functional, so these comparisons could be done at any time. The living resources components will not be available for some time.

12. The hydrodynamic model requires 12 hours of CPU time to run one calendar-year on the Cray supercomputer. The water quality model requires 3 hours of CPU time to run one year. The manpower required is about 1 man-week to develop input data for one year, and about 1 man-week to evaluate output. The elapsed time for one scenario is about one month.

13. Dr. Cerco said, to properly run long-term flow simulations, the watershed model should be run to develop the water quality input time series to the bay. If we want to look at physical aspects (e.g., salinity) only, it is necessary only to model the flow rate, which is easy to do. US EPA has 10-year water quality input sequence(s) available that can be used.

14. There is no problem with establishing initial conditions in the mathematical model.

    Dr. Cerco recommended going with the least-cost option, which would involve running the 1985 calibration period with modified flows. This could be done fairly quickly.

4.4. Conclusions

- There is generally a consensus regarding the issues which need to be addressed.
- Both salinity and water quality impacts need to be addressed.
- Natural low flows, consumptive uses and diversions, and interactions between natural low flows and consumptive uses and diversions need to be considered in developing the strategy.
- Target living resource species should be selected.
- Impacts on the following resources and uses need to be considered in developing the strategy:

    * Water Quality

        ♦ Current pattern (stratification, dispersion)
        ♦ Dissolved oxygen
        ♦ Nutrient inputs
        ♦ Temperature
        ♦ Sediment inputs
        ♦ Toxic inputs
        ♦ Alkalinity
        ♦ DIC availability

* Phytoplankton
* Zooplankton
* SAV
* EAV
* Shellfish

  ♦ Oligohaline species in general
  ♦ Oysters and oyster diseases
  ♦ Rangia (brackish clam), macoma, mya (soft clam)

* Finfish

  ♦ Anadromous, especially spawning and rearing life stages

* Municipal and industrial water supply for City of Havre de Grace
* Recreation uses especially fishing and water contact sports
* Commercial fishing
* Aesthetic impacts can be ignored.

- The following issues need to be addressed in the final report:

  * Authority and mechanism to regulate;
  * Location and operation of hydropower facilities;
  * Methodology used in Corps of Engineers' study to evaluate biological impacts; and
  * Dissolved oxygen dynamics and seasonal impacts.

- Issues that need to be discussed further in the strategy are summarized in the next section.

5.0. SUMMARY OF ISSUES

Based on the literature review and the survey results, it was determined the following issues need to be addressed in the strategy.

- What are the principles on which flow management should be based?
- What are the goals of flow management for the Chesapeake Bay?
- In what ways do natural Susquehanna River flows and consumptive uses affect the Chesapeake Bay?
- What is the effect of flows on circulation patterns?
- What is the effect of flows on salinity and water quality?
- What is the effect of flows on living resources?
- How should the adaptability of species to different conditions be considered?
- How should biological impact be determined?
- What is the effect of flows on water supply?
- What is the effect of flows on other uses of the Chesapeake Bay?
- What are the economic impacts of flows?
- What uses and resources need to be considered in future studies?
- How should indicator species be selected in order to evaluate impacts on living resources?
- What indicator species should be used?
- How should the problem be approached?
- Should natural low flows from the Susquehanna River basin be augmented under some conditions, and if so what are those conditions?
- Should consumptive uses and diversions in the Susquehanna River basin be managed to minimize effects on the Chesapeake Bay?
- How should consumptive uses and diversions be managed to minimize impacts in the Susquehanna basin and protect the bay?
- What is the relationship between consumptive use management to mitigate impacts within the Susquehanna basin and consumptive use management to mitigate impacts of consumptive uses and diversions on the bay.
- What are the management guidelines?
- What area of the Chesapeake Bay is affected by Susquehanna River flows?
- What is the effect of hydropower operations on the Chesapeake Bay?
- Does the Chesapeake and Delaware Canal have a significant effect on the salinity and the living resources of the Chesapeake Bay?
- How does the effect of the C&D Canal relate to effects of Susquehanna River low flows?
- What research questions need to be answered?
- What is the study plan for the first iteration?
- What is the appropriate time scale for evaluation of effects?
- How should this strategy be implemented?
- What is the role of monitoring data in the study of the effects of flows on the bay?

6.0. WORKSHOP

6.1. Introduction

The purpose of the workshop was to review the study findings and develop a consensus regarding a strategy to study and manage the effects of low flows from the Susquehanna River on the Chesapeake Bay.

The workshop was held at the Loew's Annapolis Hotel on September 25-26, 1995. The moderator for the workshop was Dr. Donald Boesch of the University of Maryland Center for Estuarine and Environmental Studies. The participants in the workshop are shown in Appendix D.

A summary of the final report and a draft strategy report were provided to workshop participants approximately two weeks prior to the workshop.

6.2. Workshop Process

The workshop agenda included four major parts:

- Presentation of study findings by the study team;
- Presentation of a draft strategy by the study team;
- Presentation by the rapporteur for each discussion group;
- Development of a consensus regarding the strategy.

The workshop participants were asked to review the following materials prior to the workshop:

- A summary of the final report sections describing:
    - Reasons for studying effects of low flows and the need for a strategy for studying those low flows;
    - Description of the Chesapeake Bay Program and the Susquehanna River Basin Commission Program, and the relationship between the two programs;
    - Proposed definitions of various terms used;
    - Susquehanna River natural flow hydrology and consumptive uses and diversions;
    - Effects of Susquehanna River natural high and low flows, consumptive uses, and diversions on the Chesapeake Bay uses and resources;
    - Effects of C&D Canal on Chesapeake Bay;
    - Related Studies in the San Francisco Bay Delta;
    - Summary of survey results; and
    - Issues to be addressed.

- A draft strategy, which included the following parts:
    - Statement of purpose of the strategy;
    - Definitions;
    - Issues that need to be addressed in the strategy;
    - Flow management principles, needs, and issues;
    - Bay-impact issues;

* Selected target species;
* Time scale;
* Other factors affecting Chesapeake Bay:

  - ♦ Effects of other tributaries and
  - ♦ Effects of C&D Canal;

* Proposed research questions;
* Strategy implementation; and
* Proposed studies.

6.3. Presentation of Study Results

The study team presented the results of the study. The major findings are summarized as follows:

- Study procedures to date include developing Susquehanna River hydrology, review of selected literature, a survey of interested parties, and preparation of a draft strategy.
- The Susquehanna River is the largest tributary to the Chesapeake Bay. On average, the Susquehanna River provides about 50 percent of the total freshwater inflow and more than 80 percent of the total freshwater inflow above the Potomac River.
- Susquehanna flows affect circulation, salinity, and water quality, particularly dissolved oxygen.
- Existing consumptive uses and diversions in the Susquehanna basin are presently estimated as 785 cfs.
- Effects of both high flows and low flows on bay water quality are not well understood.
- The Corps of Engineers study (1984a, 1984b) showed potentially significant impacts of natural low flows and consumptive uses on the salinity and living resources of the bay.
- Hydropower operations are not expected to significantly affect salinity, but may affect water quality and living resources.
- Natural low flows have affected water supply for the City of Havre de Grace, and also may affect the water supply for the town of Perryville in the future.
- Consumptive uses and diversions also may affect water supply.
- Recreational and commercial uses will be affected if there is a significant effect on living resources.
- Economic impacts can be expected as a result of effects on living resources and water supply.
- The area most affected by Susquehanna low flows and consumptive uses is believed to be the area upstream from the Potomac River.
- The C&D Canal also affects salinity, and needs to be considered in studies of effects of Susquehanna flows.
- Similar studies are underway in the San Francisco Bay/Delta, and in the Appalachicola River Estuary.
- The San Francisco Bay/Delta study has adopted a salinity standard based on the position of the 2 ppt isohaline.
- The Chesapeake Bay three-dimensional and tributary models are useful tools in studying the effects of low flows and consumptive uses on the bay.

- The improved hydrodynamic and water quality models are, or soon will be, available, but the living resources components will not be available for several years.
- The survey results showed a large number of issues need to be addressed in the strategy.

Following the presentation of study findings, Dr. Goshorn presented maps that showed large changes in the salinity distribution between 1994, a high flow year, and 1995, a low flow year. Mr. Lower suggested the data could be used to demonstrate impacts of flow changes. The potential effects of the flow induced salinity changes on oyster restoration were mentioned. Dr. Boicourt said the physical model used in the Corps of Engineers study (1984a, 1984b) was adequate for the area below the Bay Bridge, but may be inadequate for the area above the Bay Bridge.

6.4. Presentation of Draft Strategy

The strategy developed by the study team and the steering committee included a two-phase study. The first phase included near-term studies designed to develop interim flow management guidelines for the Chesapeake Bay and Susquehanna basin. The second phase included longer range studies leading to development of final flow management guidelines for the Susquehanna basin. These studies were designed to address impacts of Susquehanna flows, and to begin to address impacts of actions taken in the Susquehanna basin on the bay.

The draft strategy included flow management principles, needs, and issues, and proposed the purpose of the strategy is to quantify the effect of freshwater inflow, including natural flow and changes in natural flow, on the bay. The strategy also included the following proposed goals of flow management:

- Maintain tolerable salinity conditions for the target species at all times of year; and
- Maintain tolerable water quality conditions for the target species, to the extent water quality conditions are related to flows, at all times of year.

The draft strategy also included the following:

- A list of resources and uses that need to be considered in developing management plans;
- The study area should be between the head-of-tide and the mouth of the Potomac River;
- Modeling and field studies to evaluate impacts of flows and changes in flows; and
- Certain research questions to be addressed.

The most important research question is the amount of water necessary to satisfy living resource needs, including:

- Protecting biodiversity;
- Restore and protect SAV, EAV, finfish and shellfish;
- Ensure successful reproduction; and
- Enhance the population of various species.

This research question ties the effects of quantity of water into the goals of the CBP.

6.5. Discussion Groups

Participants were assigned to one of the following groups:

Group	Rapporteur
Water Supply and Water Quality Issues	Ray Alden, Old Dominion University
Living Resources Issues	Larry Lower, Corps of Engineers
Implementation Issues	Terry Clark, Maryland Dept. of Environment

The people participating in each discussion group are shown in Appendix D.

These groups were asked to address the issues shown in Table 6.1.

The discussions are summarized in the following sections.

6.5.1. Water supply and water quality issues group

Issue: Need to manage Susquehanna flows for water supply

- Present and recent history indicate effects on water supply are a minor problem. However, that history may not represent a worst-case scenario.
- Future needs are uncertain. The following studies are needed: future demand; frequency of high salinity events; and factors causing high salinity events.
- The following studies are needed to determine whether flow management can address the needs of the bay:

  - What can be accomplished with existing storage capacity;
  - Amount of additional storage capacity necessary;
  - Travel time from point-of-release to the affected water supplies;
  - Risk analysis of augmentation releases; and
  - Cost-benefit analysis of flow augmentation versus alternative measures.

- With regard to the effects of salinity on the Havre de Grace water supply, cost-benefit analysis would probably favor changing the location of the intake pipes, rather than augmenting flows. However, that could change if augmentation or consumptive use management is necessary for other purposes such as living resources protection.
- The political aspects of making releases from storage, with appropriate lead-time that will affect other uses of the reservoirs, need to be considered.

Issue: Need to manage Susquehanna flows for water quality

- Major water quality issues are dissolved oxygen and salinity, but other constituents should be considered.
- Inflow to the Conowingo pool needs to be maintained, so that minimum flow requirements can be met.

Table 6.1. Chesapeake Bay Low Flow Strategy Study Workshop Discussion Groups

Group 1: Water Supply and Water Quality Issues
Topic: Water supply and water quality issues related to managing low flows consumptive uses and diversions.

Is there a need to manage Susquehanna River flows to improve water quality?

Is the scientific consensus regarding effects of spring flows on anoxia satisfactory as a basis for managing low flows? What additional studies are necessary to either validate or extend the scientific consensus?

Is there any evidence of changes in water quality inputs during low flows?

Is there water quality degradation during low flow periods?

Does Conowingo's peaking power operation affect salinity, water quality (dissolved oxygen, nutrient pulses), and living resources in the study area?

Is it adequate to model the main stem of the bay, or is there a need to model tributaries? Is the existing mathematical model adequate for modeling salinity and water quality during low flow conditions in the main stem of the bay or the tributaries? What improvements need to be made to the model?

Spatial and temporal scale:

What area is affected by Susquehanna River low flows?
What is appropriate time scale(s) for addressing salinity and water quality impacts of low flows?

Is data available to demonstrate historical impacts of low flows on water quality?

Group 2: Living Resources Issues
Topic: Living resources issues related to managing low flows, consumptive uses and diversions.

Is there a need to manage Susquehanna River flows to improve living resources?

Proposed concepts for determining biological impact of low flows, consumptive uses, and diversions.

Are the proposed target species appropriate?

Is it necessary to model the affects of low flows on living resources? Is it adequate to model the main stem of the bay, or is there a need to model the tributaries? Is the mathematical model presently under development adequate for modeling impacts of low flows on living resources in the main stem of the bay or the tributaries? If so, when can this be done?

Spatial and temporal issues:

What area is affected by Susquehanna River low flows?
What is appropriate time scale(s) for addressing living resources impacts of low flow?

Is it useful to consider normal conditions in formulating strategy? How should normal conditions be defined relative to salinity, water quality, and living resources?

Table 6.1. Chesapeake Bay Low Flow Strategy Study Workshop Discussion Groups —Continued

Group 2: Living Resources Issues—Continued **Topic: Living resources issues related to managing low flows, consumptive uses and diversions.**
Are data available to demonstrate historical impacts of low flows on living resources? What does that data show? To what extent is biological adaptation important in managing effects of flows on the living resources?
Group 3: Implementation Issues **Topic: Policy issues related to managing natural low flows, consumptive uses and diversions.**
Implementation Issues What organization will be responsible for conducting and coordinating the proposed studies? How will proposed studies be coordinated? How will proposed studies be funded? Should certain people/organizations be designated to conduct particular studies? Legal and institutional issues (Identify barriers to implementation of strategy. How should these barriers be addressed?). Are the proposed goals for managing low flows, consumptive uses, and diversions satisfactory? What are the policy implications of considering augmentation of natural low flows? Under what circumstances should low flow augmentation be considered? How should the economic impacts of natural low flows, consumptive uses, and diversions on the Chesapeake Bay be quantified? Is it important that the historical impacts of low flows be documented, assuming data are available? Are there any policy implications of managing flows based on defined normal conditions of flow, salinity, water quality, or living resources status? Are there any policy implications of the proposals regarding the area affected by Susquehanna River low flows?

- Water quality in the middle bay is believed to be linked to high spring time flows. The effect of low flows on the quality in the upper and middle bay during spring, summer, and fall needs further investigation.
- Flow management probably will not be able to improve water quality in the springtime, because insufficient storage is presently available. Additional study is necessary to demonstrate the feasibility of high flow management.
- It is more feasible to augment summer low flows, considering the amount of storage available.
- There is insufficient data to demonstrate cause and effect relationships of low flows.

- Potential effects of low flows on water quality are primarily in the upper bay. Further study is needed to determine whether there are water quality problems in the upper bay related to low flows.
- Hypotheses that need to be investigated:

  * Low flows during the spring affect water quality in the upper bay, e.g., oxygen depletion;
  * Summer or other season low flows affect dissolved oxygen in the upper bay; and
  * There are individual season and cross season effects.

- Salinity, chlorophyll, and sediment issues need to be considered.

Issue: Changes in water quality inputs during low flows

- The loadings of nutrients are reduced during low flow periods; generally these reductions improve dissolved oxygen in the bay.
- The effects of extremely low flows on dissolved oxygen need further study.
- The Conowingo peaking operation affects salinity, at least as far as the C&D Canal, but the environmental significance needs to be studied.
- The effects of Conowingo peaking operation on water quality and living resources are presently unknown, and additional studies of these effects are needed.

Issue: Models and modeling

- Flow and nutrient dynamics of the significant tributaries, as well as the main stem bay, need to be modeled.
- Different models are available, and may be useful for studying different effects or different time scales.

Issue: Spatial and temporal scales

- For summertime low flow effects, the study area should be from the head-of-tide to the mouth of Potomac River; for studies of the effects of springtime low flows, the entire bay should be considered.
- There is a need to place more focus on the upper bay, above the Bay Bridge.
- The focus of these studies should be on the upper bay, but the potential effects on the rest of the bay should be recognized.
- Varying time scales need to be considered, e.g., days for living resources and tributary flushing patterns, weeks to months for water quality status and trends.

Issue: Historical data availability and analysis

- The literature should be investigated for data demonstrating historical impacts of low flows on water quality.
- The historical data should be analyzed for effects of low flows on water quality and living resources, if possible, to demonstrate historical relationships and the need for flow management.
- The historical time period of interest should be the period of existing conditions, i.e., since construction of Conowingo Dam.

- The study by Cooper (1995) used a time scale that is too long to be useful for studying effects of low flow, but the techniques used in that study may be helpful.
- Stable isotope techniques also may be helpful to investigate relationships between salinity and dissolved oxygen, and the effect on certain types of biota, as shown by fossils.

Issue: Use of normal (acceptable) conditions in formulating strategy

- A certain amount of natural variability is critical for natural resources, but it may be appropriate to evaluate the effects of extremes on the living resources.
- Acceptable ranges of water quality for any zone should be based on living resources requirements. Studies are needed to determine regions where low flow conditions affect living resources, and where there may be benefits of flow management. If such regions are found, critical values or ranges to trigger flow management need to be developed. The location and time of occurrence of the various species need to be considered.
- There is a need to determine the feasibility of using a certain salinity to trigger management actions. The effects of salinity on oyster diseases are one factor to be considered.
- Effects of changes in salinity on the operation of industries that withdraw water from the bay may need to be considered.

6.5.2. Living resources group

Issue: Need to manage Susquehanna flows to improve living resources

- There probably is not any value at this time in managing high flows during the spring to improve living resources, primarily because the amount of storage available is inadequate.
- There may be value in managing low flows to improve living resources.
- Flow management would be most valuable during drought periods, but there may be some value during low flow periods.
- Studies of effects of flow on living resources should focus on the area where the impacts are most dramatic, which is probably the Susquehanna flats, and perhaps the small tributaries to the upper bay. The flats may be a very important area, in terms of effects of flows on living resources, and that limited area is much easier to study than the entire study area.
- Studies of the effects of flow should focus on salinity instead of water quality, because it is easy to demonstrate a causal connection between flow and salinity.
- The goal should be to maintain salinity distributions necessary for certain species at certain times of year.
- There may be other opportunities that need to be considered such as manipulating flows to improve temperature. Turbidity also may be a factor.
- Effects of consumptive uses and diversions on living resources are more likely to be demonstrated than effects of natural low flows.
- Living resources issues are very complex. The complexity of biological systems makes it difficult to develop quantitative procedures for determining biological impact of naturally occurring low flows, or consumptive uses and diversions.

- During normal flow years, the low flows may occur at a time when submerged aquatic vegetation (SAV) and emergent aquatic vegetation (EAV) are becoming dormant. Therefore, the focus should be on periodic severe drought conditions that threaten major impacts on the living resources, rather than the normal low flow year. The studies could focus on the severe conditions, where the value of low flow management may be to carry the living resource population through the severe period.
- While major droughts occur about once every 30 years, minor low flow events occur much more frequently. It is difficult to justify taking an action for an event that occurs infrequently such as major drought.
- The primary concern should be the effects of changing conditions (increased consumptive uses and diversions, C&D Canal) on the bay and its resources.

Issue: Study needs

- Study needs that result from setting a salinity goal include:

    * Data compilation and manipulation to determine the appropriate salinity goal, timing of compensation, and the amount of compensation.
    * Determine the capability to manipulate flow and circulation.
    * Selection of models to estimate effects of low flows and consumptive uses.
    * Continuation and, perhaps, supplementation of existing monitoring programs.

- The Corps of Engineers study (1984) contributed to understanding these issues, but much additional data have been developed since then, e.g., Maryland fishery sampling for 11 years, juvenile index sampling, seine and trawl surveys, water quality monitoring, SAV surveys, crab surveys, and some EAV data.
- Existing data should be evaluated to determine the effects of low flows on living resources.
- The habitat requirements for the affected species and life stages need to be understood.
- The effects of flow on circulation and living resources in the Susquehanna flats needs to be understood.

Issue: Target species

- The following list of target species is satisfactory.

    * Submerged aquatic vegetation: wild celery; sago pondweed; redhead grass; widgeon grass;
    * Emergent aquatic vegetation: species requiring low salinities.
    * Benthic organisms: adult oysters, soft shell clam; and
    * Finfish: Alewife, blueback herring, larval menhaden, striped bass, largemouth bass.

- A matrix type of presentation of the species affected would help to understand which ones may be affected by low flow manipulation. Increased understanding of the species affected may result in further reduction of the list of target species.

- Some species may drop out if only the effects of consumptive uses and diversions during the late summer and fall are considered.
- The primary concern is for processes other than survival. Species survival should be considered as well as habitat limitations during the periods of the year when consumptive uses and diversions have an effect.
- Some species that require fresh water, e.g., largemouth bass, could be significantly affected by increased salinity. However, species such as most finfish that are mobile can be expected to move to areas where conditions are satisfactory. The species that cannot move such as SAV, EAV, and benthos may be unable to survive.

Issue: Models and modeling

- Modeling studies presently underway by the Corps of Engineers, the state of Maryland, and others may be helpful in understanding effects of flows.
- The model presently being developed will be better than the existing model for evaluating effects of flows on the upper bay.
- The models are capable of predicting the phenomena at any time scale. The major problem is the limitations of the data. As the time scale gets finer, there is little or no data for comparison. There has not been a perceived need for such data. It may be necessary to further refine the model and/or to collect additional data in order to address the issues related to flow management. These model refinements could probably be completed in a short period of time.
- The state-of-the-art in ecological modeling is such that it may be a decade or longer before we reach the same level of sophistication as water quality modeling. At present, the lower trophic levels are being incorporated into the model. A lot of work will be necessary to incorporate the higher trophic levels.

Issue: Study area

- It is important to understand the processes (e.g., circulation, salinity, transport of water quality constituents, living resources interactions) in the upper end of the bay, just as it is important to understand the processes in the Potomac and James Rivers and other tributary estuaries.
- Different study boundaries may need to be considered for salinity, water quality and different living resources. The effects of salinity patterns on oyster diseases are evidenced well downstream of the Susquehanna flats.
- The area between the Chester and the Choptank Rivers is the area where the isohalines most affect the balance between oysters and the oyster diseases. Whether it is possible to manipulate Susquehanna flows to affect that balance is a critical question.
- The appropriate boundaries depend on the realistic capabilities of the existing system of reservoirs and the realistic expectations of how much that existing system can be changed. Also, the realities of availability of funding for additional studies need to be considered.

6.5.3. Implementation issues group

Issue: Strategy implementation

- Future studies should be conducted and/or coordinated by the Chesapeake Bay Program.
- Studies will need to show that managing for salinity or other type of target will be worthwhile.
- The salinity issue should be a priority for the Chesapeake Bay Program. The effects of low flows on salinity should be recognized by the Chesapeake Bay Program as a water quantity issue that is related to water quality and living resources issues. This issue is related to other important issues such as the effects of the C&D Canal, shellfish restoration, and effects of salinity on the population of sea nettles.
- There is a need to carefully demonstrate the relationship of flow management to the goals of the Chesapeake Bay Program. In particular, there is a need to fit this into the existing program structure.
- This activity cuts across the responsibilities of several existing Chesapeake Bay Program (CBP) Subcommittees. The CBP is attempting to reduce the number of subcommittees. There is no Water Quality Subcommittee, as such. Existing work groups facilitate coordination among the subcommittees. It appears to be most appropriate to assign this activity to a work group reporting to existing subcommittee(s).
- The development of flow management guidelines for the bay should begin with the Susquehanna. Flow management guidelines for other tributaries to the bay should be considered at some later time.
- Funding may be obtained through multiple sources in a joint venture. The Corps of Engineers is interested in certain aspects of the study, but will need nonfederal matching money for feasibility level studies. Other sources of funding may include US EPA and NOAA.
- An effort should be made to determine whether other organizations have an interest in the effects of low flows, and can provide funding.
- Federal Energy Regulatory Commission (FERC) may be interested in studies of the effects of low flows.
- The studies should be a group effort, with those parties best able conducting particular studies.
- These studies need to be included in the Chesapeake Bay Program list of project priorities.
- Both interagency and intra-agency conflicts need to be addressed.
- The Susquehanna River Basin Commission has adequate authority to address the problem. Interstate disagreements will have to be worked out.

Issue: Flow management goals

- It is unlikely that support for augmenting naturally occurring low flows could be obtained, especially considering the amount of storage presently available. It is more likely that support for replacing consumptive uses could be obtained, and this is the most that can be done with the existing storage. However, the possibility of managing for other purposes should not be discarded.

- Since the Susquehanna River and Chesapeake Bay form a very complex system, specific purposes and goals for augmenting low flows need to be developed before flow augmentation can be considered. The specifics of low flow augmentation need to be developed. The problem of determining appropriate trigger conditions, and the potential for making releases when they may not actually be needed, should be considered.
- Low flow augmentation should be considered under some emergency conditions.
- Management plans need to incorporate flexibility to allow for future changes in conditions such as effects of climatic changes.

Issue: Economic impact analysis

- The economic analysis previously conducted by Corps of Engineers (1984a, 1984b) should be updated. Tradeoffs between benefits to the bay and upstream losses need to be considered.
- The costs of alternatives to consumptive use makeup such as dry cooling versus wet cooling for power plants should be evaluated.
- The effect of flows on existing investments in Chesapeake Bay protection should be considered as part of the justification.
- A risk analysis of the effects on the bay resources should be conducted.

Issue: Historical data analysis

- The historical information should be analyzed for the purpose of evaluating the impacts of low flows and consumptive uses and diversions.
- There may be enough information available to establish a target, which can then be modified as more information is obtained. Low flow management questions need to be posed so that the analysis of the existing information will properly address those issues.

Issue: Policy implications of augmenting low flows based on normal conditions

- It is more difficult to manage low flows based on normal conditions than to augment flows during droughts.
- Augmentation of natural low flows is a very complex issue. Augmentation is probably not feasible due to limited available storage at this time.

Issue: Policy implications of area affected

- The area affected by Susquehanna low flows should be assumed to be the area from head-of-tide to the mouth of the Potomac River.
- Other major tributaries need to be considered at some point. The other major tributaries may affect salinity, and their inclusion would support the entire bay perspective.
- Because of the large area involved, it is necessary to set priorities and concentrate resources in the areas that are most affected by low flows, consumptive uses and diversions.

6.6. Moderator's Summary of Issues

The moderator summarized the issues as follows:

- What are the ultimate management goals to focus on in order to scope out the studies? Should the management goal be to offset the effects of consumptive uses and diversions, or to reduce the undesirable effects of natural low flows, or both?
- Is it feasible to manage freshwater inflows in an adaptive management framework?
- How will the strategy be accomplished, and who will be responsible for carrying out the studies?
- What is the relationship between studies of effects of flows and the Chesapeake Bay Program structure? Should these studies be coordinated by the Living Resources Subcommittee, or should a separate group be established?
- What is the expected magnitude of future consumptive uses and diversions, and what risks will future consumptive uses cause for the bay?
- Are existing models, and models presently under development, adequate for analysis and problem assessment, particularly for the upper bay? Is there a need for an expanded scale and shorter time steps, especially in the upper bay? Is there a need for further refinement of the models in order to understand the interaction between mean events in the bay and unusual meteorologic events?
- What are the economic benefits and costs of different alternatives, including doing nothing?
- Can additional information be derived from existing historical data to determine whether there is a historical link between freshwater inflows and bay phenomena?
- What target species should be selected? Should single species be replaced by an indicator of biotic response?
- What is the appropriate spatial scale?
- Should the focus be only on salinity, or are there other factors related to freshwater flows that may be important to living resources?
- How should the strategy be defined in order to focus on immediate needs and also incorporate future needs and issues?

6.7. Summary of Consensus

- It is necessary to build a case, and focus the management questions more carefully, to justify additional work on this issue.
- An iterative approach to the study of flow-related issues is necessary. The first iteration should be designed to answer certain questions, and then additional questions will be developed from the results of that first iteration.
- To justify additional investment in more detailed studies of effects of flows on living resources, the order of magnitude of the effects should be assessed.
- Initial studies should focus on effects of consumptive use and diversions, but other potential needs, e.g., low flow augmentation, should not be ignored. The iterative process should have the flexibility to include other issues in the future.
- The first question is to define the area(s) impacted by low flow events, and consumptive uses and diversions. Model runs are necessary to determine the area impacted.
- The baseline for measuring impact needs to be determined. Impact can be defined in terms of some difference in salinity, or water quality, around some mean of those properties, rather than changes in harvest.

- Studies of the level of impact and causality will have to come later, and may require a different approach.
- The lower the flow, the more sensitive the bay is to changes in flow. Even though the changes in flow are relatively small, the effects on salinity or living resources may be significant. For that reason, the impact of consumptive uses and diversions needs to be determined during all seasons.
- These effects need to be studied on appropriate time and space scales.
- The historical data should be analyzed to evaluate the effect of low flows on salinity or living resources, and to help define the questions for further studies and data collection.
- Experts should be asked to evaluate the effect on the ecological system and the individual species.
- Initial studies should be conducted with existing model(s). Existing model(s) are adequate for use in initial studies.
- The adequacy of the models should be reconsidered after completion of the initial studies. If initial studies show a need for refinement of the model(s) in order to conduct further studies, those refinements can be incorporated in later stages.
- The existing three-dimensional model of the entire bay may need to be refined in order to address freshwater inflow problems, particularly in the upper bay. Expanded space and time scales may need to be considered.
- Alternative models need to be considered, especially models of the upper bay.
- Certain flow scenarios should be run through the existing model(s) to determine potential impacts on salinity. The recent (1993-95) data can be used to verify the model results.
- The question of whether there is a minimum flow that needs to be available to maintain aquatic life should be considered.
- The economic analysis described in the Corps of Engineers study (1984a, 1984b) should be updated.
- It is premature to address some of the questions posed in the draft strategy at this time, especially the longer term studies. It is necessary to take smaller steps than envisioned in the draft strategy.
- More rigorous modeling studies are needed in the first phase than indicated in the draft strategy.
- Field studies of the ecological effects of flows are not feasible on the scale that would be needed for the purpose of defining the area affected. Field studies may be necessary in future iterations.
- The long-term studies proposed in the draft strategy are too complex and costly, and not practical at this time.
- An iterative process of modeling and field studies is considered infeasible at this time because of cost.
- Adaptive management should be considered in later iterations.
- Initial studies should use the following indicator species. This list should be reviewed further to determine whether it can be reduced.

    * Submerged aquatic vegetation (SAV);

        - Tidal fresh and oligohaline zones: wild celery; sago pondweed; and
        - Mesohaline zone: sago pondweed; redhead grass; and widgeon grass.

    * Emergent aquatic vegetation (EAV);
    * Adult oysters;

* Soft shell clam;
* American shad and hickory shad spawning and rearing during the period mid-February through September;
* Alewife and blueback herring spawning and juveniles during the period March through September;
* Larval menhaden during the period April through August;
* Striped bass spawning and rearing during the period April through September;
* Yellow perch spawning during the period February through June;
* Largemouth bass spawning and nursery during the period April through September; and
* Rare and endangered aquatic flora and fauna.

- The issue of appropriate indicator species should be reviewed in preparing recommendations for subsequent studies.
- A variable spatial scale is necessary, considering the different uses and resources that are affected.
- Studies of the effect of flows on the bay need to be integrated with studies of the effects of flows in the Susquehanna basin, including instream flow needs studies.
- The feasible management alternatives within the Susquehanna basin should be determined. A hydrologic model of the Susquehanna basin is necessary to evaluate different scenarios. Reconnaissance studies on the watershed presently underway, under Corps of Engineers funding, appear to address this need.
- Once the feasible management alternatives in the Susquehanna basin have been determined, the effect on the bay should be evaluated using the Chesapeake Bay model(s).
- The Susquehanna River Basin Commission is presently developing projections of future consumptive uses. The effects of future consumptive uses on the bay need to be included in the first iteration.
- The Susquehanna River Basin Commission should consider alternatives to consumptive use makeup.
- The stakeholders need to be identified, and they need to be brought into the first phase study. The Chesapeake Bay Program subcommittees (especially the Living Resources Subcommittee) and the Maryland agencies, particularly the Department of Natural Resources, need to be brought into the process.
- Studies should be accomplished through a partnership of the interested parties. These studies should be coordinated through the Chesapeake Bay Program.
- The Scientific and Technical Advisory Committee (STAC) should be asked to sponsor a workshop regarding the analysis of historical linkages of flow, water quality, and living resources.
- The report should include a recommendation that the existing monitoring program be continued so that the data are available for future studies of the effects of flows on the Bay. This is another use of data already being collected.

6.8. Workshop Conclusions and Recommendations

The following conclusions and recommendations resulted from the workshop discussions.

- Both high and low flows need to be recognized as factors that affect the salinity, water quality, and living resources of the Chesapeake Bay.
- There is a need to develop flow management plans for the tributary watersheds. The development of flow management plans should begin with the Susquehanna River; other

tributaries to the bay may be considered at a later time. The study area should be the area where an impact of Susquehanna River flows can be demonstrated. This area is presently uncertain.

- It is difficult to justify modifications of natural flows, and particularly augmentation of natural low flows, in order to protect the bay and its living resources. Also, the existing storage in the Susquehanna basin is inadequate to provide significant augmentation of low flows at this time. Therefore, studies of the effects of natural low flows and the determination of the need for augmentation of low flows should be deferred.
- The importance of mitigating human effects on the water quality and the living resources of the bay can be easily supported. Therefore, future studies should focus on the human effects (e.g., consumptive uses and diversions, C&D Canal, Conowingo hydropower operations) on the bay.
- Effects of natural low flows and human factors affecting freshwater flows (consumptive uses and diversions, C&D Canal, Conowingo hydropower operation) on other uses such as water supply and recreation should be considered, but the primary focus should be the effects on salinity and living resources.
- The lower the flow, the more sensitive the bay is to changes in flow. Even though changes in flow are relatively small, the effects may be significant. Therefore, the effects of human factors (consumptive uses and diversions, C&D Canal, Conowingo peaking operation) should be considered during all seasons. These effects need to be studied on appropriate time and space scales, but these scales are presently unknown.
- Studies of the effect of Susquehanna flows on the Chesapeake Bay need to be coupled with studies of flow management options in the Susquehanna basin, including instream flow needs studies. Determine what is feasible, in terms of management within the Susquehanna basin, and then determine what effect it has on the bay. Ongoing studies will help to provide this information. Alternatives to consumptive use replacement should be considered. Tools are available to look at the effect of alternative scenarios in the Susquehanna basin.
- An iterative approach to the problem seems most appropriate. The first iteration should be a problem assessment to determine the order of magnitude of effects, and determine whether more detailed studies are necessary. The assessment should identify areas affected by changes in flow and consequent changes in salinity, determine appropriate time and space scales, and the species affected. The subsequent study phases will be defined after completion of this first phase.
- The problem assessment should include:

    * Analysis of historical data, if available, to determine effects of flows on salinity, water quality, and living resources.
    * Use existing models to evaluate scenarios for water management using existing storage in the Susquehanna basin.
    * Use existing Chesapeake Bay model(s) to determine the effect of these scenarios on the salinity in the bay.
    * Evaluation by experts of the effect of changes in salinity on the ecosystem and individual species.
    * Updated economic analysis.

- The use of different models, especially models of the upper bay, needs to be considered. The models currently available are adequate for the problem assessment studies.

- While the initial problem assessment study will utilize models extensively, the continuation of existing monitoring programs is necessary to provide data for use in verifying modeling results and as input to future studies.
- The interested parties should form a partnership to conduct the necessary studies. This partnership should be developed and coordinated by the Chesapeake Bay Program. The interested parties need to be identified, and they need to be included in the partnership. Various sources of funding should be considered. Possible funding sources include the Corps of Engineers, US EPA, NOAA, and FERC. The Corps of Engineers may be able to fund certain aspects of the study. They can provide full funding for reconnaissance level studies, but matching funds will be needed for feasibility studies.
- STAC should be asked to sponsor a workshop regarding the analysis of historical linkages of flow, water quality, and living resources.

7.0. STRATEGY

7.1. Purpose of Strategy

The purpose of this strategy is to define a general approach to:

- Quantify effects of low freshwater inflow, including natural flows and changes in natural flows, on the Chesapeake Bay; and
- Develop guidelines for managing low flows from the Susquehanna River into the Chesapeake Bay.

7.2. Definitions

Definitions of terms are presented in section 1.8.

7.3. Issues and Recommendations

7.3.1. Issue: *What are the principles on which flow management should be based?*

Recommendation

Flow management should be based on an acceptable level of impact on all significantly-impacted uses and resources.

7.3.2. Issue: *What are the goals of flow management for the Chesapeake Bay?*

Recommendation

The management goals for Chesapeake Bay are to maintain tolerable salinity conditions for all uses at all times, and to maintain tolerable water quality conditions for all uses at all times, to the extent that such water quality conditions are affected by low flows. The tolerable salinity and water quality conditions for living resources should be determined from the normal salinity range and the habitat requirements of the species and life stage, and will depend on location of the species. The tolerable salinity for water supply uses is the drinking water standard (250 mg/l; 0.25 ppt).

7.3.3. Issue: *In what ways do natural Susquehanna River flows and consumptive uses affect the Chesapeake Bay?*

The natural Susquehanna River flows affect a number of resources and uses of the Chesapeake Bay, as shown in Figure 7.1. Susquehanna River flows affect circulation, water quality, and salinity. The effects on circulation affect water quality. The impacts on salinity and water quality influence living resources, which, in turn, affects recreational and commercial fisheries, and causes economic and social impacts. The effect on salinity also influences water supply, which also causes economic impacts.

The effect of natural flows depends on whether the flows are high or low, as shown in Figure 7.2. The high flows generally reduce salinity and water quality. The low flows will

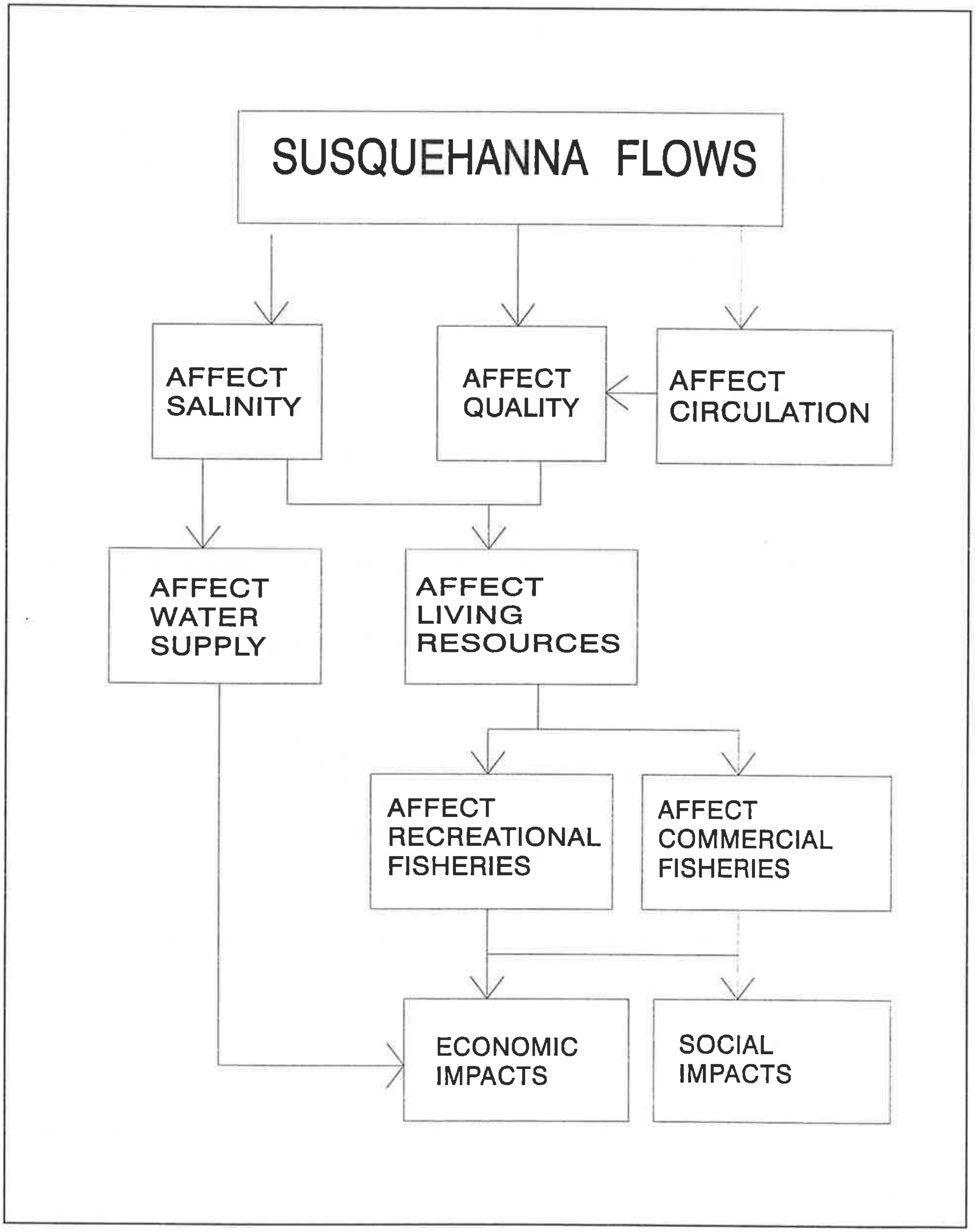

Figure 7.1. Effects of Susquehanna Flows on Resources and Uses of the Chesapeake Bay

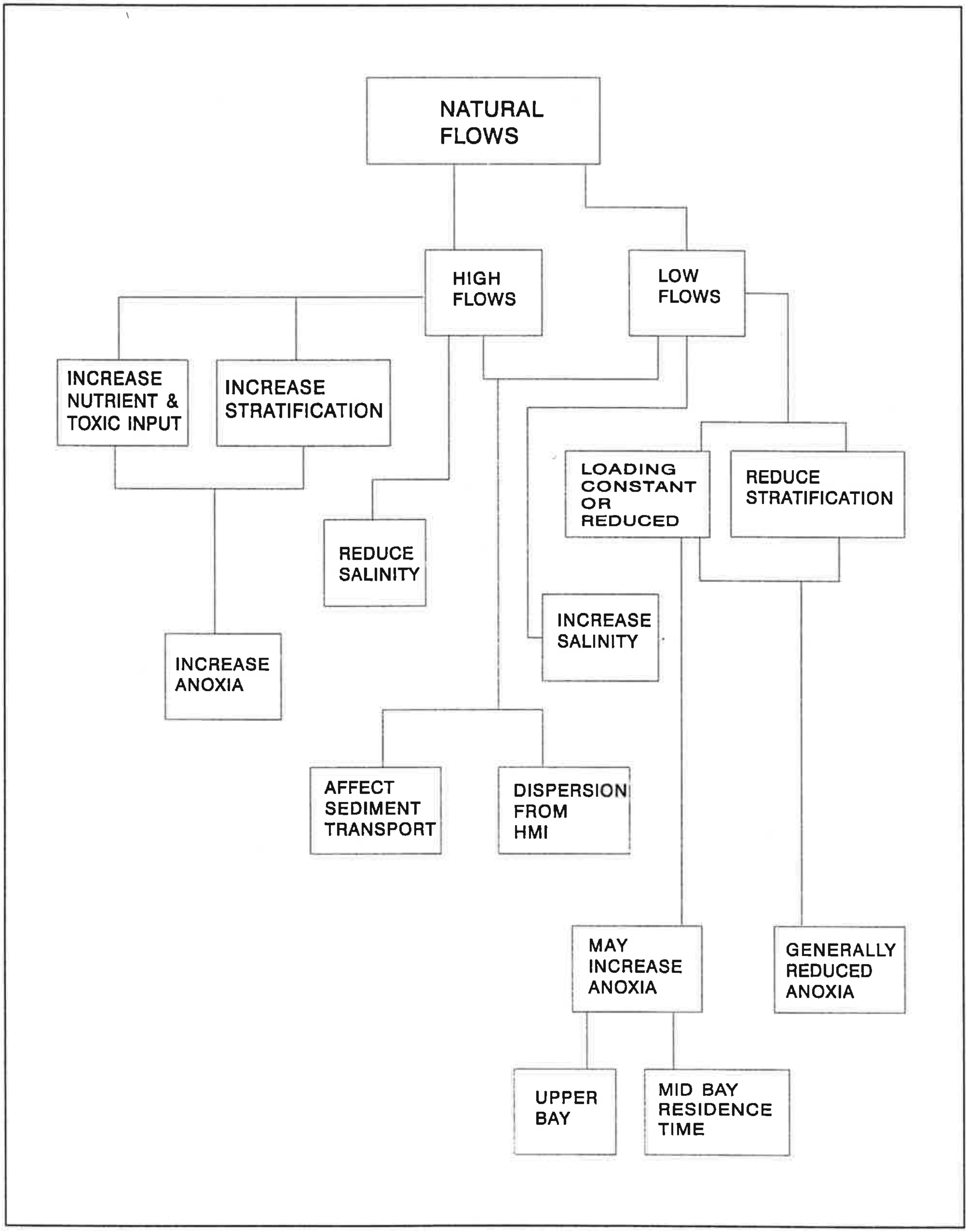

Figure 7.2. Effects of Natural Flows on Salinity and Water Quality

increase salinity. The effect of low flows on water quality is not understood, and may be either beneficial or adverse.

The effects of consumptive uses and diversions are shown in Figure 7.3. Consumptive uses and diversions generally have beneficial effects on salinity and water quality during high flow periods. Consumptive uses and diversions have adverse effects on salinity during low flow periods, but the effects on water quality are uncertain.

Recommendation

The following resources and uses appear to be the most likely to be impacted by Susquehanna River flows, and should be considered in formulating the strategy:

- Circulation patterns;
- Salinity distribution;
- Water quality, especially dissolved oxygen;
- Living resources;
- Water supply uses; and
- Recreational, commercial, and other uses.

7.3.4. *Issue*: *What is the effect of flows on circulation patterns?*

Changes in circulation patterns due to fluctuations in natural flow are discussed by Schubel and Pritchard (1986) and Wang (1992). While there is a direct effect of flows on circulation, this effect appears to be significant only as a result of indirect effects on salinity, water quality and living resources.

Recommendation

Effects of flows on circulation should be considered only as secondary effects on salinity, water quality, and living resources.

7.3.5. *Issue*: *What is the effect of flows on salinity and water quality?*

The magnitude of the effect of both high and low flows on salinity and water quality varies with the magnitude and duration of the flow event.

High flows cause isohalines to move downstream, and decrease salinity. The decreased salinity reduces habitat for species that cannot tolerate low salinity, but increases habitat for those that require low salinity.

Low flows cause isohalines to move upstream and increase salinity in the bay. Low flows also will reduce the size of the tidal freshwater and oligohaline zones of the estuary, which is expected to have an adverse effect on living resources. Changes in flows will change the location of the maximum salinity gradient, which also is the zone of maximum turbidity.

High flows also increase anoxia during the spring, summer, and fall as a result of increased inputs of pollutants, and stratification caused by the high flows. The increased anoxia reduces

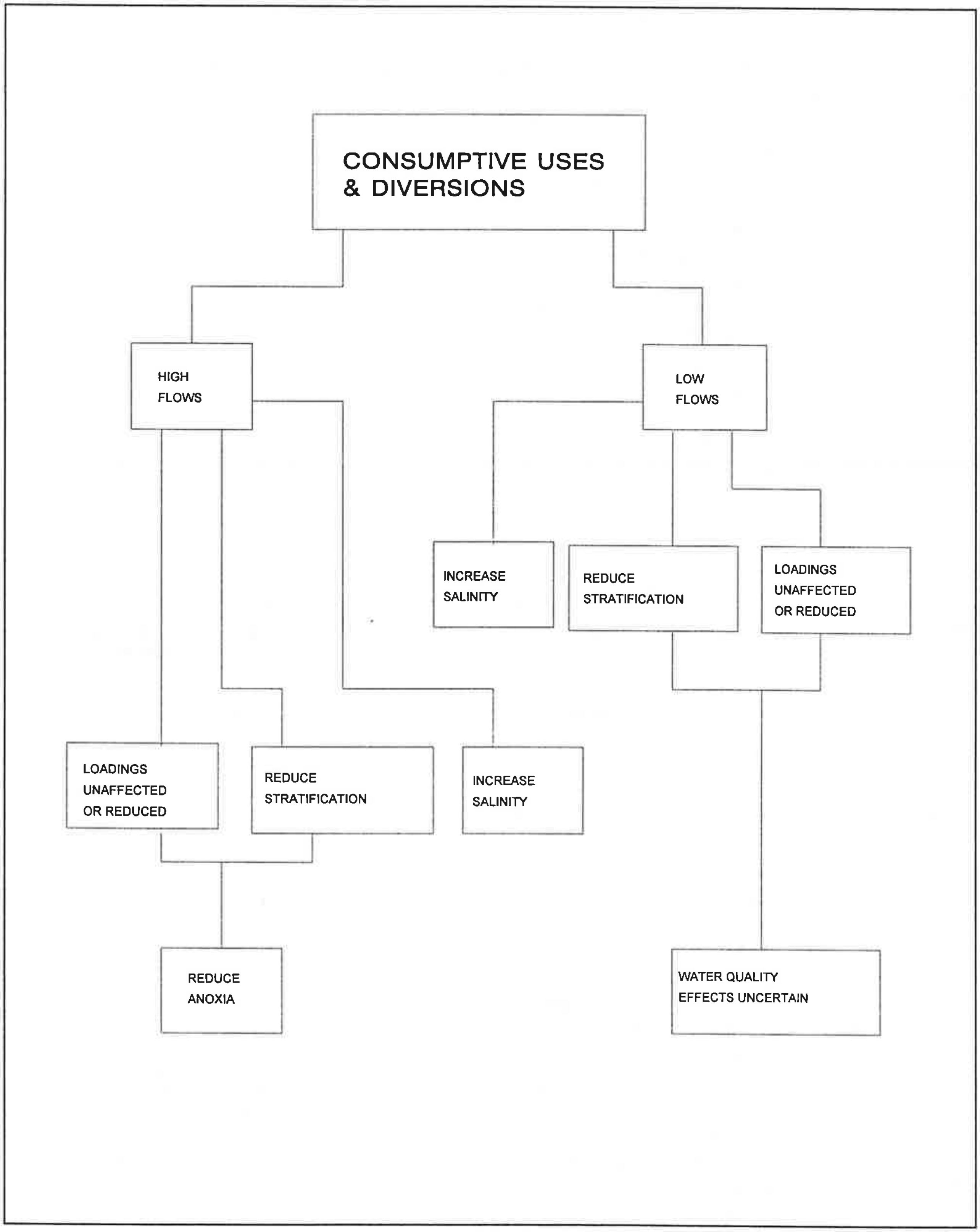

Figure 7.3. Effects of Consumptive Uses and Diversions on Salinity and Water Quality

habitat for most species, because those species cannot tolerate the low dissolved oxygen conditions found in the middle bay during spring, summer, and early fall.

Low flows affect bay water quality in different ways, and different water quality parameters may be affected.

- The inputs may change, especially dissolved oxygen, temperature, nutrients, sediments, toxics, and dissolved inorganic carbon (DIC). These changes can result from variations in loadings reaching the stream from natural processes occurring in the streams or in the impoundments on the lower river, or as a result of the peaking operation of the hydropower facilities.
- Changes in circulation patterns may result in changes in stratification, anoxia, sediment transport and deposition, transport and dispersion of pollutants released from dredge disposal areas, and transport of non-motile organisms.
- The internal water quality processes may change, and thus affect the water quality in the bay.

For the purpose of evaluating impacts of low flows and changes in low flows on the Chesapeake Bay, it is assumed that the loadings of various constituents need to be considered, but not the concentrations.

There is evidence the loadings of pollutants are much greater during high flow conditions, compared to low flow conditions (L. Zynjuk, USGS, oral communication). Most of the annual pollutant load is transported during the spring, when flows are typically higher than during the summer and fall. However, high flows can occur at any time of year, and will transport higher loads than the low flows at the same time of year.

The effects of natural low flows on water quality, in general, and dissolved oxygen, in particular, are not well understood. Conceptually, there should be no effect of natural low flows or consumptive uses and diversions on point source loadings, because those loadings are more or less constant and independent of flow rate. Since there is little surface runoff during low flow periods, and low flows are derived primarily from ground water, only the effect of pollutants derived from ground water or other nonpoint sources need to be considered. Sediment, nitrogen, and phosphorus loadings reaching the bay should decline with decreasing natural flow, and should be either unaffected by, or should decrease as a result of, consumptive uses and diversions.

Changes in circulation may affect water quality and the exposure of organisms to various water quality conditions (Klein and others, 1981; Wang, 1992). However, these changes are not well-defined or understood, with the possible exception of the effect of changes in flow on the dispersion of pollutants from the HMI dredge disposal area (Wang, 1992).

The internal water quality processes such as sediment transport, sediment deposition, and anoxia also are affected by flow.

Although Schubel and Pritchard (1986) discuss the distribution of suspended sediment for a high flow and a low flow period, the data seems too limited to draw any conclusions relevant to the effects of flow on sediment transport or deposition.

The scientific consensus (Harding and others, 1992) is that periods of low flow in the spring, summer, and early fall reduce the strength and duration of the stratification, which allows aeration of bottom waters and decreases the anoxic condition in the middle bay. This scientific consensus may be incomplete for the following reasons:

- The consensus is based on effects in the middle bay, but the effects of high flows on the upper bay are poorly understood;
- The effects of low flows on the upper bay and the middle bay, particularly interseasonal effects, are poorly understood;
- Recent data confirms low flows in the spring will decrease anoxia in the middle bay, but may have adverse effects on water quality in the upper bay (Blankenship, July–August 1995);
- There is some evidence from the water quality modeling studies (Cerco and Cole, 1994; C. Cerco, U.S. Army Corps of Engineers Waterways Experiment Station, oral communication) that low flows have both beneficial and detrimental effects on dissolved oxygen;

    * The beneficial effect is a reduction in stratification, and therefore anoxia; and
    * The detrimental effect is an increase in residence time that potentially increases anoxia; and

- The relationship between residence time and anoxia is not well understood.

This argument regarding detrimental effects of low flows is controversial, and needs further evaluation.

Assuming the effect of low flows based on the model study is valid, the relationship between anoxic-volume days and flow can be visualized as a J-shaped curve, having a minimum at an intermediate level of flow. The proposed definitions of high, intermediate, and low flows, given in section 1.8.1., assume that the interpretation of the model study data and the J-curve concept are valid.

The magnitude of the effect of low flows on salinity and dissolved oxygen varies with the magnitude and duration of the low flows.

Recommendation

- The effects of flows on the internal water quality processes, particularly stratification and anoxia, are the most significant water quality effects and need to be considered in more detail.
- The effects of natural low flows on water quality inputs to the bay are expected to be beneficial, and do not need to be considered further at this time.
- The effect of Conowingo operations on water quality inputs needs to be studied more carefully.
- The effect of flows on dispersion of pollutants at the HMI disposal area needs to be considered in future studies of the effect of low flows.

7.3.6. *Issue*: *What is the effect of flows on living resources?*

As noted previously, extreme high and low flows cause changes in salinity and water quality, which, in turn, affect the habitat available for the living resources.

Different trophic levels and different species are affected differently, depending on the species and life history stages present at particular times of year. To determine the impact of natural flows, and changes in those flows on the living resources, specific indicator species and appropriate life stages need to be selected.

7.3.7. *Issue*: *How should the adaptability of species to different conditions be considered?*

Several survey responses noted the species can adapt to changing conditions, at least to some degree. The data on adaptability is limited, but it appears the species can adapt to changes in salinity within their normal range of tolerance (Funderburk and others, 1991).

Recommendation

The assumption of the proposed studies should be that salinity needs to be kept within the normal range, and adaptation does not need to be explicitly considered.

7.3.8. *Issue: How should biological impact be determined?*

The Corps of Engineers' study used a methodology to estimate impacts on the biota based on effects of changes in salinity on habitat availability. The habitat available under different flow scenarios was mapped, considering only salinity. A panel of experts was convened to determine whether the impacts of different scenarios on habitat were significant or not.

The concept of mapping the habitat available seems reasonable. However, that appears to be the best method available at this time. There is a need to develop a more objective method for evaluating the impact of changes in flow, salinity, and water quality on the biota.

Recommendations

In the absence of the necessary methodology, and considering the uncertainty regarding the magnitude of the impacts of consumptive uses and diversions, and considering the feasibility of mitigating those impacts, biological impact should be determined by a panel of experts in a manner similar to that used in the Corps of Engineers study.

Future studies should consider the development of more objective methods for evaluating biological impact.

7.3.9. *Issue*: *What is the effect of flows on water supply?*

The City of Havre de Grace is the only public water supply system that has historically experienced high salinity problems. However, Perryville also withdraws water from about the same area, and could be affected in the future. An increased withdrawal at the Perryville intake has recently been proposed. The increased withdrawal, if approved, will service the area from Perryville to Elkton, Md., most of which is outside the Susquehanna River Basin. The increased withdrawal may affect the salinity at the Perryville intake during future low flow events.

Havre de Grace has been affected by high salinities twice in the last decade. In both cases, the problem was caused by low flow in the Susquehanna River, combined with strong winds out of the south, which effectively drove the high salinity water upstream (N. Reilman, MDE, oral communication; Roger Wagoner, City of Havre de Grace, oral communication). Neither of these occurrences were a severe drought event in the Susquehanna River Basin. It is not clear whether these historical occurrences are representative of the problem, since the recent decades have generally been a period of normal to high flows according to the U.S. Environmental Protection Agency (US EPA) hydrology studies (Cerco and Cole, 1994). By comparison, the Corps of Engineers' physical model data shows salinities of the order of 0.5 ppt (500 mg/l) at the mouth of the Susquehanna River under base drought (repeat of 1960s drought) conditions. Schubel and Pritchard (1986) do not show any salinity data at the mouth of the Susquehanna River.

Consumptive uses and diversions increase the frequency and duration of the impact of natural low flows on water supply uses.

There is a lot of uncertainty regarding the effects of natural low flows and reduced low flows on the salinity in the vicinity of the Havre de Grace intake, and other intakes in the area. One uncertainty is the effect of the C&D Canal on salinity in the area.

The consensus is that the effects of flows on water supply can be mitigated most cost-effectively by modifying the location of the intakes. However, there may be other factors that need to be considered in an overall cost/benefit analysis.

Recommendation

Defer further study of effects of flows on water supply until there is better understanding of the effects of flow on salinity and living resources.

7.3.10. *Issue*: *What is the effect of flows on other uses of the Chesapeake Bay?*

Changes in flows are expected to cause changes in salinity, which are expected to adversely affect the diversity and abundance of certain species. If the diversity and abundance are adversely affected, it is expected there will be secondary impacts on recreational, commercial and aesthetic uses of the Chesapeake Bay. The major impacts are expected to be on fishing, and possibly swimming.

Increased salinities are expected to have an impact on aesthetics, especially increased presence of jellyfish. However, these impacts are hard to define, and even harder to quantify. The need for flow management will have to be based on ecological and economic impacts. These secondary impacts are important for economic analyses.

Recommendations

The effects of flows on recreation and commercial uses need to be considered in economic impact analyses.

The aesthetic impacts should be considered qualitatively, at least for the initial studies.

7.3.11. *Issue: What are the economic impacts of flows?*

The effect of consumptive uses and diversions on living resources is expected to have adverse economic impacts that need to be evaluated. Positive economic impacts are expected to result from consumptive use management and improvements in commercial and recreational fisheries.

Recommendation

The economic analysis of the effects of consumptive uses and diversions on the Chesapeake Bay should be updated.

7.3.12. *Issue: What uses and resources need to be considered in future studies?*

Recommendation

The consensus is that the most important uses affected are salinity and living resources. Therefore, the strategy will focus on those uses.

7.3.13. *Issue: How should indicator species be selected to evaluate impacts on living resources?*

Recommendation

The following rationale for selecting indicator species is recommended:

- Changes in low flows can affect the living resources, depending on their life history and habitat requirements. The effect of changes in low flows depends on the species and life stage present at the appropriate time of year;
- The most important factors affecting the species are assumed to be increased salinity. Salinity changes affect species by changing the amount of habitat available, and may increase predation or disease. The nature and magnitude of the effect depend on the type of species;
- Since aquatic vegetation (SAV, EAV) is fixed in place, the tolerance for change in salinity, and the duration of that change, are the critical factors for that trophic level;
- Any animal species that are fixed in place (e.g., oysters) are affected by changes in salinity through their tolerance for change in salinity and the duration of salinity; the tolerance of predators and diseases for those changes in salinity also should be considered.
- Animal species that are mobile (e.g., finfish) can avoid an area that has high salinity or temperature unless:
-
    * Passage is blocked due to physical conditions, low dissolved oxygen, temperature, or chemical quality;
    * The amount of suitable habitat for a particular species/life stage is significantly reduced; or
    * Habitat is eliminated indirectly (e.g., SAV necessary for habitat for other trophic levels is eliminated or changed in some way).

- The species affected are those that are found in the study area, as defined (head-of-tide to the mouth of the Potomac River). Species and life stages found outside that area are not considered at this time.

7.3.14. *Issue*: *What indicator species should be used?*

The literature review and the survey showed the following trophic levels and species need to be considered:

Phytoplankton
Zooplankton
SAV
EAV
Shellfish

Oligohaline species
Oysters and oyster diseases
Rangia (brackish clam), *macoma, mya* (soft clam)

Finfish

Anadromous, especially spawning and rearing life stages

The habitat requirements, life history stage, and location of species (Funderburk and others, 1991; Batiuk and others, 1992; Stone and others, 1994) found in the bay were evaluated in comparison to the rationale shown in section 7.3.13 to determine the indicator species considered the most important and the most likely to be affected by reduced low flows. These species are shown in Table 7.1. Note, these references do not include habitat requirements for phytoplankton or zooplankton, so those species are not considered further in this strategy. That does not mean they are unimportant.

Although the impact of natural low flows during the period February to May is unknown and may be significant, the impact of reductions of low flows are presently expected to be insignificant during that period due to the small change in flows (section 2.4). However, small changes in salinity may have a significant effect on the indicator species, especially during spring low flows. Also, increased future diversions or consumptive uses may increase the effect of flows during that time of year. For these reasons, the effects of species/life stages present at that time need to be considered.

Recommendation

There is a consensus that the species shown in Table 7.1 should be considered, at least in the initial studies. However, the list should be examined further to reduce the number of study species to the minimum necessary to represent the interactions between species and trophic levels.

Table 7.1. Summary of Species and Life Stages to Be Considered

Trophic Level	Salinity Zone	Organism/Life Stage	Salinity Range (ppt)	Area Potentially Affected	Critical Time Period
SAV	Tidal fresh	waterweed	≤ 0.5	Conowingo to Turkey Point	April to October
SAV	Oligohaline	Water stargrass (mud plantain)	0.5 - 5	Turkey Point to Gunpowder River	April to October
EAV	Tidal fresh	Cattails, sweetflag	≤ 0.5	Conowingo to Turkey Point	April to October
Benthic organisms	Mesohaline	Adult oysters	> 5, < 20	Patapsco to Potomac	June to August
Benthic organisms	Mesohaline	Larval soft shell clam	≥8	Patapsco to Potomac	Late spring to summer
Finfish	Tidal fresh	American and hickory shad spawning and rearing	≤ 0.5	North of Turkey Point	March through July
Finfish	Tidal fresh and oligohaline	Larval and juvenile menhaden	≤ 5.0	Bay Bridge and north	May through August
Finfish	Tidal fresh	Striped bass spawning and rearing	≤ 0.5	North of Bay Bridge	March through August
Finfish	Tidal fresh	Largemouth bass spawning and rearing	≤ 0.5	North of Turkey Point	March through August
Finfish	Tidal fresh and oligohaline	Yellow perch spawning	≤ 2	North of Turkey Point	February through June
Flora and fauna	Tidal fresh, oligohaline and mesohaline	Rare and endangered	≤ 18	Head-of-tide to mouth of Potomac	Year-round

7.3.15. *Issue*: *How should the problem be approached?*

Recommendation

The consensus is that an iterative approach to the problem is most appropriate. The first iteration should be a problem assessment that should include the following studies.

- Analysis of historical data, if available, to determine effects of flows on salinity and living resources;
- Use existing watershed models to determine the effect of different flow scenarios on the salinity in the bay;
- Evaluation by experts of the effect of changes in salinity on the ecosystem and individual species; and
- Update of economic analysis.

The next iteration will be defined upon completion of the first iteration.

7.3.16. *Issue*: *Should natural low flows from the Susquehanna River Basin be augmented under some conditions; if so, what are those conditions?*

The Corps of Engineers' study (1984a, 1984b) indicates there are significant impacts of natural low flows on the salinity in the bay, and consequent impacts on the living resources. The Corps' physical model data shows the impact of natural low flows on salinity is greater than the impact of consumptive uses, even at the extremely high level of consumptive use assumed in that study.

Recommendation

Because of the complexity of the problem, and the large area potentially impacted by Susquehanna River flows, and changes in flows, resources should be concentrated on the problems most easily solved, and on the area of the bay most significantly impacted.

There is agreement that there may be an effect of natural low flows on salinity, water quality and living resources. However, studies of flow augmentation should be deferred for the following reasons:

- There is insufficient storage available in the Susquehanna River Basin at the present time to augment low flows;
- The most that can be accomplished with the available storage is to manage consumptive uses and diversions;
- It is very difficult to support the need for augmentation of natural low flows, either scientifically or politically.

7.3.17. *Issue*: *Should consumptive uses and diversions in the Susquehanna River Basin be managed to minimize effects on the Chesapeake Bay?*

The effects of consumptive uses and diversion on bay salinity, water quality, and living resources are summarized in section 7.3.3.

Consumptive uses and diversions need to be managed to minimize effects in the Susquehanna basin, and effects on the bay, to satisfy goals of the CBP and the SRBC. The management of consumptive uses to protect the bay is easily supported, if there is a significant impact on the resources and uses of the bay. Storage is available in the Susquehanna basin that could be used to meet this goal.

Recommendation

For the reasons cited, the focus of the strategy will be on the effects of consumptive uses and diversions.

7.3.18. *Issue*: *How should consumptive uses and diversions be managed to minimize impacts in the Susquehanna basin and protect the bay?*

At present, the policy of the SRBC is to replace consumptive uses when the natural flow is less than the 7-day, 10-year low flow. Although one of the purposes of this consumptive use compensation policy is to protect the Chesapeake Bay, it is not clear whether replacement of new consumptive uses at the present trigger level is adequate to protect the bay.

An alternative management policy may be to minimize consumptive uses through alternative measures, e.g., wet/dry cooling towers for industrial facilities such as power plants, restrictions on domestic outside uses during low flow periods, or other restrictions on consumptive uses during those periods.

There also is a question regarding the appropriate trigger level for consumptive use management to protect resources within the Susquehanna River Basin. That question is presently under consideration by the commission staff.

Recommendations

- Alternatives to the current SRBC policy regarding replacement of consumptive use should be investigated.
- The adequacy of the present trigger level for protecting the bay should be evaluated.
- The effect of changing the trigger level on the bay should be investigated.
- The potential impacts of the current policy and potential change in the policy on Chesapeake Bay should be evaluated.
- The allowable level of reduction of the natural flows by consumptive uses over the entire range of low flows needs to be determined.
- Studies of the appropriate trigger level for consumptive uses to protect resources within the Susquehanna basin should be continued, and the results integrated with the studies of the appropriate trigger level to protect the bay.

7.3.19. *Issue*: *What is the relationship between consumptive use management to mitigate impacts within the Susquehanna basin and consumptive use management to mitigate impacts of consumptive uses and diversions on the bay?*

Consumptive uses in the Susquehanna basin cause environmental impacts within the basin and on the Chesapeake Bay. The commission's comprehensive plan states the policy that those impacts must be mitigated.

The ultimate goal of this strategy is to develop management guidelines to mitigate the effects of consumptive uses on the bay. The management guidelines are expected to define conditions requiring mitigation, and appropriate measures for mitigation.

Recommendation

Studies of the effects of consumptive uses on the bay, and the development of management guidelines to mitigate those effects, need to be integrated with studies of consumptive use management in the basin, and development of management measures to mitigate impacts within the basin.

The following steps are recommended to develop the management guidelines for mitigating effects of consumptive uses on the bay:

- Determine the impacts of consumptive uses on the bay;
- Determine appropriate measures to mitigate those impacts;
- Evaluate the effects of consumptive use mitigation in the basin on the bay;
- Resolve any conflicts between/among these measures, considering the needs of the water users within the basin, and feasible alternatives for consumptive use management within the basin.

7.3.20. *Issue*: *What are the management guidelines?*

The ultimate objective of the strategy is to develop flow management guidelines for the Chesapeake Bay and the Susquehanna River Basin. These guidelines may be developed in stages, depending on the data available.

Recommendation

The necessary management guidelines should be developed.

The management guidelines may include, but are not limited to, one or more of the following:

- A target flow regime;
- Salinity targets; or
- Allowable level of flow reduction.

The development of salinity targets should consider the feasibility of developing a salinity standard such as the position of the 2 ppt isohaline (CALFED, 1995; Schubel, 1991, 1993).

7.3.21. *Issue*: *What area of the Chesapeake Bay is affected by Susquehanna River flows?*

The Corps of Engineers' study (1984a, 1984b) shows natural low flows affect the salinity in the entire bay. However, the effects of the Susquehanna River low flows cannot be easily separated from the effects of low flows in the other tributaries. Considering that, on average, the Susquehanna River provides 50 percent of the total freshwater inflow to the bay, the effects of Susquehanna River flows, in general, will extend to the mouth of the bay, but it is not clear whether the effects of Susquehanna River low flows will extend that far. Logically, the effects of Susquehanna River low flows can be expected to extend at least as far as the Potomac River, because there is little additional freshwater inflow to affect that reach. It also is clear the effect will be greatest at the head of the bay, and diminish going downstream. The area affected, and the magnitude of the effect, will depend on the magnitude of the low flows in the Susquehanna River.

The area affected and the magnitude of the effect also will depend on the coincident flows in the other major tributaries. Although the Susquehanna River is the most significant tributary affecting the Chesapeake Bay, the effects of the Susquehanna River may be modified by conditions in other major tributaries, particularly the Potomac and James Rivers. The flows in these streams may change salinities, and possibly water quality conditions, downstream from the mouth of the Potomac River, and thus change conditions at the Potomac River. Experience over the last two decades is that the low flows in the Susquehanna River do not necessarily coincide with low flows in the Potomac River. Additional hydrologic analyses are necessary to confirm this impression.

Previous studies have assumed the upper limit of the bay is the head-of-tide, and that seems to be an appropriate boundary for use in future studies. It is assumed, for the purposes of this study of impacts on Chesapeake Bay, that the impacts between Conowingo and head-of-tide are adequately mitigated by minimum releases from Conowingo.

The consensus is that it is not clear what part of the bay will be affected by Susquehanna River low flows, and changes in those flows. Different parts of the bay may be affected, depending on time of year and species that are present. However, the major impacts are expected to occur upstream from the Potomac River.

Additional subdivisions of this area may be appropriate based on indicator species. For example:

- The effects of flows on SAV and EAV are expected to be most important in the tidal freshwater, oligohaline, and mesohaline salinity zones.
- The effect of Susquehanna River flows on oysters is expected to be most important in the area between the mouth of the Patapsco River (Baltimore harbor) and the mouth of the Potomac River.
- Finfish species and life stages that require fresh water may be most affected in the area between the head-of-tide and the mouth of the Susquehanna River.

Recommendations

- Initial studies should focus on the effects of Susquehanna River flows on the salinity and living resources in the area between the head-of-tide on the Susquehanna River and the mouth of the Potomac River.
- Studies of the impacts of flows on SAV and EAV should focus on the tidal freshwater, oligohaline, and mesohaline salinity zones.
- Studies of the impacts of flows on soft shell clams and oysters should focus on the area between the mouth of the Patapsco River and the mouth of the Potomac River.
- Studies of the effects on finfish should focus on the species and life stages that require low salinities, and therefore, should focus on the tidal freshwater, oligohaline, and mesohaline salinity zones.

- Future studies should investigate whether additional impacts occur downstream from the Potomac River, and should evaluate the importance of those impacts.
- Future studies should investigate whether flows in the Potomac and James Rivers modify the effects of Susquehanna River flows on the salinity and living resources in the bay.

7.3.22. *Issue*: *What is the effect of hydropower operations on the Chesapeake Bay?*

Conowingo is presently required to release certain minimum flows except under certain conditions, described in section 2.5. As long as that policy is in effect, the effect of Conowingo operations on the reach of river between Conowingo Dam and head-of-tide should be adequately mitigated.

The peaking operation will affect the amount of fresh water reaching the tidal freshwater zone, on an hourly or daily basis. Those effects are expected to be damped out over a short distance. The fluctuations in flows can be observed as far as Turkey Point, but are not expected to significantly affect salinities. However, there may be effects on living resources.

Conowingo is required to release water with at least 5.0 mg/l dissolved oxygen concentration, so any effect of power operations on dissolved oxygen concentration or loadings should be adequately mitigated.

The peaking operation may affect the water quality input to the tidal freshwater zone in ways that are not presently recognized. The nutrient concentrations in the Susquehanna River flats may be affected by the peaking operation at Conowingo, and those fluctuations may have a significant adverse impact on living resources (J. C. Stevenson, Horn Point Laboratory, oral communication).

Recommendations

- There should be further studies of the effect of Conowingo operations on the Chesapeake Bay water quality and living resources, particularly the effect on SAV in the tidal freshwater zone.
- The present minimum release schedule should be maintained until these effects are adequately understood.

7.3.23. *Issue*: *Does the Chesapeake and Delaware Canal have a significant effect on the salinity and the living resources of the Chesapeake Bay?*

Previous studies (Pritchard and Gardner, 1974; Boyd and others, 1973; Hsieh and Richards, in preparation) have shown the C&D Canal has a significant effect on the salinity in the Chesapeake Bay. Proposed additional deepening of the canal may aggravate these effects on the bay. However, those effects are not well understood, and the effect on living resources has not been evaluated.

Recommendation

- The effects of the C&D Canal should be evaluated further as separate studies.
- The flow and salinity inputs to the Chesapeake Bay through the canal should be included in all modeling studies.

7.3.24. *Issue*: *How does the effect of the C&D Canal relate to effects of Susquehanna River low flows?*

The primary focus of this strategy is to evaluate the effect of consumptive uses and diversions on the bay salinity and living resources. However, it is known that the C&D Canal also affects salinity, and probably affects living resources. To develop management guidelines for the Susquehanna River Basin, the effects of Susquehanna River flows need to be separated from the effects of the canal.

Recommendation

The relationship of effects of the C&D Canal to the effects of low flows and consumptive uses in the Susquehanna River Basin needs to be defined.

7.3.25. *Issue*: *What research questions need to be answered?*

Recommendation:

The following research questions need to be answered in the problem assessment studies:

- Does the available historical data show an effect of low flows on salinity and living resources? If so, in what years, and what flow conditions? What parts of the study area are affected? What is the magnitude of the effects?
- What are the effects of consumptive uses and diversions on salinity and living resources during all seasons of the year? What part(s) of the study area are affected by changes in salinity during low flow periods? What is the magnitude of the effects on salinity and living resources?
- If there is a significant effect of consumptive uses and diversions on salinity and living resources, what additional studies are necessary to further the development of management plans?

7.3.26. *Issue*: *What is the study plan for the first iteration?*

Recommendation

The following study plan is recommended:

- Available historical data should be analyzed to determine whether there is an effect of low flows on salinity and living resources. The analysis should include the 1960s' drought, if data is available. Pertinent data sets are identified in section 3.6. The Scientific and Technical Advisory Committee should be requested to hold a workshop to identify available data and develop procedures for the analysis of the data.
- The appropriate model should be identified. There are at least three models that are believed to be applicable for modeling the effects of flows on the salinity in the study area. The feasibility of using different models should be evaluated.

- Certain low flow years should be selected to be run through the model. The years selected should include a normal year, a severe drought year, and a year of less severe below normal flows.
- Depending on the years selected, the observed flows should be adjusted for the effects of consumptive uses and diversions to obtain the baseline natural flows.
- Natural flows should be modified for the effects of present and projected future consumptive uses and diversions, and the modified flows should be run through the appropriate model to determine the area(s) of the bay affected, the time of year, and the magnitude of the effect on salinities caused by natural and reduced low flows.
- The effects of consumptive uses and diversions on salinity should be estimated from the model runs.
- A panel of experts should be asked to determine the effects of the changes in salinity on the indicator species, and the entire ecosystem.
- A workshop should be held to evaluate study results and develop consensus regarding the need for, and the scope of, additional studies.

7.3.27. *Issue*: *What is the appropriate time scale for evaluation of effects?*

The Corps of Engineers' study used seasonal average salinities to investigate impacts. The US EPA water quality modeling studies have used similar seasonal average conditions to investigate impacts. A number of respondents to the survey indicated seasonal averaging was not appropriate for the purpose of investigating flow impacts.

The existing Chesapeake Bay hydrodynamic model runs on a 5-minute time step, and is potentially able to provide salinity data at that interval. The water quality model runs on a 12-hour time step. Short time steps result in a lot of data that is difficult to analyze and interpret. The impacts being evaluated may be masked by short-term variability. However, no data are available to show appropriate time scale(s) for evaluating salinity, water quality, or living resources responses.

The Modeling Subcommittee presently recommends a temporal averaging period of a month or greater, because there is little field data to show the model is adequate for shorter time periods (L. Linker, US EPA, oral communication). The tributary model, currently being developed, is expected to be most appropriate for use in these studies. That model will improve the spatial resolution in both the main stem and the tributaries to the bay. The tributary model may improve the time resolution of the present three-dimensional model of the bay. The hydrodynamic model is expected to be available in the near future. (L. Linker, US EPA, oral communication).

Recommendations

- The appropriate time resolution for the tributary model should be determined in cooperation with the Modeling Subcommittee.
- The tributary model should be used to investigate the appropriate time scale for evaluating impacts. Pending completion of those studies, it is assumed that a 2-week averaging period is appropriate, subject to further evaluation of whether short-duration variations in inputs, caused by the peaking power operation, affect water quality or living resources, and subject to the time resolution capabilities of the tributary model or other available models (Wang, 1992; Hsieh and Richards, in preparation).

7.3.28. *Issue* *How should this strategy be implemented?*

Recommendations

- The studies should be coordinated through the CBP.
- All the interested parties should be identified and invited to participate in the studies. A tentative list of the interested parties is shown in Table 7.2.
- These studies should be coordinated with ongoing studies of the effect of consumptive uses and diversions within the Susquehanna River Basin and appropriate measures to mitigate those effects.

Table 7.2. Parties Interested in the Study of Effects of Changes in Susquehanna River Flows on the Chesapeake Bay

Chesapeake Bay Program Committees
Living Resources Subcommittee
Modeling Subcommittee
Monitoring Subcommittee
Scientific and Technical Advisory Committee
State of Maryland Agencies
Department of Natural Resources: Chesapeake Bay Program
Department of Natural Resources: Power Plant Environmental Review
Department of Natural Resources: Fisheries Management
Department of the Environment
Geological Survey
Commonwealth of Pennsylvania Agencies
Department of Environmental Protection
Federal Agencies
Environmental Protection Agency Chesapeake Bay Program
U.S. Army Corps of Engineers
U.S. Fish and Wildlife Service
NOAA National Marine Fisheries Service
NOAA Chesapeake Bay Program
U.S. Geological Survey
National Biological Service
Others
SRBC
Maryland Sea Grant College

7.3.29. *Issue: What is the role of monitoring data in the study of the effects of flows on the bay?*

The study plan includes the analysis of existing monitoring data and the use of models to evaluate impacts. Although the focus of the first iteration is on modeling studies, monitoring data is expected to be very important in future iterations, to compare with modeling results and to help understand causality.

Recommendation:

The monitoring data presently being collected will be useful for studying the effects of low flows and consumptive uses and diversions. Existing monitoring programs should be continued in order to provide the necessary data.

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APPENDIX A. SURVEY QUESTIONS

ALL PARTIES

1. The development of a strategy for managing low Susquehanna River freshwater inflow to the Chesapeake Bay needs to address the following key issues:

	Issue	Agree	Disagree	No Opinion
a.	Whether the bay is affected by natural low flows, or consumptive uses and diversions, or both.	26	0	1
b.	Which resources and uses are affected.	27	0	0
c.	Which part of the Chesapeake Bay is affected.	26	0	1
d.	The time of year that effects occur.	26	0	1
e.	Significance of factors other than salinity.	26	0	1
f.	Purposes of flow management.	24	0	3
g.	Goals of flow management.	24	0	3
h.	Effects of tributaries other than the Susquehanna River.	20	5	2
i.	Effects of C&D Canal on the bay.	17	4	6
j.	Effects of Baltimore withdrawal from the Susquehanna River.	19	1	7
k.	Whether existing data are adequate to develop flow management plans.	21	3	3
l.	Necessary additional studies.	23	0	4
m.	The appropriate time scale for evaluating impacts.	21	1	5
n.	Other issues (please list).	8	—	19

2. Susquehanna River low flows affect the salinity in the Chesapeake Bay.

Yes __23__ No __1__ No Opinion __3__

3. The effect on salinity is due to (check all that apply):

- 21 a. Natural low flows
- 20 b. Consumptive uses
- 19 c. Diversions
- 23 d Interactions among these factors
- 0 d. No opinion

4. Natural Susquehanna River low flows also affect the resources and uses:

Resources and Uses		Effect			
		Significant	Insignificant	None	No Opinion
a.	Water quality				
	(1) Dissolved Oxygen	18	4	0	5
	(2) Temperature	10	7	1	9
	(3) Other (specify)	12	2	0	13
b.	Phytoplankton	15	6	0	6
c.	Zooplankton	14	6	0	7
d.	Habitat for				
	(1) Submerged Aquatic Vegetation (SAV)	17	5	0	5
	(2) Emergent Aquatic Vegetation (EAV)	9	6	0	12
	(3) Shellfish (specify species)	17	3	0	7
	(4) Finfish (species/life stage)	14	4	0	9
e.	Municipal and industrial water supply	10	5	0	12
f.	Recreation uses	12	7	1	7
g.	Commercial uses	9	6	1	11
h.	Aesthetic uses	8	10	1	8

5 Consumptive uses and diversions from the Susquehanna River also affect the following resources and uses:

	Resources and Uses	Effect			
		Significant	Insignificant	None	No Opinion
a.	Water quality				
	(1) DO	13	4	1	9
	(2) Temperature	9	5	2	11
	(3) Other (specify)	9	3	0	15
b.	Phytoplankton	13	4	0	10
c.	Zooplankton	13	4	0	10
d.	Habitat for				
	(1) SAV	14	5	0	8
	(2) EAV	8	4	0	15
	(3) Shellfish (specify species)	16	2	0	9
	(4) Finfish (species/life stage)	15	2	0	10
e.	Municipal and industrial water supply	10	2	0	15
f.	Recreation uses	9	6	0	12
g.	Commercial uses	6	5	1	15
h.	Aesthetic uses	6	8	1	12

6. Natural Susquehanna River low flows affect the following part of the Chesapeake Bay (check 1 only)

5 a. The Susquehanna River flats
6 b. The reach from head-of-tide to the mouth of the Potomac River
10 c. Tidal fresh and low salinity (oligohaline; less than 5 ppt) zones
5 d. Other (specify)
NOTE: 1 blank

7. Consumptive uses and diversions from the Susquehanna River affect the following part of the Chesapeake Bay (check one only):

__6__ a. The Susquehanna River flats
__2__ b. The reach from head-of-tide to the mouth of the Potomac River
__13__ c. Tidal fresh and low salinity (oligohaline; less than 5 ppt) zones
__4__ d. Other (specify)

NOTE: 2 blanks

8. The effects of natural Susquehanna River low flow on the bay occur during (check all that apply):

__10__ a. Spring
__20__ b. Summer
__18__ c. Fall
__5__ d. Winter

9. The effects of consumptive uses and diversions on the bay occur during (check all that apply):

__9__ a. Spring
__19__ b. Summer
__20__ c. Fall
__9__ d. Winter

10. The following factors also are significant in assessing effects of natural low freshwater inflows on bay resources and uses:

Factor		Yes	No	No Opinion
a.	Current pattern	18	2	7
b.	pH	5	8	14
c.	Carbon dioxide	6	6	15
d.	Nutrient availability	21	1	5
e.	Biological interactions	24	0	3

11. The following factors also are significant in assessing effects of consumptive uses and diversions on bay resources and uses:

Factor		Yes	No	No Opinion
a.	Current pattern	16	2	9
b.	pH	5	7	15
c.	Carbon dioxide	5	6	16
d.	Nutrient availability	20	1	6
e.	Biological interactions	22	0	5

12. Low flows and reductions in low flows also affect the following components of bay ecology:

Component		Significant	Insignificant	No Opinion
a.	Sediment inputs	14	6	7
b.	Pollution inputs	18	4	5
c.	Dispersion of pollutants	15	6	6
d.	Nutrient input	21	2	4
e.	Nutrient transport and fate	18	3	6
f.	Transport of non-motile organisms	11	8	8

13. Flow management should be based on an acceptable level of impact on the following resources and uses (check all that apply):

Resources and Uses		Yes	No	No Opinion
a.	SAV	25	1	1
b.	EAV	19	2	6
b.	Shellfish	25	2	0
c.	Finfish	25	2	0
d.	Waterfowl	22	1	4
e.	Municipal and industrial water supply	21	3	3
f.	Recreation	17	5	5

14. There is a need to manage Susquehanna River low flows to:

	Result	Yes	No	No Opinion
a.	Augment natural low flows	7	10	10
b.	Replace consumptive uses	18	1	8
c.	Maintain appropriate seasonal salinity pattern (s)	18	3	6
d.	Prevent degradation of the inflow water quality	20	3	4
e.	Prevent degradation of the bay water quality.	17	4	6

15. The most appropriate goal for managing effects of natural low flows on the bay is (check one only):

13 a. Management of effects of natural low flows is unnecessary because it is sufficient to maintain the natural flow regime
0 b. Maintain the salinity levels experienced during a repeat of the 1960s drought
5 c. Maintain tolerable salinity levels for certain species in critical areas at all times
5 d. Maintain tolerable salinity levels for certain species in critical areas at critical times
2 e. Maintain tolerable salinity levels for certain species in critical areas ______ % of the time.
2 f. Other (specify). ______

16. The most appropriate goal for managing effects of consumptive uses and diversions on the bay is (check one only):

11 a. Specify some maximum allowable level of flow reduction
1 b. Maintain the salinity levels experienced during a repeat of the 1960s drought
5 c. Maintain tolerable salinity levels in critical areas at all times
9 d. Maintain tolerable salinity levels for certain species in critical areas at critical times
1 e. Maintain tolerable salinity levels in critical areas ______ % of the time.
2 f. Other (specify). ______

NOTE: One person checked three.

17. The protection of the species in the tidal fresh and low salinity (oligohaline) zones against changes in salinity is the most important aspect of low freshwater flow management.

Yes 15 No 6 No Opinion 6

If you answered NO, please explain what you think is the most important aspect of low freshwater flow management.

18. Is it necessary to maintain a specific size of the low salinity (oligohaline) zone during low flow periods?

Yes 11 No 9 No Opinion 7

19. Is there a need to develop a target low freshwater flow regime for the Susquehanna River?

Yes 18 No 1 No Opinion 8

20. Low flows in other tributary watersheds will affect the salinity in the bay.

Yes 22 No 2 No Opinion 3

21. Studies of the effects of low flow, consumptive use, and diversions should include all the tributaries to the bay.

Yes 18 No 5 No Opinion 4

22. Further study of the effects of the C&D Canal on salinities in the Chesapeake Bay is necessary.

Yes 12 No 3 No Opinion 12

23. The withdrawal of water from the Susquehanna River for the city of Baltimore will affect salinity and living resources in the upper bay.

Yes 13 No 2 No Opinion 12

24. The effect of the withdrawal of water from the Susquehanna River for the city of Baltimore needs further study.

Yes 17 No 1 No Opinion 9

25. The recovery time of the species following a low flow period is important in managing low freshwater inflow.

Yes 20 No 2 No Opinion 5

26. The effect of Susquehanna River low flows and consumptive uses on the living resources of the Chesapeake Bay has been adequately studied, and flow management plans can be developed from available data.

Yes 5 No 11 No Opinion 11

27. If you answered NO to question 26, which types of studies are necessary in order to define impacts on living resources and to develop management plans.

Type of Study	Yes	No	No Opinion
a. Basic data collection and analysis	7	3	3
b. Physical/biological process studies	11	1	2
c. Modeling studies using the 3-D model	8	2	3
d. Living resource impact field studies	9	3	2
e. Flow management studies	8	1	5
f. Watershed hydrology studies	9	1	3
g. Literature review and synthesis	8	2	3
h. Other (specify)	5	—	—

NOTE: Totals for each line do not check with total number of no responses to question 26. Presume that some who marked "Yes" or "No Opinion" to question 26 also responded to question 27.

28. Future studies should be designed to evaluate impacts of natural low flows, rather than determining how to satisfy preset salinity goals.

Yes ___14___ No ___6___ No Opinion ___7___

29. Future studies should be designed to evaluate impacts of consumptive uses and diversions, rather than satisfying preset salinity goals.

Yes ___19___ No ___2___ No Opinion ___6___

30. Increased salinities will significantly increase effects of wood borers on marine facilities.

Yes ___10___ No ___2___ No Opinion ___15___

Prepared By: ______________________ ______________________

Name Date

ADDITIONAL QUESTIONS FOR STATE AND FEDERAL RESOURCE AGENCIES (USFWS, NOAA/NMFS, DNR/TA, LRS, RESEARCHERS, BIOTA EVALUATION PANEL)

1. How important is salinity in determining the survivability and reproduction of the following groups of organisms in the bay?

Group	Critical	Important	Unimportant	No Opinion
a. SAV	4	9	1	2
b. EAV	2	10	1	3
c. Shellfish	8	6	1	1
d. Finfish	8	6	1	1
e. Water fowl	1	8	2	5

2. How important is water quality in determining survivability and reproduction of the groups of organisms in the bay?

Group	Critical	Important	Unimportant	No Opinion
a. SAV	7	7	0	2
b. EAV	4	6	2	4
c. Shellfish	8	7	0	0
d. Finfish	8	6	0	1
e. Water fowl	3	5	2	6

3. Is there any evidence of the need to maintain the size of the low salinity (oligohaline) zone?

Yes 5 No 1 Do Not Know 10

4. Are there any historical data showing effects of low flows on living resources?

Yes ___7___ No ___3___

If YES, where can that data be found?

5. Do you agree that all species in the following groups can adapt to small changes in salinity over short or long periods of time?

Group		Yes	No	No Opinion
a.	SAV	12	2	2
b.	EAV	11	2	3
c.	Shellfish	13	2	1
d.	Finfish	13	1	2
e.	Waterfowl	12	1	3

6. What is the appropriate time scale for addressing impacts of low flows on living resources (check all that are important)?

___7___ a. Short term (days to weeks)
___13___ b. Medium term (weeks to months)
___12___ c. Long term (years)

7. The best way to evaluate impacts of low flows and changes in low flows is to use the Chesapeake Bay 3-D Model, including the living resources components presently being developed. .

Yes ___6___ No ___2___ No Opinion ___8___

8. Will the version of the CB model, presently under development, be adequate for modeling effects of low flows on all the species that will be significantly impacted?

Yes ___2___ No ___2___ Unsure ___5___ No Opinion ___7___

If the model is not adequate for this purpose, please attach list of necessary improvements.

9. Is the procedure used in the Corps of Engineers Low Freshwater Inflow Study adequate for determining biological impacts?

Yes ___1___ No ___3___ No Opinion ___10___

If you answer NO, please attach comments regarding the inadequacies of the Corps methodology.

10. In the Corps of Engineers study, salinities were averaged over 90-day periods as follows, and then the impacts of changes in average salinities over these periods for each scenario were evaluated.

a. Is it appropriate to average salinities over seasons to evaluate impacts?

Yes ___4___ No ___8___ No Opinion ___3___

b. The following seasons are appropriate for evaluating impacts:

Dec. 1 to Feb. 28
Mar. 1 to May 31
June 1 to Aug. 3
Sept. 1 to Nov. 30

Yes ___7___ No ___6___ No Opinion ___2___

If you answer NO, to either question, please attach comments regarding reasons for that response.

ADDITIONAL QUESTIONS FOR STATE WATER RESOURCES AGENCIES (MD WRA, PA DER)

1. The methodology used in the Corps of Engineers Low Freshwater Inflow Study to evaluate impacts on the following uses was adequate for the purpose of developing low flow management plans:

Use	Yes	No	No Opinion
a. Municipal water supply	0	2	3
b. Industrial water supply	0	2	3
c. Recreation	1	0	4
d. Commercial	1	0	4
e. Economic	0	1	4
f. Social	1	0	4

2. Is a predictive relationship between salinity and low freshwater inflows needed in order to develop management plans?

Yes ___2___ No ___1___ No Opinion ___2___

If such a relationship is needed, do you have any proposals regarding how should it be developed?

Yes ______ No ___2___

3. Should future studies be designed to develop additional points on curves of impact versus flow?

Yes ___2___ No ___1___ No Opinion ___2___

4. The best way to evaluate impacts of low flows and changes in low flows is to use the Chesapeake Bay 3-D Model including the living resources components presently being developed. .

Yes ___2___ No ___0___ No Opinion ___3___

Letter to Donald Robey, Waterways Experiment Station

SUSQUEHANNA RIVER BASIN COMMISSION

1721 North Front Street • Harrisburg, Pennsylvania 17102

717-238-0423

June 30, 1995

Mr. Don Robey
Waterways Experiment Station
U.S. Army Corps of Engineers
Vicksburg, MS

Dear Don:

As we have discussed on several occasions, I'm conducting a study to develop a strategy for studying and managing impacts of natural low flows, and reductions in low flows, on the Chesapeake Bay. At present, the study is considering only Susquehanna low flows, and tentatively the study area is defined as the head of tide on the Susquehanna to the mouth of the Potomac. The study is intended to build on the work done by the Corps in the Chesapeake Bay Low Freshwater Inflow Study, including the studies conducted with the physical model of the Bay.

Regardless of whether the issue is effects of natural low flows or effects of consumptive uses/diversions, it appears that Susquehanna flows affect salinity, which in turn affects water quality, and that both salinity and water quality affect living resources. There is also an occasional impact of salinity on water supply for Havre de Grace, and a potential impact of low flows on sediment transport. Tentatively, it appears that any Susquehanna flow management to benefit the Bay will have to be justified on the basis of impacts on water quality and living resources.

Tentatively, a recommendation of the study may be to use the 3-D model of the Bay to evaluate effects of certain flow scenarios, which are as yet undefined. There are a couple of alternative ways that natural flow scenarios could be defined e.g.,

- run long periods of natural and modified flow record through the model;
- run specific years of natural and modified flow data through the model.

The water quality studies have used a seasonal averaging period, and the Corps physical model used a similar averaging period. Tentatively, a shorter averaging period (e.g., 2-4 weeks) seems more appropriate to address low flow impacts, particularly salinity and water quality changes. One of the issues we are wrestling with is whether the Susquehanna water quality needs to be considered as an independent variable in such simulations, or whether it can be considered constant.

With this as background, I would appreciate it if you and/or Carl Cerco could respond to the following questions:

1. Cerco and Cole state (p. 2-6) that "Operation of Conowingo Dam imposes high frequency almost daily flow fluctuations that are especially noticeable during low flow periods." Are these effects noticeable only with regard to the Susquehanna flow, or is there a noticeable impact on the Bay?

2. Figure 3-7 of Cerco and Cole appears to define the upper boundary of the model as the head of tide on the Susquehanna. Is that correct?

3. Have you learned anything during the development or application of the model that would help in understanding the impacts of low flows on the Bay, or in developing low flow scenarios?

4. The procedures used in the water quality analysis seem to indicate that an annual or seasonal time scale is appropriate for investigating flow effects. Is that valid for low flow effects? Do you have any opinion regarding an appropriate time scale for low flow effects?

5. Is it possible to test alternative hypotheses regarding appropriate time scales using the model?

6. Can the model be used to evaluate short-term impacts (say, 2-4 weeks) of Susquehanna flows/water quality on the Bay salinity, water quality, and living resources?

7. Are there any problems with using the model for this purpose? Is anything missing in the hydrodynamics or water quality model(s) that would limit the validity of results for these shorter time periods, or for low flows? Is there anything in the model output (e.g., oscillations) that would cause problems in such analyses?

8. Is it feasible to use existing model-generated salinity or water quality time series for the following periods:

   calibration period
   30-year simulation
   10-year simulation

   to understand salinity/water quality evolution at different locations in years with different Susquehanna flows?

9. Has review of the existing model-generated salinity or water quality time series been conducted using a short averaging period? (Dr. Chow at Horn Point said he thought Wang has looked at the short duration time series data.) I have a copy of Wang's report to Md. Geological Survey dated 1992.

10. Can the model be used to run either individual years or long-term input time series? Is there any technical or cost reason to run long records or to run specific test years?

11. How much effort (manpower, CPU time) is required to run a scenario through the model? What are the cost tradeoffs involved with running specific model years versus running a long flow record through the model?

12. In order to run long-term flow input time series, is it necessary to run the watershed model to develop input flow and water quality time series?

13. Can the flow time series be input based on available data, and the water quality be assumed constant for modeling either long-term records or individual years?

14. Is there any problem with establishing initial conditions in the model as there was with the physical model?

Any additional comments that would help in defining this problem, or in developing a strategy to solve it, would be appreciated. If the questions are not clear, please call me at (717) 238-0425, or send a fax to (717) 238-2436. Thank you for your help.

Sincerely,

Dick

Donald R. Jackson
Staff Hydrologist

cc: Larry Lower, Corps of Engineers, Baltimore
Lewis Linker, EPA CBP, Annapolis

Appendix B. Survey Mailing List

Survey Mailing List
June 22, 1995

Mr. George Abbe
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APPENDIX C. LIST OF RESPONDENTS TO SURVEY

List of Respondents to Survey

Name	Agency
G. Abbe	Benedict Estuarine Research Laboratory Philadelphia Academy of Natural Sciences
N. Beegle	Baltimore District, U.S. Army COE
E. Brezina	Pa. Department of Environmental Protection
W. R. Carter III	Md. Department of Natural Resources, Tidewater Administration
T. Clark	Maryland Department of the Environment
Ted Clista	Pa. Department of Environmental Protection
Mary Ellen Dore	Md. Department of Natural Resources
R. S. Early	Md. Department of Natural Resources
D. Fiesta	Pa. Department of Environmental Protection
W. A. Gast	Pa. Department of Environmental Protection
M. S. Haire	Md. Department of the Environment
F. Hoffman	Va. DEQ
R. Kelsey	U.S. Fish & Wildlife Service
T. E. Jordan	Smithsonian Environmental Research Center
L. Linker	US EPA Chesapeake Bay Program Office
R. L. Lippson	BEP
L. Lower	Baltimore District, U.S. Army Corps of Engineers
R. Newell	Horn Point Environmental Laboratory, University of Maryland
G. Mackiernan	Maryland Sea Grant College, University of Maryland
R. W. Osman	Benedict Estuarine Research Laboratory Philadelphia Academy of Natural Sciences
P. Sampou	Horn Point Environmental Laboratory, University of Maryland
K. Sellner	Benedict Estuarine Research Laboratory Philadelphia Academy of Natural Sciences
H. Speir	Md. Department of Natural Resources
R. St. Pierre	U.S. Fish & Wildlife Service
J. Stremple	National Marine FS
J. Court Stevenson	Horn Point Environmental Laboratory, University of Maryland
H. Zich	U.S. Fish & Wildlife Service

Appendix D.
Chesapeake Bay Low Flow Strategy Study
Workshop Attendees

Chesapeake Bay Low Flow Strategy Study Workshop Attendance

Attendee	Agency	Days Attended	Discussion Group
Ray Alden	Old Dominion Univ.	September 25-26	Water Supply and Water Quality Issues
Noel Beagle	U.S. Army Corps of Engineers	September 25-26	Implementation Issues
Kate Bennett	Chesapeake Bay Program Office	September 25-26	Water Supply and Water Quality Issues
Don Boesch	Univ. of Maryland—CEES	September 25-26	Implementation Issues
Bill Boicourt	Univ. of Maryland—CEES	September 25-26	Water Supply and Water Quality Issues
Terry Clark	Md. Dept. of the Environment	September 25-26	Implementation Issues
Pat Deliman	U.S. Army Corps of Engineers	September 25-26	Water Supply and Water Quality Issues
William A. Gast	Pa. Dept. of Environmental Protection	September 25-26	Implementation Issues
Dave Goshorn	Md. Dept. Natural Resources	September 25-26	Water Supply and Water Quality Issues
David Heicher	Susquehanna River Basin Commission	September 25-26	Living Resources Issues
Donald R. Jackson	Susquehanna River Basin Commission	September 25-26	Water Supply and Water Quality Issues
Roman Jesien	Univ. of Maryland—CEES	September 25-26	Living Resources Issues
Michael Kemp	Univ. of Maryland—CEES	September 26	Living Resources Issues
Jeff Liang	Md. Dept. of the Environment	September 25-26	Water Supply and Water Quality Issues
Larry Lower	U.S. Army Corps of Engineers	September 25-26	Living Resources Issues
John McSparran	Susquehanna River Basin Commission	September 25-26	Implementation Issues
Kenn Pattison	Pa. Dept. of Environmental Protection	September 25-26	Water Supply and Water Quality Issues
Bob Sadzonski	Md. Dept. Natural Resources	September 25	Living Resources Issues
Steve Schreiner	Versar, Inc.	September 25-26	Water Supply and Water Quality Issues
Paul W. Slunt	Md. Dept. Natural Resources	September 25-26	Water Supply and Water Quality Issues
John Stremple	National Marine Fishery Service	September 25-26	Living Resources Issues
Paul Swartz	Susquehanna River Basin Commission	September 26	Implementation Issues
Kum Sung Wong	Md. Dept. of the Environment	September 25-26	Water Supply and Water Quality Issues