Chapter One: Introduction

The Setting

The first investigations into Potomac River water quality problems were because of public health concerns with safe drinking water and waterborne diseases and were addressed mainly at the federal government level. The United States Public Health Service (US PHS) began conducting sanitary surveys of the Potomac River in the Washington, DC area as early as 1894. US PHS sanitary and biological surveys of the Upper Estuary followed in the 1910s.

In 1940, the United States Congress established the Interstate Commission on the Potomac River Basin (ICPRB) to help the Potomac basin states and federal government work cooperatively to address water quality and related resource problems in the Potomac Basin.

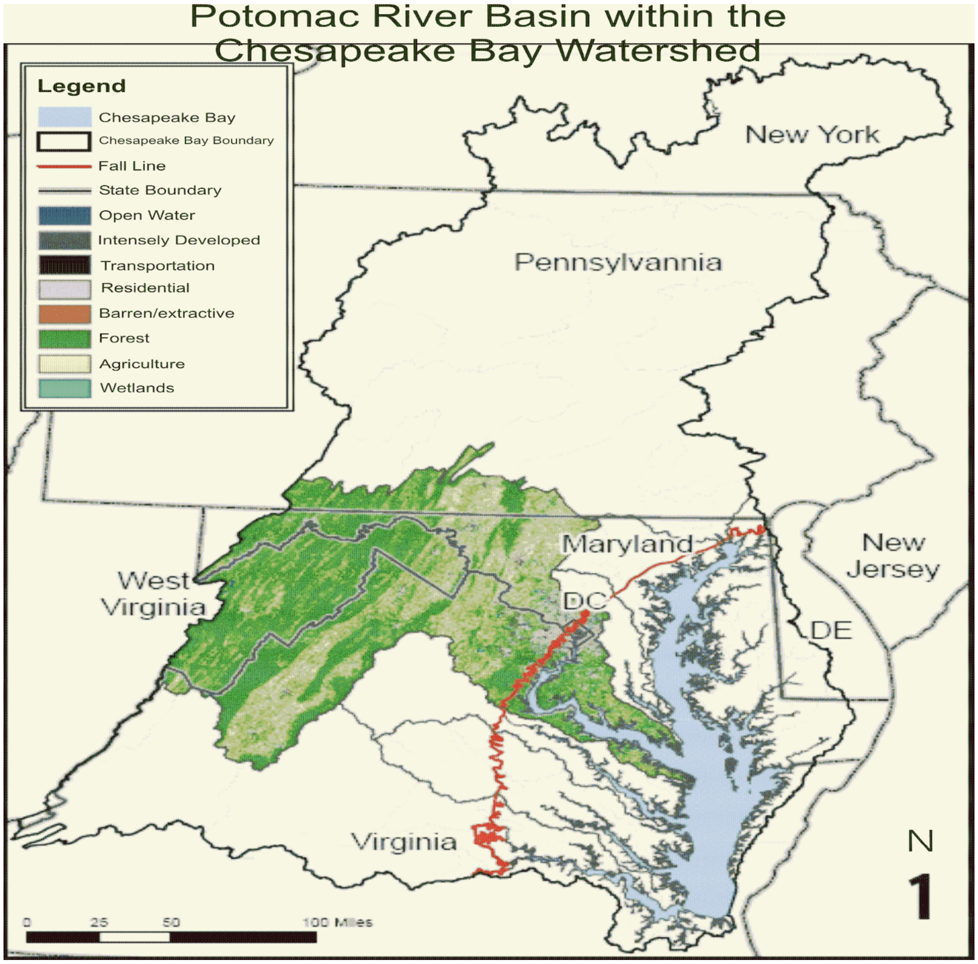
In 1956, Congress passed the first Federal Water Pollution Act (FWPA). The Act strengthened the US PHS enforcement authority, increased water quality research, and initiated the wastewater construction grants program. This Act led to the convening in 1957, and the reconvening in 1966, of the Potomac Enforcement Conference in response to the continuing degradation of the water quality of the Potomac River in the Washington, DC area. The Water Quality Act of 1965 required the establishment of water quality standards for interstate waters. These requirements applied to the Potomac River and its Estuary.

On October 1, 1968, Stewart L. Udall, Secretary of the Department of Interior, submitted a report to President Johnson entitled "***The Nation's River.***" The report was a broadly based conservation plan, intended to make the Potomac "a model of scenic and recreational values for the entire country." The first paragraph of the report stated, ***"With good reason, people sometimes claim that the Potomac has been studied more often and more thoroughly than any other American stream."***

In 1970, as a result of numerous technical studies, administrative discussions, and the reconvening in 1969 of the Potomac Enforcement Conference, a **Memorandum of Understanding (MOU)** was adopted by the conferees (the federal government, District of Columbia, and the states of Maryland and Virginia) that formalized water quality requirements and wastewater treatment goals for the Upper Estuary**.**

In 1970, the United States Environmental Protection Agency (US EPA) was established. It took over the national water quality improvement programs, including the implementation of the **MOU** mentioned above. In 1972, Congress passed the Clean Water Act, which called for development of the National Pollutant Discharge System (NPDS). In 1974, the first effluent-limited permits were issued to wastewater dischargers to the Upper Estuary.

In 1975, Congressional concern about environmental trends in the Chesapeake Bay, including the Potomac River Basin, led to a major, multi-year study and monitoring program by US EPA and the states within the boundary of the Chesapeake Bay Watershed (see map below).



Source: CBPO

Upon completion of the multi-year effort, the first Chesapeake Bay Agreement (CBA) formed the Chesapeake Bay Program (CBP) in 1983. The CBA was an agreement among the states within the Chesapeake Bay Watershed, District of Columbia, and US EPA and other federal agencies to address water quality issues of the entire Chesapeake Bay and its watersheds through the CBP. Of the numerous goals of the CBP, the top priority was, and is today, the restoration of living resources. See the CBP web site for a detailed explanation of program goals and recent agreements.

The Chesapeake Bay Program today is an ongoing restoration and monitoring effort conducted jointly by the District of Columbia, Virginia, Pennsylvania, Maryland, New York, West Virginia, US EPA, and other federal agencies.

Previous Scientific and Technical Assessments

The first reported water quality survey of the entire Potomac River Basin was conducted during the fall of 1897 when A. P. Davis, E. G. Paul, and G. H. Matthes of the Untied States Geological Survey (USGS) made a detailed study of the sources of pollution throughout the basin (1). The study included a bacteriological examination of the Potomac River. In order to obtain a general conception of the amount of pollution in the Potomac River, samples of river water were taken at the mouths of all important tributaries and at other points of interest.

In 1912-1913, the United States Department of Agriculture (USDA) Water Laboratory, Bureau of Chemistry measured the oxygen content, turbidity levels, chloride concentrations, and temperature of the Potomac Estuary, Chesapeake Bay, and Delaware Bay (3). There was particular interest in the data because of the possible relationship of low dissolved oxygen (DO) content in the water to fish and shellfish mortality at the mouth of the Potomac Estuary. In late 1913, a survey was made of the bacteriological quality of the Potomac River by the U.S. Public Health Service to determine if the waters in the Washington, DC area were safe as a source for public drinking water and bathing (4). An effort was also made by the US PHS to define the pollution and sanitary conditions of the Upper Potomac Estuary in 1913 and 1914 (5).

Since these initial four surveys, the geology, physiography, and hydrology of the Potomac River Basin have been well characterized (6), (7), (8), (9). Numerous studies (10), (11), (12) have been conducted on the water quality problems of the Potomac Estuary as part of enforcement programs in the 1950s, 1960s, and 1970s, and later, as part of the Chesapeake Bay Program. An Environmental Atlas of the Potomac Estuary (13) was conceived, sponsored, and published by the Maryland Power Plant Siting Program in 1979.

A retrospective study of the water quality issues of the Upper Potomac Estuary was published in 1990 (14). Major water quality assessments and nutrient loading synthesis studies were completed for the entire Chesapeake Bay in 1995 (15) and 1996 (16), including the Potomac River Basin. The history of the Washington Aqueduct, 1852-1992 (17), describes the planning, construction, and operation of this major drinking water facility serving our nation's capital.

The Principal Goal and Objectives of the Potomac Treatise

The principal goal of our treatise is to provide a broad, 110-year perspective of the water quality of the Potomac River Basin and its Estuary through a historical analysis of landscape loadings and resulting water quality trends from 1895 to 2005.

The specific objectives of our treatise are to:

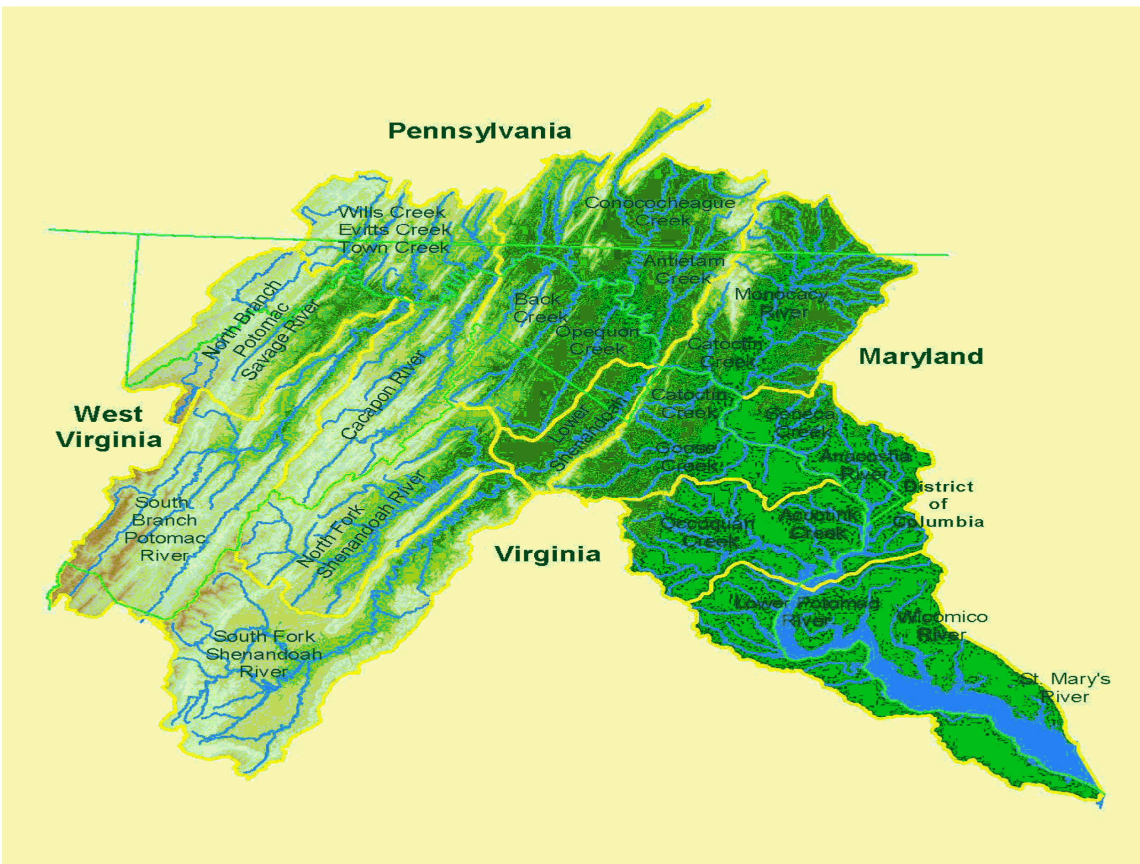
1. Describe how the landscape loadings, which are the major sources of nutrients and major ions to the Potomac River Basin and its Estuary, have changed from 1900 to 2005.
2. Compare these loadings and resulting export fluxes of the Upper Basin and its eight major sub-basins to other watersheds of the Middle Atlantic, Northeast USA, and sub-basins of the Mississippi River Basin from 1990 to 1994.
3. Describe how the water quality of the Potomac River, a major drinking water source, and its sub-basins have changed over the past 110 years.
4. Describe the current water quality conditions, as well as the historical trends, of the Potomac Estuary from 1912 to 2005, including nutrient loading trends to the Estuary.

5. Quantify how humans have used the basin’s land and water resources and how these activities have impacted the loadings and resulting water quality conditions of the Potomac River and its Estuary.
6. Examine various nutrient management strategies for improving dissolved oxygen in the Lower Estuary (see Appendix A).

While the major focus is on nutrients, it also includes major ions and chemicals.

The Potomac River Basin

For this analysis, the Potomac River Basin was divided into the Upper Basin, with a drainage area of 29,940 km^2, and the Lower Basin, with a drainage area of 8,055 km^2.



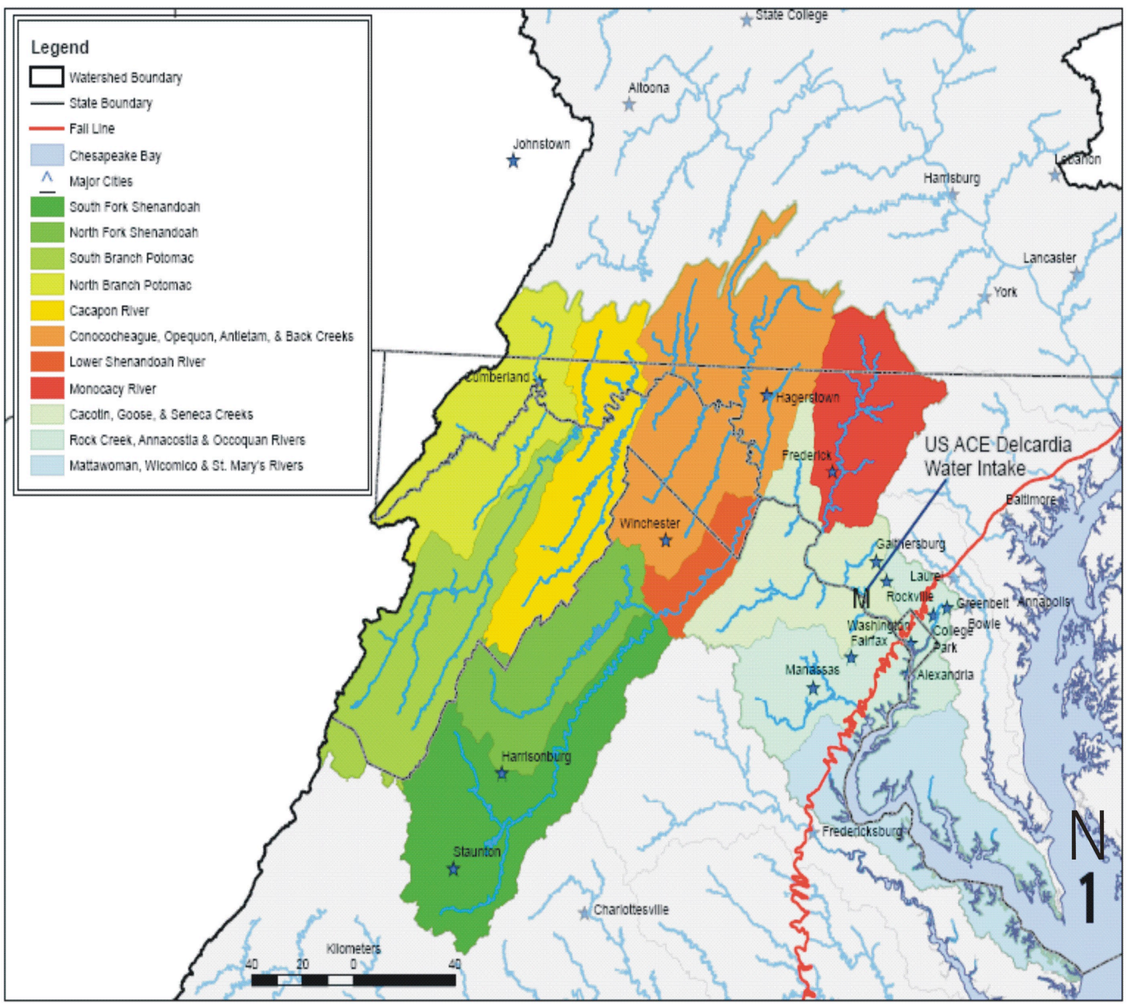
Source: ICPRB

The entire Potomac River Basin has a drainage area of 37,995 km^2 and encompasses parts of Pennsylvania, Maryland, West Virginia, Virginia, and all of the District of Columbia.

The eight major sub-basins of the Upper Basin, including their drainage areas, are shown in the table below. The upper and lower sub-basins and the fall line, which divides them, are shown in the map below.

Upper Basin Sub-basins	Drainage Area (km^2)
North Branch	2,266
South Branch	3,756
Cacapon	677
Conococheague	469
Antietam	283
Opequon	309
Shenandoah	3,012
Monocacy	813

Major sub-basins and cities of the Potomac River basin



Source: CBPO

The six major sub-basins of the Lower Basin, including their drainage areas, are:

Lower Basin Sub-basins	Drainage Area (km^2)
Rock Creek	210
Anacostia	418
Piscataway	163
Occoquan	1,614
Mattawoman	203
Wicomico	467

A 1996 United States Geological Survey (USGS) report has classified the Potomac River Basin into seven physiographic provinces (7). Of the seven, six are in the Upper Basin: the Appalachian Plateau, Valley and Ridge, Great Valley, Blue Ridge, Piedmont, and Triassic Lowlands. The Coastal Plain province lies in the Lower Basin. The USGS 1996 report has also categorized the geology of the Potomac River Basin into four groups: unconsolidated sediment, carbonate sedimentary rocks, siliciclastic sedimentary rocks, and crystalline rocks.

The Potomac Estuary

From the Chain Bridge in Washington, DC, to Point Lookout at the confluence with the Chesapeake Bay, the Potomac Estuary is a long and narrow estuary—approximately 189 km. With its many tributaries and bays, however, the Potomac Estuary has a shoreline of 1,800 km. The Estuary meanders in a south, southeasterly direction, except for a sharp bend about halfway downriver.

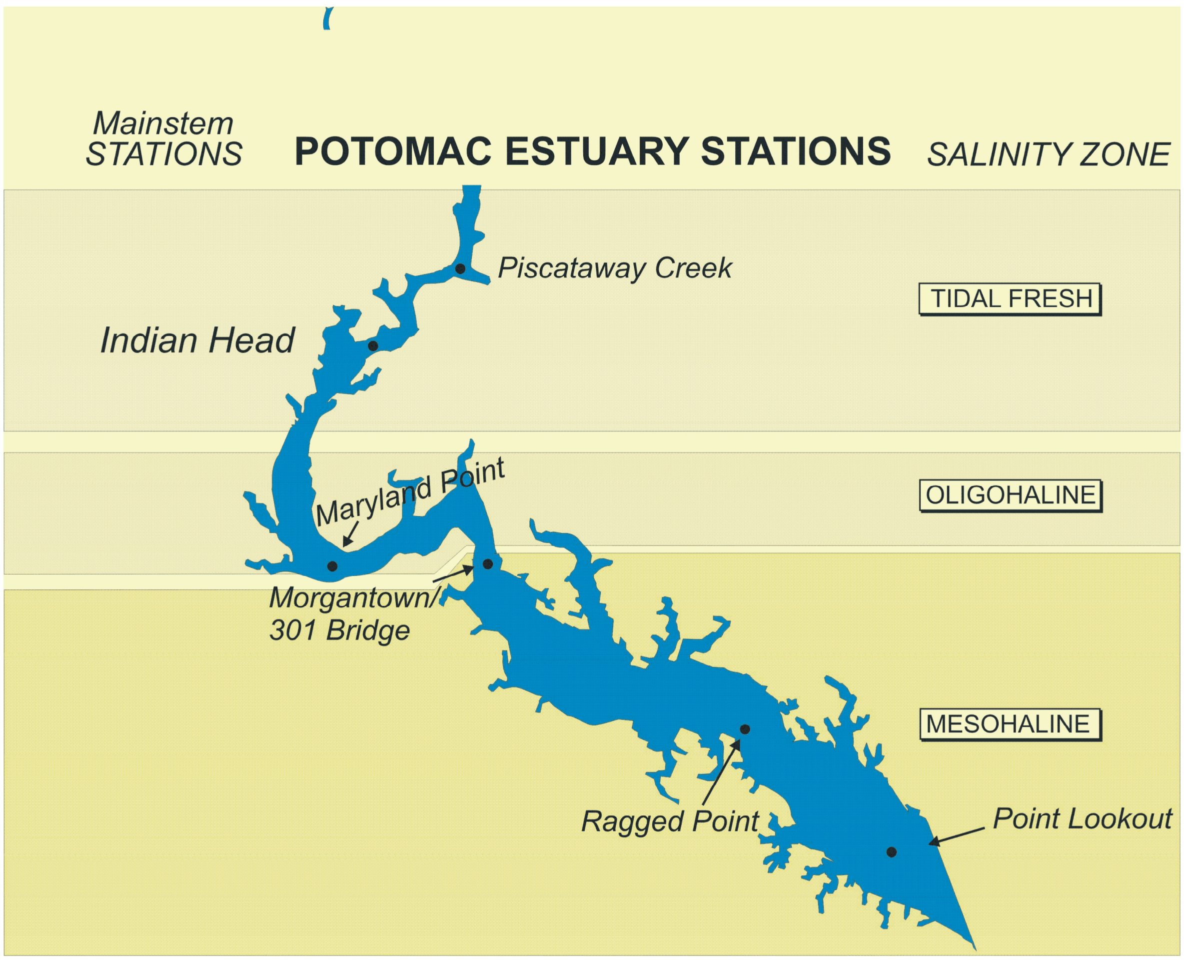
The Estuary has three well-defined and distinct zones. The upper zone, from Chain Bridge to Indian Head, is the tidal freshwater reach, with salinities of less than 0.5 parts per thousand (ppt). The middle reach, between Indian Head and the Route 301 Bridge at Morgantown, is the transition zone. The salinity of this zone varies from 0.5 to 7.0 ppt and is often referred to as the zone of maximum turbidity. The lower zone, from the 301 Bridge to Point Lookout, has salinities ranging from 7 to 16 ppt.

The basic morphometric data for the three zones are tabulated below:

Parameter	Upper	Middle	Lower
Length (km)	48.0	60.0	75.0
Ave depth (m)	4.8	5.1	7.2
Max depth (m)	6.0	26.5	23.0
Ave width (km)	1.1	3.6	9.7
Surface area (km^2)	57.4	211.6	695.2
Volume ($m^3 x 10^7$)	26.4	102.5	496.5

The mean tidal range is about 0.9 meters in the upper zone near Washington, DC, and about 0.5 meters near the Chesapeake Bay. The hydraulic detention time for all the three zones depends on the rate of freshwater inflow (11). For an annual average of 11,350 cfs, the detention times for the upper, middle, and lower zones are 0.045, 0.175, and 0.854 years respectively.

The six water quality stations and the salinity content of the Potomac Estuary are presented below.



Source: MD DNR

Data Sources and Analysis Methods

Data were obtained from numerous sources, as presented below and throughout this treatise. All the historical data have been compiled on computerized spreadsheets to facilitate the analysis and to serve as documentation of all data and analysis methods.

The USDA methods for estimating nutrients resulting from animal production and used in crop production (18), along with other nutrient conversion data (19), (20), were adopted to determine annual nutrient loadings to the Upper Basin landscape from agricultural practices. These methods are described in further detail in the Scientific Committee on Problems of the Environment (SCOPE) Nitrogen Project (21). The recent nitrogen landscape loadings from atmospheric deposition were from the National Atmospheric Deposition Program's electronic database at Colorado State University, Fort Collins, Colorado. The historical nitrogen and sulphate loadings were estimated from historical nitrogen and sulfur emission data (22).

The US PHS compiled the first complete inventory of water use and wastewater loadings in 1958. In 1968, the inventory was expanded by the Federal Water Pollution Control Agency (FWPCA) to include wastewater treatment levels and nutrients (23). Current wastewater loadings are well known. In this treatise, historical annual nutrient loadings from domestic wastewater discharges for the Upper Basin were assumed to be proportional to the historical population.

The major source of historical water quality data for the Potomac River above Washington, DC, is from the drinking water supply monitoring program of the United States Army Corps of Engineers (US ACE) Dalecarlia Treatment Plant. Except for a few years in the 1920s when the data were lost, monthly summaries of weekly chemical analyses of the "raw water" from the Potomac River above Great Falls have been compiled and annual summaries calculated for the period 1905 to 2004.

The first major nutrient survey of the watersheds of the Upper Basin was conducted by FWPCA (24) in 1966. The current water quality monitoring of the freshwater streams is conducted mainly by the USGS, Maryland Department of Natural Resources (MD DNR), and the West Virginia Department of Environmental Protection (WVA DEP).

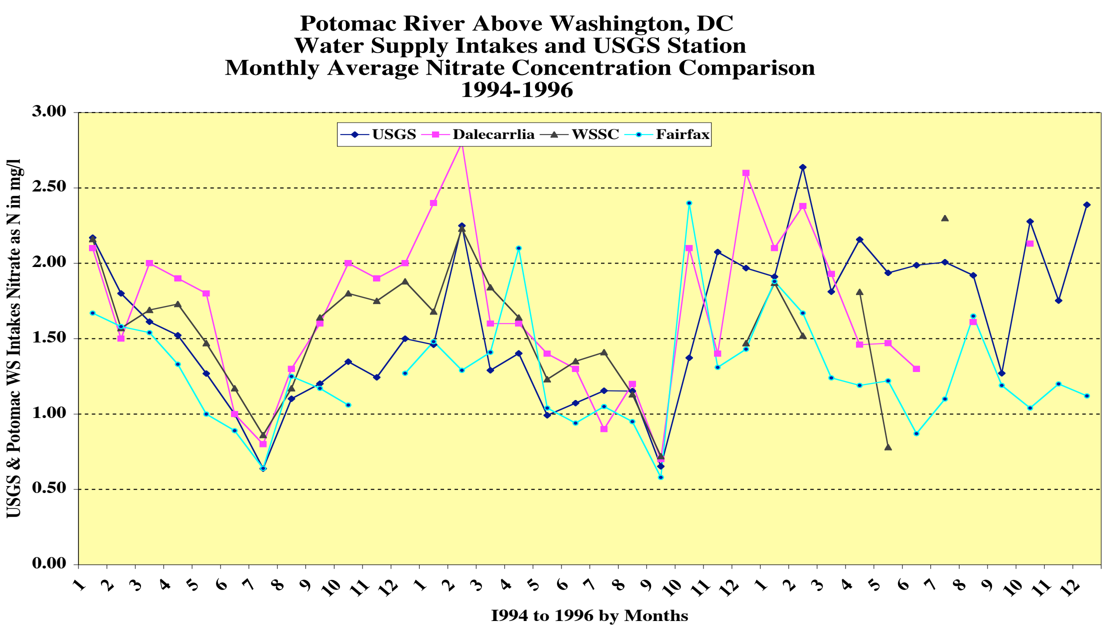
In response to continuing degradation of the water quality of the Upper Estuary, the first Potomac Washington Area Enforcement Conference was convened in 1957 by the United States Department of Health, Education, and Welfare (US DHEW). In addition to high fecal coliform counts and low dissolved oxygen levels, the Upper Estuary was highly eutrophic. As a result of the enforcement programs, a nutrient water quality monitoring program in the Upper Potomac River Basin was established in the late 1960s by the Federal Water Quality Agency (FWQA) and taken over by the US EPA in 1970.

The upgrading of the wastewater treatment facilities to include phosphorus removal and nitrification was a result of the enforcement programs. The District of Columbia's Upper Estuary monitoring was expanded to include nutrients in the 1970s and the Washington Metropolitan Council of Governments (MCOG) thereafter published annual reports. The major current watershed input monitoring program is a cooperative effort between the MCOG, USGS, and MD DNR.

The MD DNR monitors the water quality of the six estuarine stations presented in the map above. Descriptions of the monitoring program, as well as water quality data, are available on the Chesapeake Bay Program Office (CBPO) web site.

The historical annual export fluxes of nitrate nitrogen and other chemicals from the Upper Basin in kilograms per square kilometer per year ($kg/km^2/yr$) have been compiled based on the US ACE monthly chemical analyses and the USGS river discharge measurements. For the period 1965 to 1977, estimates of monthly nutrient export fluxes were based on predictive models derived using regression analysis, which describe nutrient fluxes-river discharge logarithmic relationships developed from FWQA and EPA data. Using daily USGS river discharge measurements and regression relationships (J.M. Landwehr, personal communication), monthly summaries were compiled for the 1964-1977 period. The nutrient export fluxes from 1978 to the present were provided by the USGS as part of the Chesapeake Bay Program. The export fluxes were based on the USGS ESTIMATOR program, which is a statistical load estimation technique (25).

The Potomac River above Great Falls is not well mixed and, therefore, the chemical analyses data often reflect the chemical concentrations of the upstream tributaries.
The water quality monitoring of the drinking water withdrawn from the Potomac River provides a long historical record of the changes in the quality of the Potomac River above Washington, DC. Because three of the intakes are more on the Maryland side and two are more on the Virginia side, it also provides a means of assessing any side-to-side variability.

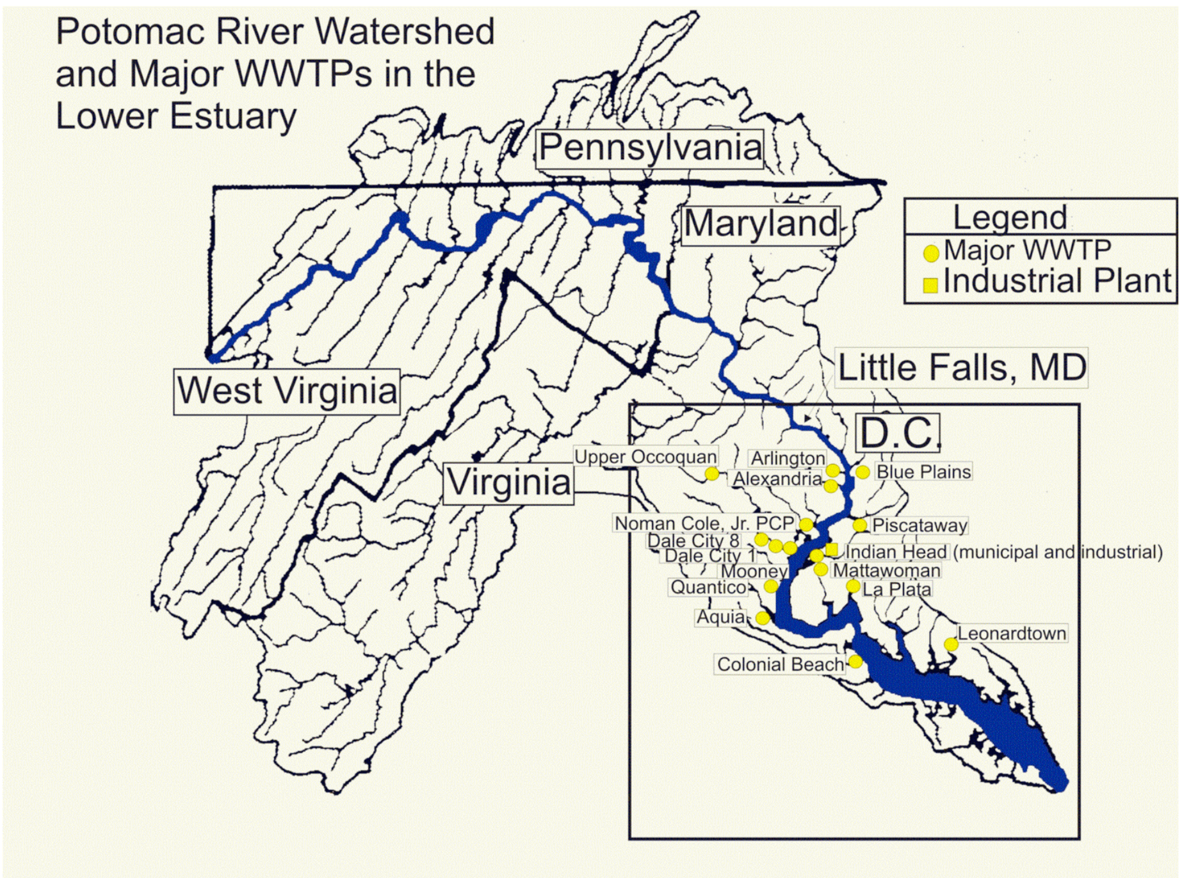


As shown above, nitrate levels are higher on the Maryland side than on the Virginia side.

The USGS water quality monitoring station is below Great Falls. The USGS water quality data is more representative of the entire flow of the Potomac River, because the river water becomes well mixed when it goes over Great Falls.

Data from each source were analyzed separately because of the side-to-side data differences. However, during low-flow months, all four monthly averages were very similar. As presented later in this treatise, we developed statistical relationships between the nutrient fluxes from the USGS Little Falls data and the fluxes from the Dalecarlia water supply data. These USGS/Dalecarlia water supply relationships formed the basis for the extrapolations of the loading flux data.

The historical nutrient loadings from WasteWater Treatment Plants (WWTPs) or Publicly Owned Treatment Works (POTWs) discharging directly into the Estuary have been compiled from numerous sources (11), (14), (26). The 17 major WWTPs discharging into the tidal Potomac are shown in the map below.



Source: MD DNR

For the period 1985 to 2002, monthly wastewater effluent flow and loading data were obtained from MCOG and the MD DNR. Current wastewater loadings for all POTWs in the entire Potomac Basin were obtained from the CBPO.

In the late 1930s, the District of Columbia began monitoring the water quality of the Upper Estuary. Numerous water quality stations have been sampled by various state and federal agencies since 1965. Data for six of the water quality estuarine monitoring stations that have the longest data records were compiled for this analysis.

The six MD DNR stations and their distances from their confluence with the Chesapeake Bay are presented below.

Station	Distance (km)
Piscataway	158
Indian Head	139
Maryland Point	103
301 Bridge	64
Ragged Point	19
Point Lookout	0

The six estuarine water quality sampling stations are presented in a map shown earlier in this section. See the MD DNR web site for a complete description of the stations.

For the estuarine trend analysis, surface water quality data were averaged for each month in which data were obtained, except for dissolved oxygen (DO). DO data include both surface and bottom waters. Because the early eutrophication problems addressed were in the Upper Estuary, the upper three stations have more monthly data than the three stations in the Lower Estuary. The period of 1978 to 2004 has the most complete monthly water quality data record throughout the 12 months for a given sampling year.

Although data from the various monitoring programs have been merged into one spreadsheet for the six stations for 40 years of data, it remains possible to identify the original data sources. The statistical trends were analyzed using the Seasonal Kendall test. In merging data from various sources, the authors recognize that there can be differences in analytical methods, especially in the detection limits. The methods used by various agencies are documented by the CBPO.

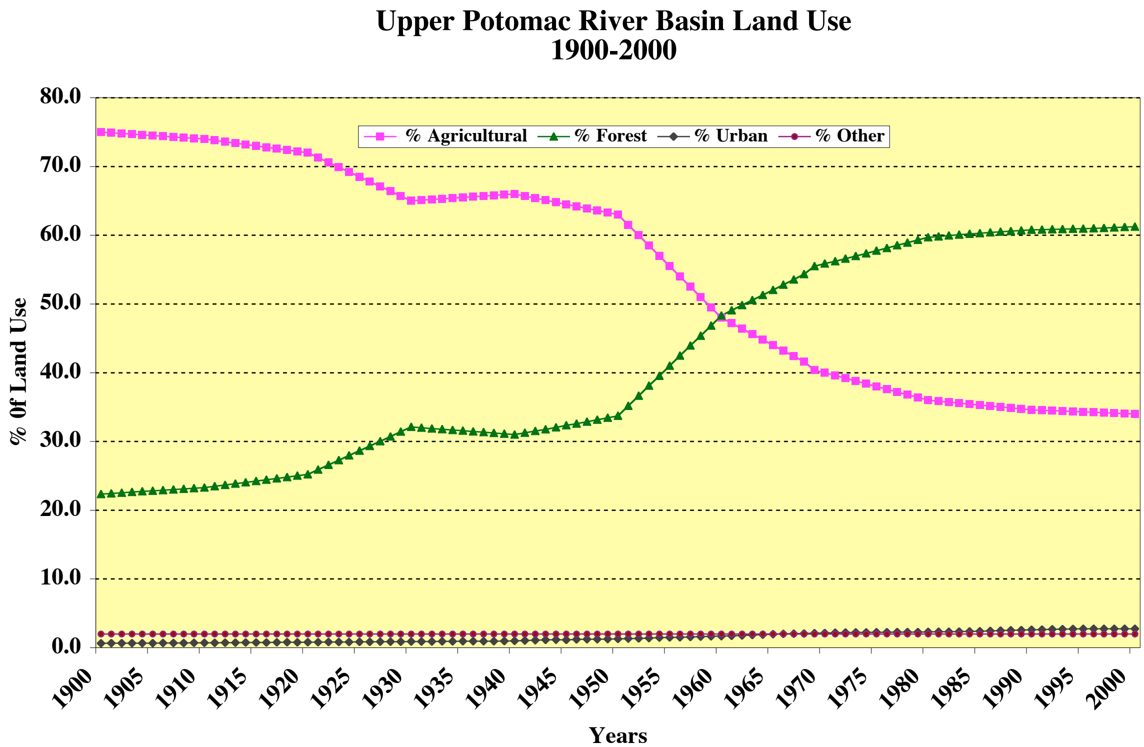
Description of Potomac River Basin

Land Use

The 1990-94 land use patterns for the Upper Basin in the SCOPE report (27) and for the Lower Basin in the 1987 USGS report (6) are presented below.

	Percentage of Basin for Each Land Use				
Basin	**Agricultural**	**Forest**	**Urban**	**Water**	**Other**
Upper Basin	34.6	60.8	2.6	1.2	0.8
Lower Basin	16.0	38.0	19.0	23.0	4.0

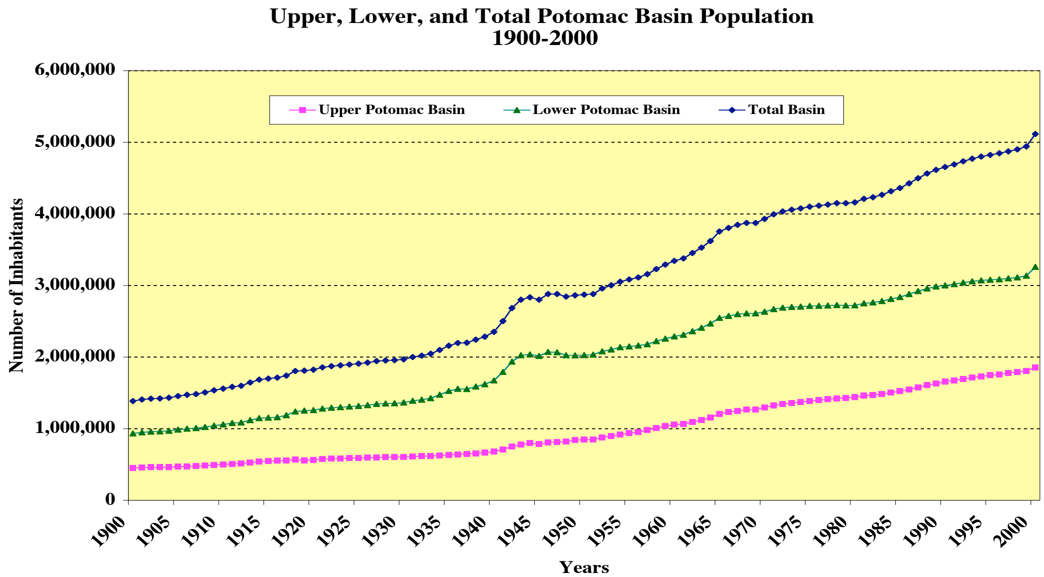
Using data from the United States Department of Commerce, National Agricultural Statistics Service (NASS), and United States Bureau of Census, we estimated the percent of land area in farmland. Calculating urban area trends based on population, and holding other uses constant, we estimated percent land use in forest by difference for the period 1900 to 2000 for the Upper Basin, as shown below.



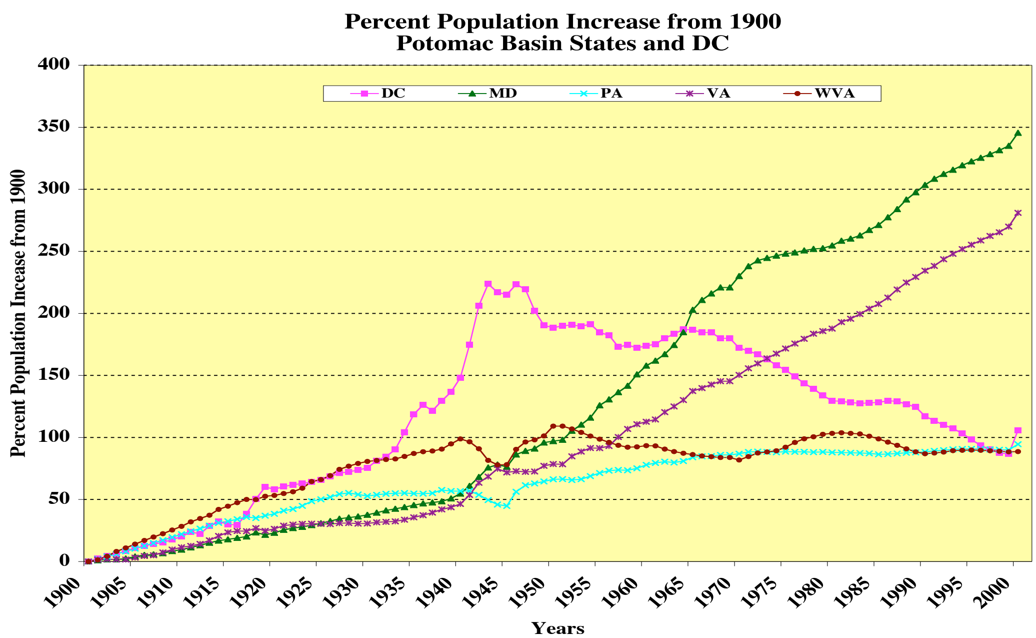
At the turn of the 20th century, about 75% of the land of the Upper Basin was used for agriculture while 22% was in forest. By the 1990s, agricultural use had decreased to 35% and forestlands increased to 61%. The major changes in land use occurred in the period from 1950 to 1975. These changes were similar to those reported in the SCOPE study (26).

Population

As presented below, the population of the Upper Basin increased about 300% during the past century, going from 452,000 to 1,823,000 inhabitants. The Lower Basin has increased about 249%, going from 933,000 to 3,259,000 inhabitants for the period 1900 to 2000. The population of the entire Potomac River Basin increased about 264%, going from 1,400,000 to over 5,100,000 inhabitants.



As presented below, the percent increases in population for the same period (1900 to 2000) for the states of Pennsylvania, Maryland, Virginia, and West Virginia have varied significantly, with Maryland and Virginia having increases of 350% and 285% respectively.

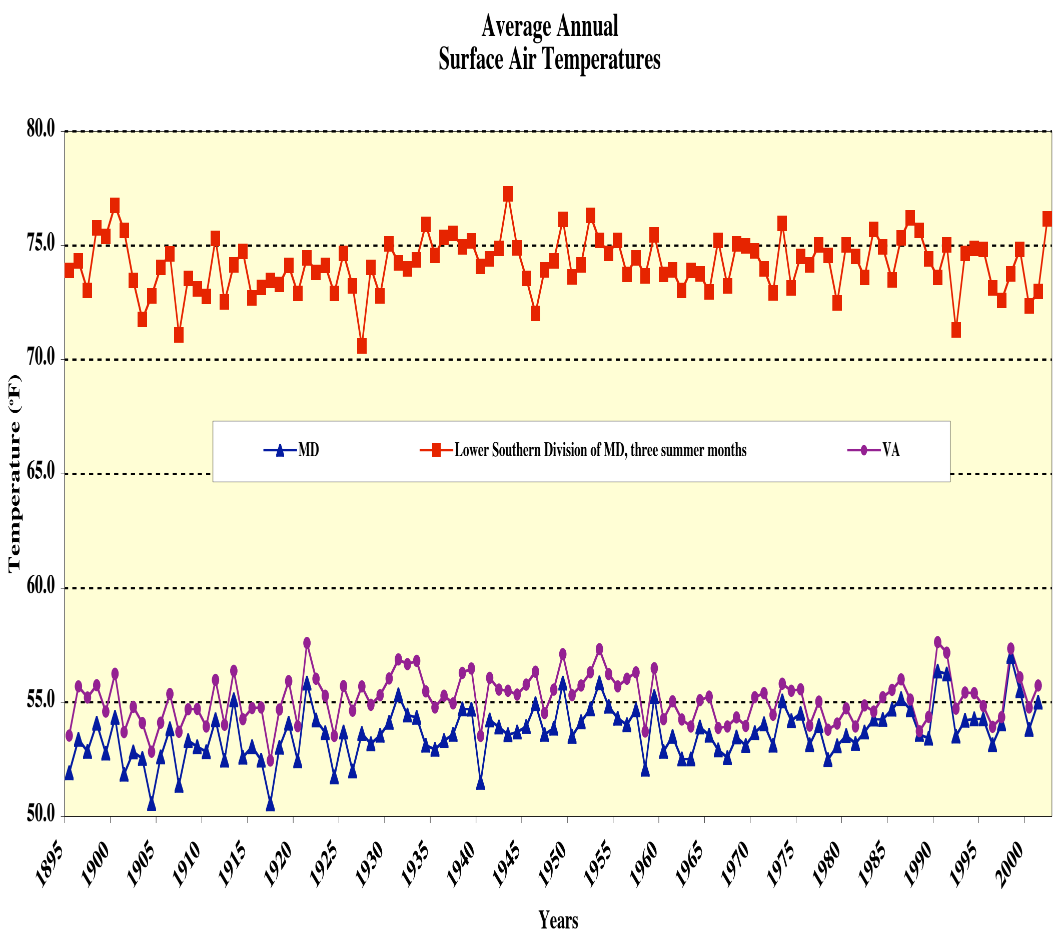


For the same period, Pennsylvania and West Virginia increased less than 100%, as shown above. The population of the District of Columbia increased by over 200% during the period from 1900 to the1940s. Since the 1940s, District of Columbia population began to decrease. By the year 2000, District of Columbia population had increased only 100% from 1900 levels.

Climate

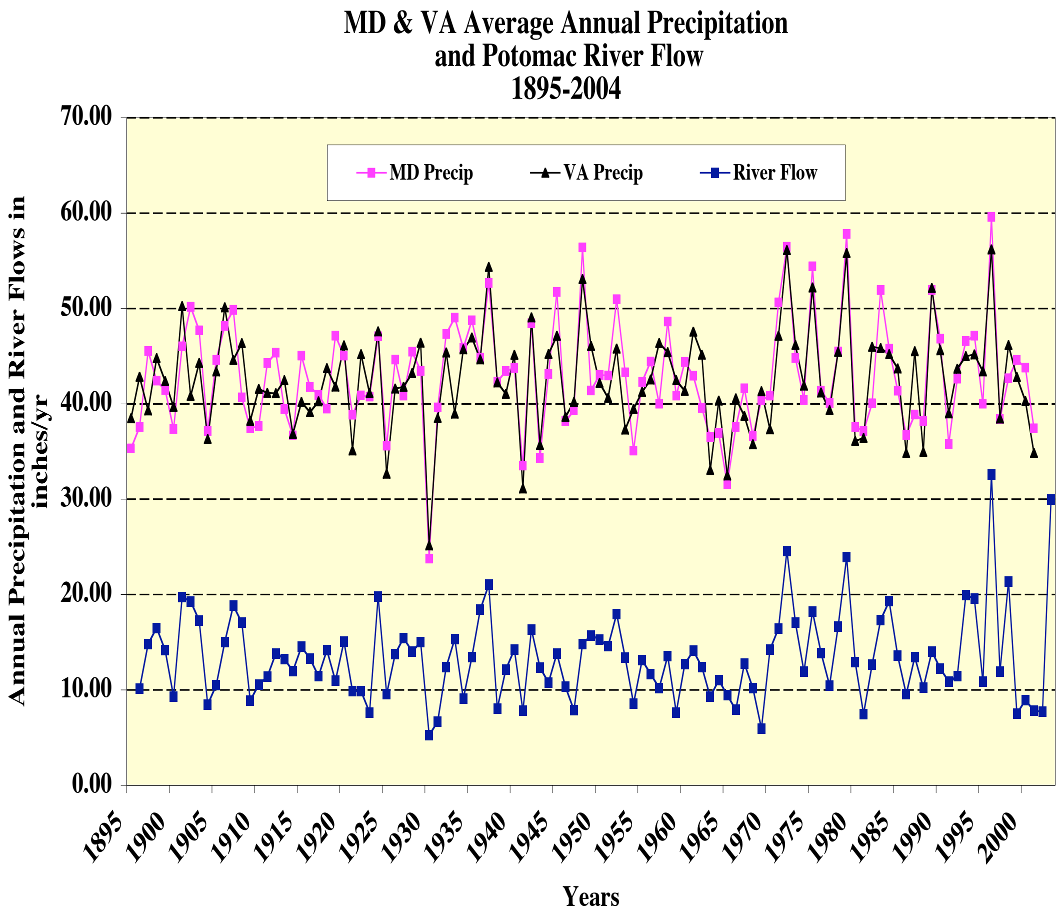
The Potomac River Basin and its Estuary lie in a climatic crossroad. During the colder months, cold air masses from Canada traverse the Basin with some protection by the Appalachian Mountains. Coastal "northeaster" storms often result in heavy rainfall or snowfall, most frequently in the winter and early spring. Occasionally, hurricanes and tropical storms pass over the Lower Basin, e.g. Hurricane Agnes (downgraded to a tropical storm) in 1972.

The average annual temperatures for the period 1895 to 2001 for the states of Maryland and Virginia were 53.5°F and 55.2°F respectively.



Trend analysis suggests that the average Maryland air temperature is increasing. No trend was observed for Virginia. For the months of June, July, and August, the average temperature of the southern portion of Maryland bordering the Potomac Estuary was about 74.2°F.

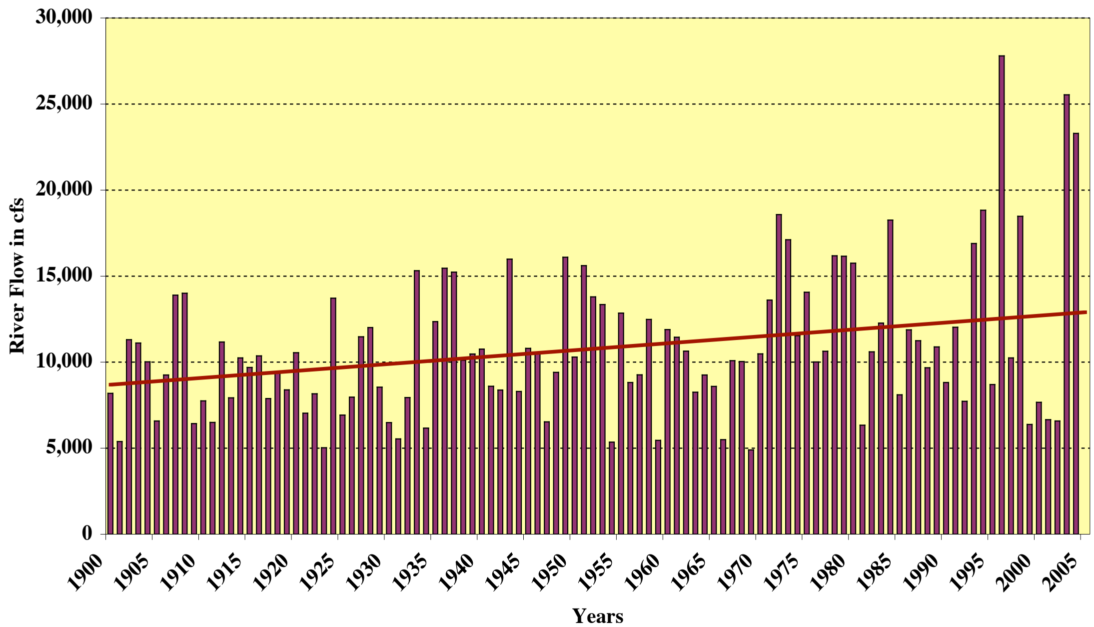
For the period 1895 to 2001, the annual average precipitation for Maryland was 43.0 inches (109.2 cm/yr), with a range of 25.0 to 60.0 inches/year, as presented below.



For the same period, the annual average and range of precipitation for Virginia was similar to Maryland, with an annual average of 42.6 inches/year (108.2 cm/yr).

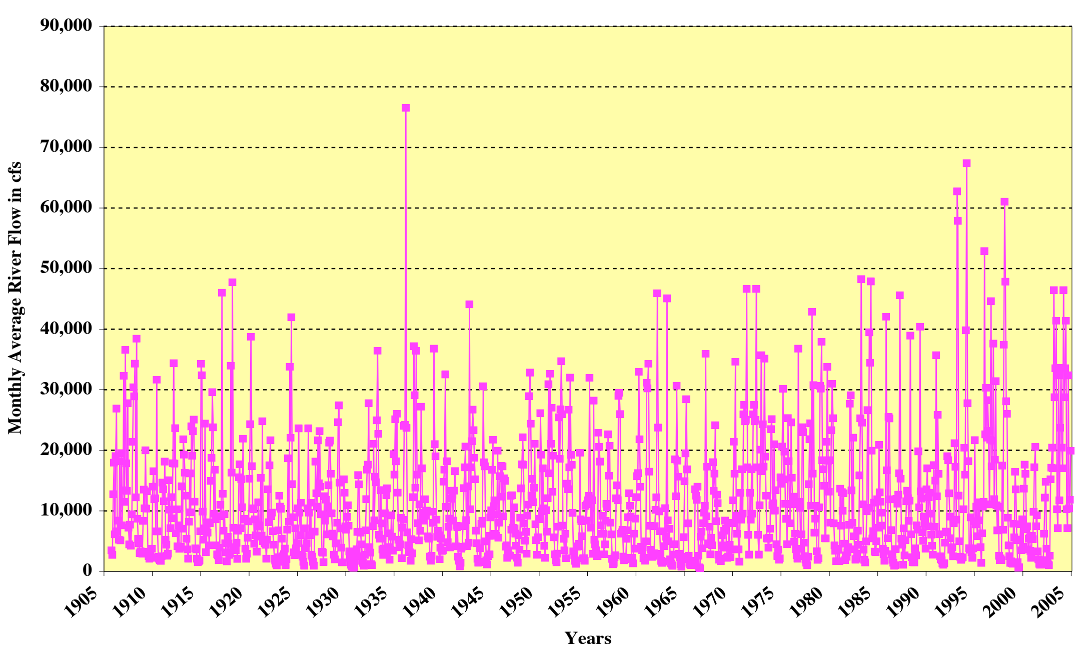
Using the Potomac River flow records at Point of Rocks, we extrapolated the Chain Bridge discharge records back to 1895. For the period 1895 to 2002, the annual average daily flow of the Potomac River at Chain Bridge was 11,350 cfs, with the lowest annual flow of 4,900 cfs in 1969, the highest flow of 27,800 cfs in 1996, and the second highest flow of 25,500 cfs in 2003 (see chart below).

Mean Annual Potomac River Discharge
Above Washington, DC
1900-2004



As shown in the two charts above, there appears to be an upward trend in both precipitation and runoff over the past century. During the past 50 years, the four largest stream flow years have occurred when the percent of forestland was highest**.** The increases could also have been influenced by increases in impervious surfaces. There has also been an increase in the number of high mean monthly flows, as presented below.

Upper Potomac River Above Washington, DC
Mean Monthly Flows



Prior to the 1950s, there was only one year, 1936, when the mean monthly flow was greater than 50,000 cfs. Since the 1950s, there have been five months in which the flow was greater than 50,000 cfs. In the 1900-1950 timeframe, there were five months when the mean monthly flow was greater than 40,000 cfs. Since the 1950s, there have been 21 months when the flow was greater than 40,000 cfs.

This is a counterintuitive observation. While there was a slight increase in precipitation, there has been a significant increase in the frequency and intensity of river flow pulses. At the same time, more of the Upper Basin is in forestland. As stated earlier in this chapter, at the turn of the 20th century about 23% of the Upper Basin was forestland. By the 1990s, about 61% of the Upper Basin was forestland. More forestland should result in more evapotranspiration, thereby *reducing* river flow not *increasing* flow. Urban land, which is more prone to be covered with impervious surfaces, makes up only 2.6% of the land use of the Upper Basin.

When the Potomac River monthly flow is 40,000 cfs, it takes about 2.7 days and 13.2 days to replace the volumes of water in the Upper Estuary and in the Middle Estuary respectively. In Chapters Five and Eight, we examined how higher stream flows during the past 50 years have increased the frequency and intensity of spring runoff pulses of nutrients from the Upper Basin, which in turn replenishes the surface nutrient pools of the Lower Estuary.

Of the 42.8 inches of annual average precipitation for the Upper Basin, 13.3 inches/year, or about 31%, runs out of the watershed. Sixty-nine percent evaprotranspirates back to the atmosphere. For the eight major sub-basins, the mean annual runoff is as follows:

Sub-basin	**Annual Runoff Inches/Yr**
North Branch	19.8
South Branch	12.1
Cacapon	11.8
Conococheague	16.1
Antietam	13.5
Opequon	10.4
Shenandoah	12.1
Monocacy	15.5

The low runoff for the South Branch, Cacapon, Opequon, and Shenandoah sub-basins reflects lower annual precipitation rates of about 5.0 inches/yr.

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