D.C. DEPARTMENT OF HEALTH
Environmental Health Administration
Bureau of Environmental Quality
Water Quality Division

DISTRICT OF COLUMBIA

FINAL
TOTAL MAXIMUM DAILY LOADS

FOR

BACTERIA

IN

TIDAL BASIN AND WASHINGTON SHIP CHANNEL

DECEMBER 2004

Government of the
District of Columbia
Anthony A. Williams, Mayor

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INTRODUCTION

Section 303(d)(1)(A) of the Federal Clean Water Act (CWA) states:

> *Each state shall identify those waters within its boundaries for which the effluent limitations required by section 301(b)(1)(A) and section 301(b)(1)(B) are not stringent enough to implement any water quality standards applicable to such waters. The State shall establish a priority ranking for such waters taking into account the severity of the pollution and the uses to be made of such waters.*

Further section 303(d)(1)(C) states:

> *Each state shall establish for the waters identified in paragraph (1)(A) of this subsection, and in accordance with the priority ranking, the total maximum daily load, for those pollutants which the Administrator identifies under section 304(a)(2) as suitable for such calculations. Such load shall be established at a level necessary to implement the applicable water quality standards with seasonal variations and a margin of safety which takes into account any lack of knowledge concerning the relationship between effluent limitations and water quality.*

Section 303(d) of the Clean Water Act and EPA's Water Quality Planning and Management Regulations (40 CFR Part 130) require states to develop Total Maximum Daily Loads (TMDLs) for waterbodies, which are exceeding water quality standards.

In 1996, the District of Columbia (DC), developed a list of impaired waters that did not or were not expected to meet water quality standards as required by Section 303(d)(1)(A). This list, submitted to the Environmental Protection Agency every two years, is known as the Section 303(d) list. This list of impaired waters was revised in 1998 and 2002 based on additional water quality monitoring data. EPA, subsequently, approved each list. The Section 303(d) list of impaired waters contains a priority list of those waters that are the most polluted. This priority listing is used to determine which waterbodies are in critical need of immediate attention. For each of the listed waters, states are required to develop a Total Maximum Daily Load (TMDL), which establishes the maximum amount of a pollutant that a waterbody can receive without violating water quality standards and allocates that load to all significant sources. Pollutants above the allocated loads must be eliminated. By following the TMDL process, states can establish water-quality based controls to reduce pollution from both point and non-point sources to restore and maintain the quality of their water resources. The Tidal Basin and the Washington Ship Channel are listed on DC’s 303(d) lists for bacteria impairment. The TMDLs developed herein are for fecal coliform bacteria in the Tidal Basin and the Washington Ship Channel.

DESIGNATED BENEFICIAL USES AND APPLICABLE D.C.WATER QUALITY STANDARDS

Categories of DC surface water designated beneficial uses and water quality standards are contained in District of Columbia Water Quality Standards, Title 21 of the District of Columbia Municipal Regulations, Chapter 11 (DC WQS, Effective January 24, 2003). Section 1101.1 states:

> *For the purposes of water quality standards, the surface waters of the District shall be classified on the basis of their (i) current uses, and (ii) future uses to which the waters will be restored.*

The categories of beneficial uses that were used to determine Water Quality standards for the surface waters of the District of Columbia are as follows:

Category of Use	Class of Water
Primary contact recreation………………………………………………	A
Secondary contact recreation and aesthetic enjoyment…………………	B
Protection and propagation of fish, shellfish, and wildlife ……………..	C
Protection of human health related to consumption of fish and shellfish	D
Navigation ………………………………………………………………	E

The table below identifies the current use and designated beneficial uses of the waters of the Tidal Basin and the Washington Ship Channel.

Waterbody	Current Use					Designated Use				
	A	B	C	D	E	A	B	C	D	E
Tidal Basin		✓	✓	✓	✓	✓	✓	✓	✓	✓
Washington Ship Channel		✓	✓	✓	✓	✓	✓	✓	✓	✓

Where, Current Use means the use which is generally and usually met in the waterbody at the present time in spite of the numeric criteria for that use not being met sometimes; and Designated use means the use specified for the waterbody in the water quality standards whether or not it is being attained.

The Tidal Basin and the Washington Ship Channel are listed on DC's 303(d) lists because of excessive counts of fecal coliform bacteria. Class A and Class B waters must achieve or exceed water quality standards for bacteria as measured by fecal coliform as an indicator organism. While fecal coliforms, which are microbes that live in the intestinal tracts of warm-blooded animals, are not harmful themselves, their presence indicates the potential for pathogens in the water. Water quality standards are derived from EPA recommendations based on risk levels associated with swimming.

The standard for fecal coliform for Class A waters is a maximum 30-day geometric mean of 200 MPN/100 ml, where MPN is a statistically-derived estimate of the "Most Probably Number" of bacteria colonies in a 100 ml sample. This statistical estimate is often called a "count" although it is represented as a concentration. The geometric mean is based on no fewer than five samples within the 30-day period. The standard for Class B waters is a 30-day geometric mean of 1000 MPN/100 ml.

The following sections of the District of Columbia Water Quality Standards have some bearing on this TMDL:

1104.2: For the waters of the District with multiple designated uses, the most stringent standards or criteria shall govern

1104.3: Class A waters shall be free of discharges of untreated sewage, litter and unmarked, submerged or partially submerged, man-made structures which would constitute a hazard to the users. Dry weather discharges of untreated sewage are prohibited.

Primary contact recreation - those water contact sports or activities, which result in frequent whole body immersion and/or involve significant risks of ingestion of the water.

Secondary contact recreation - those water contact sports or activities which seldom result in whole body immersion and/or do not involve significant risks of ingestion of the water.

The current use for the Tidal Basin and the Ship Channel is Class B, not Class A. However, Class A and B are designated uses for both of the waterbodies. The definitions of Class A primary contact recreation and Class B secondary contact recreation make clear that there is a risk level associated with recreational activities. The EPA criteria document estimated that at a geometric mean of 200 organisms per 100 ml that there would be about 8 illnesses out of 1,000 swimmers at a recreation swimming beach. The use of a geometric mean recognizes that there will be occasions where individual samples will be higher than 200 organisms/100 ml. Obviously, different types of Class A activities carry different risks, with swimming involving the highest risk. Activities such as windsurfing where the person spends most of the time out of the water but spends significant amounts of time in the water or being splashed with water runs a lesser risk. While in the case of scuba diving, because of increased pressure of the water at depths, may cause a higher prevalence of ear infections than other types of activities. Certain Class A activities maybe limited by factors other than disease risk. Issues such as current velocity, floods, clarity of the water and competing uses such as navigation or fishing may restrict these activities to certain areas at certain times and most certainly winter temperatures and heavy ice create limitations. The District of Columbia water quality standards do not guarantee risk free primary contact recreation nor do they guarantee that it can occur everywhere all of the time.

WATERSHED

The Washington Ship channel along with the Tidal Basin are man-made waterbodies located in the southwest section of Washington D.C. along the Potomac River (see Figure 1). The Tidal Basin was built in the late 19th century by the Army Corps of Engineers as a part of the comprehensive management of the Potomac River and land development of Washington D.C. The Basin is located adjacent to the Jefferson Memorial and the well-known cherry trees of the Nations Capital. The Washington Ship Channel stretches from Hains Point at the confluence of the Anacostia and Potomac Rivers to the Tidal Basin. The main function of the Tidal Basin is to flush the Washington Ship Channel with the freshwater from the Potomac River. Two sets of floodgates exist in the flushing system, one linking the Tidal Basin and the Potomac River, and the other linking the Tidal Basin and the Washington Ship Channel. Freshwater flows into the Tidal Basin through the flap gates when the tidal elevation changes and the elevation in the Potomac River is higher than that in the Tidal Basin.

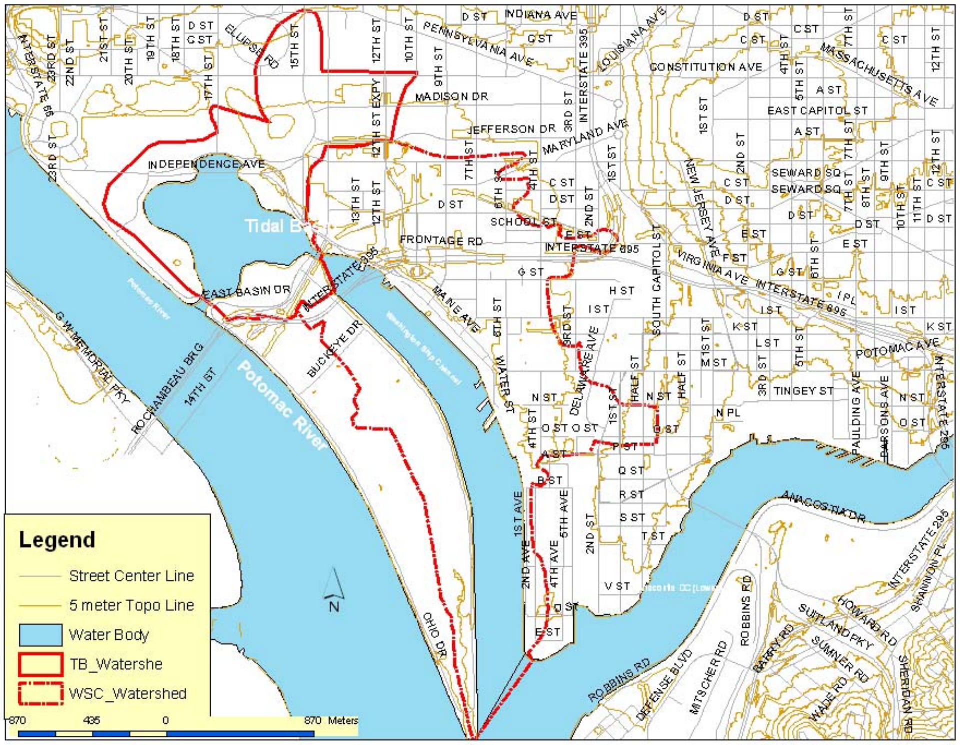

Figure 1: Tidal Basin and Washington Ship Channel

In the same way, the freshwater flushes into the Washington Ship Channel as the water surface elevation becomes higher in the Tidal Basin. The purpose of the gates is to direct flow from the Potomac River to the Tidal Basin then to the Washington Ship Channel. The Tidal Basin is shallow with an average depth of around 6.5 feet (2 meters) and a surface area of about 100 acres (0.4 km^2). The Washington Ship Channel is about 400 feet (122 meters) wide and the depth varies from 3 feet (1 meter) to 26 feet (8 meters).

As shown in Figure 2, the land use in the Tidal Basin watershed is dominated by parklands/grass areas covering about 43 percent of the watershed. The Basin itself covers about 30 percent, and the remaining areas being used mainly for commercial/government offices. The land use around the Washington Ship Channel is dominated by government/commercial/residential uses along the northern bank of the waterbody covering about 53 percent of the watershed (see Figure 3). The area along the southern bank is characterized by recreational grass and parklands, with the Channel itself covering about 25 percent of the watershed. The Channel, along the northern banks between the Tidal Basin and Fort McNair, is used as docking for small personal and large commercial touring boats. There is a large fish market and series of seafood restaurants along the docking areas.

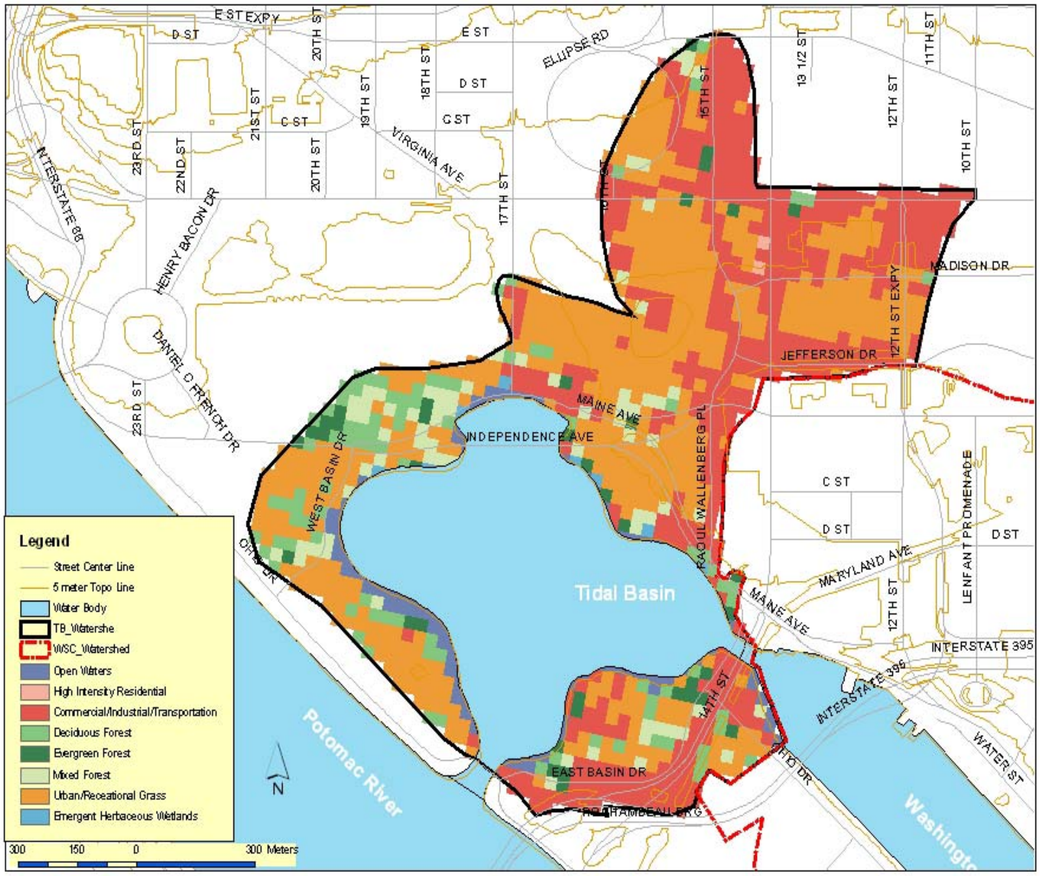

Figure 2: Land use in the Tidal Basin Watershed

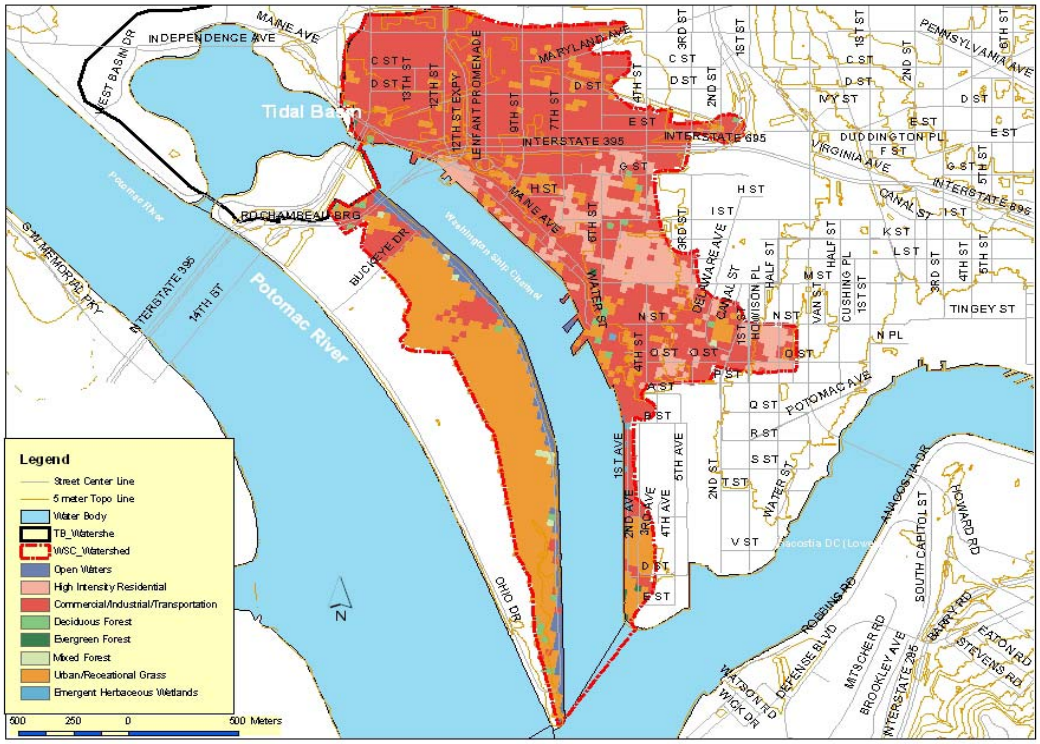

Figure 3: Landuse in the Washington Ship Channel Watershed

SOURCE ASSESSMENT

The sources of fecal Coliform are ubiquitous. Any means by which fecal matter can be transported to the receiving waters is a potential source. Such sources may include combined sewer overflows (CSOs); separate sanitary sewer overflows (SSOs), which can result from leaky or undersized sanitary sewer pipes; stormwater runoff, which includes overland flow and flow conveyed through storm sewer pipes, and direct deposits of feces into the water from wildlife sources.

Within the District of Columbia, there are three different networks for conveying wastewater. Originally, a combined sewer system was installed which collected both sanitary waste and storm water and transported the flow to the wastewater treatment plant. When storm water caused the combined flow to exceed the capacity of the treatment plant, the excess flow is discharged, untreated, through the combined sewer outfalls to the rivers. Approximately one third of the District of Columbia is served by the combined sewer system. The remaining two thirds of the District of Columbia is served by a separate system where one pipe network (separate sanitary sewage system) collects sanitary sewage that is transported to the Blue Plains wastewater treatment plant in the southeast corner of the District of Columbia and another pipe network (separate storm sewer system) collects storm water that is transported and discharged to surface water.

The Washington Ship Channel and the Tidal Basin are served by the separate storm system as shown in Figure 4. Separate storm water networks collect storm water from streets and parking lots. Collected storm runoffs are then directly discharged to the Washington Ship Channel and Tidal Basin. It is estimated that storm water from an area of about 150 acres and 445 acres of land is drained into the Tidal Basin and the Ship Channel, respectively. There are six storm sewers discharging into the Tidal Basin and nine storm sewers draining into the Washington Ship Channel. There are no combined sewer overflow outfalls in the waterbodies.

A separate sanitary sewer line should have no storm water inlets to the system and it flows directly to the wastewater treatment facility. Even though sanitary pipes are only intended to carry wastewater flow, they are influenced by rainfall. Infiltration and inflow of stormwater into sanitary pipes has the potential to cause surcharging and overflows. These overflows can reach the storm sewer system or the receiving waters directly, and can be a significant source of bacterial contamination to the waterways.

For this TMDL, sanitary sewer overflows were not modeled explicitly, as it was assumed that any bacteria from a routine SSO would be represented by the quality of the storm water. In many old cities, illicit and cross connections do exist between sanitary and storm sewers, and the District of Columbia is no exception. Illegal discharges are particularly difficult to locate as most storm water outfalls drains to the Tidal Basin and Washington

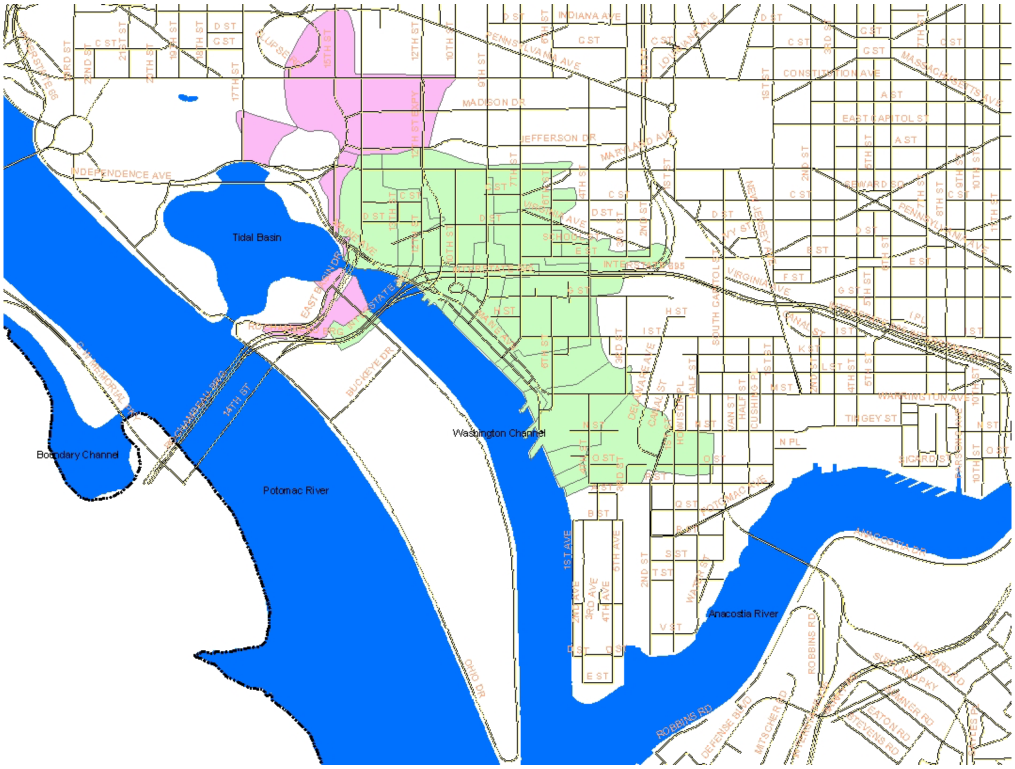

Figure 4. Separate Storm Sewer Areas in the Tidal Basin and Washington Ship Channel Watersheds

Ship Channel are partially submerged by construction and fully submerged during high tide. In this setting, identification and elimination of cross connection presents many challenges.

Direct runoffs from parklands flanking the water bodies and not serviced by storm water sewers also occur along the Tidal Basin and the Ship Channel. Therefore, during wet weather events, there is a combination of direct storm water runoff and storm water being carried by pipes to the waterbodies. Historically considered nonpoint source, storm water runoff discharged from separate storm sewer systems (SSWS) are permitted under the National Pollution Discharge Elimination System (NPDES).

In addition to storm and direct runoffs, the water quality in the Tidal Basin and the Ship Channel can be affected by direct deposits from waterfowls and the water quality conditions in the Potomac and the Anacostia Rivers because of direct hydraulic connections.

TECHNICAL APPROACH

TMDL End Points

The water quality standard for fecal coliform bacteria for Class A waters is a maximum 30-day geometric mean of 200 MPN/100 ml, where MPN is a statistically-derived estimate of the "Most Probably Number" of bacteria colonies in a 100 ml sample. For this TMDL analysis, the Class A standard for fecal coliform bacteria was used as the numerical end point.

Seasonal Variations and Critical Conditions

Because of the natural variability in rainfall and storm water runoff, developing a daily load is not an effective means of determining the assimilative capacity of the receiving waters. Rather, looking at total loads over a range of conditions is a more relevant way to determine the maximum allowable loads. A statistical analysis of rainfall records over a period of fifty years was conducted and a dry year, a wet year, and an average rainfall year, were identified based on total annual rainfall and other factors such as average intensity and number of events per year (DCWASA, 2002). The consecutive years of 1988, 1989, and 1990, represent a relatively dry year, a wet year, and an average precipitation year, respectively. These three years were considered the period of record for determining compliance with the water quality standards for the TMDL analysis. Determination of compliance with the water quality standards was based on the frequency of violations as calculated by the model for these three years.

Modeling

In order to develop bacteria TMDLs for the Tidal Basin and the Ship Channel, a model was developed to simulate the fate and transport of fecal coliform bacteria in the waterbodies (Lung, 2003). A brief description of the model is included in Appendix A. The model was developed using EFDC, a three-dimensional model capable of simulating hydrodynamics, sediment transport and water quality using a curvilinear-orthogonal grid for a waterbody. The model grid for the Tidal Basin and the Ship Channel is shown in Figure 5.

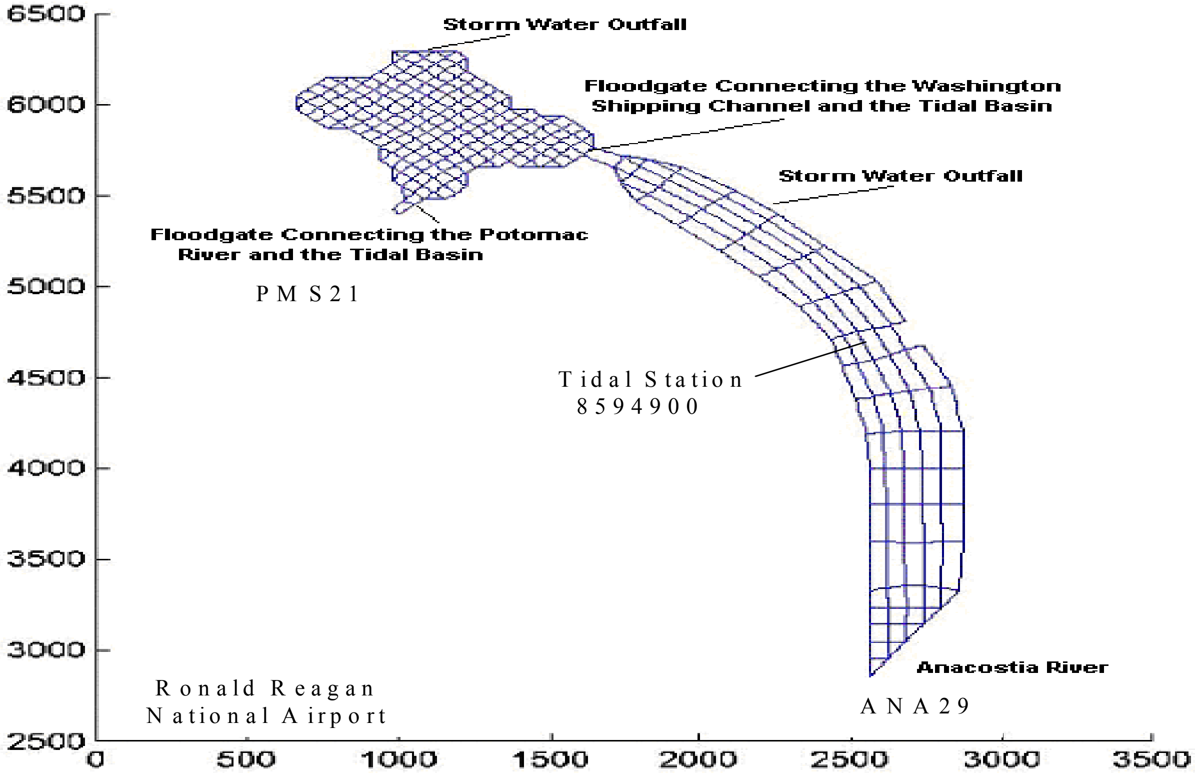

Figure 5: Hydrodynamic Grid of the Tidal Basin and Washington Ship Channel

The model input includes runoffs from the separate storm water system, direct runoffs from park areas and direct deposits from waterfowls. No illicit discharges are simulated in the model. The separate storm water and direct runoff loads were calculated using event mean concentrations for the fecal coliform bacteria and the modeled flow volume over the period of analysis. The event mean concentration is used as a representative storm water concentration. Boundary conditions at the upstream link between the Tidal Basin and the Potomac River and the downstream link between the Washington Ship Channel and the Anacostia River were also simulated in the model. The model was run for three different years (1988, 1989, 1990) and the model outputs were checked at selected locations such as close proximity to storm water outfalls, where maximum concentrations may occur.

EXISTING LOAD

There are no combined sewer overflows to the Tidal Basin and the Washington Ship Channel. The annual average existing loads from the separate storm water system, direct runoffs and direct deposits from waterfowls into each of the water bodies are listed below.

	Tidal Basin **(MPN/average Year)**	**Washington Ship Channel** **(MPN/average Year)**
Separate storm	1.60E+14	5.29E+14
Direct Runoff	1.30E+14	2.22E+14
Direct Deposits	5.26E+16	2.10E+16
Total	5.28E+16	2.18E+16

TOTAL MAXIMUM DAILY LOAD, ALLOCATION AND MARGINS OF SAFETY

For allocating maximum daily loads to different sources within the watersheds of the Tidal Basin and the Washington Ship Channel, the model was run with the existing loads for the separate storm water and direct runoffs as well as direct deposits from waterfowls. The boundary conditions were set at the water quality standard of 200 MPN/100ml at all times. The model results indicate there is no violation of the bacteria standard in the waterbodies under the existing loads. In other words, the water bodies can safely carry the existing loads without violating the water quality standard. Given the various assumptions in calibrating the model, a 10 percent margin of safety is considered for storm water and direct runoff loads to account for the modeling uncertainty.

Allocated Loads and Margins of Safety

	Tidal Basin **(MPN/average Year)**	**Washington Ship Channel** **(MPN/average Year)**
Separate storm	1.44E+14	4.76E+14
Direct Runoff	1.17E+14	2.00E+14
Direct Deposits	5.26E+16	2.10E+16
Margin of Safety	2.90E+13	7.52E+13
Total	5.28E+16	2.18E+16

REASONABLE ASSURANCE

It is evident from the model simulation that the storm water quality causes no water quality standard violations. However, the ambient water quality monitoring show high bacteria counts to promote the listing of the Tidal Basin and the Washington Ship Channel.

During the preparation of this TMDL, the Water Quality Division received information of a cross connection of wastewater drain from a major rest area facility. The facility has been taken out of service and is currently undergoing corrective actions.

In view of the discovery of the cross connections, the Water Quality Division has launched a systematic investigation of possible cross-connections in the area. Federal lands encompass a major portion of the Washington Ship Channel and Tidal Basin watershed. The Water Quality Division has established federal partnership and has initiated the investigation.

In addition the DC WASA has launched a citywide Sanitary Sewer System Investigation. The activities under this program will eliminate infiltration of sanitary sewer to the storm water system.

As the Tidal Basin and the Washington Ship Channel are affected by the water quality in theAnacostia and Potomac Rivers, different storm water and CSO management programs in theDistrict that improve water quality in the Rivers will also help improve the water quality in the Tidal Basin and the Ship Channel.

Monitoring

The Department of Health maintains an ambient monitoring network that includes stations in the Potomac and Anacostia Rivers and Rock Creek, as well as stations in the Tidal Basin and the Washington Ship Channel. The bacterial results will be closely examined for any trend.

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Appendix A

FECAL COLIFORM BACTERIA MODEL OF THE TIDAL BASIN AND THE WASHINGTON SHIP CHANNEL

The dynamics of the fecal coliform population in natural waters are influenced by various physical and chemical processes of the water and physiological processes of fecal coliform bacteria. To account for these factors, modeling fecal coliform dynamics in natural waters requires information about advection, diffusion, temperature, salinity, pH, solar radiation, and sediment transport. Therefore, an integrated modeling framework including a hydrodynamic model, a sediment transport model, a water quality model, and a fecal coliform model was used to develop the fecal coliform model for the Tidal Basin and the Washington Ship Channel (See Figure 1).

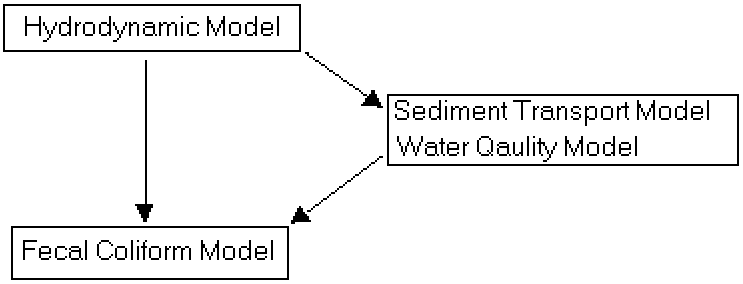


Figure 1: Fecal Coliform Modeling Framework

The general framework of Environmental Fluid Dynamics Code (EFDC) model (Hamrick, 1992) was adopted in this study. The EFDC model can be used to run hydrodynamics, sediment transport, eutrophication, and toxics coupled together. The flow field, mixing coefficients, salinity, and temperature are calculated by the hydrodynamics model in the EFDC model. The sediment transport model updates the suspended solids concentration needed to drive the fecal coliform model. Similarly, the solar radiation, which can affect the die-off rates of fecal coliform, can be obtained from the eutrophication model. However, the EFDC model does not simulate pH, which can also affect the fate of fecal coliform. Therefore, a pH-alkalinity model was added into the EFDC model for simulating fecal coliform fate and transport.

HYDRODYNAMIC AND SEDIMENT TRANSPORT MODEL

The hydrodynamic and sediment transport simulation in this study is obtained by running the EFDC model. The hydrodynamic component of EFDC solves the three-dimensional, time variable, viscous, incompressible, free surface flow governed by the Reynolds Equations. Some simplifications of the governing equations were achieved by applying a hydrostatic approximation, a Boussinesq approximation, and an eddy viscosity concept (Hamrick, 1992). Temperature and salinity are integrated in the hydrodynamics computation since water density is dependent on temperature and salinity. Wetting and drying of shallow areas because of water elevation variation is allowed in EFDC. The structure of the hydrodynamic component of EFDC is shown in Figure 2.

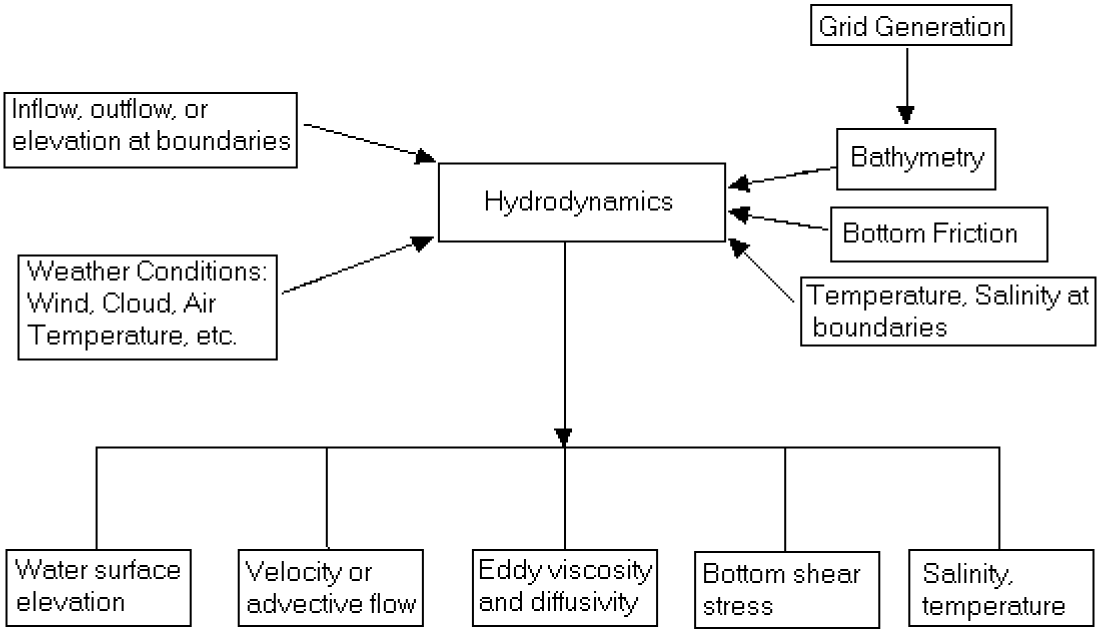


Figure 2: EFDC Hydrodynamic Model Framework (modified from Tetra Tech, Inc., 2000)

In addition to the hydrodynamics component, EFDC models sediment transport including both non-cohesive sediment, which considers bed load, and cohesive sediment. In this study, only cohesive sediment transport was considered since fecal coliform bacteria tend to adsorb onto fine particles rather than to coarse particles. The cohesive sediment transport model uses the same advection-diffusion scheme to calculate the transport in the water column as other dissolved constituents with an extra settling term. The settling velocities can be quantified with various options from simple to complex depending on whether flocculation process is considered or not. A flocculation model can be activated to compute the flocculation effects of the fine particles. In the bottom of the surface waters, multiple layers can be assigned and several consolidation options are available. The details about the hydrodynamic and sediment transport model can be found in the EFDC manual (Hamrick, 1992).

WATER QUALITY AND PH-ALKALINITY MODEL

The eutrophication module of the EFDC model was used in the study to simulate water quality processes. Since the EFDC model does not model pH level, a pH-alkalinity model was developed in this study. The modeling framework is based on the carbon dioxide-bicarbonate-carbonate equilibrium in natural surface waters. In this modeling framework, production and consumption of alkalinity and acidity through biological processes are grouped as internal sources and sinks.

The model variables include alkalinity and carbon dioxide acidity. The mass balance of alkalinity includes advection, diffusion, and alkalinity decrease due to ammonia uptake, nitrification, and sulfide oxidation, alkalinity increase due to ammonification, denitrification, and sulfate reduction. The mass balance of carbon dioxide (CO_2) acidity includes advection, diffusion, mass transfer across the air-water interface, acidity decrease due to photosynthesis, and acidity increase due to respiration. The fractional step technique was applied in calculating the alkalinity and CO_2 acidity. The advection and diffusion calculation of alkalinity and CO_2 acidity follows the dye calculation in the original EFDC model. Details on the pH-alkalinity model are described elsewhere (Lung, 2003).

FECAL COLIFORM FATE AND TRANSPORT MODEL

The fate and transport of fecal coliform is governed by an advection-diffusion-reaction equation. To account for the contribution of sediment transport, two states of fecal coliform: free-swimming and attached are considered in this study. The advection and diffusion processes for fecal coliform are the same as the processes for cohesive sediment particles and other dissolved or suspended constituents. Hence, the advection and diffusion of free and attached fecal coliform are calculated together as one variable to save computation time. The fractional step approach of the EFDC model was used to simulate the fate and transport of fecal coliform. Various fate and transport processes are briefly described herein. Details of the processes can be found elsewhere (Lung, 2003).

Physical Movement of Fecal Coliform

Advection

Two main concerns for various numerical schemes of advection are stability and accuracy. A good scheme remains stable with relatively large time steps and generates minimal numerical diffusion and dispersion. In the EFDC model, the advection scheme MPDATA is applied. For calculating the advection of fecal coliform in the water column, the same scheme is used to be consistent with other constituents.

Sediment – Water Partition of Fecal Coliform

Suspended solids have significant influences on the fate and transport for fecal coliform bacteria in surface waters. Attached fecal coliform move with the sediment particles to the bottom bed and disappear from the water column. Whenever resuspension of settled sediment particles occurs, the bottom bacteria can re-enter the water column. To include the impact of sediment transport processes to the fate and transport of fecal coliform, the free-swimming bacteria and the attached bacteria must be considered separately. The ratio between the free bacteria and the attached bacteria is calculated by assuming an equilibrium adsorption process in this study. More about the partitioning of fecal coliform can be found elsewhere (Lung, 2003).

Settling Loss of Attached Fecal Coliform from Water Column

The direct physical impact of sediment transport processes to the attached bacteria is the settling effect that brings these bacteria to the sediment bed. The settling velocity of attached bacteria is the same as the particle settling velocity, which is dependent on the properties of the particles such as the size and composition. In the EFDC model, several empirical formulas are used for calculating the settling velocity for the cohesive sediment particles and flocs. Unlike the disappearance of fecal coliform from die-off in the water column, the destination of fecal coliform settling is the bottom sediment bed. Once fecal coliform bacteria settle to the bottom, it is assumed to evenly distribute among the receiving sediment layer. The movement of fecal coliform among the sediment layers is modeled as a diffusive process for free moving bacteria and will be discussed in a following section.

Resuspension of Sediment Bed Fecal Coliform

When the bottom shear stress is stronger than critical shear stress of erosion or sediment bed shear strength, the bottom sediment can be resuspended into the overlaying water column. Depending on the relation between the shear stress and the critical shear stress and bed strength, two types of resuspension, mass erosion and surface erosion, may occur. When the bottom shear stress is higher than the bed shear strength, mass erosion will occur and the whole layer of sediment will be resuspended. If the bottom shear stress is lower than the bed shear strength and higher than the critical shear stress for resuspension, surface erosion will occur and only the top sediments will be resuspended. The bed density of fecal coliform is updated simply by using the ratio of the eroded sediment to the total sediment, which is equal to the decreased depth over the original depth before erosion.

Transport of Fecal Coliform in the Sediment Layers and across the Sediment-Water Interface

The full governing equation for total bacteria fate and transport in porous media is an advection/diffusion/adsorption/chemotactic/reaction equation. In this study, the fecal coliform movement in the sediment bed due to chemotactic response is not included since the knowledge about the preference of fecal coliform is very limited. The reaction term is solved in the kinetic portion of the model. Since the horizontal scale for modeling surface water is much greater than the vertical scale in the sediment bed and the bacteria transport in porous media is slow, only the vertical direction is considered in the model development. In addition, it is assumed that the attached bacteria in the sediment bed do not move at all. Hence, the resultant transport equation for fecal coliform is an advection-diffusion-adsorption equation in the vertical dimension for free-moving fecal coliform. In addition to the transport inside the sediment layers, the diffusive movement of bacteria across the interface between the sediment layer and the water column is also considered in the model. Since adsorption is calculated in the step of calculating sediment-water interaction, only diffusion is evaluated in this step.

Diffusion in the Water Column

Diffusion in the water column is an important process, which redistributes constituents or bacteria based on the concentration or density gradient. In this study, both the Brownian random movement and the turbulent mixing are called diffusion. In modeling surface waters, the grid horizontal dimension is usually larger than in the vertical dimension. Hence, the diffusion in the horizontal plane is omitted and only the vertical diffusion term is kept. In the fractional step approach that calculates general dissolved or suspended constituents, vertical diffusion flux is updated after the source/sink and advective fluxes. An implicit scheme is used in the EFDC code.

Fecal Coliform Die-off

Die-off is a very important process for the decrease of fecal coliform population in surface water. Current models for natural surface waters usually use very simple methods to determine the first-order die-off rate. The factors that influence the die-off rate of fecal coliform and considered in this study include solar radiation, pH, salinity, and temperature. Kinetics involved in the die-off process and the equations used to calculate the die-off rates for each of the factors are described elsewhere (Lung, 2003).

To calculate the die-off rate caused by various factors, the environmental variables must be calculated first. The temperature is calculated in the hydrodynamic module of the EFDC model. Salinity is also obtained from the hydrodynamic calculation if applicable. Solar radiation is calculated using the meteorological data. DO is calculated in the water quality module in the EFDC model. pH is obtained from the pH-alkalinity model described earlier. After these environmental factors are calculated, the die-off rates of fecal coliform caused by these factors are then updated for free-swimming bacteria, attached bacteria in the water column, and for the total bacteria in the sediment bottom. The total die-off rate is the sum of the individual die-off rates based on the assumption that these individual processes are independent from each other.

Fecal coliform bacteria can survive in the sediment bed significantly longer than in the water column for various reasons, and some researchers even found fecal coliform growth in the sediment bed. Hence, the die-off rate calculated from the water column cannot be applied directly to the fecal coliform in sediment bed. Unfortunately, no research has been conducted to link the environmental factors in the sediment bed to the fecal coliform die-off/growth rate. In addition, the salinity, pH values are not calculated for sediment layers. Therefore, a temperature dependent first-order die-off rate is set as the total die-off rate. The original EFDC model control file was modified to accommodate the simulation of fecal coliform bacteria.

FECAL COLIFORM MODELING IN TIDAL BASIN AND WASHINGTON SHIP CHANNEL

The Tidal Basin (Figure 3) was built in the late 19th century by the Army Corps of Engineers as a part of the comprehensive management of the Potomac River and land development of Washington D.C. The main function of Tidal Basin is to flush the Washington Ship Channel with the freshwater from the Potomac River. Two floodgates exist in the system, one linking the Tidal Basin and the Potomac River, and the other linking the Tidal Basin and Washington Ship Channel. Freshwater flows into the Tidal Basin through flap gate when the tidal elevation changes and the elevation in the Potomac River is higher than that in the Tidal Basin. In the same way, the freshwater flushes into the Washington Ship Channel as the water surface elevation becomes higher in the Tidal Basin. The direction of water flow is unidirectional from the Potomac River to the Tidal Basin then to the Washington Ship Channel. The Tidal Basin is shallow with an average depth of around 2 meters and a surface area of about 0.4 km^2. The Washington Ship Channel is about 122 meters wide and the depth varies from 1 meter to 8 meters (Velinsky et al. 1994). The flow field in the Tidal Basin and Washington Ship Channel is governed by the tidal fluctuation, floodgate operation, and wind.

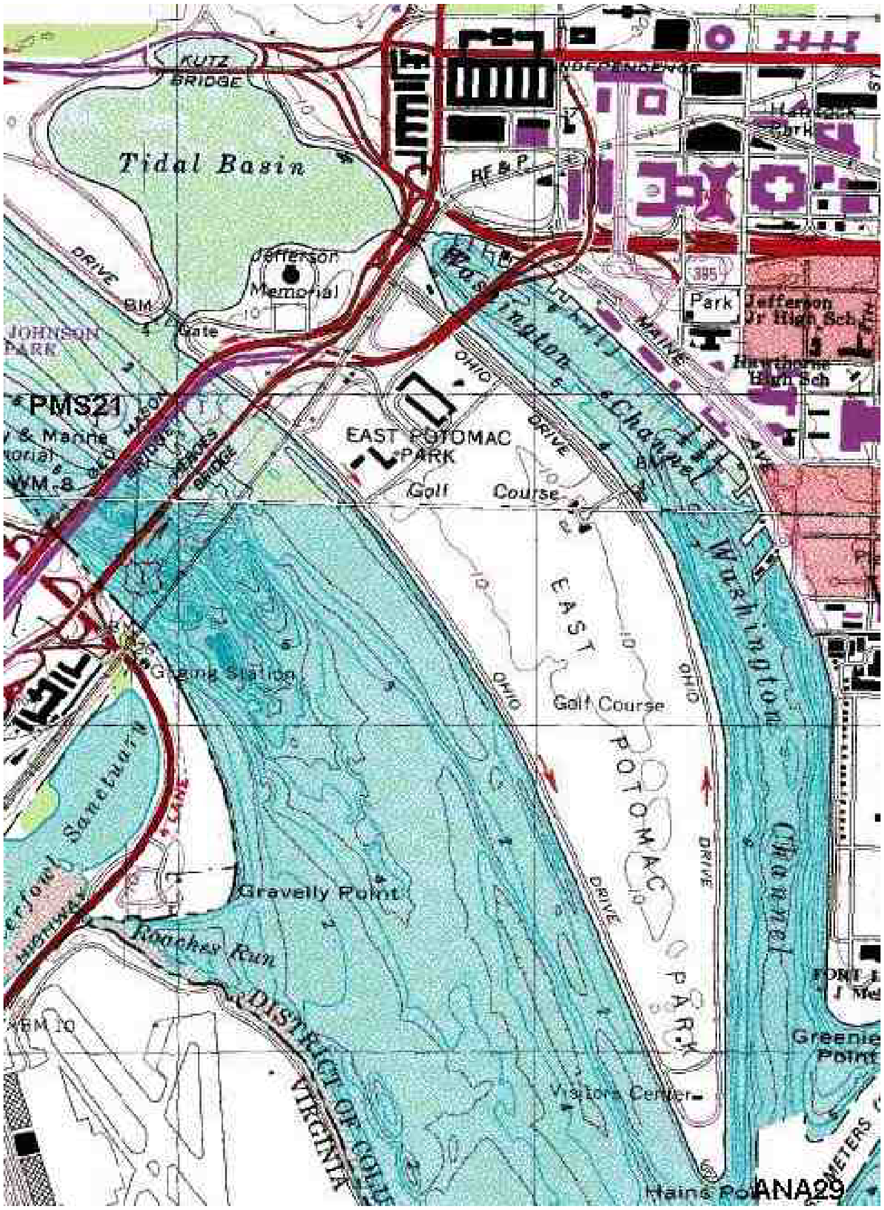


Figure 3: Tidal Basin and Washington Ship Channel

Model Grid

Since the EFDC model is able to use orthogonal and curvilinear grid that matches the natural boundary of the water body, the Tidal Basin and the Washington Ship Channel were divided to 265 active cells fitting the boundary on the horizontal plane as shown in Figure 4. Each cell is further divided into two layers with equal depth, resulting in a three-dimensional grid. Because the EFDC model uses σ-coordinates in the vertical direction, the relative depth of each layer is 0.5. More about the process of grid generation can be found elsewhere (Lung, 2003).

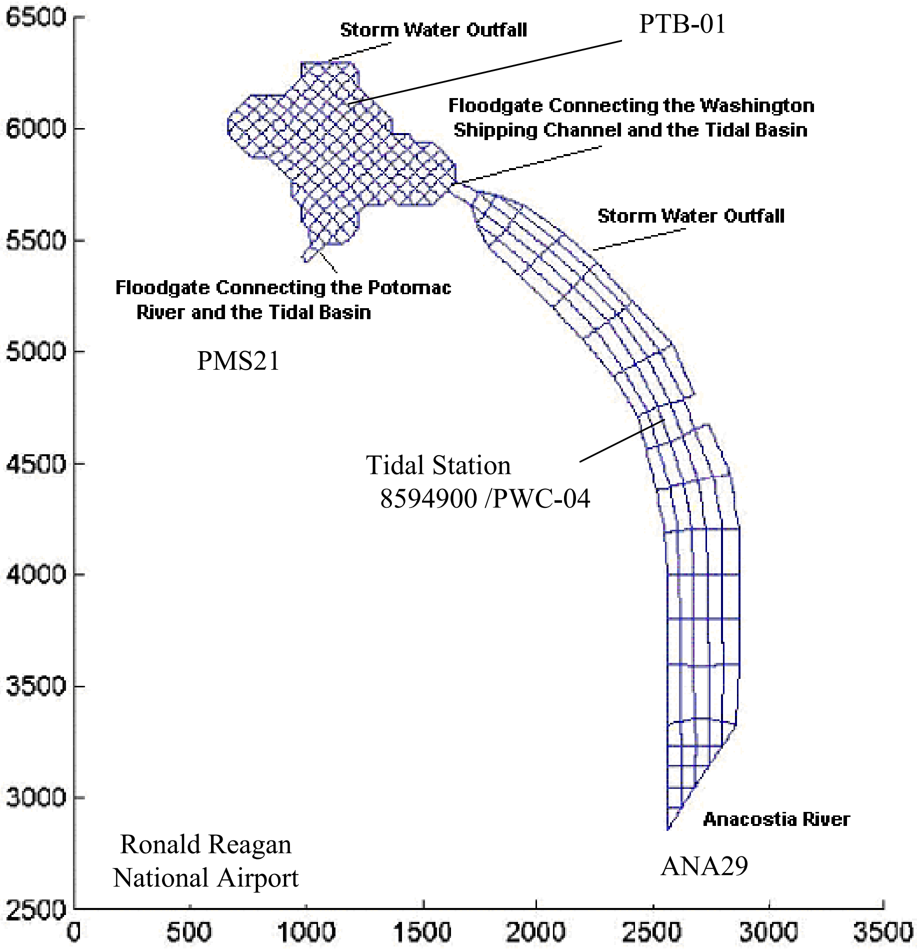


Figure 4: Hydrodynamic Grid of the Tidal Basin and Washington Ship Channel

Data Used in the Modeling Analysis and Calibration

To support the modeling analysis and calibrate the model, a large amount of data is required. For example, meteorological, tidal elevation, flap gate operation, and stormwater runoff data are needed for driving the hydrodynamic model. Similarly, TSS and fecal coliform data are needed at the boundaries of the Tidal Basin and the Ship Channel with the Potomac and Anacostia Rivers. In order to calculate loads from storm water, both TSS (total suspended solids) and fecal coliform data for storm water are also required. The model was calibrated using the data for the year 1998. Following is a brief description of the data used in the study. Details of the data used in the study can be found elsewhere (Lung, 2003).

The meteorological data including the air pressure, wet bulb air temperature, dry bulb air temperature, cloud cover, wind speed and direction, and precipitation were directly obtained from the Reagan National Airport. The tidal elevation data were obtained from the NOAA tidal station in the Washington Ship Channel. Since the area of the modeling domain is very small, the differences between the two boundaries are minimal. For modeling the freshwater flushing of the Washington Ship Channel, the flood flap gate operation tables relating the water elevation differences and the flow rates are very important. Unfortunately, no information regarding the gate operation is currently available. Therefore, the gate operation tables were assumed and adjusted during the calibration of the water elevation in the Tidal Basin, which is to have the flushing process and not to have extremely high or low water elevation.

There are six separate storm sewers outfalls in the Tidal Basin and nine outfalls in the Washington Ship Channel. Storm water loads were calculated using event mean concentrations. The storm water runoff was estimated by multiplying the precipitation rate, infiltration loss percentage, and the drainage area. For TSS and fecal coliform in the storm water, event mean concentrations (EMC) of 94 mg/L and 28265 MPN/100ml were used, respectively.

In addition to the data that drive the hydrodynamic modeling, water column suspended solids (TSS) data are needed for simulating and calibrating sediment transport processes. TSS and fecal coliform data in the Potomac River, Anacostia River, the Tidal Basin, and the Washington Ship Channel were obtained from the Chesapeake Bay Program Website (www.chesapeakebay.net). The data from the Potomac and Anacostia Rivers were used as boundary conditions.

Calibration of Hydrodynamics and Sediment Transport Models

The hydrodynamics and suspended solids were modeled prior to calculating the fate and transport of fecal coliform. The hydrodynamics and sediment transport calculation are coupled in EFDC since the change of sediment bed depth will change the water depth and bottom bathymetry. The calculation of fecal coliform fate and transport does not affect the hydrodynamics and suspended solids. The model was simulated for the entire period of year 1998 with a time step of 100 seconds. Figure 5 and 6 show both observed and simulated water surface elevations in the Washington Ship Channel for a day and for the entire year, respectively. Modeled water surface elevations in the Washington Ship Channel matches the observed elevation very well. No observed water surface elevations are available for the Tidal Basin. The change of the water surface elevation in the Tidal Basin is governed by the inflow through the floodgate from the Potomac River, precipitation, evaporation, storm water, and the outflow through the floodgate to the Washington Ship Channel. Figure 7 shows the modeled water surface elevation in the Tidal Basin, which is relatively stable with small fluctuations and reflects that the freshwater flushing into the Washington Ship Channel.

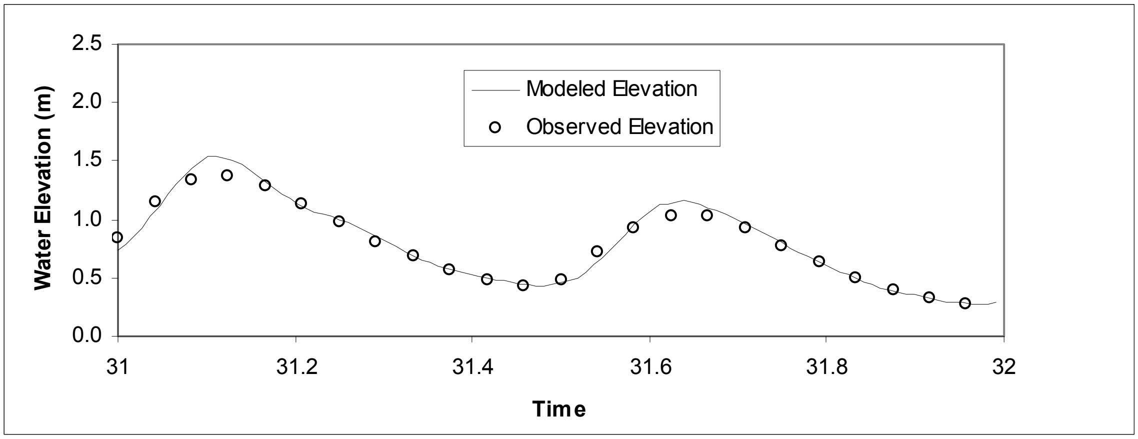


Figure 5: Observed and Modeled Water Surface Elevation in the Washington Ship Channel for a Day

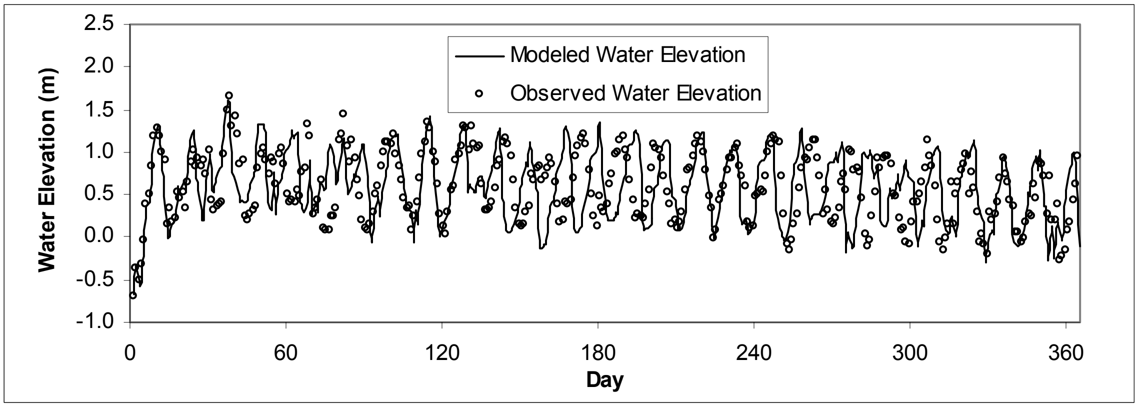


Figure 6: Observed and Modeled Water Surface Elevation in the Washington Ship Channel for Year 1998

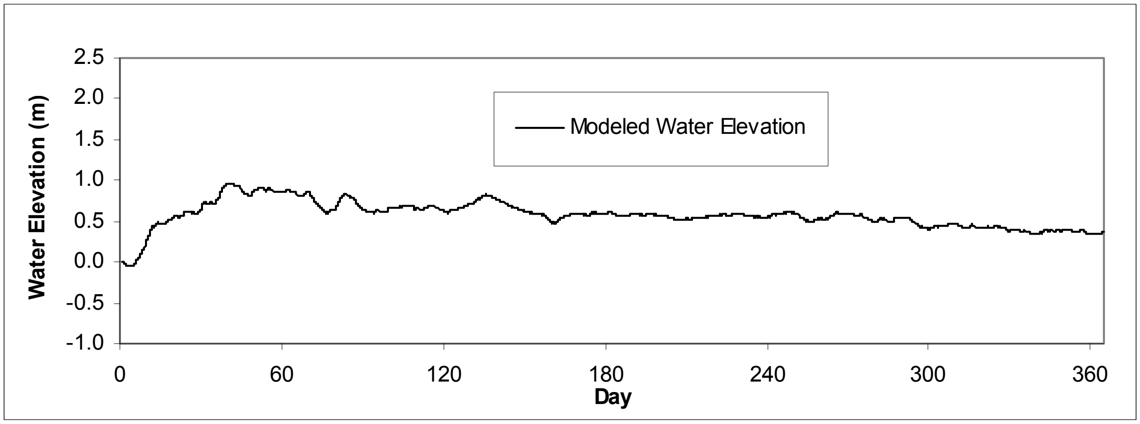
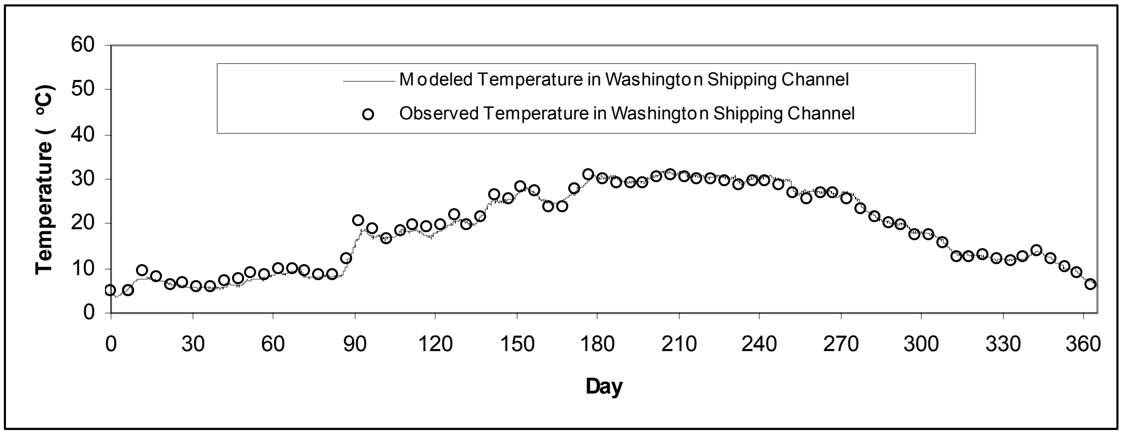


Figure 7: Modeled Water Surface Elevation in the Tidal Basin

Water temperature is also important in the determination of the water density for the hydrodynamics calculation and in computation of the die-off rate of fecal coliform. The modeled temperature results are almost identical to the observed temperature in the Ship Channel as shown in Figure 8. It also shows that the temperature in the Tidal Basin and the Washington Ship Channel do not show any significant spatial variations.



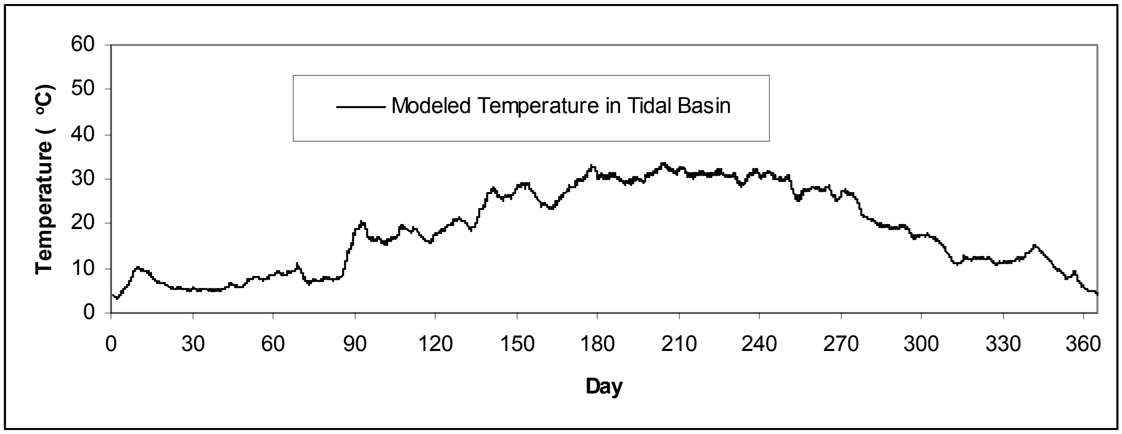


Figure 8: Comparison of Modeled and Observed Water Temperature in the Tidal Basin and Washington Ship Channel

To model the sediment transport, the properties of the sediment must be set. In this study, only cohesive sediment was considered since previous studies showed that the sediment in the bottom of the Tidal Basin and the Washington Ship Channel are mainly silt and clay. As there is no sediment bed depth data available, the initial sediment bed depth was assigned to be 50 cm to ensure that sufficient sediment is available for resuspension. The critical shear stress for deposition was considered 7.5×10^{-5} $(m/s)^2$ and the critical shear stress for resuspension was set equal to 1.0×10^{-4} $(m/s)^2$. The settling velocity was set to 5.0×10^{-6} m/s. The layer-averaged TSS results from the sediment transport model as well as the observed data are shown in Figures 9 and 10 for the Tidal Basin and Washington Ship Channel, respectively. The observed data are from station PTB-01 in the Tidal Basin and station PWC-04 in the Ship Channel. The modeled suspended solids showed that the spatial variation is high in both the Tidal Basin and the Washington Ship Channel.

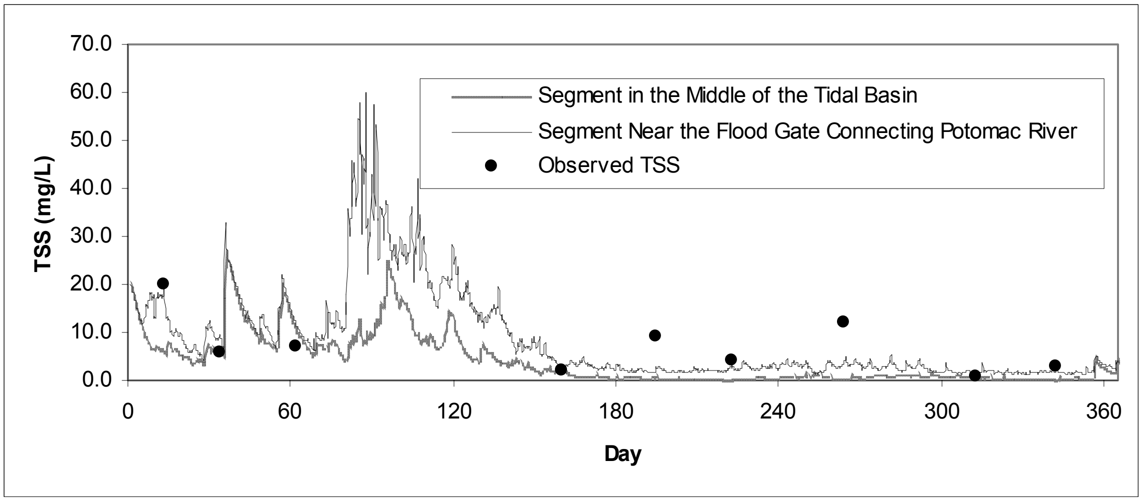


Figure 9: Modeled and Observed Suspended Solids Concentrations in the Tidal Basin

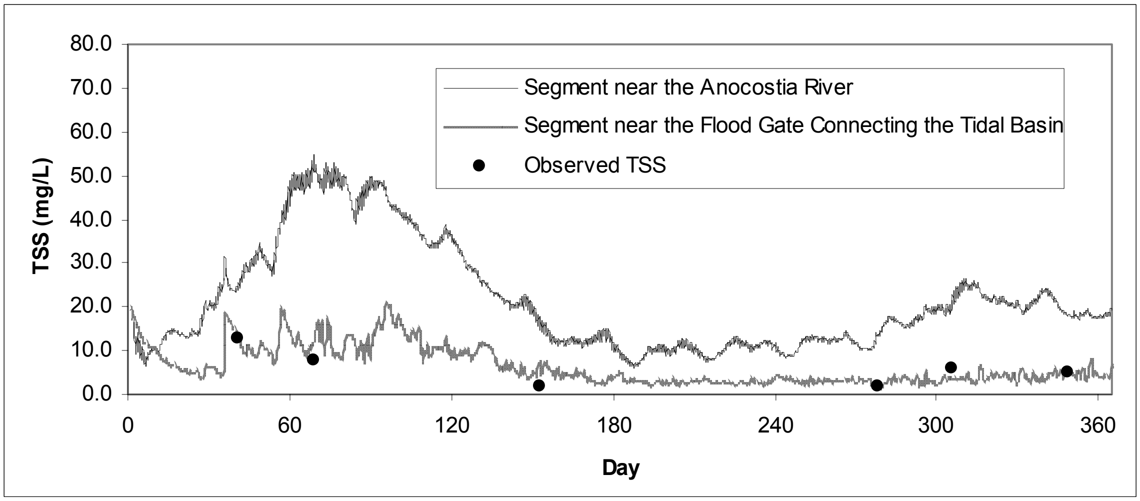


Figure 10: Modeled and Observed Suspended Solids in the Washington Ship Channel

Calibration of Fecal Coliform Model

The fecal coliform model was calibrated followed by the calibration of the hydrodynamics and the sediment transport and using the same time step for simulation. In addition to the advective and diffusive transport, the adsorption of fecal coliform to sediment particles and the die-offs were computed in the model. Various coefficients and the specific die-off rates used in the study are described elsewhere (Lung, 2003).

Figure 11 shows model results for layer averaged fecal coliform at two locations in the Tidal Basin, one near the storm water outlet shown in Figure 4, and the other near the floodgate connecting to the Potomac River along with observed data at station PTB-01 near the storm water outfall. Similarly, Figure 12 shows the model results in the Washington Ship Channel near the downstream boundary with the Anacostia River along with the observed data at station PWC-04 in the middle of the Ship Channel. Figure 13 shows model results for fecal coliform in the Washington Ship Channel near the storm water outfall shown in Figure 4.

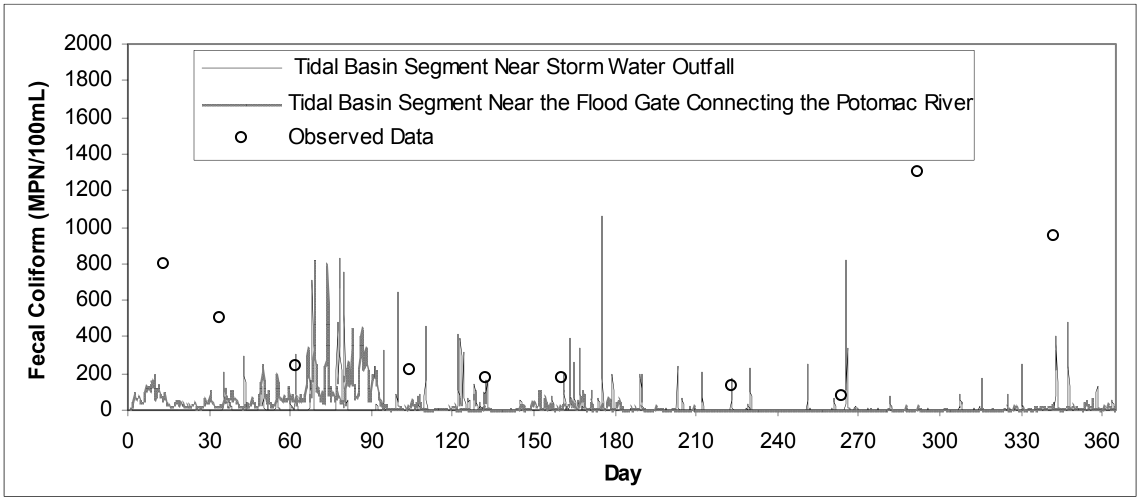


Figure 11: Modeled and Observed Fecal Coliform in the Tidal Basin for the Year 1998

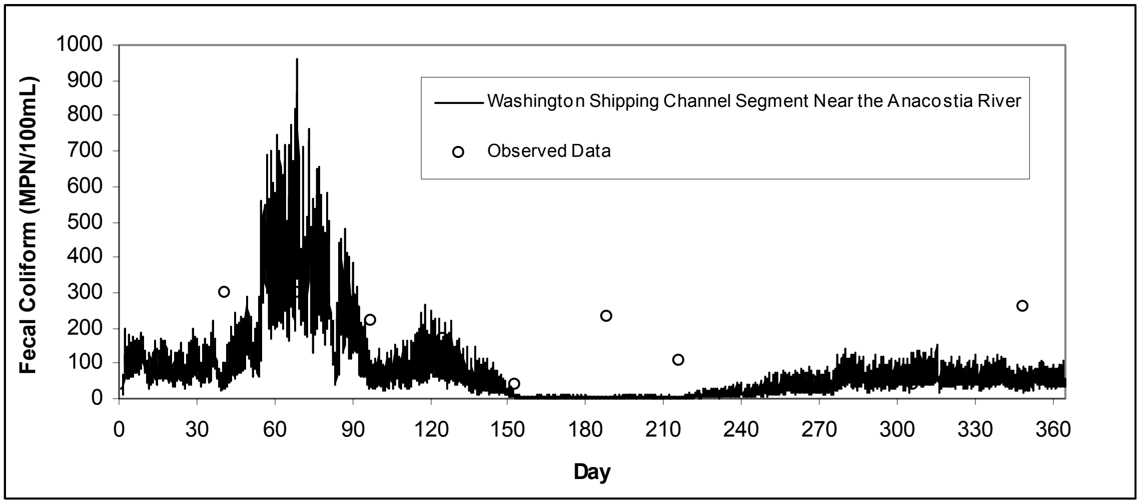


Figure 12: Modeled and Observed Fecal Coliform in the Washington Ship Channel for the Year 1998

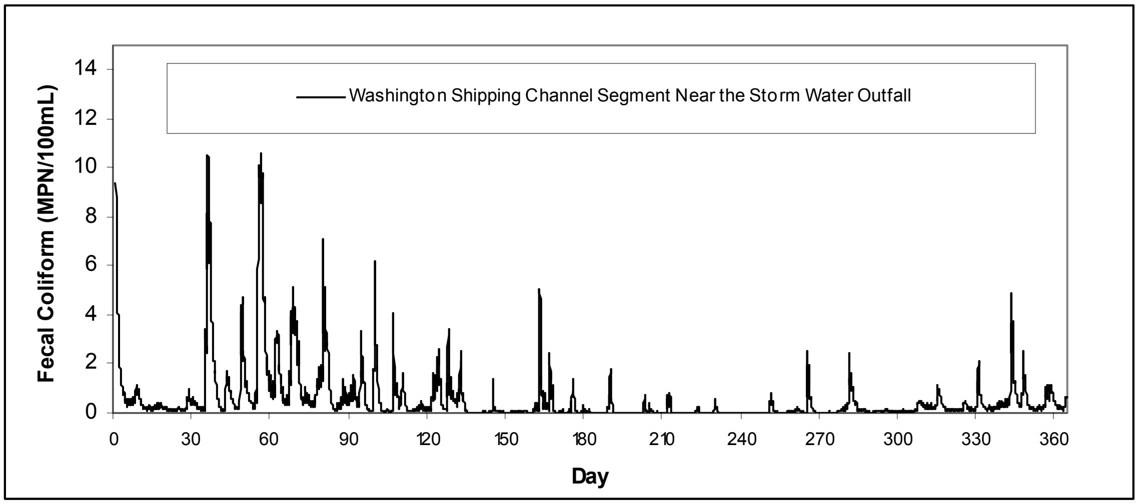


Figure 13: Modeled Fecal Coliform in the Washington Ship Channel Near Storm Water Outfall

Although the model was calibrated with very limited data, the model results still provide insights into the fecal coliform fate and transport pattern in the Tidal Basin and the Washington Ship Channel. The modeled results show significant spatial variation of the fecal coliform distribution. In the Tidal Basin, the highest fecal coliform density is near the storm water outlet as expected. The fecal coliform densities in the segments close to the floodgate connecting to the Potomac River are highly related to the fecal coliform density in the water of the Potomac River. In the Washington Ship Channel, the fecal coliform densities in the segments near the boundary are strongly affected by the tidal influence of the Anacostia River. The fecal coliform density near the storm water outfall in the Ship Channel shows a pattern similar to that in the Tidal Basin. However, the magnitude is much lower than that in the Tidal Basin although the storm water load is similar, implying that higher dilution in the Ship Channel than in the Tidal Basin.

Re-Calibration of Fecal Coliform Model

The fecal coliform model was re-calibrated using more detailed information of the watersheds. The inputs included storm water from the separate sewer system, direct runoffs from areas not served by the sewer system and direct deposits from waterfowls. The event mean concentration of 28265 MPN/100ml was used for both storm water and direct runoffs. The waterfowl daily load was estimated using 3.0×10^{10} #/day/waterfowl, which is 10 times the duck generated fecal coliform load (American Society of Agricultural Engineers, 2003) for conservative purposes. The waterfowl load was calculated by assuming 200 and 80 birds per day in the Tidal Basin and the Ship Channel, respectively. It was assumed that the total waterfowl load enters the water body within four hours each day.

Figure 14 shows model results for fecal coliform in the Tidal Basin along with observed data at station PTB-01. Similarly, Figure 15 shows the model results and the observed data in the Washington Ship Channel at station PWC-04.

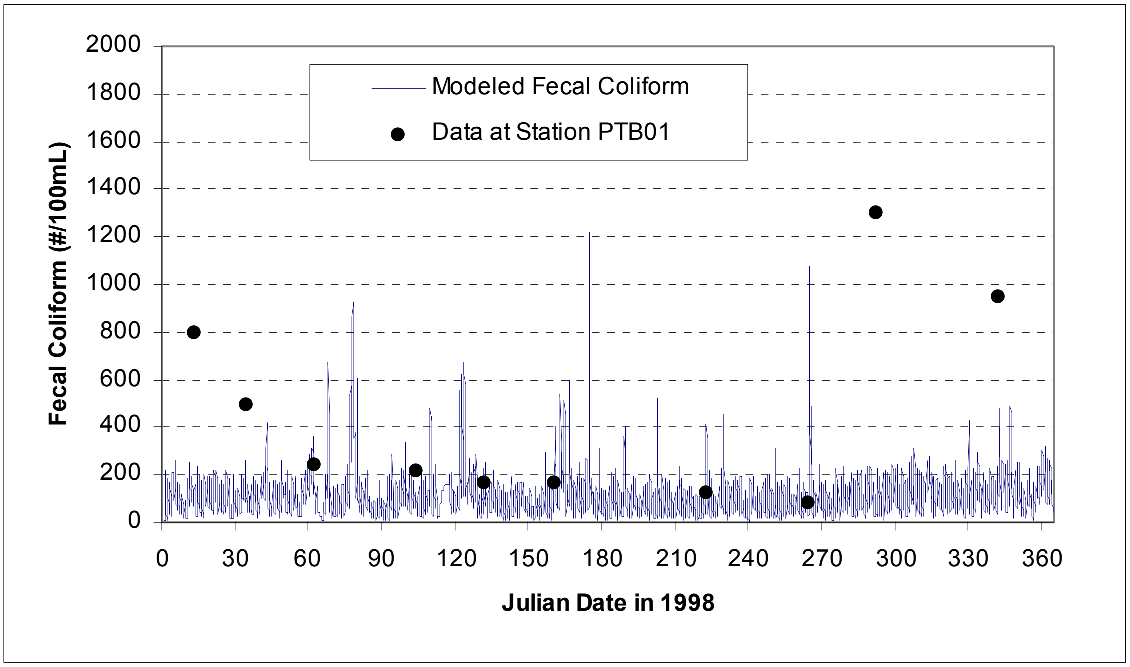


Figure 14: Modeled and Observed Fecal Coliform in the Tidal Basin for the Year 1998

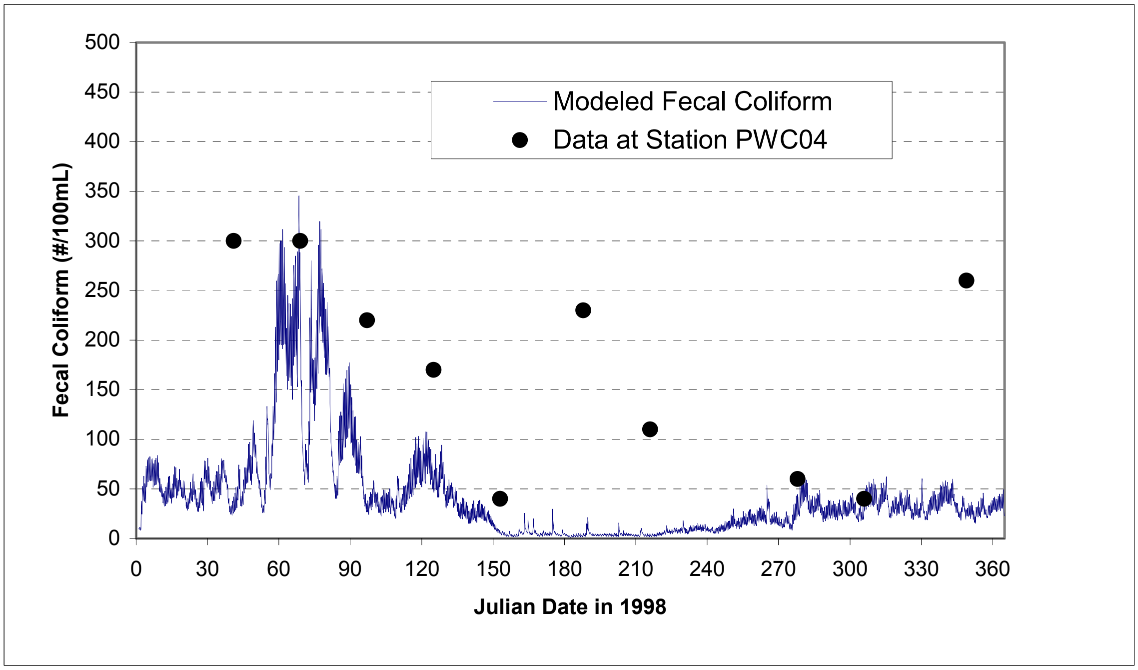


Figure 15: Modeled and Observed Fecal Coliform in the Washington Ship Channel for the Year 1998

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