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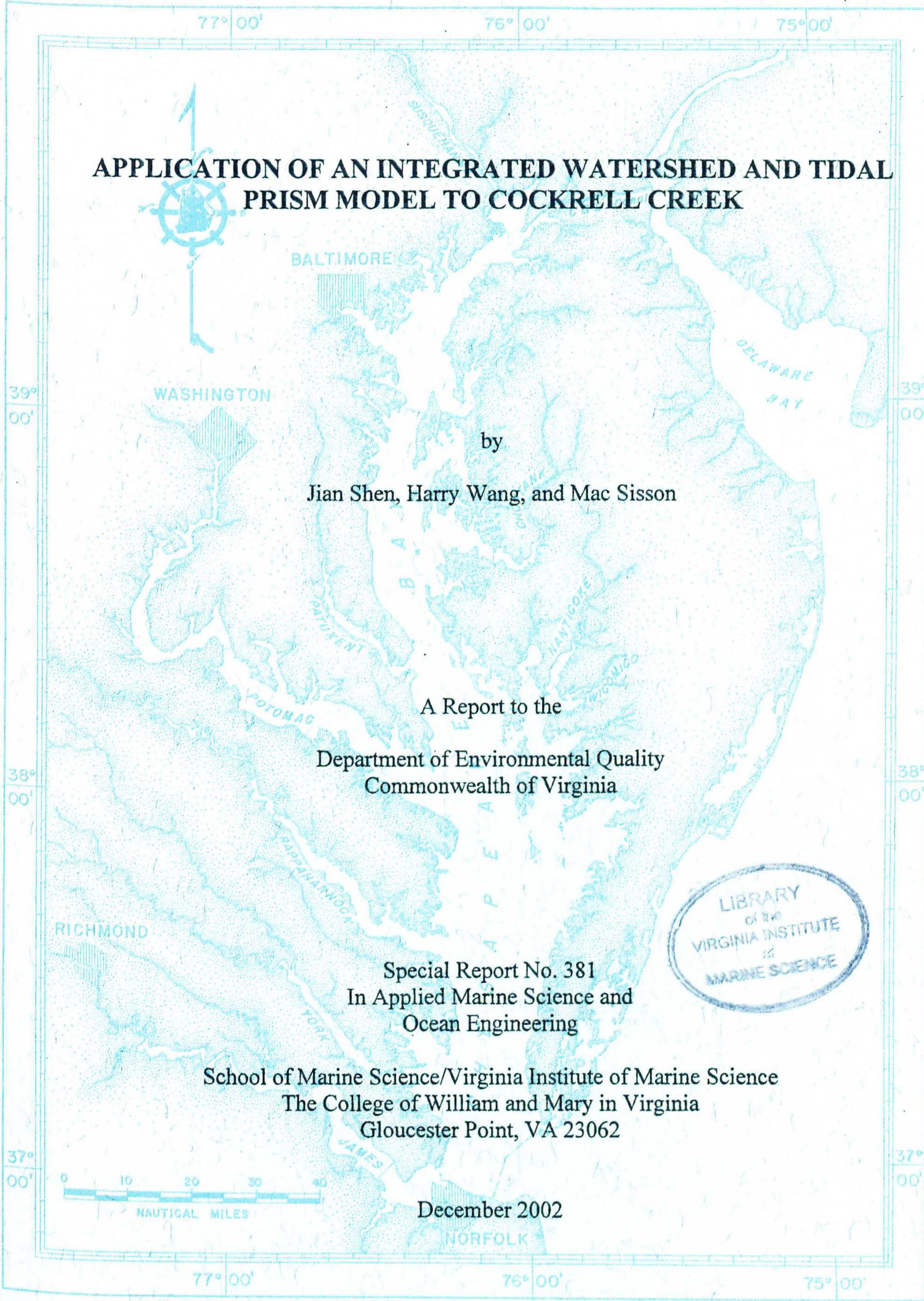
# Application of an Integrated Watershed and Tidal Prism Model to Cockrell Creek

Jian Shen
*Virginia Institute of Marine Science*

Harry V. Wang
*Virginia Institute of Marine Science*

Mac Sisson
*Virginia Institute of Marine Science*

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Jian Shen, Harry Wang, and Mac Sisson

A Report to the

Department of Environmental Quality
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School of Marine Science/Virginia Institute of Marine Science
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## Acknowledgments

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# I. Introduction

There are over 250 water segments in the small basins of the Commonwealth of Virginia, which are impaired for fecal coliform under the Section 303 (d) and required for development of a Total Maximum Daily Load (TMDL). Two factors should be recognized: 1) nonpoint source loads from watershed are the dominant influences on water quality conditions in these small coastal basins and 2) the difficulties of applying two-dimensional or three-dimensional models directly in these small basins. Therefore, a better tool is required to facilitate the development of TMDL in these regions efficiently and cost-effectively. Under the project entitled "Integrated Modeling Approach for TMDL Development of Virginia's Small Coastal Basins with Fecal Coliform Impairment" under the sponsorship of the Department of Environmental Quality, Commonwealth of Virginia, an integrated modeling system was developed. The system integrated a watershed-loading model (Loading Simulation Program C++ (LSPC)) and a hydrodynamic model (Tidal Prism Water Quality Model (TPWQM)) into a convenient PC-based interface, providing a new tool for Total Maximum Daily Load (TMDL) studies in the small coastal basins. Hydrology and fecal coliform transport are simulated for different land use categories based on source contributions in the watershed by LSPC. The loading contribution is dynamically linked to TPWQM in the coastal basins to simulate dynamic transport of fecal coliform. The integrated system is not only capable of conducting fecal coliform TMDL studies in these small basins, but also can be used as a management tool for water quality modeling in these areas.

This report is part of the final report of the project. The report documents the application of the modeling system to the Cockrell Creek watershed and its embayment. The report provides an example to illustrate the capability of the system to simulating point and nonpoint source processes in watershed and receiving waters. Furthermore, it documents the detailed procedures of applying the integrated model to simulate fecal coliform in the coastal basins including monitoring data analysis, source assessment, model setup, model calibration, and model sensitivity studies. A User's Manual of the system will be documented in a separate report. Chapter II discusses the observation data in the basin. A brief description of LSPC and TPWQM is presented in Chapter III. Chapter IV presents the source assessment. The model setup is presented in Chapter V. The model calibration is presented in Chapter VI. Model sensitivity studies and TMDL case studies are presented in Chapter VII, followed by conclusions and recommendations.

# II. Study Areas and Observation Data

## 2.1 Watershed Characterization and Delineation

Cockrell Creek and its watershed were selected as a case study area to demonstrate the application of the developed modeling tool. Cockrell Creek is one of the branches of the Great Wicomico River. It is located in Northumberland County south of the mouth of the Potomac River where it meets the Chesapeake Bay in eastern Virginia. The embayment drains the Cockrell Creek watershed of 1780 acres. On Virginia's Northern Neck, the watershed encompasses the city of Reedville, Virginia, located at the end of Hwy 360.

The 3.5-mile Cockrell Creek, with its water surface area of about 116 acres, is the main river within the watershed that connects to the Great Wicomico River at its mouth. Cockrell Creek was impaired for fecal coliform under the 1998 Section 303 (d). Both point and nonpoint sources may contribute to the impairment and the development of TMDLs was mandated.

Considering the requirement for the TMDL development in the Chesapeake Bay region and watershed model calibration, the Chesapeake Bay watershed model segmentation of phase 4.2 was used as initial watershed boundaries. In this way, the bay model segment can be further delineated to support specific requirements. It also allows the user to use the calibrated Bay model parameters directly under circumstances in which no gage stations are available in the coastal modeling region. Because the entire watershed is located on a coastal plain, the surface elevation obtained from the USGS digital elevation model data is almost uniform throughout the watershed. Therefore, both the major highways and topographic maps were used to guide the watershed delineation.

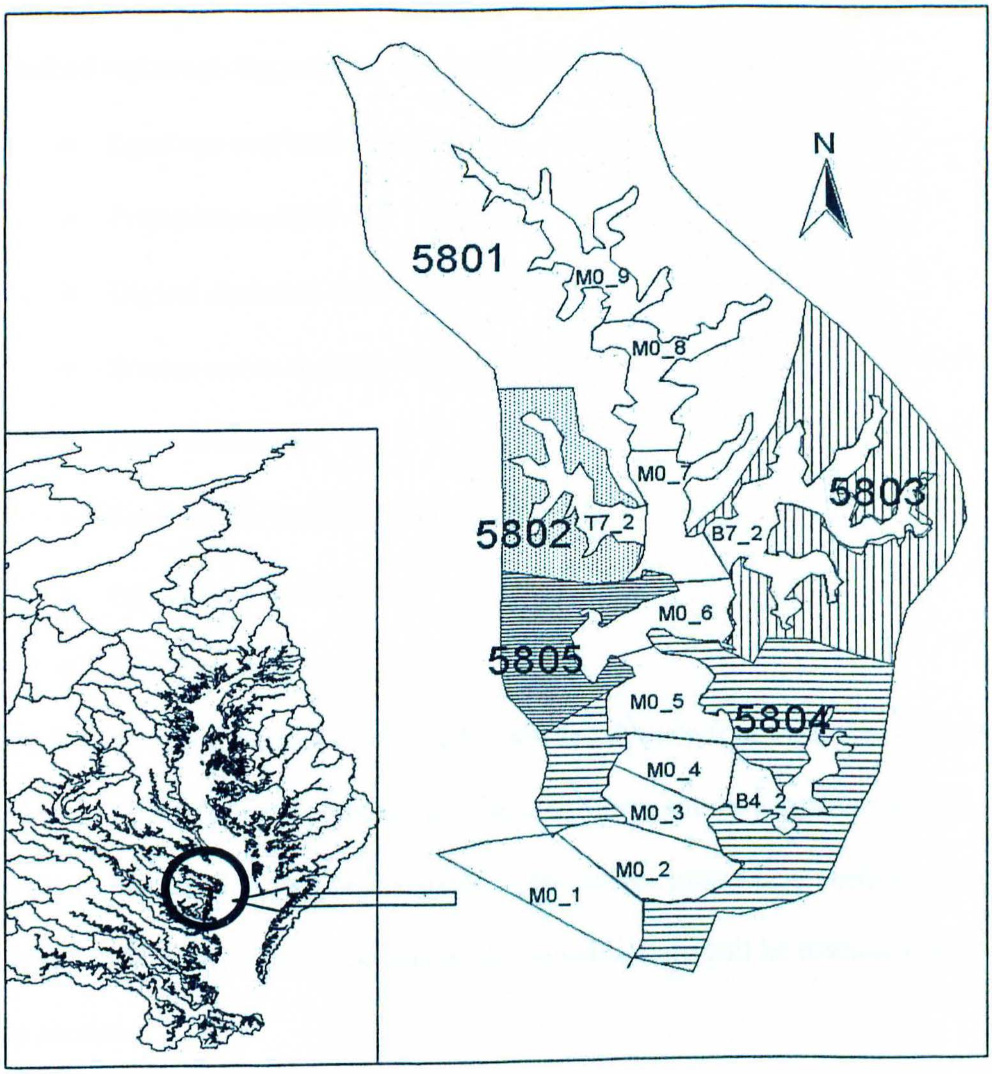



**Figure 2-1. A Diagram of Cockrell Creek, Watershed Delineation, and Tidal Prism Model Segmentation.**

To provide a better linkage of loading distribution and the tidal prism model segmentation, the tidal prism model segmentation was also used as a guideline to conduct the watershed delineation. Consequently, the Cockrell Creek watershed was delineated into 5 sub-watersheds. The watershed segmentation is shown in Figure 2-1. These sub-watersheds were used for watershed modeling and data analysis.

## 2.2 Observation Data

Various data are required for simulating fecal coliform transport processes in both watershed and receiving waters. The primary data required include:

- Land use and land cover data
- Precipitation data
- Digital elevation data
- Stream network data
- Point source data
- Fecal coliform source contribution data
- Agricultural census data
- In-stream monitoring data

These data were collected and analyzed. Detailed descriptions of the data used are presented in the following paragraphs. Fecal coliform source contribution data and agricultural census data will be discussed in the source assessment section. Channel geometry data, bathymetry data, and stream network data will be discussed in the model setup section.

## 2.3 Land use data

USGS's National Land Cover Data (NLCD) 1990s data are used to obtain land use in the basin. This land cover data set was produced as part of a cooperative project between the U.S. Geological Survey (USGS) and the U.S. Environmental Protection Agency (USEPA) to produce a consistent, land cover data layer for the conterminous U.S. based on 30-meter Landset thematic map (TM) data. National Land Cover Data

(NLCD) was developed from TM data acquired by the Multi-resolution Land Characterization (MRLC) Consortium. There are 24 categories of land use in the NLCD land use data. For modeling purposes, 24 land use categories were re-classified into 8 land use categories, which are open water, forestland, wetlands, cropland, pastureland, barren, urban pervious, and urban impervious land (Table 5-1). The percent distribution of each land use is presented in Figure 2-2, of which 41% is forestland, 32% is urban land, and 25% is pastureland and cropland. The dominant land use in the watershed is forestland and urban land followed by cropland and pastureland. Land use areas of each sub-watershed by land use categories are listed in Table 2-1.

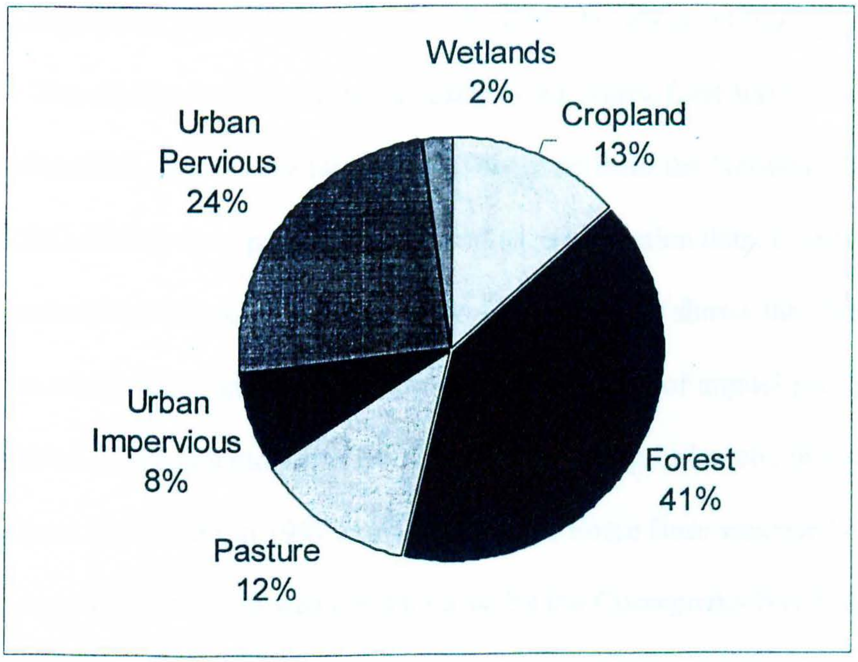



**Figure 2-2. Land Use Distribution (after reclassification).**

**Table 2-1. Land Use Distribution by Sub-watershed (Acres)**

| | Subwatershed | | | | | |
|---|---|---|---|---|---|---|
| **Land Uses** | **5801** | **5802** | **5803** | **5804** | **5805** | **SUM** |
| **Barren** | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **Cropland** | 145.00 | 6.89 | 22.68 | 40.48 | 5.34 | 220.39 |
| **Forest** | 421.90 | 47.15 | 78.95 | 76.95 | 46.70 | 671.65 |
| **Pasture** | 92.96 | 2.45 | 55.60 | 46.04 | 5.56 | 202.61 |
| **Urban Impervious** | 24.75 | 9.44 | 35.03 | 44.51 | 11.19 | 124.93 |
| **Urban Pervious** | 94.45 | 43.50 | 110.20 | 116.73 | 40.18 | 405.05 |
| **Wetlands** | 13.12 | 3.11 | 9.56 | 11.78 | 1.55 | 39.12 |
| **Sum** | 792.18 | 112.54 | 312.02 | 336.49 | 110.52 | 1663.75 |

## 2.4 Precipitation data

Precipitation is the key driving force of the nonpoint source model. The Chesapeake Bay Program used data averaged from multiple weather stations for bay-wide coastal areas. The nearest long-term weather stations are available at Gloucester Point and Langley Air Force Base, which are both located about 44 miles away from the watershed. The weather station located at Langley Air Force Base has six-hour accumulated rainfall data. These rainfall data, obtained from the National Climatic Data Center (NCDC, 2000), were processed and used as precipitation data. Comparison of weather data between Gloucester and Langley Air Force Base shows that these two stations have a high correlation with almost the same amount of annual precipitation. Since the period of precipitation data from 1998 to 2001 is problematic at both stations, a selected data set from 1985 to 1997 from Langley Air Force Base was used for the modeling. A comparison with weather data used by the Chesapeake Bay Program was also performed. A comparison of monthly rainfall from 1990 to 1995 is presented in Figure 2-3. Overall, the monthly precipitation budget agrees well with the Bay Program weather data.

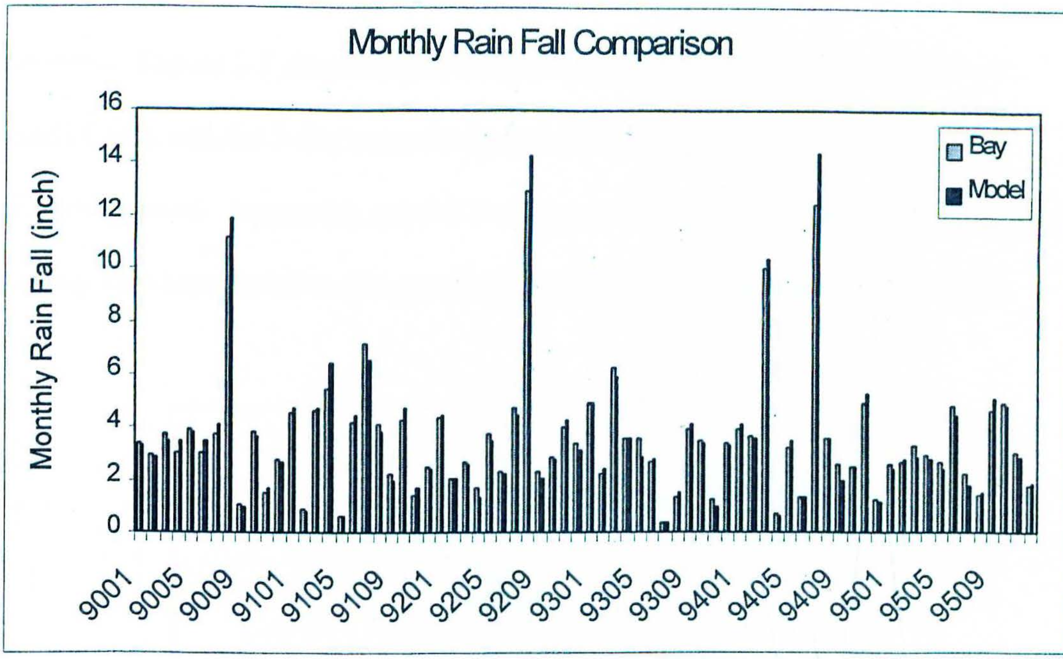



**Figure 2-3. Monthly Precipitation (Bay represents data used by EPA Chesapeake Bay).**

## 2.5 Monitoring Data

The monitoring data for fecal coliform bacteria in Cockrell Creek have been collected by the Virginia Health Department, Shellfish Sanitation Division from 1985 – 2001 every month. These data are available both for model calibration and verification. Figure 2-4 shows the locations of the monitoring stations. Fecal coliform observations have been conducted at 8 stations. There are 4 stations located inside Cockrell Creek and others are at the mouth of the Great Wicomico River. Figures 2-5 and 2-6 show the maximum fecal coliform concentration and monthly average concentration, respectively, at stations C3, C4, C5, and C6. In general, the average fecal coliform concentrations are high from July to October. The average concentration is high inside Cockrell Creek and gradually decreases. The high maximum concentration occurs during summer time for stations C3 and C6. However, high concentration also occurs during the winter at stations C4 and C5. Due to a detection limit, the highest fecal concentration is about 1100 – 1200 mpn/100ml. Figure 2-7 shows the mean fecal concentration for all stations inside Cockrell Creek and the 3-day accumulated precipitation distribution during the observation period. In general, rainfall events correspond to the high fecal concentration indicating the characteristics of nonpoint source impact. However, the high linear

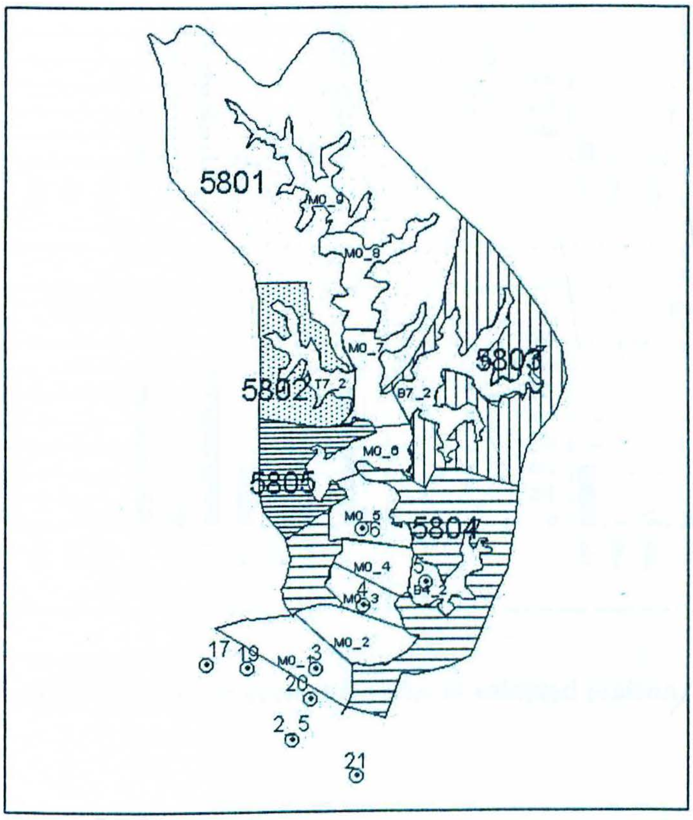



**Figure 2-4. Locations of Observation Stations (denoted by circles).**

correlation between fecal concentration and rainfall does not exist. For those concentrations higher than 200 counts/100mL, compared over time, about 50% correspond to a rainfall event. For those concentrations higher then 400 counts/100mL, about 70% correspond to a rainfall event. The high fecal concentration not only depends on the amount of rainfall, but also on its frequency and duration. An isolated event, such as point source discharge or wash off from marsh areas due to wind set-up, can also contribute to high fecal coliform concentration in the basins.

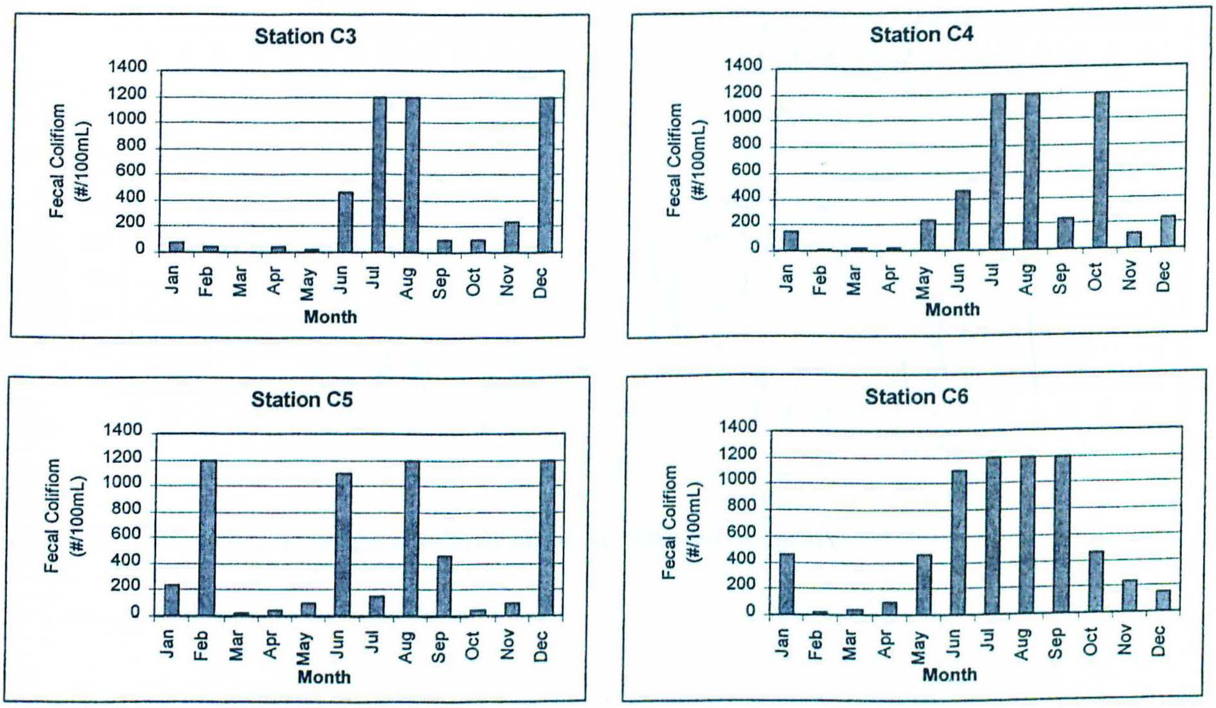



**Figure 2-5. Monthly maximum concentration at selected stations.**

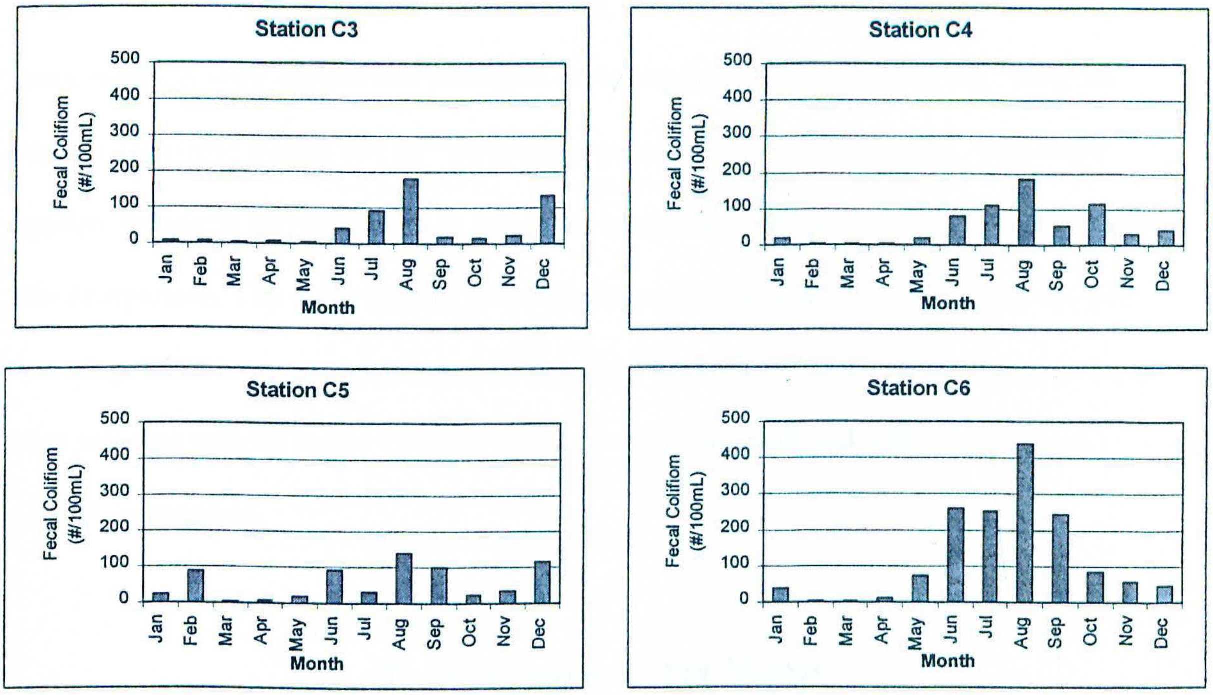



**Figure 2-6. Monthly average concentration at selected stations.**

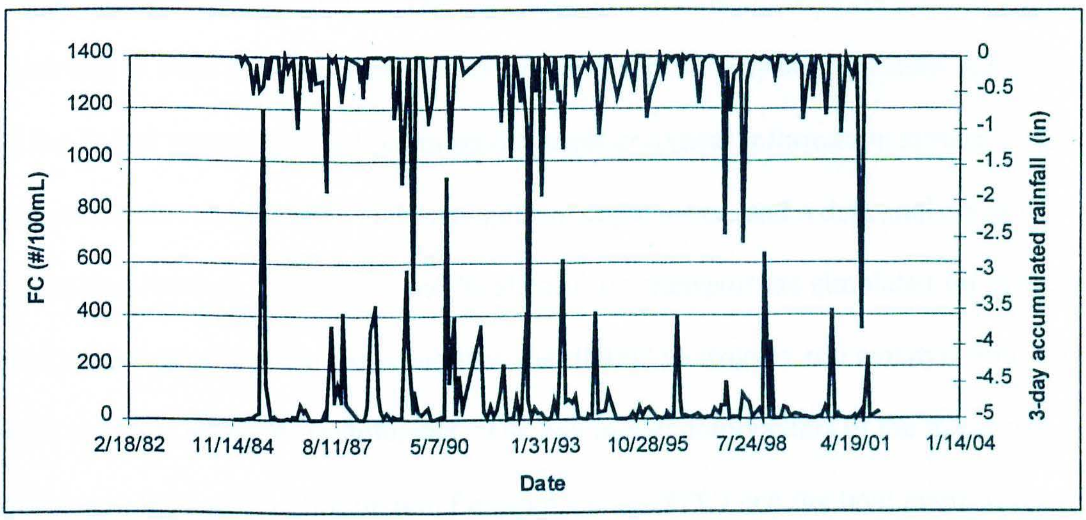



**Figure 2-7. Comparison of average fecal coliform concentration with 3-day accumulated rainfall (black line is fecal coliform concentration and blue line on the top is rainfall).**

For each station inside Cockrell Creek, time series observations of fecal coliform concentration were plotted and presented in Appendix A, Figures A1 to A9. Both 30-month geometric means and 90$^{th}$ percentiles were plotted in these figures. The water quality standards corresponding to geometric means and 90$^{th}$ percentiles were also plotted for comparison. The water quality standards for comparison are14 mpn/100mL for 30-month geometric mean and 49 mpn/100mL for 30-month 90$^{th}$ percentiles. It can be seen that selected stations inside Cockrell Creek show impairment and a development of a TMDL is required.

## III. Description of the Model

An integrated modeling system has been developed for simulating fecal coliform fate and transport in a small coastal basin's response to fecal coliform contributions under various hydrologic conditions. This new tool was used to conduct fecal coliform modeling in both the watershed and its coastal basin. The system includes an integration of the linked watershed-tidal prism model, a geographical information system (GIS), comprehensive data storage and management capabilities, and a data analysis/post-processing routine. Hydrology and fecal coliform transport are simulated for different land use categories in the basin and then distributed to streams and embayments where fecal coliform transport is simulated. The key model components of the integrated system are the Loading Simulation Program C++ (LSPC) and the tidal prism water quality model (TPWQM).

Figure 3-1 is a diagram of the integrated system. The core of the system is a database, which stores all model related data. GIS tools and analysis tools, as well as

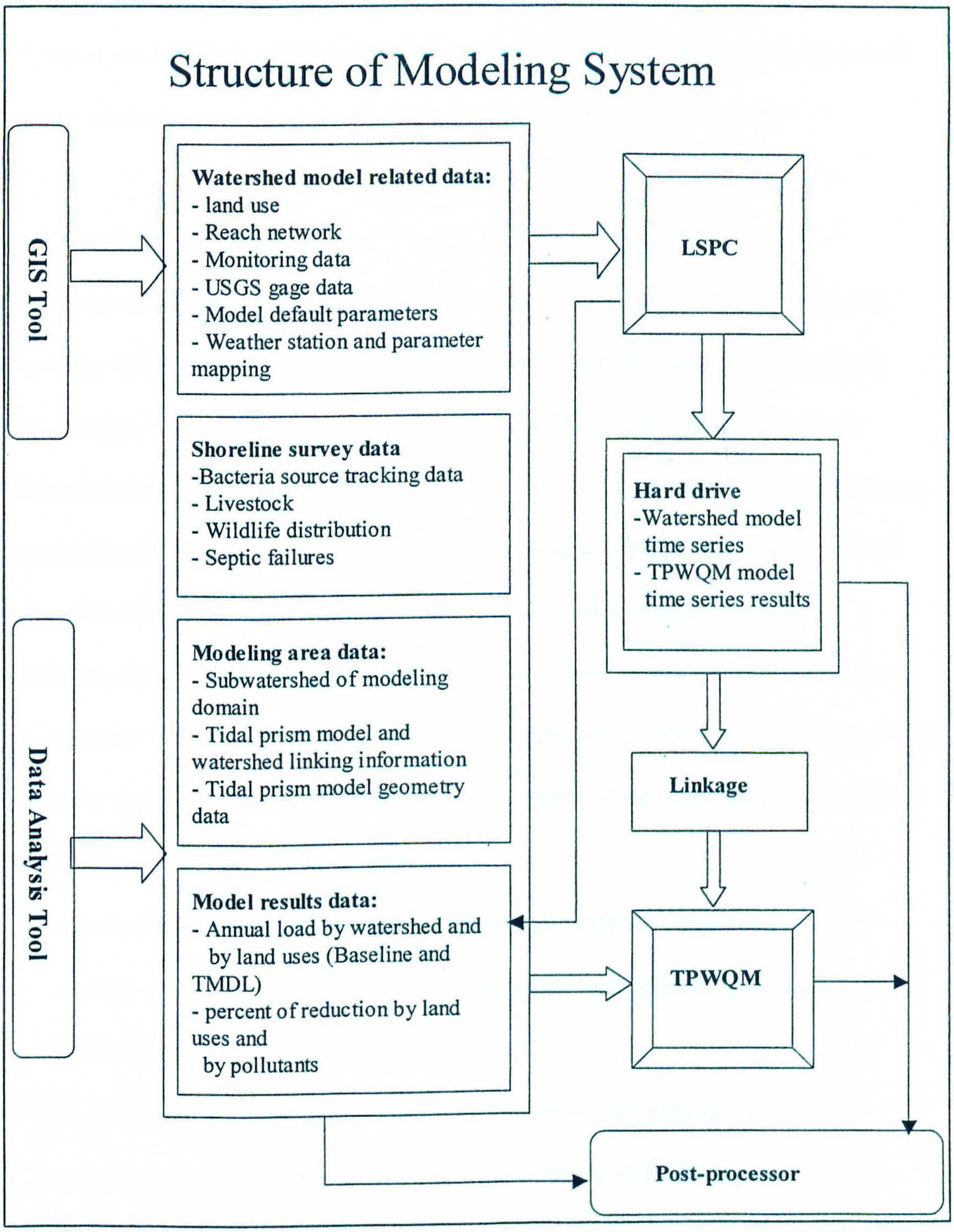



**Figure 3-1. A diagram of the integrated watershed and tidal prism modeling system.**

models, can access the database through the Windows interfaces. The time series of model output are saved on a hard drive. The model tool will automatically access these data sets as needed.

### 3.1 Watershed Model Description

LSPC is a modified version of the former Mining Data Analysis System (MDAS) developed by EPA Region 3, with the support of Tetra Tech, Inc. (Henry et al., 2002; USEPA, 2001a). The computational algorithm is based on the previous Hydrologic Simulation Program FORTRAN (HSPF) watershed model. Continued developments are supported by both EPA Regions 3 and 4. LSPC integrates a GIS, comprehensive data storage and management capabilities, a dynamic watershed model, and a data analysis/post-processing system into a convenient PC-based Windows interface. The system's greatest strength is its ability to fulfill complex and costly data organization and water quality simulation needs for large-scale watersheds while maintaining a high level of detail. The system's key features include:

- a customized GIS interface with no proprietary software requirements,
- storage of all geographic, modeling, and point source permit data in a Microsoft Access database,
- an efficient C++ based dynamic flow, sediments, conventional pollutants, metals, and pH model based on EPA's peer-reviewed Hydrologic Simulation Program-FORTRAN (HSPF), and
- post-processing and analytical tools designed specifically to support TMDL development and reporting requirements.

The key to representation of the source-response linkage for TMDL development with LSPC is a dynamic watershed model. This comprehensive model is a precipitation-driven watershed model that simulates watershed hydrology and pollutant transport, as well as stream hydraulics and in-stream water quality. It is capable of dynamically simulating flow, sediments, metals, temperature, and pH, as well as other conventional pollutants for pervious and impervious lands and waterbodies of varying order. The model is essentially a re-coded C++ version of selected HSPF modules (Bicknell et al., 1996). The numerical algorithms are identical to those in HSPF. Table 3-1 lists the modules from HSPF used in the current LSPC model. The model has been applied to many watersheds to develop TMDLs including acid mine drainage TMDL (USEPA, 2001a), fecal coliform TMDL studies (USEPA, 2001b), and nutrient related TMDLs (USEPA, 2001c).

To simplify the modeling process, LSPC automatically extracts required modeling data from its underlying database for a selected area. This greatly simplifies the model setup process, which requires a large amount of data processing, from land use and soil characteristics to stream geometry and point source contributions. Upon receiving a

**Table 3-1. Modules From HSPF Converted to LSPC's Watershed Model**

| | | |
|---|---|---|
| **RCHRES Modules** | HYDR<br>ADCALC | Simulates hydraulic behavior and pollutant transport |
| | CONS | Simulates conservative constituents |
| | HTRCH | Simulates heat exchange and water temperature |
| | SEDTRN | Simulates behavior of inorganic sediment |
| | GQUAL | Simulates behavior of a generalized quality constituent |
| | PHCARB | Simulates pH, carbon dioxide, total inorganic carbon, and alkalinity |

| | | |
|---|---|---|
| **PQUAL and IQUAL Modules** | PWATER | Simulates water budget for a pervious land segment |
| | IWATER | Simulates water budget for an impervious land segment |
| | SEDMNT | Simulates production and removal of sediment |
| | PWTGAS | Estimates water temperature and dissolved gas concentrations |
| | IQUAL | Uses simple relationships with solids and water yield |
| | PQUAL | Uses simple relationships with sediment and water yield |

user-selected modeling domain (sub-watersheds), a new project can be created to save all physical, chemical, and point source data for that domain. The system then extracts land use, stream network and geometry, and point source data from the database. After the system identifies appropriate default parameters (which are compiled based on soil characteristics, land use practices, or model calibration), default parameters are extracted from the database, which help to eliminate tedious, repetitive user input and uninformed model parameter selection. LSPC then automatically links upstream contributions to the downstream segments, allowing users to model freely any selected sub-areas while maintaining a top-down approach.

The watershed modules identical to the PQUAL and IQUAL modules in HSPF were used to simulate hydrology and fecal coliform. The accumulation rate, a specific model parameter, was used to specify fecal coliform accumulation. Selection of these model parameters will be discussed in the model setup section.

### 3.2 Tidal Prism Model Description

The TPWQM is a refined tidal prism model developed by the Virginia Institute of Marine Science (VIMS) (Kuo and Neilson, 1988). The TPWQM was developed under the sponsorship of the Virginia Coastal Resources Management Program of 1993 (Kuo and Park, 1994). The model was subsequently applied to five of Virginia's coastal basins and it has been demonstrated that it successfully simulated the water quality conditions in all of them (Park et al., 1995; Kuo et al., 1998). The TPWQM model simulates the tidal transport in terms of the concept of tidal flushing (Ketchum, 1951). The tidal prism is the amount of water entering (or exiting) a coastal basin during each tidal cycle. During flood tide, a large amount of water (i.e., the tidal prism) floods into a coastal basin. This amount of water mixes with the lower tidal water within the basin. A portion of pollutant inside the basin will be transported out of the basin during ebb tide as water is transported out of the basin. The implementation of the concept in numerical computation is simple and straightforward. It is not only applicable to a single-stem estuary, but also applicable to coastal basins with a high degree of branching. The input data required for TPWQM include tidal range, surface area, and depth of the water body. These data are readily available for most of the small coastal basins. The tidal prism for each modeling area can be estimated based on the volume of the basins and the tidal range in the area.

The TPWQM model was integrated into the LSPC modeling framework. To facilitate modeling activities, information about tidal prism model segmentation and its associated geometry data were incorporated into the existing LSPC database. Each model area was represented by a model project and a unique area key was assigned to it. Therefore, multiple modeling areas (projects) can be stored in a database table while an individual area can be extracted and modeled separately. The loading linkage between LSPC and TPWQM was achieved with the use of a linkage table, which describes the linkage between each sub-watershed and its adjacent tidal prism model cell(s). The flows and fecal coliform loads from both surface runoff and ground water from multiple sub-watersheds can be added together and fed into a tidal prism model cell. For a large sub-watershed adjacent to multiple tidal prism model cells, the flow and load are evenly divided and fed into multiple tidal prism model cells. The modification of the tidal prism model geometry and loading linkage were integrated into the PC Windows interface, which allows the user to modify the model setup easily. Once watershed simulation is completed, the daily loads of each sub-watershed including flow and fecal coliform loads will be generated. The flow and load will be fed into the tidal prism model automatically and thereby drive this model.

# IV. Source Assessment

Permitted point sources and other direct discharges, as well as nonpoint sources contribute fecal coliform loads to the streams in the watershed and to the embayment. To provide a better assessment of the contributions of these sources, several data sources were used. These include land use data, agricultural census data, shoreline sanitary survey (Va. Dept of Health, Shellfish Sanitation Division, 1995) data, and point source facility data. A summary of potential source contributions is discussed in the following sections.

### 4.1 Urban and Agricultural Sources

Urban and agricultural fecal coliform sources were estimated from land use data, U.S. Department of Agriculture (USDA) agriculture census data, and shoreline sanitary survey data. An estimate of the number of livestock by county was obtained from the USDA online database. However, the data is only available for Northumberland County. Total cattle from 1990-2000 are around 600-900. There are no hogs on record before 2000. The average count of cattle for the past 10 years is about 700. By applying an areal weight method, estimated livestock in the Cockrell Creek watershed is about 10 cattle. Since the census data do not provide detailed information about the distribution of these livestock in each sub-watershed, more information is needed. In 1997, a shoreline sanitary survey was conducted by the Virginia Department of Health, Shellfish Sanitation Division. The survey provides information for livestock count and contributions of animal pollution as well as other potential pollutant contributions, including septic failures and discharge from kitchens. Figure 4-1 shows the location of potential sources, where "animal" marked on the figure indicates the location of domestic animals. According to the shoreline survey results, total cattle in sub-watersheds 5801 and 5803 are 17 and 15, respectively. Comparison survey results and estimated livestock from the national database are on the same order. Although survey data may not include all

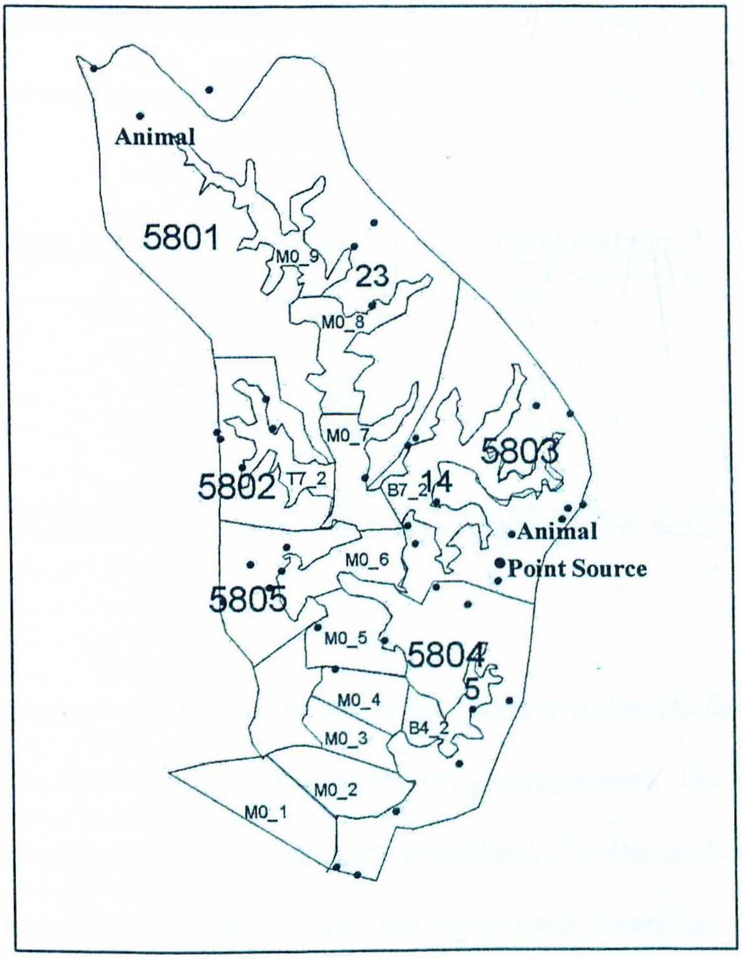



**Figure 4-1. Location of potential pollutant sources.**

animals in the county, they provide valuable information for the locations of potential sources. This set of data was used to estimate the contributions of fecal loads.

Fecal coliform loads, contributed from direct runoff of deposited fecal coliform on land during rainfall events, can be quantified by build-up rates. These build-up rates will be used to specify model parameters. The average fecal coliform production associated with animal waste is estimated using the number of fecal coliform bacteria per 1000 pounds of each animal type (ASAE, 1994) and average weight of each animal. The estimated animal weight and production of fecal coliform is listed in Table 4-1.

**Table 4-1. Average Animal Weight and Average Fecal Coliform Production**

| Animal | Average Weight (lbs) | Contribution of FC (counts/day)[a] |
|---|---|---|
| Dairy cow | 1400 | 1.01E+11 |
| Beef cow | 800 | 1.04E+11 |
| Hog | 135 | 1.08E+10 |
| Sheep | 60 | 1.20E+10 |
| Horse | 1000 | 4.20E+08 |
| Chicken (Layer) | 4 | 1.36E+08 |
| Turkey | 15 | 9.30E+07 |

[a] Based on ASAE (1998) and weight of animal to fecal produced per 1000 lb animal.

The possible introduction of fecal coliform to land surface is through the manure spreading process and direct deposition during the grazing season. For this study, the manure is assumed to apply to cropland and pastureland. For the modeling approach, cattle manure was applied to both cropland and pastureland depending on the grazing period. The seasonal variation of manure spreading and grazing activities was also considered in the calculation. Sixty percent (60%) of deposited fecal coliform were assumed to be available for runoff. The estimated contribution of fecal coliform in both pastureland and cropland for each sub-watershed are listed in Tables 4-2.

**Table 4-2. Estimated Loading Contribution from land uses (counts/acre/day)**

| WSW | Month | Forest | Cropland | Pasture | Wetlands | Urban Pervious | Urban Impervious |
|---|---|---|---|---|---|---|---|
| 5802[a] | Jan | 3.670E+07 | 3.670E+07 | 3.670E+07 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5802 | Feb | 3.670E+07 | 3.670E+07 | 3.670E+07 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5802 | Mar | 3.670E+07 | 3.670E+07 | 3.670E+07 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5802 | Apr | 3.670E+07 | 3.670E+07 | 3.670E+07 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5802 | May | 3.670E+07 | 3.670E+07 | 3.670E+07 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5802 | Jun | 3.670E+07 | 3.670E+07 | 3.670E+07 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5802 | Jul | 3.670E+07 | 3.670E+07 | 3.670E+07 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5802 | Aug | 3.670E+07 | 3.670E+07 | 3.670E+07 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5802 | Sep | 3.670E+07 | 3.670E+07 | 3.670E+07 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5802 | Oct | 3.670E+07 | 3.670E+07 | 3.670E+07 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5802 | Nov | 3.670E+07 | 3.670E+07 | 3.670E+07 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5802 | Dec | 3.670E+07 | 3.670E+07 | 3.670E+07 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5801 | Jan | 3.670E+07 | 6.309E+08 | 7.594E+08 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5801 | Feb | 3.670E+07 | 6.964E+08 | 8.249E+08 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5801 | Mar | 3.670E+07 | 6.309E+08 | 7.198E+08 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5801 | Apr | 3.670E+07 | 8.620E+08 | 1.871E+10 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5801 | May | 3.670E+07 | 8.348E+08 | 1.868E+10 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5801 | Jun | 3.670E+07 | 6.513E+08 | 1.850E+10 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5801 | Jul | 3.670E+07 | 6.309E+08 | 1.848E+10 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5801 | Aug | 3.670E+07 | 6.309E+08 | 1.848E+10 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5801 | Sep | 3.670E+07 | 6.513E+08 | 1.850E+10 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5801 | Oct | 3.670E+07 | 4.913E+09 | 2.276E+10 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5801 | Nov | 3.670E+07 | 5.076E+09 | 2.292E+10 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5801 | Dec | 3.670E+07 | 6.309E+08 | 7.594E+08 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5803 | Jan | 4.043E+07 | 8.300E+09 | 9.206E+09 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5803 | Feb | 4.043E+07 | 9.179E+09 | 1.008E+10 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5803 | Mar | 4.043E+07 | 8.300E+09 | 8.914E+09 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5803 | Apr | 4.043E+07 | 1.140E+10 | 1.430E+11 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5803 | May | 4.043E+07 | 1.103E+10 | 1.426E+11 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5803 | Jun | 4.043E+07 | 8.573E+09 | 1.402E+11 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5803 | Jul | 4.043E+07 | 8.300E+09 | 1.399E+11 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5803 | Aug | 4.043E+07 | 8.300E+09 | 1.399E+11 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5803 | Sep | 4.043E+07 | 8.573E+09 | 1.402E+11 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5803 | Oct | 4.043E+07 | 6.573E+10 | 1.973E+11 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5803 | Nov | 4.043E+07 | 6.791E+10 | 1.995E+11 | 3.382E+09 | 1.020E+07 | 0.000E+00 |
| 5803 | Dec | 4.043E+07 | 8.300E+09 | 9.206E+09 | 3.382E+09 | 1.020E+07 | 0.000E+00 |

[a] The sub-watersheds 8004 and 8005 used the same parameters as 8001

The contribution from urban land is estimated based on the mean contribution of different land use categories listed in Table 4-3. Each average value of these land use categories is used to estimate sources for build-up land, which is about $1.02\times10^7$

counts/acre/day. Dog contributions have been found to be significant sources in many other watershed studies. For a dog of average size, the fecal coliform contribution is estimated to be $4.5\times10^8$ counts/acre/day (Geldreich, 1978) up to $1.15\times10^8$ depending on per gram of dog feces. Dog population data is not available in the watershed. Assuming one dog for every 4 households and that 50% of the deposited bacteria is available for runoff, the estimated fecal production is higher than the fecal coliform production listed in Table 4-3 for urban build-up land, which is about $1.41\times10^7$ counts/acre/day. By considering the fact that most urban land is in low intensity residential areas, a low value of $1.02\times10^7$ counts/acre/day was used to estimate the load for this study as initial model setup for urban build-up land.

**Table 4-3. Fecal Coliform Loading for Urban Land**

| Land Use | Median counts/acre/day[1] |
|---|---|
| Commercial | $6.21\times10^6$ |
| Single family low density | $1.03\times10^7$ |
| Single family high density | $1.66\times10^7$ |
| Multifamily residential | $2.33\times10^7$ |
| Mean | $1.41\times10^7$ |

[1] Horner (1992)

### 4.2 Wildlife Source

The main wildlife sources considered are deer and raccoons. The source from birds can be another significant factor. Studies in the Washington, DC area show that the contribution from waterfowl can be as high as 30% of the total of all wildlife sources. Because there is no data available in this area, the total number of these animals was estimated based on a reasonable assumption, using a population model, and habitat information from the Holmans Creek TMDL (VDEQ, 2001). The average density of deer and raccoons in Shenandoah is about 0.074/acre and 0.07/acre, respectively. According to the UVA population model, the deer population density is about 42 per square mile in the York area, which is about 0.066/acre. Applying these data to the Cockrell Creek watershed, a high density of deer of 0.066/acre for forestland and pastureland was used. A raccoon density of 0.03/acre was used, which is slightly reduced. The estimated fecal coliform production in forestlands is about $3.67\times10^7$ counts/acre/day. This value was also added to the pastureland as a background value. For wetlands, one can assume 25 deer and 30 raccoons per square mile, which gives $2.54\times10^7$ counts/acre/day. For the current modeling application, the contribution of birds was only applied to wetlands. Adding bird contributions to wetlands, the final fecal coliform production rate of $3.38\times10^9$ counts/acre/day was used for wetlands in the model.

**4.3 Direct discharge to streams**

The direct discharge to streams includes point source facilities, septic failures, and animals that directly access stream(s). In the Cockrell Creek watershed, there is a wastewater facility (VA 0060712) located at sub-watershed 5803 and which discharges to the Creek. Because there is no available observation data for fecal coliform concentration for the wastewater facility, the designed flow of 0.2 MGD and permit limits of 200 counts/100mL were used to specify constant point source in the tidal prism model for the model simulation period. The total loading is about $1.51\times10^9$ counts/day or $6.3\times10^7$ counts/hour.

Cattle are always unconfined. The direct load occurs when they access stream(s). The loads due to direct access to stream(s) were considered as point sources. Table 4-4 lists the estimated hours cattle spend in stream(s) and the subsequent contribution of fecal load.

**Table 4-4. Hours/Day Cattle Spend in Stream and Fecal Load.**

| Month | Cattle in stream[1] (hours/day) | FC Production (counts/day/head of cattle) |
|---|---|---|
| January | 1 | 4.33E+09 |
| February | 1 | 4.33E+09 |
| March | 1.5 | 6.50E+09 |
| April | 2 | 8.67E+09 |
| May | 2 | 8.67E+09 |
| June | 2.5 | 1.08E+10 |
| July | 2.5 | 1.08E+10 |
| August | 2.5 | 1.08E+10 |
| September | 2 | 8.67E+09 |
| October | 1.5 | 6.50E+09 |
| November | 1.5 | 6.50E+09 |
| December | 1 | 4.33E+09 |

[1]Source: Fecal coliform TMDL development for Holmans Creek, Virginia (VDEQ, 2001)

For the current model application, a constant point source discharge of $7.58\times10^9$ counts/day was used to represent each head of cattle in-stream instead of allowing the discharge to the streams to vary monthly. The point sources were added to the tidal prism model cells adjacent to those watershed portions with cattle. Because the exact number of cattle in-stream is difficult to estimate, the constant point source estimated based on 10 cattle was used as an initial estimation of loading. The estimated loads produced by cattle is about $3.16\times10^9$ counts/hour. This value was adjusted during the model calibration.

### 4.4 Septic Failures

Only seven septic failures were observed during the 1997 survey (Table 4-5). Assuming that a concentration of $1\times10^5$ counts/100ml was used to estimate the fecal coliform load from failing septic systems and that a value of 70 gal/day/person was used to estimate the load, one can determine the estimated total fecal coliform load due to septic failure to be about $1.95 \times 10^7$ counts/day in the watershed. Half of the number of septic failures involved direct discharge to the Creek. Therefore, the load resulting in septic failures was added to the tidal prism model as point source discharge. The contribution of septic failures through indirect discharge was incorporated into the contribution from urban imperious land.

**Table 4-5. A Summary of Septic Failures in the 1997 Survey.**

| INDEX | Date | Number of people | TYPE | BRANCH | Subwatershed |
|---|---|---|---|---|---|
| 1 | 8/29/1997 | 2 | Toilet, direct | creek | 5804 |
| 4 | 5/15/1997 | 3 | septic, direct | creek | 5804 |
| 11 | 5/15/1997 | 6 | septic, indirect | ground surface | 5804 |
| 15 | 5/22/1997 | 1 | septic, direct | trench | 5803 |
| 19 | 5/28/1997 | 3 | septic, indirect | ground surface | 5803 |
| 24 | 6/13/1997 | 3 | septic direct | creek | 5801 |
| 36 | 7/3/1997 | 3 | septic, indirect | ground surface | 5805 |

### 4.5 Other potential sources

During the sanitary surveys of 1997, there was no evidence of septic failure in the marina. The load contribution of boat pollution is not clear. The fecal coliform load contributed from boats was not accounted for in the model.

## V. Model Setup

### 5.1 Land Use Mapping

For watershed model calibration, flow data in the watershed is often required. Unfortunately, there are no USGS flow gage stations in the coastal plain watershed. Since LSPC is identical to the HSPF model, the hydrology model parameters used by the Chesapeake Bay watershed model were adopted for the watershed model and the Bay model time series output was used for model calibration. Because the land use category of the Bay model is different from the NLCD land use category, a mapping between Bay land uses and NLCD land uses was applied to transfer the parameters. The land use mapping is listed in Table 5-1.

### 5.2 Watershed Model Setup

All the sub-watersheds directly connect to the tidal creek and river. Therefore, only the simulation of land processes was needed. The stream network data was not required in this application. Because there were no gage stations in the watershed, the hydrology parameters used by the Chesapeake Bay Program were used in the watershed model directly. In this way, the model results remain consistent with Bay model results.

**Table 5-1. Mapping of Land Use Categories Applied to the Model.**

| Bay Land use Category | Current Model category | NLCD |
|---|---|---|
| Water | Water | Open Water |
| Urban | Urban Pervious | Low Intensity Residential |
| | Urban Pervious | High Intensity residential |
| | Urban Pervious | High Intensity Commercial/Industrial/Transportation |
| Forest | Forest | Deciduous Forest |
| | Forest | Evergreen Forest |
| | Forest | Mixed Forest |
| | Forest | Deciduous Shrub land |
| | Forest | Evergreen Shrub land |
| | Forest | Mixed Shrub land |
| | Forest | Non-Natural Woody (Orchards/Groves/etc) |
| | Wetlands | Woody Wetlands |
| | Wetlands | Emergent Herbaceous Wetlands |
| Pasture | Pasture | Grasslands/Herbaceous (Natural/Semi Natural Herbaceous) |
| | Pasture | Pasture/Hay |
| | Pasture | Other Grasses/(Urban Grasses) |
| Conventional Till | Cropland | Row Crops |
| | Cropland | Small Grains |
| Urban Impervious | Urban Impervious | Low Intensity Residential |
| | Urban Impervious | High Intensity residential |
| | Urban Impervious | High Intensity Commercial/Industrial/Transportation |

For watersheds with different fecal coliform productions, each watershed was represented by an individual default model parameter set. In order to simulate seasonal variation, the monthly varying accumulation parameters of all land uses were specified based on the estimated values listed in Tables 4-2. For sub-watersheds SWS5802, SWS5804, and SWS5805 without domestic animal contributions, one default parameter set was used to represent these sub-watersheds, for which a constant background value used for forest was also used for pastureland and cropland. Specified default parameters, estimated based on monthly fecal coliform load, were used for sub-watersheds SWS5801 and SWS5803. A total of 3 default parameter sets were used to represent the watersheds. Constant accumulation parameters for forest, urban land, and wetlands were used, which are discussed in Chapter 4. The range of the fecal coliform decay rate in soil is about 0.025 to 0.083 per day (USEPA, 2001). A constant decay rate of 0.05/day was used for fecal coliform on land surfaces. This value is equivalent to the maximum surface buildup of 20 times the daily loading in the LSPC model.

No point source discharges, which represents cattle in-stream and septic failure, were specified in the watershed model. All the point sources were discharged to tidal prism model segments. The modeling period is from 1985 to 1997. The 13-year period simulates both wet and dry hydrology cycles.

### 5.3 Tidal Prism Model Setup

The Cockrell Creek was segmented into 9 segments with 2 tributaries (Figure 2-1). The segmentation was based on the previous model study results (Kim et al., 2001). Two requisites of the tidal prism model segmentation are that the length of a segment is less than the maximum tidal excursion and that the tidal prism upstream of a segment shall be large enough to accommodate the low tidal volume of that segment. The high tide volume, depth, and tidal prism for each segment were estimated from NOAA bathymetry data and charts. The bathymetric information is listed in Table 5-2. The linkages between watershed and tidal prism model segments are also listed in the table. If one sub-watershed covers more than one tidal prism model segment, the load will be evenly distributed to these segments. If more than one sub-watershed link to a tidal prism model segment, the loads from multiple sub-watersheds were summed together and linked to the tidal prism model segment.

The watershed model simulation is conducted on an hourly time scale, while the tidal prism model is on the scale of a tidal cycle (i.e., about 12.42 hours). Therefore, the daily load was calculated from hourly loads generated from the watershed, then the load for each tidal cycle was calculated and discharged to the coastal basins. The simulation period of the tidal prism model is the same as that of the watershed model.

Cattle in-stream and septic failures are implemented as constant point sources discharged into the tidal prism model segment. Compared with the contribution of fecal coliform from cattle in-stream, septic failure contribution is much lower, therefore loads from septic failure were not explicitly simulated in the model. Average production of fecal coliform per cattle per day is about $7.58\times10^9$ counts/day. Because the number of cattle that have access to stream(s) is difficult to ascertain, this value was used as an initial loading per head of cattle for those segments adjacent to the watershed with cattle. The point source loading was adjusted during the model calibration.

**Table 5-2. Geometry of Tidal Prism Model Segmentation**

| Segment ID | Distance (Km) | High water volume x10$^6$ (m$^3$) | Tidal Prism x10$^6$ (m$^3$) | Return Ratio | Depth (m) | Number of SWS | SWS ID1 | SWS ID2 |
|---|---|---|---|---|---|---|---|---|
| M0_1 | 0 | 0 | 1.072 | 0.3 | 0 | 0 | 0 | 0 |
| M0_2 | 0.46 | 1.09 | 0.945 | 0.3 | 2.76 | 1 | 5804 | 0 |
| M0_3 | 0.86 | 0.951 | 0.836 | 0.3 | 2.76 | 1 | 5804 | 0 |
| M0_4 | 1.22 | 0.816 | 0.727 | 0.3 | 2.76 | 1 | 5804 | 0 |
| M0_5 | 1.81 | 0.738 | 0.642 | 0.3 | 2.45 | 1 | 5804 | 0 |
| M0_6 | 2.47 | 0.647 | 0.553 | 0.3 | 2.3 | 2 | 5803 | 5805 |
| M0_7 | 3.4 | 0.653 | 0.323 | 0.3 | 1.31 | 0 | 0 | 0 |
| M0_8 | 4.5 | 0.54 | 0.2 | 0.3 | 1.31 | 1 | 5801 | 0 |
| M0_9 | 5.7 | 0.8 | 0 | 0.3 | 1.31 | 1 | 5801 | 0 |
| B4_1 | 0 | 0 | 0.03 | 0.3 | 0 | 0 | 0 | 1003 |
| B4_2 | 0.46 | 0.1 | 0 | 0.3 | 1 | 1 | 5804 | 0 |
| B7_1 | 0 | 0 | 0.1 | 0.3 | 0 | 0 | 0 | 0 |
| B7_2 | 0.4 | 0.5 | 0 | 0.3 | 1.2 | 1 | 5803 | 0 |
| T7_1 | 0 | 0 | 0.1 | 0.3 | 0 | 0 | 0 | 0 |
| T7_2 | 0.4 | 0.4 | 0 | 0.3 | 1.2 | 1 | 5802 | 0 |

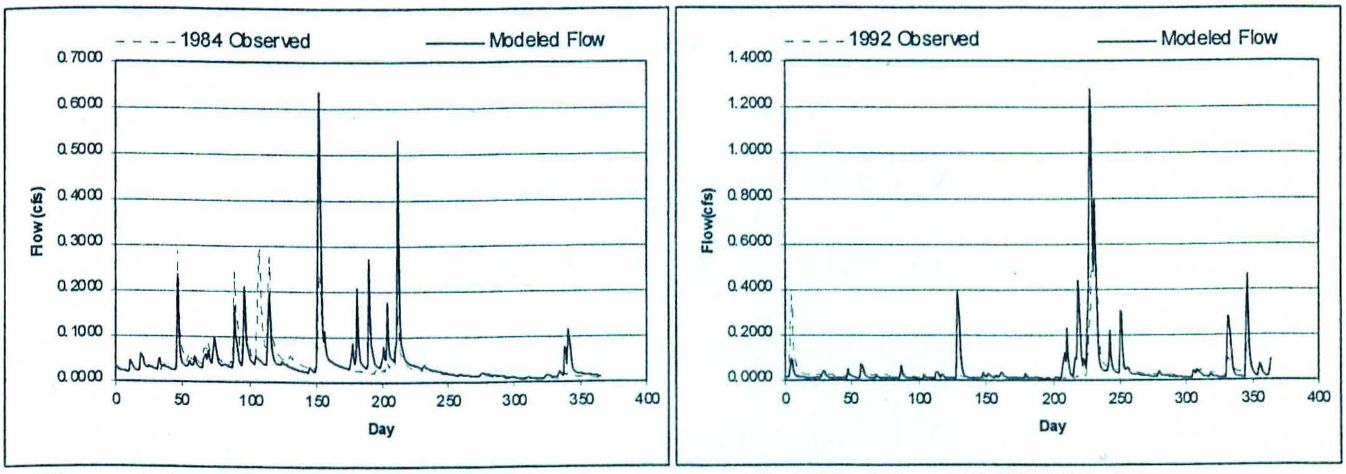



**Figure 6-1. Comparison of Hourly Outflow between Bay Model and LSPC Model. (Observation is the Bay watershed model output and modeled flow is LSPC model output using local precipitation).**

## VI. Model Validation

The period for the watershed model simulation spanned from 1985 to 1997. This section presents the model calibration and validation procedures. The current watershed model uses the Chesapeake Bay Watershed hydrological parameters in the Cockrell Creak watershed area. To obtain better simulation results, the nearest weather station data were used. Figure 6-1 is an example of hourly outflow per unit surface and subsurface from forestland. Because the hourly precipitation data differed from the precipitation data used by the Bay model, it can be expected that hourly outflow will not agree with the Bay model results exactly. Using local data, more flow peaks were observed. Figure 6-2 is a comparison of water budgets of forestland for the period of 1984 to 1994. It can be seen that the overall water budget is balanced.

The model calibration is conducted in two steps: (1) run the watershed model and generate all the input files for tidal prism model and (2) run the tidal prism model and

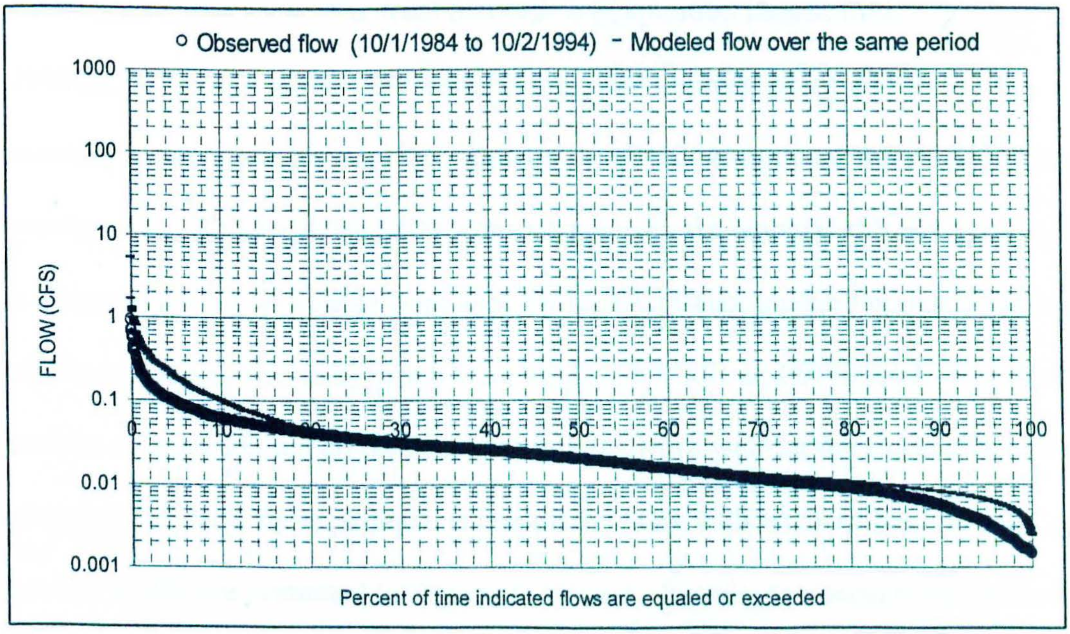



**Figure 6-2. Comparison of Flow Frequency between the Bay Model and LSPC Model.**

compare model results and observation data at selected stations. Four monitoring stations (Stations 3, 4, 5, and 6) inside Cockrell Creek were selected for the model calibration. The location of these stations is shown in Figure 2-4. Although the watershed model allows the user to adjust loading related parameters ACQOP and decay-related parameters SQOLIM for each watershed, adjustment of these parameters was kept to a minimum because the source estimation is based on the best information on the land surface.

For the methodology used to measure fecal coliform concentration, there is a cutoff in higher concentration. Therefore, the model can predict higher concentrations than those observed during wet weather. Based on the results of data analysis for fecal coliform concentration higher than 1000 mpn/100mL, about 50% -70% of the samples of high concentrations correspond to a rainfall event occurring either on the day of, or the day prior to, the sampling. The calibration effort, therefore, focused more on trend rather than individual data points. The fecal coliform concentration ranged from 5 to 1200 mpn/100mL, with most around 300 mpn/100mL. The constant point sources representing cattle in-stream were also adjusted so that in-stream concentrations during dry weather matched the low observed concentrations in the embayment. As a result, the loads estimated based on 5 cattle were used for fecal coliform production due to cattle which directly access stream(s) in sub-watersheds SWS5801 and SWS5803. The loading parameters estimated based on the source estimation work well for the Cockrell Creek watershed. Therefore, these parameters remain the same without modification. The calibration results are presented in Figures 6-3 to 6-5. In order to visualize the calibration results more clearly, a logarithmic scale was used for fecal coliform concentrations.

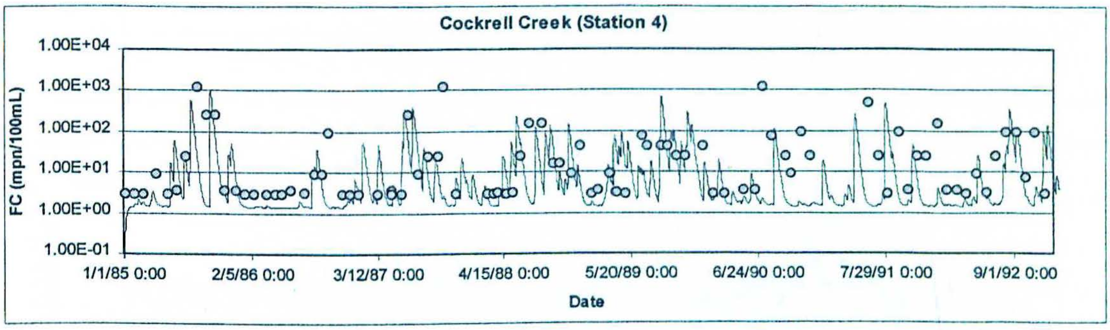
The circles are observation values and solid lines are model results. It can be seen that model results fall into a reasonable range and show seasonal variations. The model can capture wet weather events in which a higher concentration occurs. Because the loading estimation is based on the one-year survey results, discrepancies occurring in some years can be expected. These discrepancies indicate the possible changing of loads or other events that are not simulated by the model. The overall model results are satisfactory. The 30-month geometric means and $90^{th}$ percentiles for each calibration station were also computed and plotted in Figures 6-6 and 6-7. The standards are also plotted in the same figures for comparison. It can be seen that model results all show violations at these stations, which agree with the observations. The most problematic segments are segments 9 and 7-2, which received both high point and nonpoint sources discharges from the watershed. The concentration gradually reduced towards the mouth of the Creek indicating a dilution process.

The average percentages of loading distribution based on a 13-year model simulation for different land use categories by watershed are listed in Table 6-1.

**Table 6-1. Long-term Average Loading Distribution by Sub-watershed and Land Use (counts/year).**

| SWS | Cropland | Forest | Pasture | Urban Impervious | Urban Pervious | Wetlands | Point source |
|---|---|---|---|---|---|---|---|
| 5801 | 6.45E+12 | 2.30E+11 | 4.11E+13 | 2.28E-01 | 1.01E+11 | 1.77E+12 | 1.58E+09 |
| 5802 | 1.20E+10 | 2.38E+10 | 3.33E+09 | 8.71E-02 | 4.65E+10 | 3.64E+11 | 0.00E+00 |
| 5803 | 1.33E+13 | 4.02E+10 | 1.86E+14 | 3.23E-01 | 1.18E+11 | 1.24E+12 | 1.64E+09 |
| 5804 | 7.08E+10 | 3.88E+10 | 6.27E+10 | 4.11E-01 | 1.25E+11 | 1.38E+12 | 0.00E+00 |
| 5805 | 9.33E+09 | 2.36E+10 | 7.57E+09 | 1.03E-01 | 4.30E+10 | 1.81E+11 | 0.00E+00 |
| Total Loads | 1.98E+13 | 3.56E+11 | 2.27E+14 | 1.15E+00 | 4.33E+11 | 4.93E+12 | 1.18E+12 |
| Percent Loads | 7.80 | 0.14 | 89.48 | 0.00 | 0.17 | 1.94 | 0.46 |

The dominant loading contributions are from pastureland, which is responsible for nearly 89% of the total loading. These contributions possibly result from unconfined cattle grazing and manure spreading. The contributions from cropland and wetlands are 8% and 2%, respectively. The total load discharged from point sources, including cattle that directly access stream(s), is less than 1%.



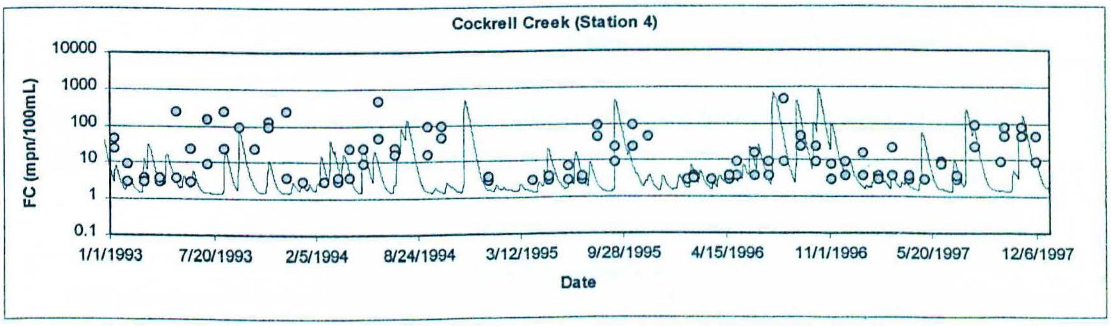




**Figure 6-3. Model predicted fecal coliform (blue line) vs. observations at Cockrell Creek, Station 4.**

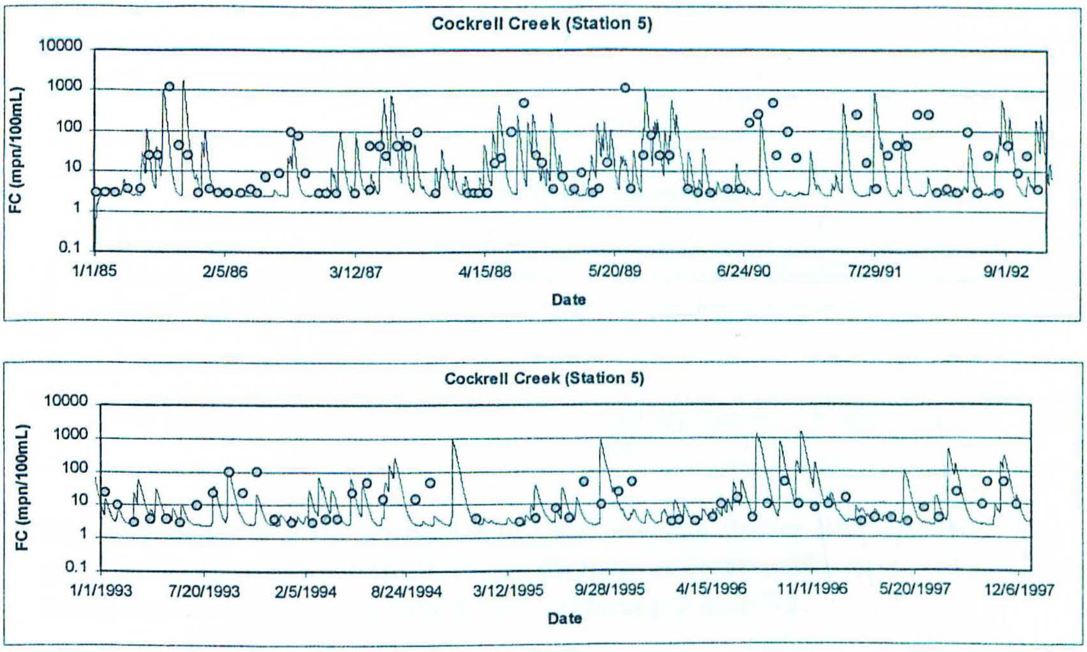



**Figure 6-4. Model predicted fecal coliform (blue line) vs. observations at Cockrell Creek, Station 5.**

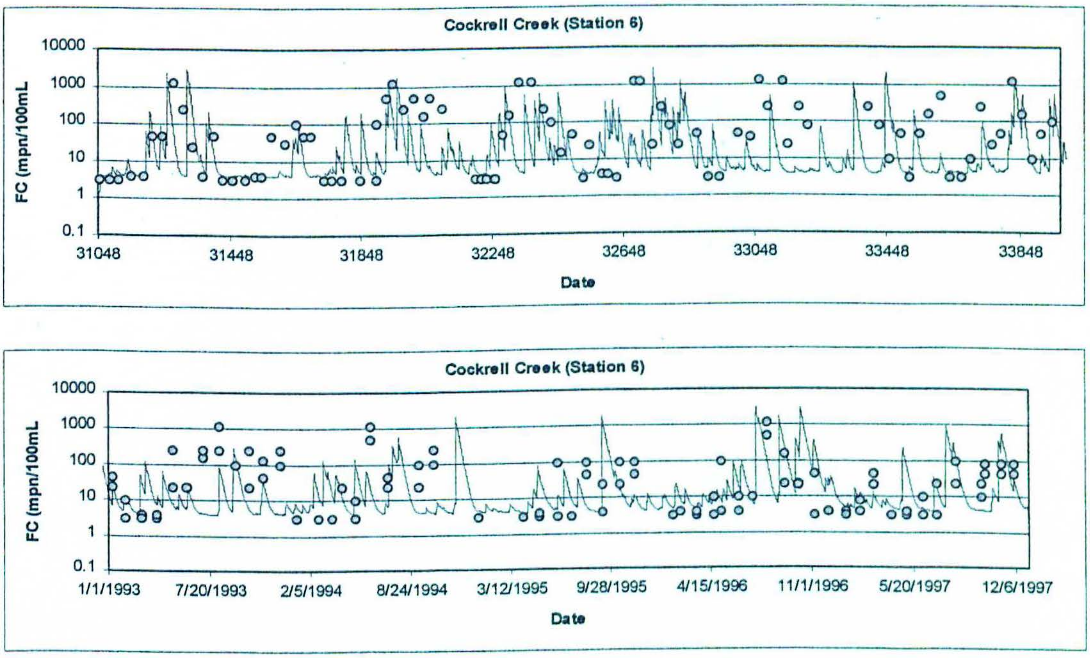
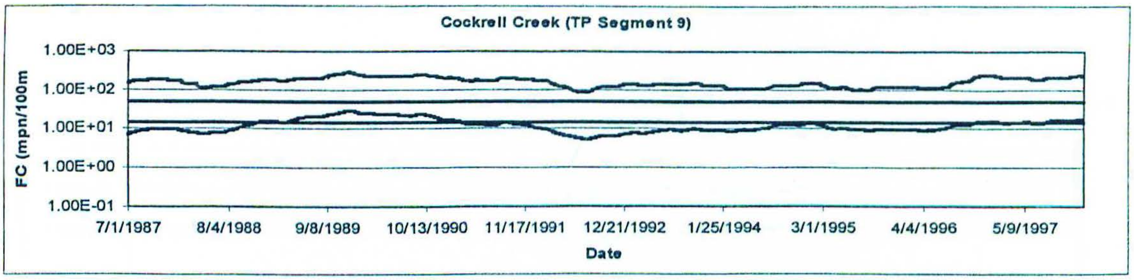



**Figure 6-5. Model predicted fecal coliform (blue line) vs. observations at Cockrell Creek, Station 6.**



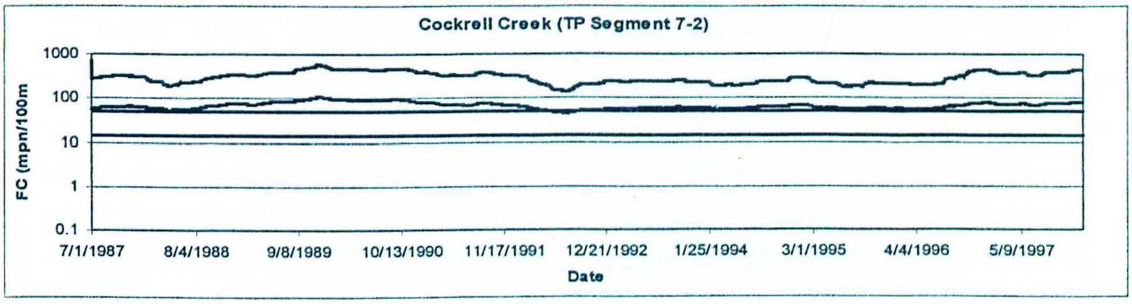
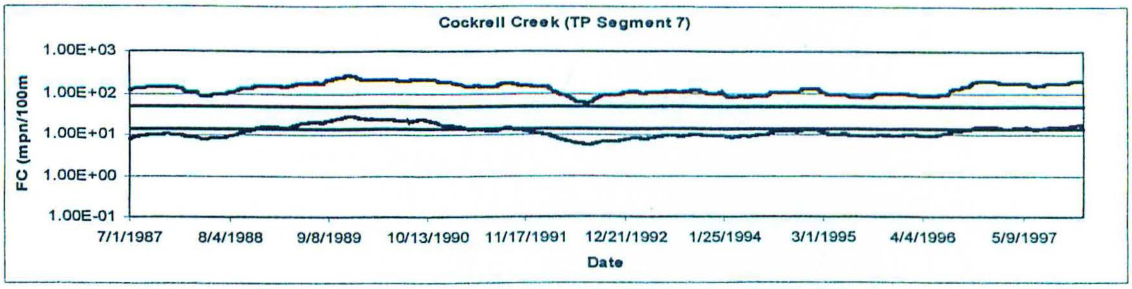




**Figure 6-6. Plots of the 30-month geometric mean (lower line) and 90th percentiles (upper line) of model predictions of fecal coliform vs. standards (red lines) for Cockrell Creek tidal prism segments 9 and 7-2.**



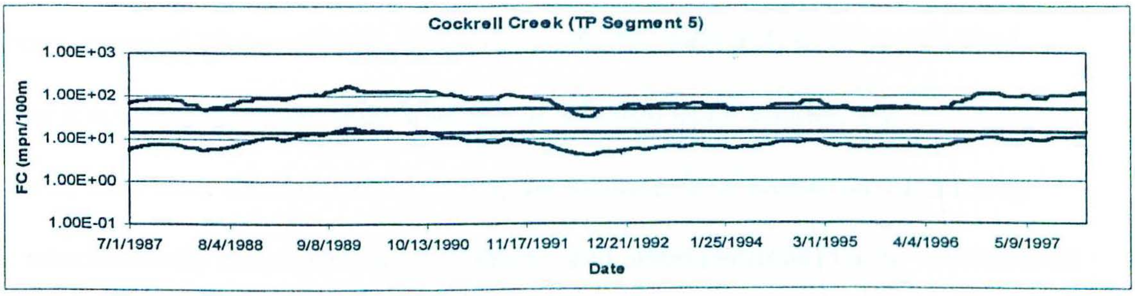




**Figure 6-7. Plots of the 30-month geometric mean (lower line) and 90th percentiles (upper line) of model predictions of fecal coliform vs. standards (red lines) for Cockrell Creek tidal prism segments 7 and 5.**

## VII. Reduction Sensitivity Run

A series of sensitivity runs were conducted to examine the feasibility of load reduction scenarios. The water quality criteria applied to the embayment are a 30-month geometric mean of 14 mpn/100mL and a 30-month 90$^{th}$ percentile of 49 mpn/100mL. Because it is difficult to control the loading contribution from wildlife, the load reduction sensitivity runs were conducted by reducing the loadings from pastureland including cattle which directly access stream(s), cropland, and urban pervious land to its maximum reduction level. If in-stream concentrations could not meet the standard after reducing loads from these three land uses, the loads from wetlands were reduced as well.

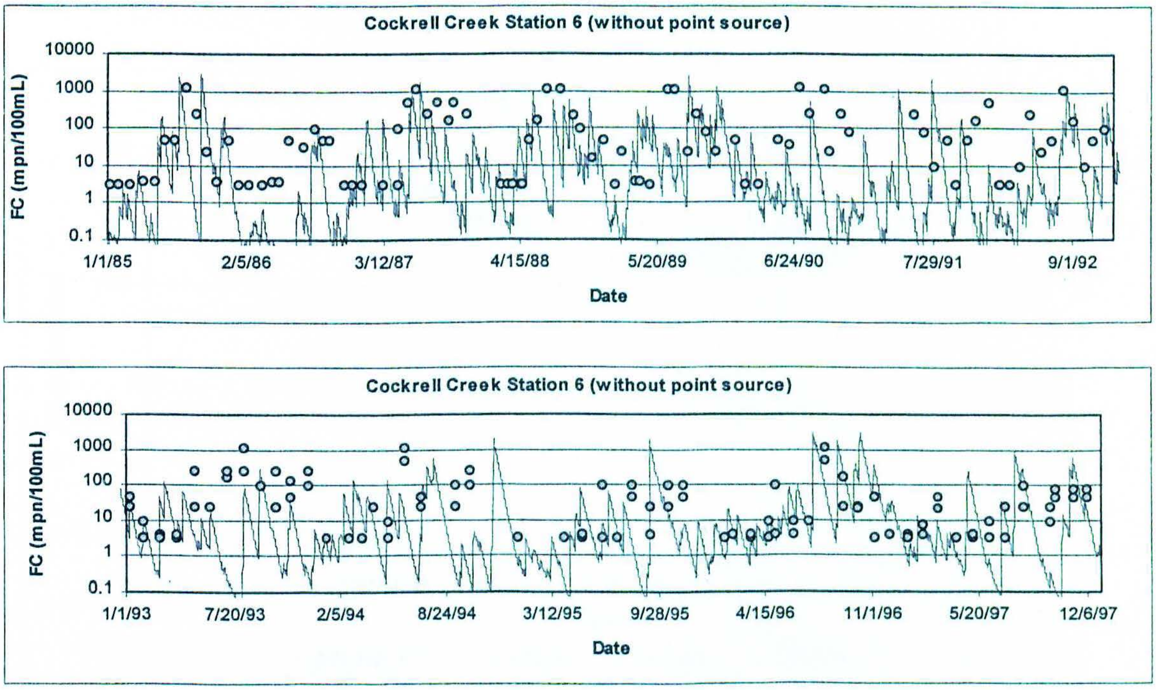



**Figure 7-1. Model predicted fecal coliform (blue line) vs. observations at Cockrell Creek, Station 6 (without point sources).**

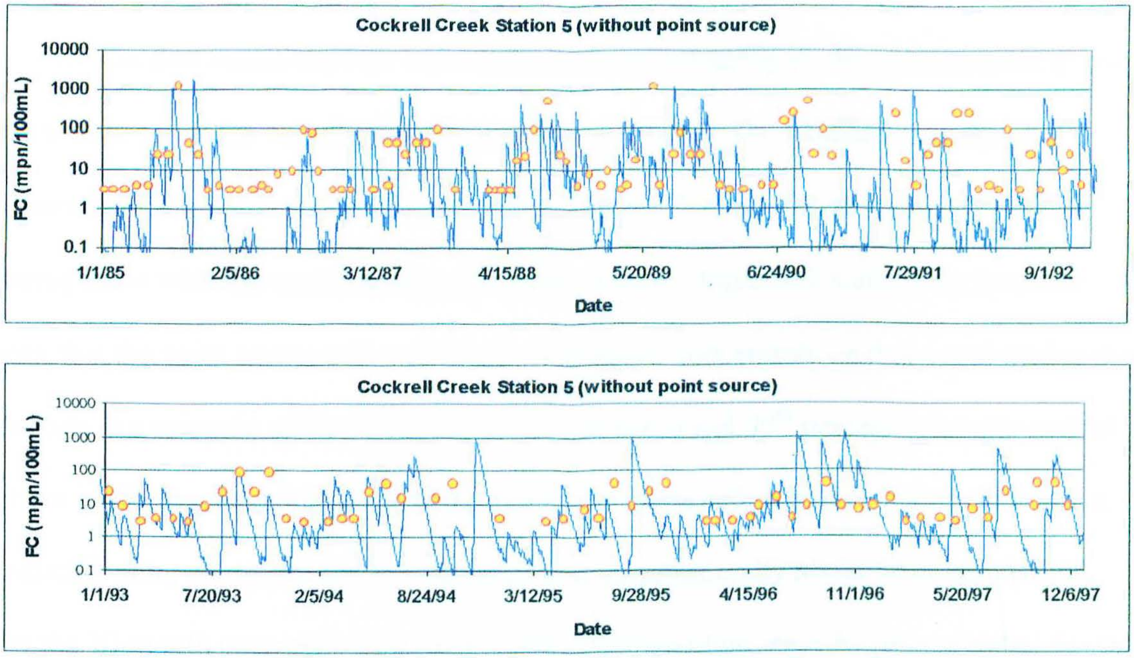



**Figure 7-2. Model predicted fecal coliform (blue line) vs. observations at Cockrell Creek, Station 5 (without point sources).**

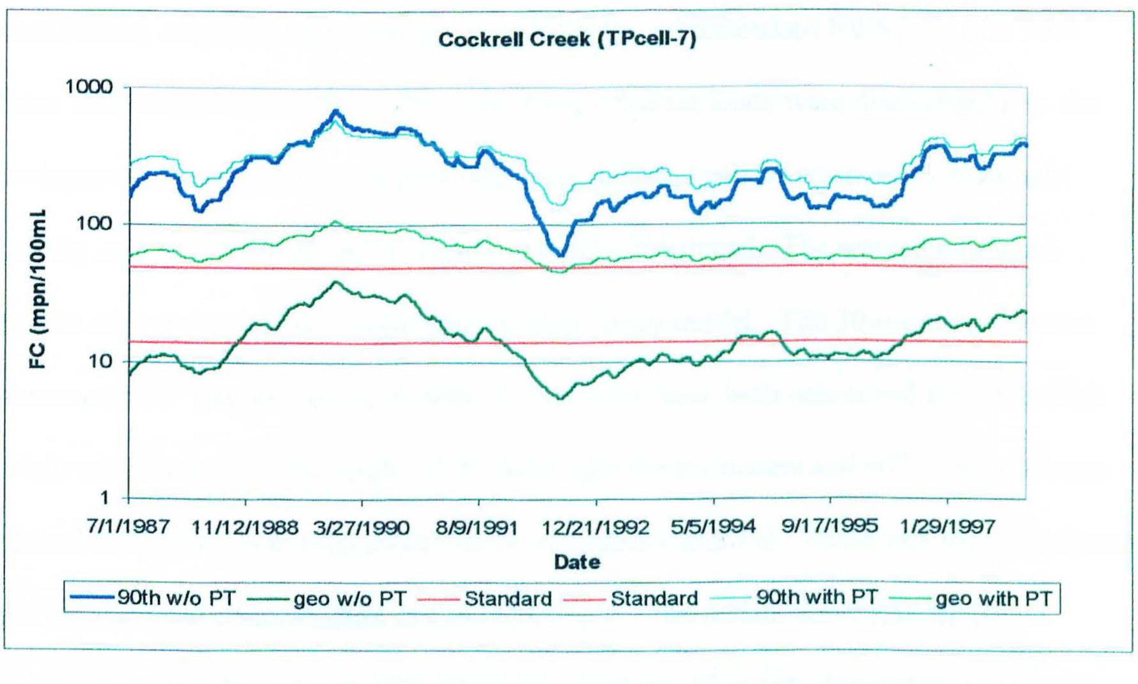
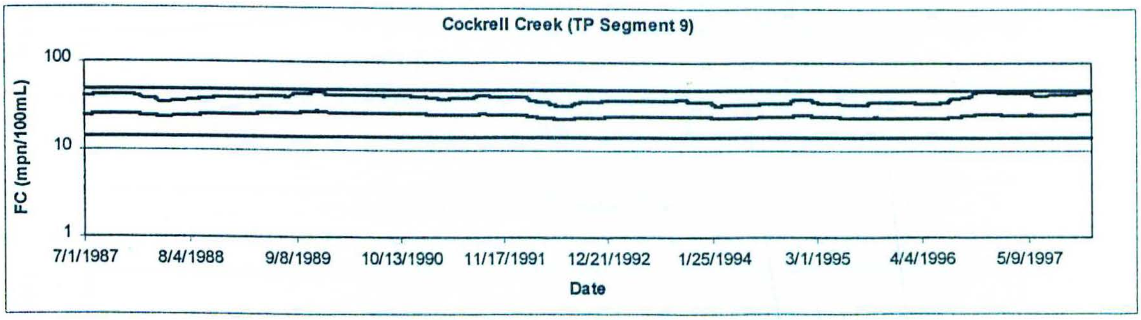



**Figure 7-3. Comparison of 30-month geometric mean and 90th percentile of model predicted fecal coliform with and without point sources. (The blue lines (heavy line) are results without point source and green line (thin line) are results with point sources.**

The first sensitivity run was conducted by eliminating all the point sources to test the sensitivity of the contribution of point source impact. The simulation results at observation stations 6 and 5 are presented in Figures 7-1 and 7-2, respectively. Comparing these with the model results with point sources (Figures 6-4 and 6-5), it can be seen that the point source will only impact minimum concentrations that occur during dry periods. An example of the 30-month geometric mean and 90$^{th}$ percentile results at tidal prism model segment 7 (outside of the branch) is presented in Figure 7-3. It shows that reducing point source results in a decrease of concentration by about 50 counts/100mL for the 30-month geometric mean and minimum concentration of 70 counts/100ml for the 30-month 90$^{th}$ percentile. However, the concentration at the segment still exceeds the water quality standards indicating the impact of nonpoint sources.

The second sensitivity run was conducted by reducing 90% loads from pastureland, cropland, and urban pervious land for subwatershed SWS5801 and 99% from subwatershed SWS5803. The main fecal coliform loads were discharged into the embayment due to animal pollution. The point source loads of wastewater treatment facility and cattle with access to stream(s) were not reduced. The watershed model results after reduction were input into the tidal prism model. The 30-month geometric means and 90$^{th}$ percentiles for stations in the Creek were both calculated from the tidal prism model results. The results of 30-month geometric means and 90$^{th}$ percentiles are plotted in Figure 7-4 at tidal prism model segments 9 and 7-2. These two segments have the highest fecal concentration in Cockrell Creek. The results show that the 90$^{th}$ percentiles meet the water quality standards while the 30-month geometric means still exceed the water quality standard, indicating the impact of the point sources. A model sensitivity run was conducted to test the impact of the point sources. The point source loads due to cattle which directly access stream(s) were reduced by 90% in both sub-watersheds SWS5801 and SWS5803, while point source discharged at the wastewater treatment facility remained unchanged. After reduction, the point source loads in



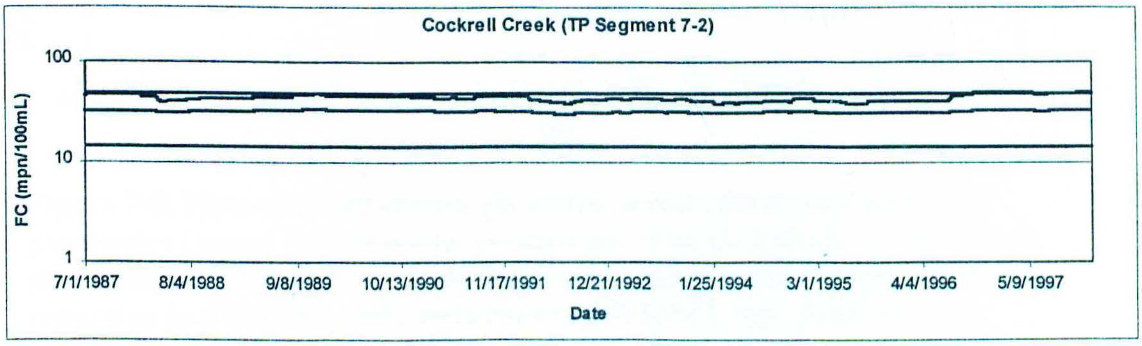




**Figure 7-4. Plots of the 30-month geometric mean (lower line) and 90th percentiles (upper line) of model predictions of fecal coliform vs. standards (red lines) for Cockrell Creek tidal prism segments 9 and 7-2 after 90% load reduction in SWS5801 and 99% reduction in SWS5803.**

SWS5801 and SWS5803 were $1.58\times10^{8}$ and $2.21\times10^{8}$ counts/hour, respectively. The model results of the 30-month geometric mean and the $90^{th}$ percentile are shown in Figure 7-5 at tidal prism model segments 9 and 7-2. Comparing model results against standards, in-stream concentrations are below the standards. Overall, the loads were reduced too much. The amount of load reduction can be reduced. Figure 7-6 shows the daily mean fecal coliform concentration at observation Station 6 with point source discharge. Comparing model results shown in Figure 6-4, it can be seen that the maximum concentration is reduced significantly.

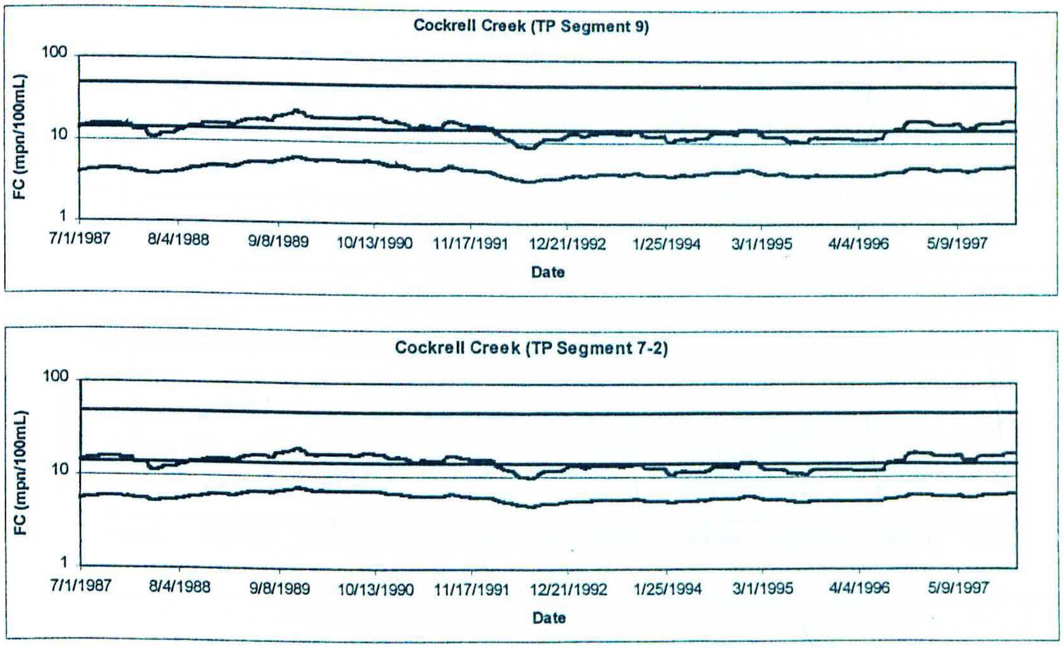



**Figure 7-5. Plots of the 30-month geometric mean (lower line) and 90th percentiles (upper line) of model predictions of fecal coliform vs. standards (red lines) for Cockrell Creek tidal prism segments 9 and 7-2 after 90% load reduction in SWS5801, 99% reduction in SWS5803, and point source reduction of 90%.**

To obtain the total maximum daily load for the Creek, a series of sensitivity runs were conducted by reducing the different percentage of loads contributed from both point source and nonpoint sources so that the in-stream concentration reached a maximum level but still remained below standards. Consequently, the nonpoint source loads of SWS5801 and SWS5803 were reduced by 85% and 95%, respectively, from pasture and cropland. The nonpoint source loads contribution of SWS5801 and SWS5803 was reduced by 85% from urban pervious land. The point source contribution of cattle with access to streams was reduced by 80%. The point source facility VA0060712 still discharges at its permitted level, i.e., 200 mpn/100mL. The model results of the 30-month geometric

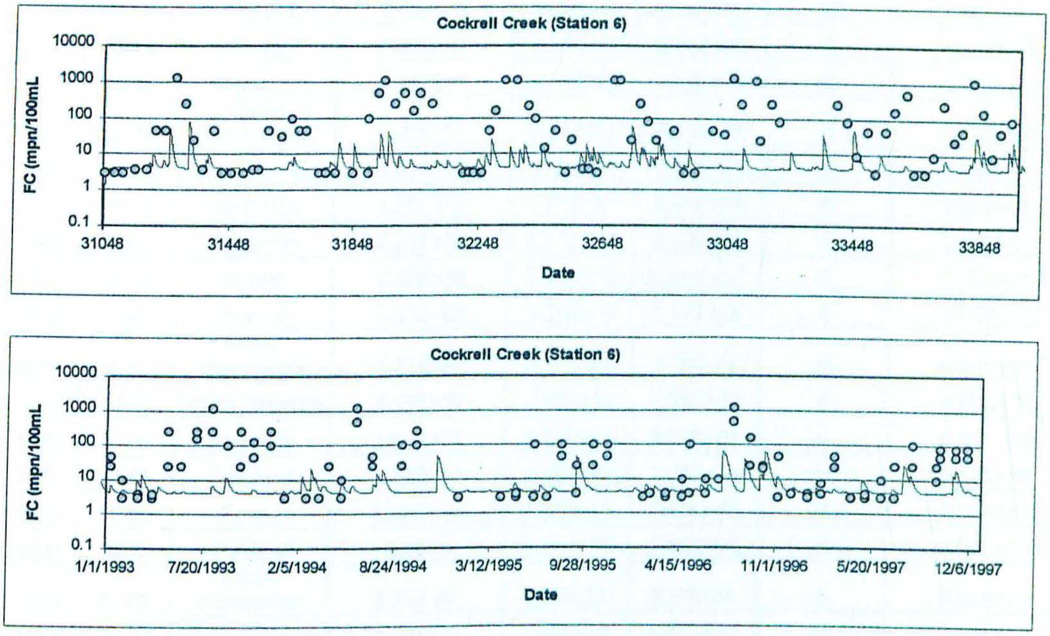



**Figure 7-6. Model predicted fecal coliform (blue line) vs. observations at Cockrell Creek, Station 6 after load reduction at SWS5801 and SWS5803.**

means and the 90th percentiles for selected stations are presented in Figures 7-7 to 7-8. An example of the estimated total maximum load for each sub-watershed is presented in Table 7-1. The purpose of the scenario run is to test the model and show the response of in-stream concentration after load reduction. Different model sensitivity runs can lead to different TMDL scenarios. More studies are warranted to achieve a successful load allocation.

**Table 7-1. Estimated load reductions and load allocations for each sub-watershed based on the existing conditions (counts).**

| SWS | Area (acre) | Land Use | Baseline Load (year) | Allocation (year) | Allocation (day) | Reduction (%) | Point Source (day) |
|---|---|---|---|---|---|---|---|
| 5801 | 145 | Cropland | 6.45E+12 | 9.67E+11 | 2.65E+09 | 85 | 7.58E+09 |
| 5801 | 421.9 | Forest | 2.30E+11 | 2.30E+11 | 6.30E+08 | 0 | 0.00E+00 |
| 5801 | 92.96 | Pasture | 4.11E+13 | 6.17E+12 | 1.69E+10 | 85 | 0.00E+00 |
| 5801 | 24.74 | Urban Impervious | 2.28E-01 | 2.28E-01 | 6.26E-04 | 0 | 0.00E+00 |
| 5801 | 94.45 | Urban Pervious | 1.01E+11 | 1.52E+10 | 4.15E+07 | 85 | 0.00E+00 |
| 5801 | 13.12 | Wetlands | 1.77E+12 | 1.77E+12 | 4.85E+09 | 0 | 0.00E+00 |
| 5802 | 6.89 | Cropland | 1.20E+10 | 1.20E+10 | 3.30E+07 | 0 | 0.00E+00 |
| 5802 | 47.15 | Forest | 2.38E+10 | 2.38E+10 | 6.52E+07 | 0 | 0.00E+00 |
| 5802 | 2.45 | Pasture | 3.33E+09 | 3.33E+09 | 9.14E+06 | 0 | 0.00E+00 |
| 5802 | 9.44 | Urban Impervious | 8.71E-02 | 8.71E-02 | 2.39E-04 | 0 | 0.00E+00 |
| 5802 | 43.49 | Urban Pervious | 4.65E+10 | 4.65E+10 | 1.28E+08 | 0 | 0.00E+00 |
| 5802 | 3.11 | Wetlands | 3.64E+11 | 3.64E+11 | 9.97E+08 | 0 | 0.00E+00 |
| 5803 | 22.68 | Cropland | 1.33E+13 | 6.63E+11 | 1.82E+09 | 95 | 9.12E+09 |
| 5803 | 78.95 | Forest | 4.02E+10 | 4.02E+10 | 1.10E+08 | 0 | 0.00E+00 |
| 5803 | 55.6 | Pasture | 1.86E+14 | 9.30E+12 | 2.55E+10 | 95 | 0.00E+00 |
| 5803 | 35.03 | Urban Impervious | 3.23E-01 | 3.23E-01 | 8.86E-04 | 0 | 0.00E+00 |
| 5803 | 110.19 | Urban Pervious | 1.18E+11 | 1.77E+10 | 4.85E+07 | 85 | 0.00E+00 |
| 5803 | 9.56 | Wetlands | 1.24E+12 | 1.24E+12 | 3.39E+09 | 0 | 0.00E+00 |
| 5804 | 40.47 | Cropland | 7.08E+10 | 7.08E+10 | 1.94E+08 | 0 | 0.00E+00 |
| 5804 | 76.94 | Forest | 3.88E+10 | 3.88E+10 | 1.06E+08 | 0 | 0.00E+00 |
| 5804 | 46.04 | Pasture | 6.27E+10 | 6.27E+10 | 1.72E+08 | 0 | 0.00E+00 |
| 5804 | 44.51 | Urban Impervious | 4.11E-01 | 4.11E-01 | 1.13E-03 | 0 | 0.00E+00 |
| 5804 | 116.72 | Urban Pervious | 1.25E+11 | 1.25E+11 | 3.42E+08 | 0 | 0.00E+00 |
| 5804 | 11.78 | Wetlands | 1.38E+12 | 1.38E+12 | 3.78E+09 | 0 | 0.00E+00 |
| 5805 | 5.34 | Cropland | 9.33E+09 | 9.33E+09 | 2.56E+07 | 0 | 0.00E+00 |
| 5805 | 46.7 | Forest | 2.36E+10 | 2.36E+10 | 6.46E+07 | 0 | 0.00E+00 |
| 5805 | 5.56 | Pasture | 7.57E+09 | 7.57E+09 | 2.07E+07 | 0 | 0.00E+00 |
| 5805 | 11.19 | Urban Impervious | 1.03E-01 | 1.03E-01 | 2.83E-04 | 0 | 0.00E+00 |
| 5805 | 40.17 | Urban Pervious | 4.30E+10 | 4.30E+10 | 1.18E+08 | 0 | 0.00E+00 |
| 5805 | 1.55 | Wetlands | 1.81E+11 | 1.81E+11 | 4.97E+08 | 0 | 0.00E+00 |

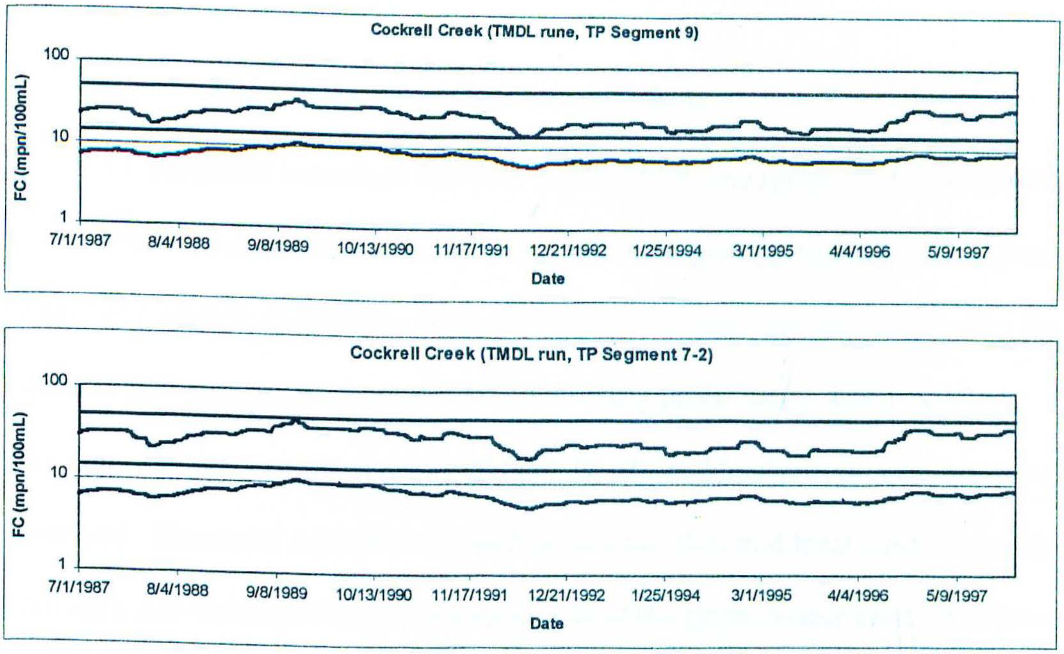



**Figure 7-7. TMDL scenario run results with non-point source reduction of 85% at SWS5801 and 95% reduction at SWS5803, and 80% reduction of point sources except WA 0060712 for tidal prism segments 9 and 7-2.**

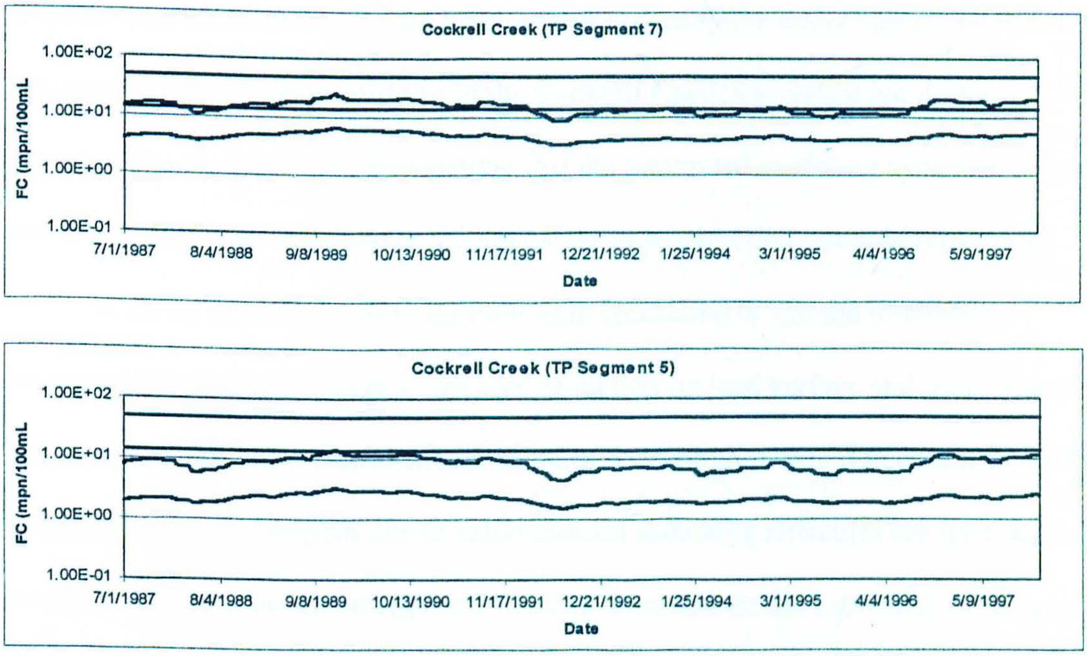



**Figure 7-8. TMDL scenario run results with non-point source reduction of 85% at SWS5801 and 95% reduction at SWS5803, and 80% reduction of point sources except WA 0060712 for tidal prism segments 7 and 5.**

## VIII. Conclusions

An integrated watershed and tidal prism model was applied to Cockrell Creek and its watershed. Multiple data sets, including land use, domestic animal distribution, septic failure, and wildlife distribution, were collected, estimated, and implemented in the model. The watershed model was driven by hourly precipitation and simulated hydrology and fecal coliform accumulation, die off, and transport processes in the watershed. Simulated surface runoff and subsurface flow and fecal coliform loading from each sub-watershed were discharged to the tidal prism model segment adjacent to the sub-watershed. The tidal prism model simulates the fecal coliform transport and fate within the embayment. The model was validated with real observation data from 1985-1997. Overall, model results are satisfactory. The model results show that both point and nonpoint sources contribute to the high concentrations in the embayment. The possible dominant sources of fecal coliform in the Cockrell Creek watershed are domestic animals. The model results demonstrate that the integrated modeling system is a good tool to simulate fecal coliform processes for the watershed and coastal embayment.

A series of model sensitivity runs were conducted to test the in-stream concentration change response to the load reduction on land surface and point sources. The model results show that in-stream bacteria concentration will decrease if loads from watershed and point sources due to cattle directly accessing stream(s) are decreased. An example of TMDL development is provided to demonstrate the capability of the system.

The purpose of this study is to test the integrated watershed and tidal model system and the feasibility of TMDL development for a coastal embayment with multiple sources. The sources of fecal coliform estimated are based on limited data collected by the authors and are used for testing purposes. Different model sensitivity runs can lead to different TMDL scenarios. More studies are warranted to achieve a successful load allocation.

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# APPENDIX A

**Cockrell Creek Observation Data**

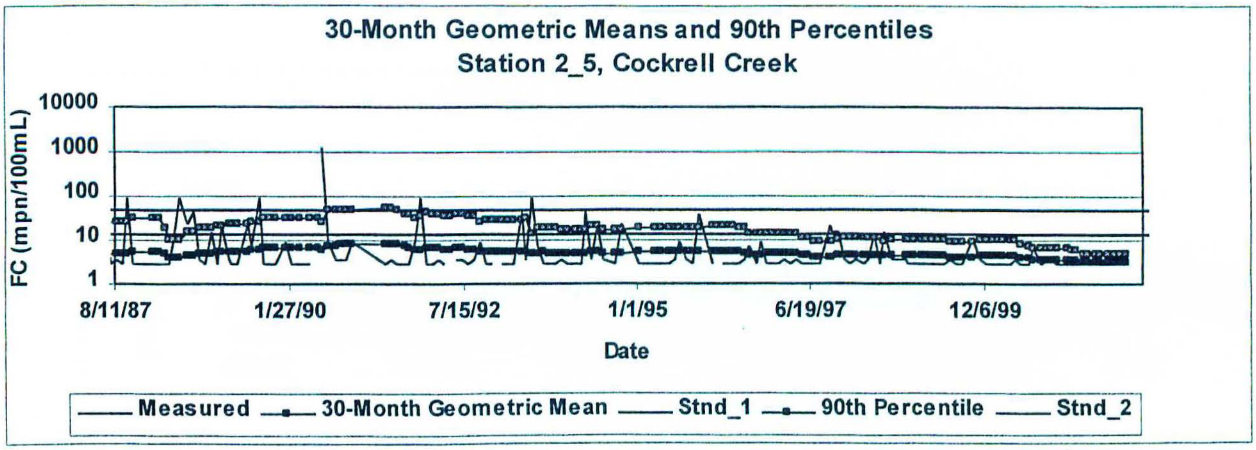


Figure A1. Observation data analyzed for 30-month geometric means and 90th percentiles for Cockrell Creek, Station 2_5, shown along with standard values for both.

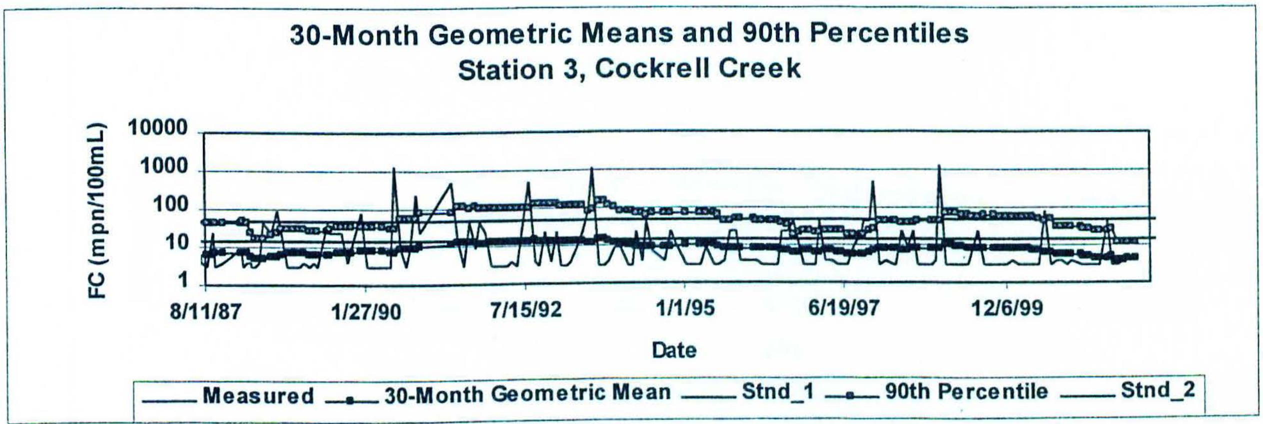


Figure A2. Observation data analyzed for 30-month geometric means and 90th percentiles for Cockrell Creek, Station 3, shown along with standard values for both.

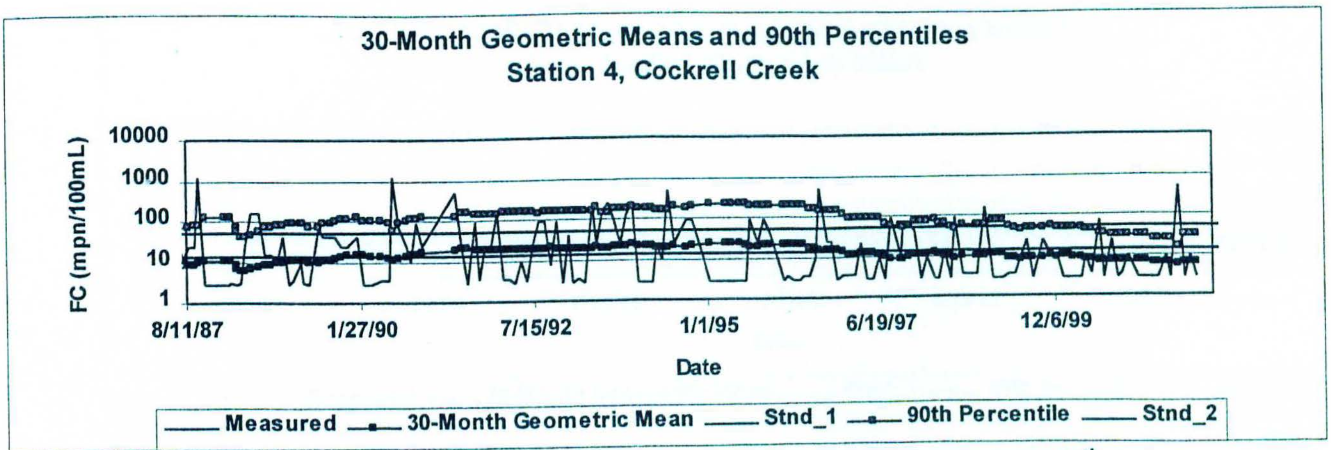


Figure A3. Observation data analyzed for 30-month geometric means and 90th percentiles for Cockrell Creek, Station 4, shown along with standard values for both.

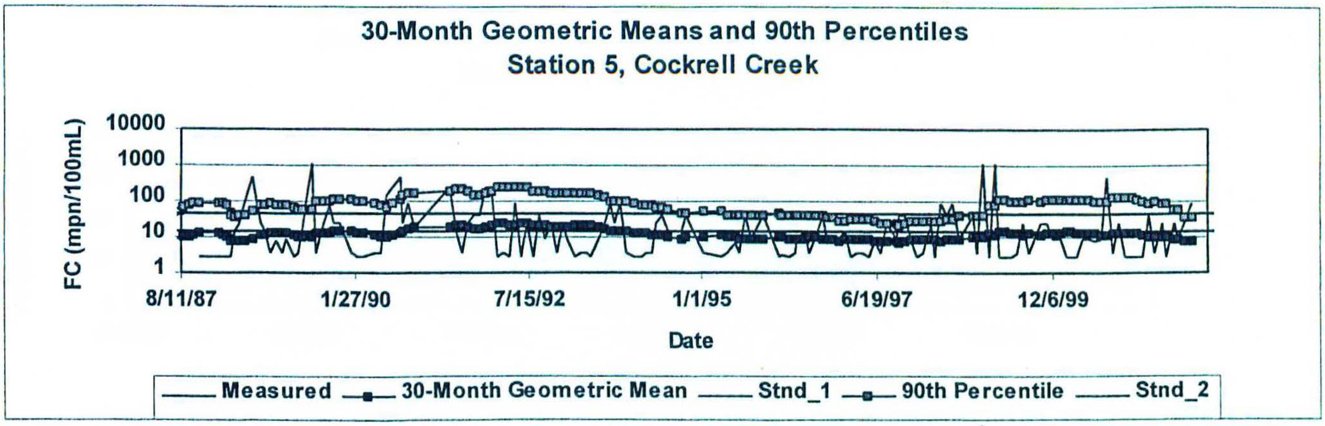


Figure A4. Observation data analyzed for 30-month geometric means and 90$^{th}$ percentiles for Cockrell Creek, Station 5, shown along with standard values for both.

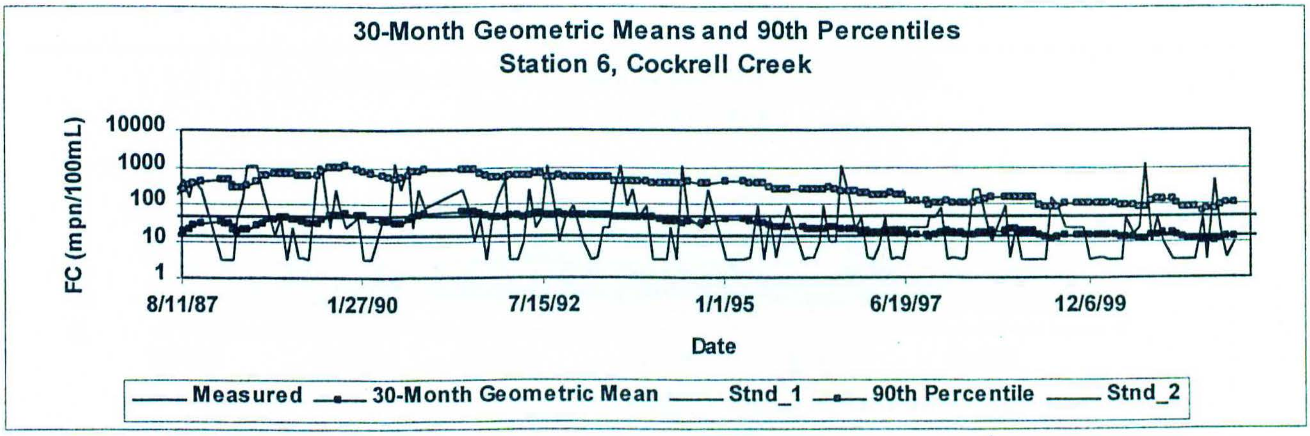


Figure A5. Observation data analyzed for 30-month geometric means and 90$^{th}$ percentiles for Cockrell Creek Station 6, shown along with standard values for both.

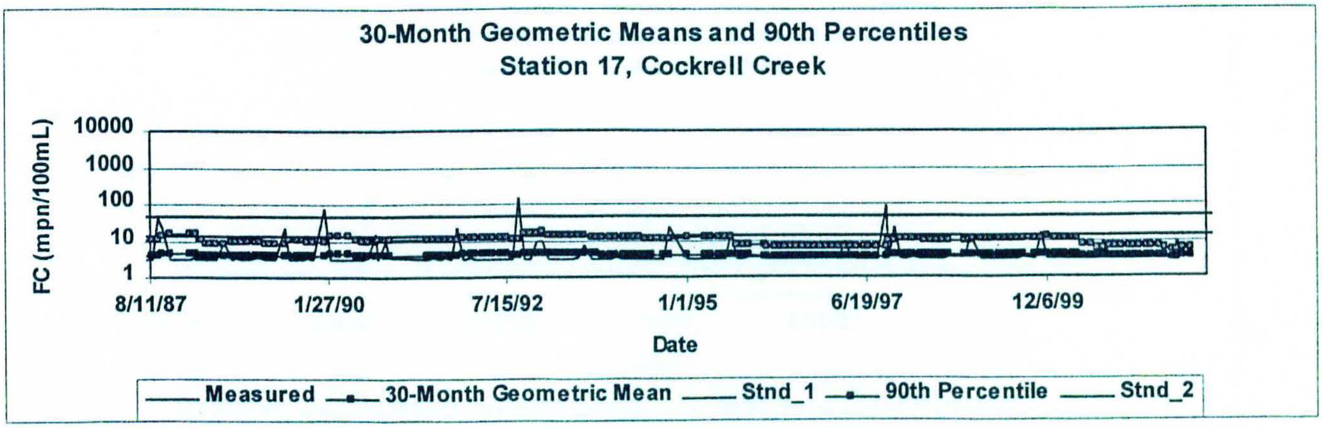


Figure A6. Observation data analyzed for 30-month geometric means and 90$^{th}$ percentiles for Cockrell Creek, Station 17, shown along with standard values for both.

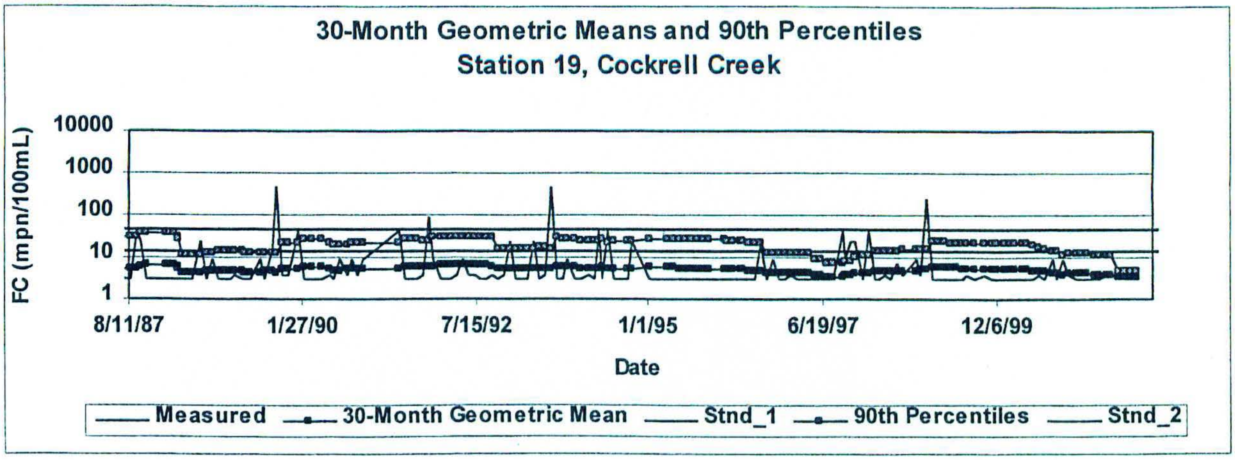


Figure A7. Observation data analyzed for 30-month geometric means and 90th percentiles for Cockrell Creek, Station 19, shown along with standard values for both.

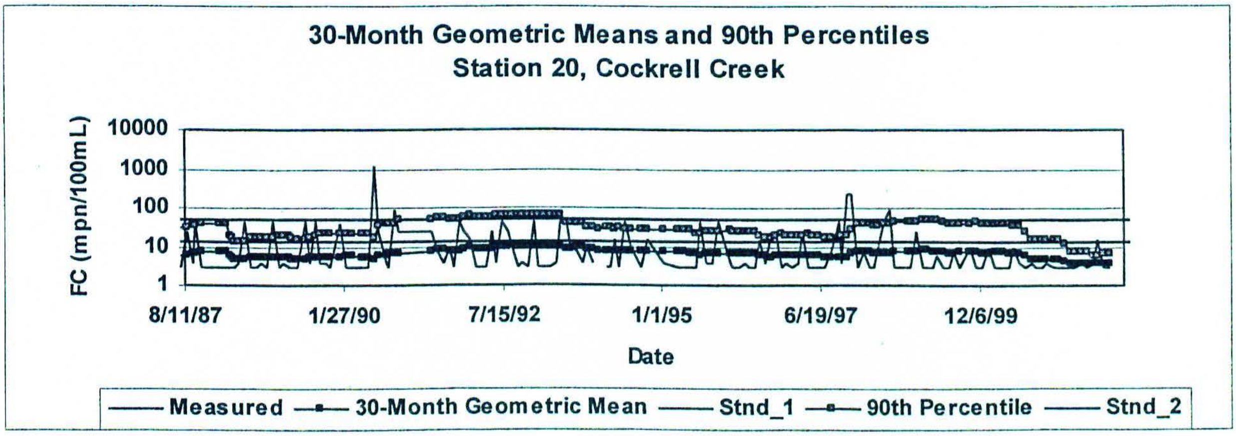


Figure A8. Observation data analyzed for 30-month geometric means and 90th percentiles for Cockrell Creek, Station 20, shown along with standard values for both.

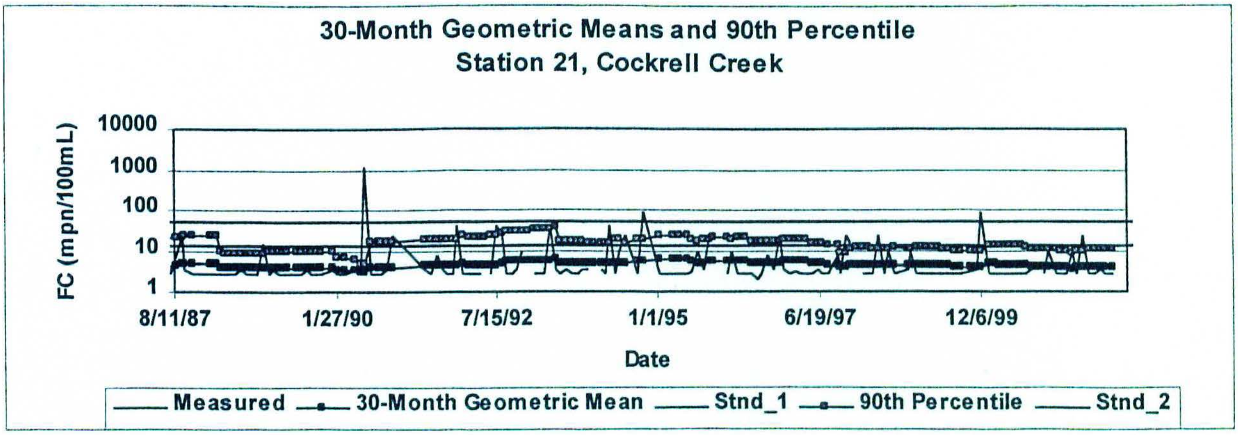


Figure A9. Observation data analyzed for 30-month geometric means and 90th percentiles for Cockrell Creek, Station 21, shown along with standard values for both.