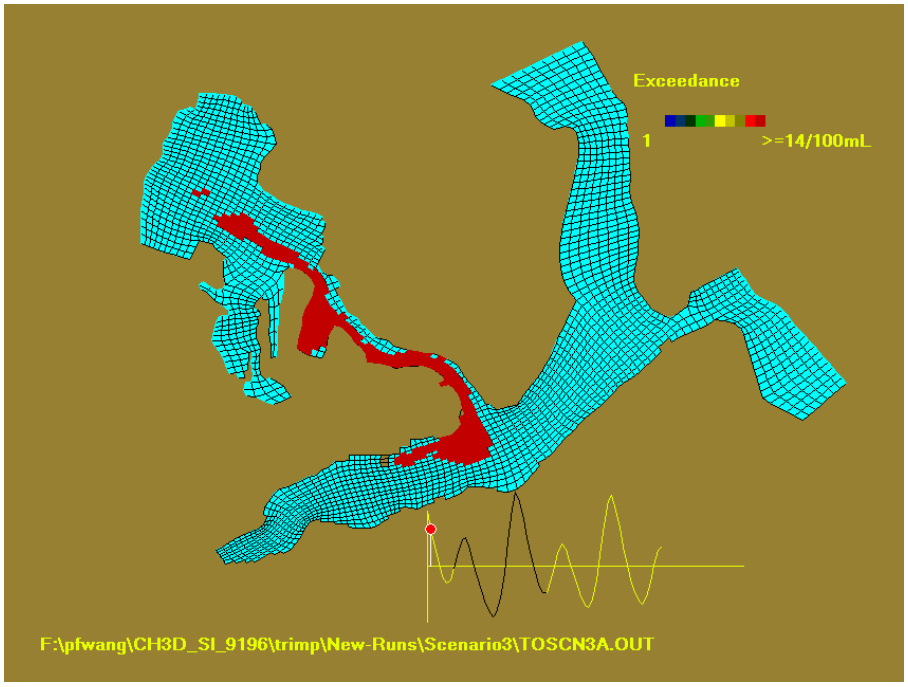
A Modeling Study of Combined Sewer Overflows in the Port Washington Narrows and Fecal Coliform Transport in Sinclair and Dyes Inlets, Washington.

P.F. Wang, R.K. Johnston, H. Halkola, R.E. Richter,
and B. Davidson,

Marine Environmental Support Office Code 2375
Environmental Sciences and Applied Systems Branch
Space and Naval Warfare Systems Center
San Diego, CA



FINAL REPORT
June 18, 2004

Acknowledgements

This report was prepared as part of the Puget Sound Naval Shipyard and Intermediate Maintenance Facility (PSNS&IMF) Project ENVVEST a cooperative project among the U.S. Navy, U.S. EPA, Washington State Department of Ecology, and technical stakeholders to help improve the environmental quality of the Sinclair and Dyes Inlet Watershed. This work was conducted under the direction of G.M. Sherrell, PSNS&IMF Project ENVVEST Program Manager and R.K. Johnston Project ENVVEST Technical Coordinator with contributions from members of the working group. The authors greatly appreciate the contributions to this work made by the members of the CSO modeling subworking group including Frank Meriwether, Washington State Department of Health; Paul Williams, Tom Ostrom, and Vivian Barry, Suquamish Tribe; Chance Berthiaume, Mike Mecham, and Mindy Fohn, City of Bremerton; Stan Olsen and Mauro Hein, Kitsap County Surface and Storm Water Management, Jim Zimny, Kitsap County Health District; Joe Wright, Vickie Whitney, and Steve Swanson, PSNS & IMF; and Chris Collins, CTC. Without their assistance and technical contributions this work would not have been possible.

Dyes Inlet drogue study (Project ENVVEST file photo).

Table of Contents

1. INTRODUCTION 4

2. BACKGROUND 5

2.1 Discharges from CSOs 5

2.2 CH3D-FC Model Development 5

2.2.1 CH3D Model Description 5

2.2.2 Fecal Coliform Transport Module 8

3. RESULTS OF FIELD STUDIES 12

3.1 Drogue and Current Meter Study 12

3.2 Dye Release Study 15

4. CSO SIMULATION SCENARIO 18

4.1 Calculating Volume of CSO 18

4.2 Simulation of CSO Overflow Events 21

5. CONCLUSIONS 24

6. REFERENCES 25

1. Introduction

As part of Project ENVVEST, a subworking group of stakeholders was established in June 2000 to address the issue of fecal coliform (FC) contamination of shellfish beds in Dyes Inlet from Combined Sewer Overflow (CSO) events in the Port Washington Narrows. Participants in the working group included the Suquamish Tribe, Washington State Department of Health, City of Bremerton, Kitsap County, Puget Sound Naval Shipyard (PSNS), and the Space and Naval Warfare Systems Center San Diego (SSC-SD). The working group determined that shellfish beds in upper Dyes Inlet remained closed, in part, due to uncertainty about CSO overflows in the Port Washington Narrows. A modeling study was proposed to model "typical" CSO overflow events on an incoming tide. Key issues identified were the lack of knowledge on current and transport patterns in upper Dyes Inlet, the need for data on CSO events and discharge parameters, and other data needed to support the modeling approach. The Navy and Stakeholder Team planned and cooperatively executed a drogue and current meter study for Dyes Inlet in the fall of 2000. The CSO working group also identified the need to conduct a dye-release study to confirm and verify the model. In partnership with the City of Bremerton, Washington State Department of Health, Suquamish Tribe, Kitsap County SSWM, and the Bremerton-Kitsap Health District a dye-release study was conducted in March 2002 to provide data for model verification and confirmation.

This document presents the results of the study to model discharges from CSOs in the Port Washington Narrows in Sinclair and Dyes Inlets, WA and is an update of the draft report provided to the working group in Sept. 2003 (Wang et al. 2003). The ability to simulate FC fate and transport in the Inlets assisted in the reopening of 1500 acres of shellfish beds in Dyes Inlet (WDOH 2003a). The reopening came about because the City of Bremerton has nearly eliminated CSOs and the modeling study showed that FC released from CSO events mostly dissipates before reaching the shellfishing areas subject to the new classification (WDOH 2003b). The model is currently being used to support the development of a water clean up plan for the Sinclair/Dyes Inlet watershed to improve the environmental quality of the Sinclair and Dyes Inlet Watershed.

2. Background

2.1 Discharges from CSOs

One of the major point sources of pathogens into water bodies is discharge from combined sewer overflows (CSOs). In combined storm water and sewage systems, storm water is normally routed to and treated in wastewater treatment plants (WWTPs). When the wet weather flow exceeds the conveyance and storage capacity of the treatment system, a mix of storm water and raw sewage can overflow at storm water outfalls – usually into receiving waters. Raw sewage typically has a total coliform counts of 10^7 to 10^9 cfu/100 ml (colony-forming units – cfu/100 ml) so the total bacterial load and concentrations in CSOs may be quite high relative to environmental standards, ranging from 10^5 to 10^7 cfu/100 ml. Typically, municipal waste water treatment plants reduce total coliform counts to 10^4 to 10^6 cfu/100 ml (USEPA, 2001).

CSOs differ from other point sources of pathogens (e.g. waste water treatment plants) because the loading is derived from a relatively constant sewage load, mixed with episodic storm water of varying volume. As a result, the water body pathogen load can be less predictable. The amount of FC discharged will be dependent on the concentration of FC in the sewage, the storage capacity of the plant, rate of rainfall, and rate of treatment plant processing.

2.2 CH3D-FC Model Development

2.2.1 CH3D Model Description

The numerical model, CH3D, Curvilinear Hydrodynamics in Three Dimensions, was chosen to model Sinclair and Dyes Inlets. CH3D is a mathematical 3-dimensional time-varying hydrodynamic model, which was developed by the Waterways Experiment Station, ACOE, Vicksburg, MS, for the Chesapeake Bay study (Johnson et al. 1991). The Chesapeake Bay Program, established in 1983, aimed to develop strategies to reverse the decline of the quality of the Bay water. Over the past decade, CH3D, along with a water quality sub-model, was used to predict flow and transport in the Bay, providing a detailed assessment of the system's response to nutrient inputs and other parameters over time and space.

The governing equations in CH3D are the shallow-water equations transformed into the curvilinear plane. Several assumptions are made in the model formulation, including the hydrostatic (shallow water) approximation, the Boussinesq approximation, and incompressibility. As with any numerical model, the model domain is divided into many small numerical 3D grid cells. It is assumed that velocity and density are constant within each cell. Horizontal density gradients in the momentum equations are treated explicitly. Bottom shear stress is approximated using a Manning-Chezy formulation with Manning's n coefficient assigned as a function of local water depth. It is further assumed that the direction of bottom shear stress is exactly opposite to the depth-averaged velocity.

For transport of conservative solutes, a transport equation is solved for each conservative species, C_i. Solutes are assumed to be dilute, thus the solute transport equations are uncoupled

from hydrodynamics. Furthermore, the transport equation is solved at one time step behind the continuity and momentum equations, effectively uncoupling the transport equation (Wang and Richter 1999, Wang 2001). This approach is valid because baroclinic (density) forcing changes less rapidly than barotropic (static head pressure – tidal) forcing.

All variables in CH3D are defined on a staggered grid. Water surface elevation, salinity and solute concentrations are defined at the center of a grid stencil (i,j), while the *U* velocity is defined at (i+1/2, j), the *V* velocity at (i, j+1/2), and water depths at (i+1/2,j) and (i,j+1/2).

CH3D uses curvilinear boundary-fitted numerical grids in the horizontal plane. In Sinclair Inlet, the vertical direction – the water column, is divided into multiple layers of equal thickness, with the number of layers varying from over 10 layers for deeper regions to one layer for extremely shallow regions (depth < 3 meters, Figure 1). CH3D solves the time-dependent differential equations for water surface displacement ($\varsigma(x,y,t)$), and 3-D velocities ($u(x,y,z,t)$, $v(x,y,z,t)$), temperature, salinity and density. CH3D is capable of handling a variety of external forcing, including tides, winds, tributary flows, point and non-point sources, as well as baroclinic effect due to density differences between freshwater inflows and saline Inlet water. CH3D accounts for the wind field, which introduces shears over the water surface, driving water mass transport in addition to tidal forcing. Flows in the Inlet are driven at the model boundaries. The k-ε turbulence closure scheme is used to estimate the vertical diffusivity, a parameter governing the mixing in the water column.

We obtained historical tide data at Clam Bay and Brownsville from NOAA. These NOAA tide data were collected during early 1970s and were recorded in hard copy only, there is no background descriptions about how these data were collected. We analyzed these data and found that these tide data contained large phase errors. Therefore, these data were discarded and not used for our study. Instead, tides at Clam Bay and Brownsville were generated using the software TIDE1 (Micronautics, Inc., Rockport, ME), which is a commercial product capable of predicting tides at several locations inside Puget Sound, including Clam Bay and Brownsville. Generated tides were processed and harmonic constants of 16 major tidal constituents were extracted. The extracted tidal harmonic constants were modified to reproduce tides at the two model boundaries, Clam Bay and Brownsville (Wang and Richter 1999).

Using a grid-generation program, we generated curvilinear model grids with grid cells of different sizes, ranging from 40-100 meters inside the Inlet to over 200 meters in Port Orchard and Rich Passage (Figure 1). Model results based on such variable grid cells provide currents and contaminant transport with finer resolutions inside the Inlet. Resolutions, and thus model accuracy, outside the Inlet are sacrificed, due to the coarser grid cells in those areas. Model time-step is partially limited by the small grid cells inside Sinclair Inlet and a time step of 60 seconds was used in the model, which produces stable results over all the simulation periods.

While grid cells vary in the horizontal direction, grid size (Dz) in the vertical direction (water column) is fixed with Dz=3 meters. This depth resolution was chosen based on model experiment results and the fact that tidal amplitudes in the Inlet are large, reaching 2.8 meters during Spring tides. For Dz < 3, model runs would become unstable for periods of very low tides when surface grid cells become exposed. The grid size of 3 meters was chosen to always keep the surface layers wet even during the lowest Spring tides

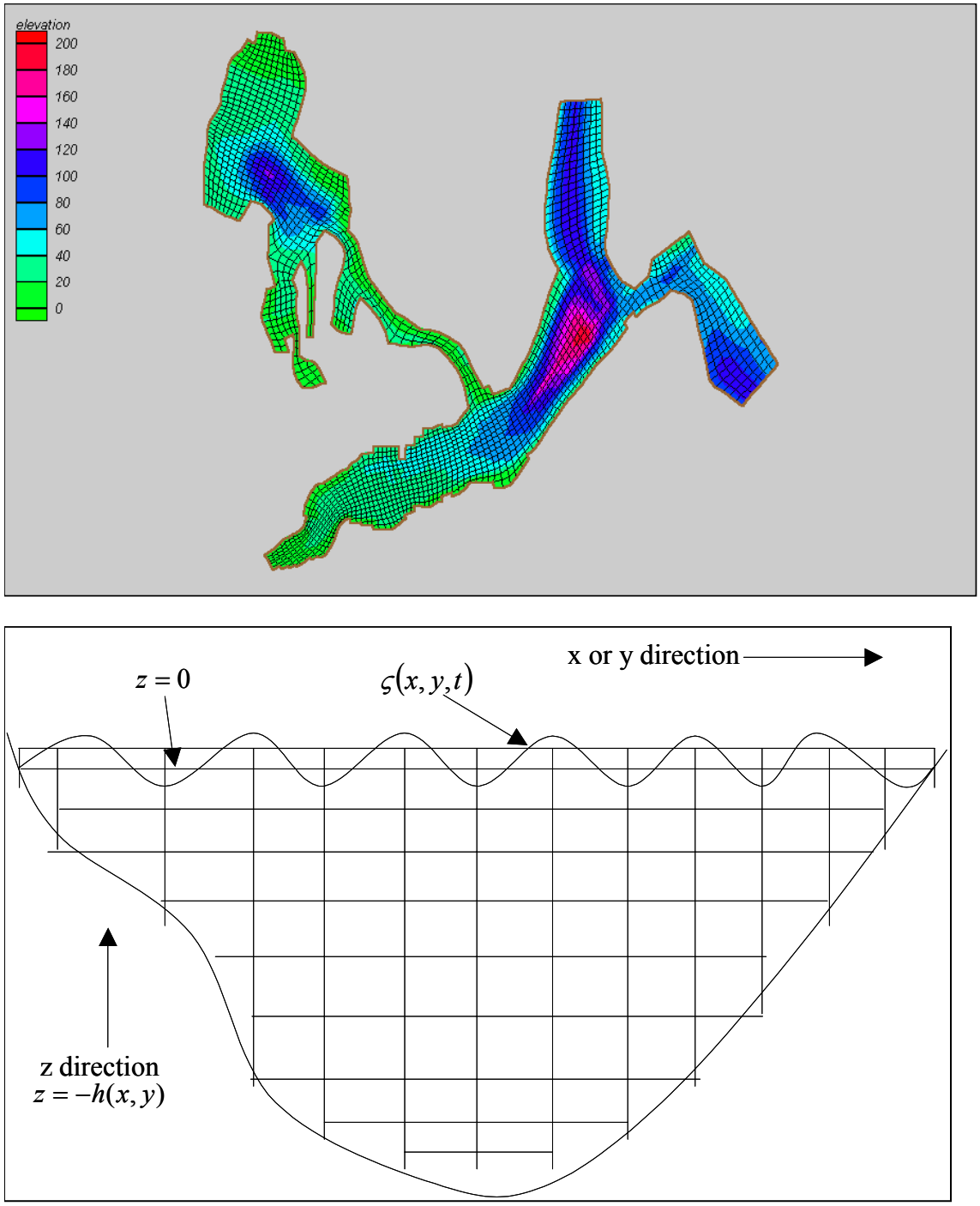


Figure. 1. Numerical grid for CH3D model of Sinclair and Dyes Inlets (upper), three-dimensional grids are added for increasing depth in the z-direction (lower).

CH3D was set up to simulate tides and currents measured with Acoustic Doppler Current Profilers (ADCPs) deployed in Sinclair Inlet by the USGS during February-April and July-August, 1994 (Ralph T. Cheng, USGS, Menlo Park, CA, personal communication). Model results were compared with the measured data for the first period (February-April) for model calibration. Field data of July-August were used for model verification. The calibrated CH3D provides flow transport (currents) for contaminants entering into the Inlet from the multiple external sources. (See Richter 2004 for details of model calibration and verification for current predictions in Sinclair Inlet and Port Washington Narrows).

2.2.2 Fecal Coliform Transport Module

Mancini (1978) described the kinetics of FC fate in the marine environment. Derived from comprehensive datasets, the Mancini equation is an empirical formula that correlates FC death rate with salinity, temperature and light. A module to simulate fecal coliform (FC) die off as a function of salinity, temperature, mixing depth and sunlight (Mancini Equation) was added to the CH3D model code to create CH3D-FC:

$$C_t = C_0 e^{-kt}$$

Where:

C_t = surviving concentration C_0 = initial concentration t = time *k* = bacterial death rate = $[0.8+.006(S)1.07(T-20)+I/K_E H[1-e-(K_E H)]$

and S = % seawater

I = incident radiation in Langleys T = Temperature ^oC

K_E = light extinction coefficient of PAR H = mixing depth

The mixing depth (H) of the water column, the light extinction coefficient (K_E) averaged over 400 nm to 700 nm wavelength (photosynthetically active radiation or PAR), and the incident light levels a the water surface are most important in this equation. The mixing depth of the water column can be estimated by measuring and modeling the water density profile. The light extinction coefficient of PAR can be estimated by measuring the secchi disk depth (a white and black disk lowered in the water column to a depth where it disappears from site) as:

$$K_E=(0.757/\text{secchi depth})+0.07 \quad \text{where depth is in meters}$$

A further modification can be employed to estimate the extinction coefficient of blue light as a proxy for ultraviolet radiation from K_E that can be substituted as a more conservative value for K_E (Bukata et al. 1988):

$$K_{blue}=1.3K_E-0.05$$

The Mancini equation has been incorporated into many pathogen fate models and appears to hold for *Enterococcus* die-off rates as well (USEPA 2001; SCCWRP 2002). Estimates of solar radiation, in Langleys, were based on average values for Seattle, WA (obtained from http://rredc.nrel.gov/solar/pubs/SBF/b.html).

Salinity, temperature and secchi disk data collected in Sinclair and Dyes Inlets by Washington's Department of Ecology from 1990 to 1995 (Figure 2) were combined with 30 year average, monthly mean irradiance values to evaluate their effect on the range of likely *k* values.

The effect on bacterial die-off as a function of temperature, salinity, secchi disk depth, and solar radiation is shown in Figure 3. The greatest effect on bacterial die-off, for the range of values expected for Sinclair and Dyes Inlets was for solar radiation.

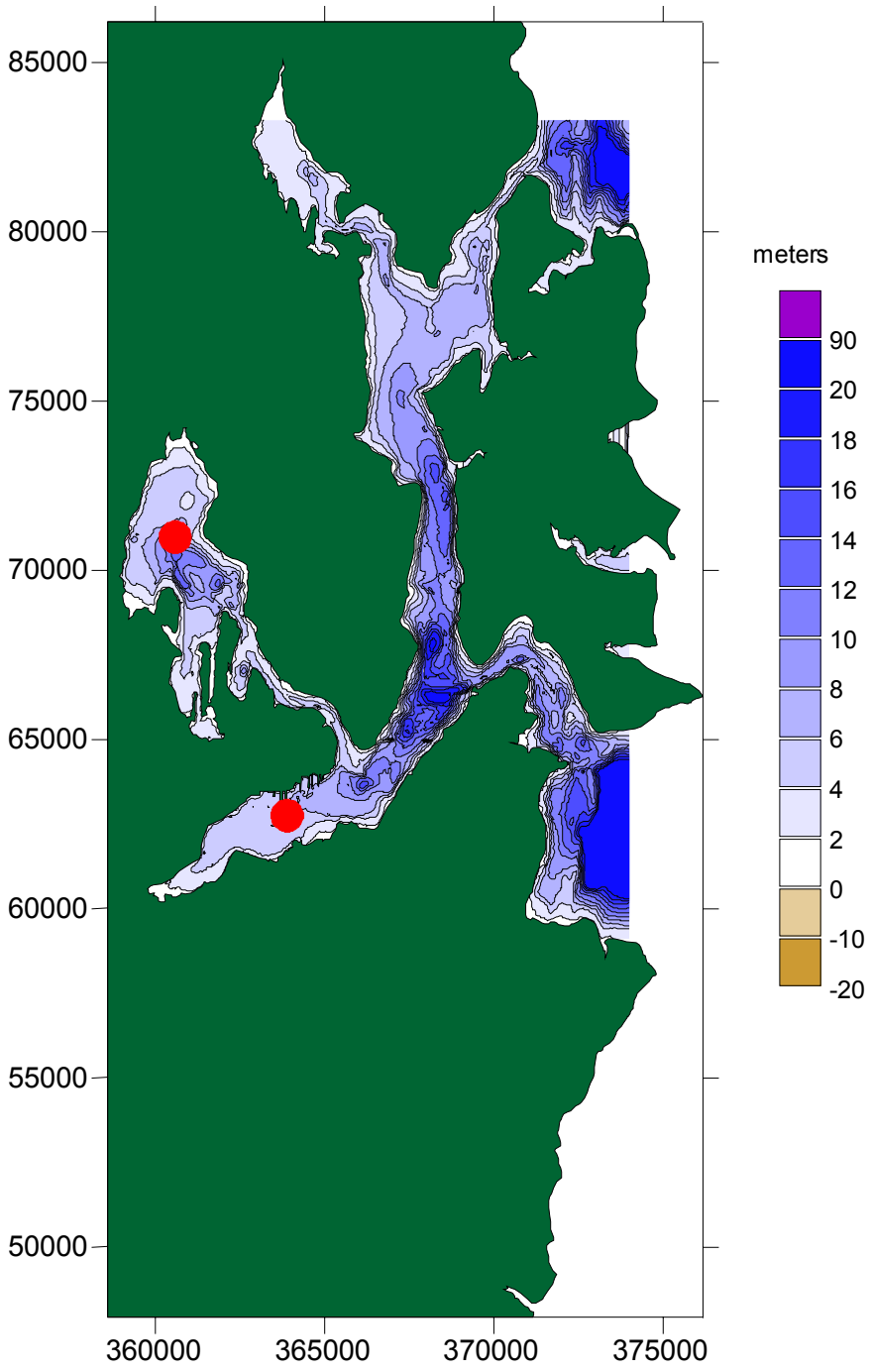


Figure 2. Bathymetry of the study area and the location of DOE's monitoring stations for monthly surveys from 1990-1995 of temperature, salinity and secchi disk depths.

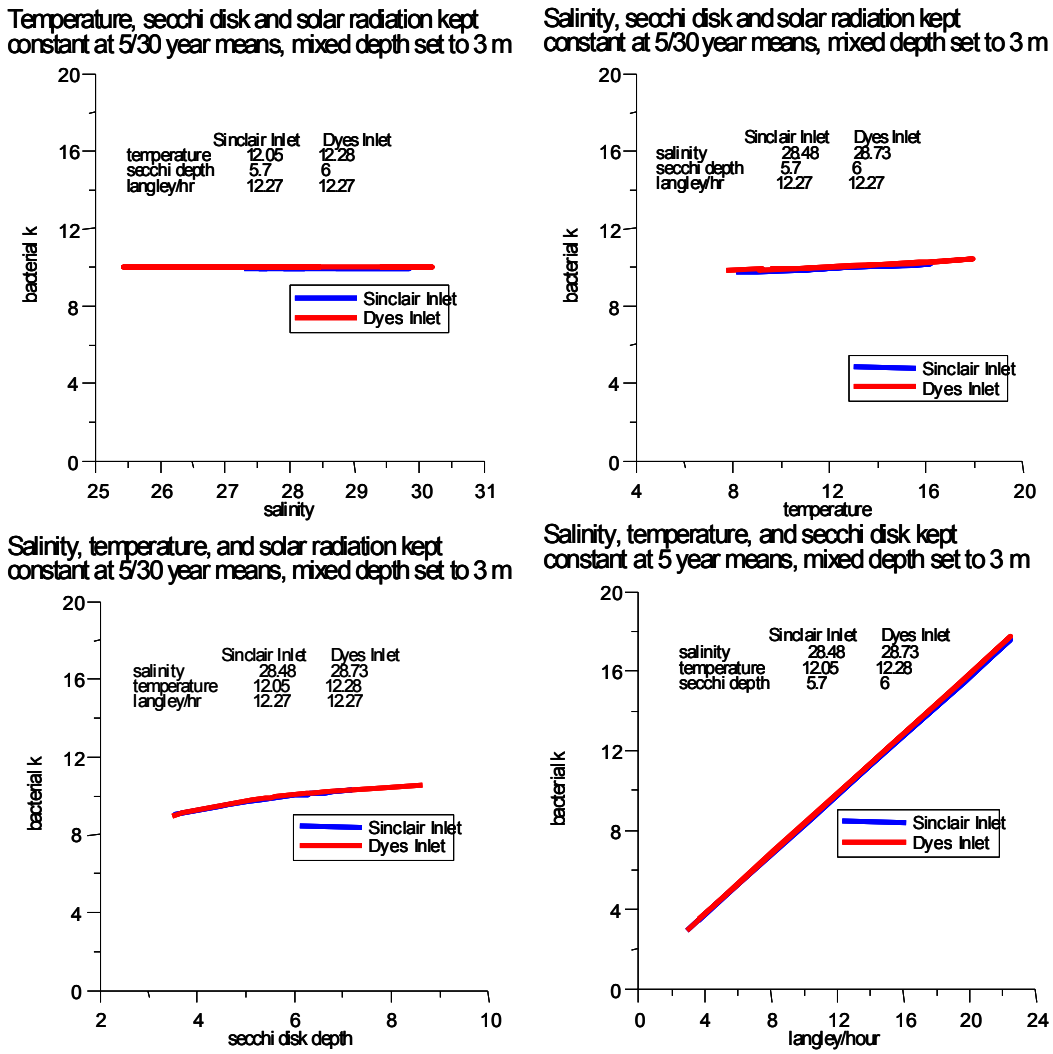


Figure 3. The effect of salinity, temperature, secchi disk depth, and solar radiation on FC bacterial die-off rate (bacterial k).

The seasonal variation in FC die-off rate in the Inlets for depths of 1 m to 10 m shows that the lowest *k* values occur in the winter months (Figure 4). Lower *k* values increase the time, in days, to reach 90% of bacteria extinction (Figure 5). Water quality of the receiving waters will be dependent on the bacterial load being discharged from storm water, streams, WWTPs, and CSOs, the rate of mixing into the water column, and the extinction rate of the bacteria. Sunlight (incident radiation) and water clarity are the two most important variables controlling FC die-off in the receiving waters of the Inlets.

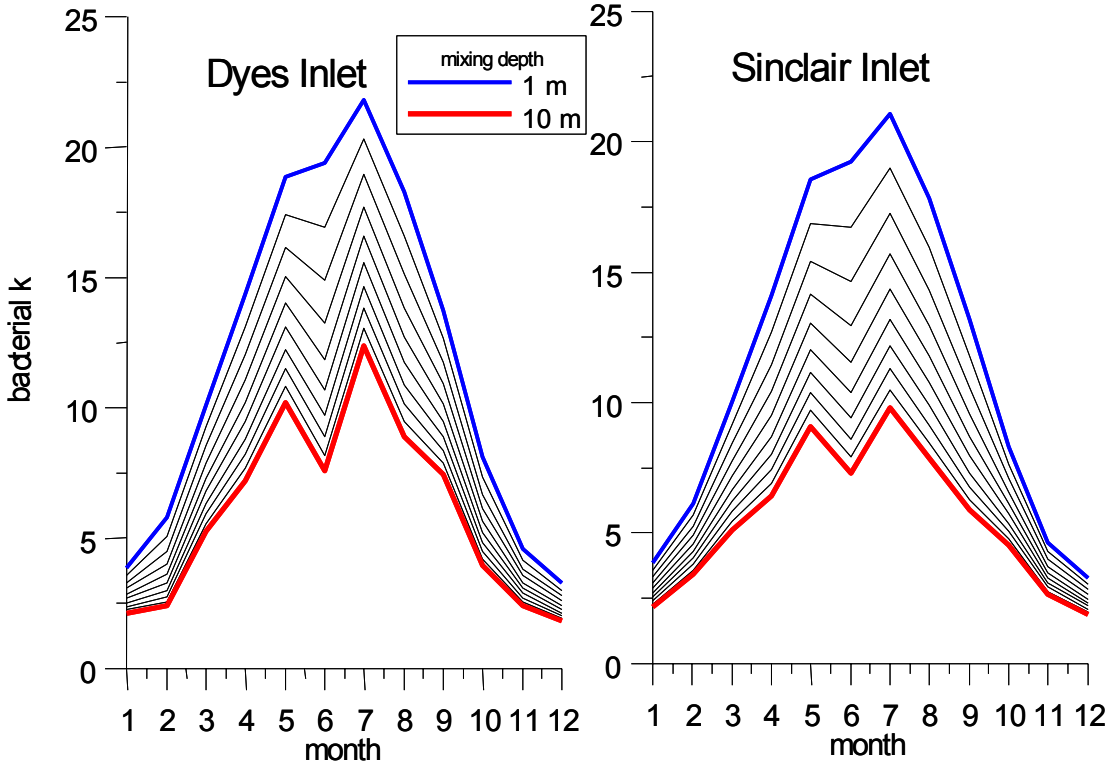


Figure 4. Seasonal variation of FC bacteria die-off rate (bacterial *k*) in Sinclair and Dyes Inlets for depths of 1 m to 10 m.

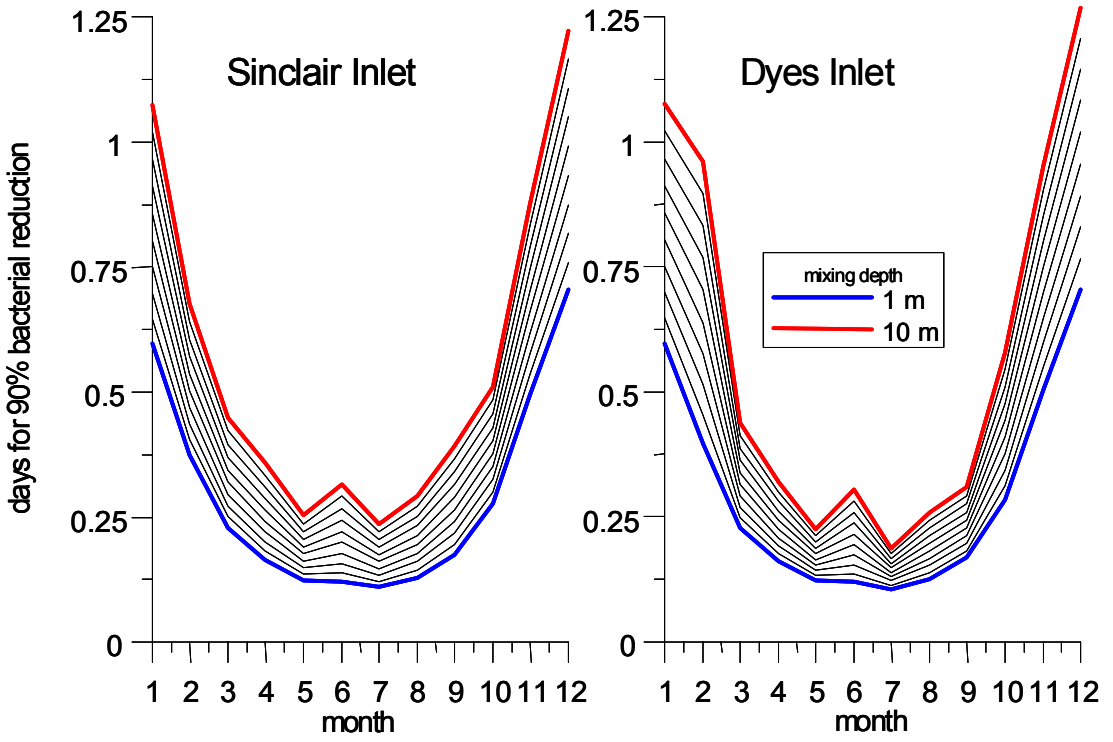


Figure 5. Seasonal variation in number of days required to reduce FC concentration by 90% for depths of 1 m to 10 m in Sinclair and Dyes Inlets, WA.

3. Results of Field Studies

3.1 Drogue and Current Meter Study

The CSO subworking group identified the lack of knowledge on current and transport patterns in Upper Dyes Inlet as key issues that would have to be addressed before any decision could be made to open shellfish beds in Dyes Inlet. Therefore, the participants cooperatively executed a drogue and current meter study to provided data to address key issues for the CSO modeling study (DOH 2000). A drogue study is a very effective means of determining discharge trajectories and dispersion dynamics of simulated CSO event(s). Moreover, improvements and refinements to the model obtained from the data obtained during the study improved the modeling capability for Sinclair Inlet as well.

The drogue and current meter study was completed in fall 2000. A series of drogue releases at the start of incoming tide were conducted in the Port Washington Narrows (Oct. 23, 2000), at Rocky Point (Oct. 20, 2000), in Ostrich Bay (Oct. 13, 2000), and adjacent to Windy Point (Oct. 24, 2000) in Northern Dyes Inlet (see Drogue Study Overview Page). ADCP current meters were deployed from Oct. 12 to Nov. 14, 2000 at the mouth of Dyes Inlet near Rocky Point and in the northern portion of Dyes Inlet near Windy Point to measure vertical profiles of current from the bottom to the surface of the water column. Additionally, two S4 current meters were deployed in Ostrich Bay to measure currents at a fixed depth (see Drogue Study Overview Page). Data from current meter and drogues were used to calibrate the CH3D model for Dyes Inlet.

Hydrodynamics in Dyes Inlet are complicated, encompassing multiple, yet unique, hydrodynamic phenomena. These observed phenomena include jet plumes, local vortices, wind-driven and tide-driven circulations. To understand and quantify transport in Dyes Inlet, four drogue release studies were conducted. For each study, surface drogues were released during flood tides. Each drogue had a Global Positioning System (GPS) device onboard. After the drogues were retrieved within 1-6 hours, the GPS data were downloaded to a PC and the trajectories of the drogues were obtained. Trajectory data were compared with the predicted results from the 3-D hydrodynamic model, CH3D. Local winds and tides were included in analysis and their effects on the drogue drifts were quantified. After developing a higher resolution CH3D grid for Dyes Inlet (Figure 6) the model was able to reproduce the ADCP current velocities (Figure 7) and drogue trajectories (Figure 8 and 9) with acceptable accuracy. To view animations of the drogue tracks and obtain more information about the drogue study please see the Drogue Study Overview Page.

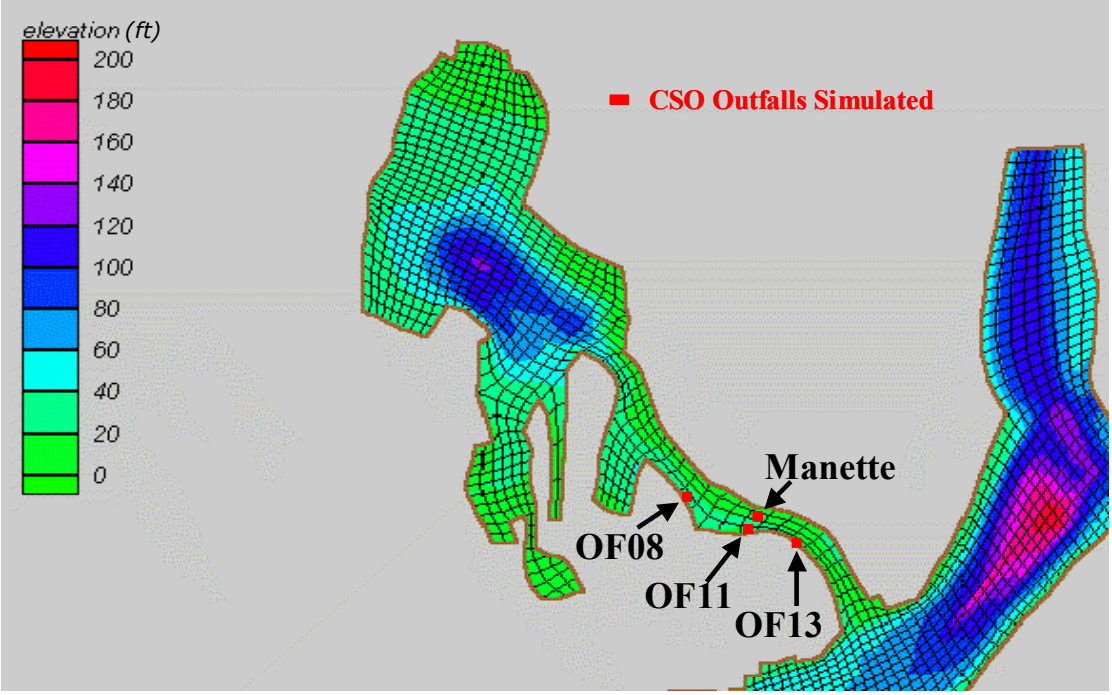


Figure 6. Refined CH3D grid for Dyes Inlet with higher resolution grids and the location of CSO outfalls (OF).

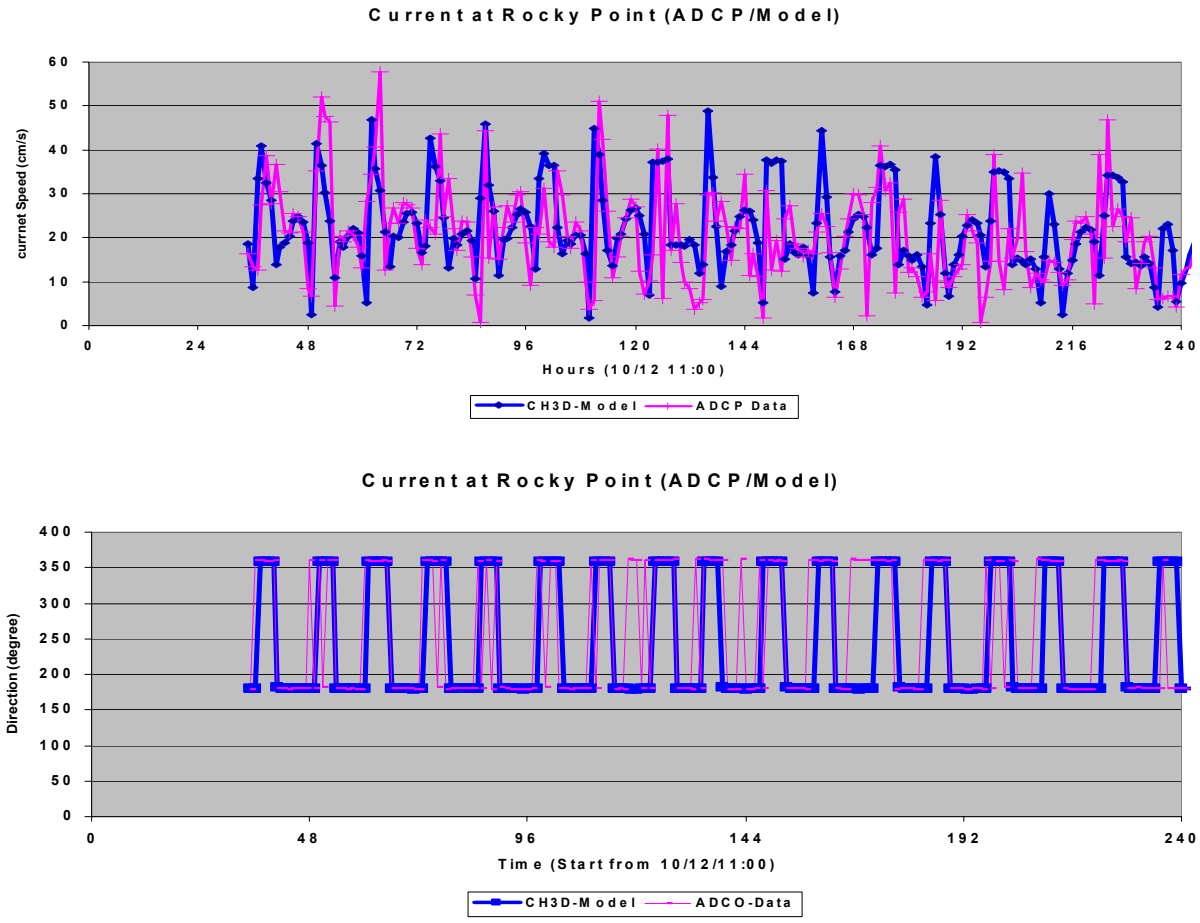


Figure 7. Comparison between predicted and measured currents in Dyes Inlet.

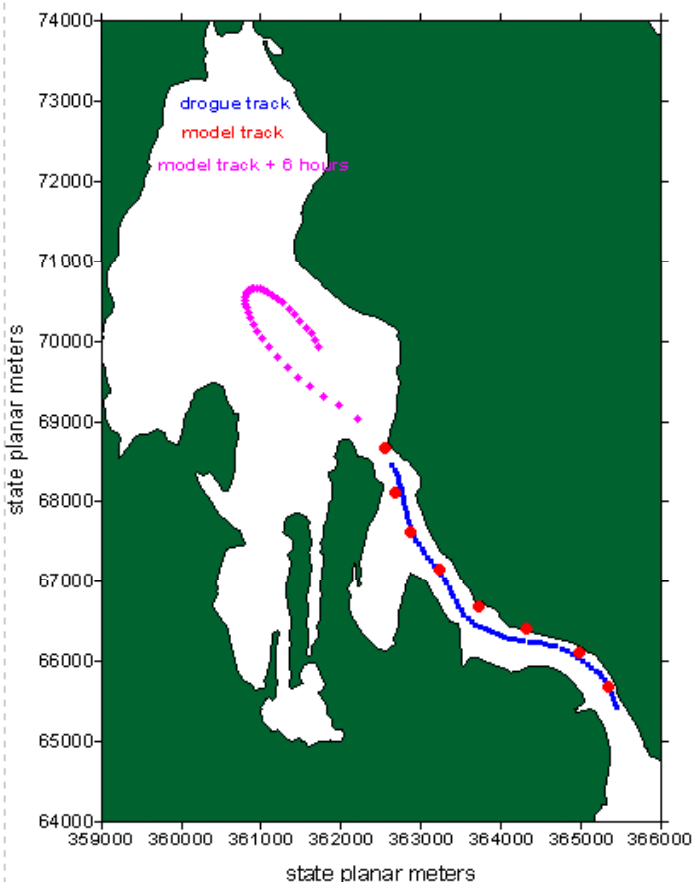


Figure 8. Observed, modeled, and predicted drogue tracks for Port Washington Narrows.

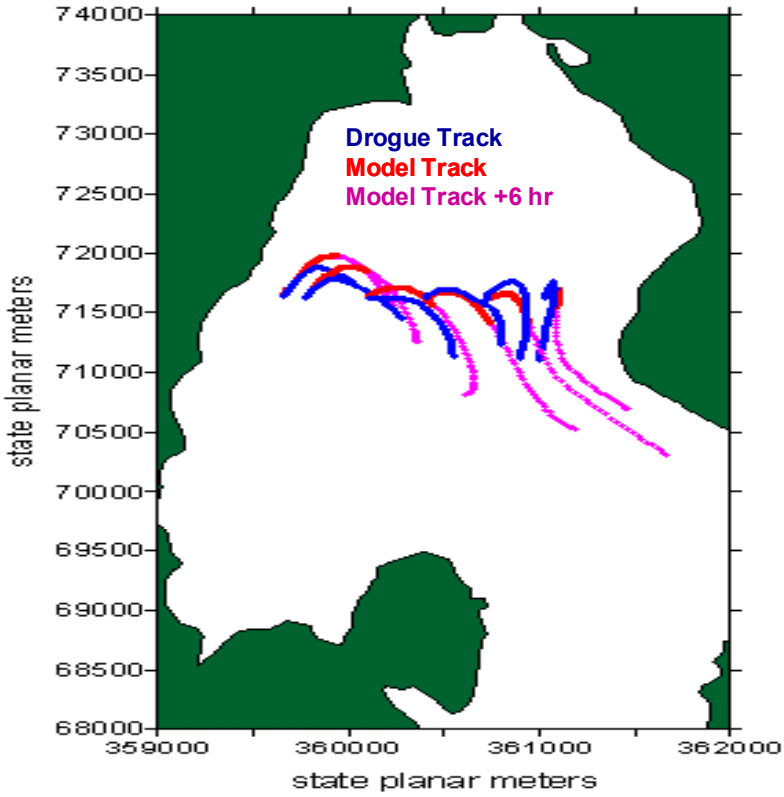


Figure 9. Observed, modeled, and predicted drogue tracks for Windy Point.

3.2 Dye Release Study

The dye release study was conducted to simulate a CSO discharge event in the Port Washington Narrows on the incoming tide. The data collected during the dye release study provided physical and chemical data sets for validating model performance and developed data on ambient concentrations of fecal coliform and selected contaminants in the estuary (Project ENVVEST 2001). The dye study was conducted during the "wet" season on March 12, 2002. The "wet" period was defined as the condition when enough rainfall has fallen to thoroughly saturate soils and streams in the surrounding watershed are running at high levels. This represents the conditions that CSO events are most likely to occur. Another consideration was to conduct the dye study after construction of the new Eastside Treatment Facility (ETF) was completed (Dec 2000) and brought on line (Jan 2001).

On March 6 2002, prior to the dye injection, an ADCP was deployed at the mouth of Dyes Inlet at Rocky Point. On May 12, 2002 dye injection began at the beginning of a flood tide and continued until slack tide from the ETF outfall in the center of the Port Washington Narrows (Figure 10, 11). Drogues were periodically deployed at the injection point to mark the plume while "Vessel A" tracked the plume up the Port Washington Narrows and "Vessel B" conducted continuous transects across the mouth of Dyes Inlet at Rocky Point. Both vessels were outfitted with real-time monitoring equipment and positioning systems (GPS) to continuously record the boat position, dye concentration, temperature, salinity, dissolved oxygen, turbidity, and pH. Because the model simulates the whole Sinclair-Port Washington Narrows-Dyes Inlet system, the plume movement measured both up the Port Washington Narrows to Dyes Inlet and down the Narrows to Sinclair Inlet was equally valid for obtaining scientifically defensible data for model confirmation and validation.

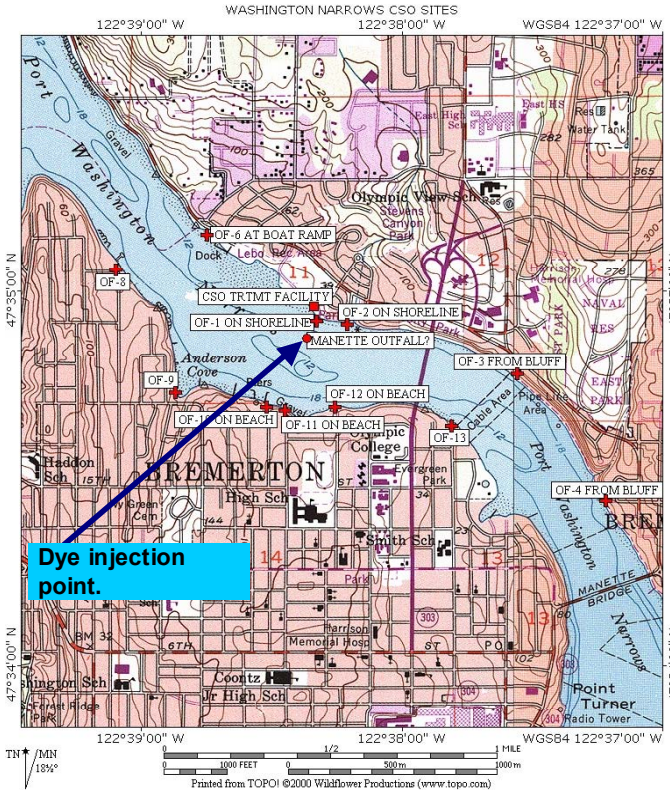


Figure 10. Location of dye injection point in the Port Washington Narrows.

Figure 11. Dye injection study in Port Washington Narrows, clockwise from top left, mixing Rhodamine dye, initiating injection, metering dye into outfall, and tracking plume with vessel.

The plume was tracked for about 8 hrs (until nightfall). "Vessel A" followed the plume up the Narrows and into Dyes Inlet (Figure 12) while "Vessel B" remained at Rocky Point conducting transects across the mouth of Dyes Inlet (Figure 13). Current speeds were obtained from the ADCP moored in the mouth of Dyes Inlet at Rock Point (Figure 14). Model predictions showed good agreement with the observed data.

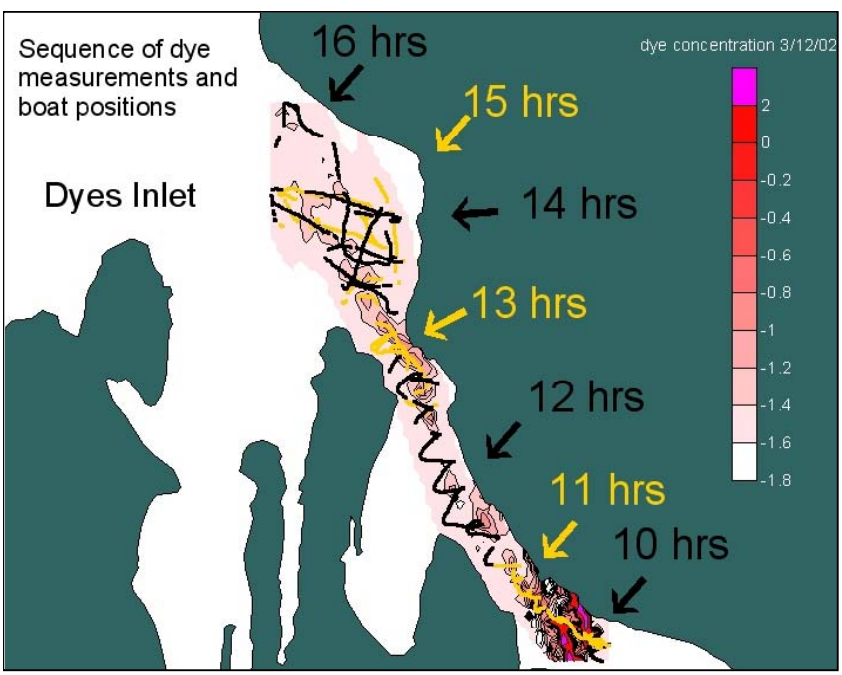


Figure 12. Observation of dye plume made by "Vessel A" transiting the Narrows.

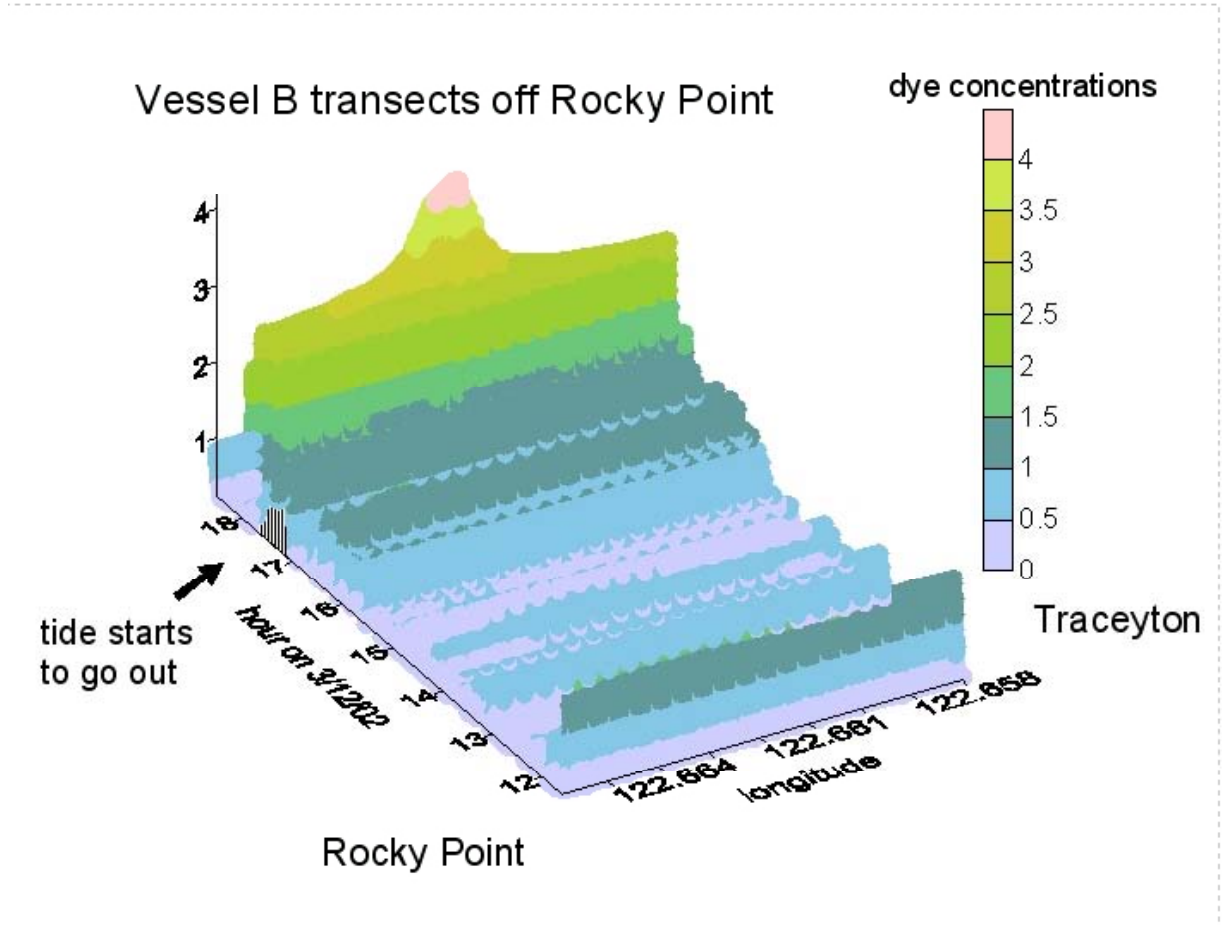


Figure 13. Observations of dye concentrations measured across the mouth of Dyes Inlet by "Vessel B".

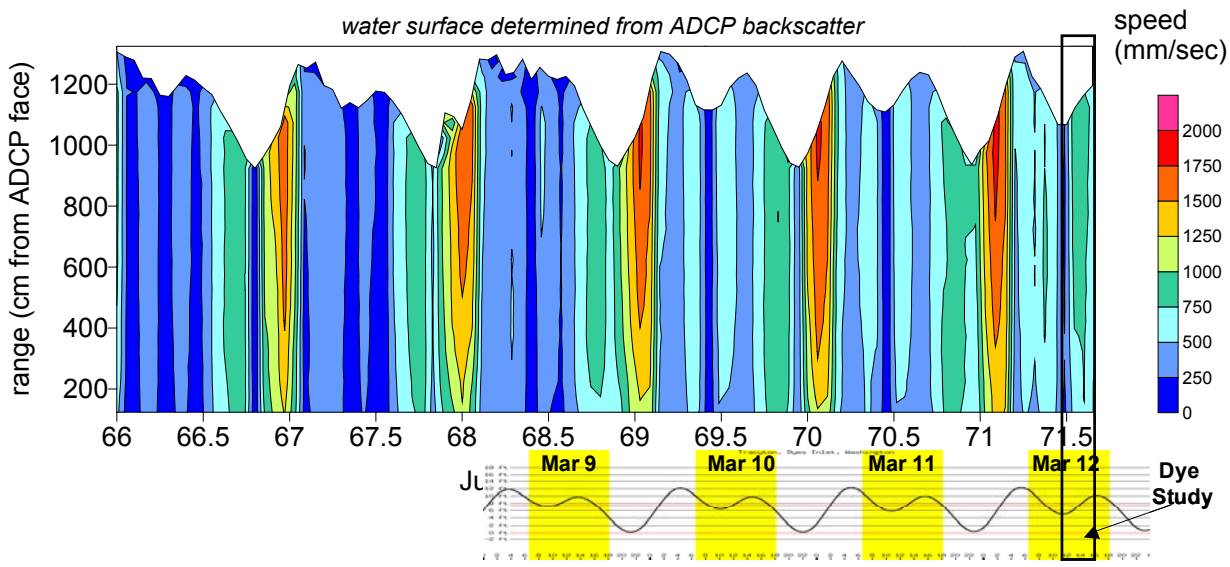


Figure 14. Observations of current speeds made at the mouth of Dyes Inlet.

4. CSO Simulation Scenario

4.1 Calculating Volume of CSO

The volume of water discharged during a (24 hr) CSO event can be calculated as:

CSO_V = (Rainfall × TIA)F – **TV**

Where

CSO_V = volume of CSO in gallons
Rainfall = inches of rain during storm event
TIA = total impervious area of the contributing watershed
F = the fraction of total rainfall volume that runs off the watershed into the combined system
TV = apparent threshold flow value of treatment plant capacity

Based on the equation above, it was assumed that CSO flows occur when storm water inflow rate exceeds the threshold value (**TV**) of the treatment plant, that the total runoff to the treatment plant is composed of treated water plus the overflow volume (CSO_V), that only a fraction (F) of the water falling on the surface of the catchment area goes into the combined system, and that F is proportional to the impervious area within the catchment area. Data from CSO events measured on Jan 6 and Jan 7, 2002 were used to estimate F and **TV** and it was further assumed that the CSO flows and rainfall data measured on those days were accurate and consistent representations of "typical" overflow events. The TIA was obtained from geographic information system (GIS) analysis of the catchment areas within the City of Bremerton that contributed to the overflow events on Jan 6 and 7, 2002 (Figure 15). The two events provided two equations with two unknowns:

[1] Jan 6: 24,120 gal = (1.78 in x 3.64 km^2)F - **TV**

[2] Jan 7: 2,700,120 gal = (3.37 in x 3.64 km^2)F – **TV**

The **TV** was estimated using empirical data from the Jan 6 and Jan 7, 2002 storm events as 613,782 gal/15 min. Inserting the estimated **TV** into Eqs. [1] and [2], the Runoff Fraction was calculated as

F = 0.3667 for Jan 6, 2002 and F = 0.3654 for Jan 7, 2002

The average (F= 0.366) was used to calculate the volumes of overflow from two storm events: a two-year storm that occurred on Nov. 28, 1998 (2.7 inches, Nov. 98); and a five-year storm that occurred on March 17, 1997 (3.48 inches, Mar. 97). The subworking group selected these storms as "typical" storms that could generate CSO events. The runoff volume was predicted for the "current system" configuration in place during the storm events of Jan 6-7, 2002, which was considered to represent 80% of the anticipated improvements in the City's storm water system. Future conditions, when 100% of the system improvements are completed, were estimated as a 125% improvement in the treatment capacity of the "current system" (Table 1). Owing to the greater storm intensity, the Nov. 98 (2-yr) storm generated more overflow than the Mar. 97 (5-yr) storm (Figure 16).

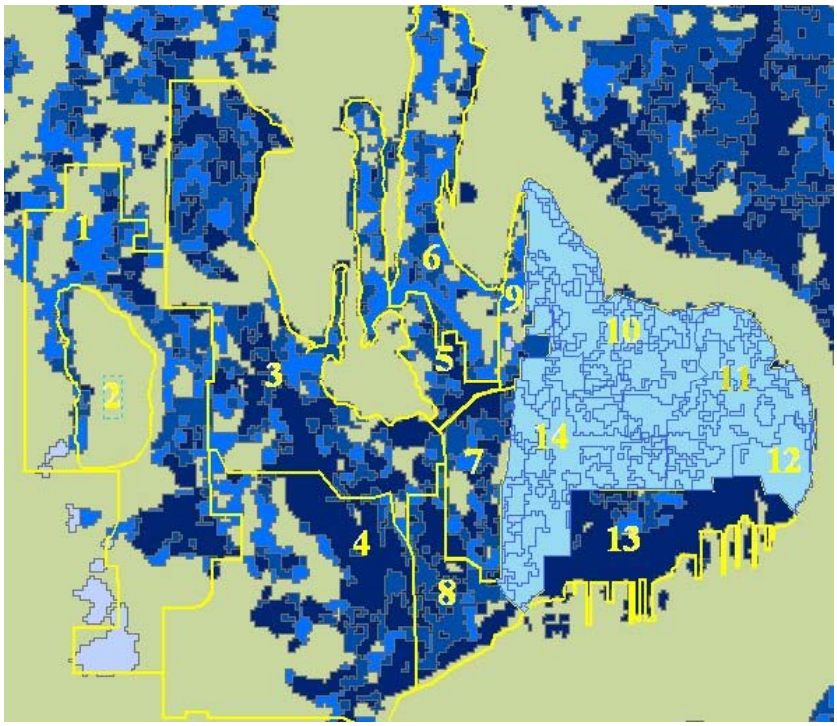


Figure 15. Impervious area within the catch basins (blue areas within basins 1, 2, 3, 4, 5, 6, 7. and 13) contributing to the overflows that occurred on Jan. 6 – 7, 2002.

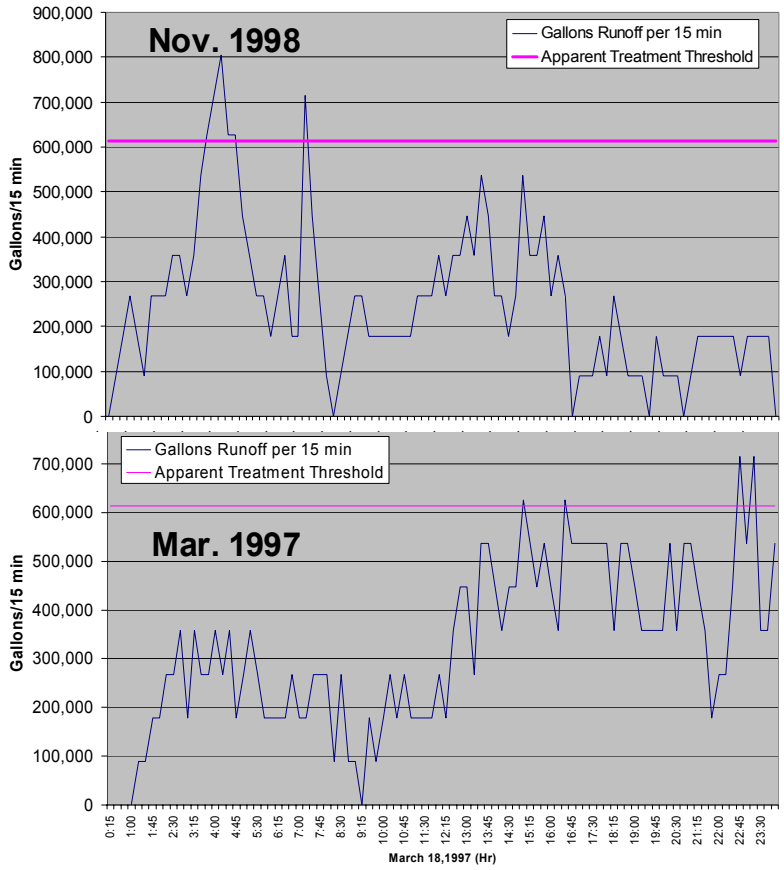


Figure 16. Apparent treatment threshold and predicted overflow volumes for the Nov. 28, 1998 and March 17, 1997 storm events.

Table 1. Predicted overflow volumes for current and future systems.

Storm Event	Current System 80% Capacity	Future System Full Design 100% Capacity
Nov 98 Storm (2 yr Storm)	429,900 gallons/day	37,400 gallons/day
Mar 97 Storm (5 yr Strom)	227,000 gallons/day	0 gallons/day

The calculated runoff fraction (*F*) was similar between Jan 6 and 7, 2001 implying that *F* was independent of the storm intensity. However, when the relationship was used to predict CSO volumes for a storm event that occurred on Jan 2, 2003 (1.7 in of rain), the CSO volumes were over predicted. This is because rain rate of 0.26 in/15 min far exceeded the empirical data used to develop the relationship. Nevertheless, there was good agreement with storm events where the rainfall rate was within the empirical range (Figure 17). Based on the calculations above, the total amount of storm water that goes to the treatment plant is about 24-32 MGD, which agrees with the capacity of the WWTP (M. Mecham, City of Bremerton, personal communication).

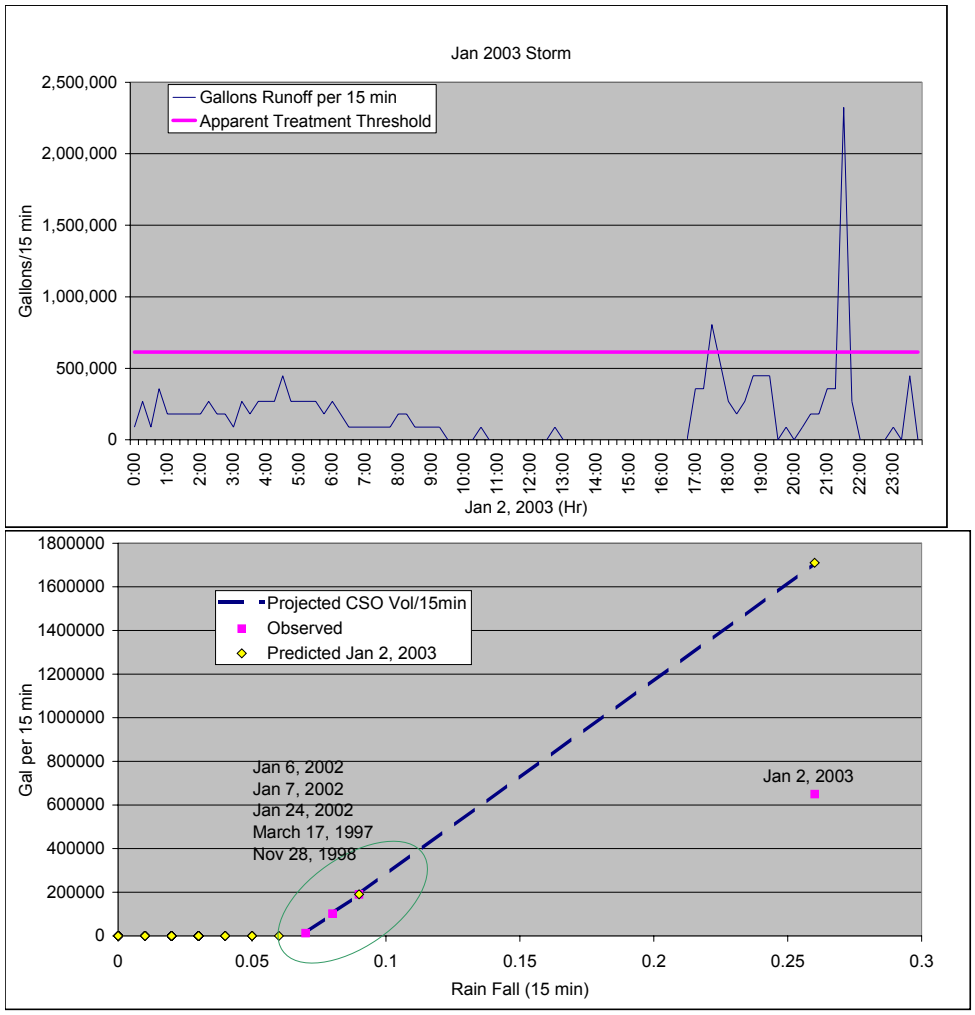


Figure 17. The predicted overflow volumes for the Jan 2, 2002 storm (upper figure) and a comparison between rainfall rate and predicted overflows showing that with the "current system" overflows are likely to occur when rainfall exceeds 0.75 in/15 min (lower figure).

4.2 Simulation of CSO Overflow Events

The model was set up to simulate overflow events in the Port Washington Narrows by programming the model to simulate a reoccurring strong tide with winter (Jan.) solar radiation, temperature, and mixing depth. CSO discharges were simulated as a constant discharge over a 24 or 6-hr period and the discharge concentration was set to 10^6 cfu/100 ml (raw sewage). The 24-hr discharge was simulated from 31 h to 55 h and the 6-hr discharge was simulated from 37 h to 49 h with max flood occurring at 43 h. This assured that maximum flooding would occur at night when there is no die-off of FC due to sunlight (Figure 18). Overflows from all CSOs were combined and discharged from outfall 11 (OF-11), the closest outfall to Dyes Inlet where CSOs are likely to occur. Time series from selected model nodes (Figure 19) for the surface, water column-average, and water column-maximum FC concentrations, animations of the surface and water column-average FC concentrations, and the domain-exceeded were generated for each scenario simulated. The criterion was set to the shellfish standard of 14 cfu/100 ml and values exceeding the standard were color coded as red. The domain exceeded displayed the nodes in the model that exceeded the standard at any time or depth during the simulation.

Four simulations were conducted for the "current system" (scenario #1, #2, #3, and #4) where the overflow discharged from OF-11, the storm events were for Mar. 97 and Nov. 98, and the discharge was over 24 or 6 hours (see CSO SIMULATION SCENARIOS Page). Because the results of the model could be scaled, the animation and domain exceeded were redisplayed by increasing the standard to 140 cfu/100 ml. This has the same effect as reducing the discharge concentration by a factor of 10 to 10^5 cfu/100 ml. Discharges from the ETF (scenario #5 and #6) were simulated assuming that the plant was operating at maximum capacity of 7000 gal/min with a failure of the uV disinfection system resulting in a discharge concentration of 10^5 cfu/100 ml. Future conditions were simulated (scenario #7 and #8) assuming that the "current system" was improved by 125% (see CSO SIMULATION SCENARIOS Page).

Sensitivity analysis was conducted by selecting scenario #3 as the base condition and rerunning the simulation by changing the following (see CSO SIMULATION SCENARIOS Page page):

#9 Wind – Constant wind 5 m/s (11.3 mph) from SW
#10 Turbidity – Decreased secchi depth by 50%
#11 Sunlight – Decreased sunlight intensity by 50%
#12 Fresh water inflow – Turn on annual mean flow from 10 major streams (Barker, Clear, Stawberry, Chico, Gorst, Anderson, Blackjack, Olny, Beaver, and Dee Creeks).
#13 No fecal coliform die-off – FC were treated like a conservative substance

Removing FC die-off had the greatest effect on FC concentrations followed by sunlight and freshwater inflow. The model was also used to simulate a sewage spill that occurred in Sinclair Inlet in July 2002 (scenario #14). The spill was simulated as follows: 280,000 gals were discharged for one week starting 1200 Tuesday July 16, 2002; equal amounts of the spill were discharged on the surface from two outfalls ST28 (84" outfall) and CSO 17 (54" outfall); the initial fecal coliform concentration was assumed to be 10^6 cfu/100ml; sun light intensity was set equal to 30-year daily mean for July in the Seattle area; and the light extinction coefficient was set to the average for Sinclair Inlet (see CSO SIMULATION SCENARIOS Page). The simulation showed good agreement with the two samples collected in ambient waters following the spill (Figure 20).

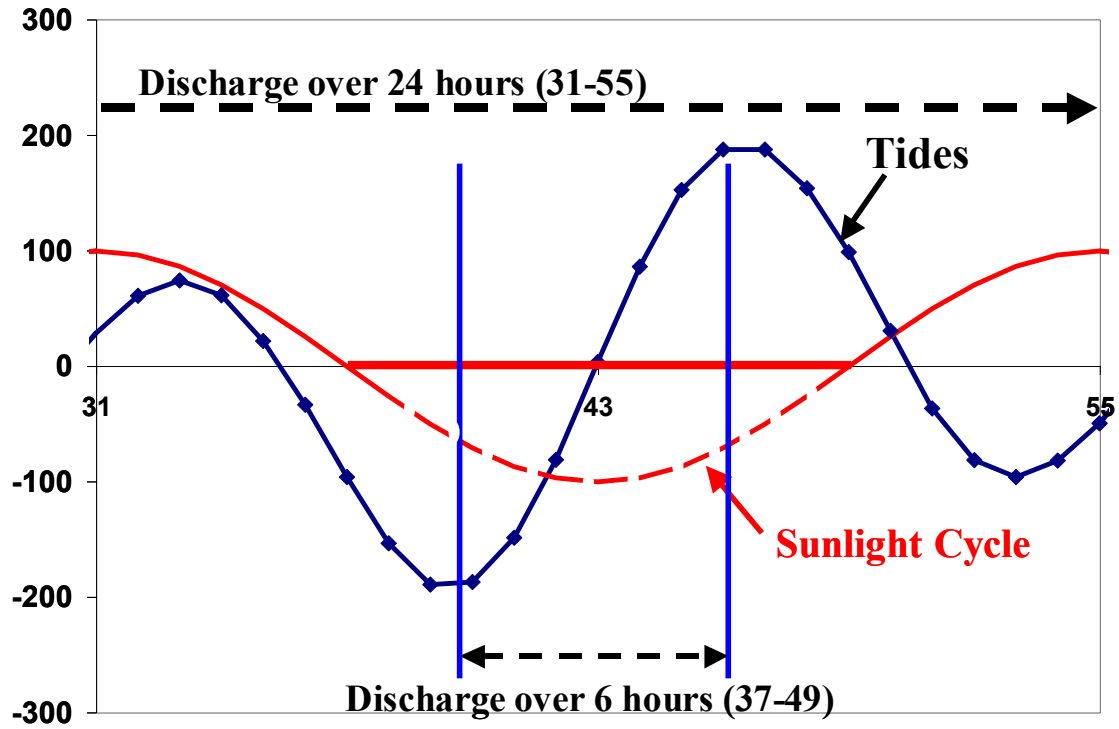


Figure 18. Tidal and sunlight conditions simulated for 24 and 6 hour discharges.

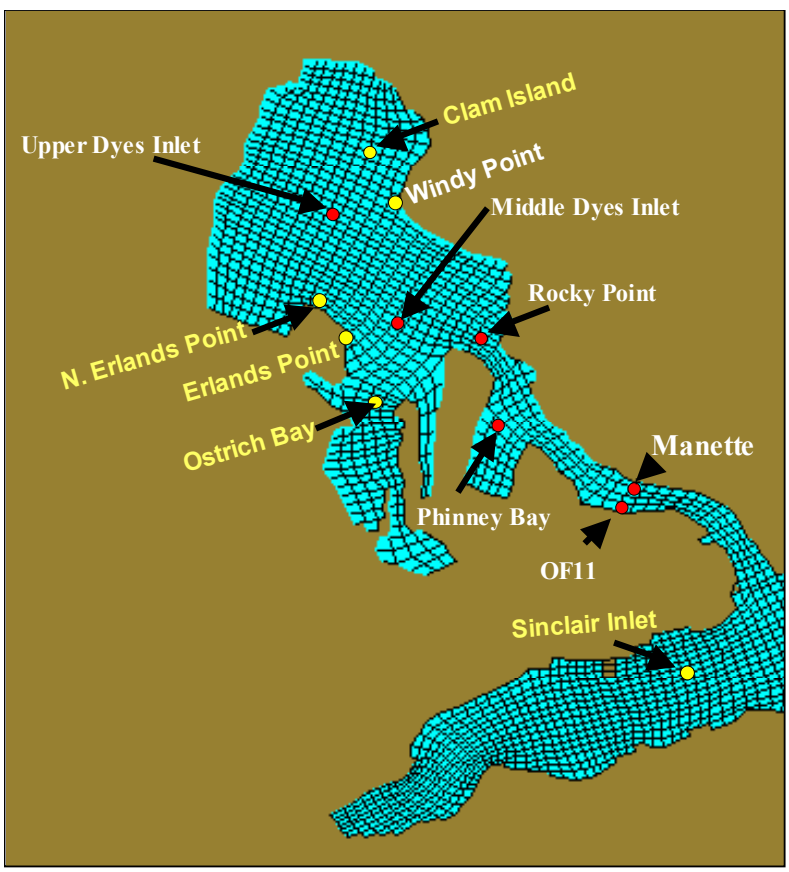


Figure 19. Locations of model nodes for obtaining time series of model results.

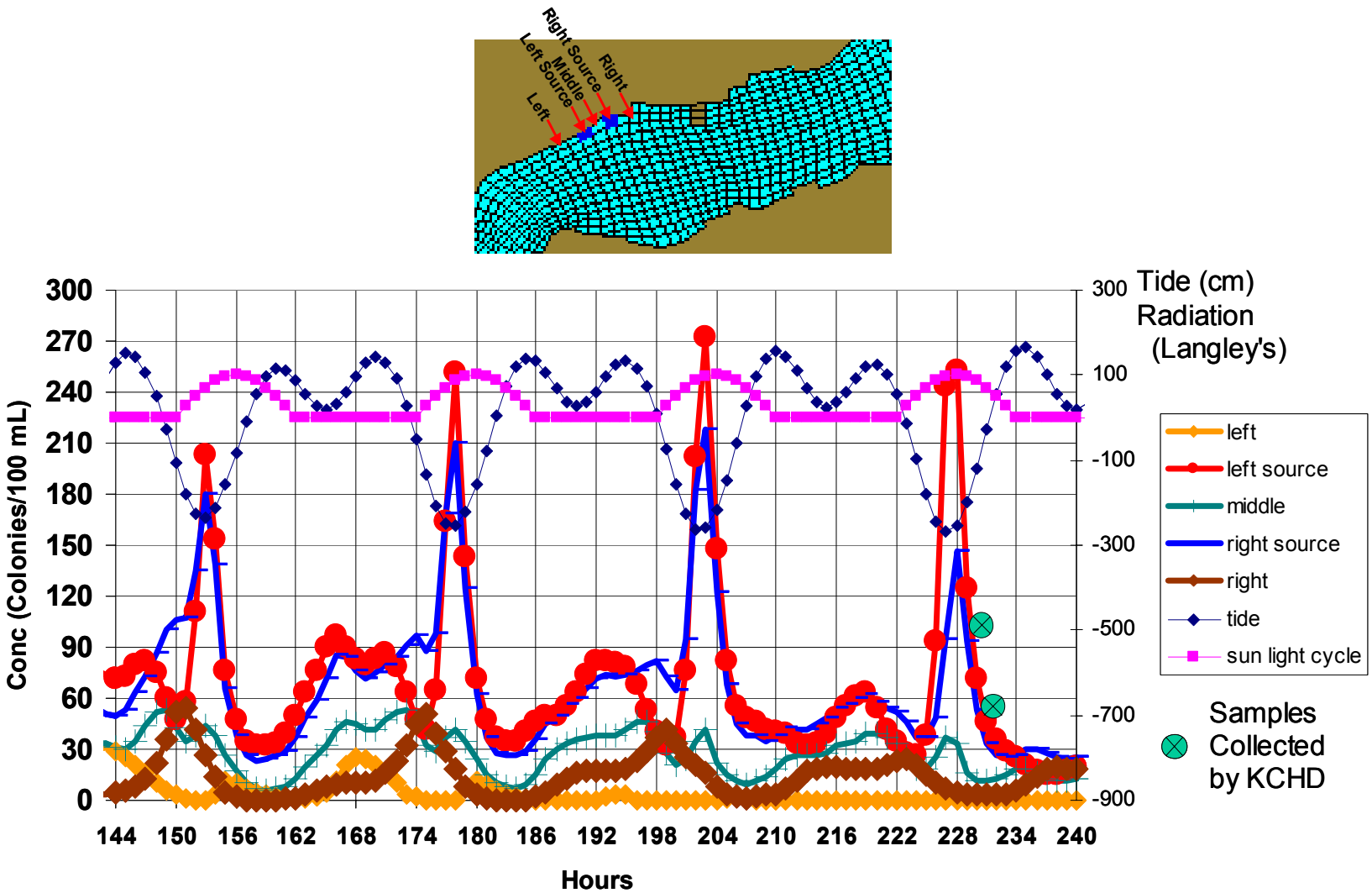


Figure 20. Simulation data from the July 2002 sewage spill in Sinclair Inlet showing simulated FC concentration and results of two samples collected following the spill.

5. Conclusions

This report documents the calibration and verification of CH3D-FC to simulate FC transport (Mancini's Equ) in Sinclair and Dyes Inlets. An empirical approach used to estimate "typical" CSO volumes and historical storm events (Nov '98 and Mar '97) were used to simulate overflow conditions. The sensitivity analysis showed that FC persistence is controlled by dispersion and decay from sunlight. Because FC concentrations predicted by model are based on conservative assumptions, it is highly unlikely that the model underpredicted potential FC concentrations. The simulation of the July 2002 spill in Sinclair Inlet showed good agreement with the two samples collected in ambient waters following the spill.

The ability to simulate FC fate and transport in the Inlets assisted in the reopening of 1500 acres of shellfish beds in Dyes Inlet (WDOH 2003a). The reopening came about because the City of Bremerton has nearly eliminated CSOs and the modeling study showed that FC released from CSO events mostly dissipates before reaching the shellfishing areas subject to the new classification (WDOH 2003b). The model is currently being used to support the development of a water clean up plan for the Sinclair/Dyes Inlet watershed to improve the environmental quality of the Sinclair and Dyes Inlet Watershed.

6. References

Bukata et al. 1988 Optical Properties and Remote Sensing of Inland and Coastal Watters. CRC Press.

Cheng, R. T. , and Gartner, J.W., 1985, Harmonic Analysis of Tides and Tidal Currents in South San Francisco Bay, California, Estuarine, Coastal and Shelf Science, Vol. 21, p. 57-74.

Cheng, R. T., Casulli, V. and Gartner, J. W., 1993, Tidal, Residual, Intertidal Mudflat (TRIM) Model and its Applications to San Francisco Bay, California, Estuarine, Coastal and Shelf Science, Vol. 36, p. 235-280.

Foreman, M., 1977, Manual for Tidal Heights Analysis and Predication, Pacific Marine Science Report 77-10, Institute of Ocean Sciences, Sidney, British Columbia, Canada (1993 revision), 66p.

Foreman, M., 1978, Manual for Tidal Currents Analysis and Predication, Pacific Marine Science Report 78-6, Institute of Ocean Sciences, Sidney, British Columbia, Canada (1993 revision), 66p.

Johnson, B.H., Kim, K.W., Heath, R., Hsieh, B., and Butler L., 1991. "Validation of a Three Dimensional Hydrodynamic Model of Chesapeake Bay", Journal of Hydraulic Engineering, ASCE, 1991,2-20.

Mancini, J. L. 1978. Numerical estimates of coliform mortality rates under various conditions. J. Water Poll. Control Fed. 50:2477-2484.

NOAA Atlas 2, Western US Precipitation Frequency Maps, HDSC/NWS Office of Hydrology, published 1973, http://www.wrcc.dri.edu/pcpnfreq.html viewed on 3 July 2003.

Richter, K.E. 2004. CH3D Hydrodynamic Model Validation Draft Report. Space and Naval Warfare Systems Center, San Diego, CA. September 12, 2004

Project ENVVEST 2001. Dye release study in the Port Washington Narrows, Draft Final Workplan. Prepared by Project ENVVEST CSO-Modeling Subworking Group, December 18, 2001.

USEPA,1986. Ambient Water Quality Criteria for Bacteria. EPA-A440/5-84-002.

USEPA, 1994. "Application Guide for Hydrological Simulation Program-FORTRAN (HSPF). Technical Report EPA/600/3-84-065. U.S. Environmental Protection Agency, Environmental Research Laboratory, Office of Research and Development, Athens, Georgia

USEPA 2001. Protocol for Developing Pathogen TMDLS First Edition, January 2001. EPA 841-R-00-002. http://www.epa.gov/owow/tmdl/pathogen_all.pdf

WDOH et al. 2000. Drogue Study for Dyes Inlet Sampling Plan. September 20, 2000. Prepared by: Washington Department of Health, Shellfish Protection Division, Space and Naval Warfare Systems Center, Environmental Sciences Division, Puget Sound Naval Shipyard, Suquamish Tribe, City of Bremerton, and Concurrent Technologies Corporation.

WDOH (Washington State Department of Health). 2003a. *Shellfish harvesting opens in Northern Dyes Inlet*, News Release Oct. 31, 2003. http://www.doh.wa.gov/Publicat/2003_News/03-176.htm

WDOH 2003b. Sanitary Survey of North Dyes Inlet. October 2003. Office of Food Safety and Shellfish Programs. 50 pp.

Wang, P.F and K.E. Richter 1999. A Hydrodynamic Modeling Study Using CH3D for Sinclair Inlet, Draft Report. Space and Naval Warfare Systems Center, San Diego, CA, November 3, 1999.

Wang, P.F. 2001. Dispersion resulting from aggregating hydrodynamic properties in water quality modeling. International Journal of Engineering Science, 39:95-112.

Wang, P.F., Robert K. Johnston, Heather Samaitis, and Brian Skahill 2001. Developing Urban Watershed Runoff Models for Navy Harbors and Facilities. Science & Technologies Capabilities Initiative Proposal to the Office of Naval Research

Wang, P.F., Robert K. Johnston, Brad Davidson, Bart Chadwick, Woo-Hee, Choi, Steve Swanson, Frank Meriweather, Paul Williams, Mindy Fohn, Stan Olsen, and Chris Collins 2001. Lagrangian Drifts in the Tide and Wind-Driven Dyes Inlet, WA, Proceedings of the ASCE Mechanics of Engineering conference (San Diego), June 27, 2001.

Wang, P.F., Brian Skahill, Heather Samaitis, and Robert Johnston 2002. GIS-Based Artificial Neural Network and Processed-Based HSPF Model for Watershed Runoff in Sinclair and Dyes Inlet, WA. Proceedings of Watershed 2002 Conference.

Wang, P.F., Woo-Hee Choi, Ken Richter, Brad Davidson, Bart Chadwick, R.K. Johnston, Steve Swanson, Frank Meriwether, Paul Williams, and Robert Ambrose, 2002. Fate and Transport Modeling for TMDL in Sinclair and Dyes Inlets. Paper presented American Water Resources Association (AWRA) 2002 Spring Specialty Conference, Coastal Water Resources, New Orleans, Louisiana, May 13-15, 2002.

Wang, P.F., R.K. Johnston, H. Halkola, R.E. Richter, and B. Davidson, 2003. A Modeling Study of Combined Sewer Overflows in the Port Washington Narrows and Fecal Coliform Transport in Sinclair and Dyes Inlets, Washington. Prepared by Space and Naval Warfare Systems Center, San Diego for Puget Sound Naval Shipyard & Intermediate Maintenance Facility Project ENVVEST, Draft Report of September 2, 2003. Link to simulation results page