Environment Canada

SEMIAHMOO BAY CIRCULATION STUDY

TECHNICAL REPORT

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EXECUTIVE SUMMARY

This report describes a study of fecal coliform dynamics in Semiahmoo Bay and Drayton Harbour. Shellfish harvesting has been closed within Semiahmoo Bay for many years due to bacteriological contamination. The specific goal of this study is to develop a circulation model for the marine waters of Semiahmoo Bay and Drayton Harbour. The model is used to study the temporal and spatial dispersion of contaminants, in particular fecal coliform bacteria, from identified point sources. The study consists of a numerical simulation of circulation as well as a program of field observations for model validation.

The field data collection took place from July 23 to 25, 2002. A survey vessel repeatedly travelled a single transect, collecting conductivity-temperature-depth (CTD) profiles at three locations and continuously measuring current profiles with an Acoustic Doppler Current Profiler. A weather station measured winds at Crescent Beach for a period of two months bracketing the field program.

Circulation in the study area was simulated using Hay & Company's proprietary three-dimensional hydrodynamic model H3D. Modelling was conducted in a nested configuration. A model of the Strait of Georgia / Juan de Fuca Strait with a 2-km grid provided boundary conditions to a model of Boundary Bay and Semiahmoo Bay with a 200-m grid.

After validation of the model dynamics with the 2002 field data, a simulation was run for the entire year 2001. Six sources of fecal coliform were identified for the study: Serpentine River, Nicomekl River, Little Campbell River, Dakota Creek, California Creek, and the Blaine Sewage Treatment Plant (STP). Existing data from water quality sampling programs were used to create time series of flow and fecal coliform concentration for each source as inputs to the model. For some sources, very little data was available, requiring interpolation and/or extrapolation to synthesize the time series.

The model shows complex circulation patterns in Semiahmoo Bay and Drayton Harbour. Around slack tide, eddies form in the surface layer and flow in adjacent layers can be in opposite directions.

A goal of the study is to identify which source of fecal coliform has the greatest impact on shellfish growing waters. The water quality standard for fecal coliform of 14 CFU/100 mL (Canadian shellfish growing water and US Class AA/A marine water) was used to identify contaminated areas. Based on the loadings used in the simulations, the Little Campbell River has by far the largest effect. The Serpentine River and Dakota Creek had sizable effects as well, in terms of area affected and number of months in which contamination was predicted. California Creek caused contamination in only one month, while the Nicomekl River and the Blaine STP never caused exceedance of the water quality standard. The areas affected included Semiahmoo Bay from Blaine to Kwomais Point, much of Drayton Harbour, and a portion of Mud Bay.

The modelled concentrations were generally less than observed concentrations from sampling programs in the area. The discrepancy could be due to inaccuracy in the loading data for the model, which was based on sparse observations, and/or model processes that result in excessive dilution. Other problems are the restriction to only six point sources. Future studies should consider the remaining sources (shoreline outfalls and the Blaine commercial marina, for example).

In order to understand better the dynamics of small river plumes, internal development of an adjustable-layer model was accelerated. In a preliminary version of this new model, the surface layer, which is 5 m thick in the present model, is replaced by a number of 1-m thick layers that appear and disappear as the tide fluctuates. The fecal matter from the rivers is confined in a smaller volume, which results in less dilution in the model cells and consequently higher concentrations. The dynamics of the river plumes change as well when confined to the thinner layers, allowing the fecal matter to spread more extensively. A preliminary run of the new model shows a much larger area with fecal coliform concentrations exceeding the water quality standards. Since the new model provides more realistic simulations, it is recommended that it be used for future simulations.

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1 INTRODUCTION

This report describes a study of fecal coliform dynamics in Semiahmoo Bay and Drayton Harbour. The study consists of a numerical simulation of circulation in these waters and the resulting distribution of fecal coliform, as well as a program of field observations for model validation.

The Semiahmoo Bay / Drayton Harbour system is situated in the southern Strait of Georgia and crosses the Canada – USA international boundary. The system is a unique estuary with a long history of commercial oyster harvesting as well as tribal and recreational shellfish harvesting. Due to point and non-point source pollution of the system, shellfish and oyster harvesting has declined since the 1980s. Shellfish harvesting has been closed within Semiahmoo Bay for many years due to bacteriological contamination. A link has been established between fecal coliform counts along the Semiahmoo Bay shoreline and reduction in shellfish growing water quality. Additional knowledge of the circulation patterns within the system will assist in the identification and tracking of sources contributing to contamination of shellfish growing water. The goal of this study is to develop a circulation model for the marine waters of Semiahmoo Bay and Drayton Harbour. The model is used to study the temporal and spatial dispersion of contaminants, specifically fecal coliform bacteria, from identified point sources.

2 METHODS

2.1 Field Program

The field data collection took place from July 23 to 25, 2002, coinciding with a period of spring tides. A survey vessel repeatedly traversed a transect, of length 8.6 km, running between Birch Point and White Rock (see Figure 2.1).

Continuous profiles of currents along the transect were measured using an Acoustic Doppler Current Profiler (ADCP) mounted on the survey vessel. The transect was chosen for ease of navigation and to provide data that resolved tidal fluctuations, i.e. it could be traveled in approximately one hour. The survey process was repeated continuously over forty-eight hours; due to heavy weather which swamped the generator, data was collected for only a thirty-six hour period such that one and a half complete tidal cycles were observed. Such a transect provides a reasonable amount of high quality data for model validation, even though the model region is too large for a single ADCP transect to provide a complete description of circulation in the system. The complete set of ADCP data is presented in Appendix A.
Conductivity-Temperature-Depth (CTD) profiles were collected using a CTD probe lowered vertically from the survey vessel. CTD profiles were collected at the beginning, middle and end of each traverse of the transect (see Figure 2.1). The CTD probe includes sensors for conductivity, temperature and depth, and computes salinity and density. The computed CTD profiles are shown in Appendix B.

A weather station that measured wind speed and direction was mounted at Crescent Beach (on the Beecher Street recreation centre) from July 19 to September 24, to provide winds for a period bracketing the time of the field program. Appendix C contains wind roses and plots of other meteorological data from the station.

2.2 Numerical Circulation Model

Circulation patterns within Semiahmoo Bay were simulated using Hay & Company's proprietary three-dimensional hydrodynamic model H3D. This model is derived from GF8 (Stronach, Backhaus and Murty, 1993), developed for Fisheries and Oceans Canada. H3D is a three-dimensional time-stepping numerical model that computes the three components of velocity (u,v,w) on a regular grid in three dimensions (x,y,z), as well as such fields as temperature, salinity and contaminant concentrations.

The spatial grid may be visualized as a number of interconnecting computational cells collectively representing the water body. Figure 2.2 shows a typical grid layout. Velocities are determined on the faces of each cell, and non-vector variables, such as temperature or contaminant concentration, are situated in the centre of each cell. All cells have identical x and y dimensions. The selection of grid size is based on consideration of the scale of the phenomena of interest.

In the vertical, the cells are usually configured such that they are relatively thin near the surface and increase in thickness at depth. The increased vertical resolution near the surface is needed because much of the variability (stratification, wind mixing, inputs from streams and land drainage) is concentrated near the surface.

In fact, two models were required to execute this study: a 2-km overall model of the Strait of Georgia / Juan de Fuca Strait system (Figure 2.3), and a nested 200-m grid model of the Boundary Bay / Semiahmoo Bay region (Figure 2.4). The following discussion provides characteristics common to both models.

- The principal driving force is due to water level fluctuations, primarily tidal, derived from water level variations at the open boundaries of the model. Tidal fluctuations are presented as boundary conditions computed from tidal constituents for the 2-km model at its open boundaries, and are provided from the 2-km grid model to the 200-m grid model as a time series.
- Wind forcing causes currents within enclosed water bodies as well as water level differences. Consideration of wind forcing is also important since wind energy has a significant impact on vertical mixing, and hence temperature and salinity distributions. Wind stresses acting at the water surface are derived from wind records collected from coastal Atmospheric Environment Service stations, lighthouses or other stations and are processed to compute over-water wind fields at hourly intervals

for the 2-km model. H3D then interpolates these wind fields in space and time to meet model requirements. Details of wind forcing for the 200-m grid model are given in Section 2.2.2 below.

- The model permits consideration of inflows such as rivers, creeks and land drainage. For rivers, these inflows contribute mass and momentum to the water body as well as contaminants. The boundary condition is represented by a time varying flow rate. Where available, the flow rate is generated from hydrographs of the particular inflow under consideration. H3D also embeds the US-EPA PLUMES model (Baumgartner *et al*., 1994) to simulate municipal waste outfalls.
- In most applications, data is limited for calculating heat flux across the water surface. Reasonable estimates can be made from wind speed, wet bulb and dry bulb air temperatures, and cloud cover or insolation. In the summer, heat input leads to increased stratification. Near-surface effects, such as contaminant concentrations and water velocities, are generally more significant when the water body is stratified. In the winter, cooling can lead to static instabilities and overturning in lakes, as well as ice cover. Since the model was run over all seasons, the ability to simulate winter cooling is important.
- Turbulence modelling is important in determining the correct distribution of velocity and scalars such as contaminants. The diffusion coefficients for momentum and scalars at each computational cell depend on the level of turbulence at that point. H3D uses a shear-dependent turbulence formulation in the horizontal, and a shear- and stratification-dependent formulation in the vertical for momentum. These parameters have been shown to work well when simulating the annual cycle of salinity and temperature in the Strait of Georgia, and are consistent with current practice. For scalars, such as salinity, constant horizontal eddy diffusivity is used, and the vertical diffusivity is similar to the vertical eddy viscosity, but scaled by a fixed ratio.
- Water quality modelling capabilities are built into H3D. It incorporates a highly accurate transport/diffusion module, which deals with the movement of contaminants by means of currents, and their diffusion by sub-grid-scale turbulent processes. In a high-resolution grid, dispersion due to current shear (spatial gradients in velocity) is also modelled. The non-conservative behaviour of each scalar and interactions between scalars can be modelled. For instance, the temperature field is affected by water currents, such as when a cold river enters a warm lake. This is a conservative process: no new heat is generated. However, the input of heat at the water surface is a non-conservative process, which is simulated by H3D. Similarly, bacteria enter the system at specified locations, and are carried around and dispersed by currents and diffusion processes. They also experience a die-off, a non-conservative process. H3D calculates a die-off coefficient that is a function of variables such as temperature, salinity and sunlight.
- The model operates in a time-stepping mode over the period of simulation. During each time step, values of velocity, temperature, salinity and contaminant concentration are updated in each cell. Typically, data were archived (saved to disk) on an hourly or daily basis, so that a manageable amount of data was generated for subsequent analysis.

2.2.1 Modelling Implementation

For this study, H3D was implemented in a nested configuration. An existing coarse grid implementation was applied to the Strait of Georgia and coupled to a finer grid model of Boundary Bay and Semiahmoo Bay.

The coarse grid Strait of Georgia model encompasses the entire strait with open boundaries at Johnston Strait and at the entrance to Juan de Fuca (Figure 2.3). The solution grid had a cell size of 2 km, developed from a rectangular discretization of available bathymetric charts. Wind forcing for the coarse grid model was derived from an array of Atmospheric Environment Service (AES) stations including Ballenas, Entrance, Saturna, and Sisters Islands, Grief Point, Race Rocks, Sand Heads, Sheringham Point and Sentry Shoal. Flows from the Fraser River were applied to the 2-km grid model.

The coarse grid model was coupled to a fine grid (200 x 200 m) bay model that encompasses Boundary Bay, Semiahmoo Bay and Drayton Harbour. Figure 2.4 shows the grid layout. The bay model was coupled to the coarse grid model along a line extending southeast from Point Roberts. Flows from the Serpentine, Nickomekl and Little Campbell Rivers were applied to the 200-m grid nested model, as well as California and Dakota Creeks discharging to Drayton Harbour. The influence of the Fraser River in the nested model is felt through the fresher surface waters of the southern Strait of Georgia, which enter the region south of Point Roberts.

The coarse and fine grid models were run separately, but communicated continuously across the common boundary. The coarse grid model essentially provided the necessary hydrodynamic boundary conditions to the fine grid bay model. The two grids were made compatible along their common boundary, and the total surface area and volume within the fine grid model was the same as the corresponding variables in the coarse grid model, to ensure minimum inconsistencies between the two models.

The year 2001 was chosen for the simulation, as this is the most recent year for which a complete data set of inputs to the model was available.

2.2.2 Winds

The available AES stations are not optimally situated to provide winds for the fine grid bay model. The meteorological station installed at Crescent Beach in summer 2002 showed that the bay is sheltered from most of the strong winds seen in the Strait of Georgia and that the winds in Semiahmoo Bay are highly diurnal (Figure 2.5). As part of a model sensitivity study, it was found that the validation of the model against the field study, discussed in section 3.2 below, improved markedly when the winds were changed from the interpolated Strait of Georgia winds to the local Crescent Beach winds.

Because the validation study indicated considerable improvements when winds from Crescent Beach were used, a time series for 2001 winds representative of those at Crescent Beach was synthesized for input to the fine grid in the year-long simulation. An average diurnal pattern of wind at Crescent Beach was created from the data observed in summer 2002. The highest winds were recorded in the afternoon; winds were very low at night. To recreate this diurnal pattern, the day was divided into three-hour bins, and the average of the data in each time bin from the field study of July 19 to September 22 was assigned to each bin, for both the north-south and the east-west components of wind.

Winds vary throughout the year as well as during the day. Wind speed tends to be higher in the winter months. The yearly pattern of wind in 2001 was obtained by averaging wind speed at the East Point (Saturna Is.) and Sandheads AES stations into monthly values. The ratio between the 2001 average monthly wind at East Point and Sandheads and the 2001 average summer (July to September) wind at East Point and Sandheads was obtained. The average summer daily wind (three-hour bins) at Crescent Beach was then scaled for each month using the above ratios. The highest average wind was observed in December and the lowest in September. The average winds for the other months fall between the two, in descending order: December, November, October, March, February, January, April, July, August, May, June, September. By repeating the daily wind pattern for each day of the month, a year-long record of hourly wind was created for input to the fine grid model for the 2001 simulation. Data in the month of July is shown in Figure 2.5.

2.2.3 Freshwater Inflows

For each river and creek flowing into the coarse and fine grid models, an annual hydrograph for 2001 was developed. The Fraser River is the sole input to the coarse grid model. Daily flow records at Hope were propagated by a one-dimensional model to New Westminster, the upstream limit of the Fraser in the 2-km model.

For the Little Campbell River, hourly flow data at 12 Avenue (from the City of Surrey Streamflow Monitoring Program) showed a gap from August 27 to October 2. The missing values were set equal to the average of the flow from the remainder of the summer data (June 1 to August 27). The missing flow values were augmented with peaks corresponding to several small rainfall events. The data series was then increased by 15% (based on watershed areas) to account for two tributaries, Fergus Creek and Sam Hill Creek, downstream of the flow gauge at 12 Avenue.

Flow measurements for 2001 were not available for Dakota and California Creeks. However, synthesized monthly hydrographs were available from the USGS Water Resources Inventory Area 1 (WRIA 1) Watershed Management Project. The ratio between the mean annual flow of Dakota Creek and California Creek to the mean annual flow of Little Campbell River at 12 Avenue in 2001 was used to scale the Little Campbell River hydrograph to Dakota Creek (a ratio of 1.6) and California Creek (a ratio of 1.3).

Sea dams on the Nicomekl and Serpentine Rivers allow outflow to Mud Bay only when the tide is very low. This occurs for only a short time once or twice in each 25-hour tidal period. (Discharge occurs only when the tide is below roughly –0.6 m GSC; the exact water level in each tidal cycle that corresponds to outflow conditions depends on river stage and flow as well). While no 2001 flow record exists for the mouth of the rivers, five-minute data was available upstream on the Serpentine River at Highway 10. For both rivers, five-minute readings of stage at locations on either side of the sea dams were also available (only January to May 2001 for the Serpentine). Generating a time series of flow for both rivers for the entire year required several steps. First, for the Serpentine River a correlation was developed between the head difference on either side of the sea gates and flow at Highway 10 during periods of outflow for January to May 2001. The mass balance of the observed flow was used to determine a proportionality constant between head difference and flow to ensure that the amount of water released in the created time series at the sea dams was equal to the observed flows upstream over the period of record. Second, applying the proportionality constant to the head difference on the Nicomekl generated a time series for the entire year 2001. The created time series corresponds to times when the sea dams are open at low tide. Finally, the time series for the Serpentine was extended for the entire year 2001 by scaling the Nicomekl time series based on the ratio of the mean annual flow for the two rivers from 1965 to 1966. (The Nicomekl River flow is 8.2 times that of the Serpentine River).

Daily flows were obtained for Blaine STP. Depending on the ambient conditions, the effluent may rise to the surface or remain trapped in a lower layer. This behaviour is modelled by H3D using the US-EPA PLUMES numerical model (Baumgartner *et al*., 1994), the commonly accepted standard for determining environmental impacts from effluent discharge through an outfall. The outfall diffuser for the Blaine STP is located at a depth of 9.6 m (MLLW), at a distance of 730 m from shore. The diffuser consists of six ports of 0.15 m diameter, spaced 3.7 m apart. The model assumes that the outfall diffuser is intact and functioning as designed.

2.2.4 Contaminant Sources

The study is concerned with bacteriological contamination, specifically fecal coliform bacteria. The request for proposal indicated that approximately fifty point sources of contamination have been identified within the study area. The most significant of these are the Little Campbell River, Drayton Harbour outflow and the Blaine municipal wastewater treatment plant. Other potential sources may include urban and agricultural run-off, groundwater inflows derived from sewage disposal fields, leaking underground sanitary infrastructure, fecal matter from migratory birds and sewage discharge from pleasurecraft. Of these sources of fecal coliform loading, six were chosen for the model:

- Serpentine River,
- Nicomekl River,
- Little Campbell River,
- Dakota Creek,
- California Creek,
- and the Blaine STP.

Water quality sampling programs by various Canadian and American government departments and by other agencies provided some records of fecal coliform levels in each of the six sources.

Sparse coliform data was available for the Nicomekl and Serpentine Rivers (only six measurements from July 1999 to August 2000). Instead of attempting to create a time series of fecal coliform concentration, the average of the available data for each was used as a base concentration in the input. It is known that contaminant loadings associated with the "first flush" are greatest and decay thereafter. Thus, when observed flow was above a certain threshold, the fecal coliform concentration was increased in proportion to flow to recreate the "first flush" that typically accompanies storm events. The proportionality constant between fecal coliform and flow was chosen so that it gave a maximum fecal coliform value comparable to the maximum measured value from the 1999 – 2002 data set.

On the Little Campbell River, a total of 46 samples of fecal coliform were taken from June 1999 to February 2002 at a single location near the mouth of the river. The fecal coliform values for 2001-2002 were lower than those for 1999-2000. It is not clear whether this reduction reflects changes in pollution control measures or simply reflects the sporadic nature of the testing. Samples were also taken on six days in March and April of 2002 at six locations further upstream on the river. The values were typically lower than those at the mouth. Since additional sources may input fecal coliform between the sampling stations and the mouth, data at the mouth was chosen as representative of the loading to Semiahmoo Bay. The average of all available data at the mouth of the river from (46 measurements in 1999-2002) was used as a minimum value for the model input. When observed flows were above a certain threshold, the fecal coliform data were scaled in proportion to flow to reflect the "first flush" that typically accompanies storm events. Again the proportionality constant was chosen to give maximum fecal coliform values equal to the maximum measured values.

Bi-monthly fecal coliform samples were taken at several stations on Dakota and California Creeks (see Figure 2.6) from mid-March 2001 to the end of December 2001. Data from station DG was used for Dakota Creek, as it was the farthest downstream of the stations upstream of the saltwater intrusion, and thus most representative of the actual inflow to Drayton Harbour without being affected by tides. On California Creek, site C3 was the only site upstream of the saltwater intrusion, but was quite far upstream and immediately downstream of a livestock operation. It did not appear representative of California Creek inflow as readings were significantly higher at C3 than at the other stations. Hence the data at C3 were scaled by the ratio between the mean of readings at C3 and the mean at C2, the next station downstream. For each creek, a linear regression was performed on the fecal coliform levels and flows on the sampling days. The correlation was then applied to the daily series of flows to create a daily series of fecal coliform data. On days when samples were taken, the actual data was used; values for one day on each side of the sampling day were interpolated between the actual and artificial data.

For the Blaine STP, fecal coliform samples were taken on 159 days of the year in 2001, at intervals ranging from one to four days. A daily series for fecal coliform at the Blaine STP was created by linear interpolation between the data points.

Figures 2.7 to 2.12 show the inputs to the model, i.e. flow and fecal coliform concentration, for each source. The loading of fecal coliform is obtained by multiplying the concentration by the flow. The loading is instrumental in comparing the sources: for example, the Nicomekl River flow is 8.2 times the Serpentine River flow, but the average fecal coliform concentration in the Serpentine River is 50 times the Nicomekl River concentration, so that the loading from the Serpentine River is more significant than that from the Nicomekl River, despite it being a smaller river. Note that the 50:1 ratio of fecal coliform concentrations is a very rough estimate based on the limited amount of data.

The flow and fecal coliform concentration for each of the six sources was synthesized as best possible from the available data. The flow monitoring and fecal coliform sampling programs for some sources were sporadic or non-existent. As such, the model simulation cannot be expected to replicate the actual behaviour of 2001, but will give an indication of the relative impact of the six sources and the expected extent of contamination.

2.2.5 Decay of fecal coliform

Fecal coliform are known to decay due to a number of factors including photo-oxidation, adsorption, flocculation, coagulation, sedimentation and temperature effects. A comprehensive review of these decay mechanisms has been compiled by the US Environmental Protection Agency (1985). Traditionally, simple first-order kinetics are used to model coliform disappearance:

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

where C_t = coliform concentration at time t (CFU/100 mL)
C_O = initial coliform concentration (CFU/100 mL)
k = decay rate constant (h^{-1})
t = exposure time (h)

Fecal coliform die-off increases with increasing temperature, salinity and light. Of the various formulations for calculating the decay rate (k), that of Mancini (1978, in USEPA 1985) was chosen as it incorporates the effects of all three factors:

$$k = \frac{\left(0.8 + 0.006 P_{SW}\right)}{24} 1.07^{T-20} + k_l \bar{l}$$

where P_{SW} = percent seawater (%)
T = temperature (^{o}C)
k_l = proportionality constant for the specific organism (cm^{2} cal^{-1})
$\bar{l}$ = depth-averaged light intensity (cal cm^{-2} h^{-1})

The value of k_l was set equal to 0.00377, from Lantrip's study of coliforms (1982, in USEPA 1985).

In the H3D model, the decay constant (k) was calculated in each grid cell at each time step using the temperature, salinity and light in that cell. The fecal coliform concentration in each cell was then reduced according to the first-order kinetics, with an elapsed time (t) equal to the model time-step.

3 MODEL VALIDATION

Before presenting the simulation results, we first discuss the model validation. This involves verification that the model correctly predicts the spatial and temporal distribution of currents throughout the water body of interest as well as verification of temperature/salinity profiles in the vertical. The model is validated by the field data collected in July 2002. The assumption is that if the model reproduces observed values at a limited number of points (i.e. along the transect), it is equally valid elsewhere in the model domain.

3.1 Validation of the Circulation Model against CTD Data

From the CTD data, vertical profiles of temperature, salinity, and density can be computed. The CTD profiles typically show warmer, less saline water at the surface, which corresponds to density increasing with depth. For example, Figure 3.1 shows a layer of near-uniform density overlying a thin, denser layer of colder, more saline water. The entire series of CTD profiles collected during the field study can be plotted against time to create vertical sections of salinity at each CTD station (Figure 3.2). The tidal signal can be deduced by the upper limit (i.e. water level) of each coloured panel.

Data can be extracted from the model to compare with the field study. At the grid locations corresponding to the CTD stations, the salinity values in the various model layers were extracted hourly to create vertical sections with time (Figure 3.3). Recall that model values are averaged over a 200-m by 200-m area. Comparing Figures 3.2 and 3.3, we see that the model reproduces two key aspects of the observed data. First, the increase in salinity observed from north to south along the transect (CTD3 to CTD 1) occurs at roughly the same rate. The bottom salinity increases about 3 units from station CTD3 to station CTD1. Second, at stations CTD1 and CTD2, the model reproduces the observed increase in salinity just before each high tide. These increases in salinity show more saline water from the Strait of Georgia entering the bay on the flood tide. This saline wedge appears as the lower layer of higher salinity in the individual CTD profile in Figure 3.1.

The modelled salinity is on average 1.7 units lower than the measured salinity. To match the salinity exactly would require perfect reproduction of salinity by the coarse grid Strait of Georgia model. This is highly dependent on the Fraser River flow, the rate of saltwater intrusion in Juan de Fuca Strait, and the initial salinity conditions in the entire grid at the start of the simulation, for which limited information is available. Salinity measurements in the Strait of Georgia in July 1968 were used to initialize the 2-km coarse grid model. These measurements would be substantially different than the actual salinities in 2001, since the flow in the Fraser from May to July 1968 was 40% higher than in the corresponding months of 2001. Thus the model started the simulation with a higher freshwater content than actually occurred in 2001, which is manifested in the difference between modelled and observed salinities. The goal of this study is not to reproduce exactly the salinity values in Semiahmoo Bay but rather to model the salinity structure, which in turn influences circulation patterns that affect the replacement of fresher water in the bay with more saline water from the Strait. Thus, salinity differences, both horizontally and vertically, are more important than the absolute values of salinity.

3.2 Validation of the Circulation Model against ADCP Data

Data was extracted from the model output to compare with the ADCP transects. The model data is a snapshot of the section at one point in time whereas the ADCP data is collected over an elapsed time of 45 to 55 minutes. The time in the model nearest to the midpoint of the ADCP transect time was chosen for comparison.

The circulation patterns in Semiahmoo Bay are quite complex, due to the influences of the Fraser River flow and flow through the Strait of Georgia, the numerous inflows to the bay, bathymetric and topographic features (Figure 3.4), and the flooding and drying of the intertidal banks. Velocity data from the field study showed two-layer and three-layer flow along the transect. The direction of flow often changed several times along a given transect. For example, Figures 3.5 and 3.6 show plan views of vectors from both the field transect and the model for the top two layers of the model, for the first transect. The field data is chosen from the ADCP depth bin closest to the mid-depth of the model layer. (The ADCP data is measured in depth from the surface, which changes with the tide, whereas the model data is measured from a fixed datum). The velocity field is characterized by eddies that are seen in both the field data and the model data. The relatively flat shoal area west of Birch Point leads to a large baroclinic eddy with the two layers moving in different directions. The two-layer flow is evidenced by flow in different directions at the different depths, clockwise at 3.16 m depth and counterclockwise at 8.66 m depth.

The same data can be visualized as colour contours of velocity in vertical sections along the transect. Comparing the field data (Figure 3.7) and the model data (Figure 3.8) shows that the model can reproduce the complex velocity structures throughout the depth. The vertical patch of high south-west velocity (dark blue in both panels) near the start of the transect (left hand side of figure) is apparent in the model results. Two-layer flow along the remainder of the transect is also modelled. This model data was produced using the synthesized diurnal winds at Crescent Beach. It is a distinct improvement over a model run using the interpolated Strait of Georgia winds. In that case, the model did not reproduce many of the features observed in the field (Figure 3.9).

To validate the model, we can compare the velocity sections for all 19 transects, which are shown in Appendix A (field data) and Appendix D (corresponding model data). Figure 3.10 shows the tide in Semiahmoo Bay for each transect during the field study. An examination of the pairs of section plots shows that the model agrees qualitatively with the ADCP data. In general the model shows velocities in the same direction as those observed (i.e. blues, yellows and reds are in roughly the same areas of the plots).

The goodness of agreement varies with the point in the tide. The model agreement is best on the ebb tide from higher high water, when large velocities to the west and south are observed (transects 1, 2, 13 and 14 in Appendices A and D). As seen in Figures 3.5 to 3.8, the model successfully predicted complex circulation patterns. On the flood tide from low tide to higher high tide, when velocities are strong to the north-east, agreement is quite good as well (transects 11 and 12).

The model agreement is poorest at low tide (transect 9 in Appendices A and D) and on the flood tide to lower high water (transects 3, 4, 5 and 6). Since the forcing pressure gradient in the model is not as strong at these points in the tide, it is harder to predict velocities. At this point, the velocities have more the character of turbulence, which is by definition random. Many small scale eddies are present in the bay and velocities are not very high. The model shows large patches of near-zero velocity (i.e. white patches) while the observed data shows slightly higher velocities.

At other points in the tide, when velocities have intermediate values, the agreement between the model and the ADCP data is fair. The fact that the model does not always agree absolutely with the observed data is not reason to dismiss the validity of the model. The circulation study is concerned with transport of contaminants and replenishment of the water in the bay. The most significant movement of water occurs during the ebb and flood when velocities are high, which the model represented well. A major success of the model is its ability to reproduce the eddy that forms off Birch Point (Figures 3.5 and 3.6). The validation is thus sufficiently good to proceed with the model simulation.

4 RESULTS

4.1 Circulation

The model shows circulation patterns in Boundary Bay, Semiahmoo Bay and Drayton Harbour, which affect the distribution of fecal coliform from the identified sources. Appendix E shows vector diagrams of modelled surface velocity from one tidal cycle on December 14, 2001. In these figures, vectors are shown at every other grid point of the model. On the flood tide, water sweeps into the bay (e.g. Figure E-4), and on the ebb tide it sweeps back out into the Strait (e.g. Figure E-20). The maximum predicted velocities, which occur during the flood and ebb, are around 1 m/s. These velocities tend to occur at considerable distance from the sources studied in this report, except for the Nicomekl River, so have little impact on the distributions of contamination being modelled. Around slack tide, the surface circulation is characterized by many eddies. One eddy forms between Birch Point and Semiahmoo Spit (e.g. Figures E-5 to E-7), which would affect the dispersion of the Blaine STP discharge. Another eddy in Mud Bay (e.g. Figure E-6) would impact the discharge from the Serpentine and Nicomekl Rivers. Circulation in Drayton Harbour and outside the harbour mouth is complex and warrants a closer look.

Vector diagrams for modelled surface velocity in Drayton Harbour for one tidal cycle are included in Appendix F. In these figures, vectors are shown for every grid point in the model. A number of eddies form in the harbour during each flood, and persist through high water around slack tide. A counter-clockwise eddy along the northwest shore (e.g. Figures F-13 to F-17) lies in the path of the flow from Dakota Creek. Flow patterns outside the mouth of California Creek show flow in adjacent model grid cells moving in opposite directions, as well as a small eddy just west of the creek outlet (e.g. Figures F-6 to F-8). A clockwise eddy inside Semiahmoo Spit (e.g. Figures F-5 to F-7) could entrain discharge from Dakota that would bypass the harbour exit, both on the flood tide (Figure F-6) and perhaps even at the start of the ebb tide (Figure F-17). Flow exiting the harbour can be transported south-west along Semiahmoo Spit and towards Birch Point (e.g. Figure F-8), or north-east towards the Little Campbell River (e.g. Figure F-12).

In Appendix G, vector diagrams of a cross-section from Semiahmoo Bay into Drayton Harbour show the vertical variation of modelled velocity at hourly intervals during one tidal cycle. The apparently large vertical motions are in fact relatively small; they appear large because of the large vertical exaggeration in the plots, since the ratio of horizontal to vertical scale is greater than 100:1. The chosen section is mapped in Figure G-1. Two-layer flow, where flow is in opposing directions in adjacent layers in the model, is evident around slack tide in Semiahmoo Bay (Figures G-11 to G-13, G-18, G-23 to G-25), across the entrance to Drayton Harbour (Figures G-8, G-13, G-18, G-25), and in Drayton Harbour itself (Figures G-6 to G-9, G-13, G-18 and G-25). This two-layer flow shows that circulation in the harbour is more complicated than evidenced by surface flow alone. Fecal coliform from the harbour can be exiting in the surface layer while at the same time relatively uncontaminated water from the bay can be entering in lower layers. However, the flushing of the harbour is dominated by the strong uni-directional currents during the ebb and flood tides, which replace the water in the harbour with water from Semiahmoo Bay.

4.2 Fecal coliform contamination

A primary objective of the study is to determine the contaminant source(s) having the greatest significance in terms of negative impact on shellfish growing water quality. This will aid in developing strategies to reduce contamination in Semiahmoo Bay and Drayton Harbour.

Water quality standards differ depending on the designation of the water body in question. For shellfish growing waters, Environment Canada uses the following water quality standard:

> The median or geometric mean fecal coliform Most Probable Number (MPN) does not exceed 14/100 mL and not more than 10% of the samples exceed 43/100 mL in the multiple tube fermentation test.

Water quality standards in the state of Washington depend on the class of the surface water. Three classes apply to shellfish growing and harvesting water. Class AA (extraordinary) and Class A (excellent) marine water can be used for shellfish rearing, spawning and harvesting. The water quality standard for fecal coliform for Classes AA and A is the same as the Environment Canada standard above. Class B (good) marine water is considered sufficient for shellfish rearing and spawning but not harvesting. The Class B water quality standard reads:

> Fecal coliform organism levels shall both not exceed a geometric mean value of 100 colonies/100 mL, and not have more than 10 percent of all samples obtained for calculating the geometric mean value exceeding 200 colonies/100 mL.

Class C (fair) marine water is not suitable for any use related to shellfish. The Class C water quality standard for fecal coliform is a geometric mean not exceeding 200 colonies/100 mL. Incidentally, this corresponds to the recreational use limit (for primary contact) in British Columbia.

The six significant sources were assigned individual scalars in the model for tracking. The model simulation was run for a period of one year such that seasonal variability was considered. Data was archived on an hourly basis. At the end of the simulation, the hourly data was processed to generate contour plots of peak and average predicted contaminant concentration for each scalar on a monthly basis. The average monthly values were considered uninformative, since the nature of fecal coliform contamination typically consists of low levels most of the time with occasional high spikes. Contamination of a shellfish growing area would occur due to the high concentration events, not due to the persistent low levels, at least for the inputs associated with the six sources under investigation. It is important to note the difference between the mean or average monthly concentration in the model and the geometric mean upon which water quality standards are based. The average monthly concentration at each location in the model is the average of all the hourly values over the month. The water quality standard is the geometric mean of a number of samples taken at one time at a specific location. Multiple samples are taken to improve the accuracy of the testing methods and the geometric mean is the statistical measure chosen to represent the multiple values. The numerical model essentially simulates the behaviour of the geometric mean, at least when the distribution of numbers which define the mean is narrow. Any instantaneous value in the model, including the peak concentration predicted in a month by the model, can be compared with the water quality standards, since they both correspond to specific locations and times. Model values are averaged somewhat over the 200-m model grid.

For the six coliform sources, a total of seventy-two plots were generated to show the maximum monthly concentrations. The contour levels are the same in all figures and all animations to ease comparison of the sources. In all figures, the lower limit of the values shown by the coloured areas is 1 CFU/100 mL. The dividing lines between the different-coloured contours show the various water quality standards as follows:

Table 4.1 Water quality standards

Fecal coliform concentration	Water quality standard
14 CFU/100 mL	Canada shellfish growing water and US Class AA/A marine water
100 CFU/100 mL	US Class B marine water
200 CFU/100 mL	US Class C marine water and Canada recreational use

The results for each source over the twelve months of the year are animated in Animation4-1.rm to Animation4-5.rm. The animation for the Blaine STP is omitted, as the concentration of fecal coliform never exceeded 1 CFU/100 mL, the lowest value shown in the plots. The low values occurred even on the days of greatest flows and concentrations, December 15-16. The actual flow from the outfall is so small relative to the flow in the receiving waters that concentrations are reduced very quickly once the effluent leaves the outfall.

A smaller subset of the plots is presented here to summarize seasonal variability for each source by showing representative months for groupings of similar months. For each source, months where the concentration did not exceed even the most stringent standard of 14 CFU/100 mL are omitted from the table below. The Blaine STP is again omitted entirely as all months met this standard; similarly the Nicomekl River is omitted as the area beyond its mouth always met the standard. The following table shows the groupings for months with similar extent of contamination.

Table 4.2 Summary of model results exceeding water quality standards

Source	Months in grouping (plotted month in bold)	Approx. area with FC > 14 CFU/100 mL	Figure number
Little Campbell River	**December**	6 km x 1.4 km	4.1
	January, February, March, April, October, November	4 km x 1.4 km	4.2
	May, June, July, August, September	3 km x 1 km	4.3
Serpentine River	**December**	3 km x 0.5 km	4.4
	January, October, November	2 km x 0.5 km	4.5
	March, April, **May**, June, July, August, September	1 km x 0.5 km	4.6
Dakota Creek	**December**	1.8 km x 1.2 km	4.7
	January, October, November	0.8 km x 0.5 km	4.8
California Creek	**December**	1.4 km x 0.6 km	4.9

Of the six sources, the fecal coliform from the Little Campbell River spreads the most extensively throughout the model domain, for every month modelled. Fecal coliform originating from the Little Campbell River even enters Drayton Harbour in the high- and medium-loading months (Figures 4.1 and 4.2), albeit at low levels. The area exceeding the 14 CFU/100 mL water quality standard runs roughly 3 km along the coast in the lower-loading months (Figure 4.3) and reaches a length of about 5 km in the highest-loading month of December. The Little Campbell River is the only source to produce fecal coliform concentrations greater than the recreational use limit of 200 CFU/100 mL outside its mouth. In the month of December, the area exceeding the recreation standard measures almost 1 km^2.

The discharge from the Serpentine is the next most significant in terms of area exceeding the water quality standards. The Serpentine discharges to Mud Bay only at low tide due to the presence of the sea dam. The model resolves the deeper channel protruding into the bay from the mouth of the Serpentine, which allows the discharge to flow into the bay during the short windows of time when the sea dam was open at low tide. This channel through the mud banks is seen in bathymetric surveys and satellite photos. As the tide rises, the discharge is then mixed throughout the bay. High concentrations of fecal coliform were only observed within the confines of this idealized channel, as seen in Figures 4.4 to 4.6, corresponding to times of low tide when discharge is possible. The rising tide mixed the Serpentine discharge, quickly diluting concentrations below the lowest value shown in the plots (1 CFU/100 mL). Hence the concentrations appear as a thin finger within the channel. The area of concentrations exceeding the 14 CFU/100 mL water quality standard extends roughly 1 km from the river mouth in the lower-loading months (Figure 4.6) and reaches up to 3 km in length in the month of December (Figure 4.4). The Serpentine also shows a small finger, up to 1 km long, of discharge in Mud Bay with concentrations above the Class B standard of 100 CFU/100 mL in the high- and medium-loading months (Figures 4.4 and 4.5).

While its hydraulic behaviour is similar to that of the Serpentine River, the concentration of fecal coliform in the Nicomekl River at its origin was several orders of magnitude lower than that in the Serpentine. The Nicomekl discharge did not show any instances where fecal coliform exceeded the water quality standards beyond its mouth. The concentration for the highest-loading month of December is shown in Figure 4.7. It should be remembered that the differences in fecal coliform concentration between the Serpentine and Nicomekl Rivers are based on an extremely small set of observations.

Dakota Creek and California Creek discharge into Drayton Harbour, which is connected to Semiahmoo Bay by a narrow channel. Fecal coliform from Dakota Creek spreads throughout Drayton Harbour, with the lowest level contour reaching nearly to Semiahmoo Bay in the month of December (Figure 4.8). The area of Drayton Harbour where Dakota Creek fecal coliform concentration exceeds the 14 CFU/100 mL standard measures approximately 2 km^2 in the month of December. In the other months when discharge exceeded the standards, the plume consisted of a small finger extending about 1 km from the mouth of the creek (Figure 4.9). California Creek had a lesser impact on Drayton Harbour, violating water quality standards only in the month of December and only over a small area (Figure 4.10).

The model results were archived on an hourly basis for the surface layer only. At times the Blaine STP plume is trapped in the second layer (5 to 10 m below the mean water level or model datum). In this case the fecal coliform is trapped deeper than the shellfish harvesting areas so is likely not a concern. Hence we are only concerned with examining the concentration of coliform in the surface layer of the model (0 to 5 m depth). The effluent from the Blaine STP shows no fecal coliform concentrations above the water quality standards in the surface layer over the period of simulation. This observation was confirmed by separately computing dilution for the Blaine STP using the US-EPA Visual Plumes model (Frick *et al.*, 2001), the stand-alone version of the PLUMES model embedded in H3D. It was found that even on the day of highest loading, December 16, 2001, dilution of 100 times was achieved within 6 m of the outfall, confirming the validity of the application of H3D.

The fecal coliform concentrations from the individual sources can be summed to give the overall fecal coliform concentration in the bay. The resulting values for December, the month with the highest levels, are shown in Figure 4.11. The plumes from the various sources overlap slightly. The discharge from the Serpentine River (Figure 4.4) and the Nicomekl River (Figure 4.7) combine to produce a small additional area with values between 1 and 14 CFU/100 mL near the mouth of the Nicomekl River. Fecal coliform from the Little Campbell River, Dakota Creek and California Creek combine to create additional areas of fecal coliform above 14 CFU/100 mL within Drayton Harbour and a small area outside the Harbour just opposite the Blaine Marina.

Additional understanding of the contamination is gained by considering the exposure time to elevated coliform levels. Figures 4.12 to 4.15 show the length of time water quality standards were exceeded in December, the month with the highest concentrations. Note that the exposure times are not consecutive times, but simply the sum of hours during which the fecal coliform exceeded 14 CFU/100 mL in the month of December. For the Little Campbell River (Figure 4.12), much of the area showing concentrations between 14 and 100 CFU/100 mL in Figure 4.1 had exceedances for less than 5% of the month. The area with exposures of over 25% of the month is roughly one-third of the entire area with exceedances, but is still significant, covering over 2 km of shoreline. For the Serpentine River (Figure 4.13), Dakota Creek (Figure 4.14) and California Creek (Figure 4.15), exposures were quite low for most of the area beyond the immediate vicinity of their mouths.

While predicted concentrations exceeded the water quality standards in some areas for some sources, fecal coliform was essentially undetectable during many months. Since every source supplied fecal coliform at levels well above 14 CFU/100 mL and even several orders of magnitude higher (see Figures 2.6 to 2.11), this indicates that a number of processes are acting on the fecal coliform while the contamination is being distributed throughout the bay. First, the coliform are dispersed by the water circulation. In the model, the fecal coliform originate from a "point source" representing the river at a specified flow rate and concentration. The loading is distributed uniformly in the 200-m by 200-m model cell corresponding to the river origin. This reduces the concentration compared to the source value in the river. The coliform is then spread to neighbouring cells through the processes of vertical and horizontal advection and diffusion. As the loading spreads throughout the model domain, the concentration decreases further. Second, the coliform are decaying at a rate that increases with increasing light, temperature and salinity, as described in Section 2.2.5.

Fecal coliform samples taken in Drayton Harbour and Semiahmoo Bay have frequently exceeded the water quality standards. Figure 4.16 shows data from Canadian and American sampling programs at various marine sites. The "White Rock" sites (Environment Canada) stretch along the shore of Semiahmoo Bay between the Canada-US border and Kwomais Point. The "Drayton Harbour" sites are in shellfish growing areas within the harbour, monitored by the Washington State Department of Health. The "Blaine Marina" sites (sampled by the Port of Bellingham) are located within the marina breakwater as well as four sites on a trajectory extending northwest from the tip of Semiahmoo Spit.

The model does not show elevated fecal coliform levels at a number of the sample sites. This suggests that fecal coliform contamination is highly localized. Other sources of fecal coliform – for example shoreline outfalls, marine animals, birds, boats discharging sewage, and fish processing wastes – have been identified but are thought to be very small in terms of their loading relative to the creeks and rivers (Beard and Conner 2002). Perhaps they are significant in their immediate vicinity or immediately upon entering the water body.

The time series created for the six sources in the model were subject to much interpolation and extrapolation. Refinements to the loadings in the model might increase the extent of the contaminated area. Also, the model may create more dilution than actually occurs.

5 CONCLUSIONS

The three-dimensional hydrodynamic model H3D successfully reproduced circulation patterns in Semiahmoo Bay and Drayton Harbour, as verified by the July 2002 field study. The use of local winds (i.e. at Crescent Beach) was essential to modelling the circulation. Six sources of fecal coliform were applied to the model for the 2001 year-long simulation:

- Serpentine River,
- Nicomekl River,
- Little Campbell River,
- Dakota Creek,
- California Creek,
- and the Blaine STP.

The loadings for each of the six sources were created by interpolation and extrapolation from data that was quite sparse for some sources. To generate more useful data about the fecal coliform levels in the major sources, the freshwater sampling programs should be increased in frequency.

Based on the inputs used in the model, the Little Campbell River caused by far the most extensive and frequent contamination. It affected Semiahmoo Bay along the shore of White Rock. Dakota Creek and Serpentine River were the next most significant sources. Dakota Creek affected only Drayton Harbour while the Serpentine River affected a small area in Mud Bay. California Creek had a minor impact in Drayton Harbour. The Nicomekl River and the Blaine STP did not cause any exceedances of water quality standards.

These model results suggest that the greatest benefit to water quality in Semiahmoo Bay would be achieved by concentrating on reducing fecal coliform levels in the Little Campbell River. Within Drayton Harbour, the water quality could be improved by focusing on Dakota Creek.

Independently of this study, an adjustable-layer version of H3D was developed. In this new version, the present surface layer of 5 m thickness is replaced by a number of 1 m thick layers that appear and disappear as the tide fluctuates. This causes the fecal matter from the rivers to be confined in a smaller volume, which results in less dilution in the model cells and consequently higher concentrations. The dynamics of the river plumes change as well when they are confined to the thinner layers, allowing the fecal matter to spread more extensively. An unvalidated run of a preliminary version of this new model shows a much larger area with fecal coliform concentrations exceeding the water quality standards.

The present model did not predict contamination levels as high as those observed by various sampling programs in marine waters. The model performance could be improved by using the new adjustable-layer version, which results in less dilution of the fecal coliform from the sources. As well, other sources could be incorporated into the model, for example the distributed source of ocean outfalls along the White Rock shoreline.

6 RECOMMENDATIONS

To further benefit water quality improvement programs, the following recommendations are made:

1. Using the new adjustable-layer model, re-run the 2001 simulation;
2. Add distributed sources to the model; and,
3. Where possible, upgrade the coliform sampling programs

The adjustable-layer model predicts much larger areas where fecal coliform standards are exceeded than the present model predicts. For example, compare the January 2001 results of the new adjustable-layer model for the Little Campbell River (Figure 6.1) with the results from the fixed-layer model used in the present study (Figure 4.2). The adjustable-layer model predicts that almost all of Semiahmoo Bay and Boundary Bay, as well as Drayton Harbour (approximately 150 km^2 in total), are exposed to coliform above the 14 CFU/100 mL level, compared to an area of roughly 8 km^2 predicted by the fixed-layer model. This dramatic result is made more meaningful by examining the length of time of exposure to these coliform levels (Figure 6.2), compared to exposure times for the fixed-layer model (Figure 4.12). Note that the exposure times are not consecutive times, but simply the sum of hours during which the fecal coliform exceeded 14 CFU/100 mL in the month of January. Large areas with coliform concentration above 14 CFU/100 mL in Figure 6.1 correspond to total exposures of only a day or two in Figure 6.2. The area experiencing contamination for over 25% of the month is still significant, stretching nearly from the mouth of the Nicomekl River to the mouth of Drayton Harbour (almost 15 km of shoreline) and extending up to 4 km offshore in Semiahmoo Bay. The results from the adjustable-layer model are in keeping with values from various marine sampling programs that showed high levels of contamination quite a distance offshore (see Figure 4.16).

Upgrading fecal coliform sampling programs on the major freshwater sources to Semiahmoo Bay will provide better inputs to the model. A more complete information archive could be used to compare the sources outside of the modelling exercise as well, for example to track the impact of remediation efforts. More frequent sampling programs within marine waters would provide a better basis for comparison with the model results and would indicate improvements to water quality in shellfish harvesting areas.

7 REFERENCES

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FIGURES

APPENDIX A
ADCP SECTIONS

APPENDIX B
CTD PROFILES

APPENDIX C
METEOROLOGICAL STATION DATA

APPENDIX D
MODELLED VELOCITY SECTIONS ALONG TRANSECT

APPENDIX E
MODELLED VELOCITY VECTORS –
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MODELLED VELOCITY VECTORS –
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APPENDIX G
MODELLED VELOCITY VECTORS –
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