FLUSHING SIMULATION REPORT

VESSUP BAY MARINA FLUSHING STUDY
St. Thomas, U.S. Virgin Islands

For
Jack Rock B-A C, LLC

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Applied Technology & Management, Inc.
www.appliedtm.com
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Cover photograph in 2020 by C. Mueller, Applied Technology & Management, Inc.
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List of Abbreviations and Acronyms

ADCP  acoustic Doppler current profiler
ATM  Applied Technology and Management, Inc.
cm/s  centimeters per second
CTD  conductivity temperature depth
EFDC  Environmental Fluid Dynamics Code
EPA  U.S. Environmental Protection Agency
K1  lunar diurnal
m  meter
m/s  meters per second
M2  lunar semidiurnal
mi²  square mile
mg/L  milligrams per liter
MLW  mean low water
NDBC  National Data Buoy Center
NOAA  National Oceanic and Atmospheric Administration
ORD  Office of Research and Development
SA  solar annual
USACE  U.S. Army Corps of Engineers
USVI  U.S. Virgin Islands
1.0 Introduction

Jack Rock B-A C, LLC (the Owner), at the request of Mr. Lee Steiner, retained Applied Technology and Management, Inc. (ATM) to provide a marina flushing study to evaluate the potential impacts of a marina wave protection structure on the flushing of Vessup Bay. This task was part of the studies for the permitting of the marina at Vessup Point in St Thomas, U.S. Virgin Islands (USVI).

ATM has worked with OBMI International in the planning for redevelopment of the marina at Vessup Point. Pre-application meetings by the project environmental consultant with the U.S. Army Corps of Engineers (USACE) resulted in the request to assess impacts of the marina project on the flushing of Vessup Bay. ATM’s proposed marina concept plan, which includes a wave protection structure, was evaluated using a flushing model.

1.1 Study Area and Project Description

Vessup Bay is located on the eastern end of St. Thomas in the USVI (Figure 1-1). The planned marina is located at Vessup Point. Vessup Point juts out to the north at the Vessup Bay entrance. Vessup Bay is connected to Muller Bay and Redhook Bay (Figure 1-1). The distance from Vessup Point to the west end of Vessup Bay is about 0.47 mile, and the width at the east entrance at Vessup Point is about 0.12 mile. The area of Vessup Bay is about 0.05 square mile ($\text{mi}^2$).

Figure 1-2 presents a view of Vessup Bay with the proposed marina docks and the final design of the wave protection structure. Various alternative layouts of the wave protection structure were evaluated and are presented in this report. The final wave protection structure design will extend from the surface down to the bottom and will have two components. One component will sit perpendicular to the shoreline, with a length of around 190 feet. A gap of approximately 70 feet will exist between the barrier and the shoreline to allow flow to pass through. This gap was identified through the alternative analyses presented later. The second component will run parallel to the shoreline at the end of the perpendicular barrier. This barrier is approximately 260 feet in length.

1.2 Objectives

To inform the marina design and in response to the regulatory requirement, ATM conducted the following tasks.

1. Collect desktop and field data for the model setup and calibration.
2. Develop a hydrodynamic model that is capable of simulating the circulation within, and exchange between, Vessup Bay with the adjacent waters of Muller Bay, including the proposed marina area.
3. Utilize the model to assess the degree of flushing/exchange in Vessup Bay under the present conditions and the conditions after construction of the marina and the installation of the wave protection structure.
4. Evaluate alternative conditions for the design of the wave protection structure to minimize changes in the overall flushing of Vessup Bay.
5. Prepare a technical report to support the permit application.
1.3 Report Outline

The report is presented in 3 sections following this introduction. Section 2 presents the field data studies conducted to support the model development. Section 3 outlines the development of the hydrodynamic model. Section 4 presents the flushing simulations performed and the findings from the study.

Figure 1-1. Vessup Bay and Marina Location Map
Figure 1-2. Vessup Point Plan View with Proposed Marina Location and Wave Protection Structure (Design Condition)
2.0 Field Studies

ATM conducted field studies within Vessup Bay for the purpose of providing data to validate that the hydrodynamic model is reasonably simulating the circulation and exchange conditions within Vessup Bay. The primary goal was to collect water level data at various locations and characterize the velocity and circulation characteristics in the vicinity of the proposed marina area.

Field data were collected during two trips. The first trip was from September 8 to September 11, 2020. The second trip was from October 7 to October 8, 2020. Due to the relatively small tidal amplitudes in the area, along with the dead-end nature of Vessup Bay, the velocities at the entrance are very small and generally more driven by winds than tides. This was an issue that impacted the field data collection described in the following paragraphs.

On the first trip, instruments to measure conductivity, temperature, and depth (CTD) were installed at three locations as shown in Figure 2-1. The CTDs recorded water levels, temperature and salinity. In addition, a barometric pressure sensor was installed at Vessup Point to provide pressure readings to be utilized to correct the data from the CTDs. In addition to the CTD data, a towed acoustic Doppler current profiler (ADCP) was utilized to record velocities along a transect at the proposed project site (Figure 2-1). Due to issues with one of the frequency sensors on the ADCP, along with the very low velocity magnitudes, the ADCP data from this deployment was determined to not be useable.

The second trip, from October 7 to October 8, was designed to collect useable ADCP data. As such, only one CTD was installed at the CTD-2 location. For this work, the methodology for collecting the transect data was modified. First, instead of using the ADCP in towed mode, it was boat mounted to provide a more fixed and stable mount. Wind chop, experienced on the first trip, was such that, given the very low nature of the velocities (near the capabilities of the ADCP accuracy), the movement of the sensor in the towed array was unacceptable. Second, the ADCP data collection was alternated between running transects and measuring at a fixed location (anchored boat) for periods of 15 minutes. This allowed point velocity readings that were averaged over time to help reduce the impact of noise on the results and provide a better assessment of net flows. The point velocity measurements were taken in the vicinity of the marina basin, the middle of the cross-section, and on the northern side of the transect. A CTD was installed at Vessup Point to record water levels through the ADCP data collection. Figure 2-1 presents the locations of the transect, the point velocity measurements, and the installation of the CTD (CTD-2).

Figure 2-2 presents plots of the data collected by the CTDs during the first trips. Figure 2-3 presents the CTD data from the second trip. The data show that there is no significant variation in the tidal signal from the offshore station to the upper end of Vessup Bay, i.e. no damping or amplification. The salinity data show that other than the first part of the measurements in September, where the salinities at the offshore station are low, the salinity gradient between the offshore and nearshore is very small with salinity levels near ocean conditions [35 parts per thousand (ppt)]. Salinities at the interior station are slightly higher indicating little freshwater inflow and the potential for evaporation creating higher salinity levels. Temperatures fluctuate as expected with the response to the heating a cooling throughout the day more pronounced at the more interior stations reflective of the shallow stagnant nature of the waters.
Figures 2-4 a,b through 2-6 a,b present the point velocity measurements throughout the day for each of the three point stations respectively (North, Middle and South). Figure 2-7 presents the transects collected on October 8 plotted over one another. Hand-held wind measurements were taken during the times of the point and transect measurements.
Figure 2-2. Measured Water Level, Temperature and Salinity for September 8 through 11, 2020 Trip

Figure 2-3. Measured Water Level, Temperature and Salinity for October 7 and 8, 2020 Trip
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Figure 2-6b. Point Current Measurements at the South Station October 8, 2020
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Examination of the measured currents shows that first the velocities are very low overall, generally at or near 3 centimeters per second (cm/s). This is close to the measuring capability of the ADCP current meter. Examination of the current measurements as a collective, illustrates the development of a counterclockwise gyre forming at the entrance due to the winds coming out of the ESE. This makes sense as the winds are blowing at an angle to the entrance from the south and setting up a gyre coming off Vessup Point. This creates currents that are generally pushing in on the north side, varied from pushing in to rotating southward in the middle, and then flowing out near the tip of Vessup Point. This can also be seen in the transect data presented in Figure 2-7. While there is noise in the data and variation, this is the overall pattern that was seen during the measurements. This pattern will be the primary aspect to represent in the results presented within the model validation section (3.4).

Table 2-1 presents the measured winds. Throughout the measurements the winds were coming from an ESE direction.
3.0 Hydrodynamic Model Development

ATM studied the hydrodynamics of both the base conditions (existing) of Vessup Bay, various alternative designs for the wave protection structure, and the final proposed design condition with the wave breaker that will exist after the proposed infrastructure construction. The objective of the hydrodynamic study was to characterize circulation in the bay and flushing of constituents from Vessup Point to the south end of Vessup Bay, forced by tide and wind. The objective is to quantify any changes in the baseline flushing due to the installation of the structure.

ATM used a numerical model to simulate circulation and the time to flush a conservative tracer from Vessup Bay to Redhook Bay. The model is described in Section 3.1. The simulation grid and bathymetry are described in Section 3.2. Boundary conditions are described in Section 3.3. The validation of the reasonableness of the simulations based on the data described in Section 2 is presented in Section 3.4.

3.1 Model Description

ATM used the Environmental Fluid Dynamics Code (EFDC) to simulate hydrodynamics and flushing of a conservative tracer. EFDC is a general-purpose hydrodynamic model, typically used to simulate two-dimensional and three-dimensional flow, circulation, transport, and biogeochemical processes in surface water systems, including rivers, lakes, estuaries, reservoirs, wetlands, and nearshore-scale to continental-shelf-scale coastal systems. EFDC is open-source software in the public domain, currently supported by the U.S. Environmental Protection Agency (EPA) Office of Research and Development (ORD).

EFDC solves three-dimensional, hydrostatic, free-surface, turbulent-averaged equations of motions for a variable-density fluid. Dynamically coupled transport equations for turbulent kinetic energy, turbulent length scale, salinity, and temperature are also solved. Two turbulent transport equations implement the Mellor-Yamada level 2.5 turbulence closure scheme. EFDC uses a grid with a stretched or sigma vertical geometry and curvilinear, orthogonal, horizontal geometry.

EFDC solves the equations of motion with a second-order accurate spatial finite differencing scheme on a staggered or C grid. The model’s time integration employs a second-order accurate three-time-level, finite difference scheme with an internal-external mode splitting procedure to separate the internal shear or baroclinic mode from the external free-surface gravity wave or barotropic mode. The external mode solution is semi-implicit and simultaneously computes the two-dimensional surface elevation field by a preconditioned conjugate gradient procedure. The external solution is completed with the calculation of depth-average barotropic velocities using the new surface elevation field. The model’s semi-implicit external solution allows large time steps constrained by stability criteria of either the explicit central difference scheme, or by a higher-order upwind advection scheme used for nonlinear accelerations. Horizontal boundary conditions for the external mode solution include options for simultaneously specifying the surface elevation only, the characteristic of an incoming wave, free radiation of an outgoing wave, or the normal volumetric flux on arbitrary parts of the boundary.

3.2 Simulation Grid and Bathymetry

ATM developed an overall model grid that covers a much larger region including Vessup Bay, Muller Bay, Redhook Bay, and portions of St. Johns Bay (Figure 3-1). The larger-scale domain allows currents to develop in hydrodynamic stability that force Vessup Bay and Redhook Bay
domains. The larger-scale domain also allows the transport and dispersion of conservative dye tracer into a region that is not influenced by boundary conditions.

ATM discretized the domain with 3,689 horizontal grid cells and four vertical layers. The base grid is fit to the shoreline based upon aerial photography. The base grid represents present or existing conditions, prior to proposed construction. Figure 3-2 presents a zoomed-in view of the grid including Vessup Bay for the base conditions, with the proposed docks and the final design barrier outlined. The only changes on the grid for the design condition and the alternatives is that barriers are identified within the model domain blocking the grid faces that the barrier extends along.

Bathymetry for the base modeling was taken from a combination of National Oceanic and Atmospheric Administration (NOAA) navigation charts and measured bathymetry in the vicinity of the project. The bathymetry in the vicinity of the proposed dock structures was not altered from the base bathymetry. Figure 3-3 shows the overall model bathymetry, and Figure 3-4 shows a zoomed-in view of the bathymetry for Vessup Bay. The datum for the bathymetry and the water levels was mean low water (MLW).

3.3 Boundary Conditions

3.3.1 Offshore Water Levels

ATM forced the simulation with tides on the eastern open boundary of the domain. The data from the field studies was of a relatively short duration and used primarily for the model validation presented in Section 3.4. To perform longer simulations, ATM performed a least-square analysis to compute tidal harmonics with the high-low tides provided from NOAA Tides & Currents at Redhook Bay. The blue solid line presents the harmonic tide above MLW, which is calculated by the high-low tides in red circles (Figure 3-5) for a period of time in February 2020. The range of the harmonic tides was 0.45 meters (m) from February 5 to March 10, 2020, with the dominance of lunar diurnal (K1). Using this methodology, harmonic tide conditions were generated for the periods of the simulations presented in Section 4.
Figure 3-1. Overall Model Grid
Figure 3-2. Model Grid within Vessup Bay
Figure 3-3. Overall Model Bathymetry
Figure 3-4. Model Bathymetry within Vessup Bay

Figure 3-5. Predicted Tide (in blue solid line) Computed from NOAA High-Low tide Prediction (in red circle) at Redhook Bay
3.3.2 Winds

In addition to the tidal forcing, wind conditions were utilized to simulate hydrodynamics and transports of conservative dye tracers. Wind data for this project were obtained from Charlotte Amalie, USVI, where 6-minute interval data were available from 2005 to 2017 (NOAA, 2020a). ATM analyzed the available wind data to develop wind conditions for use in the simulations presented in Section 4.

ATM performed a statistical analysis for approximately 10 years of wind data from January 2007 to September 2017, since the wind data were not recorded from June 2011 to January 2012. The wind rose (Figure 3-6) presents the distribution of wind speed and direction. Wind direction is expressed at a point from which the wind blows, for example, a northerly wind direction blows from the north. The frequency of wind direction over a time period is described by a polar coordinate system (the circle in Figure 3-6), with color band showing the range of wind speed. Most of the wind directions were oriented from the east, which indicate the wind blew onshore. The most dominant direction, with 15 percent of the total, was 80° clockwise from the north, and the 10-year average wind speed was 1.95 meters per second (m/s). The data were analyzed to define the average monthly wind (Figure 3-7), which was averaged by month for 10 years. This plot shows that winds are stronger in the summer and weaker in the winter.

From the statistical analyses of the data, 10-day wind periods were defined from the record that reflected low wind conditions, average wind conditions, and high wind conditions. The periods were based on 10-day moving averages of the data and choosing time periods which reflect the average of the full record (average wind), 90th percentile (high wind) and 10th percentile (low wind). The time series for these 10-day periods were used in the simulations in Section 4.

![Wind Rose for 10 Years](image)

*Figure 3-6. Wind Rose from January 2007 to September 2017*
3.4 Model Validation

Based on the nature of the measured velocities presented in Section 2, the validation of the model came from comparisons of the overall current patterns within the model with those seen in the measured data. The currents in Section 2 identified the existence of a gyre at the mouth of the bay with the flows going out along the shoreline areas and flowing in for the middle.

The model was run for the conditions which existed at the time of the successful velocity measurements in October. Figures 3-8a and 3-8b present vector plots showing snapshots of the simulated velocity vectors. The plots show the gyre with the flows out along the edges with the flows moving into the bay in the middle. The gyre, based on the winds out of the southeast, exists at the mouth with velocity magnitudes similar to those measured in the field. In order to get the model to reproduce this condition, wind shading was applied to the more nearshore areas. This allowed the pattern found in the measurements to be simulated as shown in the figures. This provides qualitative and somewhat quantitative validation of the model simulations.
Figure 3-8a. Velocity Vectors in Mouth of Vessup Bay (Time 254.208)

Figure 3-8b. Velocity Vectors in Mouth of Vessup Bay (Time 254.208)
4.0 Flushing Assessment

4.1 Methods

Using the model described in Section 3, ATM performed flushing evaluations through a spring-neap tidal cycle under varying wind conditions. ATM simulated the concentration of a synthetic, hypothetical tracer initialized in the Vessup Bay area with a dye concentration of 100. As stated previously, the goal is to determine differences in the flushing between the existing (base) condition and the conditions following installation of the wave protection structure (design).

The concentration of the hypothetical, synthetic tracer was nominally 100 milligrams per liter (mg/L) at the beginning of each scenario simulation. The tracer was uniformly distributed in a 0.05-mi² area in Vessup Bay Marina. The concentration decreased as tracer in the marina was transported to Muller Bay and Redhook Bay, and as water in Muller Bay and Redhook Bay mixed with water in Vessup Bay.

ATM simulated concentration of a conservative tracer forced by harmonic tide and winds. The model configurations in Table 4-1 describes the wind conditions for each scenario as the low, average and high winds as defined in Section 3.3.2 along with the design conditions and alternatives. The tide conditions cycle through a spring/neap condition for the simulations. Figure 4-1 presents the tides for the 10-day simulations presented below. The simulations start at neap tide conditions. As the tidal influence is low, and the goal is to provide a relative comparison of the flushing between the base, design and alternative conditions, rather than an absolute assessment of the flushing times, these conditions are reasonable for the analyses.

![Figure 4-1. Tide Conditions for Flushing Simulations](image-url)
Table 4-1. Model Configurations

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</tr>
<tr>
<td>VSSP-HWND-DSGNA1</td>
<td>Alternative 1</td>
<td>Neap to Spring</td>
<td>High Wind</td>
</tr>
<tr>
<td>VSSP-HWND-DSGNA2</td>
<td>Alternative 2</td>
<td>Neap to Spring</td>
<td>High Wind</td>
</tr>
<tr>
<td>VSSP-HWND-DSGNA3</td>
<td>Alternative 3</td>
<td>Neap to Spring</td>
<td>High Wind</td>
</tr>
</tbody>
</table>

4.2 Alternatives Assessment

For the wave protection structure, various alternatives were simulated. Initially, the design looked to extend the portion of the barrier that was shore parallel all the way to the shoreline to provide the maximum protection for the boats on the inside of the marina area (Alternative 1). Initial flushing simulation results showed that this would increase the overall flushing times within Vessup Bay significantly. Two other alternatives were run. The first had a gap of 23 feet between the shoreline and the wave protection structure (Alternative 2). The second had a gap of 46 feet (Alternative 3). The final runs looked at the Design condition with a gap of 70 feet (Figure 1.2).

- Base Condition – no structures
- Design condition - gap of 70 feet between the shoreline and the wave protection structure
- Alternative 1 – wave panels connecting to the shoreline
- Alternative 2 – gap of 23 feet between the shoreline and the wave protection structure
- Alternative 3 - gap of 46 feet between the shoreline and the wave protection structure
Figures 4-2a through 4-2c present graphs of the percent mass remaining for the average wind, high wind, and low wind conditions for each alternative compared to the baseline condition. Examination of the figures shows that a gap of 70 feet (Design condition) is required between the shore perpendicular wave protection structure and the shoreline in order to not significantly impact the flushing in Vessup Bay. Section 4.3 presents a more detailed presentation of the design results.

4.3 Detail Results for Design Simulation

Detailed results for the design condition simulation runs versus the baseline are presented in the series of Figures from 4-3 to 4-5. The graphics presented include snapshot plots of the vertically averaged dye concentrations at different points through the simulation. Results are presented for the starting condition (day 0) then for days 1, 4, 7, and 10. The snapshot plots show how for each of the wind and physical (base versus design) conditions the dye concentration distribution changes over time as the waters between Vessup Bay, Muller Bay, and Redhook Bay mix. The base and design plots are presented on the same page for each time and condition to allow comparison between the two. The design plots show the location and extent of the wave protection structure under the design condition.

Figures 4-2a through 4-2c present the plots of the time series of the percent mass remaining for the base and design conditions that are shown in the snapshot plots. This provides the direct quantitative comparison of the differences in the flushing with and without the wave protection structure.

Figure 4-2a. Comparison of the Percent Mass Remaining for the Alternatives, the Design Condition and the Baseline Condition under Average Wind Conditions
Figure 4-2b. Comparison of the Percent Mass Remaining for the Alternatives, the Design Condition and the Baseline Condition under High Wind Conditions

Figure 4-2c. Comparison of the Percent Mass Remaining for the Alternatives, the Design Condition and the Baseline Condition under Low Wind Conditions
Figure 4-3a. Base and Design Vertically Averaged Dye Concentrations for Low Wind Simulation (Day 0)
Figure 4-3b. Base and Design Vertically Averaged Dye Concentrations for Low Wind Simulation (Day 1)
Figure 4-3c. Base and Design Vertically Averaged Dye Concentrations for Low Wind Simulation (Day 4)
Figure 4-3d. Base and Design Vertically Averaged Dye Concentrations for Low Wind Simulation (Day 7)
Figure 4-3e. Base and Design Vertically Averaged Dye Concentrations for Low Wind Simulation (Day 10)
Figure 4-4a. Base and Design Vertically Averaged Dye Concentrations for Average Wind Simulation (Day 0)
Vessup Bay, Base Condition - Average Wind

Water Column
[Time << 0.001]
Dye (mg/l)
Depth Averaged
Dye

Vessup Bay, Design Condition - Average Wind

Water Column
[Time 47.000]
Dye (mg/l)
Depth Averaged
Dye

Figure 4-4b. Base and Design Vertically Averaged Dye Concentrations for Average Wind Simulation (Day 1)
Figure 4.4c. Base and Design Vertically Averaged Dye Concentrations for Average Wind Simulation (Day 4)
Figure 4-4d. Base and Design Vertically Averaged Dye Concentrations for Average Wind Simulation (Day 7)
Figure 4-4e. Base and Design Vertically Averaged Dye Concentrations for Average Wind Simulation (Day 10)
Vessup Bay, Base Condition - High Wind

Vessup Bay, Design Condition - High Wind

Figure 4-5a. Base and Design Vertically Averaged Dye Concentrations for High Wind Simulation (Day 0)
Figure 4-5b. Base and Design Vertically Averaged Dye Concentrations for High Wind Simulation (Day 1)
Figure 4-5c. Base and Design Vertically Averaged Dye Concentrations for High Wind Simulation (Day 4)
Figure 4-5d. Base and Design Vertically Averaged Dye Concentrations for High Wind Simulation (Day 7)
Figure 4-5e. Base and Design Vertically Averaged Dye Concentrations for High Wind Simulation (Day 10)
Examination of the plots shows a number of aspects. First, the patterns of the movement of the dye exchanging into and out of the system reflect the findings from the field observations with the general pattern of movement into the bay through the middle and out of the bay along the edges. This is also the case with the design wave protection structure in place. Second, the degree of flushing in the system is a function of the wind conditions, with the highest level of flushing occurring during the higher wind conditions and the overall level of flushing decreasing as the lower winds are used in the simulations.

The most significant finding from the results is that the inclusion of the wave protection structure, under the proposed design condition with the 70-foot gap, does not significantly impact the overall flushing of the bay. While the snapshot plots show some trapping that occurs in the area of the structure and its influence is clearly seen in the local dye patterns in the immediate vicinity, the overall levels of exchange are not altered in a significant way. The time series plots for all the wind conditions show only minor differences, with the overall percent mass remaining at the end of the 10-day periods nearly identical for all wind conditions.

4.4 Findings

Based on the simulations presented in Section 4.2, no significant differences were found in the degrees of flushing within Vessup Bay between the base simulations and the simulations with the wave barrier in place (design condition with 70 foot gap). This was the case for all three wind conditions simulated. Based on this, it is determined that the installation of the wave protection structure in the design condition will not impact the present level of flushing within Vessup Bay.

5.0 References

