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DRAFT REPORT

Currents in Nassau Harbour **Nassau Harbour Port Improvement Project**

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Currents in Nassau Harbour

Nassau Harbour Port Improvement Project

Draft Report

Prepared for

**Cox & SHAL Consultants
and the Government of the Bahamas**

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1.0 INTRODUCTION

Expansion of Nassau Harbour, shown in Figure 1.1, is planned for 2009, and will involve the widening of the approaches to the harbour and an increase in the size of the turning basin. The dredging that will take place during this operation will result in some turbidity, and there is concern over where this turbidity will spread. In particular, the region to the west of Arawak Cay and the region east of the harbour have been identified as a possible locations where adverse impacts may occur.

Baird & Associates was retained by Cox & SHAL to complete a study of the current patterns in the Nassau Harbour area, and specifically in the vicinity of Arawak Cay. This investigation focused on the collection of current data in the field, rather than completing extensive numerical modeling. This report makes use of metocean data that were compiled in a previous study by Baird & Associates in 2008 (Baird, 2008) that examined the impact of the proposed changes to beach stability in Nassau Harbour.

The report summarizes the field studies that were completed and provides a summary of the general current patterns in the area for the conditions that were measured. The report also provides some general discussion of the manner in which these currents may affect dredge plumes in the area.



Figure 1.1 Aerial Image of Nassau Harbour Main Navigation Channel

2.0 FIELD INVESTIGATIONS

A site visit and field data collection programme were undertaken by a Baird & Associates staff member from October 27th to 30th, 2008. Activities included a general site visit, observations of currents and wave patterns, tidal measurements, and boat-mounted current profile measurements in the vicinity of Arawak Cay.

2.1 Instrumentation

Currents were measured with a RDI Rio Grande 600 kHz Acoustic Doppler Current Profiler (ADCP), which is shown in Figure 2.1. The ADCP uses acoustic pulses from four beams on the instrument to measure the current velocity through the water column. These measurements rely on reflections of the acoustic pulse from tiny particles in the water column. Based on the Doppler shift principle and trigonometric relationships between the beams, the water speed and direction at discrete bins through the water column is computed (relative to the boat). The instrument is also capable of determining the movement of the boat through a bottom-tracking feature, which allows the corrected currents (relative to the bottom) to be computed. As the boat and instrument move across a transect, thousands of readings are collected, resulting in a detailed current profile. In any single “ping” from the instrument there can be considerable error; however, by virtue of the vast number of readings that are collected, the general current patterns are very well represented.

Typical graphical output from an ADCP transect is shown in Figure 2.2. The colours in this figure indicate the current speed at different depths across the transect. Current measurements very close to the bed of the channel and in the top one metre of the water column are not possible. Therefore, the software in the instrument uses a logarithmic relationship to estimate these flow velocities. In addition to measuring the currents along the transect, the instrument also provides an estimate of the total amount of water discharged through the cross section.



Figure 2.1 ADCP Current Meter

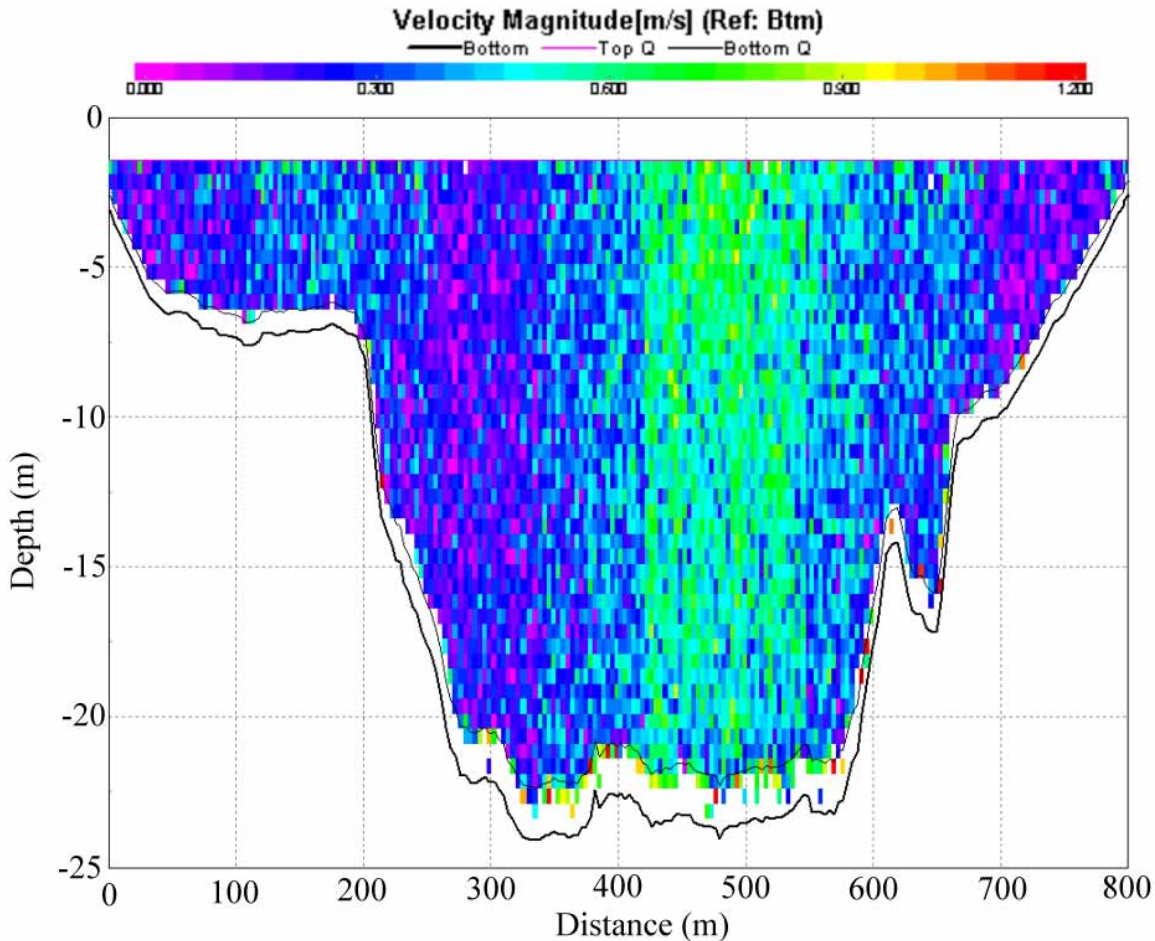


Figure 2.2 Typical Output from the ADCP Instrument

2.2 Current Measurement Summary

Current measurements were undertaken on October 28th and 29th, 2008 in order to gain insight to the typical tidal currents, as well as the effect of wind and waves on currents around Arawak Cay. Conditions on the 28th involved strong northwesterly winds, while the 29th was much calmer and more typical of conditions in the area. The wind conditions on the 28th were unusual, in that winds over 10 m/s from the NW quadrant occur only about one percent of the time. Tides during the sampling, shown in Figure 2.3, were mid-range in terms of magnitude and are approximately equal to mean tides at the site. The tide range was slightly higher in the morning compared to the evening on these particular days.

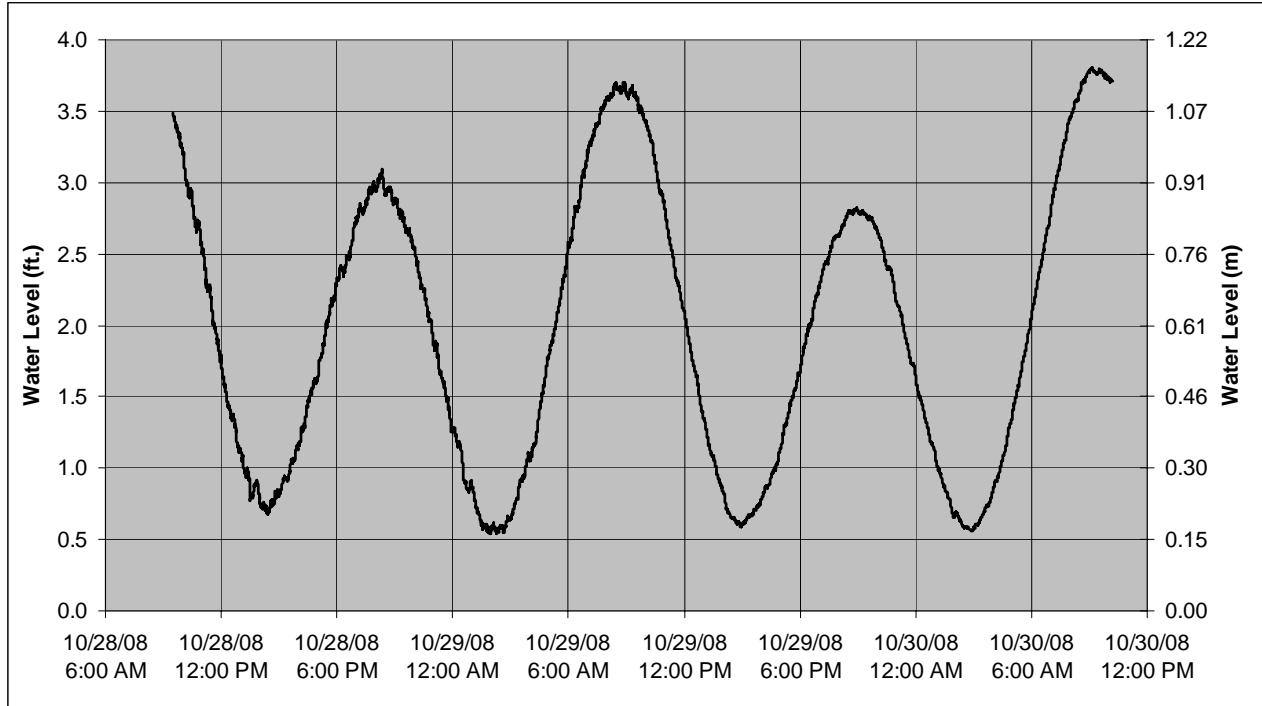


Figure 2.3 Tides at Nassau During the Current Measurements

Current measurements were repeated in specific locations at various times during each day in order to acquire samples throughout the tidal cycle. A total of 83 transect lines were recorded with the ADCP, at different channel locations around the site and at various times throughout the tidal cycle. Wind, tide and wave conditions were also observed, for discussion and interpretation of the collected water current data.

The resulting data yielded total flow rates at each transect, velocity profiles at various depths, and current direction along the transect line. This data allowed for a comparison of the effects of wind and waves on currents, as well as an idea of the proportion of water volume that ebbs and floods through certain channels around Arawak Cay. Information provided in this report is in the form of both discharge and current velocities. Note that discharges are representative values for a channel, while the current velocities reported will have variation across the transect lines, ranging from zero in some areas, to significantly more than the channel average. Changes in the channel cross section and blockage from structures may cause local maximums that may be twice the channel average.

Figure 2.4 shows the approximate locations of the current measurement transects, as well as reference numbers for each repeatable transect.

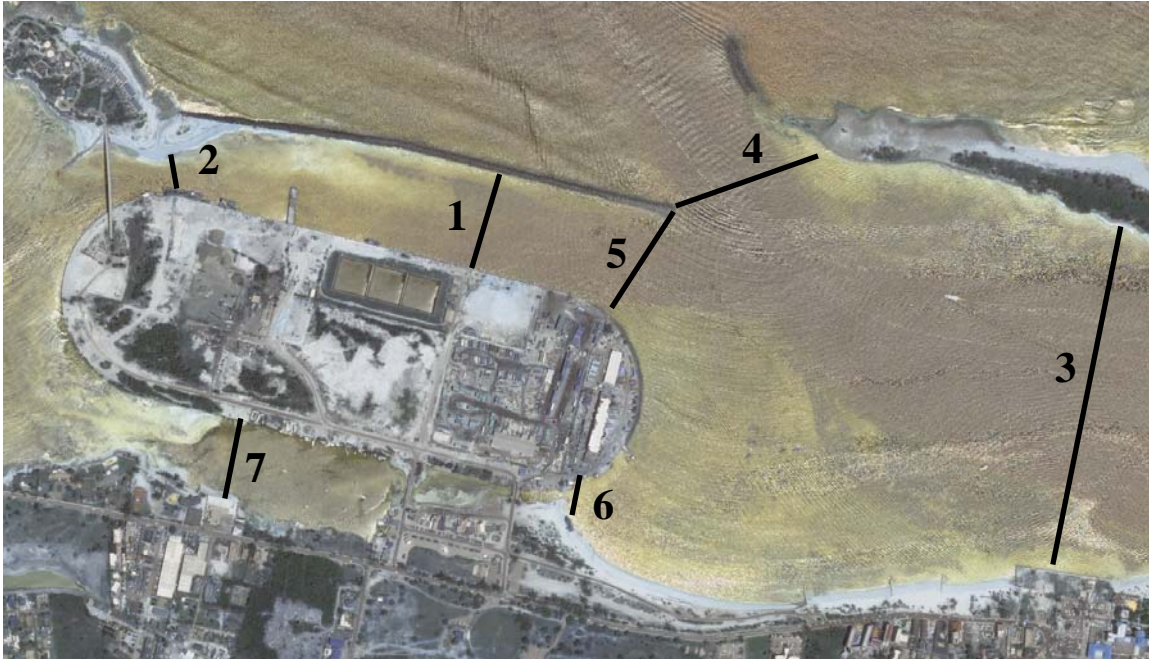


Figure 2.4 Study Area With Current Transect Reference Numbers

The findings from the current transect investigations provide insight as to where suspended sediment resulting from dredge operations in Nassau Harbour may travel. In general, tidal flood (rising tide) causes movement of water from the west to the east. Conversely, ebb (falling) tide moves the water volume from the east to the west. It was shown from the field measurements that the total peak flow rate during the tidal cycle for the area between the mainland and Paradise Island is approximately $900 \text{ m}^3/\text{s}$. The majority of this tidal flow enters and exits through the harbour mouth (via the dredged navigation channel), whereas a smaller fraction of the flow passes between the west breakwater and Arawak Cay. In addition, a very small amount of the flow passes through the small boat channel to the south of Arawak Cay.

The peak tidal flood and tidal ebb flow rates are subject to direct influence from wind and wave stresses. This can result in a potentially significant amplification or reduction of either the peak flood or ebb discharge. For example, on October 28th, with a significant wind blowing from the NNW, the ebb tide flow (i.e. moving from east to west, against the wind direction) across the entire harbour was approximately $450 \text{ m}^3/\text{s}$. At almost exactly the same point in the tidal cycle the following day, a repeat measurement across the harbour yielded an ebb tide discharge of approximately $900 \text{ m}^3/\text{s}$. Similarly, wind and wave effects were observed to have a secondary effect on the channel between the western breakwater and Arawak Cay. Comparison of the peak discharge that passes through the smaller navigation channel on the north side of Arawak Cay reveals that a significant volume of water is driven through the channel constriction resulting from wind-induced flow arriving from the area west of Arawak Cay. This can be seen by comparing similarly measured ebb tide flow rates in this channel on October 28th (significant NNW wind) of approximately $100 \text{ m}^3/\text{s}$ (west to east) to the similarly recorded flow on October 29th (negligible wind effects) of approximately $25 \text{ m}^3/\text{s}$, east to west. Therefore, the force of the wind accounts for approximately $125 \text{ m}^3/\text{s}$ of excess flow in this channel, or five times the amount of discharge, compared to the ambient tides alone. It is reasonable to assume that a strong easterly wind would also affect the tidal currents and would increase the ebb flow through this channel by a similar amount.

2.3 Flood Tide Measurements

As previously described, the general direction of the baseline tidal flood discharge is from west to east. The data collected from the two days of current measurements was reduced in order to yield a general continuity plot around Arawak Cay (Figure 2.5). Due to the inability of the field program to record at each transect continuously at the same time, the flow rates indicated in this figure are best estimates of discharge at each of the sampling locations, based upon the measured data.

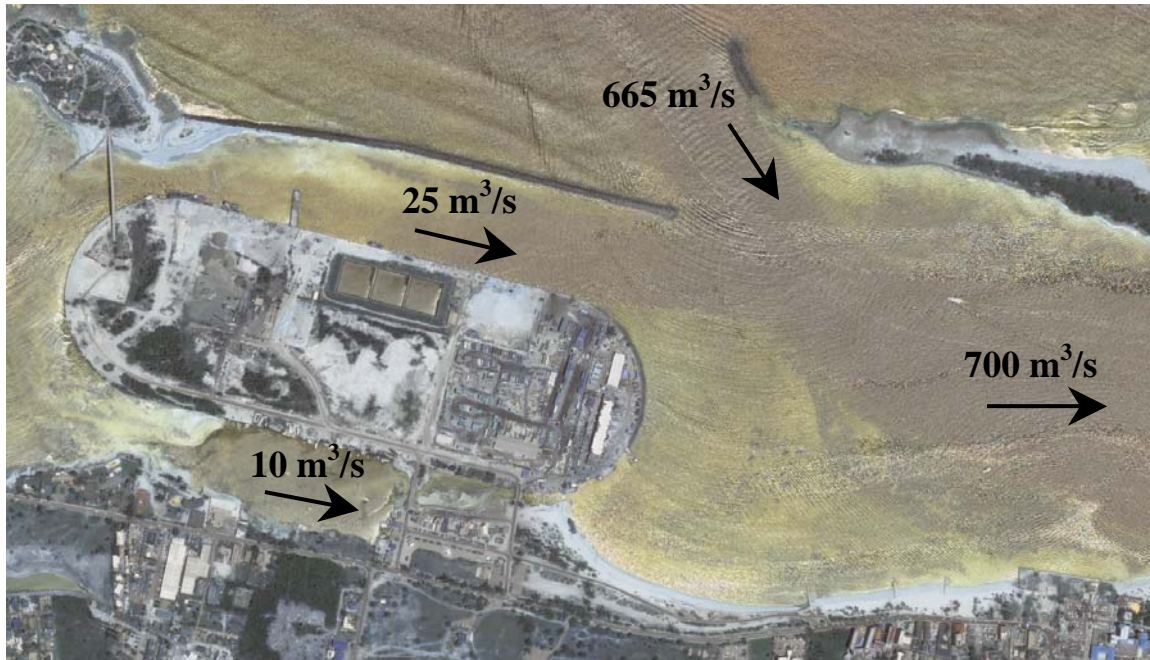


Figure 2.5 Generalized Ambient Flood Tide Measurements

Most of the tidal flood flow enters Nassau harbour through the harbour mouth, between the east and west breakwaters. This region has a channel cross section of about 3250 m², and typical current velocities of about 0.20 m/s. In the main part of harbour, the larger cross section means that the current velocities are lower than they are in the entrance, at about 0.10 m/s. These velocities will increase as the channel cross section narrows further to the east.

A relatively small amount of flow passes through both the north and south channels adjacent to Arawak Cay, with velocities of about 0.02 m/s in the wider parts of the north channel, which increase to about 0.10 m/s in the narrower areas. Evidence from the bathymetry in this area suggests that under storm conditions the flows and current velocities are much higher in the narrow area and some scour occurs. The higher velocities driven by winds on October 28th (these strong NW winds are a relatively rare occurrence at only about one percent of the time) resulted in currents at transect 2 that were in the order of 0.5 m/s. Current velocities in the south channel were also very weak, at about 0.02 to 0.04 m/s. In the shallow water of this channel, wind may well be the dominant factor in determining the current velocities.

2.4 Ebb Tide Measurements

The ambient ebb tide in Nassau Harbour drives water from the east to the west. This flow direction would be of primary concern relating to the development of a suspended sediment control strategy to mitigate the introduction of dredge sediment to the area west of Arawak Cay. Similar to the results shown from the flood tide data, the majority of the water volume exchanged from Nassau Harbour passes out of the mouth of the harbour, between the east and west breakwaters. Figure 2.6 shows the approximate peak discharge values for a baseline ebb tide condition. Similar to the flood tide values presented above, these estimated discharge values were based upon collected data during field exercises.

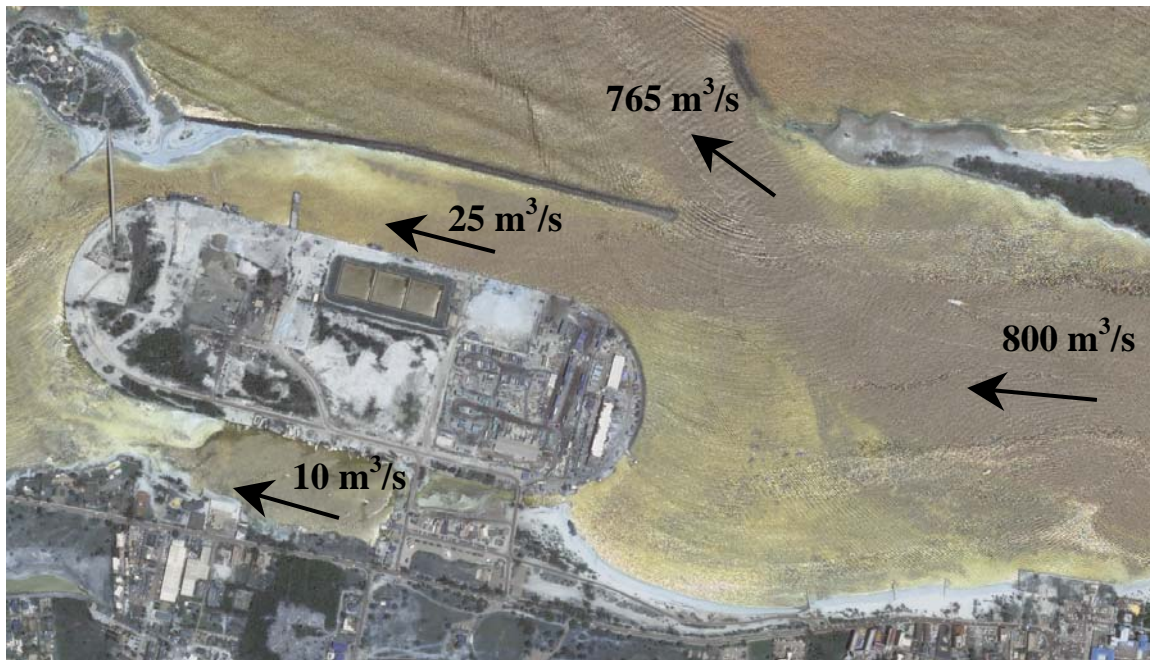


Figure 2.6 Generalized Ambient Ebb Tide Measurements

This schematic representation shows that less than 5% of the total flow passing through the harbour enters either of the channels that pass north or south of Arawak Cay. Despite the fact that this is only a small portion of the water passing through the harbour, it still represents a significant total volume of water over the duration of the tidal cycle.

Flows from the east through the harbour area appear to be marginally stronger than the opposing flood tide, perhaps due to the prevailing east winds. Currents velocities in the main harbour area are in the order of 0.10 m/s as a average cross sectional velocity.

Throughout most of the area, current velocities during the ebb tide were very similar to those during the flood tide, but in the opposite direction. The small differences in the flow rates on ebb and flood are not significant compared to the spatial variations in the current due to varied channel cross section and other factors.

2.5 Additional Notes on Current Measurements

Some additional observations were made during the field investigations that may lend themselves to the development of additional suspended sediment control strategies. In particular, it was found that during a period of significant northerly wind and waves, the measured current values along the channel north of Arawak Cay were not consistent. The measured discharges at transect 1 (mid-channel north of Arawak Cay) and transect 5 (east end of channel, near mouth of harbour) varied by 10-25% throughout the tidal cycle. Although this could be attributed to experimental error, it is most likely due to current transmission through the body of the eastern section of the west breakwater (flow through the porous armour unit structure). While on-site, the transmission rate for longer period wave activity through the breakwater was noticeably visible. This most likely explains why the discharge measurements vary along this flow conduit. Although this phenomena may not have a profound effect on the net transport finally passing through the north channel, it does provide an additional reason to undertake suspended sediment mitigation measures at the west end of the channel versus the east end.

Recorded velocity data in the north channel (in calm, tidal conditions only) varies significantly from one end to the other. Although the cross-sectional discharge remains relatively constant, the flow velocity increases from approximately 0.02 m/s at mid-channel (transect 1) to roughly 0.1 m/s near the bridge to Silver Cay (transect 2). However, these velocities increase proportionally with any additional discharge caused by wind and wave action. Both of these values were less than the comparable flow velocity of 0.20 m/s across the main harbour, at peak ebb tidal flow.

Appendix A provides a summary of the discharges measured through various cross sections, in addition to some sample data from the ADCP current measurement program.

3.0 DISCUSSION OF DREDGE PLUME

The work that is presented in this section does not provide specific recommendations about sedimentation or how Baird & Associates recommends dredging activities could take place. The discussion below is intended to provide some general information about the currents and turbidity. In order to provide specific recommendations, further information and analysis would be required.

3.1 Possible Sediment Movement During Dredging

3.1.1 Western Regions

With the observed current directions in the vicinity of Arawak Cay, the ebb tide is the condition that could move turbid water into the region west of Arawak Cay. To better understand the volume of water moving through the area, the following discussion is provided.

Field observations indicate that the change in direction of tidal current is fairly abrupt, and that the currents are fairly uniform throughout the ebb. Therefore to assess the total volume of water passing to the west of Arawak Cay, the nominal flow rate from Figure 2.6 is applied over six hours (the approximate duration of a semi-diurnal ebb tide). This results in about 750,000 m³ of water entering the region west of Arawak Cay. With an average depth of about 3 m, this volume of water could completely fill an area with a surface area of 250,000 m². This might be (for example) an area of 500 m by 500 m in size, as shown in Figure 3.1. The shape and extent of the region that is affected will certainly not be as indicated in this figure; this figure is intended to provide a representation of scale.

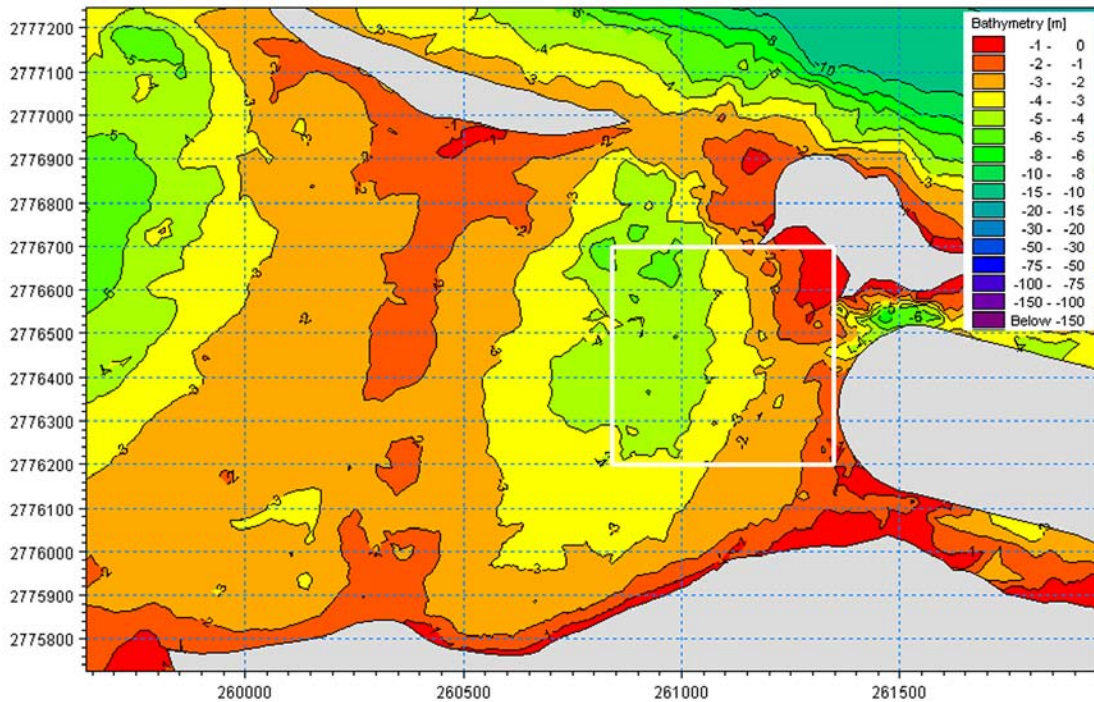


Figure 3.1 Representation of 250,000 m² in Region West of Arawak Cay

There are many factors that need to be considered in defining the actual extent of the region that may see some increased turbidity, including the following factors listed below.

- The turbidity levels east of Arawak Cay are presently undefined.
- The distribution of turbidity east of Arawak Cay is also important. The location where the dredger is operating may create conditions where the most turbid water is far from Arawak Cay, or perhaps very close the north channel. Figure 3.2 provides an aerial view of a dredging plume from 1989, which shows a large amount of spatial variability.
- The region that may be affected by turbid water will depend on wind and wave conditions that will disperse the turbid water in the region west of Arawak Cay.
- Dispersion may result in an area many times larger than that indicated in Figure 3.1 having some increase in turbidity.
- Different wave and wind conditions may create an environment where turbidity does not settle due to the currents and turbulence in the water column.
- It is uncertain what will happen to the water that passes out of the harbour entrance on an ebb tide. Some of this water may stay close to the west breakwater and move into the region west of Arawak Cay by entering the area through the gap between Silver Cay and Long Cay.



Figure 3.2 Example of a Dredging Plume from 1989 Aerial Photograph

It should also be noted that during periods of ebb tide when wind and wave conditions originate from the NNW, the discharge in the north and south channels around Arawak Cay would most likely travel from west to east (i.e. overcome the baseline ebb tide flow direction). This occurrence was observed and recorded on October 28th, with the discharge in the north channel shown to be approximately 100 m³/s, traveling from west to east.

3.1.2 Eastern Regions

The region to the east of Nassau Harbour is also at risk of seeing higher than normal turbidity during dredging operations. The flow of about 700 m³/s towards the east during the tidal cycle will move turbid water at velocities of about 0.1 m/s towards the east on the flood tide. This transport would also be significantly augmented when the wind conditions are from the NNW, based on the increase in discharge measurements recorded under these wind conditions. However, these NW wind conditions are very infrequent, with winds over 10 m/s from the NW quadrant occurring only about one percent of the time.

The manner in which the water moves is complex since this flood tide will be traveling against the prevailing winds. The result of this may be greater turbidity moving east deeper in the water column, while the surface or nearshore (shallow) areas may have somewhat lower turbidity concentrations.

The distance that this plume will move is also complicated by the varied bathymetry in the area, with a greater channel cross section near the turning basin (Transect #3) compared to shallower water depths to the east. If the current velocity is 0.1 m/s, then during a five hour flood tide, it follows that the plume would move about 2 km in distance. In regions east of the harbour, the channel cross sections is about one third to one quarter of the cross section where measurements took place. This will result of velocities that may be in the order of 0.4 m/s and will result in turbid water moving a substantial distance to the east, perhaps close to the east end of Paradise Island. The severity of the turbidity that would exist in these eastern areas at this time cannot be determined, since dredging practices, turbidity control measures, tidal amplitudes and wind conditions will influence turbidity patterns.

3.2 Possible Mitigation Measures

In order to reduce the amount of turbid water that enters the region west of Arawak Cay, consideration should be given to either implementing silt curtains or completely blocking the southern channel at the east end of Arawak Cay. This channel is small in size and could be relatively easily blocked during the course of construction.

The north channel presents greater challenges for controlling the turbid water. Sediment mitigation measures could be employed at the west end of the north channel out of the main navigation area, near the bridge spanning from Arawak Cay to Silver Cay. The channel in this region is narrower, and perhaps more conducive to controlling the turbidity. The typical velocities in this area are still less than the one knot criteria (U.S.A.C.E., 2005) for use of a silt curtain. A silt curtain may

significantly reduce the turbidity under more mild conditions; however, such a device may be of limited use in a wind enhanced flow situation.

Even if a silt curtain is successfully deployed (or a fixed barrier put in place), it is possible that strong tidal currents, coupled with the possibility of current and discharge enhancement from wind and wave forces, could bypass suspended sediment through the harbour entrance and around the western breakwater, to a location west of Arawak Cay. While this is thought to be theoretically possible, the probability of this occurring is very remote, and the turbid water would be very dispersed before moving back into this area. However, consideration should be given to this scenario during the planning phase for the dredging operations, and should be reflected in the dredging operations protocol, as well as the Environmental Management Plan.

Silt curtains are typically deployed close to the area of the site to be dredged, and help limit the turbidity in the upper part of the water column by forcing any flow near the bed. If a silt curtain was deployed near Silver Cay, which is distant from the dredging site, then any turbidity at that location would be very fine, and it is unlikely that the turbidity curtain would be particularly effective. Therefore, the only manner in which the turbidity curtain could be somewhat effective near Silver Cay would be if it were able to significantly reduce the total volume of water passing through this channel. This is not the normal manner in which silt curtains are deployed, and it may or may not be effective depending on the characteristics of the curtain.

Regions to the east of Nassau Harbour will be subject to turbid water from the dredging. The open water in this area means that controlling the turbidity in this region may be difficult. Measures to control turbidity close to the dredge site may be the best manner in which to reduce turbidity to the east.

The implementation of groyne structures to deflect the flow away from sensitive areas is not recommended as these structures are generally ineffective. In the slow moving currents that are present in this area, the momentum of the water will be quickly overcome by other forces such as waves, winds and dispersion. Therefore deflection structures are easily circumnavigated by turbid water.

The choice of whether and/or how to control turbidity passing to the west of Arawak Cay requires further consideration. A solid structure to prevent flows may be costly and disruptive during installation and removal. It could also affect the flow patterns in the area and have, or be perceived to have, other adverse effects (perhaps changing the water temperature or circulation). During a strong wind or hurricane, the differential water level across such a structure could also be significant, requiring a more substantial design.

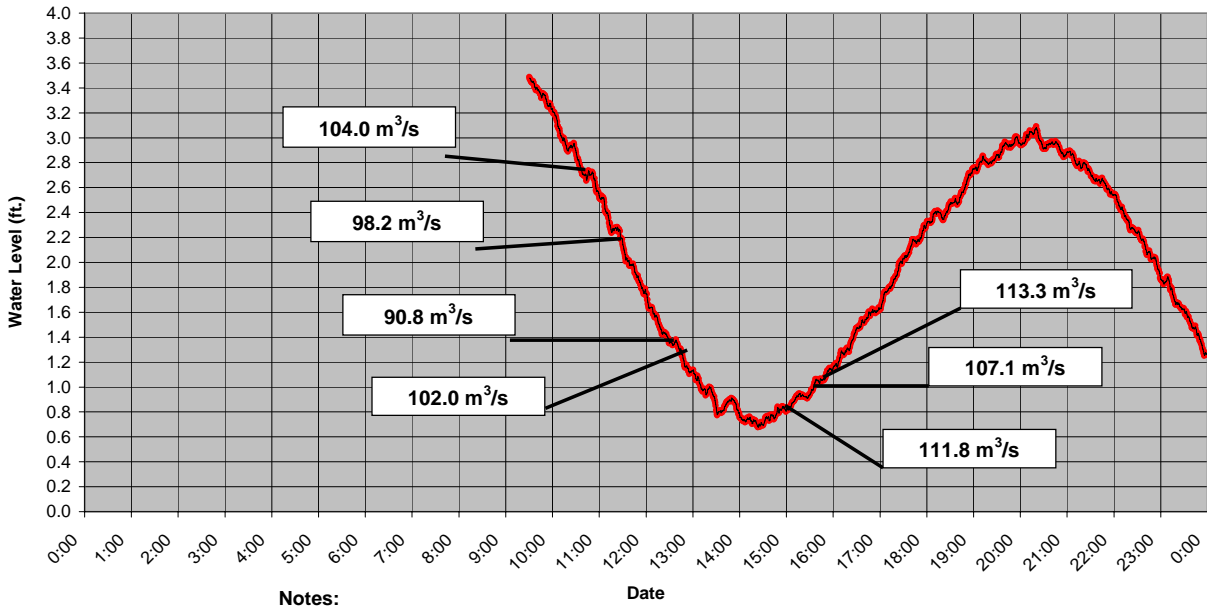
A silt curtain may be somewhat effective if properly deployed, but would need to be removable or stowed during high current events.

4.0 REFERENCES

- Baird, 2008. "Wave Climate and Dredging Impacts, Nassau Harbour Port Improvement Project" Report prepared for Cox & SHAL Consultants and the Government of the Bahamas, August 2008.
- U.S.A.C.E., 2005. "Silt Curtains as a Dredging Project Management Practice" DOER Technical Notes Collection (TN DOER-E21). U.S. Army Engineer Research and Development Center, Vicksburg, MS. <http://el.erdc.usace.army.mil/elpubs/pdf/doere21.pdf>

**APPENDIX A
SUMMARY AND SAMPLE ADCP DATA**

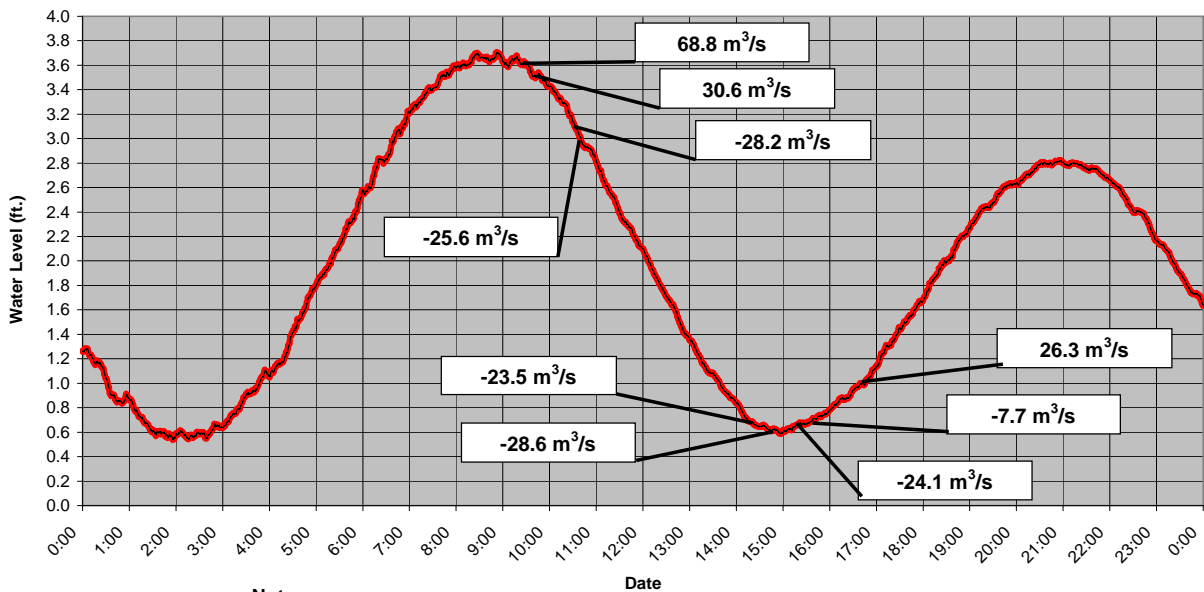
Recorded Discharge Values for Transects 1 and 2 - October 28th, 2008



Notes:

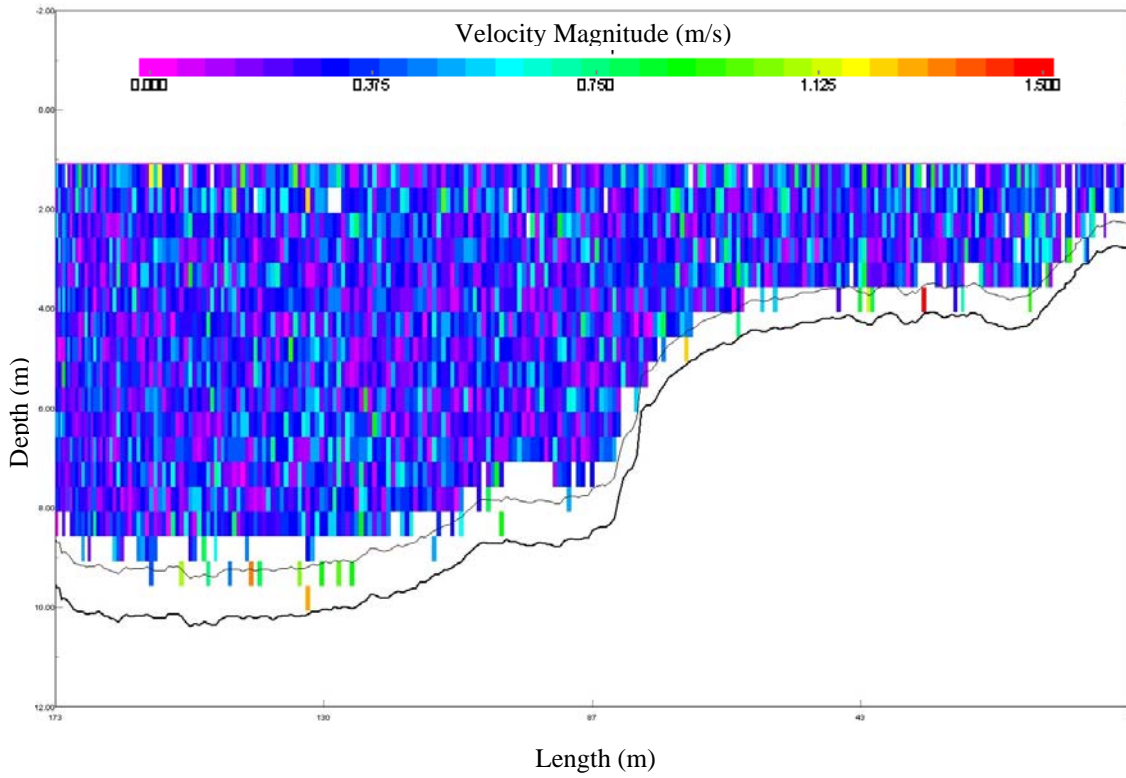
- (1) Tides reduced to MLWS;
- (2) Positive discharge values denote flow from west to east;
- (3) Channel cross-section was approximately 1275 m² for Transect 1;
- (4) Channel cross-section was approximately 310 m² for Transect 2;
- (5) Strong NNE wind present during measurements on October 28th, 2008.

Recorded Discharge Values for Transects 1 and 2 - October 29th, 2008

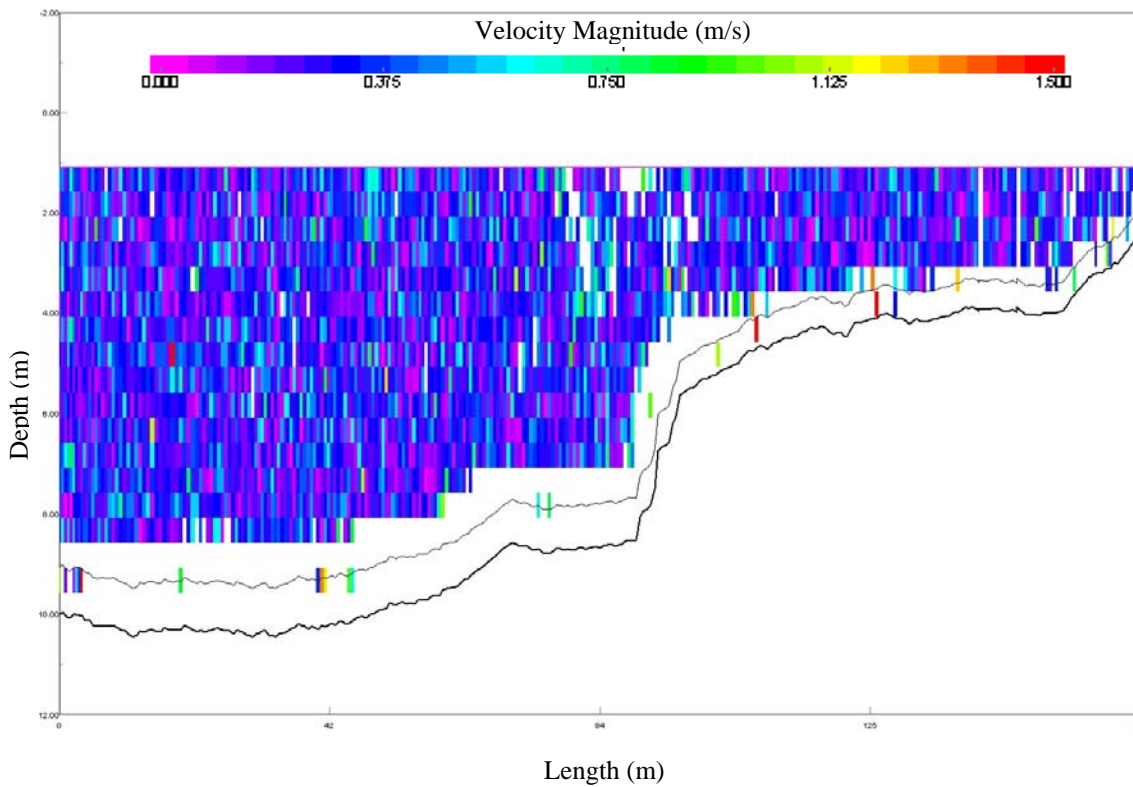


Notes:

- (1) Tides reduced to MLWS;
- (2) Positive discharge values denote flow from west to east;
- (3) Channel cross-section was approximately 1275 m² for Transect 1;
- (4) Channel cross-section was approximately 310 m² for Transect 2;
- (5) Mild NNW wind present during measurements on October 29th, 2008.

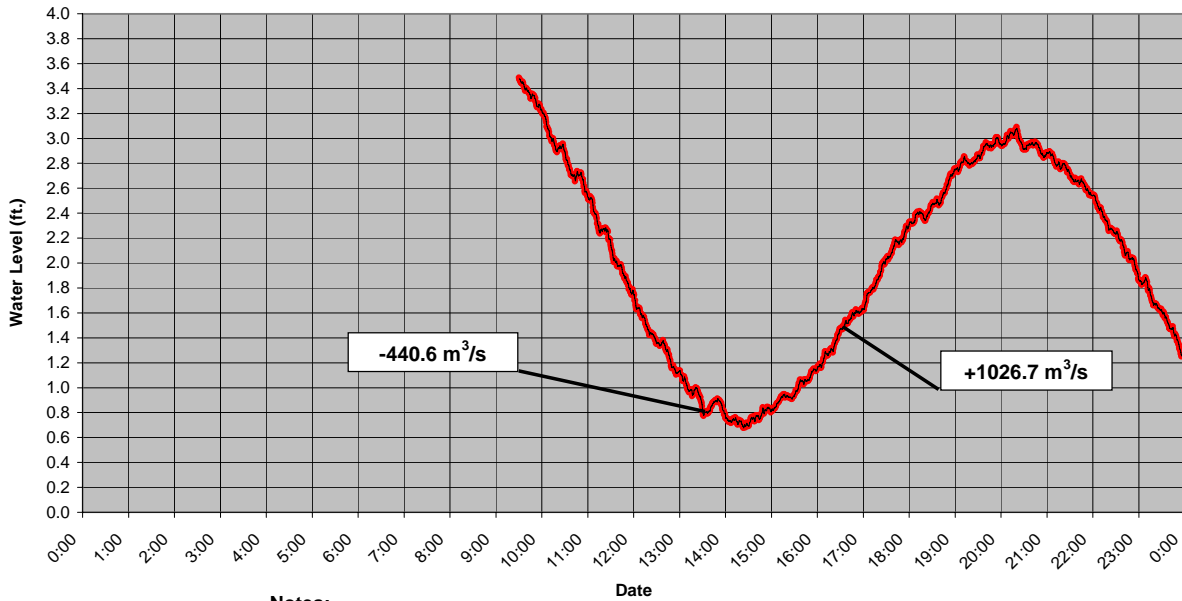


Sample Current Profile for Channel Transect 1 During Ebb Tide, October 28th, 2008



Sample Current Profile for Channel Transect 1 During Flood Tide, October 29th, 2008

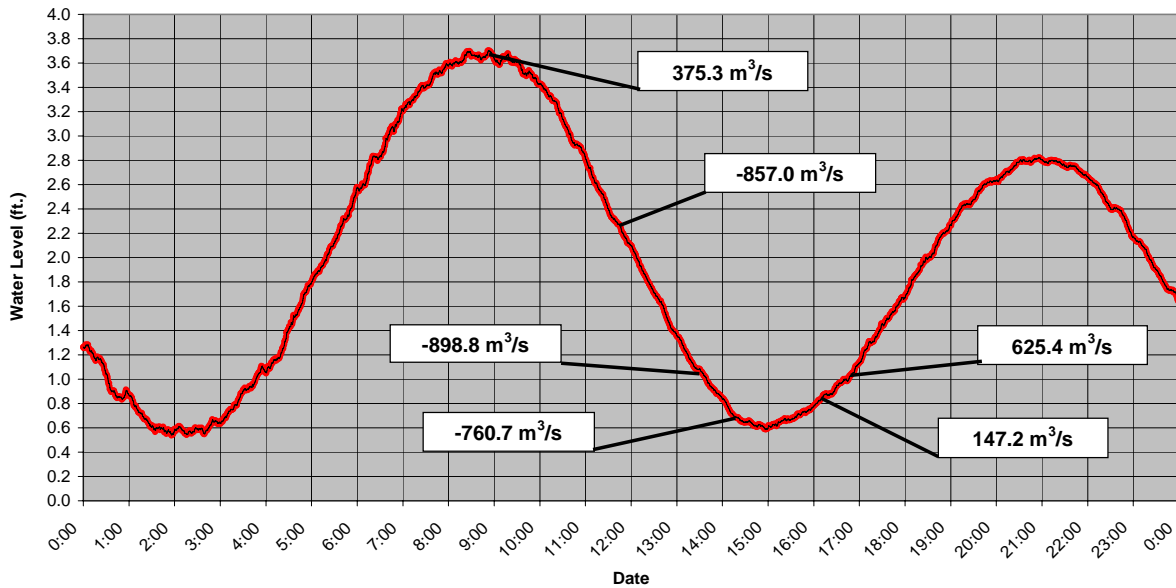
Recorded Discharge Values for Transect 3 - October 28th, 2008



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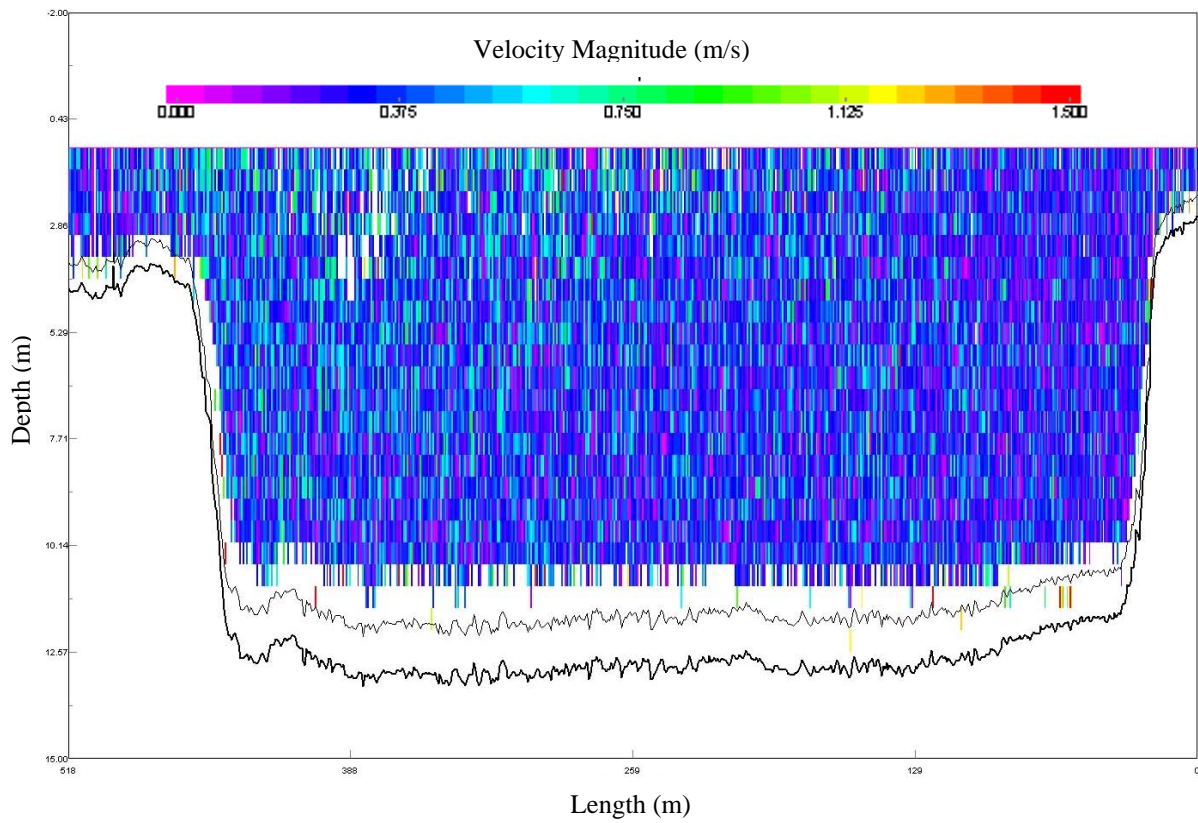
- (1) Tides reduced to MLWS;
- (2) Positive discharge values denote flow from west to east;
- (3) Channel cross-section was approximately 6100 m² for Transect 3;
- (4) Strong NNE wind present during measurements on October 28th, 2008.

Recorded Discharge Values for Transect 3 - October 29th, 2008

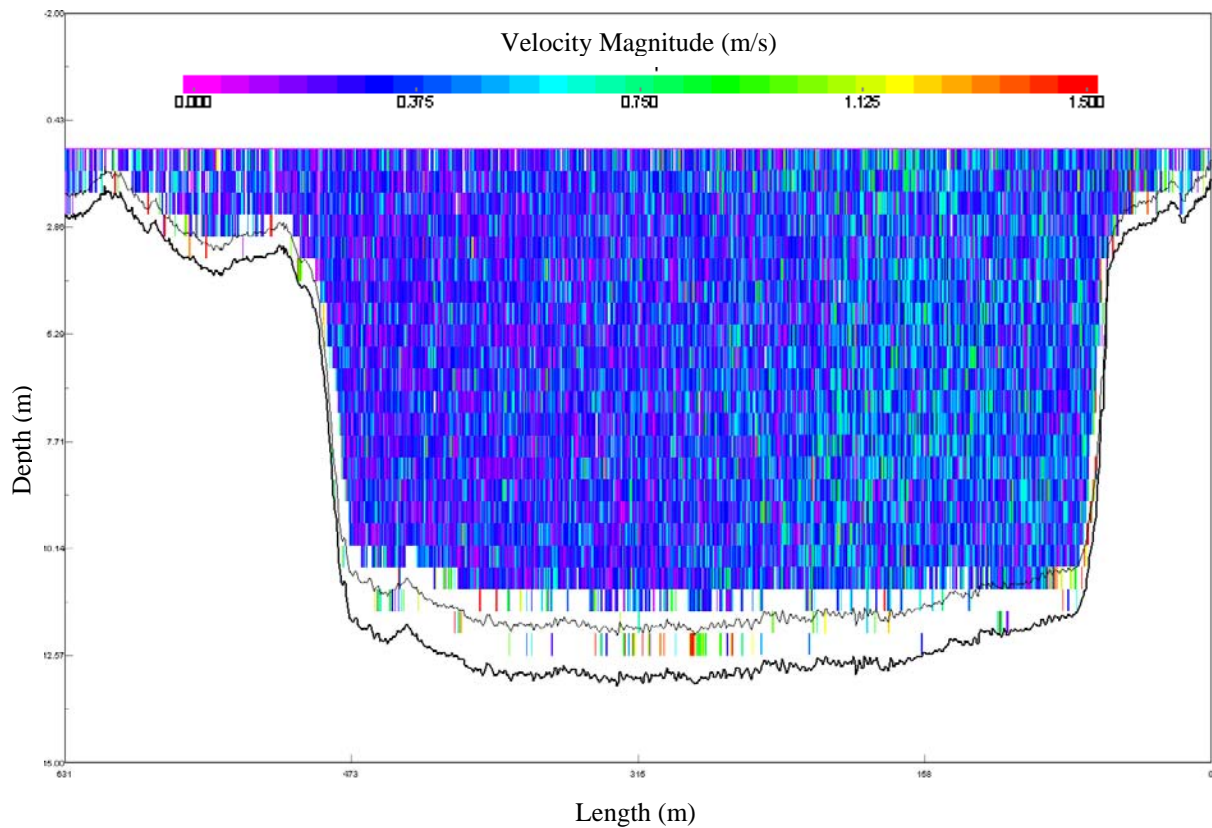


Notes:

- (1) Tides reduced to MLWS;
- (2) Positive discharge values denote flow from west to east;
- (3) Channel cross-section was approximately 6100 m² for Transect 3;
- (4) Mild NNW wind present during measurements on October 29th, 2008.

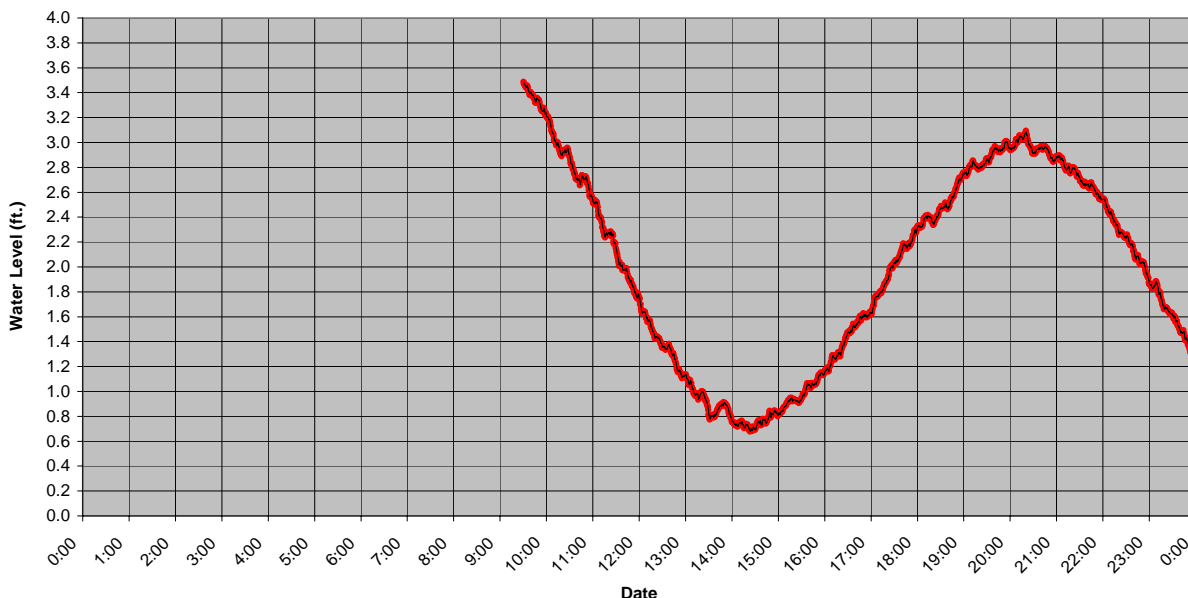


Sample Current Profile for Channel Transect 3 During Flood Tide, October 28th, 2008



Sample Current Profile for Channel Transect 3 During Ebb Tide, October 29th, 2008

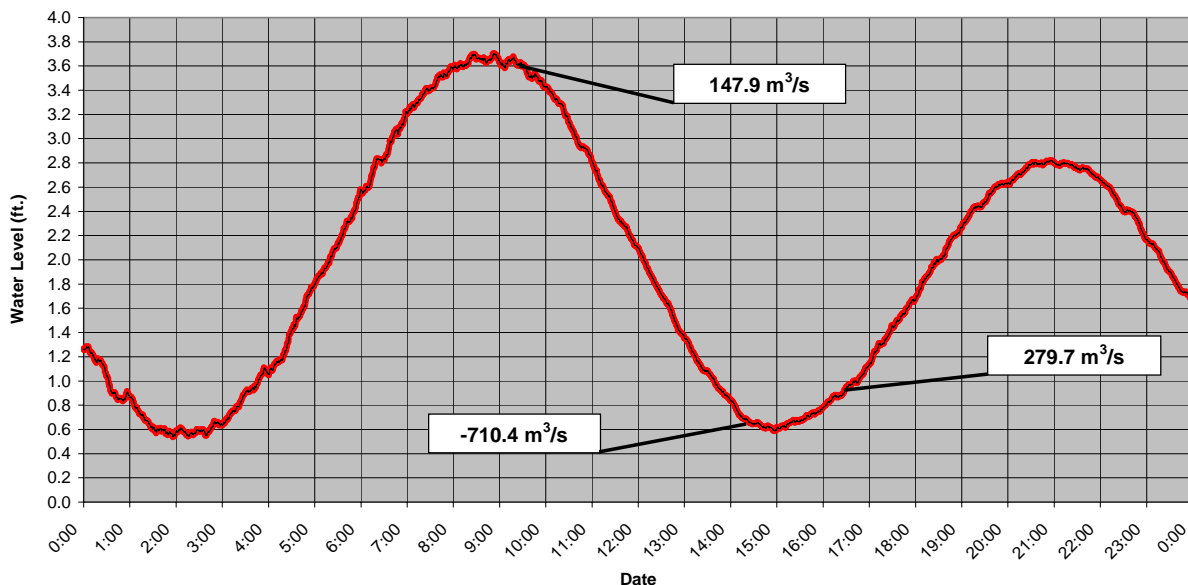
Recorded Discharge Values for Transect 4 - October 28th, 2008



Notes:

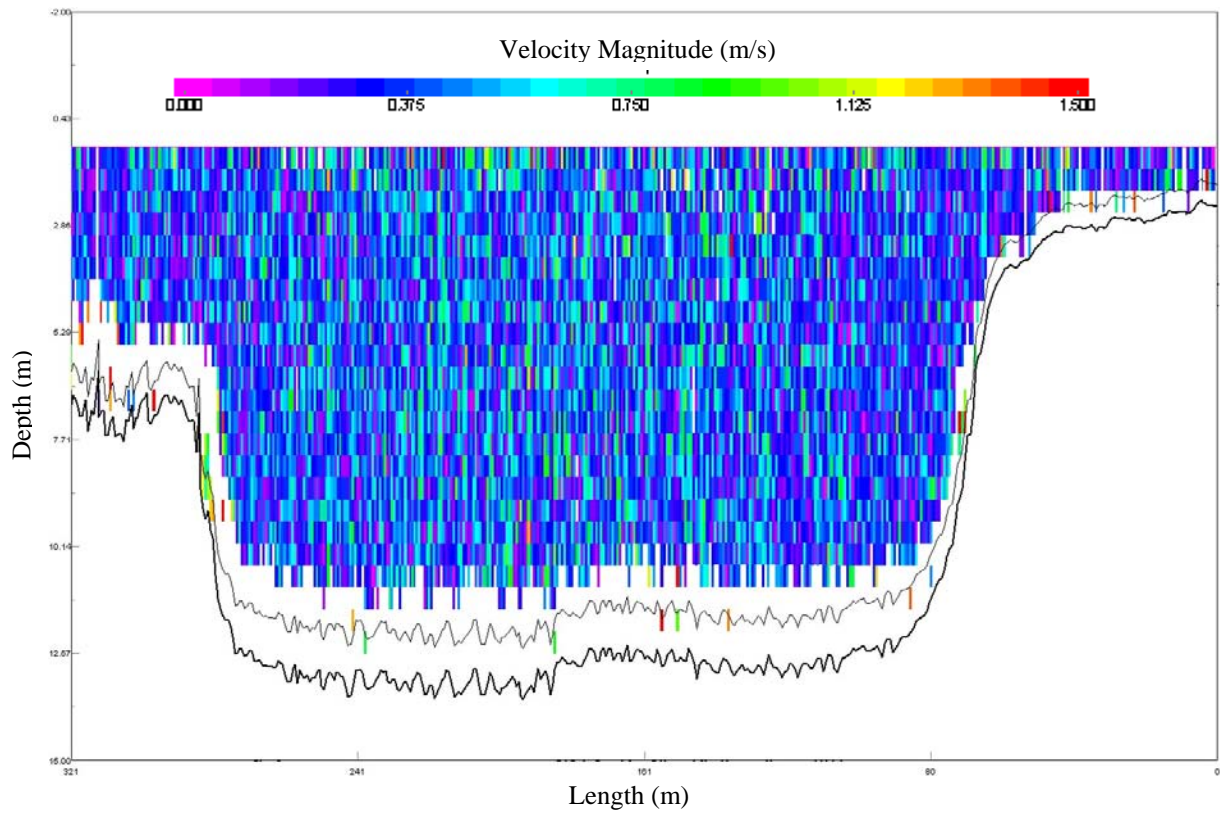
- (1) No data taken on October 28th due to strong NNE wind present during measurements;
- (2) Tides reduced to MLWS;
- (3) Positive discharge values denote flow from west to east;
- (4) Channel cross-section was approximately 3250 m² for Transect 4.

Recorded Discharge Values for Transect 4 - October 29th, 2008

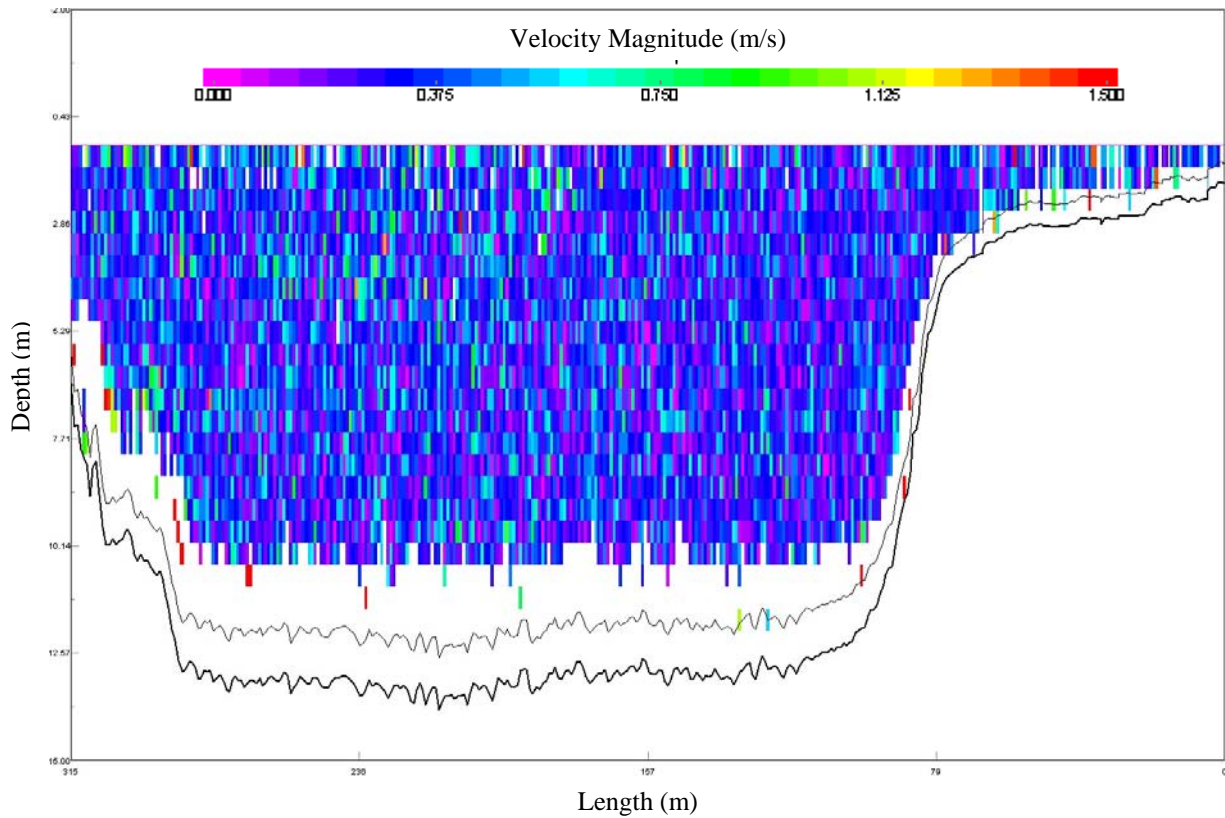


Notes:

- (1) Tides reduced to MLWS;
- (2) Positive discharge values denote flow from west to east;
- (3) Channel cross-section was approximately 3250 m² for Transect 4;
- (4) Mild NNW wind present during measurements on October 29th, 2008.

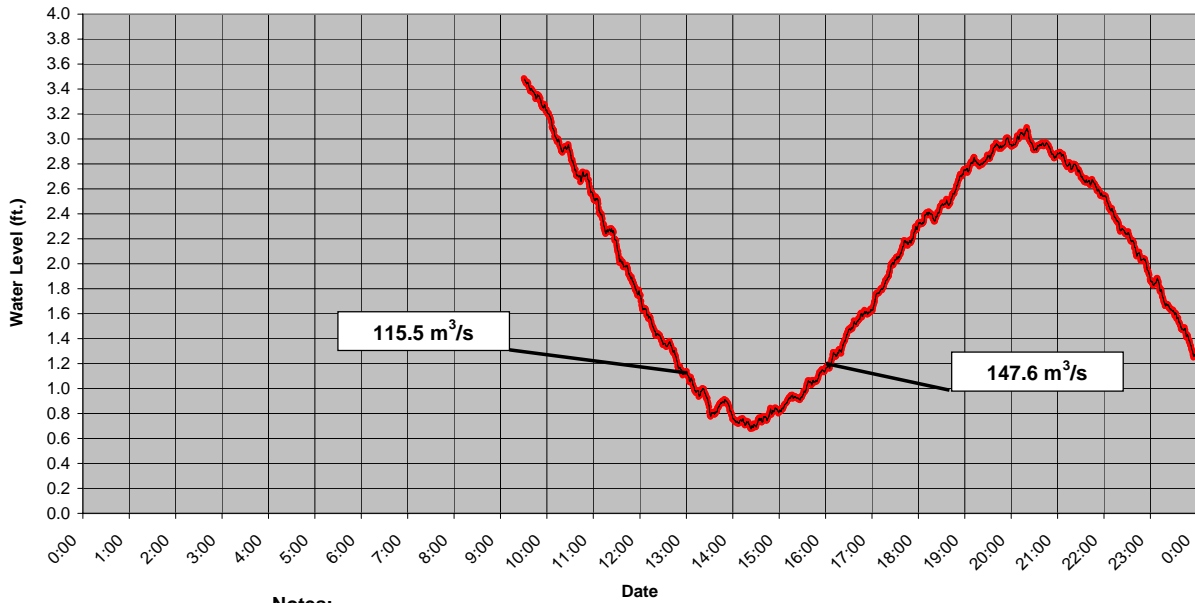


Sample Current Profile for Channel Transect 4 During Ebb Tide, October 29th, 2008



Sample Current Profile for Channel Transect 4 During Flood Tide, October 29th, 2008

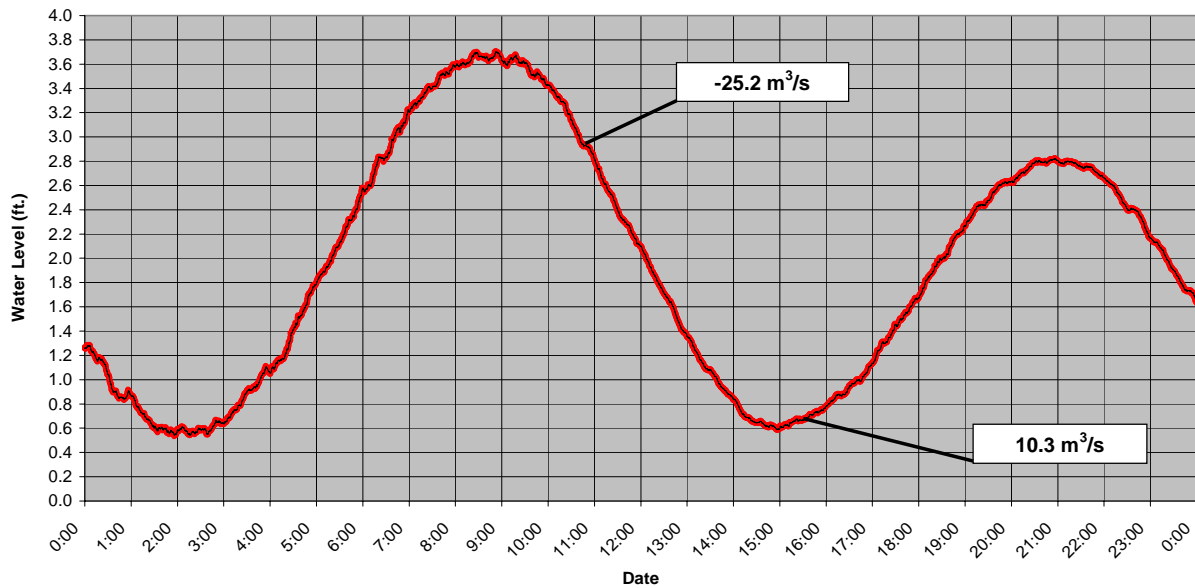
Recorded Discharge Values for Transect 5 - October 28th, 2008



Notes:

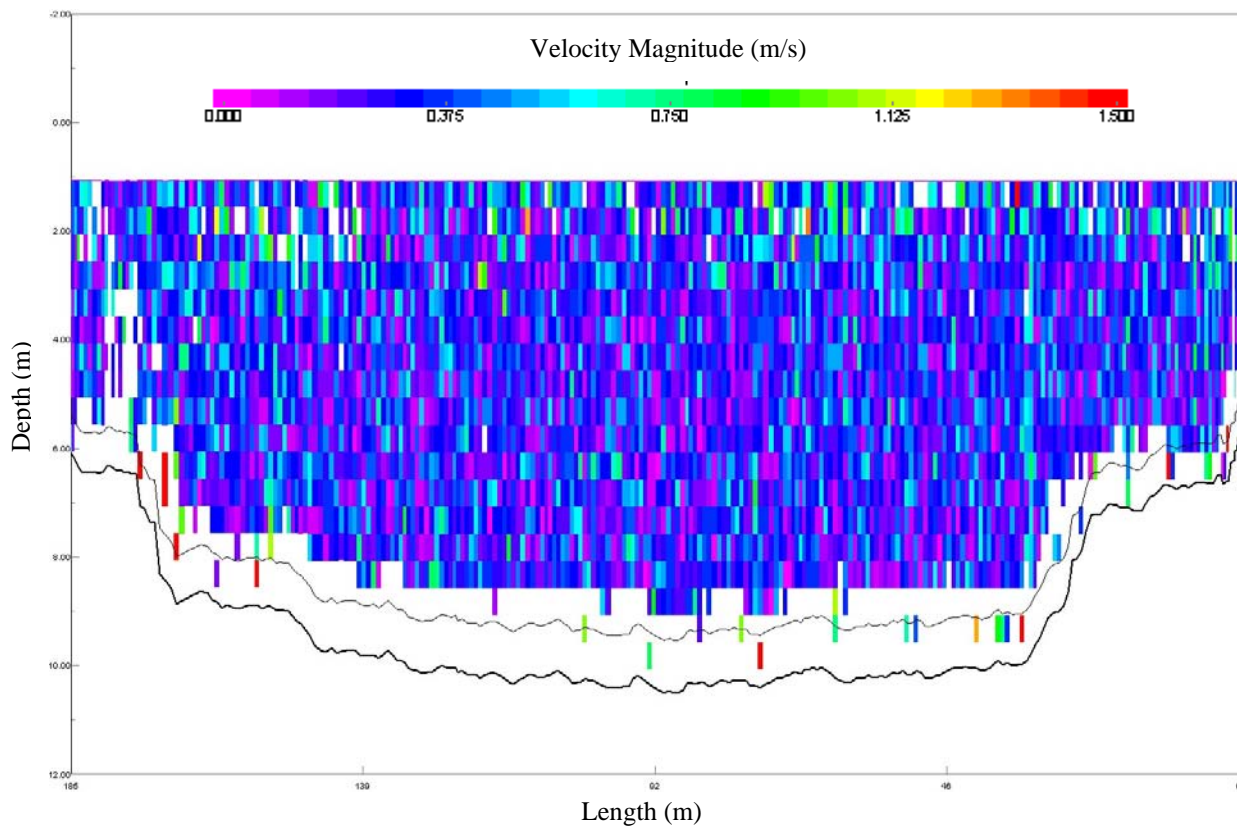
- (1) Tides reduced to MLWS;
- (2) Positive discharge values denote flow from west to east;
- (3) Channel cross-section was approximately 1825 m² for Transect 5;
- (4) Strong NNE wind present during measurements on October 28th, 2008.

Recorded Discharge Values for Transect 5 - October 29th, 2008

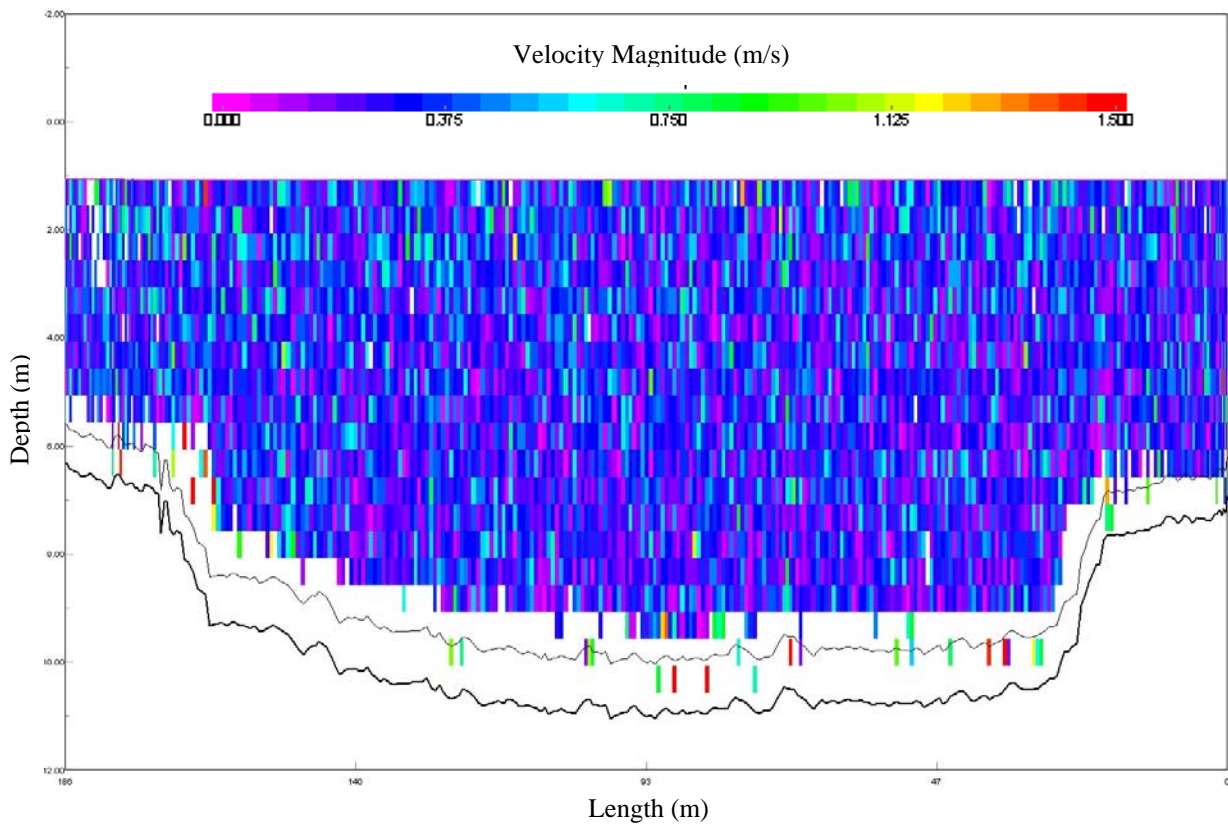


Notes:

- (1) Tides reduced to MLWS;
- (2) Positive discharge values denote flow from west to east;
- (3) Channel cross-section was approximately 1825 m² for Transect 5;
- (4) Mild NNW wind present during measurements on October 29th, 2008.



Sample Current Profile for Channel Transect 5 During Flood Tide, October 28th, 2008



Sample Current Profile for Channel Transect 5 During Ebb Tide, October 29th, 2008