Ship Effects Study for Sabine Neches Project

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Ship Effects Before and After Deepening of the Sabine-Neches Waterway, Port Arthur, Texas

1 INTRODUCTION

Project Description

The Sabine-Neches Waterway (SNWW) is located in southeast Texas and provides access to the Gulf of Mexico for the harbor facilities of Sabine Pass, Port Arthur, Beaumont, and Orange, Texas (Figure 1). The existing project has an authorized depth of 40 ft and includes approximately 65 miles of deep-draft navigation channels. The waterway consists of the Sabine Bank and Sabine Pass outer bar channels (42 ft by 800 ft), Sabine Pass Jetty channel (42 ft by 800 ft narrowing to 500 ft), Sabine Pass Channel and Port Arthur Canal (40 ft by 500 ft), Sabine-Neches Canal and Neches River Channel (40 ft by 400 ft), and the Sabine-Neches Canal to Sabine River (30 ft by 200 ft). This study focuses on the Port Arthur and Sabine-Neches Canals in the reach adjacent to Pleasure Island.

Vessels using the SNWW include ships, barges, service boats, and recreational boats. Due to the large petrochemical industry in the area, most ships using the waterway are tankers. Since the deepening was done to address ship traffic, this report focuses on the changes in ship effects in the existing and deepened channels.

Ship effects in navigation channels can be broadly classified as short period and long period. Short period effects include waves formed at the bow and stern and, in some

cases, short period waves that result from drawdown of the water level in shallow water for relatively high speed ships. Long period effects include drawdown of the water level, return velocity, and surge of the water level above the ambient level. Immediately following the drawdown, a transverse stern wave (TSW) can form, depending on ship speed, and is often the dominant loading on the bank (Figure 2). Long period effects of a ship increase with increasing speed and increasing blockage factor, the ratio of ship cross sectional area to channel area. Navigation channels with blockage ratios exceeding 0.05 to 0.10 are classified as confined or restricted. The largest ships at SNWW along Pleasure Island have blockage ratios of about 0.2. SNWW is typical of several deep draft ship channels in that it has a shallow berm between the shoreline and the navigation channel.

Objective

The USACE Galveston District is proposing to deepen and, in some reaches, widen the SNWW. The District contracted with the Engineering Research and Development Center (ERDC) in Vicksburg, Mississippi to determine the ship wave conditions in the existing canal and after deepening of the canal. The focus of this study is the reach adjacent to Pleasure Island. In the south portion of the island adjacent to the Port Arthur Canal, the channel is proposed to be deepened to –50 ft MLT and widened to a bottom width of 700 ft. In the north portion of the island adjacent to the Sabine Neches Canal, the channel will be deepened to –50 ft MLT while remaining at 400 ft bottom width. The north portion also includes a barge lane on the East side of the ship canal.

ERDC used field measurements in the existing canal and numerical modeling of the existing and deepened channels. This report evaluates change in bank erosion by

quantifying change in ship induced bankline forces. Two scenarios can lead to changes in ship-induced bank forces in the proposed SNWW channel:

a) Scenario 1- Ships presently using the SNWW will be able to go faster in the larger channel leading to changes in bank forces. This scenario is investigated herein by selecting a design ship and comparing the design ship effects in existing and proposed channels.

b) Scenario 2- Larger ships will use the proposed channel and bank forces will differ from ships in the existing channel. This scenario is investigated herein by selecting a larger ship and comparing forces from the design ship in the existing channel to the larger ship in the proposed channel.

In addition to comparing ship wave forces in existing and proposed channels, this study evaluates speed restrictions to 1) limit ship waves in the proposed channel to those in the existing channel and 2) reduce ship waves in the proposed channel to less than those in the existing channel.

2 FIELD EXPERIMENTS

Previous Field Experiments

Herbich, Schiller, and Kim (1979) conducted field measurement of ship effects in the SNWW in a study prepared for the State Department of Highways and Public Transportation, Beaumont District. This writer found a progress report for that study but was unable to obtain any further information other than a conference paper by Herbich and Schiller (1984). Phone calls were made to the authors, Texas A&M University, and Texas Department of Transportation (TDOT). The Beaumont District office of the TDOT was visited but no additional information was found. The progress report and the conference paper included similar information. The conference paper uses the term "surge" that is equal to the transverse stern wave (TSW) used herein. In this report "surge" is the rise of the water level above the still water level and surge plus drawdown is equal to the TSW. Herbich and Schiller (1984) concluded that TSW from large ships is considerably larger than short period waves from large ships. They also found short period waves from small vessels are much larger than TSW from small vessels. Their measurements indicated that TSW from large ships was larger than short period waves from small vessels. TSW height in the progress report of Herbich, Schiller, and Kim (1979) was up to 10 ft. TSW height from all measurements in Herbich and Schiller (1984) was up to 5.8 ft at a location on the Port Arthur Canal. The lack of the 10 ft measured TSW in the later report casts some doubt on its validity.

General Description of Present Field Studies

The field investigation of the existing channel at SNWW was conducted from 30 April to 4 May 02. During the field investigation, pressure cells, a velocity meter, and capacitance gages were deployed at the North and South sites along Pleasure Island (Figure 3) to measure waves and drawdown from passing ships, barges, and recreational boats. The North site is in the Sabine-Neches Canal and the South site is in the Port Arthur Canal. All gages were located on the shallow berm on the East side of the navigation channel adjacent to Pleasure Island. All times used in this report are in Central Standard Time (CST).

Bathymetry

The USACE Galveston District provided detailed bathymetry of the navigation channel but data was not available for the shallow berm adjacent to the channel. During the field experiments, bathymetry measurements were made of the berm from the shoreline to the navigation channel in the vicinity of the instruments. For this reason, the numerical modeling is strictly applicable to the sites near the instruments, but conclusions are considered applicable to the reach because the North and South sites are representative of their respective reaches.

Gage Description and Location

Figure 3 shows the Pleasure Island reach including the locations of the pressure cells, capacitance gages, and the velocity gage. Table 1 shows the State Plane coordinates (NAD83, Texas South Central – 4204, in feet) of the pressure cells and the depth at Mean Low Tide (MLT) at each cell. Conversion from MLT to NAVD88 is:

MLT = NAVD + 0.8 ft. At the South site, both pressure cells were at the shoreline. At the North site, both pressure cells were located in similar depths and similar distances from the ship channel to facilitate ship speed measurement. The wide shallow section at the North site resulted in the pressure cells being relatively far from the shoreline. The pressure cells were mounted on temporary piles driven into the bay or attached to existing piles. The sensor in the pressure cells was positioned about 1 ft above the channel bottom. The pressure cells measured data at 4 hz during the field study which is valid for capturing the long period vessel drawdown but is not a high enough frequency to capture the short period waves. The pressure cell data was recorded for 19 min 50 sec and stored for 10 sec. During the 10 sec of storage, data was not collected.

Table 2 shows the location of the capacitance gages and the depth at MLT. The capacitance gages were rod type commercial gages having a length of 3 m and diameter of 5 mm. The gages were set to record data at 10 hz which provided good description of the short period vessel and wind waves. The mount and gage are shown in Figure 4. Galvanized steel pipe was driven into the bottom of the bay to support the capacitance gages which were spaced at about 16.8 m(55 ft) in an array perpendicular to the bank. The gages recorded data on a data logger that was set to record for 14 minutes and write to the hard disk for 1 minute. Data could not be collected during the 1 minute of write to the hard disk. Consequently, some of the data records have a one minute gap in the capacitance data.

The velocity gage was a bottom mounted acoustic gage that sampled velocity at various distances above the bottom. The gage was located immediately beside the channel capacitance gage at the South site.

Ambient Conditions

The Conrad Bucher tide gage at Port Arthur was used to obtain the ambient water levels during the field study. The tide range is typically up to about 0.46m (1.5 ft). Tidal currents at SNWW are not large based on the observed velocity data.

Ship Traffic

All ships using the SNWW are entered in a log that was provided by the Sabine Pilots. The log provides vessel name, date of passage, direction of travel, vessel beam, length, and draft, vessel type, and times at various points along the waterway. The ship characteristics, date/time of passage, and water level description are shown in Table 3 for ships that passed the site during the field data collection.

Time Histories of Water Level and Drawdown and Surge Data

Selected time histories of the measured data collected in the existing channel are shown in Appendix A in Figures A1 to A29. The plotted data has not been filtered or averaged. Several features of the time histories are as follows:

1) The datum for the time histories was the ambient water level except for some of the capacitance gage plots which were offset from the ambient level by 1, 2, or 4 ft to facilitate plotting. Figure A3 is an example where the shoreline gage has been offset by 2 ft.

2) Some of the drawdown went below the gage that resulted in a flat indication of water level such as Figure A1 at 790 sec.

3) The 10 sec loss of data from the pressure cell while writing the data to the disk can be seen in Figure A13 at 1190 sec.

Drawdown is the drop to the minimum water level during the event. Surge is the rise to the maximum water level during the event. Both drawdown and surge are measured from the average ambient water level. For defining drawdown and surge from the ship, the minimum and maximum water levels exclude any short period waves from the ship or wind. Tables 4 and 5 summarize drawdown and surge for the ships observed during the field study at the North and South sites, respectively.

Validation Ship for Existing Channel

A validation ship was needed to show that the HIVEL2D model (discussed in Chapter 4) could be used to model the long period ship effects of drawdown at SNWW. This requires selection of a typical ship for which field data was collected. The ship characteristics in Table 3 were evaluated for typical beam, length, draft, and water level. The drawdown and surge data in these tables were examined for ships producing drawdown and surge values that would not be classified as outliers. The Pacific Sapphire, which was inbound on 1 May 02, was selected as the validation ship for the existing channel. The Pacific Sapphire had the characteristics shown in Table 6.

Other Vessels

Barges passed through the SNWW during the field experiments. Due to their small cross sectional area and their slow speed compared to ships, drawdown from barges could not be detected in the measured time history of water level for many of the barges. In all cases of barge passage, the magnitude of the barge drawdown was small compared to the ships.

Service and recreational boats passed the field measurement site and often caused significant wave activity. Speed of service and recreational boats should not be

significantly affected by the deepening. Wave activity from service and recreational boats may be greater where channel widths are increased because boats can travel closer to the bankline. Even with this potential increase due to closer proximity to the bank, wave height from service and recreational boats is small compared to the TSW from the ships.

3 Ship Speeds and Ship Sizes Used in Comparison

General

The most critical and most difficult part of any ship effects study is selecting comparable speeds in existing and proposed channels which is further complicated when ship sizes are proposed to increase. The speed selection almost entirely dictates the outcome of any comparison of ship effects under existing and proposed conditions. Ship speed is strongly affected by ship and channel size. In confined channels like the SNWW, the channel size relative to the ship size places a physical limit on the speed of displacement ships. The limit speed depends on the waterway cross section area and shape, the vessel underwater cross section area and, to a much lesser extent, the shape and length of the ship. The limit speed procedure used herein is documented in Maynord (1996). Past experience suggest that ships rarely travel at more than 80-90% of the limiting speed because the power required becomes extremely large as the ship approaches the limit speed. This report places great emphasis on relating ship speed to a percentage of limit speed because it provides a means of relating SNWW speed to speeds in other channels and provides a physical basis for speed projections. Channel alignment and the presence of mooring areas are other factors that can limit and further complicate selection of ship speed, particularly in proposed channels with proposed ships. All of these factors were considered in the speed recommendations.

Speed Data from Field Studies

Ship speed at SNWW was determined using two techniques as follows:

a. Bow to stern passage time was measured with a stop watch using a fixed point on the horizon with ship length to determine ship speed.

b. The arrival time of vessel drawdown at the known locations of the pressure cells and the capacitance gages allowed determination of speed between these points.

Table 7 shows ship speed determined from the pressure cells and from the bow to stern timing.

Design Ship in Existing and Proposed Waterway

A design ship was needed to use in the HIVEL2D simulations to compare ship forces on the shoreline in the existing and proposed channels to address the first erosion scenario. The USACE Galveston District wanted to use the ship that uses the channel most frequently and has the greatest forces at the shoreline. Based on data collected during the field experiments in 30 April-4 May 2002, ships were categorized according to beam width as less than 75 ft, 75 ft to less than 100 ft, 100 ft to less than 125 ft, and equal to or greater than 125 ft. Frequency of occurrence during the field study is shown in Figure 5. The largest ships having beam of 125-150 ft occurred most frequently and represented 38% of the 69 ships that used the channel during the field study. The actual range of ships beams in the largest class is 129-142 ft.

Figure 6 shows ship speed versus ship beam at the South measurement site. Outbound ships are generally unloaded whereas inbound ships are loaded. A dependency of speed on ship size is shown in the figure. Figure 7 is a plot of ship drawdown measured during the field study versus ship beam at the South site. Drawdown is the maximum drop in water level below ambient during ship passage. Although the data is scattered due to different speeds and drafts, no significant difference in drawdown is shown for the two

largest ship classes. This is a result of the 100-125 ft beam ships traveling faster than the 125-150 ft beam ships as shown in the speed versus ship beam plot in Figure 6. Figure 8 is a plot of ship surge measured during the field study versus ship beam. Surge is the maximum rise of the water level above ambient conditions during ship passage. Although the data is scattered due to different speeds and drafts, the expected increase in surge from the smaller, faster ships is present in the data. Figure 9 shows a plot of surge versus ship speed for the 125-150 ft beam class that was previously shown to be the most frequent ship. The plot includes the ship draft by each data point and shows that the unloaded ships (draft about 28-30 ft) are the fastest and produce the largest surge. The conclusion of largest ship effects from the largest ships traveling unloaded is consistent with observations of USACE area office personnel at SNWW.

Based on the data presented herein, the ship using the channel most frequently is the largest class having beam widths of 125-150 ft. Most ships in this class are about 800 ft in length and have beams of 129-142 ft. In this largest class, the loaded and unloaded ships produce about the same drawdown but the unloaded ships, because of their higher speeds, produce more surge. The design ship was selected to be 140 ft beam by 800 ft length with a 29 ft draft typical of the unloaded ships.

Larger Ship in Proposed Channel

In addition to comparing the design ship in the existing and proposed channels (scenario 1), a larger ship that will use the proposed channel will be compared to the design ship in the existing waterway (scenario 2). Based on the simulator studies, a typical ship using the proposed channel is projected to be 899 ft by 164 ft by 48 ft at maximum loaded

condition. In the larger ship, ship effects will be evaluated for the unloaded condition, which is estimated to be a 30 ft draft, and the 48 ft loaded draft.

Observed ship speed in the existing channel

South site For the ships observed during the field study, ships at the South site averaged 78% of their limit speed and ranged from 66 to 91 %. Figure 10 shows speed at the South site versus cross sectional area of the ship. Also shown are lines of 70, 80, 90, and 100% of computed limit speed. The channel width and area at the South site at a water level of 2.5 ft MLT used in this computation were 740 ft and 29170 sq ft, respectively, and exclude the shallow berm areas. Ships similar to the design ship were observed during the field study to travel at about 10 knots at the South site and is 86% of limit speed.

North site Observed ship speeds at the North site are shown in Figure 11 and averaged 84% of the limiting speed. In the existing channel at the North site, the channel cross-section area at 2.5 ft MLT excluding the shallow berms is 25000 sq ft which about 86% of the cross-section area at the South site. Water surface width at the North site excluding berms is 670 ft.

Simulator Speeds

Based on the simulator report (Seamen's Church Institute, 2002), the average speed for the 899 ft X 164 ft X 38 ft ship in the existing channel was 6.2 knots (73% of limit speed). The same ship drafting 48 ft in a 400 ft X 50 ft and 500 ft X 50 ft alternative channels traveled at 6.3 and 6.9 knots, respectively (both are 75% of limit speed).

Proposed channel cross section characteristics

South site- In the 700 ft X 50 ft proposed channel with 1V:2H side slopes, the channel area and water surface width at a 2.5 ft MLT water surface excluding shallow berms are 42262 sq ft and 910 ft, respectively.

North site- In the 400 ft X 50 ft proposed channel with 1V:2H side slopes and a barge lane, the navigation channel (not including barge lane) area and water surface width at a 2.5 ft MLT water surface are 28760 sq ft and 670 ft, respectively.

Rules Used in Ship Speed Selection

Rules used in establishing speeds were as follows:

1. Speeds at both North and South sites in the existing channel for the design ship were 85% of limit speed.
2. Speeds at both North and South sites in the proposed channel for the design ship will be between 80 and 85% of limit speed.
3. Speeds at both North and South sites in the proposed channels for the unloaded larger ship will be between 80 and 85% of limit speed.
4. Speeds at both North and South sites in the proposed channels for the loaded larger ship will be between 75 and 80% of limit speed. The reduced speed range for the loaded ship is due to the largest loaded ships in Figure 10 traveling at less than 80% of limit speed.

Table 8 summarizes the speeds used in the two reaches and two ships for the existing and proposed channels in the HIVEL2D modeling.

4 HIVEL2D SIMULATIONS

General

The numerical model HIVEL2D (Stockstill and Berger, 2001) is a finite element description of the 2-dimensional shallow water equations in conservative form. The HIVEL2D model has been used for long period vessel effects from both shallow draft navigation (Stockstill and Berger, 2001) and deep draft navigation (Maynord, 2000). The model is not applicable for determining short period waves from vessels. HIVEL2D was used to compare the effects of ships in the existing and after deepened channels using the two scenarios presented in the Introduction. HIVEL2D was also used to determine the effects of ship speed restrictions in the deepened channel.

Grid Refinement

The long period drawdown produced by the ship has a wavelength of approximately the ship length or 700 ft. Sensitivity test were run in a HIVEL2D study (Maynord, draft) in which the longitudinal elements describing the ship were 25, 50, and 100 ft in length. Peak drawdown increased more than 20% when changing from 100 ft long elements to 50 ft long elements describing the ship. Peak drawdown increased 10% or less when changing from 50 ft long elements to 25 ft long elements describing the ship. The manner in which the boat shape is discretized also affects the selection of 25 ft, 50 ft, or 100 ft long longitudinal elements. At the bow, the draft of the boat changes from zero to full draft over the length of one element. Consequently longer elements result in a more gradual change in draft which is likely more representative of the streamlined shape of a typical ship. This fact favors selection of the longer elements. In the validation

phase of this study and another study (Maynord, draft), good reproduction of field measured ship drawdown was obtained with 50 ft long elements describing the ship. The 50 ft longitudinal cell length along the boat path was used in both the existing and after deepened channels.

Bathymetry used in the HIVEL2D simulations

Bathymetry at the North and South sites is shown in Figures 12 and 13 for the existing channel and Figures 14 and 15 for the proposed channels. Average cross sections at the North and South sites are shown in Figures 16 and 17 for the existing channel based on data collected during the field study.

Pressure Field Representing Ship

Along the boat path, the elements were 20 ft wide by 50 ft long. An important point to note is that the discretization of the grid and the sailing line establish the actual size of boat being modeled. The specification of the region to experience the moving pressure field is shown in Figure 18. For the example shown in Figure 18, the sailing line was centered on the nodes. Any node within the bounded region in Figure 18 was subjected to the pressure drop. In the example shown in Figure 18, the free-surface pressure head was dropped equal to the boat draft at the sailing line node and at 2 nodes on either side of the sailing line. This results in a 4 element wide ship at the bottom of the ship. At the next node outside the last draft node, the free-surface pressure head is zero. Interpolations are made on the elemental level using bilinear functions. Therefore linear interpolation is made in directions parallel to a rectangular element's side. The use of rectangular elements to describe the vessel shape results in a linear distribution of free-surface pressure being imposed between the outer most draft node and the next water

level node. This pressure distribution gives the ship cross section a trapezoidal shape. (By the same procedure, the longitudinal cross section of the boat also has a trapezoidal shape.) This trapezoidal shape is 4 elements wide at the bottom and 6 elements wide at the water level giving an average width of 5 elements * 20 ft = 100 ft. This procedure results in the ability to model ship widths equal to odd multiples of the cell width (100, 140, 180 ft) for a sailing line centered on the nodes and even multiples of the cell width (80, 120, 160, 200 ft) for a sailing line centered between the nodes.

One problem arises in using HIVEL2D when ship drafts approach channel depths. Depending on speed, channel size and ship size, the computed depth beneath the ship can tend to zero at which there is a singularity in the bed friction term and so the model will not run. In Maynord (2000), this problem of numerical instability occurred and various means of avoidance were tried in the model. This problem was solved by modeling a narrow deep ship with a wider shallow ship. Comparative run were conducted with HIVEL2D in Maynord (2000) and similar drawdown and return velocity were obtained as long as the cross sectional area of the ship was maintained equal to the prototype. This same problem occurred in the SNWW simulations and a wider ship with lesser draft had to be used in some of the simulations. Problems did not occur for the unloaded design ship and a 140 ft beam was used. For the validation ship, Pacific Sapphire, having 137 ft beam by 40 ft draft, HIVEL2D would not run using a 40 ft draft and the ship was modeled as 160 ft beam by 34.25 ft draft that maintained the correct cross sectional area. For the larger loaded ship having dimension of 164 ft beam by 48 ft draft, the modeled ship was 200 ft beam by 39.4 ft draft. For the larger unloaded ship having dimensions of 164 ft beam by 30 ft draft, the modeled ship was 160 ft beam by 30.75 ft draft.

Adjustment of Ship Speed to Account for Tidal Currents

All HIVEL2D simulations in this study were conducted with slackwater, i.e. without tidal velocities. This required that boat speeds be adjusted to simulate the correct speed of the ship through the water. Based on a tidal range of about 1.5 ft at Mesquite Point, peak velocity in the numerical model of SNWW was about 1.5 ft/sec in the navigation channel. Tidal velocities were used to convert ship speed relative to ground to ship speed relative to water.

Validation of HIVEL2D using Existing Channel Data

As stated previously, the Pacific Sapphire was selected as the ship to use in validation of the HIVEL2D model of the existing channel at both the North and South sites. The computational grids of the existing channel are shown in Figures 19 and 20 and contain 32005 and 27234 elements for the North and South sites respectively. The North and South site grids are 14 and 11 miles long. The center of the navigation channel was used to define the ship path in both the existing and deepened channels. The Pacific Sapphire was accelerated at 0.118 knots/sec/sec until reaching a speed of 8.3 and 8.6 knots at the North and South sites, respectively. Water level used in the existing channel simulations was 3.16 ft above MLT and was specified on the North boundary of the computational grid for the inbound Pacific Sapphire. Time steps of 2 sec were used in both validation simulations at the North and South sites. The turbulence coefficient was 0.25 and the α coefficient was 1.5 ($\alpha = 1$ specifies first-order backward difference, $\alpha = 2$ specifies second order backward difference, see Stockstill and Berger, 1999). Manning's *n* for all surfaces was 0.025. Water levels were compared at the locations of the pressure cells and the capacitance gages as shown in Figures 21 to 24. Figure 25 shows computed

velocity for the outbound, unloaded Bornes because the velocity gage was not installed during passage of the Pacific Sapphire. Measured velocity for the Bornes is shown in Figure A11. Observed and computed values were in agreement and the HIVEL2D model was considered validated.

HIVEL2D Simulations at the South Site

The design ship was run in the existing and proposed channels and the larger ship was run in the proposed channel at the speeds shown in Table 8 for the South site. Ambient water level for both channels and all runs was 2.5 ft MLT. Figures 26-29 show contour plots of the water level and velocity for the design ship for the existing and proposed channels. Figures 30-33 show time histories of water level and velocity magnitude at the shoreline, respectively at node 16002 which is at the location of the near-bank capacitance gage. The time history of velocity magnitude in Figure 33 shows a negative spike in velocity which is at time = 690 secs for the existing channel. This is the location of flow reversal from velocity opposite to the direction of ship travel before the spike to velocity in the same direction as ship travel after the spike. The flow reversal can be seen in the velocity vectors in Figures 27 and 29.

HIVEL2D Simulations at the North Site

The design ship was run in the existing and proposed channels and the larger ship was run in the proposed channel at the speeds shown in Table 8 for the North site. Ambient water level for both channels and all runs was 2.5 ft MLT. Figures 33-37 show contour plots of the water level and velocity for the design ship in the existing and proposed channels. Figures 38 to 41 show time histories of water level and velocity at the shoreline at node 16952 (3582603, 13907953 are Easting, Northing State Plane

coordinates) that is near the shoreline in the middle of the North site near pressure cell 350. Figure 42 shows time history of water level at the shoreline at node 7953 (3579443, 13904643) to show variation of effects along the North site. This additional node was used at the North site because the shoreline is irregular as opposed to the relatively uniform shoreline at the South site.

5 Surge and Transverse Stern Wave in Existing and Proposed Canals

Surge

Based on the field observations, the TSW is the dominant loading on the bank and is used herein to quantify and compare the attack of the ship on the bank. The TSW is determined herein as the sum of the drawdown and surge. The HIVEL2D model is used to determine drawdown. Surge at the bankline depends on many factors that were not modeled in HIVEL2D including bank slope, bank height, etc. Surge calculations are given subsequently.

Dand and White (1978) studied surge wave formation on the Suez Canal which has a shallow berm adjacent to the navigation channel similar to SNWW. The surge waves of Dand and White are the TSW used herein. At a blockage ratio typical of the SNWW of 0.16, Dand and White found no wave disturbance below berm Froude number F_b of 0.75, undular waves for F_b from 0.75 to 1.1, and "broken water" for F_b greater than 1.1. Berm Froude number is defined as

$$F_b = \frac{V}{\sqrt{g\, h_b}} \qquad \text{Equation 1}$$

Where V= ship speed, h_b = berm depth, and g = gravity. In the SNWW, berm Froude numbers at the South site for the field data ships were all greater than 0.75 and 2/3 of the ships had berm Froude numbers greater than 1.1.

The surge data from the field experiments for all ships were evaluated using dimensional analysis to develop an equation to estimate surge. The parameters that are likely to have an effect on the magnitude of surge height are

$$H_s = f(V, h_b, d, g, n) \qquad \text{Equation 2}$$

Where H_s = surge height, d = drawdown, and n = blockage ratio = ship area/channel area. Dimensional analysis results in

$$\frac{H_s}{h_b} = f\left(\frac{d}{h_b}, \frac{V}{\sqrt{gh_b}}, n\right) \qquad \text{Equation 3}$$

The second parameter on the right side of equation 3 is the berm Froude number F_b used by Dand and White (1978).

The SNWW data from North and South sites was tested against the parameters in equation 3. The blockage ratio n in equation 3 provided no improvement of the fit of the data and was omitted. Most of the variation in H_s/h_b was explained by the berm Froude number with some improvement in the fit of the data with the addition of d/h_b. The best fit equation is

$$\frac{H_s}{h_b} = 0.22\left(\frac{d}{h_b}\right)^{0.6} F_b^{1.8} \qquad \text{Equation 4}$$

Equation 4 has an adjusted R squared of 0.58. A design equation is used herein where the coefficient in equation in equation 4 is increased to 0.26 resulting in

$$\frac{H_s}{h_b} = 0.26\left(\frac{d}{h_b}\right)^{0.6} F_b^{1.8} \qquad \text{Equation 5}$$

The comparison of observed and predicted surge using equation 5 is shown in Figure 43. The design equation 5 provides some conservatism in the surge estimate and is used for all surge height determinations in this report.

Transverse Stern Wave Comparison

As stated previously, the TSW is used herein to quantify and compare bank forces and is equal to the drawdown from HIVEL2D and the surge height from equation 5. The TSW is shown in Tables 9 and 10 for the existing and proposed channels for the design and larger ship at typical speeds in the existing channel and a range of expected speeds in the proposed channel. Typical speeds in the existing channel for the design ship are based on field observations and are equal to 85% of the computed limit speed of the channel. Expected speeds in the proposed channels are based on a range of speeds equal to 80-85% of limit speed for unloaded ships and 75-80% for loaded ships. It is important to note that basing speeds on percent of limit speeds results in increased speed in the proposed channel for the design ship. For example, at the South site, existing ships similar to the design ship typically travel at 10 knots (85% of limit). The same design ship is expected to travel somewhere between 11.5 knots (80% of limit) and 12.2 knots (85% of limit) in the proposed channel. Also note that these speeds are typical or close to average speeds and not maximum values.

One difference between the North and South sites shown in Tables 9 and 10 is the influence of speed increases. Change in speed at the South site results in significant changes in drawdown. For example, an increase of speed of the design ship from 11.5 knots to 12.2 knots results in an increase in drawdown from 3.55 ft to 4.55 ft at the South site (Table 9). At the North site, an increase of speed of the design ship from 9.6 knots to 10.2 knots results in an increase in drawdown from 3.0 ft to 3.2 ft. The North site is located where the berm adjacent to the channel is much wider and also more shallow. The

wider, more shallow berm has a significant effect on the wave characteristics at the shoreline.

From the TSW values in Table 9, under scenario 1, bank forces are worse in the proposed channel than in the existing channel for the design ship. TSW height under scenario 1 will increase at the South site from 7 to 39% and at the North site from 9 to 19%. The lower percentages of 7 and 9% indicate small impacts and the North at 9% being greater than the South at 7% is not a significant difference. The primary differences causing the lower values at the North site (19% versus 39%) results from two factors. First, the proposed channel size does not increase as much at the North site as at the South site. Second, the berm at the North site is wider and more shallow than at the South site.

From the TSW values in Table 10, under scenario 2 bank forces are worse in the proposed channel than in the existing channel when comparing the larger ships in the proposed channel to the design ship in the existing channel. The larger unloaded ship creates significantly larger TSW than the larger loaded ship (both in the proposed channel). This is consistent with observations in the existing channel. TSW height for the unloaded larger ship compared to the design ship under scenario 2 will increase at the South site 3 to 31% and at the North site 9 to 14%.

Table 11 shows the TSW height for the design ship in the existing and proposed channels at speeds close to the maximum for use in determining bank protection requirements. Values are based on ships traveling at 90% of limit speed which is recommended for design of bank protection in PIANC (1987). Transverse stern wave height should be used to design bank protection rather than velocity. The 3.4 ft surge for

the proposed ship at the South site is a significant extrapolation of equation 5 and must be viewed as approximate.

6 Speed Restrictions in Proposed Channel

One of the objectives of this study was to evaluate the effects of speed restrictions in the proposed channel. The speed restriction evaluation has two parts. The first part is to determine speeds in the proposed canal that will result in the same ship forces on the bank as in the existing canal. The second part is to determine speeds in the proposed canal that will result in various levels of reduced ship forces compared to the existing canal. Both parts can only be achieved if speeds in the proposed channel are less than the expected speeds used previously in this report and shown in Table 8. As in the previous portion of this report, the transverse stern wave (TSW) will be used to quantify and compare the various ship speeds in existing and proposed channels.

The first step is to determine typical speeds in the existing canal for all ships**.** To describe ship size, the simplest parameter that describes ship effects is the ship area that is equal to beam multiplied times average draft. Neither length nor beam nor draft alone properly describes the size effects of the ship. Consideration was given to using a tonnage but this parameter may be more difficult to define for an unloaded ship than simply beam time draft. The design ship used in the earlier part of this report traveled at about 85% of limit speed in the existing channel at both the North and South sites. When considering all ships and both sites, ships in the SNWW travel at about 80% of limit speed (see Figures 10 and 11). Figure 44 shows speeds at 80% of limit speed for both sites at a range of ship areas. As an example, a 39 ft draft ship having a beam of 106 ft has a ship area of 39X106 = 4134 sq ft. Based on Figure 44, the 106 ft beam X 39 ft draft ship travels at an average speed of 8.4 knots in the Sabine Neches Canal (North site). Figure 44 can only be used with beam and draft in feet and speed in knots.

The next step is to determine ship forces in the existing canal using the typical speeds shown in Figure 44. Three ship areas along the speed curves in Figure 44 were used in the speed evaluations of the existing channel as shown in Table 12. Note that some of the ships were modeled with wider, lesser drafts to prevent run problems discussed previously. As stated previously, use of a wider, less draft ship in the HIVEL2D model has negligible impact on the drawdown as long as the correct ship area is maintained. Using the Table 12 ships and the speeds from Figure 44, HIVEL2D simulations were conducted to determine the drawdown in the existing channel. Equation 5 was used to determine surge in the existing channel. Drawdown and surge were summed to provide the TSW and results are shown in Table 13 at the South site and Table 14 at the North site.

The next step is to determine ship speeds in the proposed canal that result in the same TSW that occurs in the existing canal. This step requires modeling various speeds for each ship size to find the speed that gives the same TSW height in the existing and the proposed canals. This step is relatively straightforward except for ships that do not presently travel in the existing canal such as the 900 ft X 164 ft X 48 ft ship proposed to use the deepened canal. This ship represents one of the largest ships in the proposed waterway. The target TSW height for this size ship will be set equal to the TSW height from the largest ships in the existing waterway. Based on Tables 13 and 14, the target TSW height for the largest ships in the proposed canal are 3.6 ft at the South site and 3.1 ft at the North site. Results of the various HIVEL2D simulations and equation 5 for the proposed canals are shown in Tables 15 and 16 at the South and North sites respectively. Using TSW heights in the existing channel from Tables 13 and 14, speed in the proposed

channel giving the same TSW was interpolated from Tables 15 and 16. Results are plotted in Figures 45 and 46 for equal TSW at the South and North sites, respectively. Also shown are the expected speeds for the design ship (810 ft X 140 ft X 29 ft), the larger loaded ship (900 ft X 164 ft X 48 ft), and the larger unloaded ship (900 ft X 164 ft X 30 ft). Note that the expected speeds and the restricted speeds for the larger loaded ship are about the same. This results from the assumption stated previously that the largest loaded ship in the proposed channel will have the same TSW as the largest loaded ship in the existing channel. At the South site, equal TSW height is achieved when ships travel about 1.2 to 1.5 knots faster in the proposed channel than in the existing channel. At the North site, equal TSW height is achieved when ships travel about 0.3 to 0.5 knots faster in the proposed channel than in the existing channel. The lesser increase at the North site is due to the smaller change in cross-section size in the proposed channel. The restricted speed curve at the South site is about 1 to 1.5 knots less than the expected speeds. The restricted speed curve at the North site is about 0.8 to 1.3 knots less than the expected speeds.

Figure 47 and 48 show speeds required in the proposed channel to achieve TSW height of 75% and 50% of the TSW height in the existing channel.

Figures 45-48 show that the SNWW ships operate in speed ranges where small changes in speed make large changes in TSW. This results primarily from two factors. First, the ships are operating at a large percentage of their limit speed. Second, the shallow berm amplifies drawdown, surge, and thus TSW.

7 Summary and Conclusions

The SNWW is a confined navigation channel with a shallow berm adjacent to the navigation channel whose berm width varies from near zero to over 800 ft in the Sabine-Neches Canal. Confined channels are those in which the ship cross-sectional area is large compared to the channel cross sectional area, being as much as 20% at SNWW. In this comparison of ship effects before and after enlargement of the channel, ship speed is the most critical and most difficult parameter to define. Confined channels have a limiting speed that cannot be exceeded by a self-propelled ship. The limit speed primarily depends on ship area relative to channel area. At SNWW, ships are traveling at 66-95% of their limit speeds. As a ship's speed nears the limit speed, the shallow berm and fast ship speed result in a large breaking wave forming adjacent to the shoreline. This wave, referred to herein as the transverse stern wave (TSW), moves at the ship speed and has a magnitude of up to 5.5 ft based on measurements reported herein and is calculated to be up to 8.4 ft for extremely fast ships in the proposed channel. The TSW is used herein to quantify and compare ship effects on the shoreline.

To evaluate ship effects, a North site was used to represent the Sabine-Neches Canal and a South site to represent the Port Arthur Canal. The Sabine-Neches Canal is proposed to be deepened to 50 ft while remaining at the current 400 ft bottom width. The Port Arthur Canal is proposed to be deepened to 50 ft and bottom width increased from 500 to 700 ft.

HIVEL2D is a 2-dimensional numerical model that was used herein to calculate the long period ship drawdown at SNWW. The model was validated using data from one of the ships measured during the field data collection portion of this study.

The TSW is equal to the drawdown, the fall below the ambient level, plus the surge, the rise above the ambient level. The field data collected for this study was used to develop an equation for surge based on ship speed, berm depth, and drawdown.

Two scenarios were evaluated that have the potential for increased bank attack in the proposed channel. The first scenario is that ships currently using the SNWW will be able to travel faster in the larger proposed channel resulting in an increase in bank attack. The first scenario is evaluated by comparing TSW in existing and proposed channels using a design ship having dimensions of 810 ft X 140 ft X 29 ft. This design ship was chosen because it has a high frequency of passage in the existing SNWW and it creates some of the largest TSW in the existing SNWW. The second scenario is that future ships will be larger than those using the existing SNWW and will cause larger bank attack. Scenario 2 is evaluated by comparing TSW in the existing channel using the design ship having dimensions of 810 ft X 140 ft X 29 ft to TSW in the proposed channel using a larger 900 ft X 164 ft X loaded (48 ft draft) and unloaded (30 ft draft) ship.

The two bank attack scenarios were evaluated using average or typical speeds equal to 85% of limit speed for the design ship in the existing channels, expected speeds ranging from 80-85% of limit speed for the design ship and larger unloaded ship in the proposed channels, and expected speeds ranging from 75-80% of limit speed for the larger loaded ship in the proposed channels.

Results show that at the lower end of the range of expected speeds in the proposed channels, the TSW will increase in height less than 10% for both bank attack scenarios in both the Port Arthur and Sabine-Neches Canals. At the upper end of the range of expected speeds in the proposed channels, the TSW will increase an average of 35% in

the Port Arthur Canal and an average of 17% in the Sabine-Neches Canal for both bank attack scenarios. The lesser change in the Sabine-Neches Canal is due to the smaller increase in cross section and the wider berm.

Speed restriction tests were conducted with the proposed channel to determine speeds that will (1) result in equal TSW in the existing and proposed channels and (2) lessen TSW in the proposed channel compared to the existing channel. In the Port Arthur Canal, equal TSW is achieved when ships travel about 1.2 to 1.5 knots faster in the proposed channel than in the existing channel. The restricted speeds in the proposed Port Arthur Canal are about 1 to 1.5 knots less than the expected speeds. In the Sabine-Neches Canal, equal TSW is achieved when ships travel about 0.3 to 0.5 knots faster in the proposed channel than in the existing channel. The restricted speeds in the proposed Sabine-Neches Canal are about 0.8 to 1.3 knots less than the expected speeds.

All of the results herein show that ships in the existing and proposed SNWW are operating at speeds where small changes in speed make large changes in TSW. This results primarily from two factors. First the ships are operating at a large percentage of their limit speed. Second, the shallow berm amplifies drawdown, surge, and thus TSW.

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Table 1. Pressure cell descriptions and locations

Cell Number	Location	Time in/out water	Depth m (ft) below MLT	State Plane, NAD83, Texas South Central-4204
1200346B	South	04/30/02-0705 CST-in	0.5(1.7)	3571268, 13868525-about 660 ft from channel centerline
“	“	05/01/02-1420 CST-out		
1210346B	“	05/01/02-1500 CST-in		
“	“	05/03/02-0750 CST-out		
1200347B	“	04/30/02-0750 CST-in	1.1(3.6)	3570555, 13870352-about 620 ft from channel centerline
“	“	05/02/02-1500 CST-out		
1210347B	“	05/01/02-1520 CST-in		
“	“	05/03/02-0740 CST-out		
1230347B	“	05/03/02-0830 CST-in		
“	“	05/04/02-0830 CST-out		
1200349B	North	04/30/02-1035 CST-in	1.2(3.8)	3581227, 13906697-about 740 ft from channel centerline
“	“	05/01/02-1635 CST-out		
1210349B	“	05/01/02-1705 CST-in		
“	“	05/03/02-1320 CST-out		
1230349B	“	05/03/02-1430 CST-in		
“	“	05/04/02-0745 CST-out		
1200350B	“	04/30/02-1120 CST-in	1.2(3.8)	3582598, 13908337-about 670 ft from channel centerline
“	“	05/01/02-1615 CST-out		
1210350B	“	05/01/02-1700 CST-in		
“	“	05/03/02-1320 CST-out		
1230350B	“	05/03/02-1425 CST-in		
“	“	05/04/02-0725 CST-out		

Table 2. Capacitance gage descriptions

Array/gage	Location	Time in/out water	Depth, m (ft) below MLT	State Plane, NAD83, Texas South Central 4204
1200522B	South	04/30/02-1550 CST-in	Near channel = 1.3 (4.4),	Near Channel- 3570930, 13869253
“	“	05/01/02-1330 CST-out		
“	“	04/30/02-1550 CST-in		
“	“	05/01/02-1330 CST-out		
1210520B	“	05/01/02-1430 CST-in		
“	“	05/03/02-0950 CST-out		
“	“	05/01/02-1430 CST-in	near shoreline = 0.8 (2.5)	Near Bank- 3570988, 13869290
“	“	05/03/02-0950 CST-out		
1220526B	”	05/03/02-0945 CST-in		
“	“	05/04/02-0900 CST-out		
“	“	05/03/02-0945 CST-in		
“	“	05/04/02-0900 CST-out		
1210526B	North	05/01/02-1045 CST-in	Near channel = middle = near shoreline = 0.3 (1.0)	Near Channel- 3583596, 13908863
“	“	05/02/02-0845 CST-out		
“	“	05/01/02-1045 CST-in		
“	“	05/02/02-0845 CST-out		
“	“	05/01/02-1045 CST-in		Middle- 3583647, 13908823
“	“	05/02/02-0845 CST-out		
1220522B	“	05/02/02-1045 CST-in		
“	“	05/04/02-1015 CST-out		
“	“	05/02/02-1045 CST-in		Near bank- 3583676, 13908800
“	“	05/04/02-1015 CST-out		
“	“	05/02/02-1045 CST-in		
“	“	05/04/02-1015 CST-out		

Table 3. Log of Sabine Ships

Ship Name, type T=tanker, B=bulk	Date (2002), Time	Dir	Length, m (ft)	Beam, m (ft)	Draft, m (ft)	Tide MLT , m (ft)
Eagle Augusta,T	29 Apr, 1624	Out	243.6(799)	42.4(139)	8.5(28)	Ebb, 0.92 (3.03)
Noblesse,B	29 Apr, 1702	In	158.8(521)	22.6(74)	6.1(20)	Ebb, 0.93 (3.05)
Dafnis, B	29 Apr, 1740	Out	160.1(525)	23.5(77)	7.0(23)	Ebb, 0.88 (2.88)
Nordlight, T	30 Apr, 0820	Out	244.2 (801)	42.1 (138)	9.1 (30)	Flood, 0.90 (2.98)
Frankopan, T	30 Apr, 0945	Out	244.5 (802)	39.3 (129)	9.1 (30)	Slack, 0.94 (3.10)
Minerva Joanna, T	30 Apr, 1015	Out	182.9 (600)	32.3 (106)	9.1 (30)	Slack, 0.94 (3.08)
Star America, B	30 Apr, 1350	In	169.5 (556)	26.5 (87)	8.2 (27)	Slack, 0.95 (3.13)
Zeebruggee, LGP	30 Apr, 1400	In	159.4 (523)	24.3 (80)	10.1 (33)	Slack, 0.97 (3.21)
Bornes, T	30 Apr, 1440	In	243.9 (800)	42.1 (138)	11.6 (38)	Slack, 0.97 (3.19)
Bernhard Oldendorf,B	30 Apr, 1635	In	245.1 (804)	32.3 (106)	9.5 (31)	Slack, 0.95 (3.13)
Kite Arrow, B	30 Apr, 2135	Out	199.7 (655)	32.3 (106)	10.1 (33)	Ebb, 0.83 (2.73)
Sunor, B	30 Apr, 2300	Out	180.1 (591)	30.5 (100)	11.6 (38)	Ebb, 0.74 (2.43)
Anette, T	30 Apr, 2350	In	224.7 (737)	32.3 (106)	11.6 (38)	Ebb, 0.62 (2.04)
Noblesse, B	1 May, 0215	Out	158.8 (521)	22.6 (74)	6.1 (20)	Ebb, 0.59 (1.96)
Olga Topic, B	1 May, 0515	Out	185.7 (609)	30.5 (100)	7.9 (26)	Flood, 0.77 (2.55)
Saraband, T	1 May, 0930	In	182.6 (599)	32.0 (105)	8.2 (27)	Flood, 0.97 (3.18)
Zrinkski, T	1 May, 1225	In	244.5 (802)	39.3 (129)	11.9 (39)	Slack, 1.02 (3.37)
Astro Antares, T	1 May, 1345	In	248.2 (814)	43.3 (142)	11.9 (39)	Slack, 1.03 (3.38)
Pacific Sapphire, T	1 May, 1305	In	247.0 (810)	41.7 (137)	12.2 (40)	Slack, 0.96 (3.16)
Project Europa, H	1 May, 1530	In	139.0 (456)	22.9 (75)	7.3 (24)	Ebb, 0.98 (3.24)
S/R Charleston, T	1 May, 2135	In	193.9 (636)	32.3 (106)	8.8 (29)	Ebb, 0.82 (2.69)

Milagro, T	2 May, 0349	Out	196.0 (643)	24.3 (80)	8.8 (29)	Ebb, 0.66 (2.17)
Bornes, T	2 May, 0805	Out	243.9 (800)	42.1 (138)	9.8 (32)	Flood, 0.71 (2.34)
Jo Lonn, T	2 May, 1100	In	175.0 (574)	32.0 (105)	9.5 (31)	Slack, 0.97 (3.21)
Eagle Carina, T	2 May, 1215	In	247.0 (810)	42.1 (138)	10.7 (35)	Slack, 0.99 (3.26)
Bunga Kelana Dua, T	2 May, 1230	In	243.9 (800)	42.1 (138)	11.6 (38)	Slack, 0.99 (3.26)
Grand Orchid, B	2 May, 1450	In	189.9 (623)	31.1 (102)	11.3 (37)	Ebb, 0.97 (3.21)
Olga Topic, B	2 May, 1815	Out	185.6 (609)	30.5 (100)	11.6 (38)	Ebb, 0.89 (2.94)
Bernhard Oldendorf, B	2 May, 1920	Out	245.1 (804)	32.3 (106)	11.6 (38)	Ebb, 0.84 (2.76)
Zeebruggee, LGP	2 May, 1935	Out	159.4 (523)	24.3 (80)	7.0 (23)	Ebb, 0.85 (2.90)
Anette, T	3 May, 0215	Out	224.7 (737)	32.3 (106)	8.5 (28)	Ebb, 0.72 (2.36)
Astro Antares, T	3 May, 0930	Out	248.2 (814)	43.3 (142)	8.8 (29)	Flood, 0.79 (2.60)
Genmar Alexandra, T	3 May, 1305	In	241.5 (792)	42.1 (138)	11.6 (38)	Slack, 0.93 (3.05)
Eagle Subaru, T	3 May, 1320	In	247.0 (810)	42.1 (138)	12.2 (40)	Slack, 0.92 (3.02)
Alderbaran, T	3 May, 1335	In	243.9 (800)	39.9 (131)	10.7 (35)	Slack, 0.93 (3.05)
Eagle Auriga, T	3 May, 1620	In	241.5 (792)	42.1 (138)	11.9 (39)	Ebb, 0.84 (2.78)
Shetland, Lig Gas	3 May, 1940	In	153.4 (503)	25.0 (82)	7.0 (23)	Ebb, 0.84 (2.77)
Jo Lonn, T	3 May, 2055	Out	175.3 (575)	32.0 (105)	10.1 (33)	Ebb, 0.86 (2.83)
Stolt Tarus, T	3 May, 2150	Out	123.5 (405)	20.4 (67)	10.1 (33)	Ebb, 0.84 (2.78)
Pacific Sapphire, T	4 May, 0735	Out	247.0 (810)	41.7 (137)	8.5 (28)	Slack, 0.58 (1.93)

Table 4. Drawdown and Surge at North Site												
Ship Name	Date (2002)	Dir	Drawdown Pressure Cell 349 m (ft)	Drawdown Pressure Cell 350 m (ft)	Drawdown Capacitance Cell 526, bank, m (ft)	Drawdown Capacitance Cell 526, middle, m (ft)	Drawdown Capacitance Cell 526, channel, m (ft)	Surge Pressure Cell 349 m (ft)	Surge Pressure Cell 350 m (ft)	Surge Capacitance Cell 526, bank, m (ft)	Surge Capacitance Cell 526, middle, m (ft)	Surge Capacitance Cell 526, channel, m (ft)
Nordlight	30-Apr	Out	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Frankopan	30-Apr	Out	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Minerva Joanna	30-Apr	Out	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Star America	30-Apr	In	0.60 (2.0)	0.60 (2.0)	NA	NA	NA	0.05 (0.2)	0.0 (0.00)	NA	NA	NA
Zeebruggee	30-Apr	In	1.20 (3.9)	0.80 (2.6)	NA	NA	NA	0.10 (0.3)	0.20 (0.7)	NA	NA	NA
Bornes	30-Apr	In			NA	NA	NA	NA	NA	NA	NA	NA
Bernhard Oldendorf	30-Apr	In	1.35 (4.4)	0.95 (3.1)	NA	NA	NA	0.25 (0.8)	0.20 (0.7)	NA	NA	NA
Kite Arrow	30-Apr	Out			NA	NA	NA			NA	NA	NA
Sunor	30-Apr	Out	0.30 (1.0)	0.30 (1.0)	NA	NA	NA	0.05 (0.2)	0.35 (1.1)	NA	NA	NA
Anette	30-Apr	In	0.80 (2.6)	0.50 (1.6)	NA	NA	NA	0.0 (0.0)	0.0 (0.0)	NA	NA	NA
Noblesse	1-May	Out			NA	NA	NA	NA	NA	NA	NA	NA
Olga Topic	1-May	Out			NA	NA	NA	NA	NA	NA	NA	NA
Saraband	1-May	In	0.70 (2.3)	0.60 (2.0)	NA	NA	NA	0.10 (0.3)	0.10 (0.3)	NA	NA	NA
Zrinski	1-May	In	0.55 (1.8)	1.50 (4.9)	0.75 (2.5)	0.75 (2.5)	0.85 (2.8)	0.20 (0.7)	0.20 (0.7)	0.65(2.1)	0.40(1.3)	0.40 (1.3)
Astro Antares	1-May	In	1.00 (3.3)	1.80 (5.9)	NA	NA	NA	0.25 (0.8)	0.35 (1.1)	NA	NA	NA
Pacific Sapphire	1-May	In	0.75 (2.5)	1.75 (5.7)	0.95 (3.1)	0.80 (2.6)	0.95(3.1)	0.25 (0.8)	0.30 (1.0)	0.4(1.3)	0.3(1.0)	0.35(1.1)
Project Europa	1-May	In	0.50 (1.6)	1.25 (4.1)	0.80 (2.6)	0.60(2.0)	0.50 (1.6)	0.05 (0.2)	0.05 (0.2)	0.20(0.7)	0.15(0.5)	0.15(0.5)
S/R Charleston	1-May	In	0.70 (2.3)	0.80 (2.6)	0.70 (2.3)	0.55 (1.8)	0.70 (2.3)	0.15 (0.5)	0.0 (0.0)	0.25(0.8)	0.1(0.3)	0.25(0.8)
Milagro	2-May	Out	0.50 (1.6)	0.65 (2.1)	0.60 (2.0)	0.45 (1.5)	0.60 (2.0)	0.05 (0.2)	0.30 (1.0)	0.35 (1.1)	0.25(0.8)	0.35(1.1)
Bornes	2-May	Out	0.70 (2.3)	0.75 (2.5)	0.65(2.1)	0.50 (1.6)	0.60 (2.0)	0.35 (1.1)	0.50 (1.6)	NA	NA	NA
Jo Lonn	2-May	In	0.75 (2.5)	0.70 (2.3)	0.7(2.3)	0.7(2.3)	0.75(2.5)	0.05 (0.2)	0.05 (0.2)	0.3(1.0)	0.25(0.8)	0.4(1.3)
Eagle Carina	2-May	In	0.65 (2.1)	0.70 (2.3)	0.70 (2.3)	0.75 (2.5)	0.75 (2.5)	0.20 (0.7)	0.05 (0.2)	0.30 (1.0)	0.3(1.0)	0.35(1.1)
Bunga Kelana Dua	2-May	In	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Grand Orchid	2-May	In	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Olga Topic	2-May	Out	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Bernhard Oldendorf	2-May	Out	0.55 (1.8)	0.45 (1.5)	0.60 (2.0)	0.65 (2.1)	0.60 (2.0)	0.0 (0.0)	0.45 (1.5)	NA	NA	NA
Zeebruggee	2-May	Out	NA	NA	0.55(1.8)	0.55(1.8)	0.55(1.8)	NA	NA	0.25(0.8)	0.25(0.8)	0.2(0.7)
Anette	3-May	Out	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Astro Antares	3-May	Out	1.05 (3.4)	0.90 (3.0)	0.55 (1.8)	0.60 (2.0)	0.75 (2.5)	0.0 (0.0)	0.60 (2.0)	0.4(1.3)	0.4(1.3)	0.45(1.5)
Genmar Alexandra	3-May	In	0.35 (1.1)	0.35 (1.1)	0.40 (1.3)	0.60 (2.0)	0.45 (1.5)	0.10 (0.3)	0.10 (0.3)	0.3(1.0)	0.3(1.0)	0.25(0.8)
Eagle Subaru	3-May	In	NA	NA	0.4(1.3)	NA	0.35(1.1)	NA	NA	0.25(0.8)	NA	0.2(0.7)
Aldebaran	3-May	In	NA	NA	0.3(1.0)	NA	0.3(1.0)	NA	NA	0.2(0.7)	NA	0.15(0.5)
Eagle Auriga	3-May	In	0.40 (1.3)	0.45 (1.5)	0.60 (2.0)	0.60 (2.0)	0.55 (1.8)	0.05 (0.2)	0.20 (0.7)	0.35(1.1)	0.4(1.3)	0.25(0.8)
Sthetland	3-May	In	0.60 (2.0)	0.35 (1.1)	0.40 (1.3)	0.55 (1.8)	0.45 (1.5)	0.0 (0.0)	0.10 (0.3)	0.35(1.1)	0.3(1.0)	0.25(0.8)
Jo Lonn	3-May	Out	0.50 (1.6)	0.60 (2.0)				0.05 (0.2)	0.45 (1.5)	NA	NA	NA
Stolt Tarus	3-May	Out	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Pacific Sapphire	4-May	Out	NA	NA	0.85 (2.8)	0.65 c (2.1)	0.35 c (1.1)	NA	NA	0.5(1.6)	NA	NA

Table 5. Drawdown and Surge at South Site										
Ship Name	Date (2002	Direction	Drawdown Pressure Cell 346 m (ft)	Drawdown Pressure Cell 347 m (ft)	Drawdown Capacitance Cell 522, channel, m (ft)	Drawdown Capacitance Cell 522, Bank, m (ft)	Surge Pressure Cell 346 m (ft)	Surge Pressure Cell 347 m (ft)	Surge Capacitance Cell 522, channel, m (ft)	Surge Capacitance Cell 522, bank, m (ft)
Nordlight	30-Apr	Out	0.90 c (3.0)	1.15 (3.8)	NA	NA	0.40 (1.3)	0.45(1.5)	NA	NA
Frankopan	30-Apr	Out	0.65 (2.1)	0.70 (2.3)	NA	NA	0.30 (1.0)	0.25(0.8)	NA	NA
Minerva Joanna	30-Apr	Out	0.70(2.3)	0.70 (2.3)	NA	NA	0.50(1.6)	0.4(1.3)	NA	NA
Star America	30-Apr	In	0.90 (3.0)	1.00 (3.3)	NA	NA	0.35 (1.1)	0.50(1.6)	NA	NA
Zeebruggee	30-Apr	In	0.90 c (3.0)	0.90 (3.0)	NA	NA	0.45(1.5)	0.50(1.6)	NA	NA
Bornes	30-Apr	In	0.85 c (2.8)	1.10 (3.6)	NA	NA	0.30(1.0)	0.10(0.3)	NA	NA
Bernhard Oldendorf	30-Apr	In	0.75 c (2.5)	0.95 (3.1)	1.05(3.4)	0.85 c (2.8)	0.15 (0.5)	0.35(1.1)	0.45(1.5)	0.85(2.8)
Kite Arrow	30-Apr	Out	0.60 c (2.0)	0.80 (2.6)	0.60 (2.0)	0.55 c (1.8)	0.4(1.3)	0.55(1.8)	0.4(1.3)	0.45(1.5)
Sunor	30-Apr	Out	0.40 (1.3)	0.55 (1.8)	NA	NA	0.25 (0.8)	0.3(1.0)	NA	NA
Anette	30-Apr	In	0.50 c (1.6)	0.95 (3.1)	0.70 (2.3)	0.45 c (1.5)	0.20(0.7)	0.45(1.5)	0.3(1.0)	0.45(1.5)
Noblesse	1-May	Out	0.25 (0.8)	0.40 (1.3)	NA	NA	0.20 (0.7)	0.35 (1.1)	0.25(0.8)	0.20(0.7)
Olga Topic	1-May	Out	0.65 (2.1)	0.50 (1.6)	0.4(1.3)	0.55(1.8)	0.35 (1.1)	0.35(1.1)	0.30 (1.0)	0.35 (1.1)
Saraband	1-May	In	0.90 (3.0)	0.85 (2.8)	NA	NA	0.40 (1.3)	0.40(1.3)	NA	NA
Zrinski	1-May	In	0.70 (2.3)	0.80 (2.6)	0.60 (2.0)	0.70 (2.3)	0.30(1.1)	0.10 (0.3)	0.30(1.0)	NA
Astro Antares	1-May	In	0.9 c(3.0)	1.0(3.3)	NA	NA	0.25(0.8)	0.10(0.3)	NA	NA
Pacific Sapphire	1-May	In	0.90 (3.0)	0.95(3.1)	1.05 (3.4)	0.95 c (3.1)	0.3(1.0)	0.15 (0.5)	0.25(0.8)	0.3(1.0)
Project Europa	1-May	In	0.70 (2.3)	0.55 (1.8)	NA	NA	0.35 (1.1)	0.4(1.3)	NA	NA
S/R Charleston	1-May	In	0.75 (2.5)	1.10 (3.6)	0.95 (3.1)	0.75 c (2.5)	0.15 (0.5)	0.35(1.1)	0.25(0.8)	NA
Milagro	2-May	Out	0.65 (2.1)	0.65 (2.1)	0.60 (2.0)	0.55 c (1.8)	0.45(1.5)	0.50(1.6)	0.50(1.6)	0.4(1.3)
Bornes	2-May	Out	0.70 (2.3)	0.80 (2.6)	0.75 (2.5)	NA	0.50(1.6)	0.45(1.5)	0.40(1.3)	NA
Jo Lonn	2-May	In	0.45(1.5)	0.75 (2.5)	0.50 (1.6)	0.65 (2.1)	NA	0.45(1.5)	0.40 (1.3)	NA
Eagle Carina	2-May	In	0.65 (2.1)	0.65 (2.1)	0.60 (2.0)	NA	0.25 (0.8)	0.10 (0.3)	0.1(0.3)	NA
Bunga Kelana Dua	2-May	In	0.45 (1.5)	0.60 (2.0)	0.45(1.5)	0.55 (1.8)	0.15 (0.5)	0.10 (0.3)	0.05 (0.2)	0.15(0.5)
Grand Orchid	2-May	In	0.50 (1.6)	0.50 (1.6)	0.45(1.5)	0.60 (2.0)	0.20 (0.7)	0.10 (0.3)	0.20(0.7)	0.40(1.3)
Olga Topic	2-May	Out	0.40 (1.3)	0.55 (1.8)	0.40 (1.3)	0.50 (1.6)	0.15 (0.5)	0.20(0.7)	0.20 (0.7)	0.25 (0.8)
Bernhard Oldendorf	2-May	Out	0.75 (2.5)	0.95(3.1)	0.75 (2.5)	0.80 c (2.6)	0.45(1.5)	0.45(1.5)	0.45 (1.5)	NA
Zeebruggee	2-May	Out	0.55 (1.8)	0.75 (2.5)	0.45(1.5)	0.65 (2.1)	0.55 (1.8)	0.60 (2.0)	0.5(1.6)	NA
Anette	3-May	Out	0.60 (2.0)	0.65 (2.1)	0.50 (1.6)	0.50 c (1.6)	0.40(1.3)	0.45(1.5)	NA	NA
Astro Antares	3-May	Out	0.40 (1.3)	0.75(2.5)	0.45(1.5)	0.60 (2.0)	0.20 (0.7)	0.3(1.0)	0.3(1.0)	NA
Genmar Alexandra	3-May	In	0.30 (1.0)	0.60 (2.0)	0.50 (1.5)	0.60 (2.0)	0.25(0.8)	0.20 (0.7)	0.05 (0.2)	0.20 (0.7)
Eagle Subaru	3-May	In	0.40 (1.3)	0.45(1.5)	0.30(1.0)	0.40 (1.3)	0.20 (0.7)	0.05 (0.2)	0.1(1.3)	0.10 (0.3)
Aldebaran	3-May	In	0.65 (2.1)	0.60 (2.0)	0.7(2.3)	0.8(2.6)	0.20 (0.7)	0.10 (0.3)	0.15(0.5)	NA
Eagle Auriga	3-May	In	0.65 (2.1)	0.75 (2.5)	0.65 (2.1)	0.65 (2.1)	0.15 (0.5)	0.05 (0.2)	0.05(0.2)	0.1(0.3)
Sthetland	3-May	In	0.95 (3.1)	0.95 (3.1)	0.65 (2.1)	0.85 c (2.8)	0.50(1.6)	0.55(1.8)	0.55 (1.8)	NA
Jo Lonn	3-May	Out	0.55 (1.8)	0.65 92.1)	0.4(1.3)	0.5(1.6)	0.35(1.1)	0.40(1.3)	0.40(1.3)	NA
Stolt Tarus	3-May	Out	0.50 (1.6)	0.60 (2.0)	0.35 (1.1)	0.55 (1.8)	0.45(1.5)	0.50 (1.6)	0.40 (1.3)	NA
Pacific Sapphire	4-May	Out	0.80 (2.6)	0.90 (3.0)	0.85(2.8)	0.65 c(2.1)	0.6(2.0)	0.6(2.0)	0.6(2.0)	NA

Table 6. Characteristics of Pacific Sapphire passage on 1 May 02.

Characteristic	Dimension
Beam, ft	137
Length, ft	810
Draft, ft	40
Ship x-section area, sq ft	5480
Speed at North and South sites, knots relative to ground	8.3, 8.6
Water level, ft MLT (tide)	3.16 (slack)
Shoreline drawdown at North and South sites, ft	2.9, 3.3
Shoreline Surge at North and South sites, ft	1.3, 1.0

Table 7. Ship speeds relative to ground.

			South Site		North Site	
Ship Name	**Date (2002)**	**Direction**	**Speed from 346 to 347 knots (ft/sec)**	**Bow-Stern Timing, knots (ft/sec)**	**Speed from 349 to 350 knots (ft/sec)**	**Bow-Stern Timing, knots (ft/sec)**
Eagle Augus	29-Apr	Out	NA	10.0(16.8)	NA	NA
Mount Lady	29-Apr	Out	NA	8.4(14.1)	NA	NA
Noblesse	29-Apr	In	NA	9.1(15.3)	NA	NA
Dafnis	29-Apr	Out	NA	13.0(21.9)	NA	NA
Nordlight	30-Apr	Out	10.3 (17.3)	NA	NA	NA
Frankopan	30-Apr	Out	9.8 (16.5)	NA	NA	NA
Minerva Joanna	30-Apr	Out	9.9 (16.7)	NA	NA	NA
Star America	30-Apr	In	10.1 (17.0)	NA	11.5 (19.4)	11.4 (19.2)
Zeebruggee	30-Apr	In	9.9 (16.7)	NA	8.2 (13.9)	11.9 (20.1)
Bornes	30-Apr	In	8.1 (13.7)	NA	NA	NA
Bernhard Oldendorf	30-Apr	In	9.8 (16.5)	NA	10.0 (16.9)	NA
Kite Arrow	30-Apr	Out	11.7 (19.8)	NA	NA	NA
Sunor	30-Apr	Out	9.8 (16.6)	NA	8.5 (14.3)	NA
Anette	30-Apr	In	8.8 (14.9)	NA	10.9 (18.4)	NA
Noblesse	1-May	Out	11.5 (19.4)	NA	NA	NA
Olga Topic	1-May	Out	10.0 (16.9)	NA	NA	NA
Saraband	1-May	In	11.2 (18.9)	12.3 (20.7)	12.3 (20.8)	12.7(21.4)
Zrinski	1-May	In	8.4 (14.2)	7.6(12.9)	9.0 (15.2)	NA
Astro Antares	1-May	In	9.0 (15.2)	9.0(15.2)	7.5 (12.6)	8.8(14.8)
Pacific Sapphire	1-May	In	8.6 (14.5)	8.6(14.5)	7.5 (12.7)	8.3(14.0)
Project Europa	1-May	In	11.4 (19.2)	12.3(20.7)	NA	NA
S/R Charleston	1-May	In	9.2 (15.6)	NA	9.3 (15.7)	NA
Milagro	2-May	Out	11.0 (18.6)	NA	10.1 (17.1)	NA
Bornes	2-May	Out	10.3 (17.3)	9.9 (16.7)	9.5 (16.1)	NA
Jo Lonn	2-May	In	10.3 (17.3)	11.0(18.5)	11.5 (19.4)	11.0(18.5)
Eagle Carina	2-May	In	8.2 (13.8)	8.4(14.2)	8.2 (13.8)	8.3(14.0)
Bunga Kelana Dua	2-May	In	8.0 (13.6)	NA	NA	5.6(9.5)
Grand Orchid	2-May	In	8.8 (14.9)	NA	NA	NA
Olga Topic	2-May	Out	10.0 (16.9)	NA	NA	NA
Bernhard Oldendorf	2-May	Out	9.8 (16.6)	NA	8.5 (14.4)	NA
Zeebruggee	2-May	Out	13.4 (22.6)	NA	NA	NA
Anette	3-May	Out	11.0 (18.6)	NA	NA	NA
Astro Antares	3-May	Out	9.2 (15.6)	NA	9.3 (15.7)	NA

Genmar Alexandra	3-May	In	8.0 (13.5)	NA	8.5 (14.4)	NA
Eagle Subaru	3-May	In	7.3 (12.3)	NA	NA	NA
Aldebaran	3-May	In	8.8 (14.9)	NA	NA	NA
Eagle Auriga	3-May	In	7.5 (12.7)	NA	6.4 (10.8)	NA
Shetland	3-May	In	11.9 (20.0)	NA	11.8 (19.9)	NA
Jo Lonn	3-May	Out	9.8 (16.5)	NA	9.4 (15.9)	NA
Stolt Tarus	3-May	Out	13.3 (22.4)	NA	NA	NA
Pacific Sapphire	4-May	Out	10.6 (17.8)	NA	NA	NA

Table 8. Summary of speeds used in ship comparison

channel	ship	Speed used in HIVEL2D model, knots (%Vlimit)	
		South	North
existing	800X140X29	10(86)	9(85)
700X50	“	11.5(80) and 12.2(85)	NA
“	899X164X30	10.8(80) and 11.5(85)	NA
“	899X164X48	8.3(75) and 8.9(80)	NA
Existing*	899X164X38	NA	6.2(73) from simulator
400X50*	899X164X48	NA	6.3(75) “ “
500X50*	899X164X48	NA	6.9(75) “ “
400X50	800X140X29	NA	9.6(80) and 10.2(85)
“	899X164X30	NA	8.9(80) and 9.4(85)
“	899X164X48	NA	6.3(75) and 6.8(80)

* These were not one of the HIVEL2D simulations but the data is provided to show the % of limit speed used in the simulator study. NA=not applicable

Table 9. Comparison of drawdown, surge, and transverse stern wave, Scenario 1.

Channel	Ship	Speed, knots South/ North (%limit)	Drawdown, ft		Surge, ft		Transverse stern wave, ft	
			South	North	South	North	South	North
Existing	Design	10/9 (85)	3.6	2.9	1.8	1.4	5.4	4.3
Proposed	“	11.5/9.6(80)	3.55	3.0	2.3	1.7	5.8	4.7
“	“	12.2/10.2(85)	4.55	3.2	2.9	1.9	7.5	5.1

Table 10. Comparison of drawdown, surge, and transverse stern wave, Scenario 2.

Channel	Ship	Speed, knots South/ North (%limit)	Drawdown, ft		Surge, ft		Transverse stern wave, ft	
			South	North	South	North	South	North
Existing	Design	10/9 (85)	3.6	2.9	1.8	1.4	5.4	4.3
Proposed	Larger Unloaded	10.8/8.9 (80)	3.6	3.2	2.0	1.5	5.6	4.7
“	“	11.5/9.4 (85)	4.5	3.2	2.6	1.7	7.1	4.9
“	Larger Loaded	8.3/6.3 (75)	3.15	2.25	1.2	0.7	4.4	2.9
“	“	8.9/6.8 (80)	4.15	2.8	1.6	0.9	5.7	3.7

Table 11. Drawdown, surge, and transverse stern wave for 90% of limit speed.

Channel	Ship	Speed, knots South/ North (%limit)	Drawdown, ft		Surge, ft		Transverse stern wave, ft	
			South	North	South	North	South	North
Existing	Design	10.6/9.5(90)	4.55	3.2	2.3	1.7	6.8	4.9
Proposed	“	12.9/10.8(90)	5.0	3.3	3.4	2.2	8.4	5.5

Table 12. Ships used in speed restriction evaluation.

Channel	Area, sq ft	Actual & Modeled Length	Actual beam, ft	Actual draft, ft	Modeled beam, ft	Modeled draft
E&P*	1500	500	80	18.75	80	18.75
“	3500	650	106	33.0	120	29.17
“	5500	810	140	39.3	180	30.56
P only	7872	900	164	48	200	39.36

E=existing channel, P=proposed channel

Table 13. Results of HIVEL2D and Equation 5 in speed evaluation of existing canal, South site. Based on HIVEL2D node 16002.

Area, sq ft	Speed, knots	Drawdown, ft (HIVEL2D)	Surge, ft (Eq. 5)	Transverse stern wave, ft
1500	12.2	2.0	1.8	3.8
3500	9.8	2.8	1.5	4.3
5500	8.1	2.6	1.0	3.6

Table 14. Results of HIVEL2D and Equation 5 in speed evaluation of existing canal, North site. Based on HIVEL2D node 16952.

Area, sq ft	Speed, knots	Drawdown, ft (HIVEL2D)	Surge, ft (Eq. 5)	Transverse stern wave, ft
1500	11.5	1.6	1.6	3.2
3500	9.0	2.4	1.3	3.7
5500	7.3	2.3	0.8	3.1

Table 15. Results of HIVEL2D and Equation 5 in speed evaluation of proposed canal, South site. Based on HIVEL2D node 16002.

Area, sq ft	Speed, knots (% limit)	Drawdown, ft (HIVEL2D)	Surge, ft (Eq. 5)	Transverse stern wave, ft
1500	14.1(80)	1.9	2.3	4.2
“	13.2(75)	1.7	1.8	3.5
“	11.9(67.5)	1.0	1.1	2.1
“	10.55(60)	0.7	0.7	1.4
3500	11.9(80)	3.2	2.3	5.5
“	11.2(75)	2.5	1.7	4.2
“	10.1(67.5)	1.7	1.1	2.8
“	8.9(60)	1.0	0.7	1.7
5500	9.7(75)	3.0	1.5	4.5
“	8.7(67.5)	1.9	0.9	2.8

“	7.8(60)	1.1	0.6	1.7
7872	8.3(75)	2.9	1.1	4.0
“	7.5(67.5)	1.9	0.7	2.6
“	6.7(60)	1.2	0.5	1.7

Table 16. Results of HIVEL2D and Equation 5 in speed evaluation of proposed canal, North site. Based on HIVEL2D node 16952.

Area, sq ft	Speed, knots (% limit)	Drawdown, ft (HIVEL2D)	Surge, ft (Eq. 5)	Transverse stern wave, ft
1500	11.9(75)	1.5	1.6	3.1
“	10.7(67.5)	1.0	1.1	2.1
“	9.5(60)	0.7	0.7	1.4
3500	9.6(75)	2.4	1.4	3.8
“	8.6(67.5)	1.8	1.0	2.8
“	7.7(60)	1.2	0.6	1.8
5500	7.9(75)	2.5	1.0	3.5
“	7.1(67.5)	1.6	0.7	2.3
“	6.3(60)	1.0	0.4	1.4
7872	6.7(80)			
“	6.3(75)	2.0	0.6	2.6
“	5.7(67.5)	1.4	0.4	1.8
“	5.1(60)	1.1	0.3	1.4

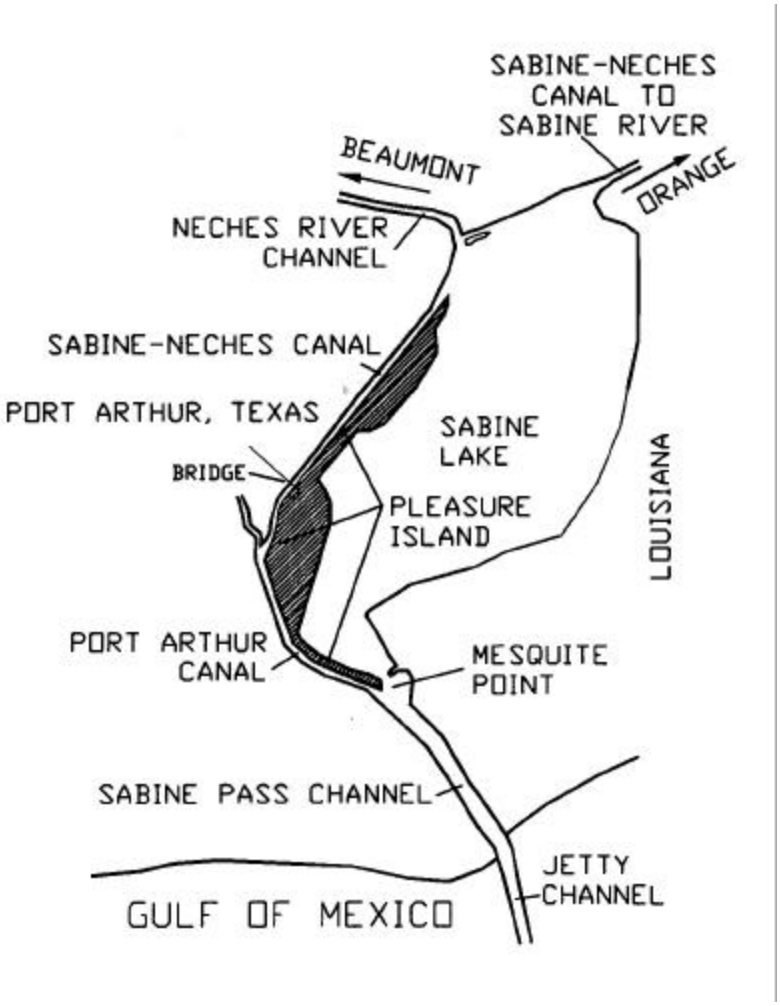

Figure 1. Sabine-Neches Waterway

Figure 2a. Nordlight in Port Arthur Canal, 801 ft by 138 ft by 30 ft, outbound, 10.3 knots.

Figure 2b. Transverse stern wave from Nordlight.

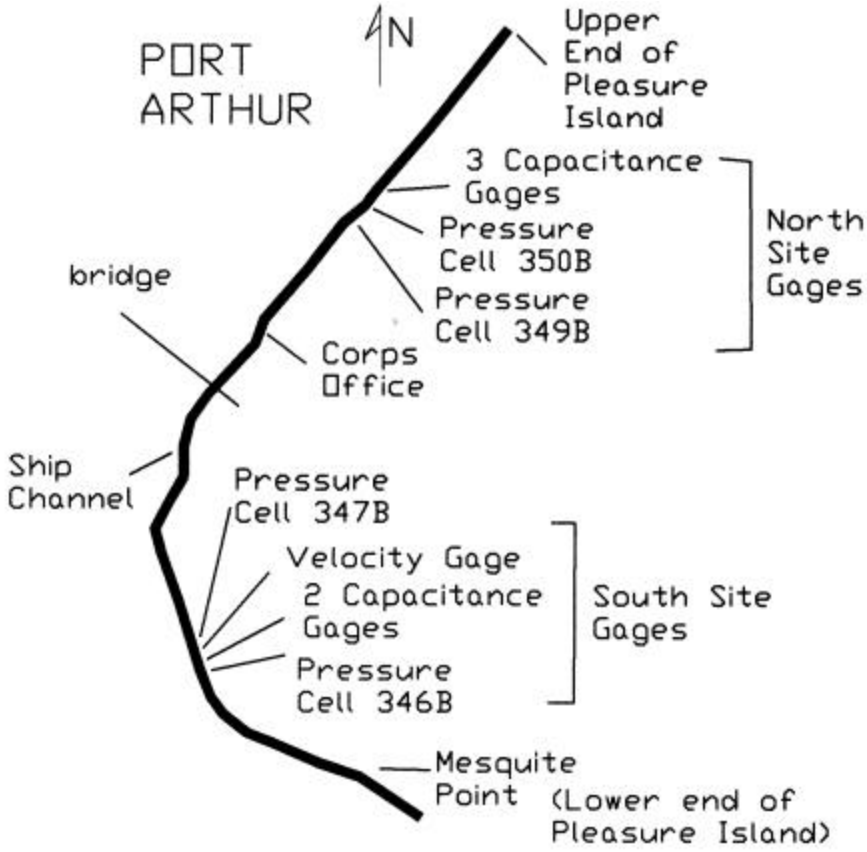

Figure 3. Schematic of SNWW South Site, North Site, and gage locations.

Figure 4. Capacitance water level gage and mount

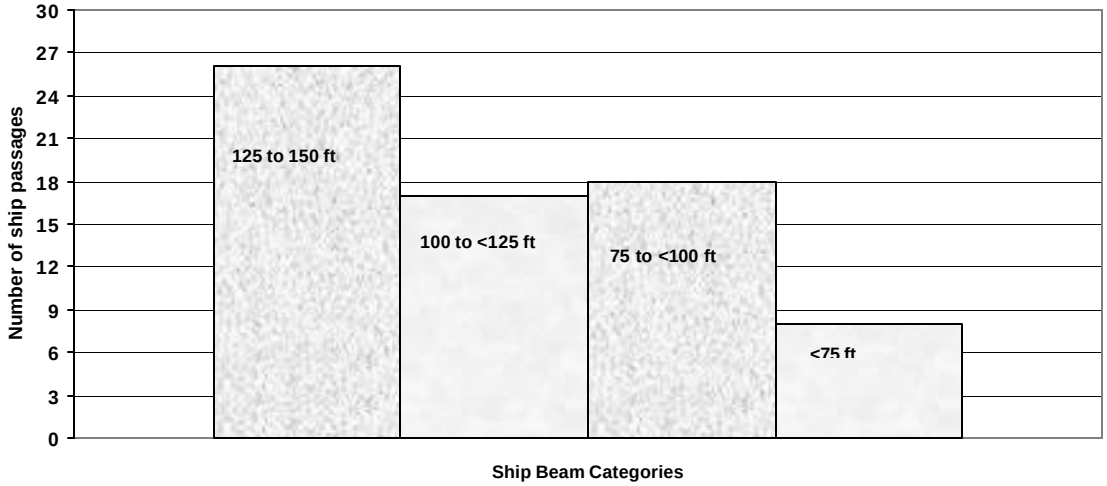

Figure 5. Ship Frequency versus Ship Beam During 30 Apr - 4 May 2002 Field Study

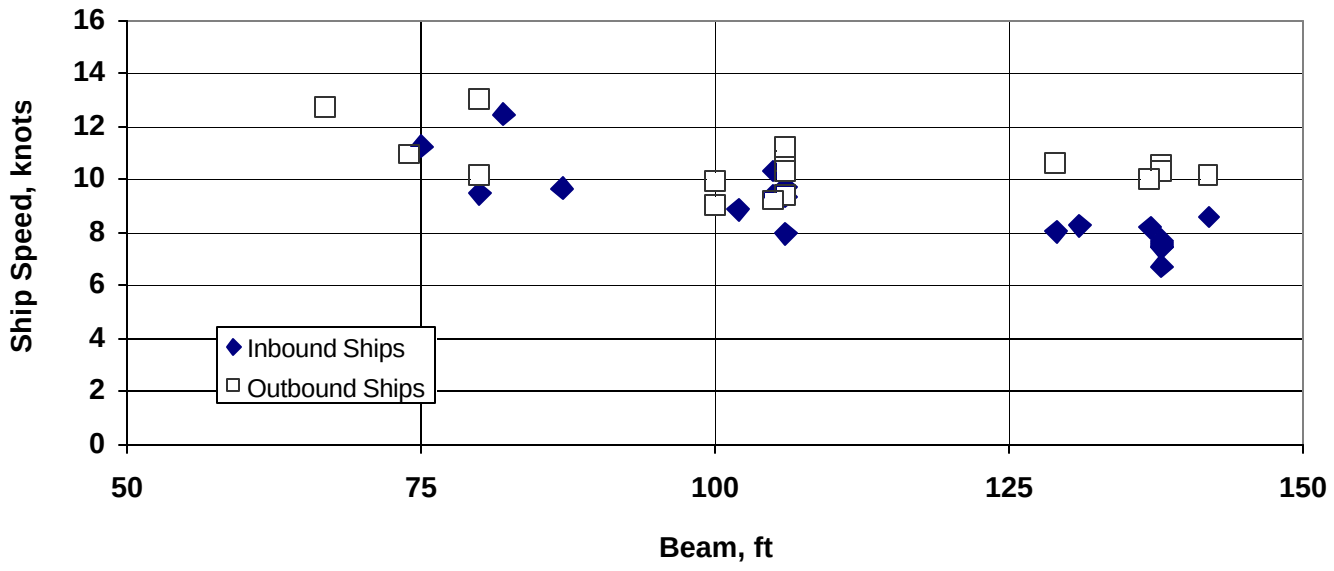

Figure 6. Observed ship speed versus ship beam, South site.

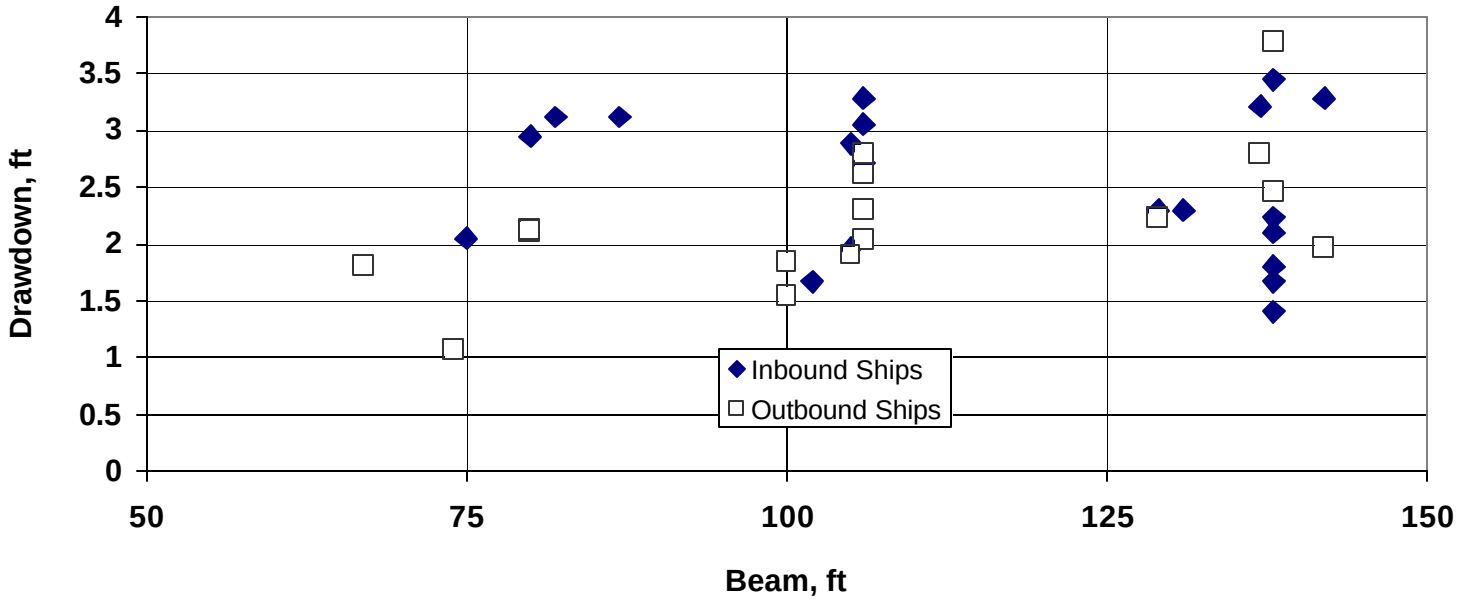

Figure 7. Observed drawdown versus ship beam, South site.

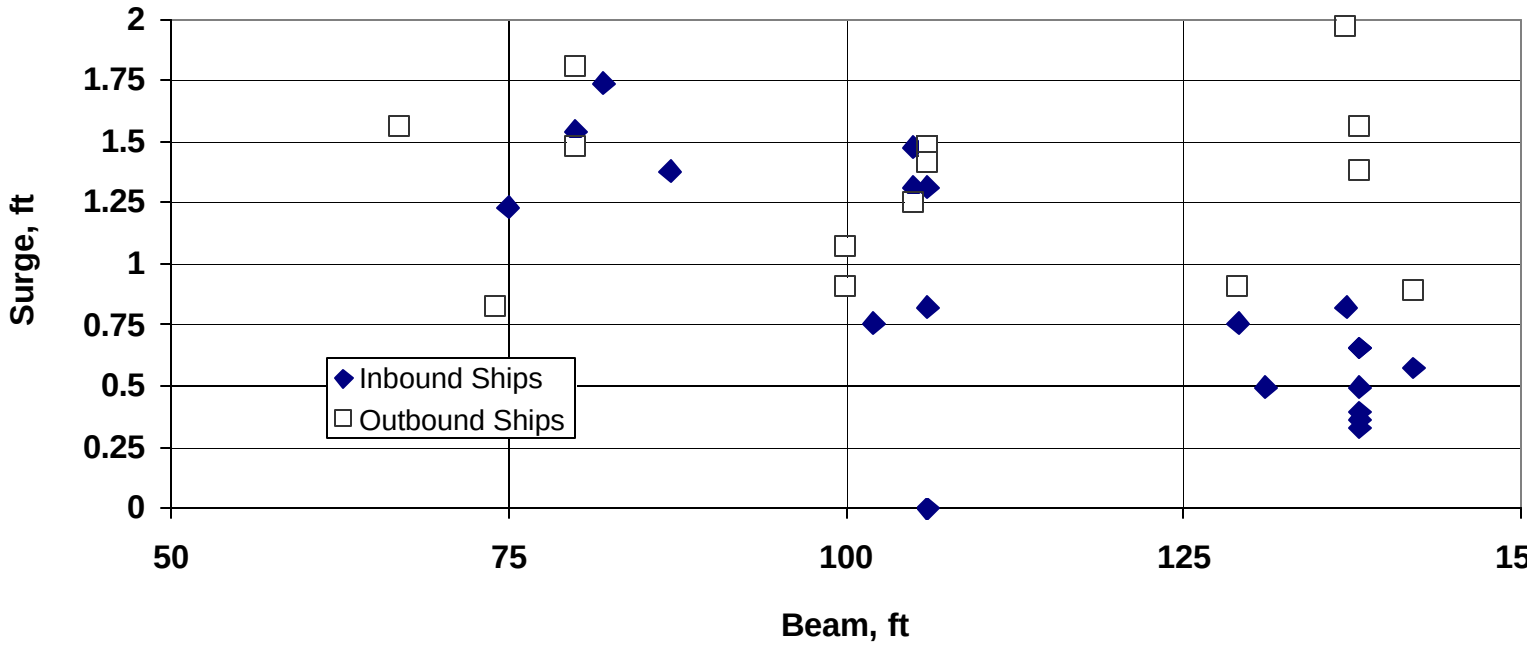

Figure 8. Observed surge versus ship beam, South site.

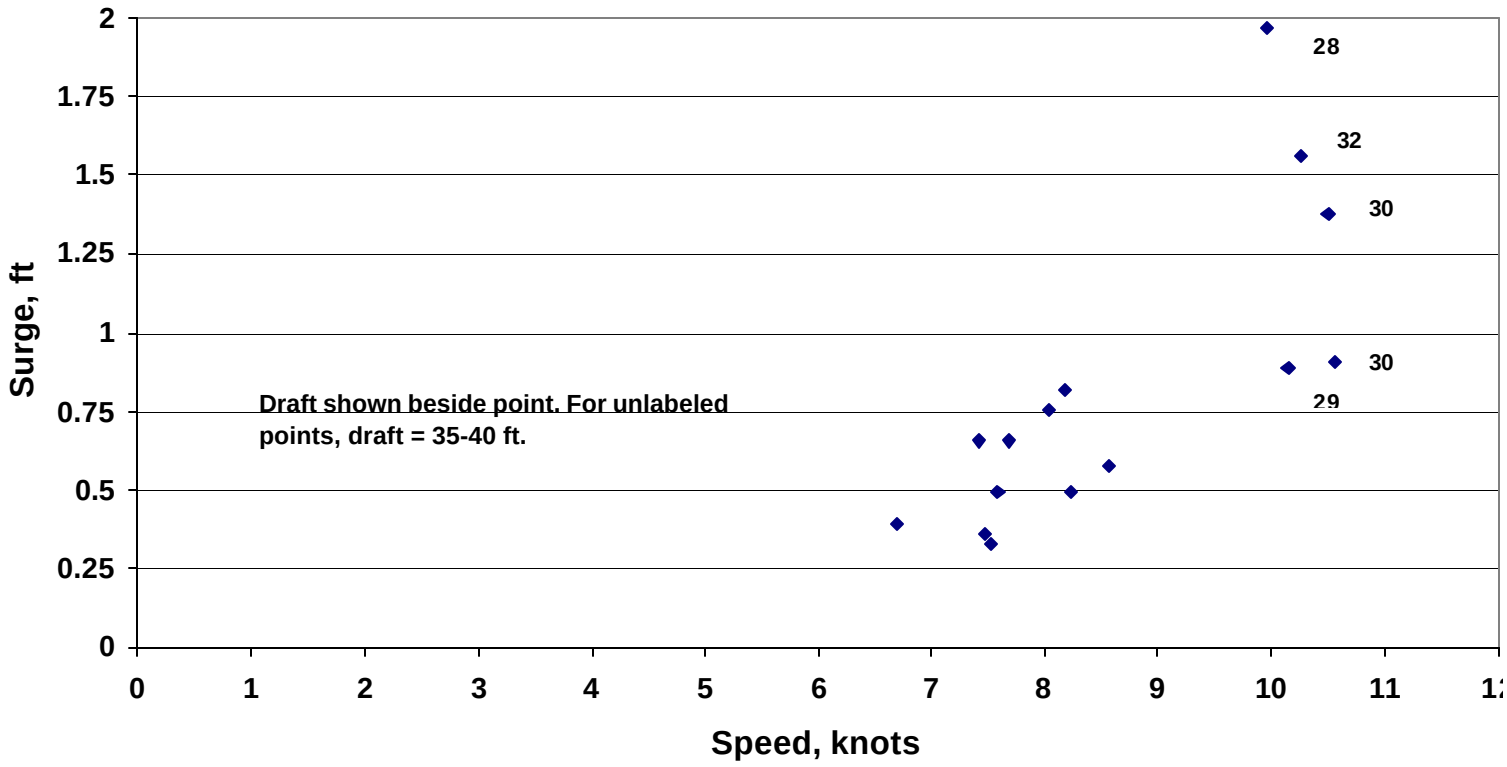

Figure 9. Observed surge versus ship speed, 125-150 ft beam ships, South site.

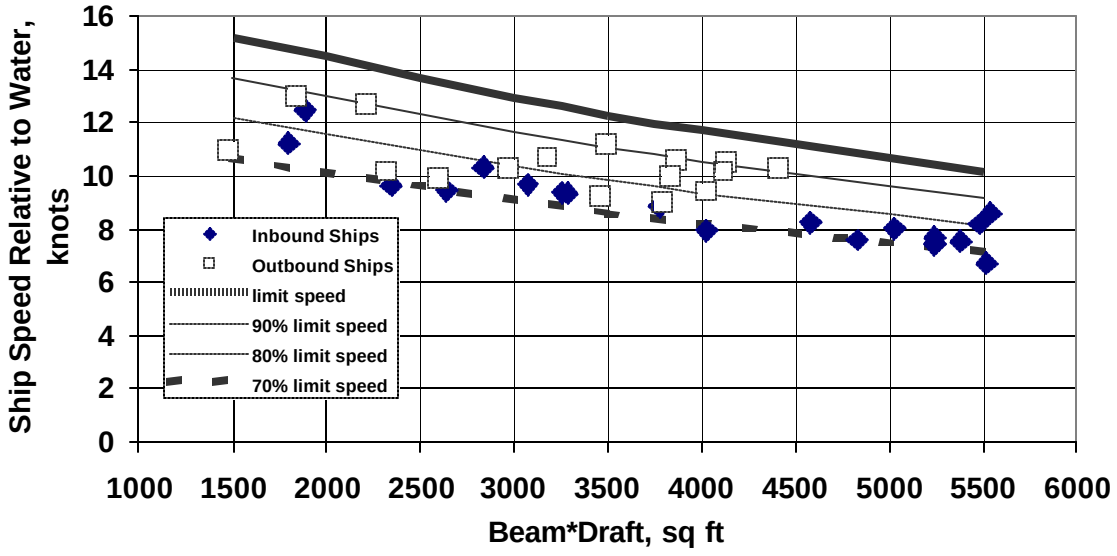

Figure 10. Ship speed versus beam*draft, South Site.

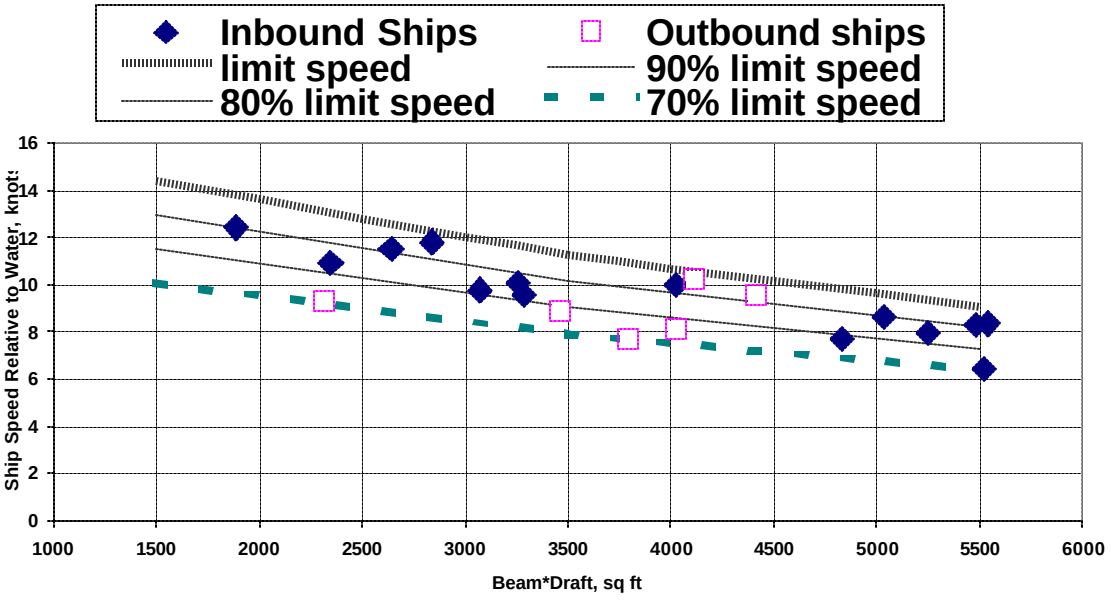

Figure 11. Ship speed versus beam*draft, North Site.

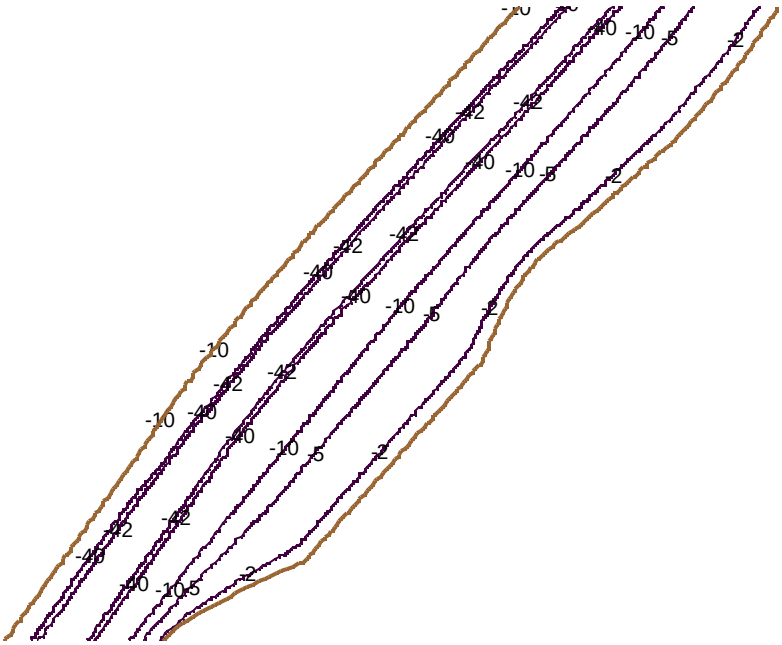

Figure 12. Bathymetry, North Site, Existing Channel, contours are feet below MLT.

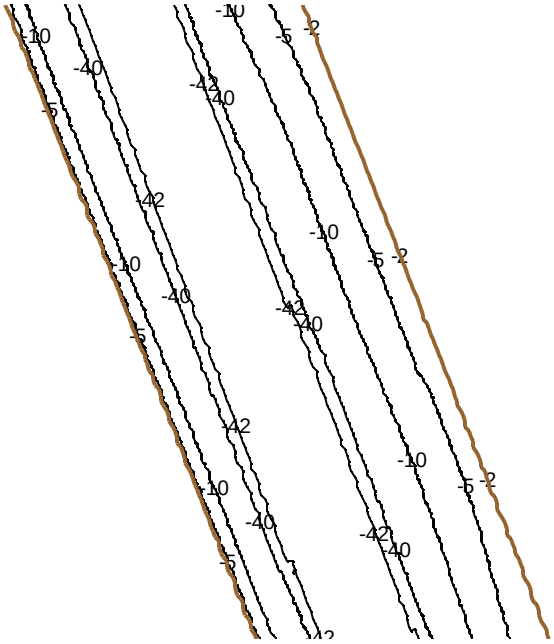

Figure 13. Bathymetry, South Site, Existing channel, contours are feet, MLT.

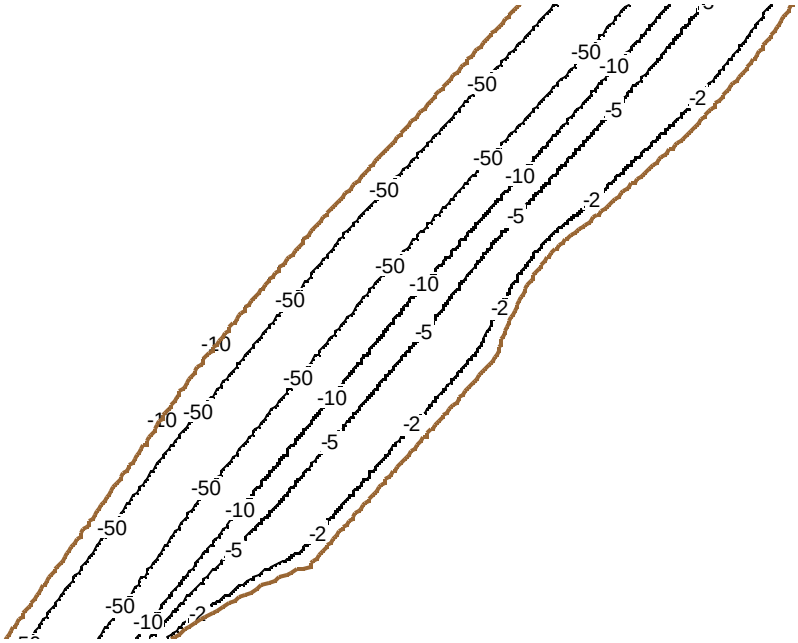

Figure 14. Bathymetry, North Site, Proposed Channel, contours are in feet, MLT.

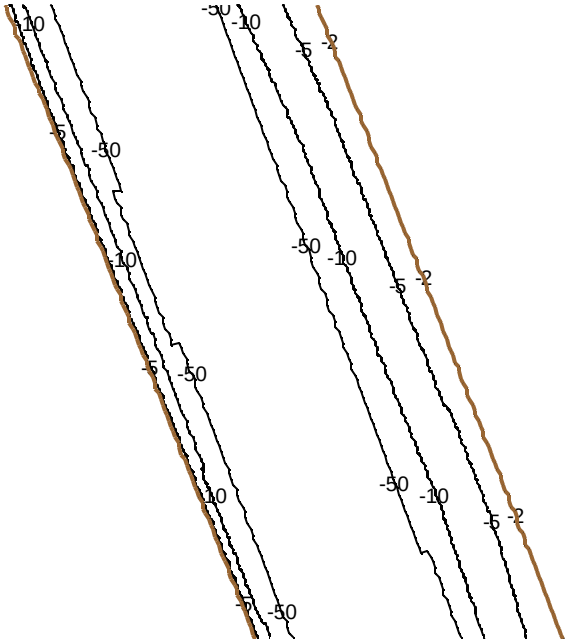

Figure 15. Bathymetry, South site, proposed channel, contours are feet, MLT.

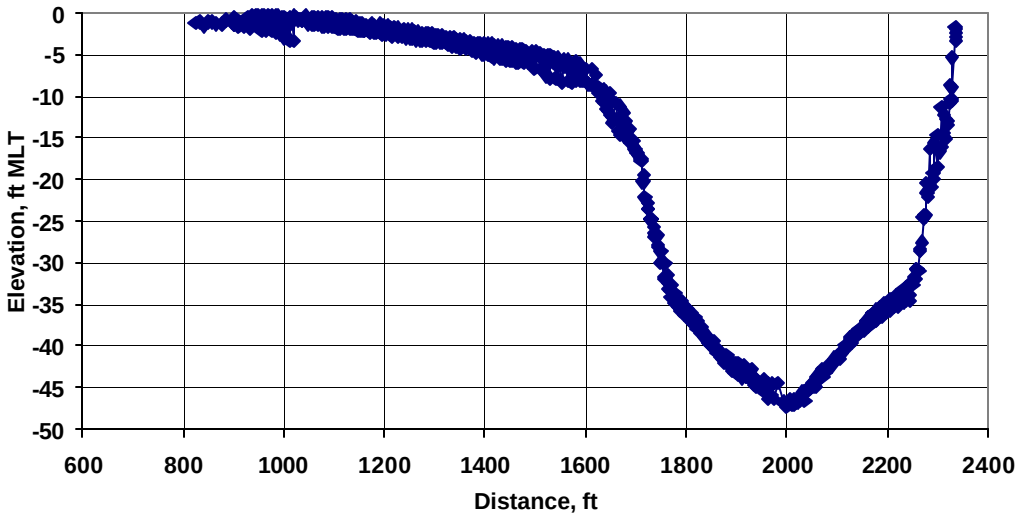

Figure 16. Cross section at North Site of Existing Channel.

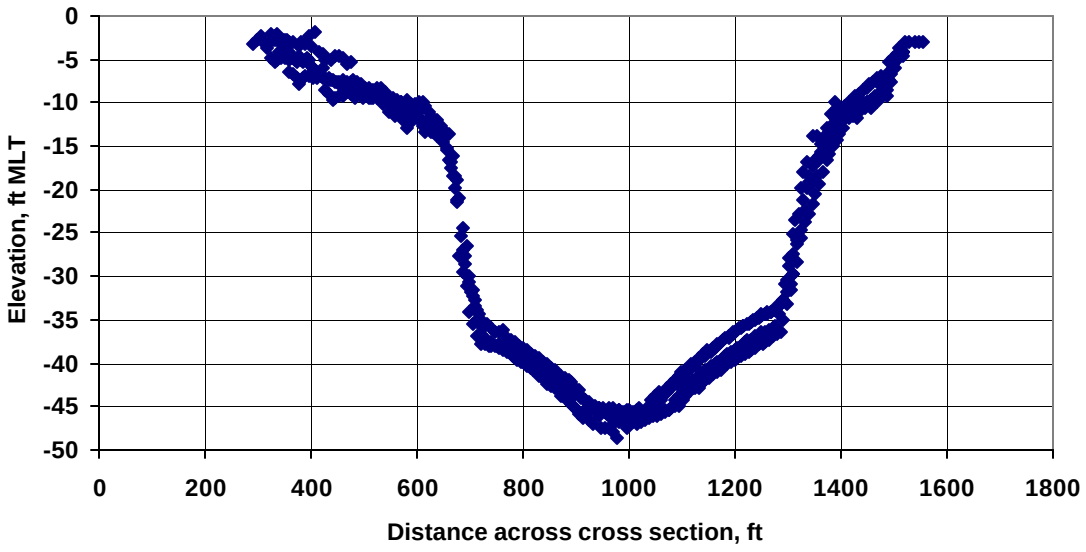

Figure 17. Cross section at South Site of Existing Channel.

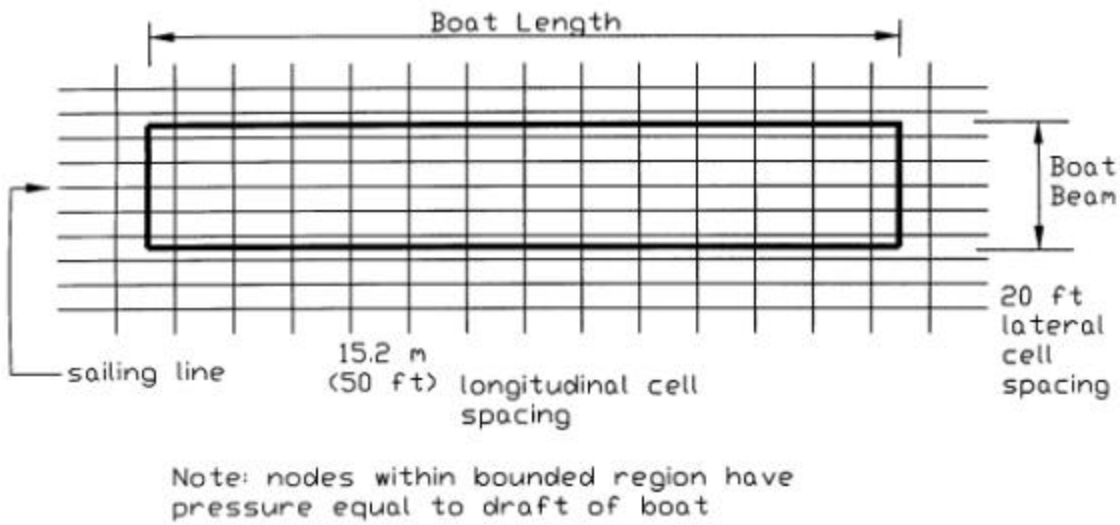

Figure 18. Pressure field representing ship.

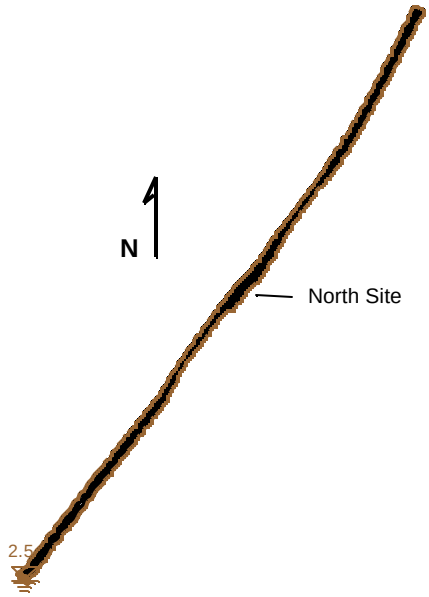

Figure 19. North site mesh.

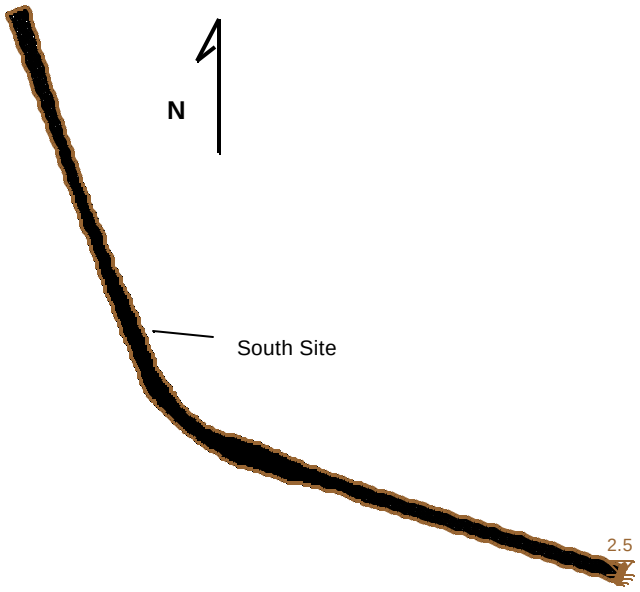

Figure 20. South site mesh.

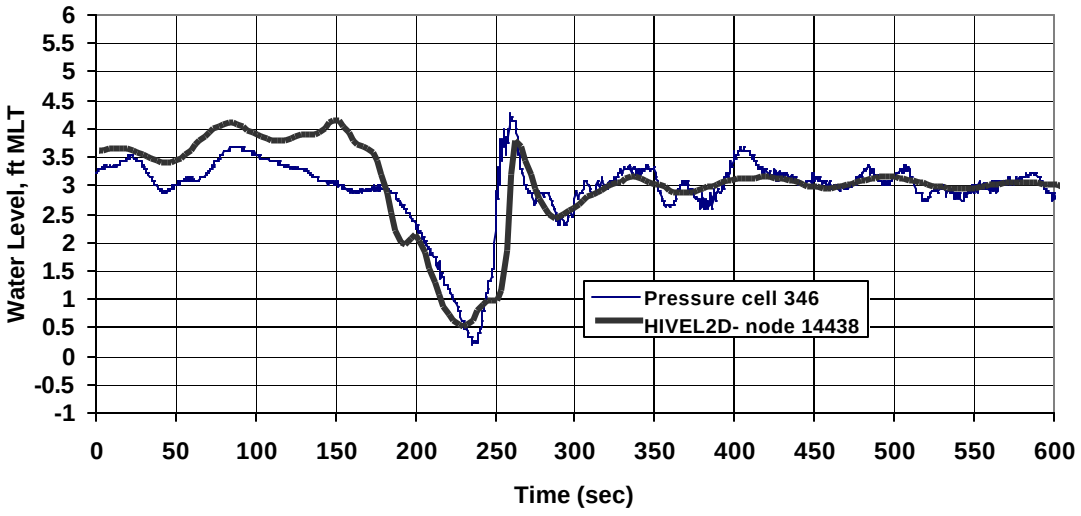

Figure 21. Observed and HIVEL2D Water Level for Pacific Sapphire at Pressure cell 10346, South Site, existing channel.

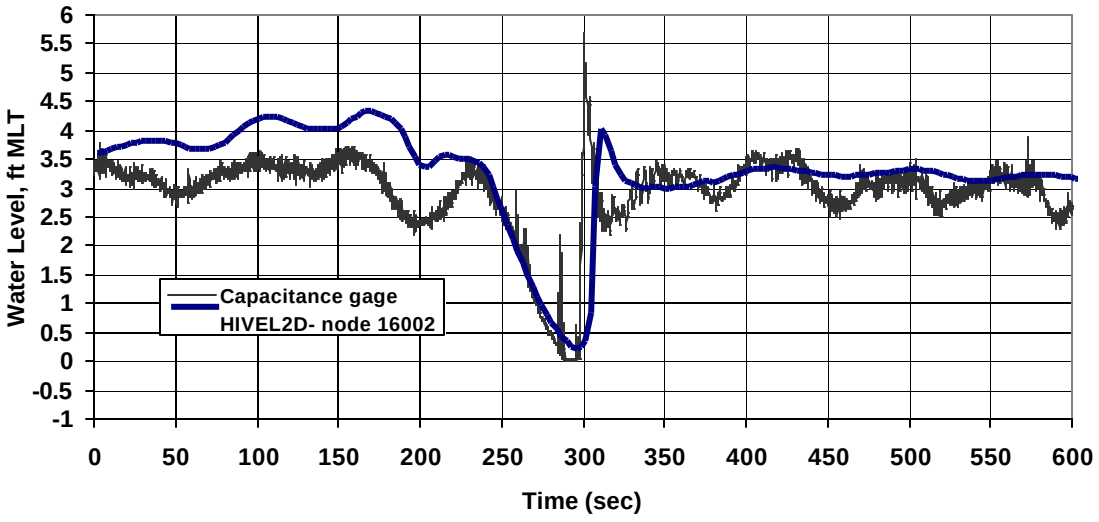

Figure 22. Observed and HIVEL2D Water Level for Pacific Sapphire at near-bank capacitance gage 10522, South Site, existing channel.

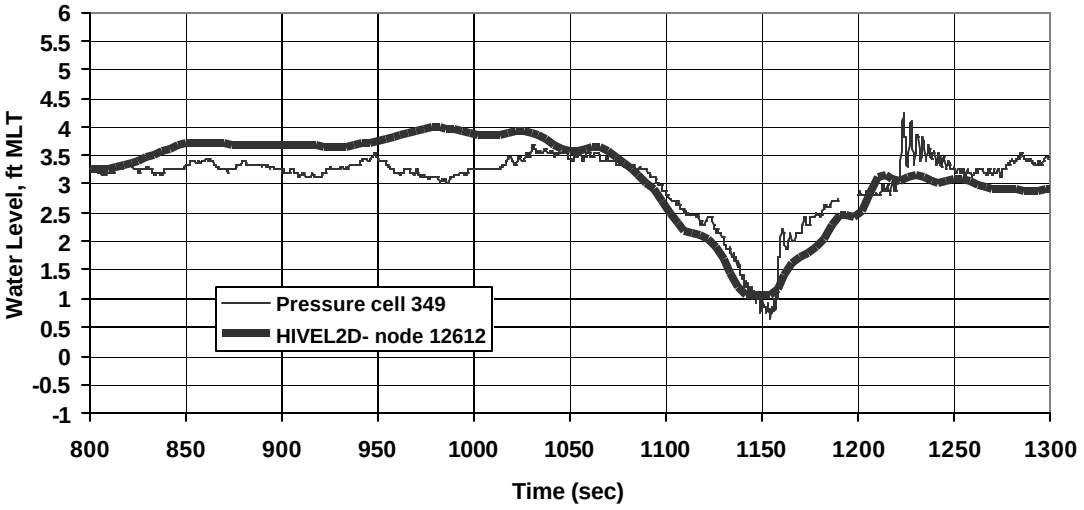

Figure 23. Observed and HIVEL2D Water Level for Pacific Sapphire at Pressure cell 10349, North Site, existing channel.

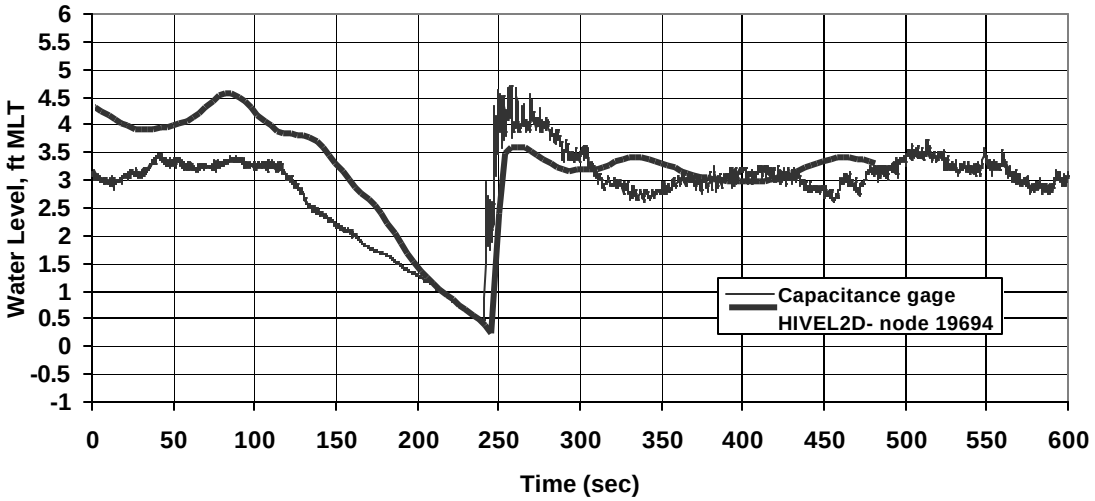

Figure 24. Observed and HIVEL2D Water Level for Pacific Sapphire at near-bank capacitance gage 10526, North Site, existing channel.

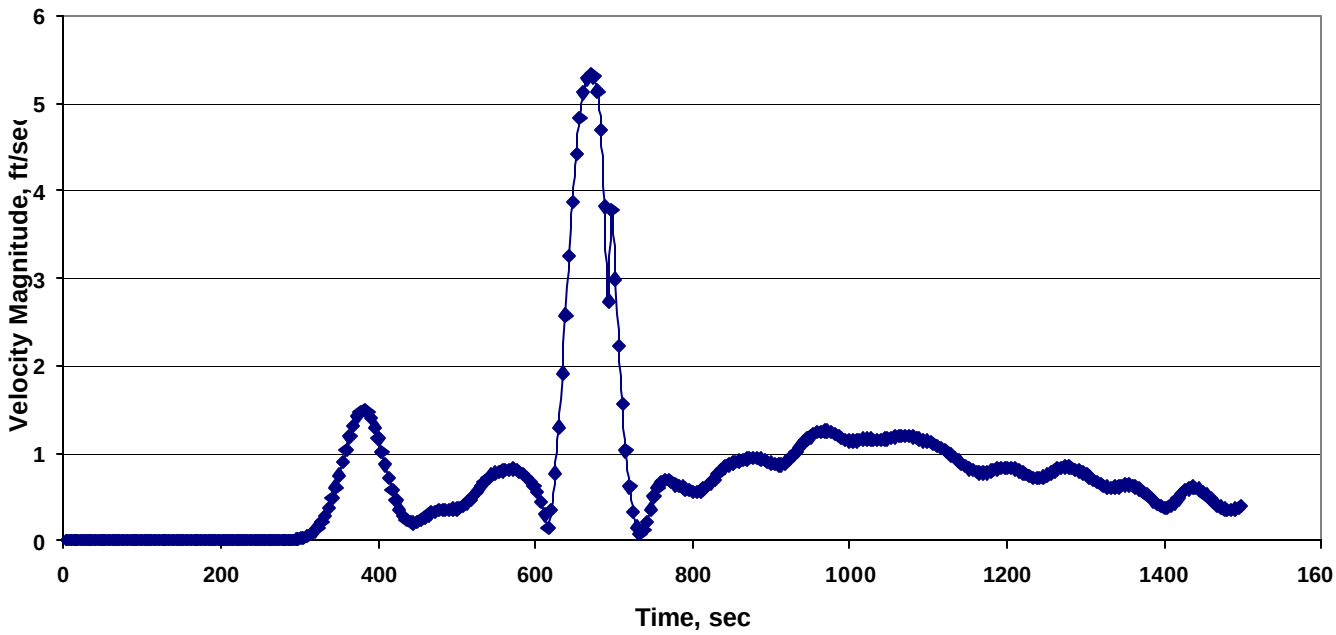

Figure 25. Computed Velocity for Bornes at South Site. Compare to measured velocity in Appendix Figure A11.

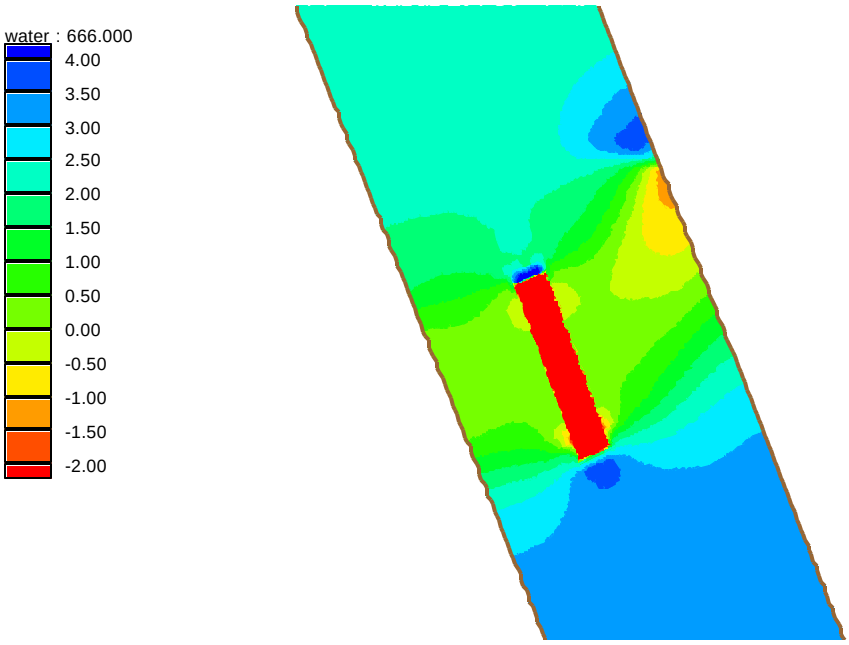

Figure 26. Water Level, Design Ship, South Site, Existing channel, 10 knots, contours are ft MLT.

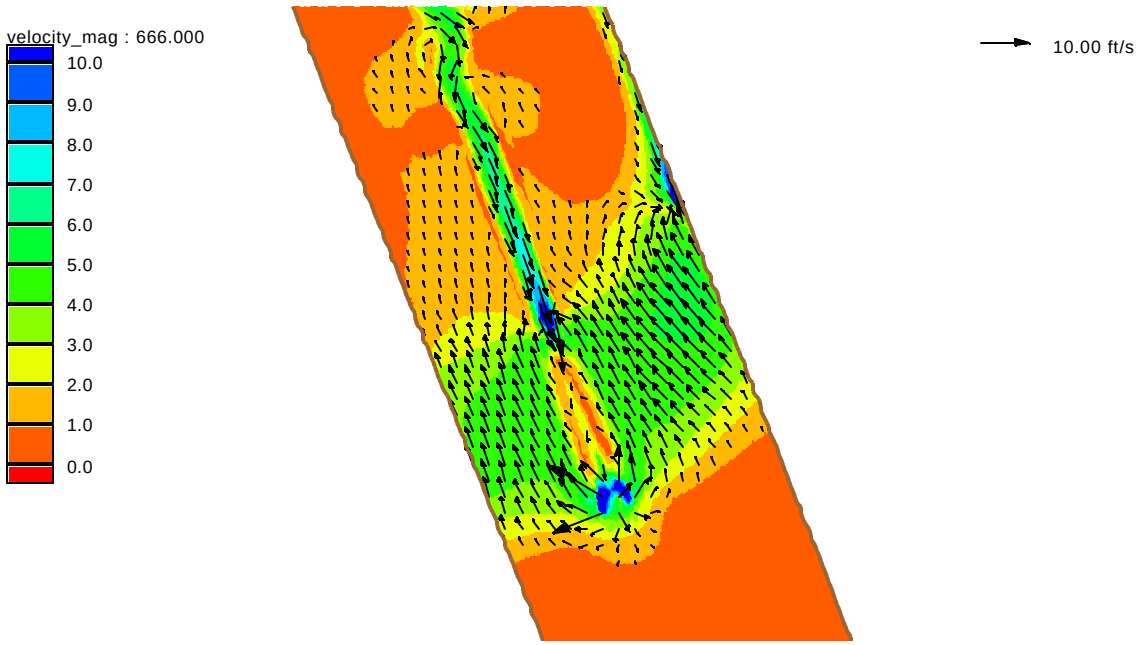

Figure 27. Velocity, Design Ship, South Site, Existing Channel, 10 knots, contours are ft/sec.

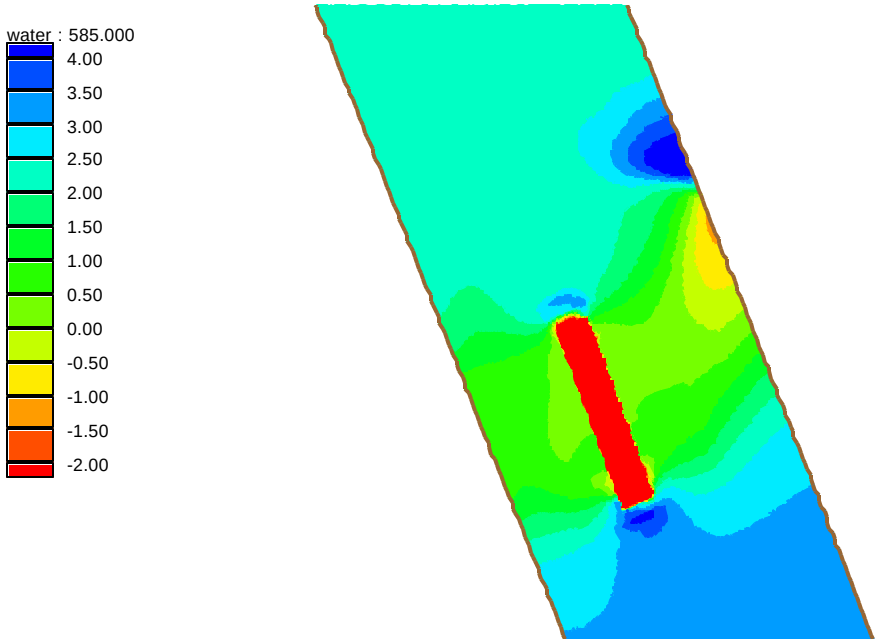

Figure 28. Water level, design ship, South site, proposed channel, 11.5 knots, contours are feet, MLT.

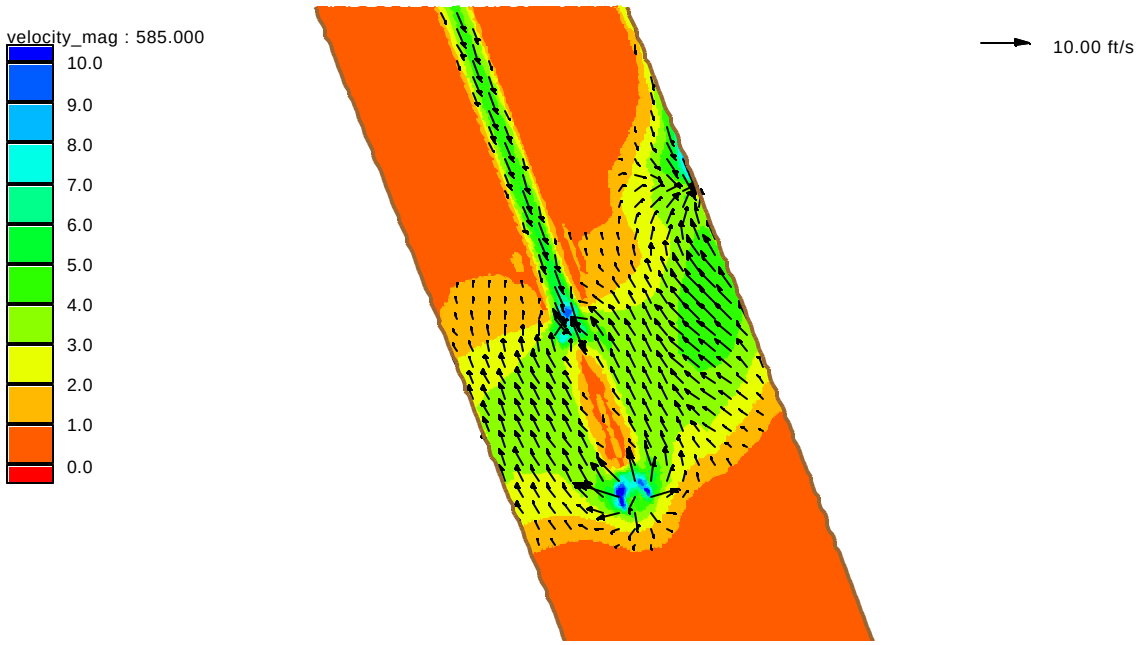

Figure 29. Velocity, Design Ship, South Site, Proposed channel, 11.5 knots, contours are ft/sec.

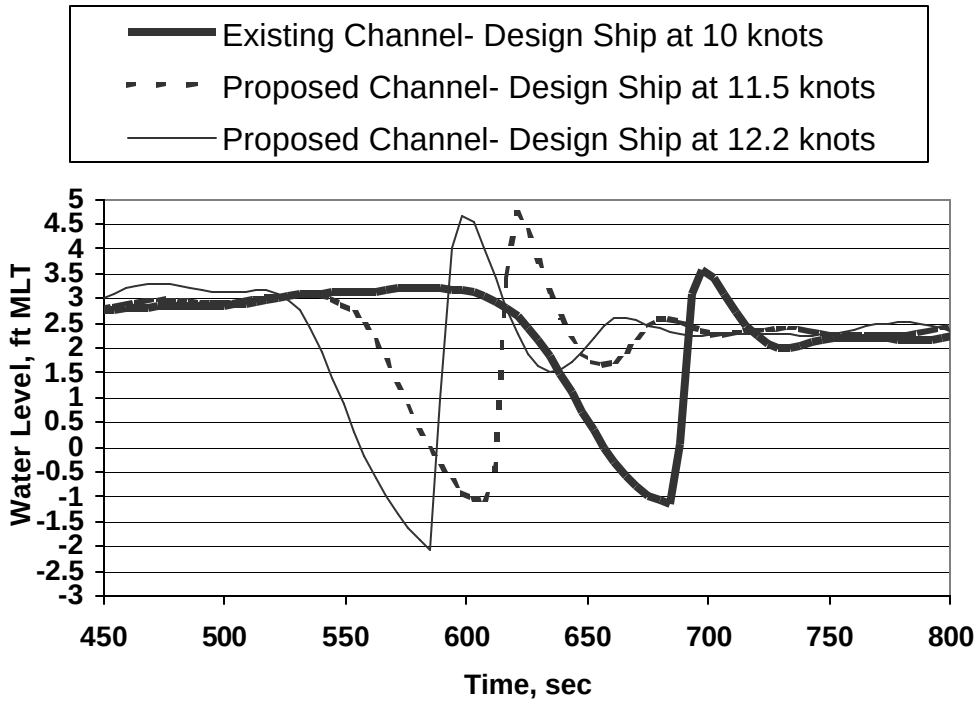

Figure 30. Computed Water Level at Shoreline, South Site, Design Ship, Existing and Proposed Channels, node 16002.

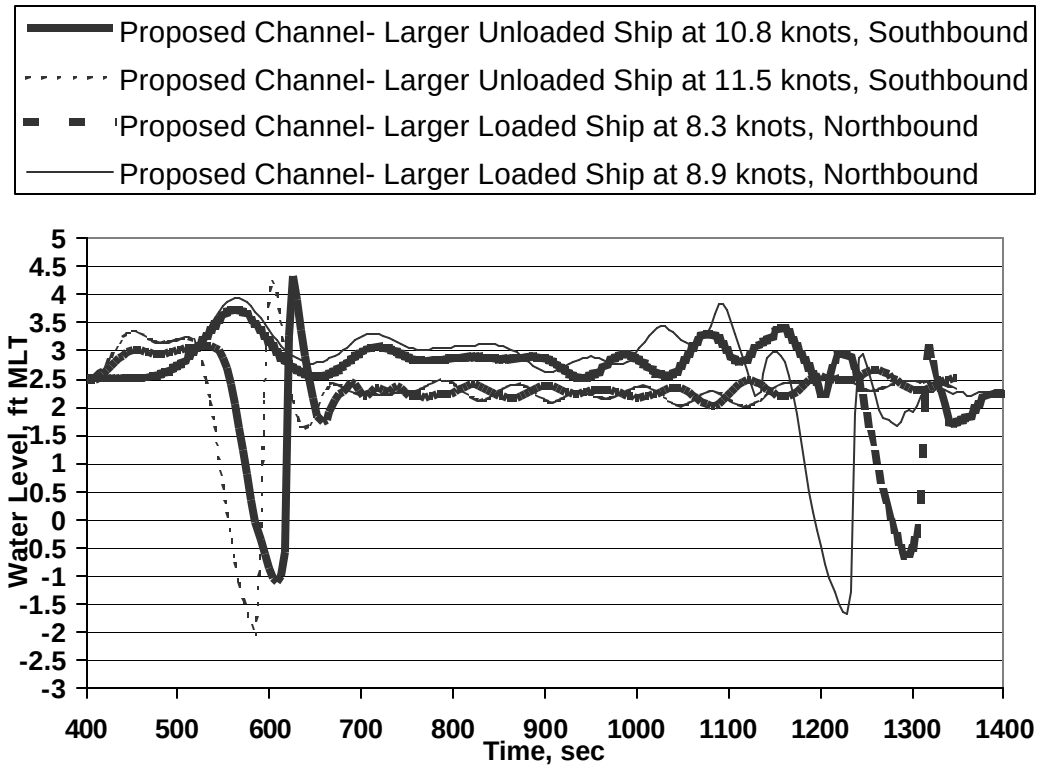

Figure 31. Computed Water Level at Shoreline, South Site, Loaded and Unloaded Larger Ship, Proposed Channel, node 16002.

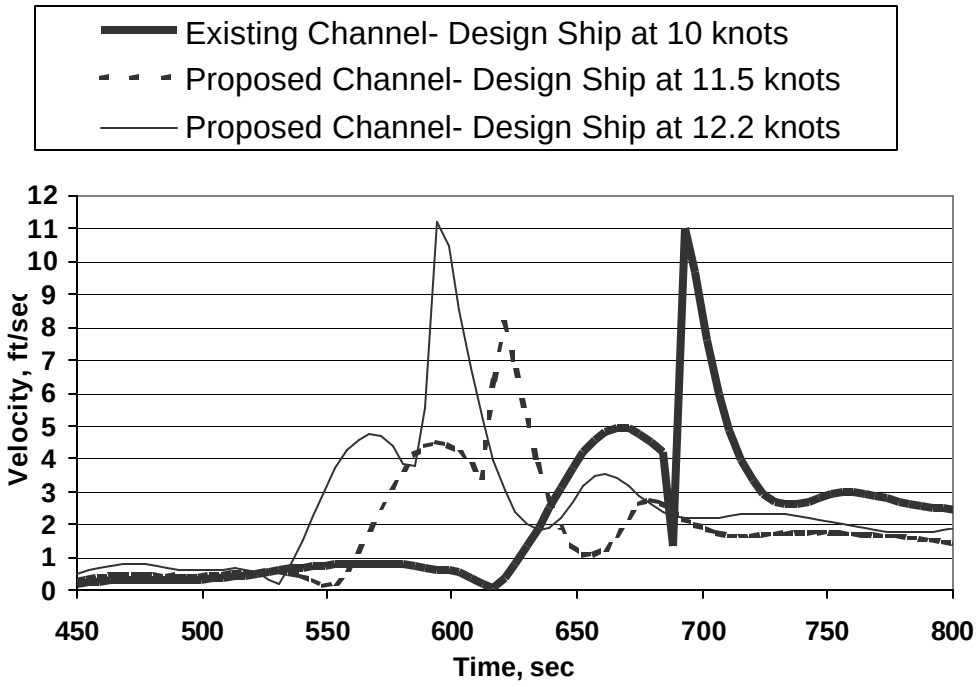

Figure 32. Computed Velocity at Shoreline, South Site, Design Ship, Existing and Proposed Channels, node 16002.

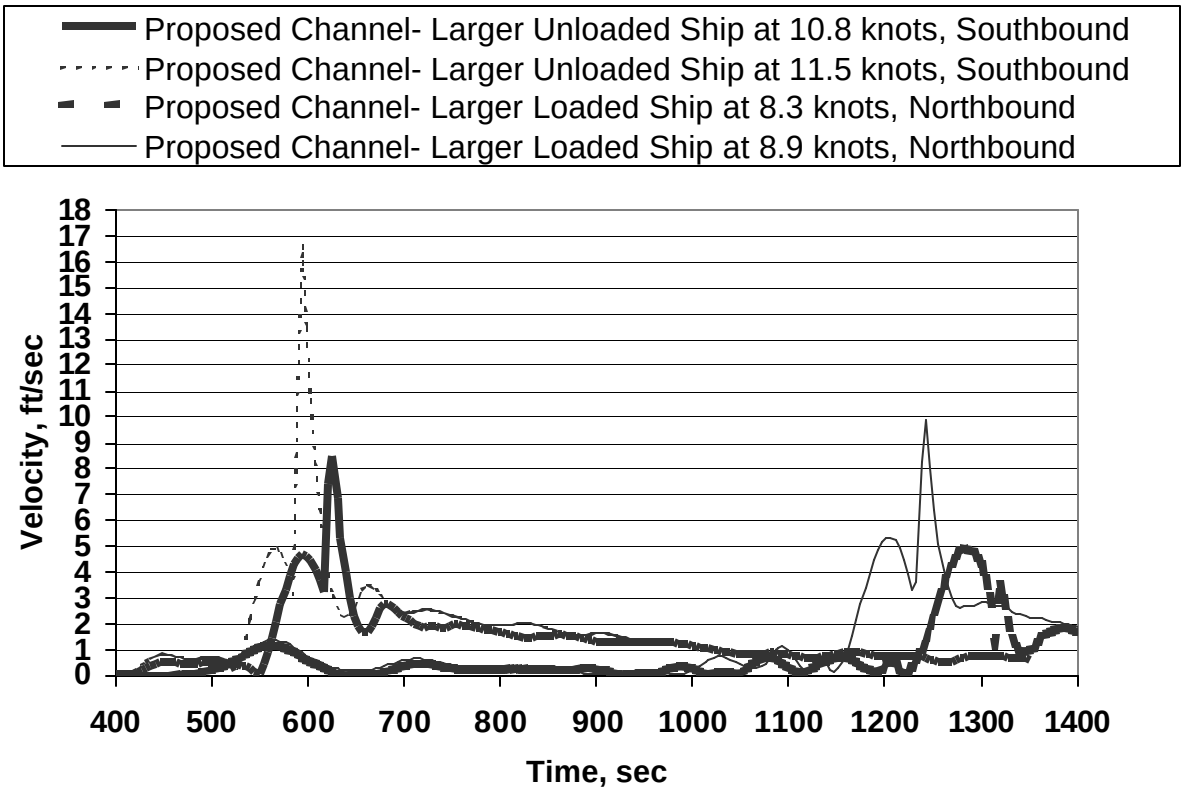

Figure 33. Computed Velocity at Shoreline, South Site, Loaded and Unloaded Larger Ship, Proposed Channel, node 16002.

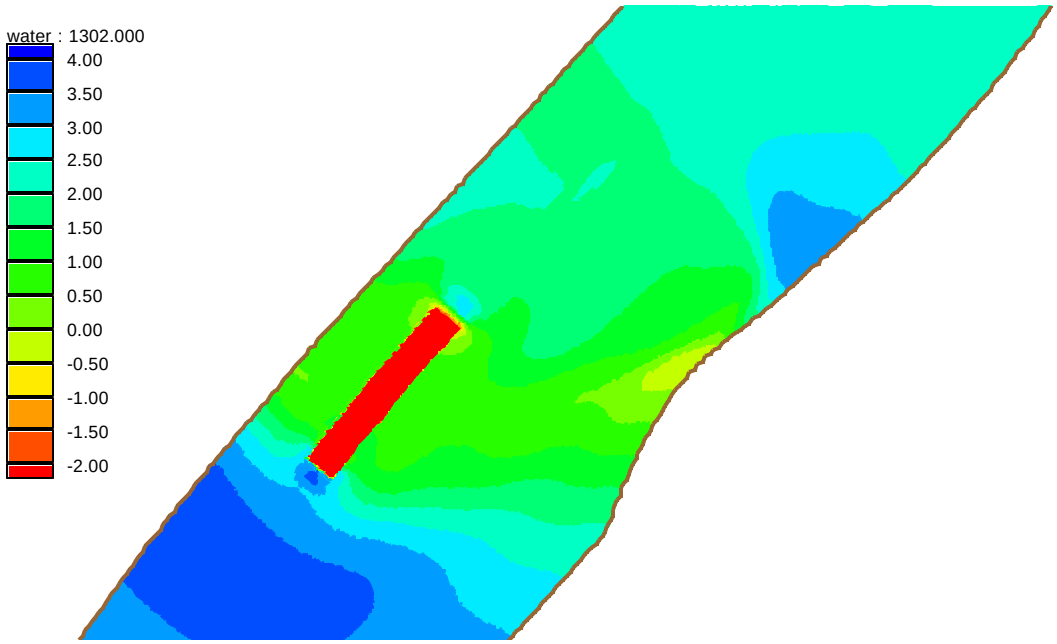

Figure 34. Water Level, Design Ship, North Site, Existing Channel, 9 knots, Contours in feet, MLT, ship travels from upper right to lower left.

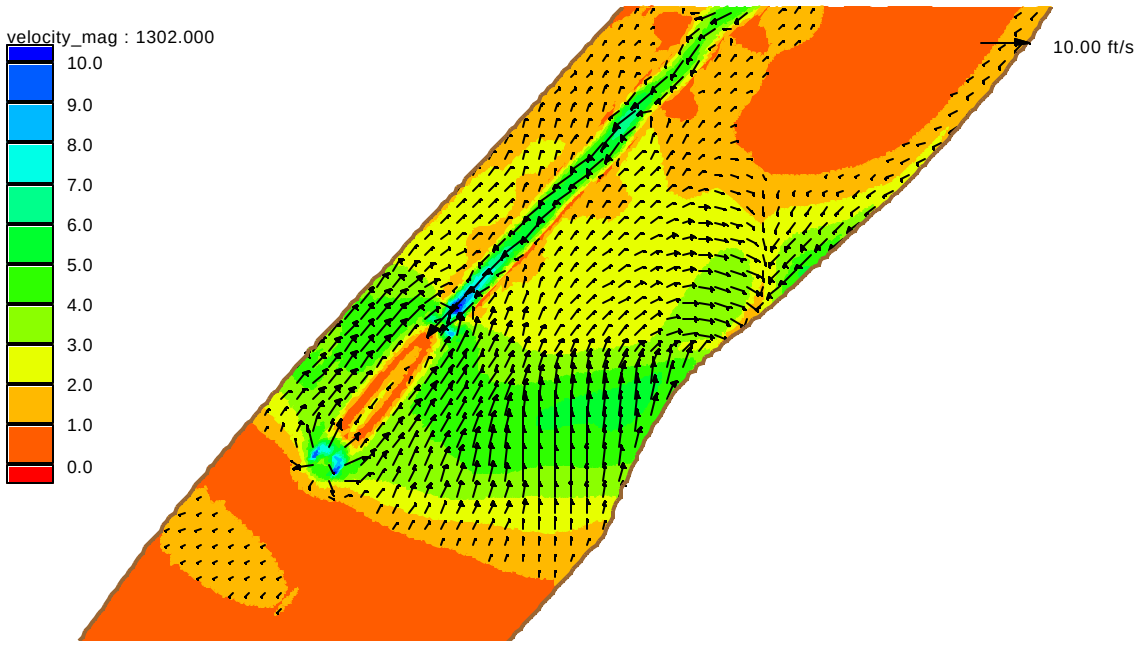

Figure 35. Velocity, Design Ship, North Site, Existing Channel, 9 knots, contours in ft/sec, ship travels from upper right to lower left.

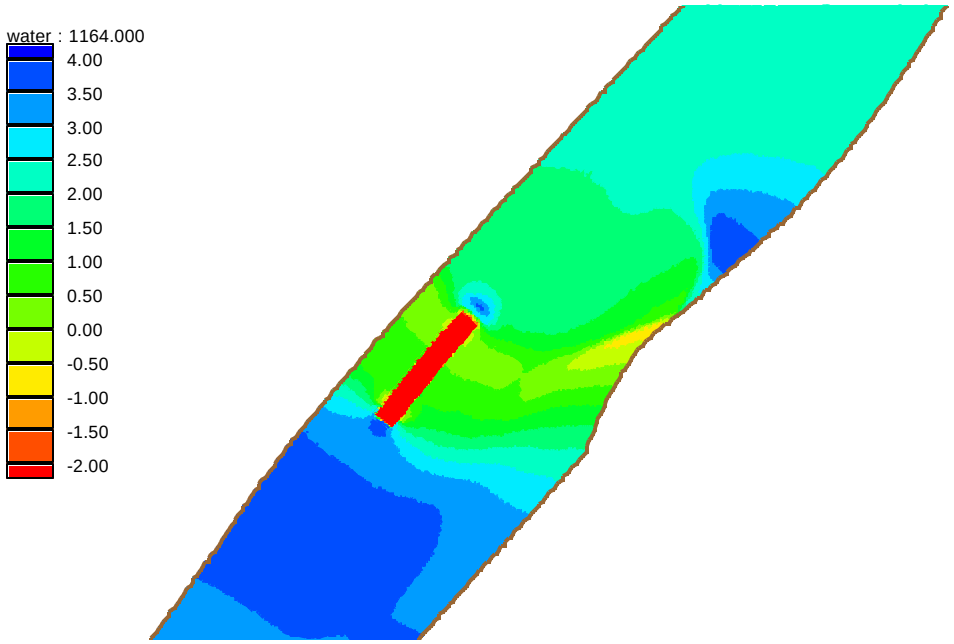

Figure 36. Water Level, Design Ship, North Site, Proposed Channel, 10.2 knots, contours are in feet, MLT, ship travels from upper right to lower left.

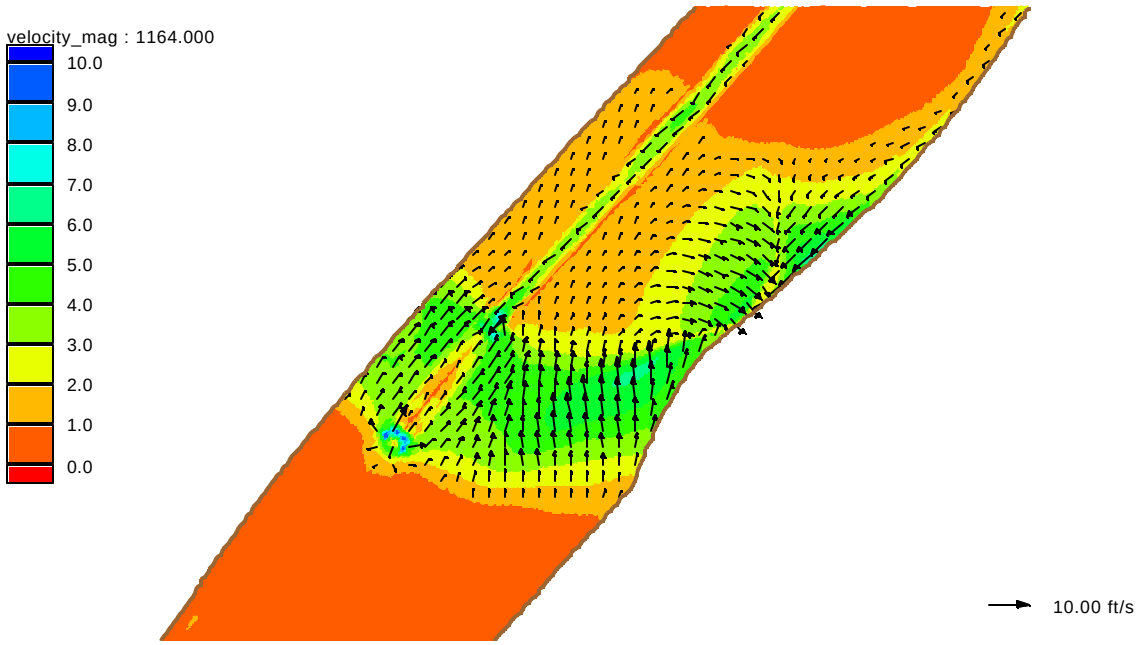

Figure 37. Velocity, Design Ship, North Site, Proposed Channel, 10.2 knots, velocity contours in ft/sec.

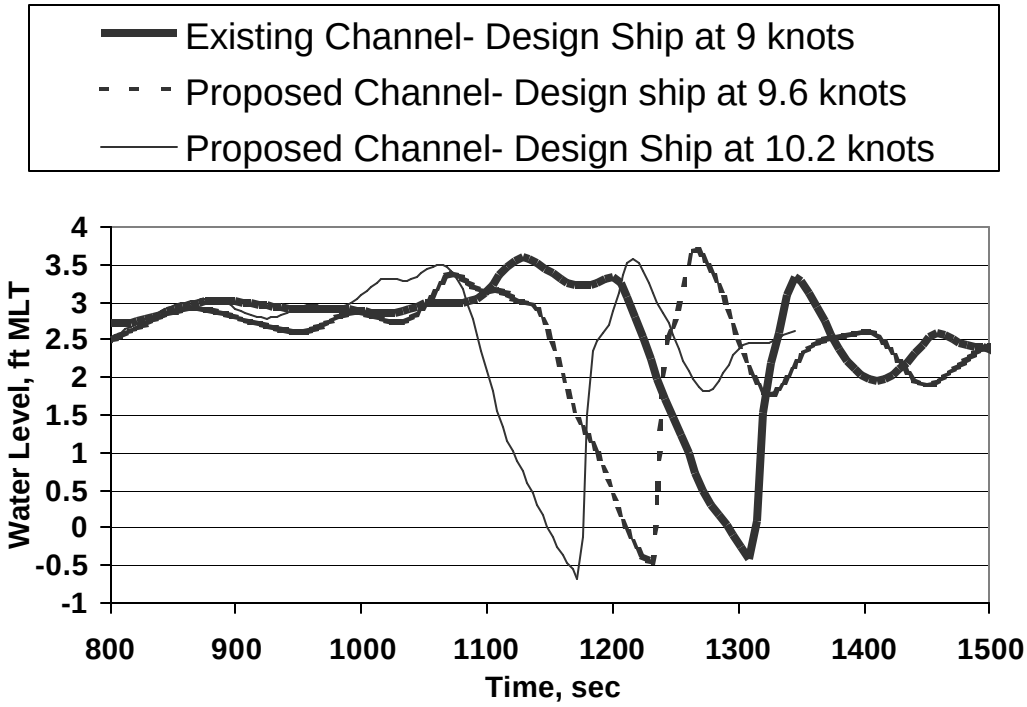

Figure 38. Computed Water Level at Shoreline, North Site, Design Ship, Existing and Proposed Channels, node 16952.

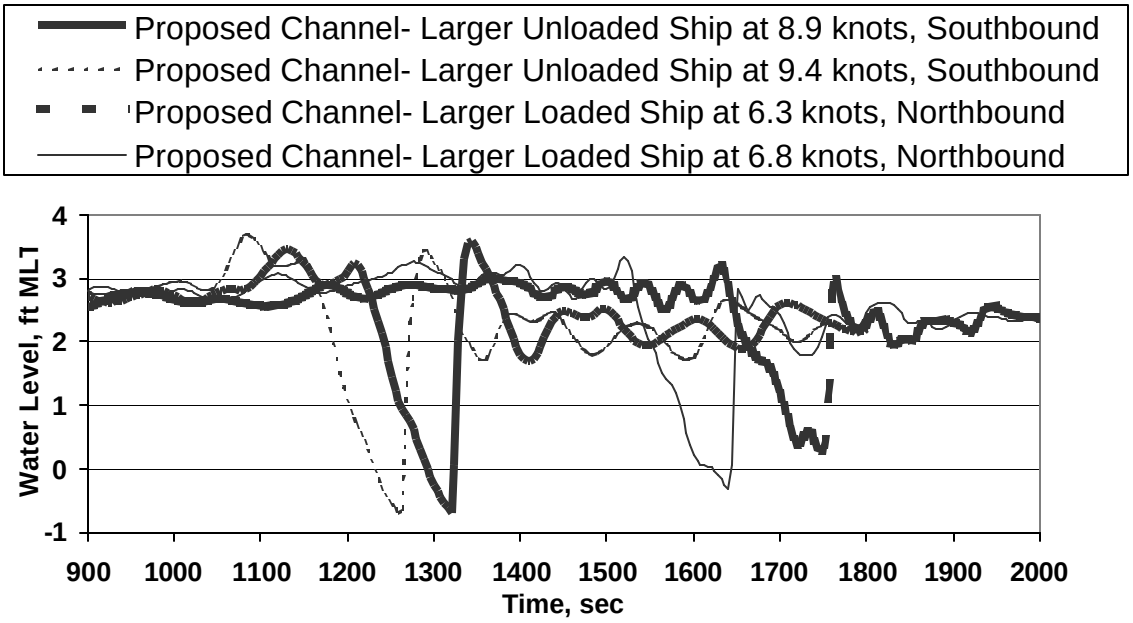

Figure 39. Computed Water Level at Shoreline, North Site, Loaded and Unloaded Larger Ship, Proposed Channel, node 16952.

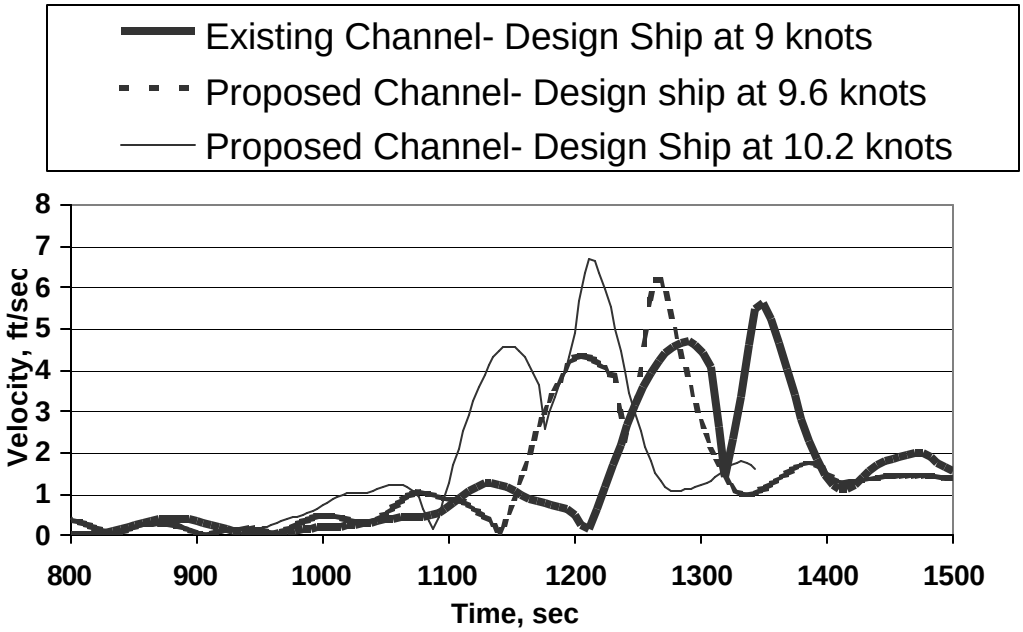

Figure 40. Computed Velocity at Shoreline, North Site, Design Ship, Existing and Proposed Channels, node 16952.

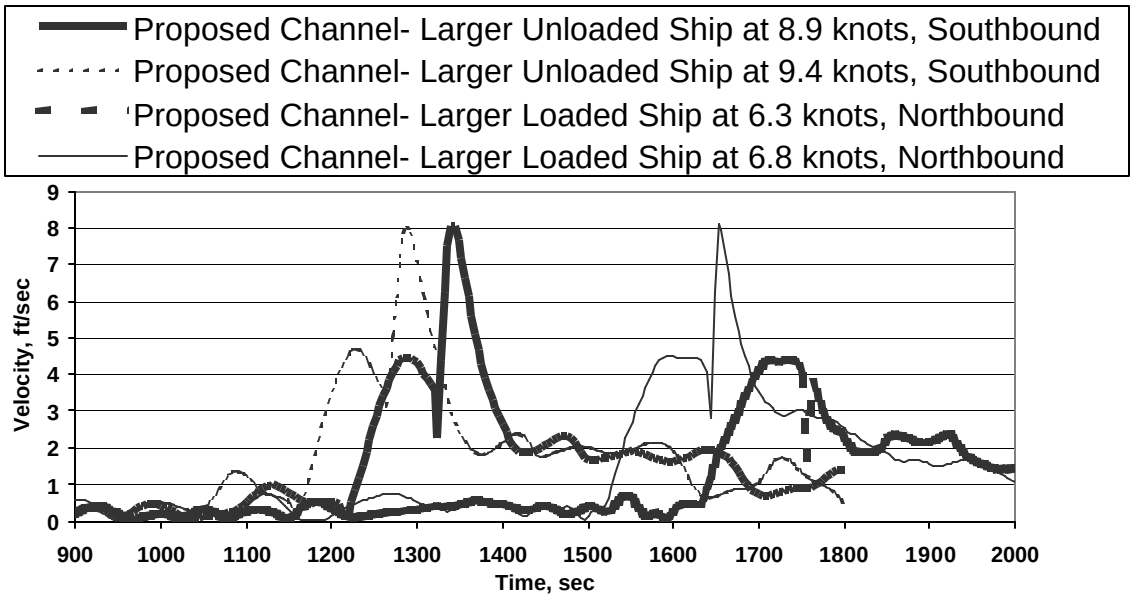

Figure 41. Computed Velocity at Shoreline, North Site, Loaded and Unloaded Larger Ship, Proposed Channel, node 16952.

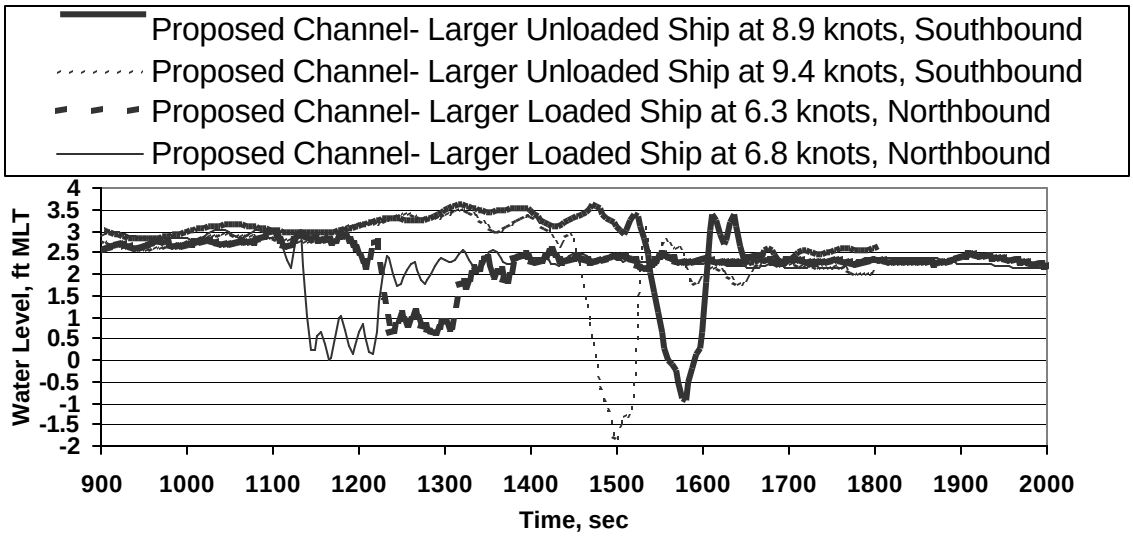

Figure 42. Computed Water Level at Shoreline, North Site, Loaded and Unloaded Larger Ship, Proposed Channel, node 9753.

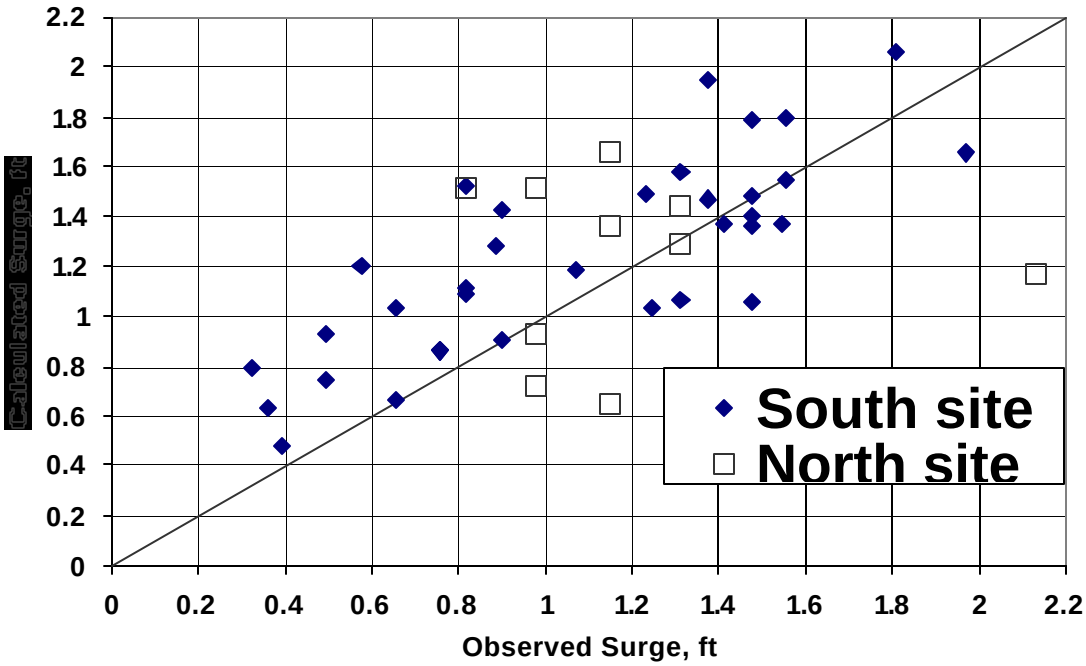

Figure 43. Scatterplot of Observed versus Calculated Surge using Equation 5.

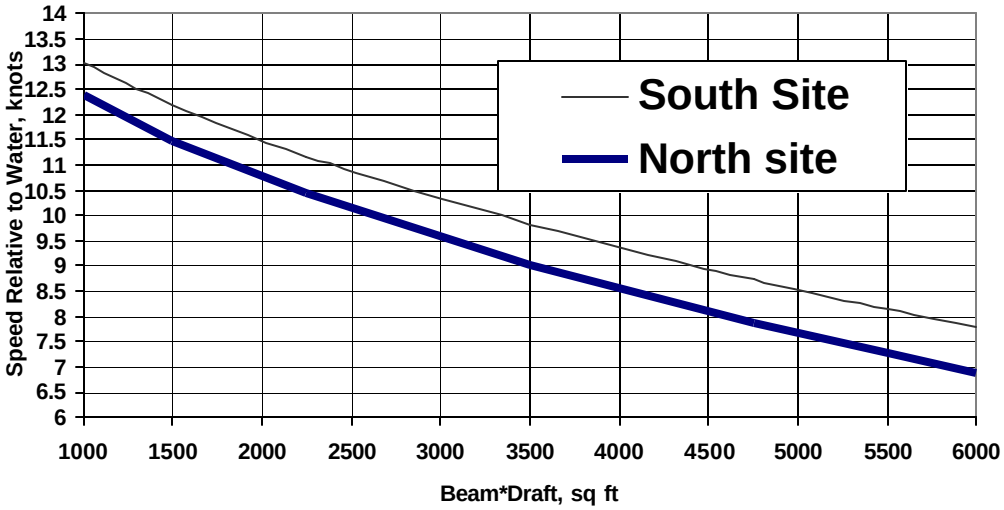

Figure 44. Speeds used in speed effects study equal to 80% of limit speed.

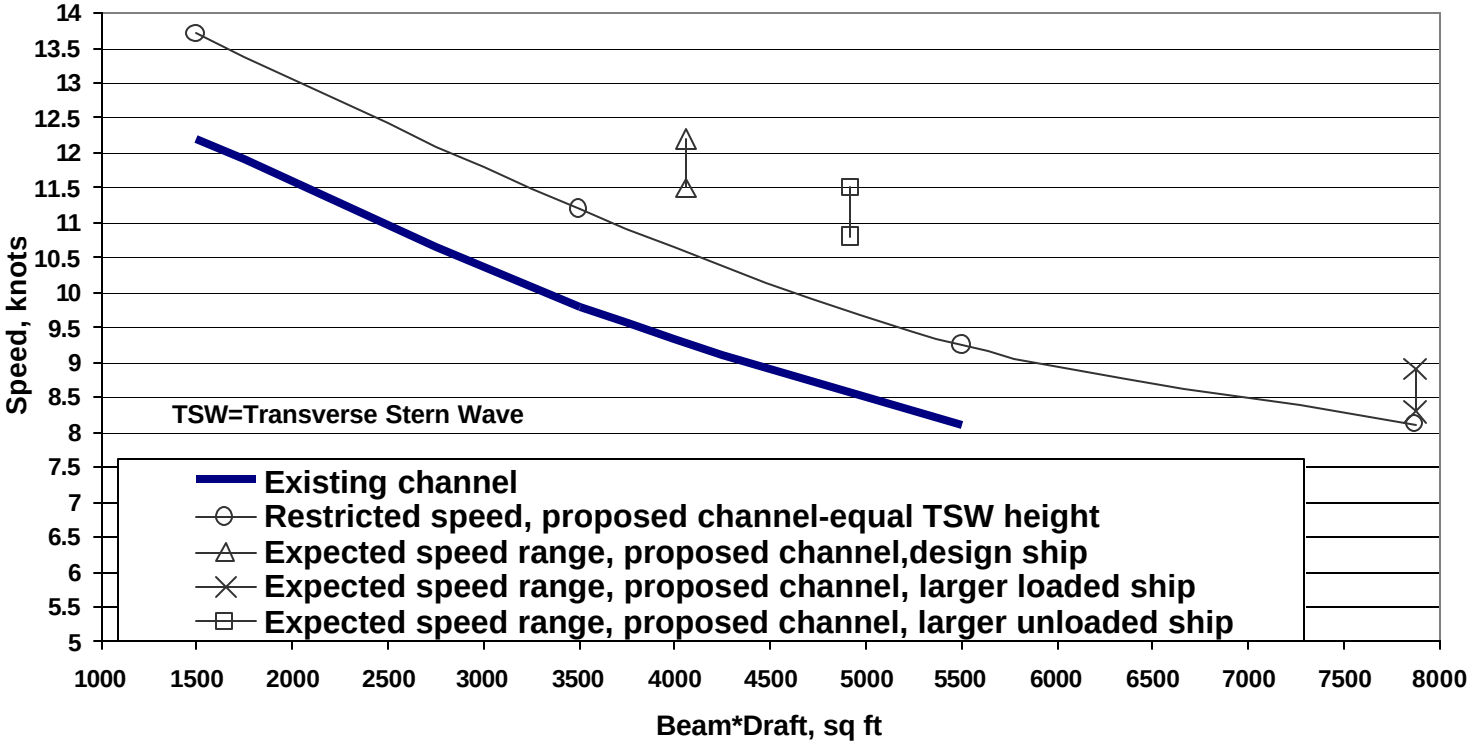

Figure 45. Speeds in proposed channel, equal TSW, South site, Port Arthur Canal.

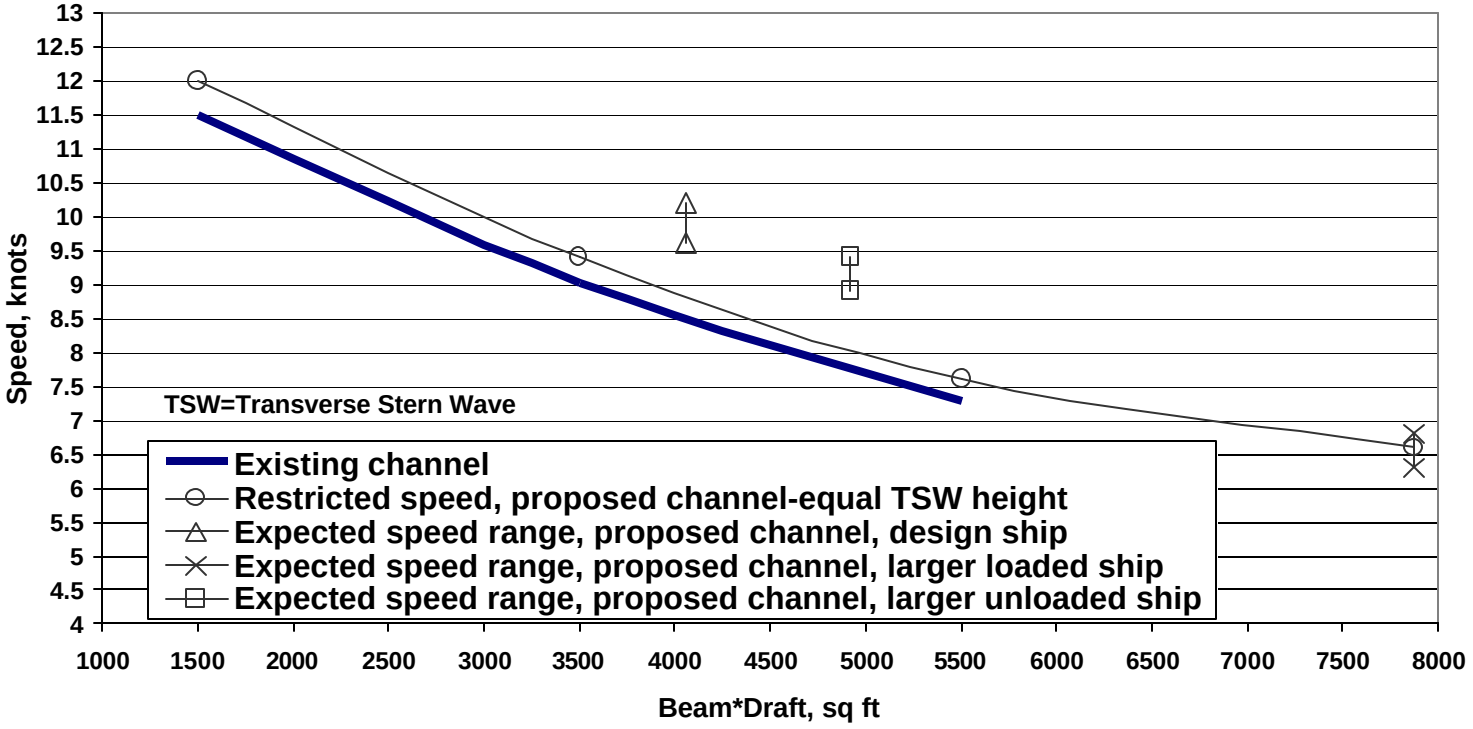

Figure 46. Speeds in proposed channel, equal TSW, North site, Sabine-Neches Canal

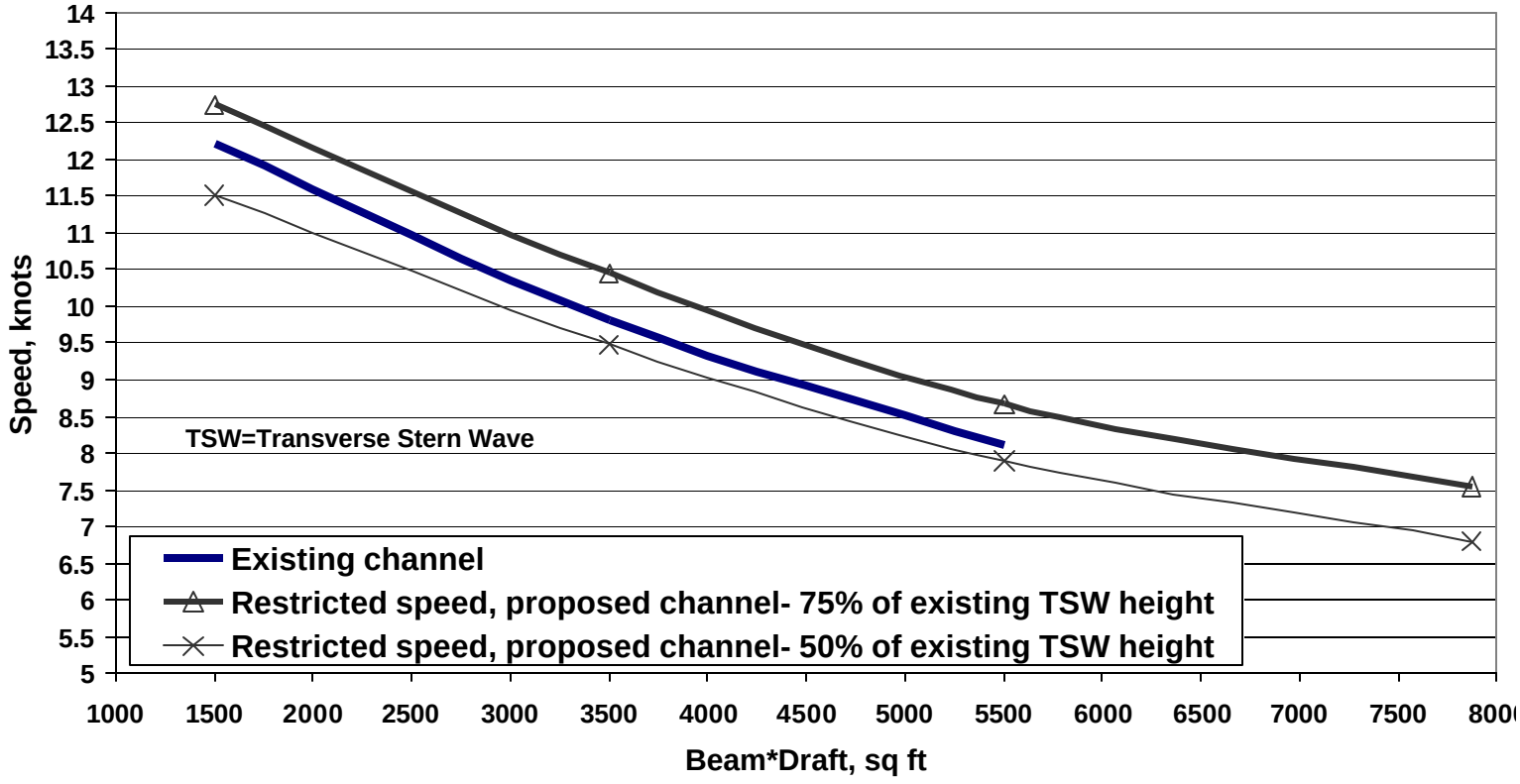

Figure 47. Speeds in proposed channel, less TSW, South Site, Port Arthur Canal

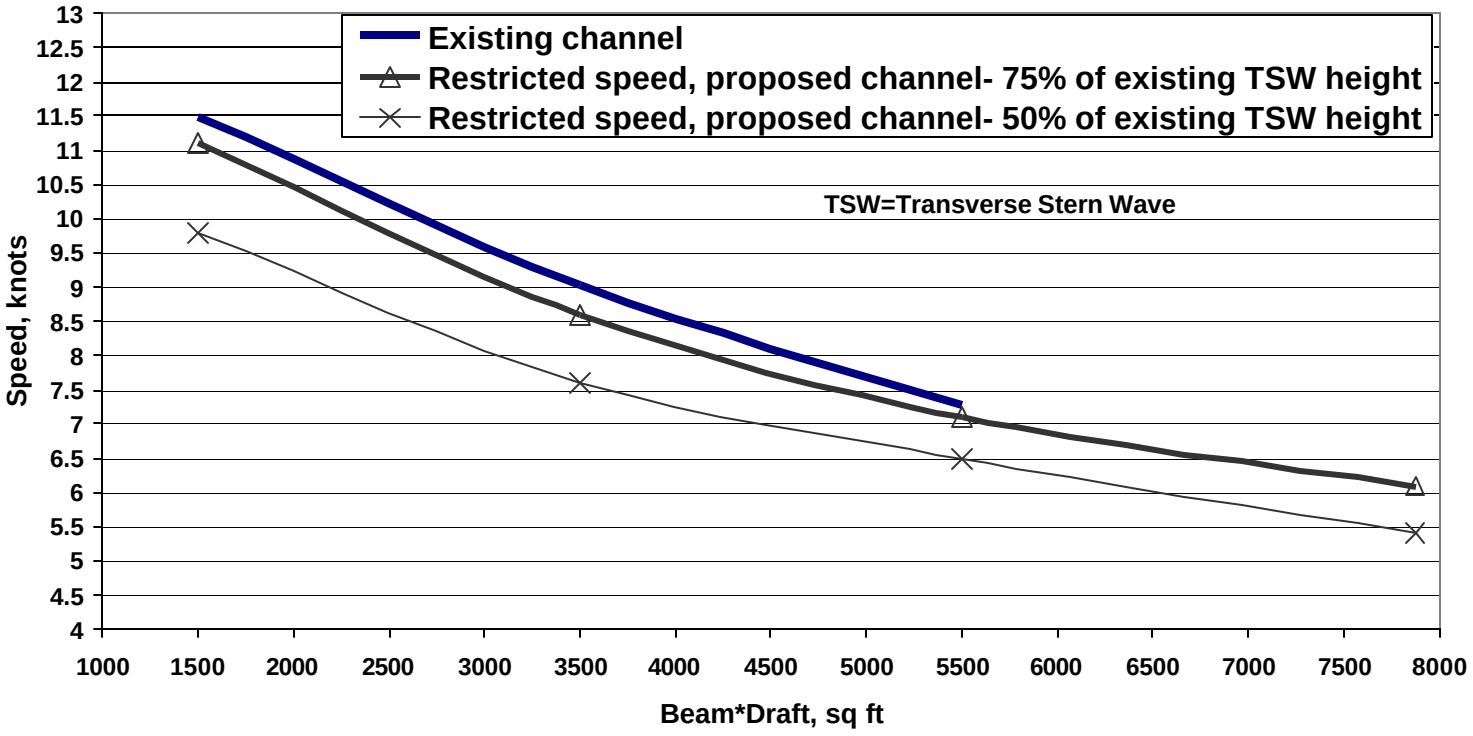

Figure 48. Speeds in proposed channel, less TSW, North site, Sabine-Neches Canal

Appendix A- Time histories of water level, existing channel

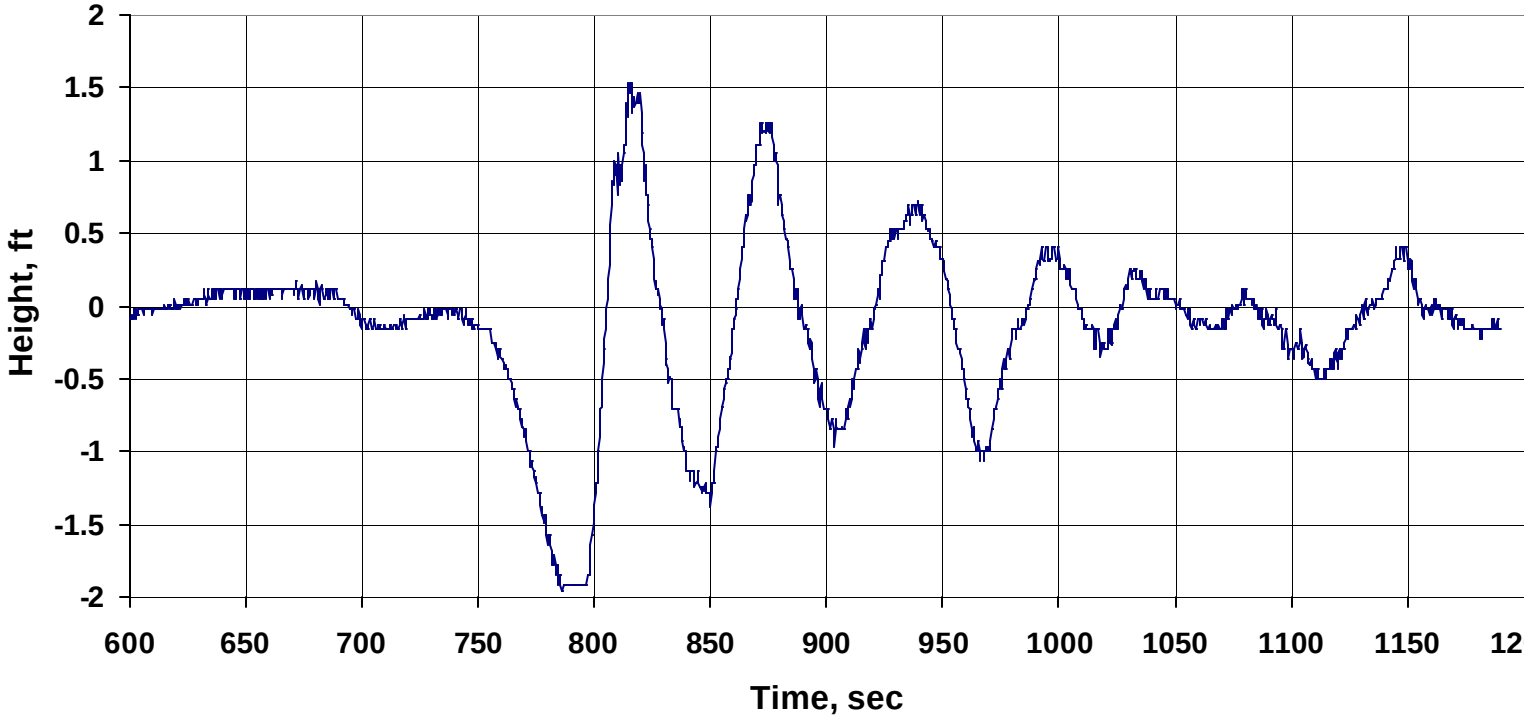

Figure A1. Kite Arrow, South Site, Outbound, Time 0 = 2120, 30 April 2002, Pressure Cell 1200346b

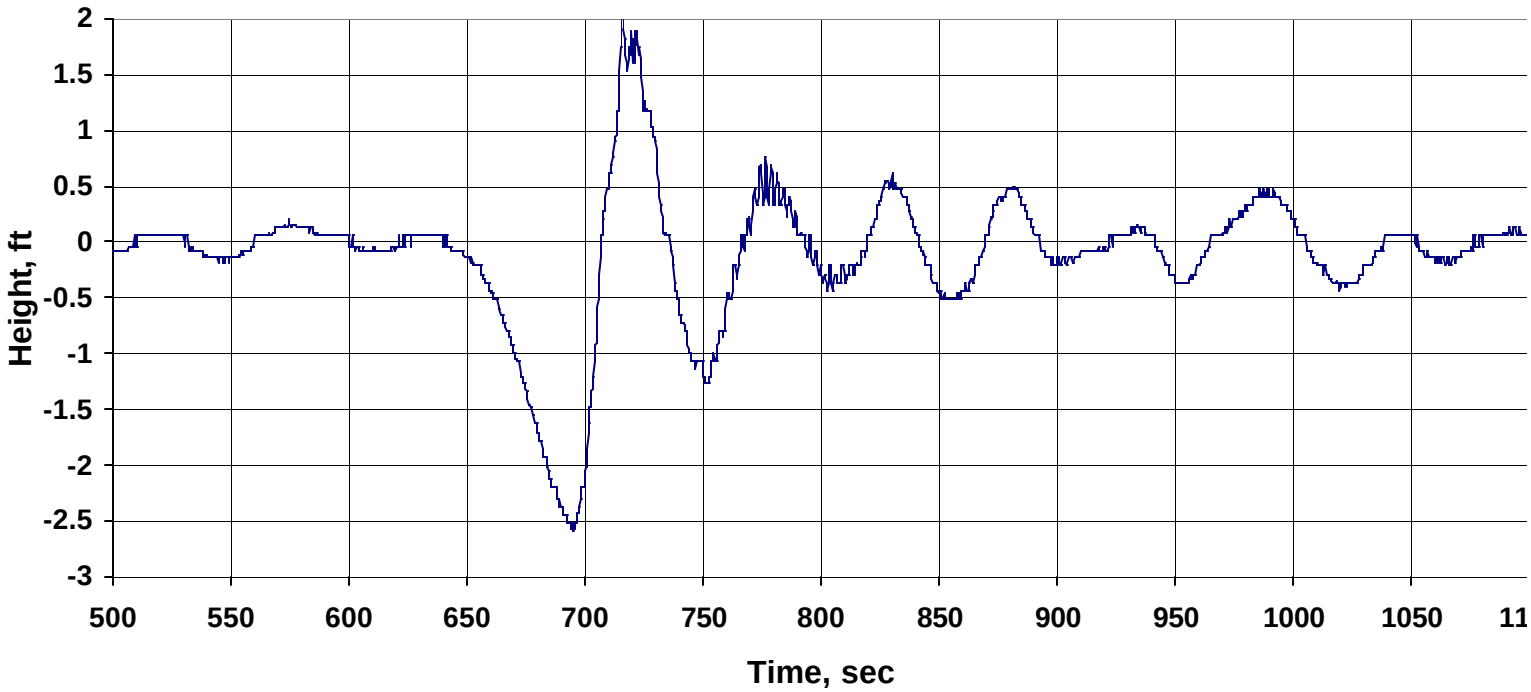

Figure A2. Kite Arrow, South Site, Outbound, Time 0 = 2120, 30 April 2002, Pressure Cell 1200347b

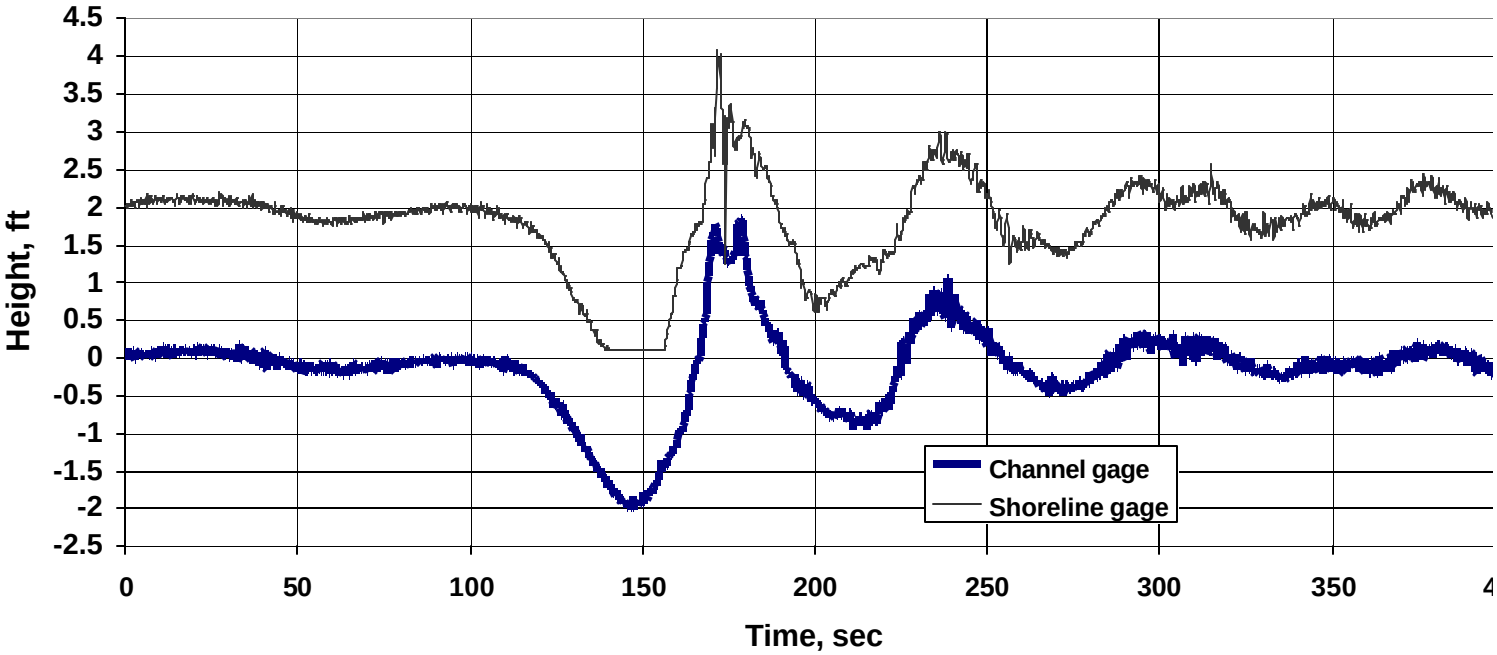

Figure A3. Kite Arrow, South Site, Outbound, Time 0 = 2130, 30 Apr 2002, Capactiance Cell 1200522b

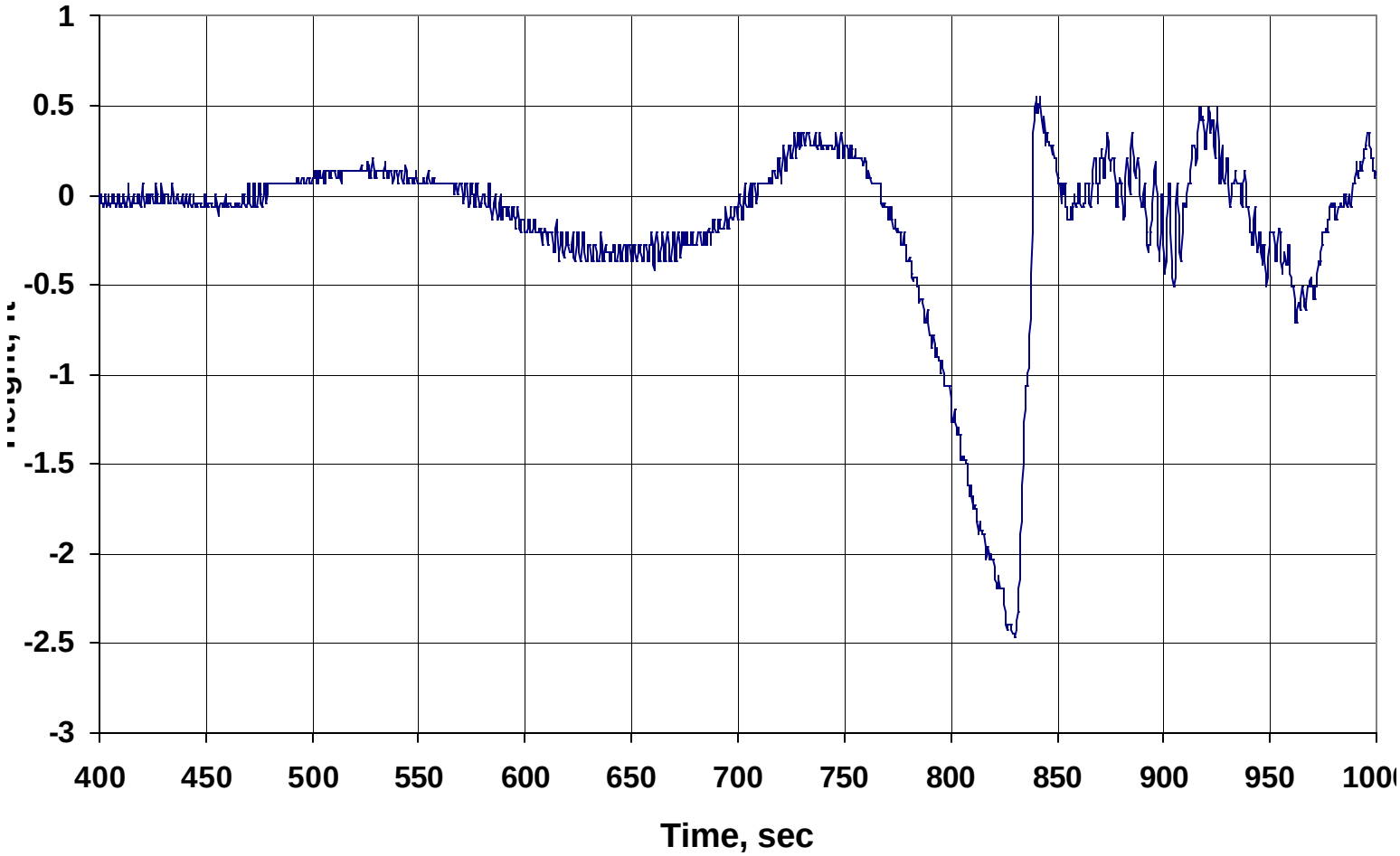

Figure A4. S/R Charleston, South Site, Inbound, Time 0 = 2120, 1 May 2002, Pressure Cell 1210346b

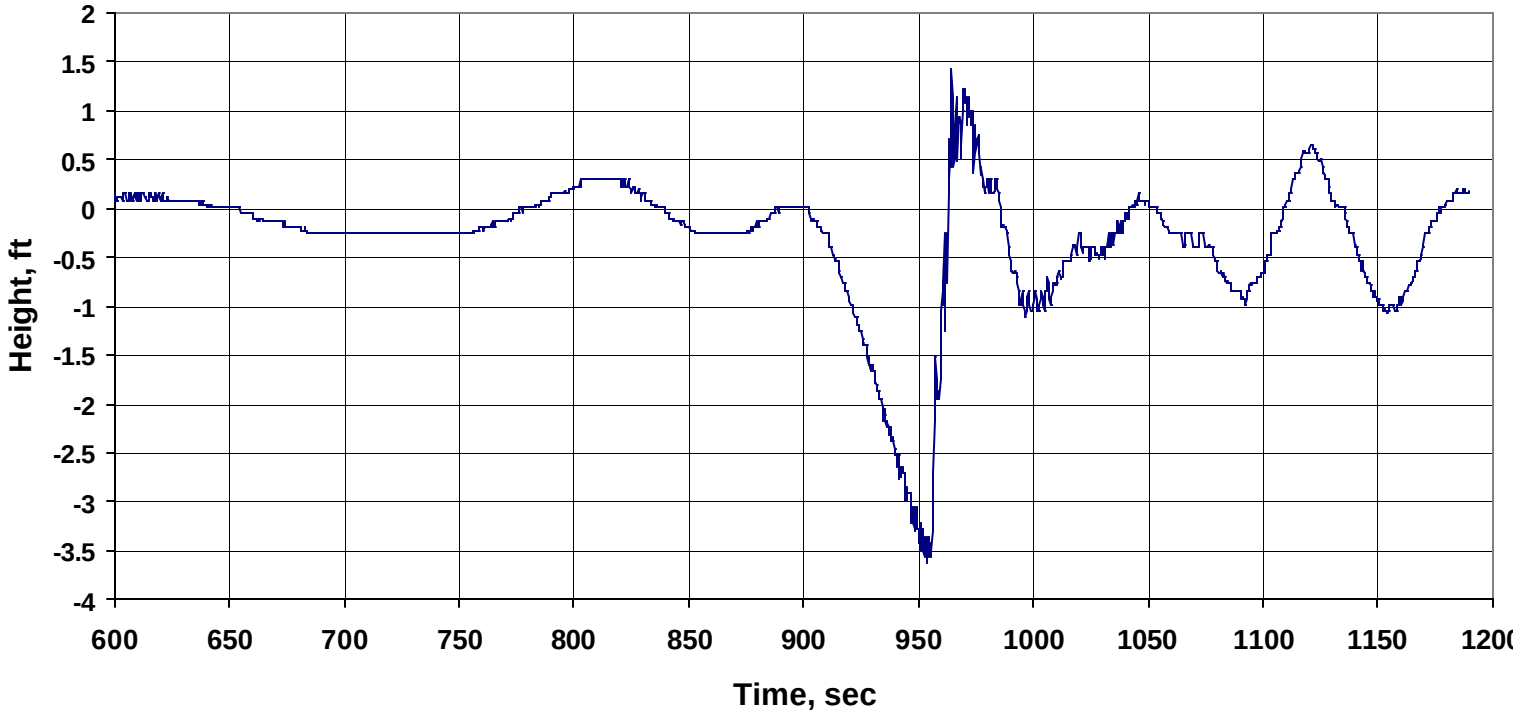

Figure A5. S/R Charleston, South Site, Inbound, Time 0 = 2120, 1 May 2002, Pressure Cell 1210347b

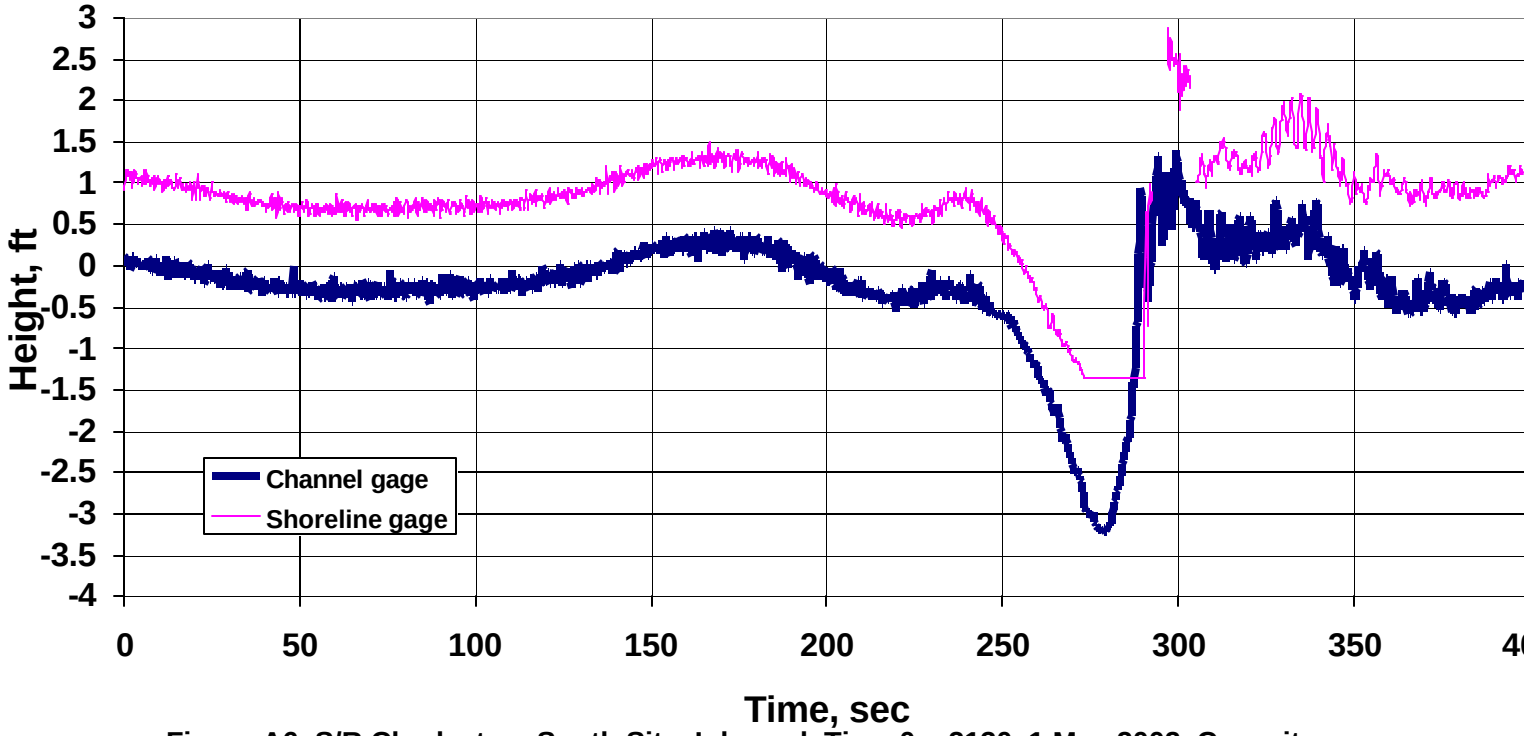

Figure A6. S/R Charleston, South Site, Inbound, Time 0 = 2130, 1 May 2002, Capacitance Cell 1210520b

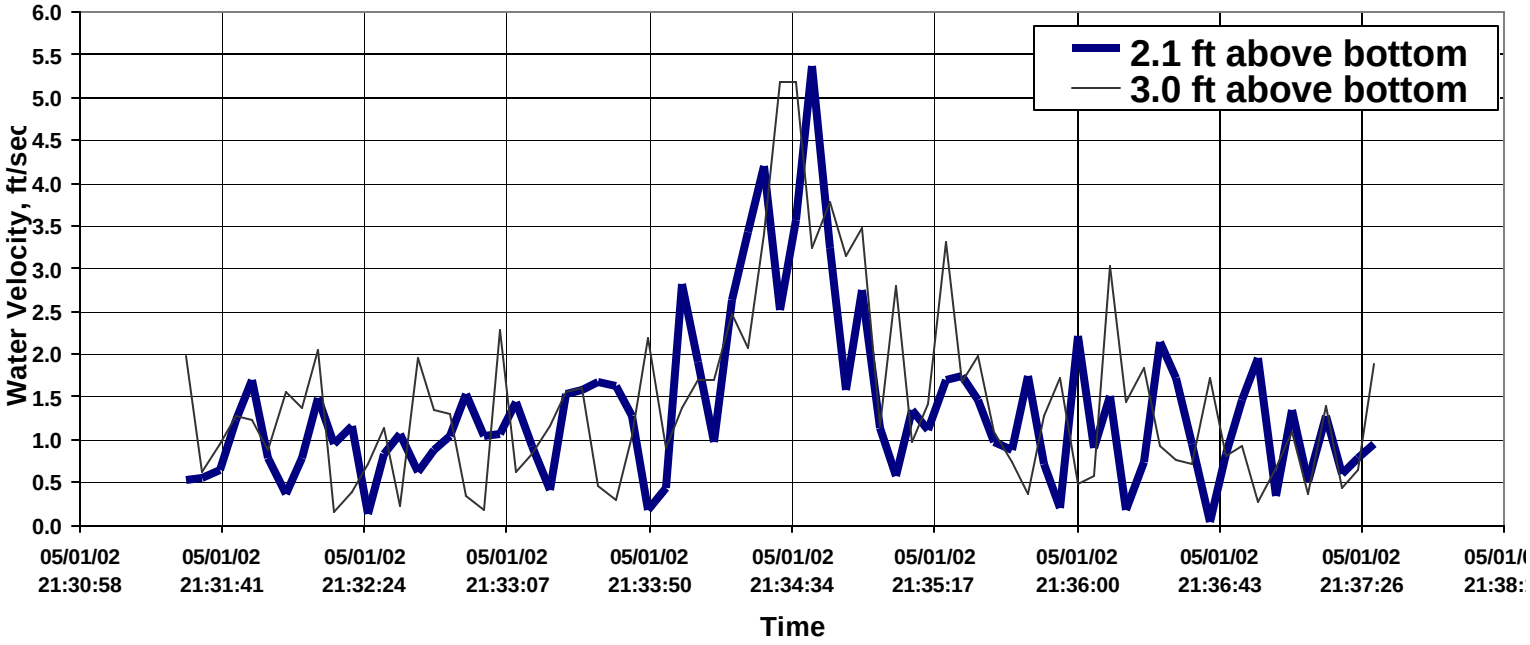

Figure A7. S/R Charleston, South Site, Inbound, 1 May 2002, Water Velocity

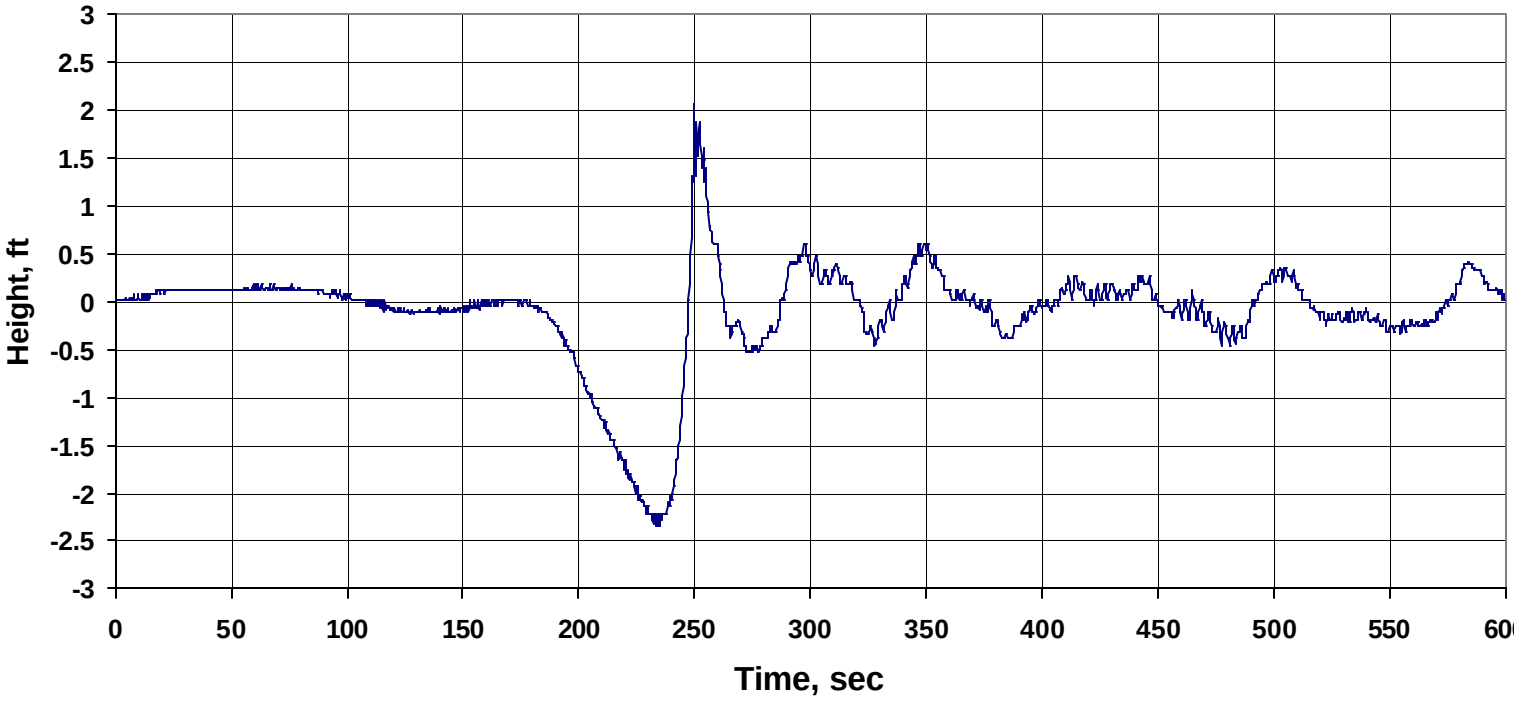

Figure A8, Bornes, South Site, Outbound, Time 0 = 0800, 2 May 2002, Pressure Cell 1210346b

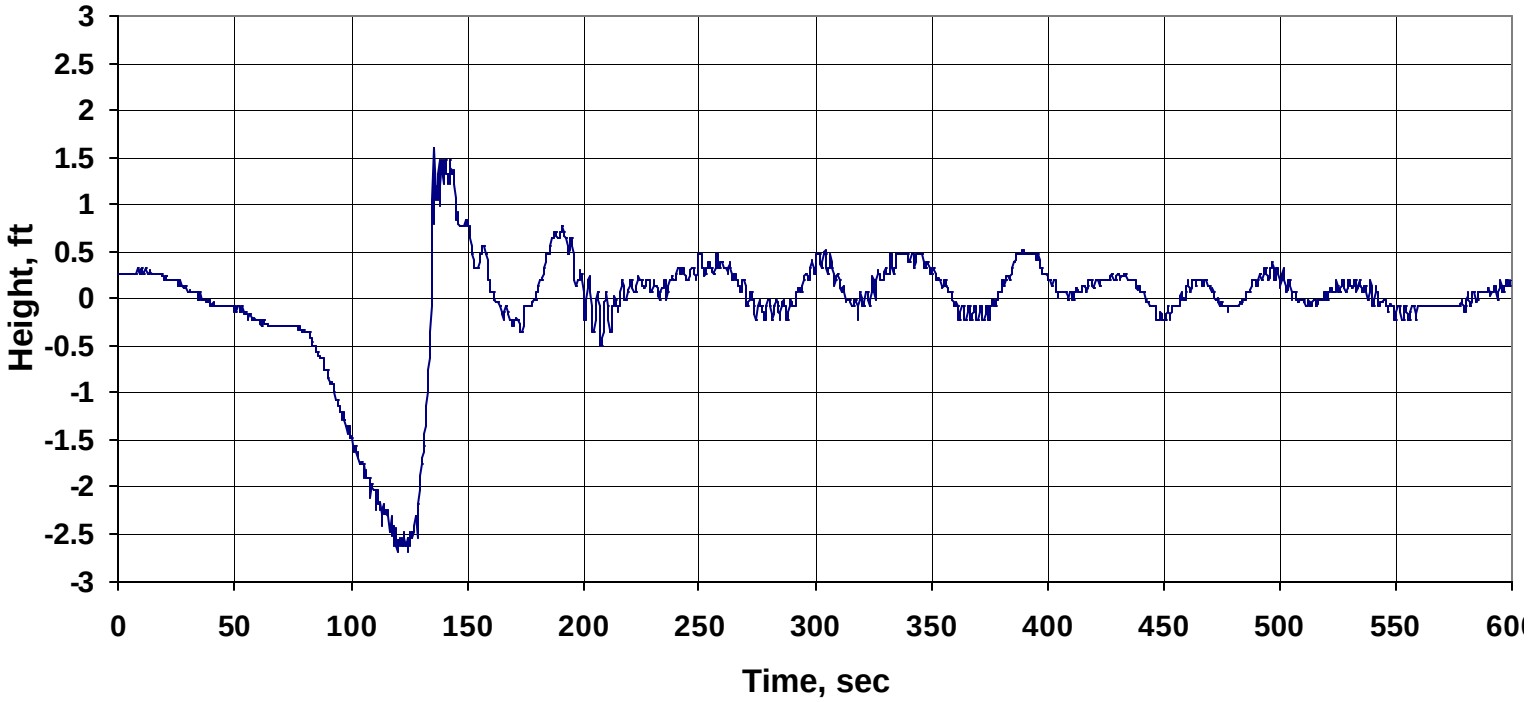

Figure A9, Bornes, South Site, Outbound, Time 0 = 0800, 2 May 2002, Pressure Cell 1210347b

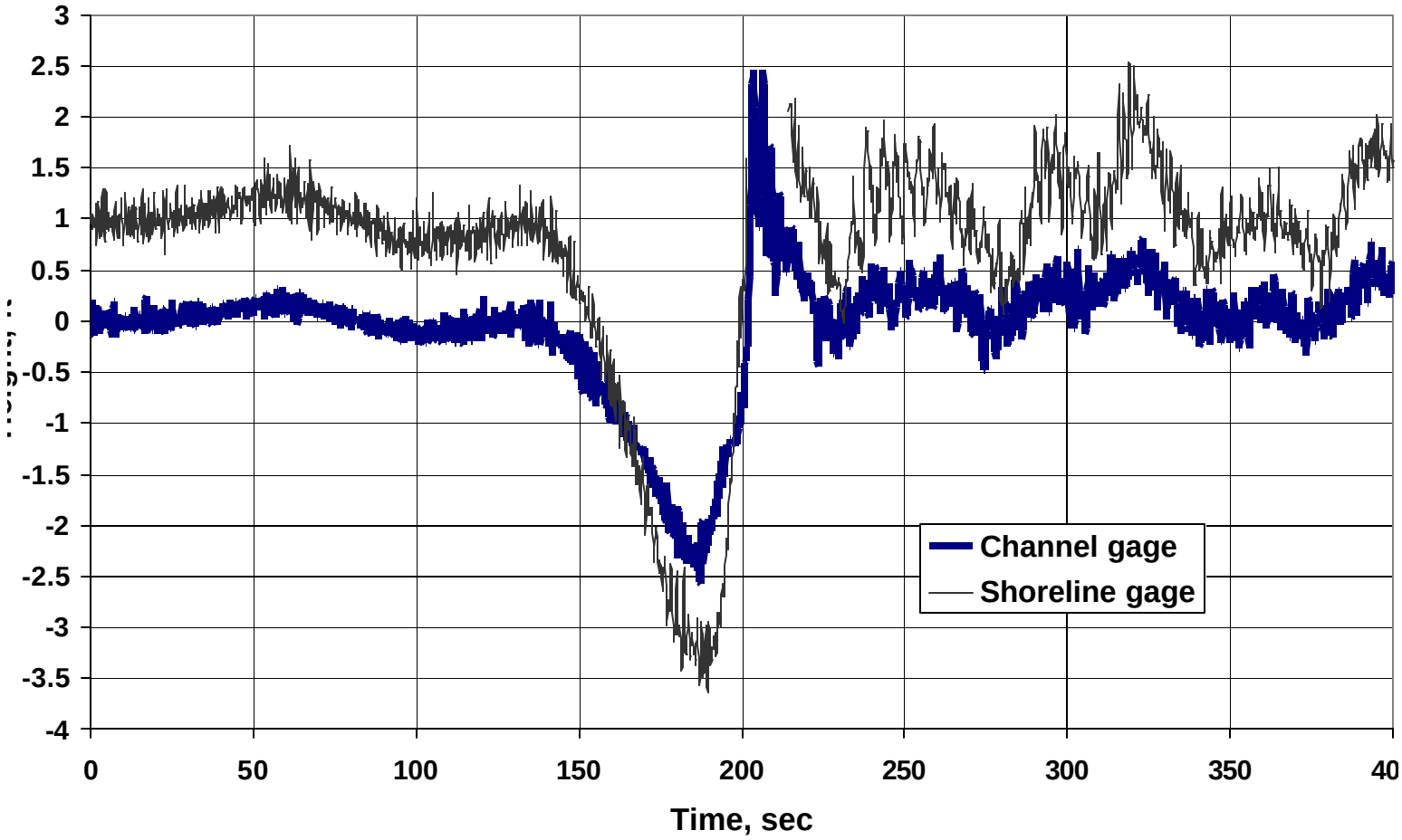

Figure A10, Bornes, South Site, Outbound, Time 0 = 0800, 2 May 2002, Capacitance Cell 1210520b

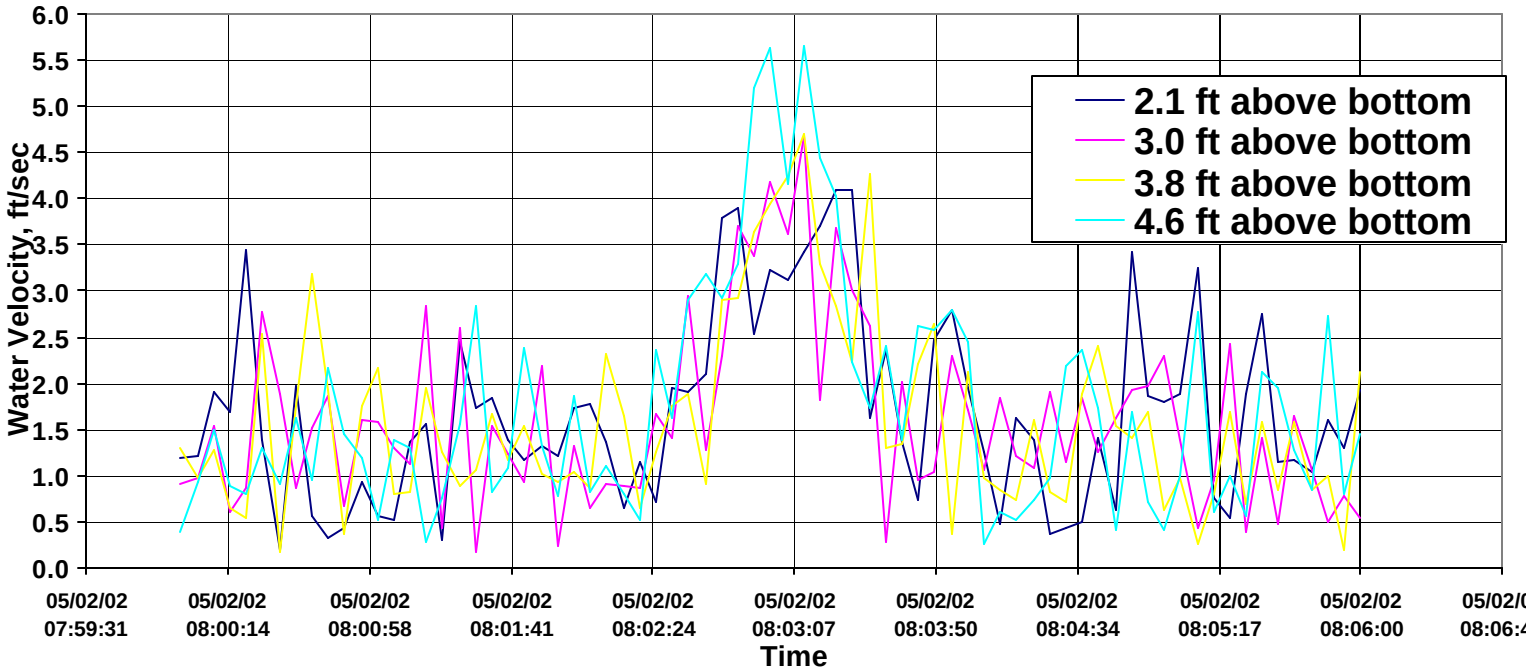

Figure A11, Bornes, South Site, Outbound, 2 May 2002, Water Velocity

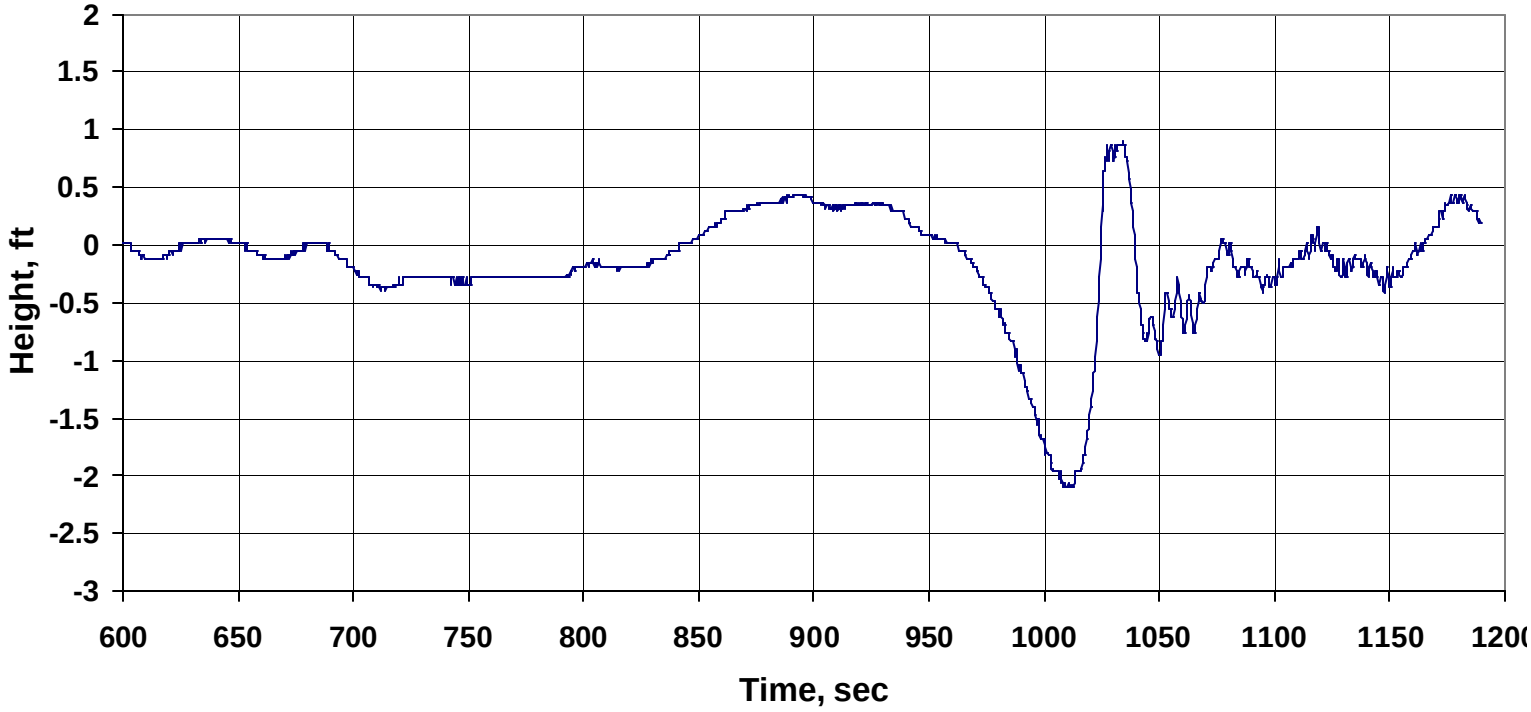

Figure A12. Eagle Carina, South Site, Inbound, Time 0 = 1200, 2 May 2002, Pressure Cell 1210346b

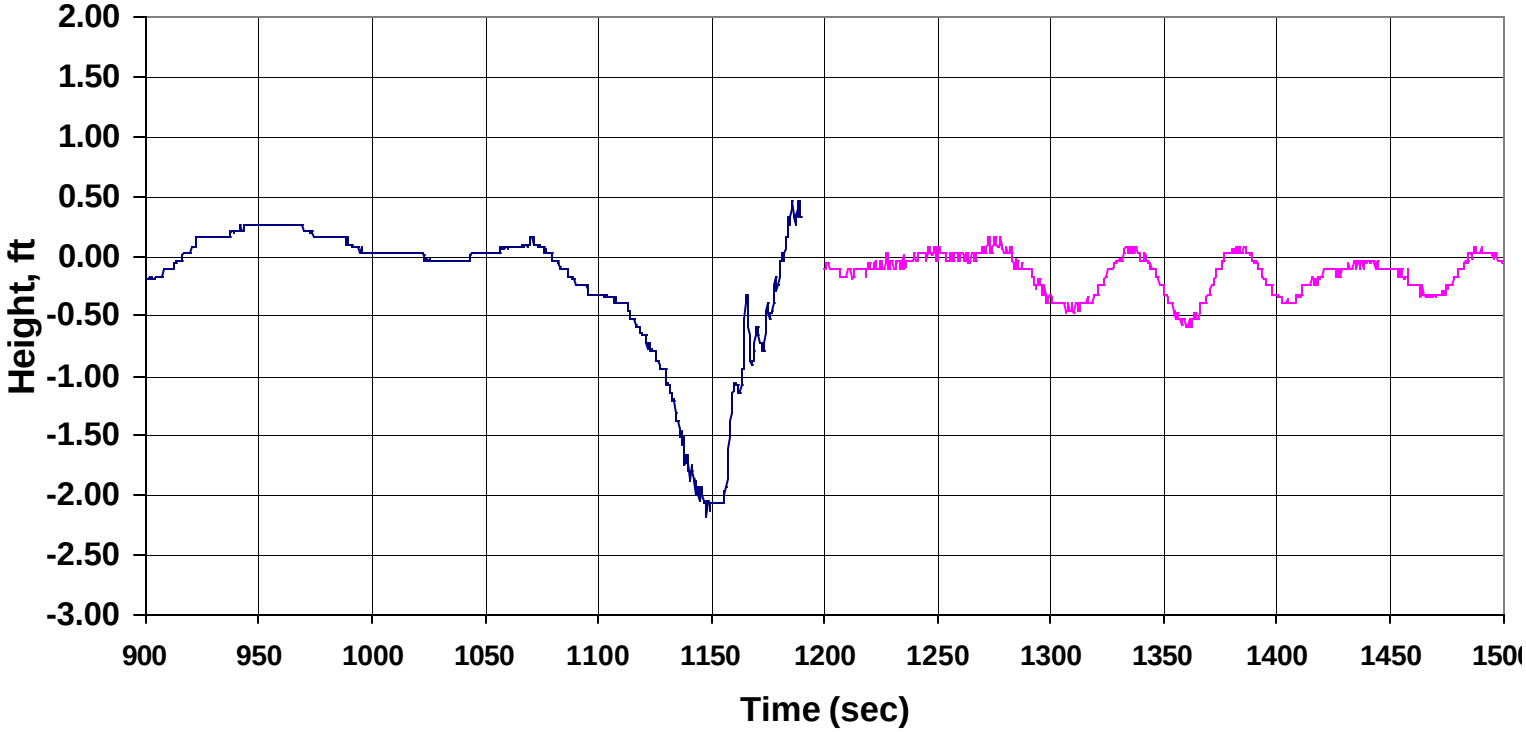

Figure A13. Eagle Carina, South Site, Inbound, Time 0 = 1200, 2 May 2002, Pressure Cell 1210347b

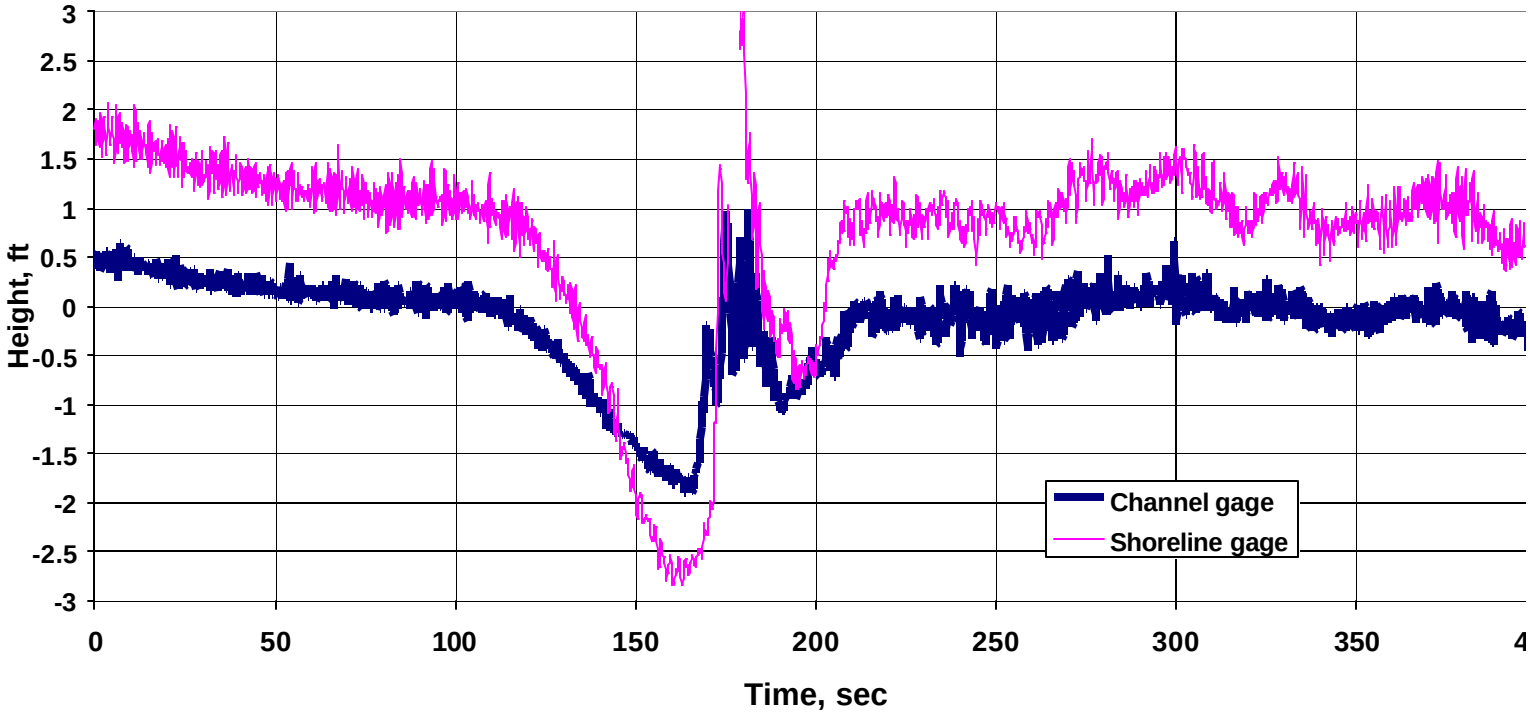

Figure A14. Eagle Carina, South Site, Inbound, Time 0 = 1215, 2 May 2002, Capacitance Cell 1210520b

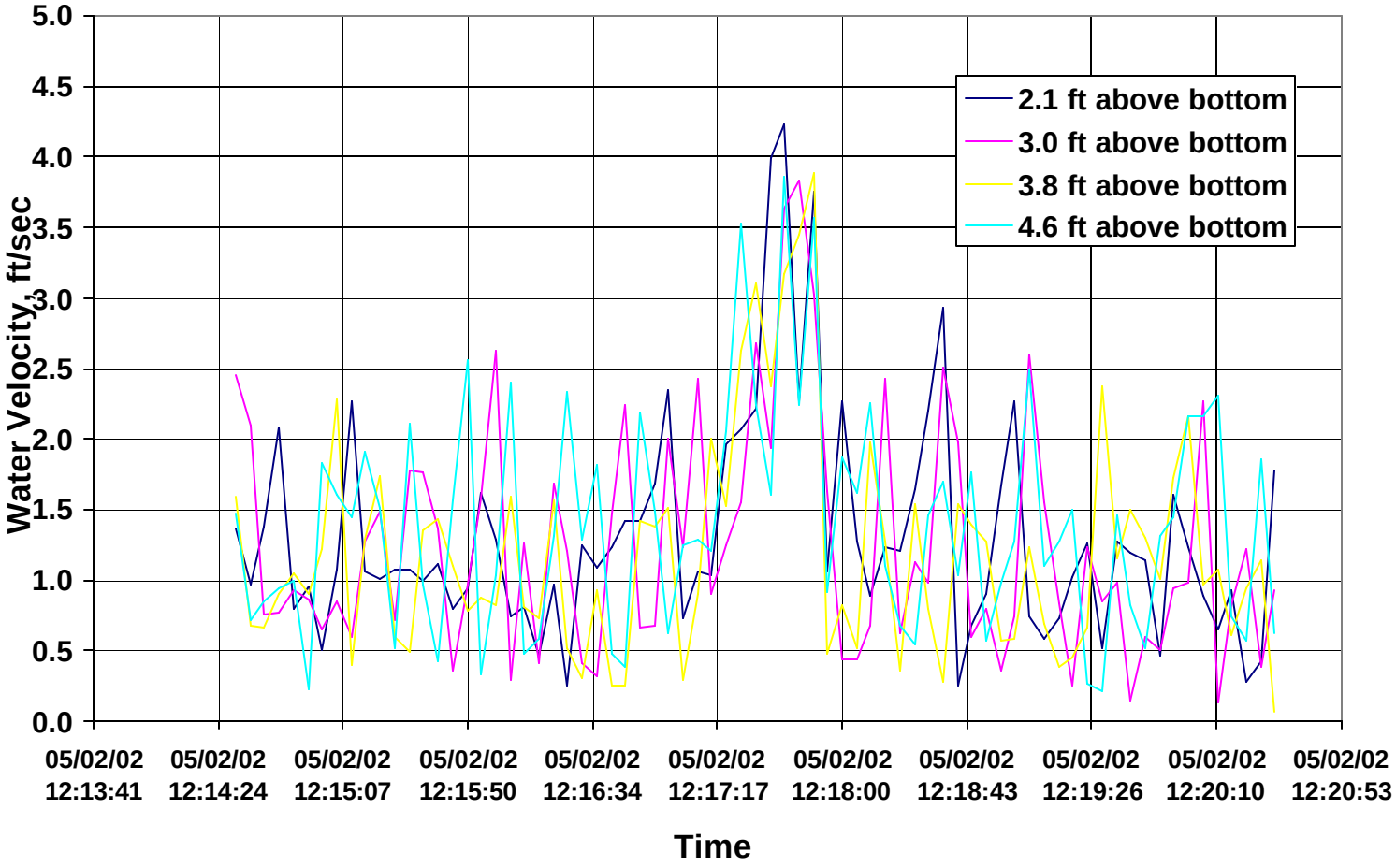

Figure A15, Eagle Carina, South Site, Inbound, 2 May 2002, Water Velocity

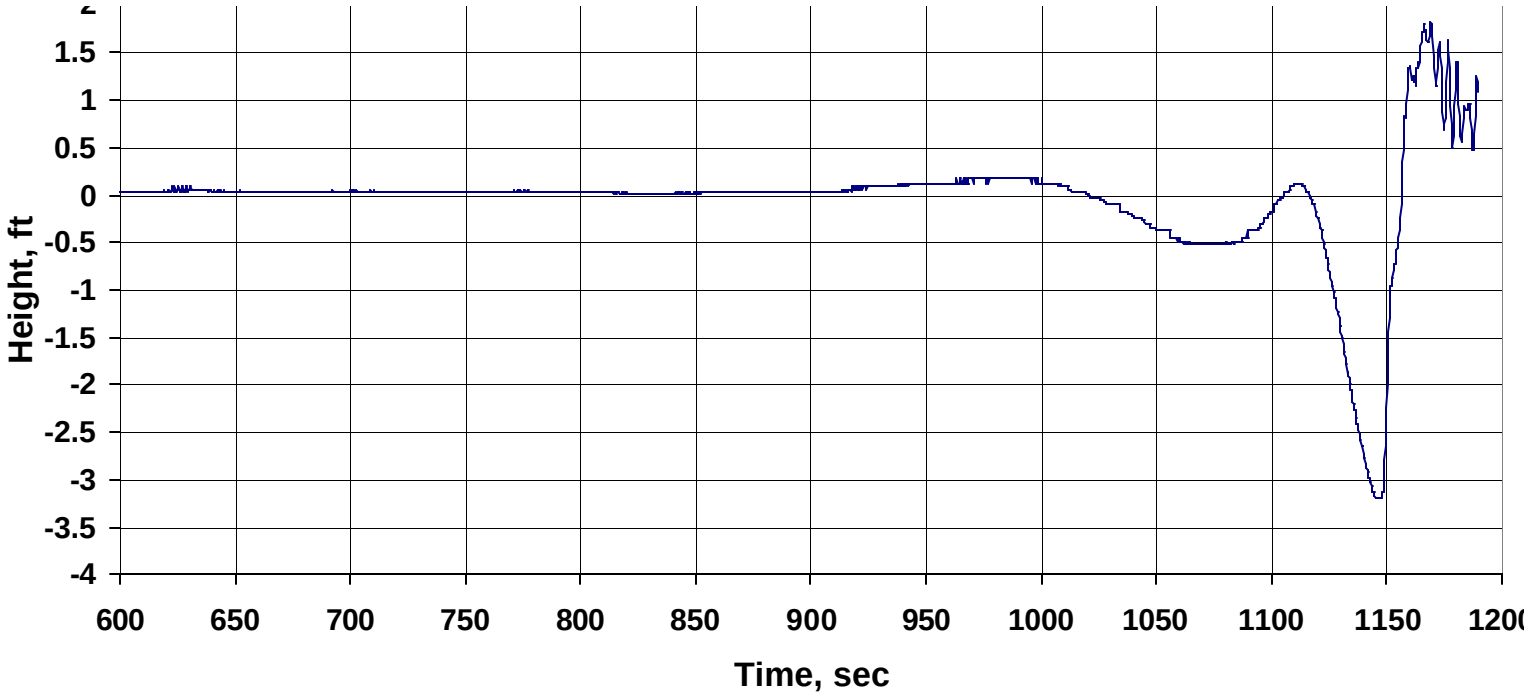

Figure A16, Shetland, South Site, Inbound, Time 0 = 1920, 3 May 2002, Pressure Cell 1230346b

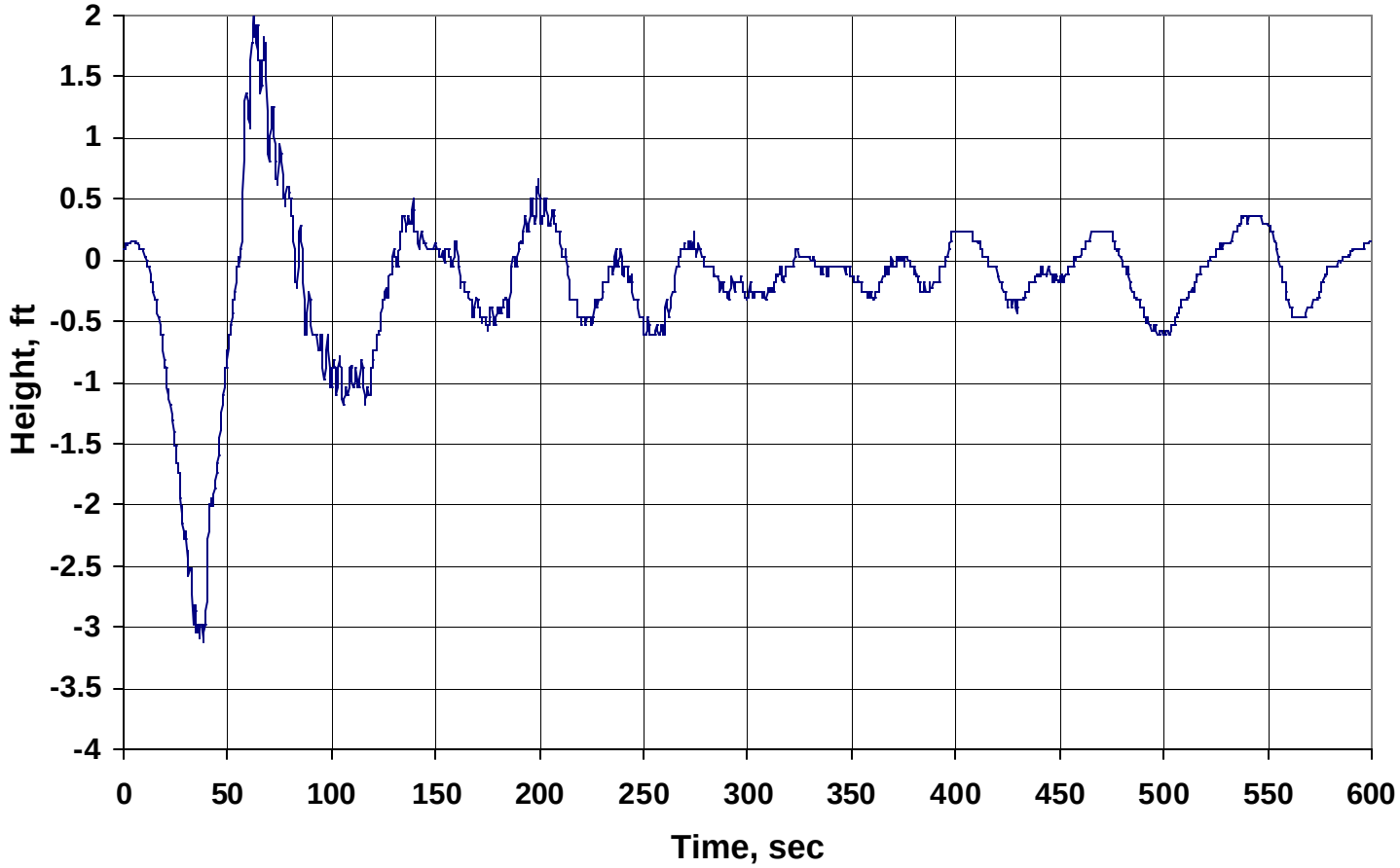

Figure A17, Shetland, South Site, Inbound, Time 0 = 1940, 3 May 2002, Pressure Cell 1230347b

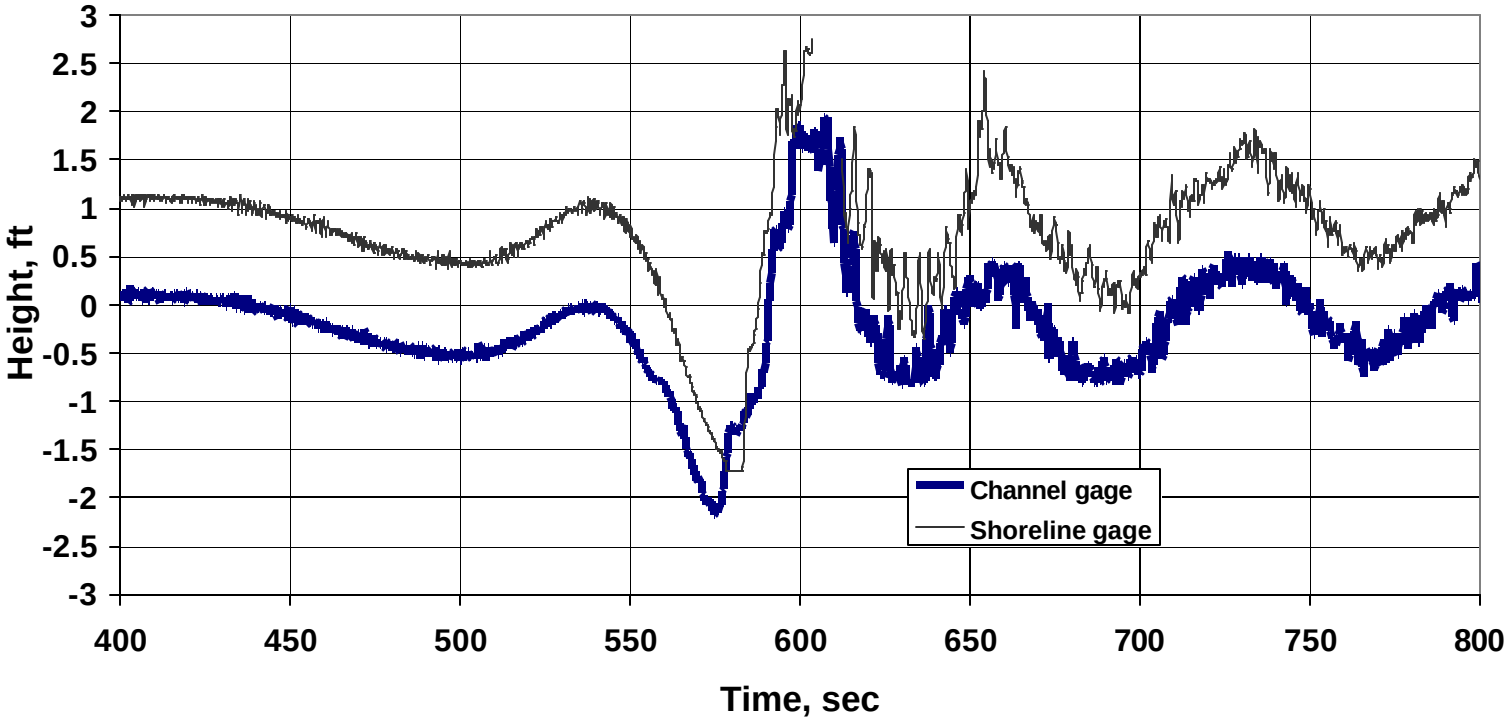

Figure A18, Shetland, South Site, Inbound, Time 0 = 1930, 3 May 2002, Capacitance Cell 1220526b

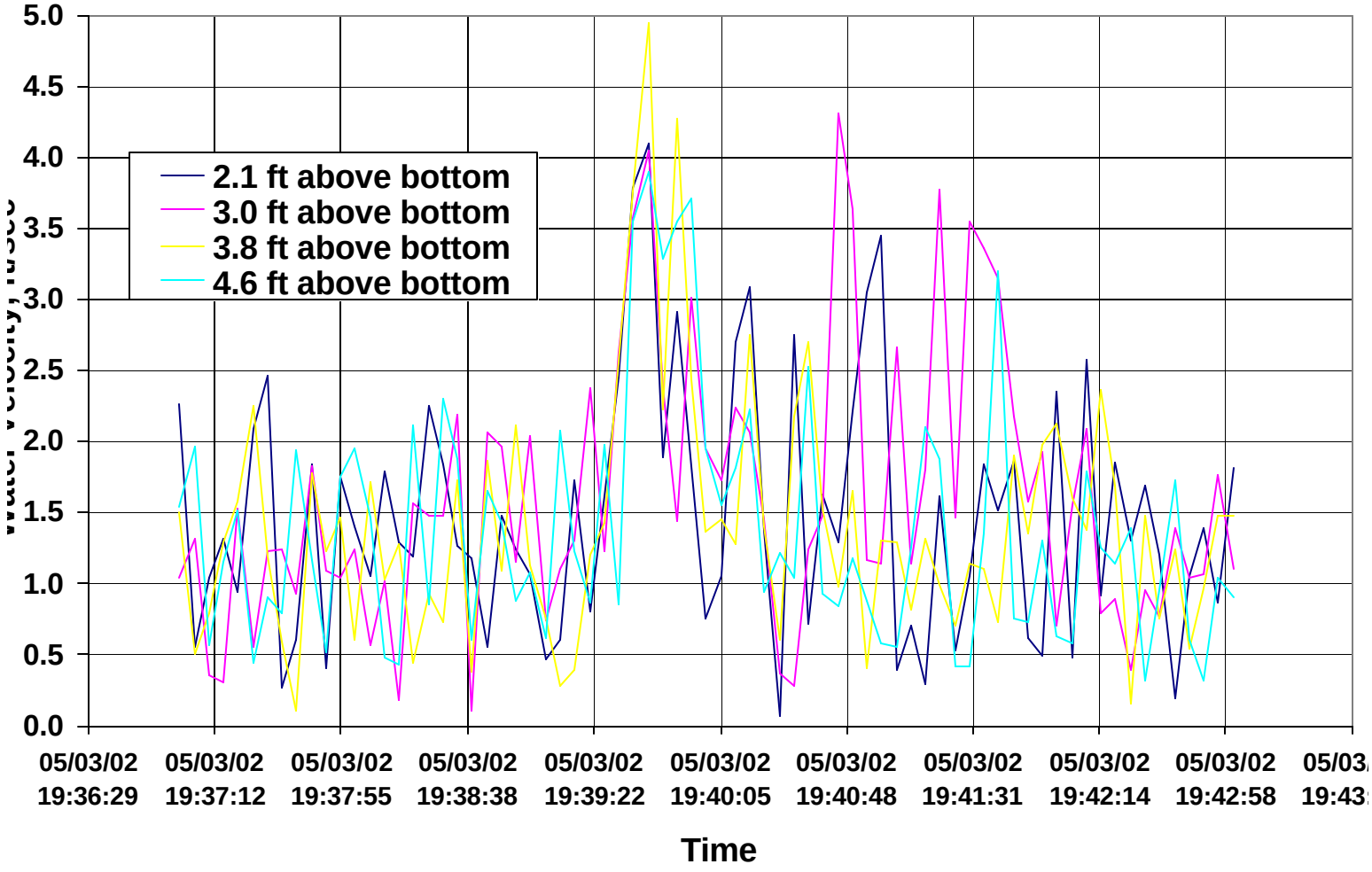

Figure A19, Shetland, Inbound, South Site, 3 May 2002, Water Velocity

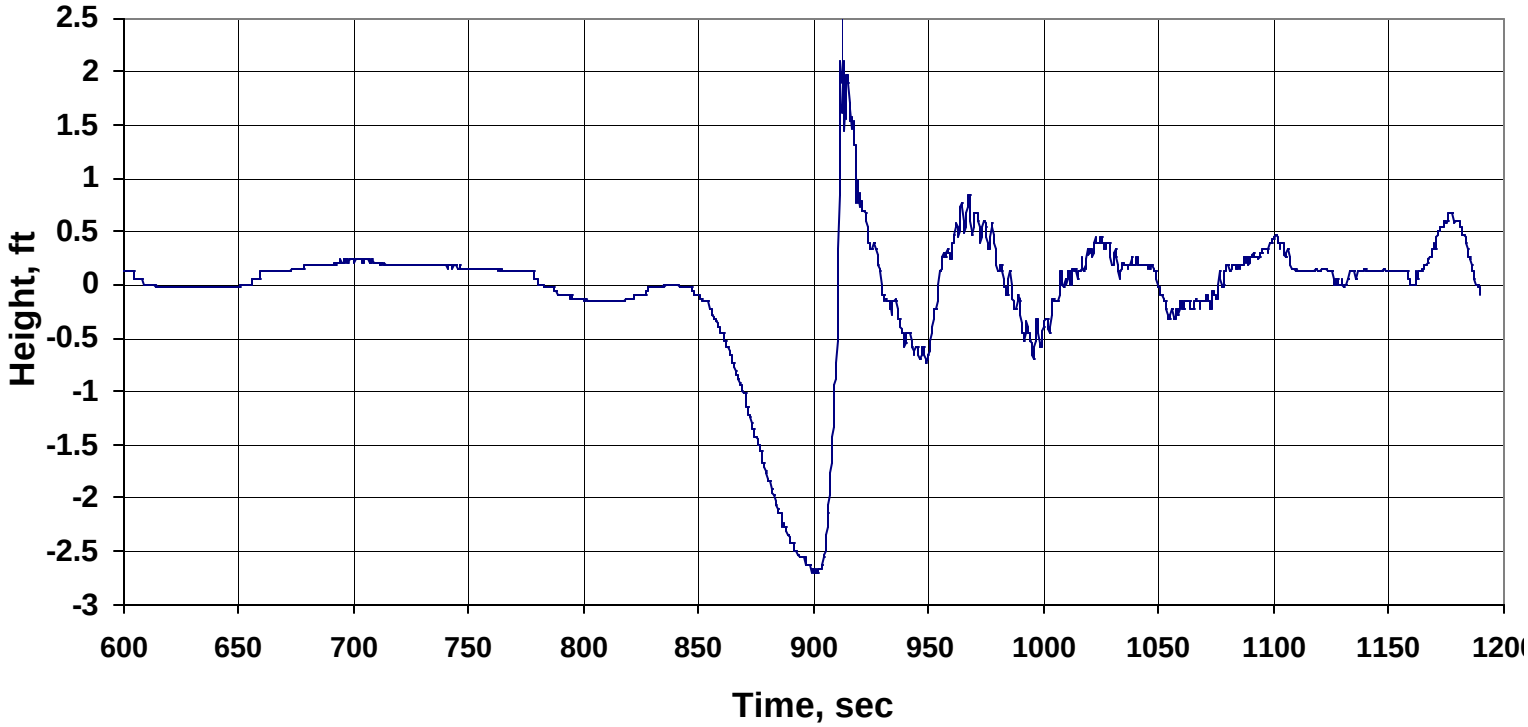

Figure A20, Pacific Sapphire, Outbound, South Site, Time 0 = 0720, 4 May 2002, Pressure Cell 1230346b

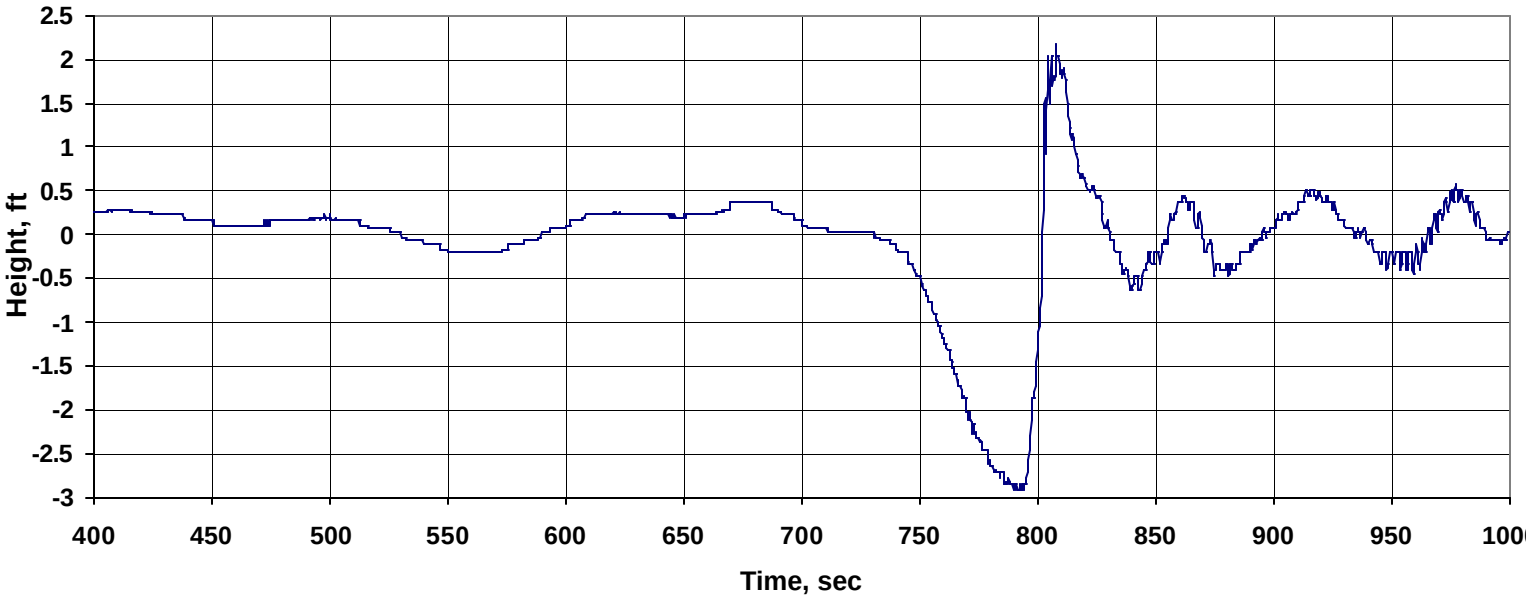

Figure A21, Pacific Sapphire, South Site, Outbound, Time 0 = 0720, 4 May 2002, Pressure Cell 1230347b

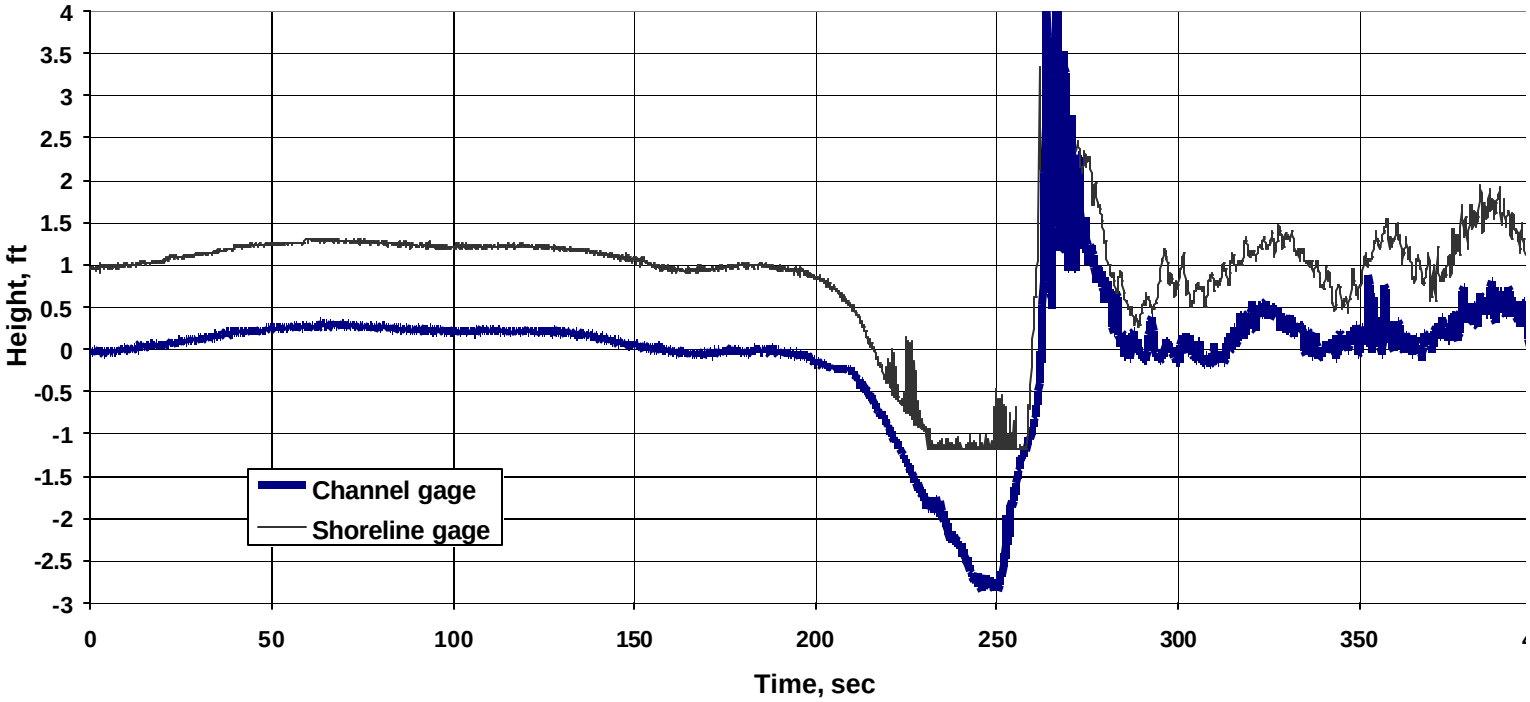

Figure A22, Pacific Sapphire, South Site, Outbound, Time 0 = 0730, 4 May 2002, Capacitance Cell 1220526b

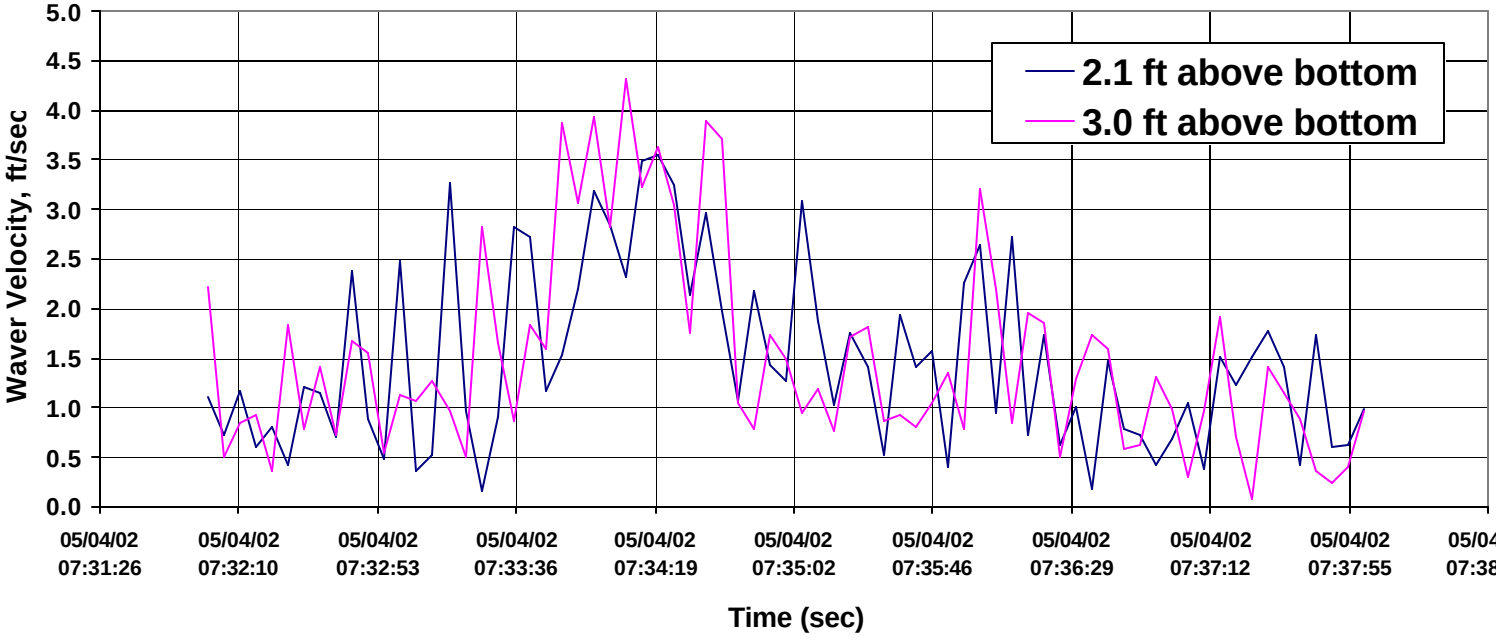

Figure A23. Pacific Sapphire, South Site, Outbound, 4 May 2002, Water Velocity

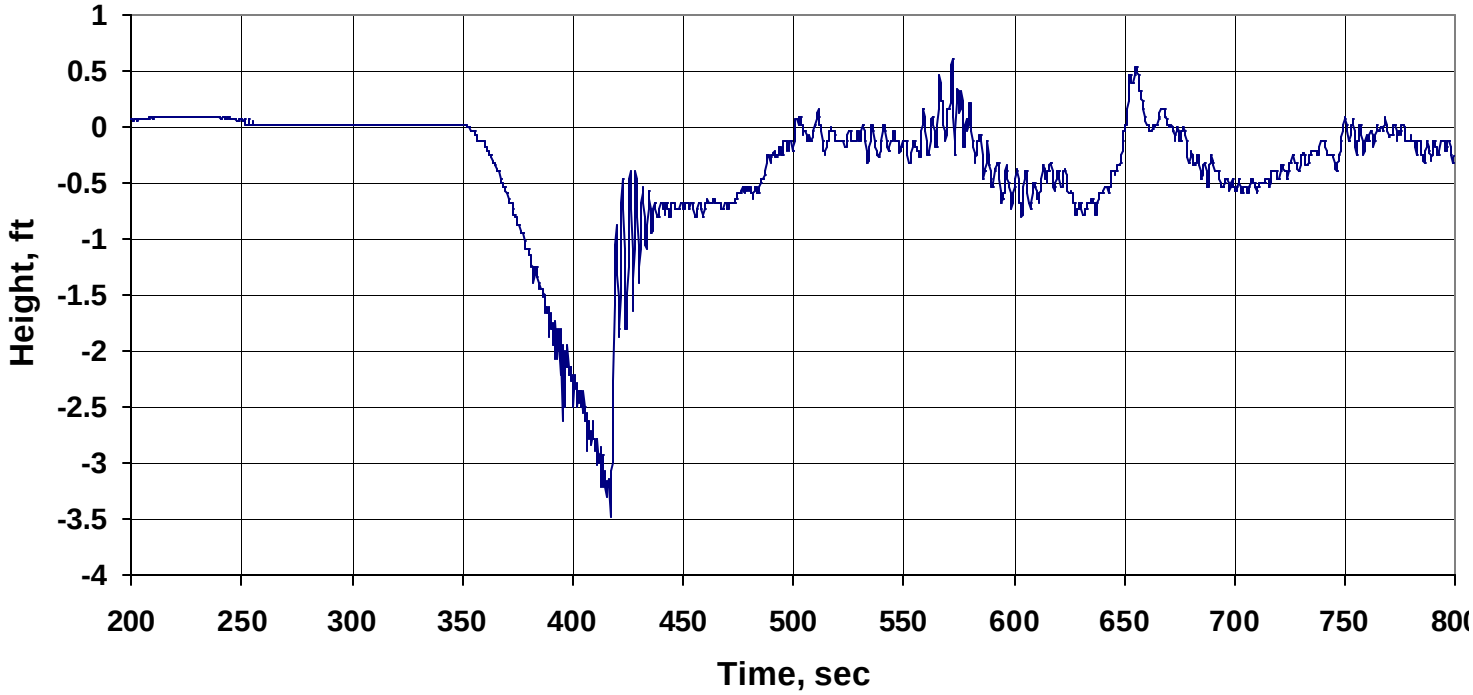

Figure A24. Astro Antares, North Site, Outbound, Time 0 = 0820, 3 May 2002, Pressure Cell 1210349b

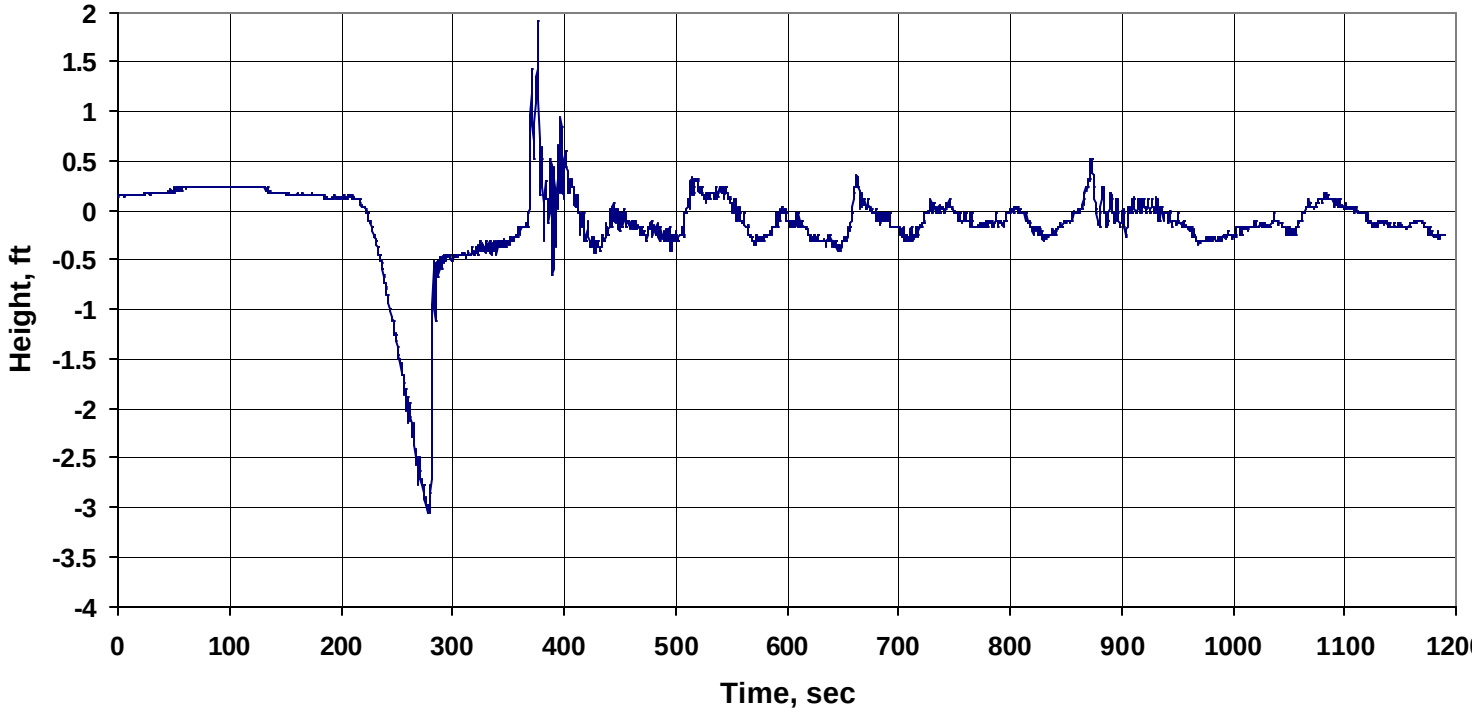

Figure A25. Astro Antares, North Site, Outbound, Time 0 = 0820, 3 May 2002, Pressure Cell 1210350b

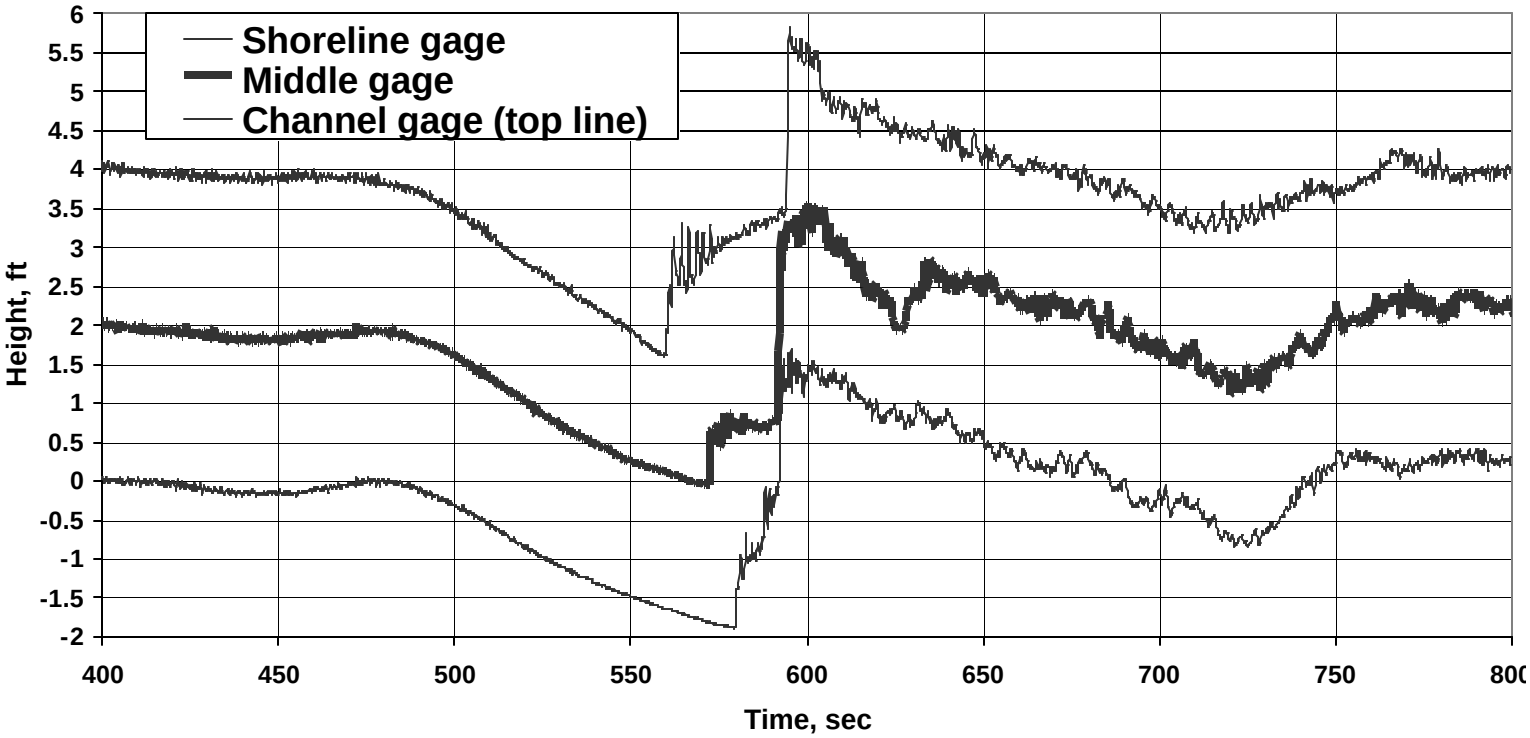

Figure A26. Astro Antares, North Site, Outbound, Time 0 = 0815, 3 May 2002 Capacitance Cell 1220522b

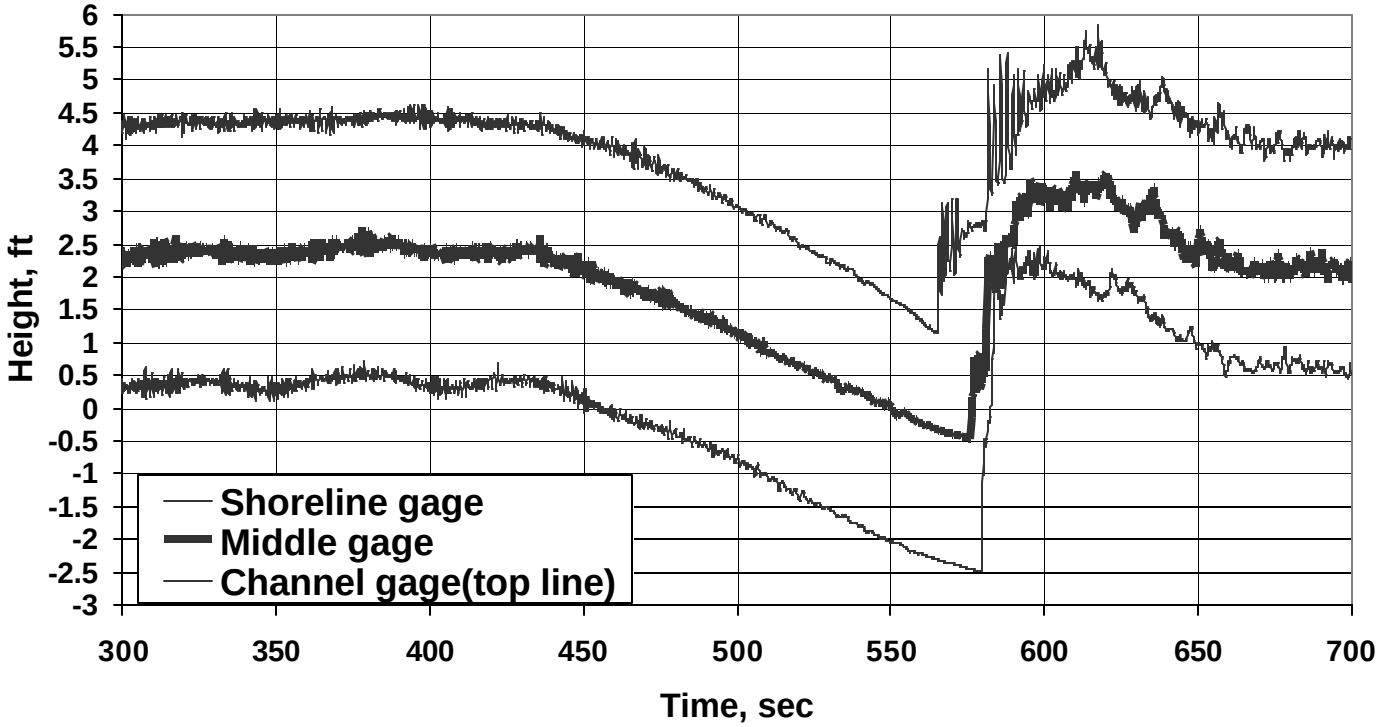

Figure A27, Zrinski, North Site, Inbound, Time 0 = 1315, 1 May 2002, Capacitance Cell 1210526b

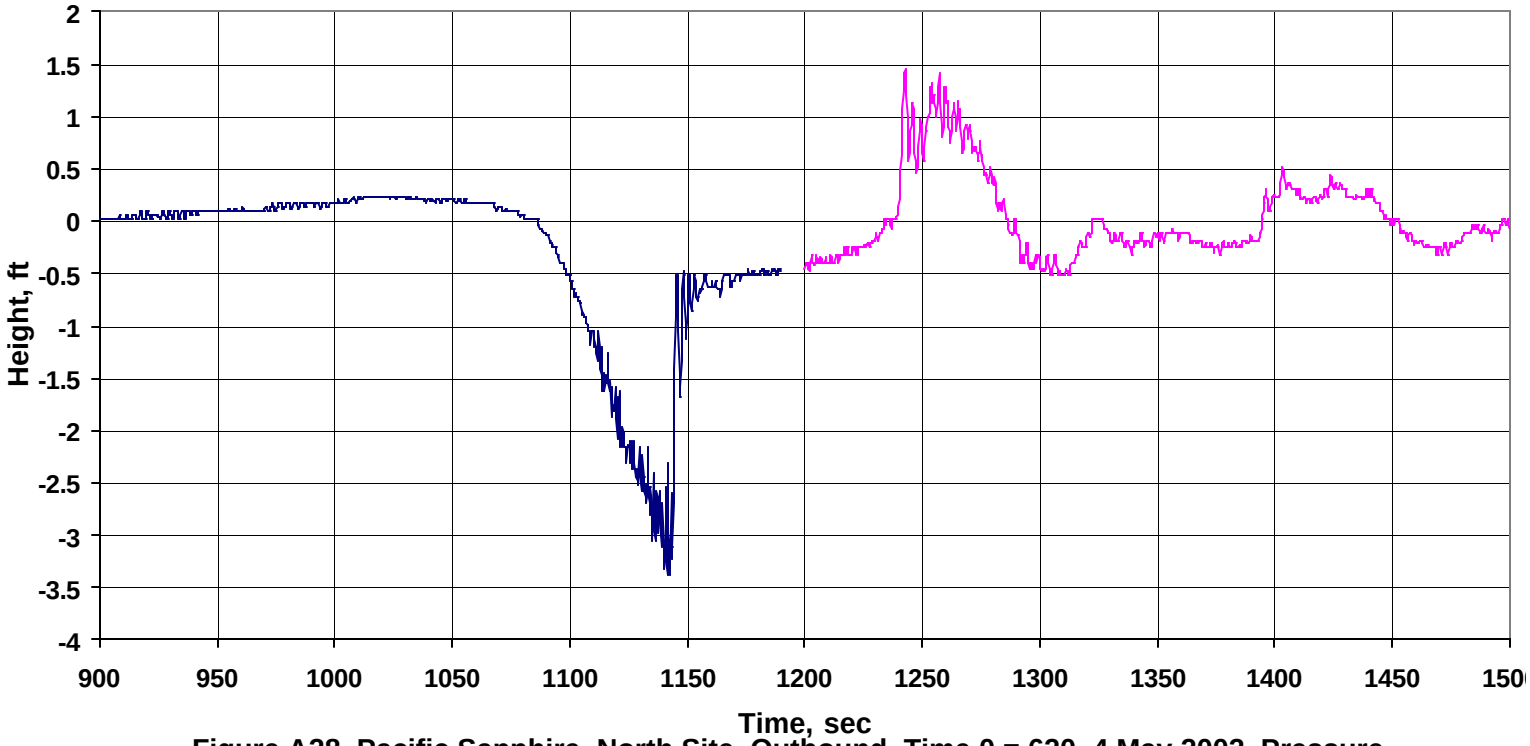

Figure A28, Pacific Sapphire, North Site, Outbound, Time 0 = 620, 4 May 2002, Pressure Cell 1230350b

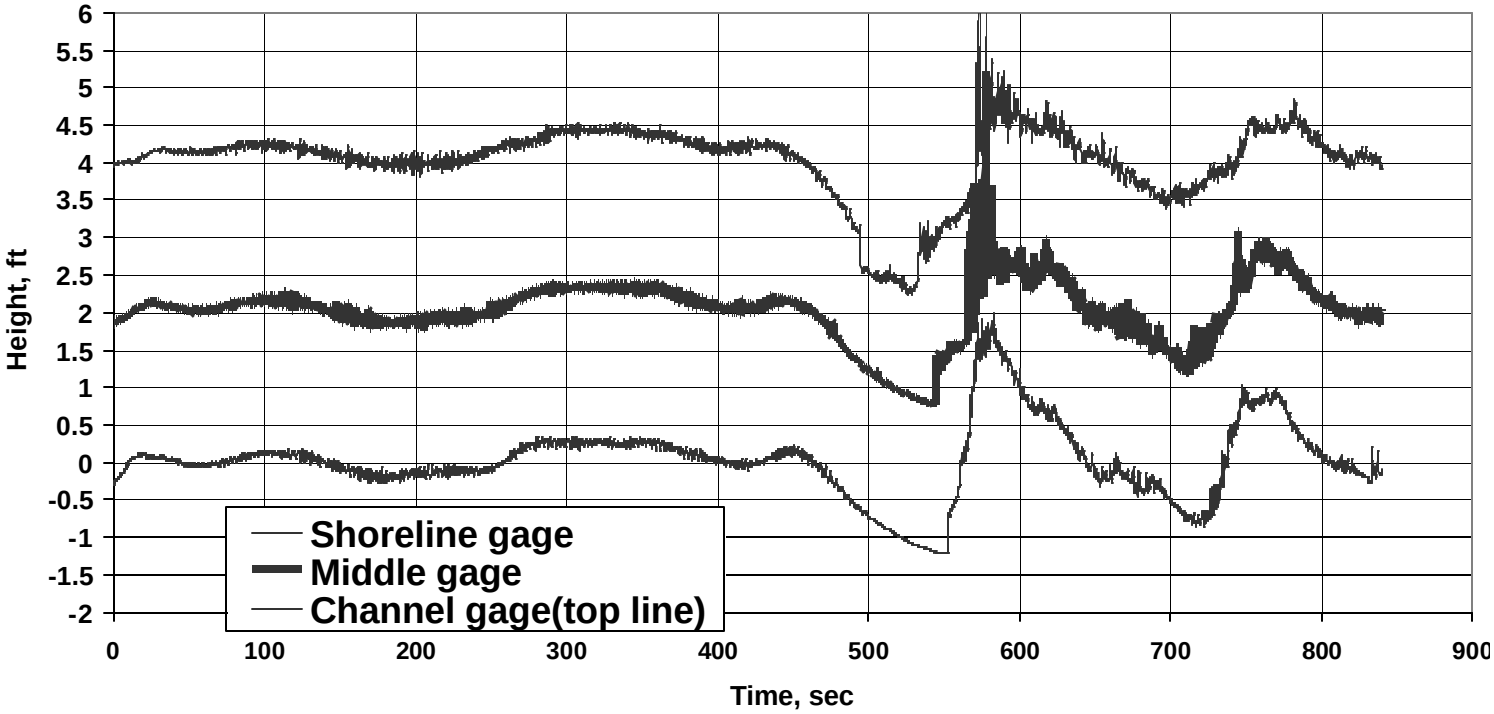

Figure A29, Pacific Sapphire, North Site, Outbound, Time 0 = 630, 4 May 2002, Capacitance Cell 1220522b