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Modeling of Vessel Effects: Selection of Adaption Parameters for Modeling Vessels in ADH

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PURPOSE: In this investigation the ADaptive Hydrology (ADH) code is being used to produce the effect of a vessel in a waterway by moving a pressure field that displaces the vessel "footprint" along the navigation channel. As the vessel moves, it creates a drawdown and return current pattern. The adaption is being relied upon to capture the hydrodynamics and also to precisely match the forcing supplied by the vessel pressure field. ADH allows the user to set up a mesh that only needs to capture the geometry of the domain, and the model will then automatically refine the mesh to accurately represent the flow field. ADH is a code that can be used for a variety of hydrodynamic problems, including groundwater and flow in and around hydraulic structures. In this case, ADH is being used in the two-dimensional (2-D) shallow-water mode. For more information on ADH see Berger and Stockstill (1999) or Stockstill and Berger (2001). The Shallow-water Refinement Tolerance (SRT) value used in ADH triggers the adaptive refinement. This CHETN allows users to estimate the appropriate value of SRT so that they may conduct accurate investigations of vessel effects in deep-draft waterways. This technical note is intended for investigators with some experience with the shallow-water mode of ADH.

BACKGROUND: As a vessel moves through a waterway it produces a depression in the water surface and generates return currents around the vessel. This depression wave has a length of roughly that of the vessel. With long vessels in relatively shallow waterways, the shallow water or long-wave equations are a reasonable representation of the physics. In confined waterways, this drawdown wave is generally more important than the short waves associated with the bow, for example. This drawdown wave is transformed when it enters shallow water. The rise in water surface associated with the stern of the vessel tends to travel faster than the depression part of the wave. The wave will become progressively steeper until a bore may be formed. This is common in many deep-draft waterways where the navigation channel is much deeper than the surrounding shallow bay.

In order to represent these events, the model must accurately capture the forcing (the vessel) as well as the hydraulic phenomena, such as a bore. In a static grid model the user must put in a dense mesh in all areas where the vessel, a bore, or other significant hydraulic event might occur. This would then require high resolution along the complete path of the vessel and perhaps over a good bit of the surrounding shallows. The computational expense can be prohibitive. The ADH code dynamically refines its grid during the run. If the hydrodynamics demand more resolution, the model will add it at that time. In this manner the fine resolution can move along with the vessel, and is removed after the vessel passes. The computational expense will be considerably less. The refinement is invoked when the "error" tolerance is exceeded. The error is the norm of the model solution continuity equation residual at the corners of the element. The individual elements that exceed this tolerance are refined. If a refined element later has an error that is less than one-tenth of this tolerance, it will be unrefined.

Therefore, modelers need to be able to estimate this tolerance (SRT). This technical note details that effort for use with simulation of vessel effects.

A reasonable a priori estimate of the shallow-water refinement tolerance (SRT) is needed to achieve a certain precision. The precision is achieved through refinement of the mesh. This enables ADH to better represent the shallow-water equations and also to better represent the vessel itself.

Grid refinement improves representation in two basic ways. The first is that as the grid becomes finer, the discrete model more closely represents the shallow-water equations. The second is with increased resolution, the vessel footprint is more accurately formed. Considering the first issue, ADH is second order accurate in terms of the L_2 norm (e.g., Greenberg 1998) for depth as well as velocity. This means that the error is reduced by a factor of 4 if the grid size is cut in half. This is only true if the solution of the equations is continuous. If the true solution to the shallow-water equations is discontinuous, as is the case for a bore, the accuracy can only be first order. This means that cutting the grid size in half will cut the error in half.

Now consider the representation of the vessel. As the mesh is refined, the pressure field representing the vessel will more accurately reflect the blockage area. In ADH, a moving pressure field represents the vessel. Nodes that fall within the footprint of the vessel have an applied pressure that depresses the water surface by the draft of the vessel (see Figure 1). The shape functions used to interpolate depth and velocity in ADH are linear and continuous. Therefore, the modeled vessel will have sloping sides. As the resolution is increased, the sides will become steeper, but they will never be vertical.

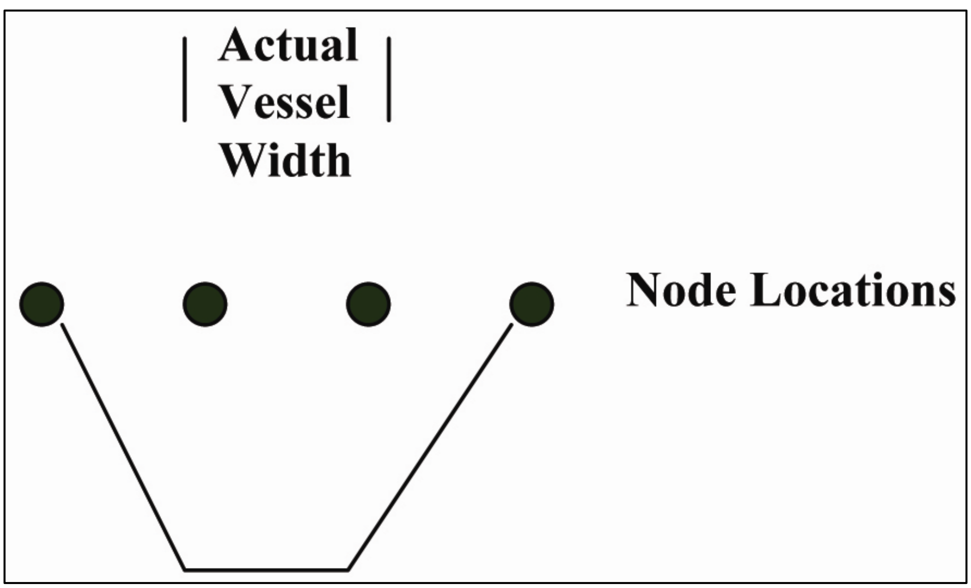

Figure 1. Nodal locations and vessel/pressure field and resulting model vessel

In prior work Stockstill and Berger (1999) found that matching the blockage area of the vessel was important in order to match the peak drawdown. In that work the grid was static and was set up so that the blockage area of the modeled vessel, even with sloping sides, precisely matched the actual vessel. This was done by making the element half-overlap the vessel's edge (see Figure 2). A static grid can be set up this precisely. However, this requires a great deal of effort from the modeler.

Furthermore, if the vessel size changes or the modeler wants to change the path of the vessel within the channel, then he must regenerate the mesh. Users need more flexibility than this, and they need to have quicker setup time. ADH can address this by using its capability to refine the mesh automatically. The idea is that a more general mesh can be developed that can be suitable for many vessels and paths. It will not be set up to precisely match a particular path or vessel. Instead it will rely on ADH adding enough resolution around the vessel to accurately capture the blockage area.

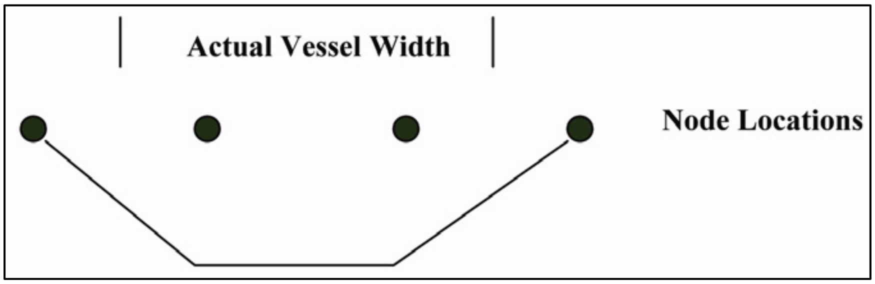

Figure 2. Node locations and vessel/pressure field that results in an accurate representation of blockage area

Since the true vessel sides are essentially vertical, then its representation is a discontinuity. Even a higher-order model cannot converge more rapidly than first order for a discontinuity. So as resolution is doubled around the vessel, the error would be cut in half. Therefore, the grid may need to be very fine in these places.

RESULTS: In order to estimate the appropriate value of SRT for adaption, a series of tests in a numerical flume of a cross-section shape (similar to ones that are often studied) were conducted. This consists of a deep-draft navigation channel through a relatively shallow bay. Two channel dimensions and three vessels were studied. Each of the vessels were tested with at least two speeds. The side slopes were 1 vertical on 7 horizontal up to a shoulder depth of 3.05 m (10.0 ft). The channel dimensions were similar to those found along the Houston Ship Channel in Galveston Bay, TX. The cross section of the test flume is shown in Figure 3 along with the actual values in Table 1.

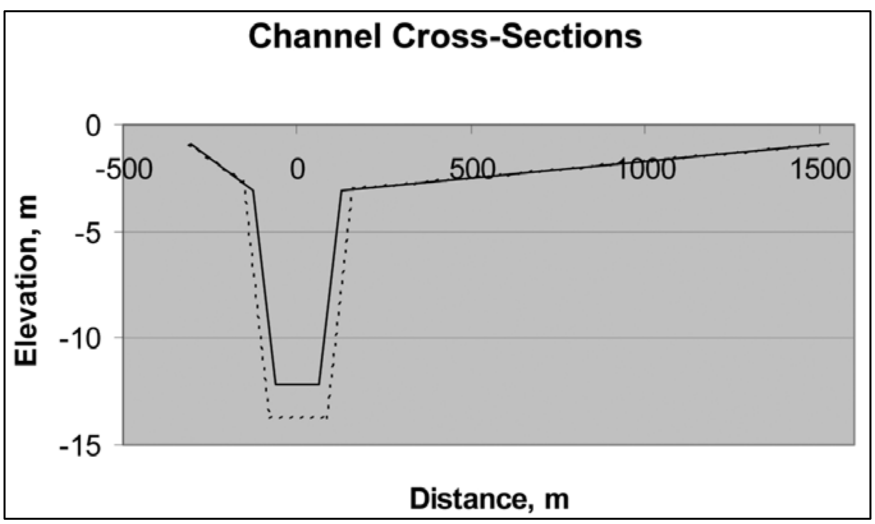

Figure 3. Cross section of test flume used for the small channel (solid line) and the large channel (dashed line)

Table 1
Description of Test Flume Cross Section

Base Channel		Large Channel	
Distance, m	Elevation, m	Distance, m	Elevation, m
-304.8	-0.9144	-304.8	-0.9144
-125	-3.048	-158.21	-2.653
-61	-12.192	-80.77	-13.72
61	-12.192	80.77	-13.72
125	-3.048	155.75	-2.996
1524	-0.9144	1524	-0.9144

A series of runs over a range SRT values from 2.83 m^3/s (100 ft^3/s) to 142 m^3/s (5,000 ft^3/s) for the three vessels were made. The SRT of 2.83 run was the most accurate and was assumed to be correct. The error using other SRT values was determined from these results. The drawdown associated with 2 and 4 percent of the 2.83 SRT run was calculated. The time-step was found by a convergence test. In these tests the time-step was reduced until no noticeable difference in the solution was found. This was usually about the time required for between 10 and 20 increments for a vessel passage of a fixed point. The time-step convergence test confirmed a time-step of 4 sec. For our tests, this ranged between 11 and 28 time-step increments for a vessel to pass a fixed point, depending on the vessel speed and length.

The numerical flume was 30,480 m (100,000 ft) long. The vessels were run along the center line of the channel. There were eight station locations in which the velocity and water-surface elevations were recorded. These were located at distances of 527.4 m (1721 ft) at a bed elevation of -2.438 m (-8 ft) and at 1,524 m (5,000 ft) at a bed elevation of –0.9144 m (-3 ft). Of all the stations, the one at the center of the length and 527.4 m from the channel center line generally recorded the largest changes in drawdown and velocity. This station was used in developing Table 2.

Table 2
Channel and Vessel Information Used in Tests

Channel		Vessel				Normalized SRT		Channel Cross-Section Average	
Depth, m	Width, m	Draft, m	Beam, m	Length, m	Speed, m/s	2%	4%	Drawdown, m	Current, m/s
12.2	122	9.30	32.3	232	4.48	0.010	0.031	0.454	0.905
12.2	122	9.30	32.3	232	3.96	0.033	0.107	0.317	0.722
12.2	122	9.30	32.3	232	3.41	0.114	*	0.216	0.573
12.2	122	9.30	32.3	232	2.65	0.176	*	0.119	0.408
12.2	122	9.30	42.7	232	3.99	0.008	0.015	0.494	1.07
12.2	122	9.30	42.7	232	3.05	0.017	*	0.241	0.695
12.2	122	10.5	54.9	274	3.20	0.002	0.010	0.503	1.28
12.2	122	10.5	54.9	274	2.47	0.013	0.093	0.259	0.872
13.7	162	9.30	32.3	232	5.27	0.007	0.012	0.436	0.759
13.7	162	9.30	42.7	232	4.02	0.009	0.075	0.293	0.658
13.7	162	10.5	54.9	274	4.02	0.007	0.011	0.503	1.08

* No values could be found within the bounds of the data set. Extrapolation would be needed to produce values. Rather than including extrapolation, the results were not included.

The normalized SRT values (shown in columns 7 and 8 in Table 2) give results that are within 2 and 4 percent of the results for drawdown for the finest grid (SRT=2.83). The product of the vessel draft, speed, and width normalizes these SRT values. This product will be termed the displacement rate. This is the rate at which water must be displaced for the vessel of this size to move at the given speed.

The final two columns are channel cross-section average drawdown and velocity estimated by using the one-dimensional (1-D) energy and continuity equations (Jansen and Schijf 1953). These columns are found using only the channel base and side slope sections and not the overbank. These are easy to produce and at least weakly correlate with the needed SRT value. The equations are as follows:

$$\begin{aligned} z &= \frac{\left(V_s + V_r\right)^2 - V_s^2}{2g} \\ V_s A_c &= \left(V_r + V_s\right) A_w \end{aligned} \qquad (1)$$

Where z is the drawdown, V_s is the speed of the vessel relative to a fixed reference frame, V_r is the return current, g is the acceleration due to gravity, A_c is the cross-sectional area before drawdown and A_w is the channel cross-sectional area at midlength of the vessel. Note that in this equation set V_s and A_c are known. Both z and V_r need to be calculated. A_w depends upon z. So these equations will need to be solved iteratively.

This information is used to estimate the value of SRT needed for accurate results. Figure 4 shows the inverse of the normalized SRT versus drawdown/depth and the actual data for the 2 and 4 percent results. Remember that the displacement rate is the product of the vessel draft, speed, and width. That is, these are the values of SRT that yields water-surface drawdown within 2 and 4 percent of the most accurate run, respectively. There is also provided a linear fit for each line. The correlation is weak, with R^2 values of only slightly larger than one-half. However, these estimates are just to be used as a starting point. Good model practice requires that some test of convergence be done too.

As a check on this recommendation, a test was conducted to demonstrate the degree to which the modeled vessel matches the actual vessel. The test consisted of running a vessel with dimensions: 9.30-m draft; 32.3-m beam; 232-m length. The vessel speed was 5.27 m/s. This yielded a displacement rate of about 1,580 m^3/s (9.30 draft x 32.3 beam x 5.27 speed). The channel dimensions were 13.7-m depth with a 162-m base width. The estimated drawdown, from equations set (1), was 0.436 m. The drawdown/channel depth ratio was 0.032. The two equations in Figure 4 yield displacement rate/SRT ratios of 160 for 2 percent precision and 80 for 4 percent precision. Choosing a value between these of 100 will yield an SRT of about 16, (1,580/SRT = 100). A test with this value results in a grid, near the midway point of the flume, as shown in Figure 5.

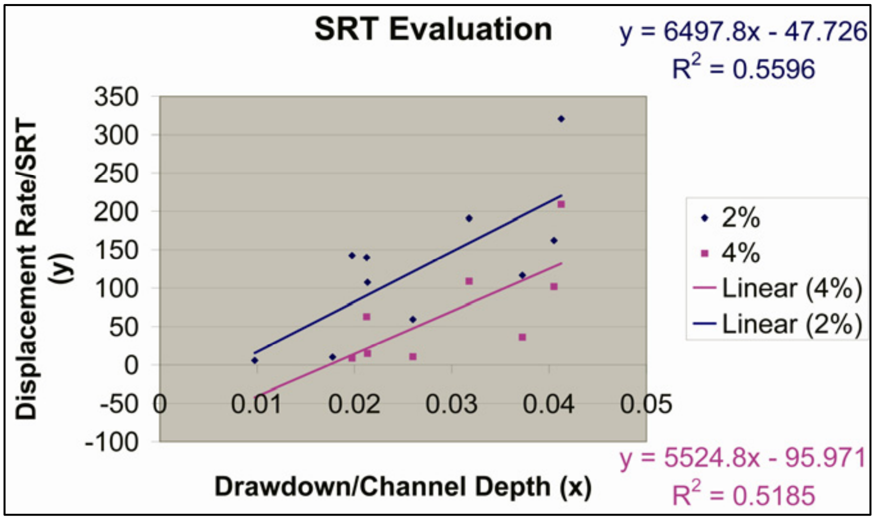

Figure 4. SRT-Drawdown distribution

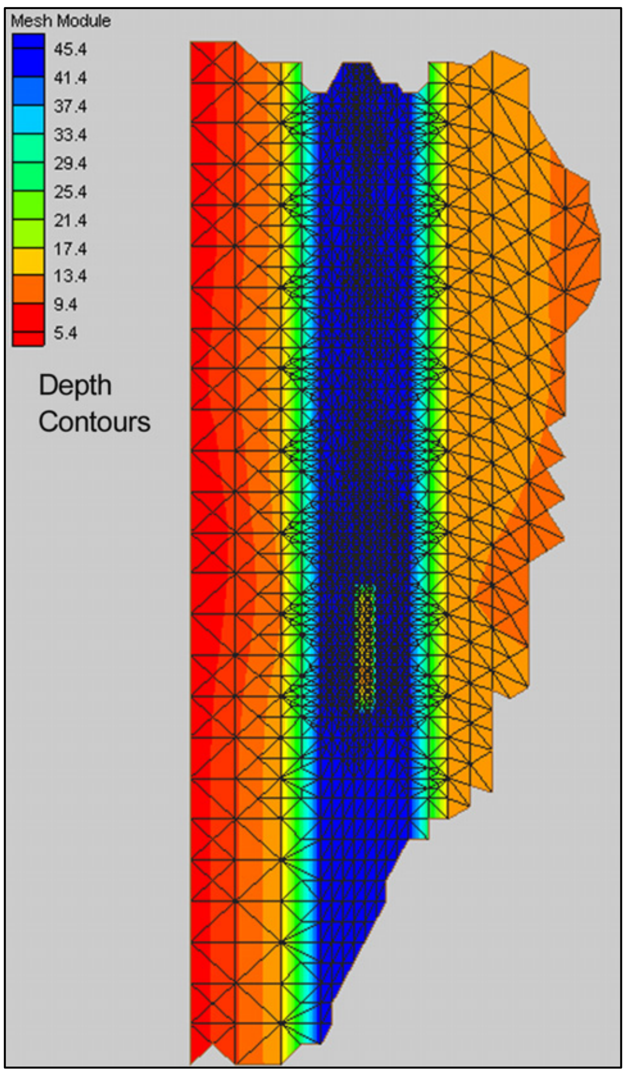

Figure 5. Adapted mesh and water depth contours

In this figure the dark blue area is the channel (deepest water). On either side the orange represents the shallows. The orange and green rectangle within the channel is the position of the vessel. Typically ADH does not output the adapted grid and solution. Instead it outputs the results to the original mesh. This is done just to demonstrate what is actually being solved. The vessel is moving in the downward direction relative to the figure. The area somewhat in front of the vessel has no refined mesh. Behind and around the vessel the mesh has been refined. The mesh is approximately four times as dense near the vessel compared to the original mesh. Figure 6 shows two cross sections near midlength of the vessel at this time and also the true vessel section.

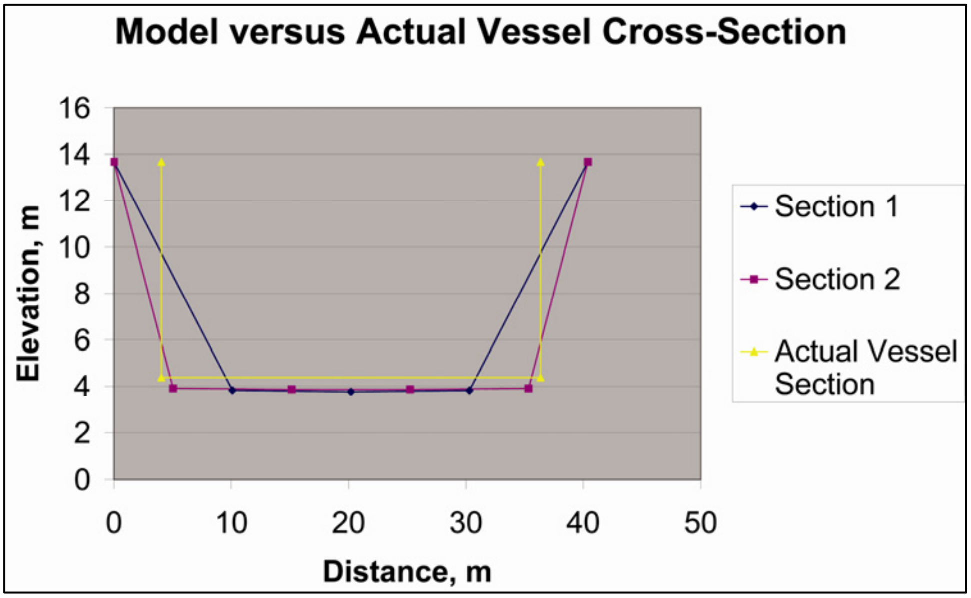

Figure 6. Two modeled cross sections near midlength of vessel and actual vessel cross section

The represented vessel is not completely uniform. The two sections represent the variability; section 1 is the narrower and section 2 the wider. The true blockage area is 300 m^2. The blockage areas for sections 1 and 2 are 299 and 346 m^2, respectively. The recommended SRT then gives a reasonable representation of the vessel blockage.

SUMMARY: This CHETN provides guidance for the parameters needed to make an accurate estimate of vessel effects using the ADH model. The key is providing sufficient resolution. This is controlled by the SRT parameter. The error is measured for each element at every time-step. If the error for that element is greater than the SRT parameter, the element is refined. More resolution results in a discrete model that is closer to the physics described by the differential equations. More resolution is also more expensive computationally. Therefore, this SRT parameter must be chosen wisely. Through a series of tests on a realistic flume with several vessel sizes and speeds, the SRT parameter is shown to be related to estimated drawdown, channel depth, and displacement rate. Figure 4 contains the relationships to determine the SRT value. The modeler should continue using good model practice by making a check run using a smaller SRT as well. However, this estimate will provide a good initial value. The modeler will still need to choose the time-step size to create accurate results by doing a convergence test. This will mean making runs of the same event with successively smaller time-steps until a suitable size is found. This will generally be about one-twentieth of the time required for a vessel to pass a stationary location.

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