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of Engineers**
Waterways Experiment
Station

Navigation Hydraulic Research Program

Numerical Solution for the Determination of Towboat Return Currents

by *Sandra K. Martin*

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**Navigation Hydraulic
Research Program**

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Numerical Solution for the Determination of Towboat Return Currents

by Sandra K. Martin

U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

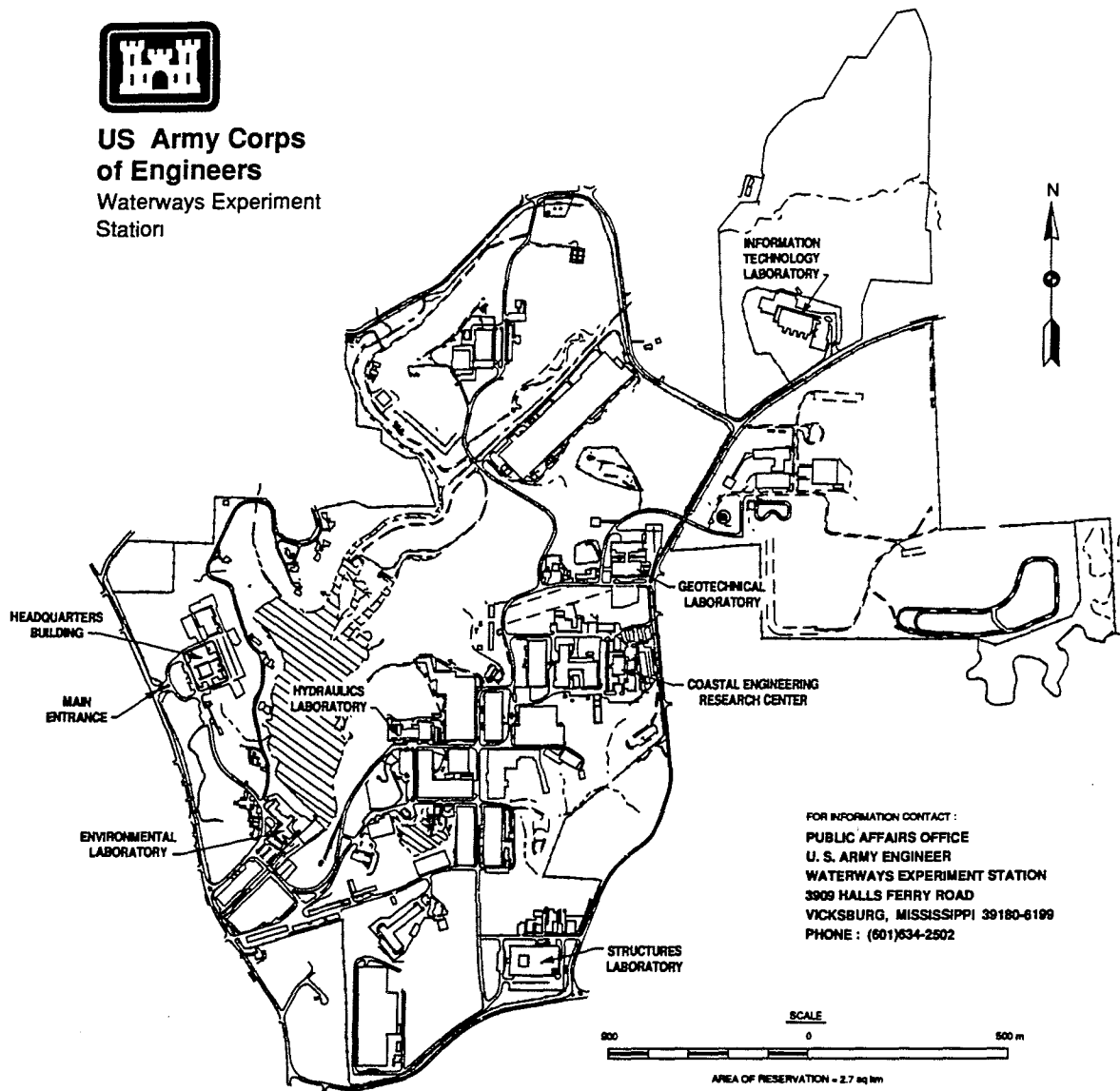
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Preface

The numerical investigation conducted for this study was funded by the Computational Hydraulics Institute (CHI), Hydraulics Laboratory (HL), U.S. Army Waterways Experiment Station (WES). Data were collected prior to this study from a model investigation performed for the U.S. Army Engineer District, Louisville, and from the model tests conducted for the Navigation Hydraulics Research Program under Work Unit 32601, "Vessel Generated Forces and Protection in Navigation Channels," funded by Headquarters, U.S. Army Corps of Engineers, during Fiscal year 1992. Results from this study support the objectives of the research work unit regarding the investigation of tow-induced currents.

This study, and tests supporting this study, were conducted by HL personnel under the direction of Messrs. F. A. Herrmann, Jr., Director, HL; R. A. Sager, Assistant Director, HL; G. A. Pickering, Chief, Hydraulic Structures Division (HSD), HL; and Dr. J. P. Holland, Director, CHI. The tests were conducted by Ms. Sandra K. Martin, project engineer, Locks and Conduits Branch, HSD; Dr. Stephen T. Maynard, project engineer, Spillways and Channels Branch, HSD; Mr. Doug White, Spillways and Channels Branch, HSD; and Mes. Sheila Knight and Olie Blansett, WES contract students, Locks and Conduits Branch, under the supervision of Mr. Noel R. Oswalt, Chief, Spillways and Channels Branch, and Mr. John F. George, Chief, Locks and Conduits Branch. The numerical investigation was conducted and the report written by Ms. Martin.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
feet	0.3048	meters
square feet	0.09290304	square meters

1 Introduction

Problem

Vessels navigating through inland waterways generate complex physical forces in the form of waves and currents. The forces are important for both engineering as well as biological components of the riverine environment. From the engineering design perspective, the magnitude and characteristics of boat-generated waves and currents are important parameters in the design of stable beds and banks. From a biological standpoint, the organisms that live on the bed and banks and in the side channels and backwater areas of the river may experience adverse effects from velocities that increase above the ambient current, turbulence of the propeller jets, impact with the propellers, water surface fluctuations along the bank line, pressure fluctuations and shear stress, and/or the general disturbance to their habitat as a result of changing flow conditions. The need therefore arises to accurately assess these physical forces and to couple their effects with biological responses.

Navigation Effects

Most methods for quantification of physical forces have been based on simplistic theory coupled with empirical data obtained in controlled physical model studies and from composite field data. The physical forces are a complex composite of three-dimensional waves and currents. Methods for characterizing and obtaining quantitative wave force information are beyond the scope of this report. The following definitions are related to the currents produced by navigation effects:

- a. *Ambient current.* The river current undisturbed by the presence of a tow.
- b. *Blockage ratio.* The ratio of the channel cross-sectional area to the submerged tow cross-sectional area.
- c. *Bottom displacement current.* The current beneath the tow acting in the opposite direction to the movement of the tow.

- d. *Bow current.* The current moving ahead of the tow in the general direction of the tow.
- e. *Drawdown.* Also called the water level depression. As the tow moves forward and water is displaced from bow to stern, a drop in the water level alongside the barges accompanies the return currents. Drawdown is a function of ship speed, ship size, and channel geometry.
- f. *Propeller jet.* The highly three-dimensional currents associated with propeller jets, which cause localized disturbances to the flow field.
- g. *Return current.* A towboat induces a current in which the flow moves from bow to stern as the tow is moving forward. This current acts in the direction opposite of tow movement and generally parallel to the bank. The magnitude of this current is a function of the tow's speed, the shape and size of the hull, and the channel geometry.
- h. *Wake flow.* The current produced as water fills in behind the stern to replace the water displaced as the tow moves forward.

Purpose and Scope

Unlike previous one-dimensional analytical solutions which only provide a value for the return current, a numerical solution can provide velocities for the entire flow field. This report focuses on the existing methods of quantifying return currents, and offers a numerical solution using the STREMR two-dimensional hydrodynamic code developed by Bernard (1993). The work was performed for the Computational Hydraulic Institute (CHI), Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station (WES) in an effort to broaden existing applications of the code.

2 Theory

Bernoulli's Equation and Irrotational Flow

Continuity in two dimensions is defined by the following:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)$$

where

u = velocity in x-direction

v = velocity in y-direction

In two dimensions, irrotationality is defined mathematically as

$$\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} = 0 \quad (2)$$

A velocity potential function ϕ is defined such that $u = \partial\phi/\partial x$ and $v = \partial\phi/\partial y$. Substitution of these relationships for u and v into the continuity equation results in the Laplace equation for irrotational flow:

$$\nabla^2\phi = 0 \quad (3)$$

A stream function ψ is defined by $u = \partial\psi/\partial y$ and $v = \partial\psi/\partial x$. Substitution of these relationships for u and v into the equation for irrotational flow results in

$$\nabla^2\psi = 0 \quad (4)$$

Irrotational flow components are found by the solution of either Equation 3 or 4.

For irrotational steady flow without friction along a streamline, the well-known Bernoulli equation can be applied:

$$\frac{V^2}{2g} + h + z = \text{constant} \quad (5)$$

where

V = velocity
g = gravitational constant
h = depth
z = datum

Flow can be assumed to be irrotational if the shape, not the friction, of the boundary drives the velocity distribution; the streamlines are converging, not diverging; and the boundary layer is thin (Le MeHauté 1976). In the case of a moving tow passing a particular location, the shape is the driving condition although friction does have some influence. The free-stream conditions sufficiently distant from the vessel can, therefore, be approximated by potential flow theory. As the boundary layer develops during the passage of the tow, this assumption may not be valid. The longer the tow, the more dependent the velocity is on Reynolds or viscous forces, particularly in the wake region following the stern. Viscous forces can dominate the conditions near the vessel.

Analytical Solutions

Schijf's equation

Using the Bernoulli equation for energy and the continuity equation, equations for return current and drawdown can be derived. This is the approach that was taken by Jansen and Schijf (1953). Other researchers have taken similar approaches using the momentum equation rather than energy. Equating the energy along a streamline using a point midlength of the tow and one in the undisturbed channel results in

$$z = \frac{(V_s + V_r)^2 - V_s^2}{2g} \quad (6)$$

where

z = drawdown
 V_s = speed of tow relative to earth
 V_r = return current
 g = gravitational constant

Based on continuity, the equation follows:

$$V_s A_c = (V_r + V_s) A_w \quad (7)$$

where

A_c = channel cross-sectional area before drawdown
 A_w = channel cross-sectional area at midlength of the barges

Development of these equations is based on the following assumptions:

- a. Uniform cross section.
- b. Uniform return current.
- c. Uniform water level drawdown.
- d. No friction.
- e. Negligible ambient current.
- f. Center-line placement of the vessel.

Maynard's methods

In confined channels where blockage ratios are small, a uniform distribution of return currents is a reasonable assumption. Even when the tow is sailing off the center line of the channel, the lateral distributions are uniform even if the relative magnitudes for each side of the channel are different. In larger rivers the strength of the return current decays with distance from the tow. Maynard (1990) presents methods for estimating return velocities in large rivers. These methods account (a) for off-center sailing by applying coefficients of skewness for the port and starboard sides of the tow, and (b) for decay with distance from the tow based on a coefficient α , which is the ratio of maximum return velocity V_{rm} to the average return velocity V_r . For an α of 1, return currents are uniformly distributed on either side of the tow; linearly distributed for α between 1 and 1.35; and exponentially distributed for α greater than 1.35. For the conditions tested in this report, α was either 1 or

less than 1.35. The equation for the linear distribution of the return current across the channel section is as follows:

$$\frac{V_r(y)}{V_{rm}} = \left(\frac{2}{\alpha} - 2\right) \left(\frac{y - B_t}{B_s - B_t}\right) + 1 \quad (8)$$

where

- y = lateral distance from the tow center line
- B_t = width of barge train
- B_s = distance from tow center line to the bank on one side

3 Numerical Model Study

Numerical Solution of Potential Flow

STREMR is a finite-volume numerical model that discretizes the solution of the Navier-Stokes equation for two-dimensional (2-D) incompressible flow. The numerical flow solutions are applicable in 2-D depth-averaged solutions where Froude numbers are less than approximately 0.7. The model was originally developed by Bernard (1989) for the evaluation of approach flows at hydraulic structures. Numerous applications have been modeled with STREMR since its origin, and many modifications to the code have been made to accommodate its users. The use of the code for this study explores yet another new application: the flow field around a moving tow. The model initiates its flow conditions by solving for potential flow. It then steps through time and computes the developing flow field.

Since previous methods for the computation of return currents relied on an irrotational flow solution of the energy equation, it seemed logical that a discretized variation to the approach would offer a more comprehensive answer. As a sensitivity test, the model rotational solution was also determined. However, the analysis of the flow field was primarily evaluated using the potential flow solution (cold start, 0 time-steps).

Geometry and Grid Development

Sensitivity tests were conducted using STREMR to determine the potential of modeling the flow field around a tow. A grid was developed that was 63 cells long by 36 cells wide. Each cell represented 100 ft¹ by 25 ft in prototype. The grid represented a rectangular channel 900 ft wide and 21 ft deep. The tow was modeled by taking a four-wide by seven-long matrix of cells out of the flow field (STREMR OUT cells) near the center of the longitudinal length of the grid. The "tow" position along the width of the channel was varied, as were the flow conditions. Streamlines resulting from

¹ A table of factors for converting non-SI units of measurement to SI units is found on page vii.

the simulations were compared to time-lapse confetti photos from a 1:35 scale test.

Physical model testing was conducted at a scale of 1:37.5 in January 1992 to evaluate the navigation effects of an island in the flow field. A new grid was developed that was 51 cells long by 31 cells wide with variable length and width cells (more resolution near the tow) to simulate the navigation effects from these tests. The grid represented, at prototype dimensions, a rectangular channel 4,500 ft long by 965 ft wide. The tow, modeled as OUT cells, was 950 ft long by 105 ft wide. The tow was centrally placed longitudinally in the grid at a tow center line offset from the starboard bank of 602.5 ft. The tow "moved" from left to right across the grid. Most tests were conducted with no island in the flow field. When an island was analyzed, its location was approximately 250 ft from the bank on the starboard side of the tow. The island was created by changing a line of cells into OUT cells. Figure 1 shows the grid used without an island.

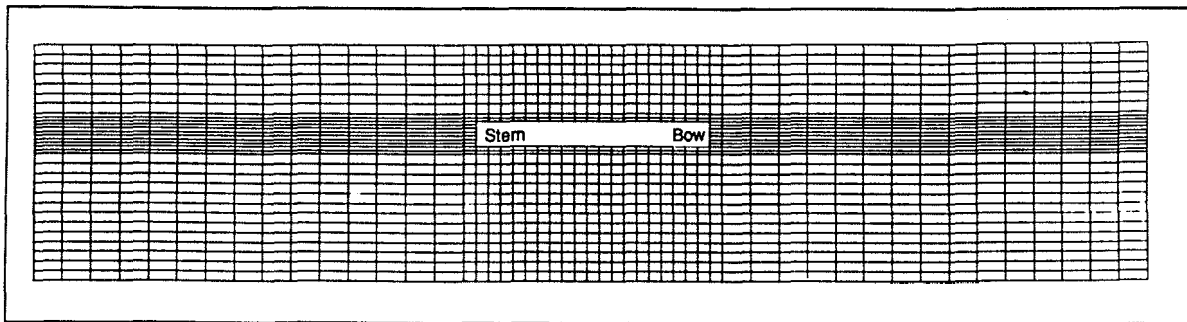


Figure 1. Numerical grid representing channel and towboat used in island tests (no-island condition)

Boundaries

From the sensitivity study conducted with the first grid, it was determined that velocities (related to the boat speed) should be specified at flux boundaries located on the ends of the tow. For both grids and all simulations, flow left the grid through the stern (sink) and enters the grid through the bow (source). The model was set up to have flux boundaries at the left end of the grid or channel, at the bow, and at the stern of the boat. Open cells were placed at the right end of the grid or channel, and slip cells were placed along channel banks and the tow's side.

It was apparent that the strength of the source/sink on the flux boundaries was directly related to the speed of the tow. In fact, if the code was three-dimensional, the boundary fluxes should have been specified as the boat speed (ignoring propeller jets). However, since STREMR is a depth-averaged code, the OUT cells, which represent the tow, displace more cross-sectional flow area than in the prototype. That is, the tow consumes the full depth of the

water (15 ft) column over its width. Since there is less conveyance area, using the actual boat speed would produce return currents that are too high. Therefore, the input velocity needs to be adjusted to accommodate this effect. Two basic philosophies were applied that essentially created a lower and upper bound to the strength of the sink/source. Discussion of the results follows in the next section. Both concepts assumed that the reduction in cross-sectional area can be accounted for by proportionally lowering the boat speed. The first, or lower limit, assumed that since the boundary velocity is applied only over the width of the tow, the reduction in speed is proportional to the draft of the boat over the depth of the water (9 ft/15 ft or 0.60). That is, STREMR inaccurately removes 40 percent of the flow depth. Then, the lower limit was obtained by multiplying the boat speed by 0.6. The upper limit compared the differences in the cross-sectional areas over the whole width of the channel. That is, the ratio of the conveyance area in STREMR over the actual conveyance area is the multiplier for the boat speed (12,900 sq ft/13,530 sq ft or 0.953). There are several other potential methods of accounting for the loss of conveyance that will be tested in future analyses.

Effects of Other Inputs

A number of sensitivity tests were conducted to determine the effects of other parameters in STREMR. Manning's n values were added, time series analysis was performed, the boundary types were changed, and some of the other variables in STREMR were varied to determine their effects on the solution. It was concluded that, until more accurate verification data are available, the best solution is obtained using the designation for these boundaries with no frictional resistance and 0 time-steps.

Limitations/Assumptions

The numerical solution does have some limitations and inherent assumptions. These include the following:

- a.* May be valid only away from the boat. How near to the boat the information is valid is a function of the grid resolution, viscous effects, and the two-dimensionality of the flow.
- b.* Only 2-D approximation in near field flows. Currents near the boat are three-dimensional especially near the propellers.
- c.* Potential flow does not develop the velocity profile at all. There are some viscous effects, especially near field, which are not accounted for using this method.
- d.* Since the flow is not progressed with time, it does not show separation around the bow.

- e.* Because the tow fills the entire water depth, flow exchange through this area is ignored.
- f.* The STREMR solution is a more complicated method though it is becoming increasingly more adaptable to the personal computer environment.

4 Results

STREMR results were compared with four different sources of information. First, the STREMR plots were qualitatively compared with confetti photographs taken on a 1:35-scale physical model study completed in 1991. Secondly, quantitative comparisons were made between cross-sectional data from STREMR and data obtained using a Video Tracking System (VTS) on a physical model study conducted for the U.S. Army Engineer District, Louisville, in 1991-1992. This same study was also used to compare qualitatively the influence of an island in the flow field. The third comparison evaluated STREMR-generated currents with return currents calculated by existing theoretical and empirical methods for a cross section at midship using the method Jansen and Schijf (1953) developed and then the method by Maynard (1990) that modifies the distribution of the return current over the cross-sectional width. Finally, trends in the longitudinal and transverse components of the currents were compared to Laser Doppler Velocimetry (LDV) data obtained in the physical model in 1992.

Confetti

Comparisons of numerical model results and time-lapse confetti photos of a moving physical model tow showed that by using STREMR, currents produced by moving tows can be represented numerically. The concept of using a source/sink approach to the input can be intuitively understood by comparing the streamline plots and velocity vector plots determined with STREMR to the photos (not included). The "source" displaces or pushes the water ahead of the bow, while the "sink" attempts to fill in the water at the stern that was displaced by the tow. Just as the confetti leaves circular streaks from bow to stern, the streamlines represent the same phenomenon. The relative positions of isolated confetti streaks at different locations around the tow compare reasonably to the distribution of velocity vectors produced by STREMR. That is, as one might expect, the speed of the streaks (or vectors) approaches the speed of the tow near the bow and stern and dissipates rapidly with distance from the source (the boat). This comparison gives a qualitative appreciation for the ability to model the flow field in this manner. Results from simulations using the more recent grid (island tests) and showing a zoomed-in section of this grid near the tow are found in Figures 2-5. The first tests

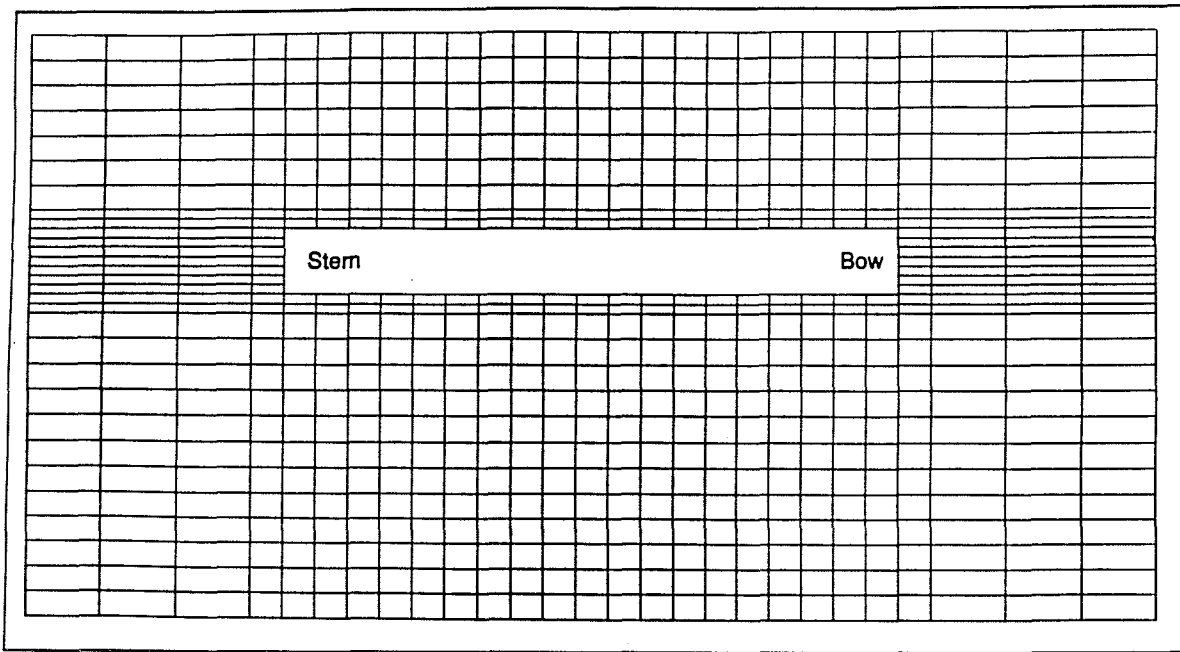


Figure 2. Zoomed-in section of the grid (no-island condition)

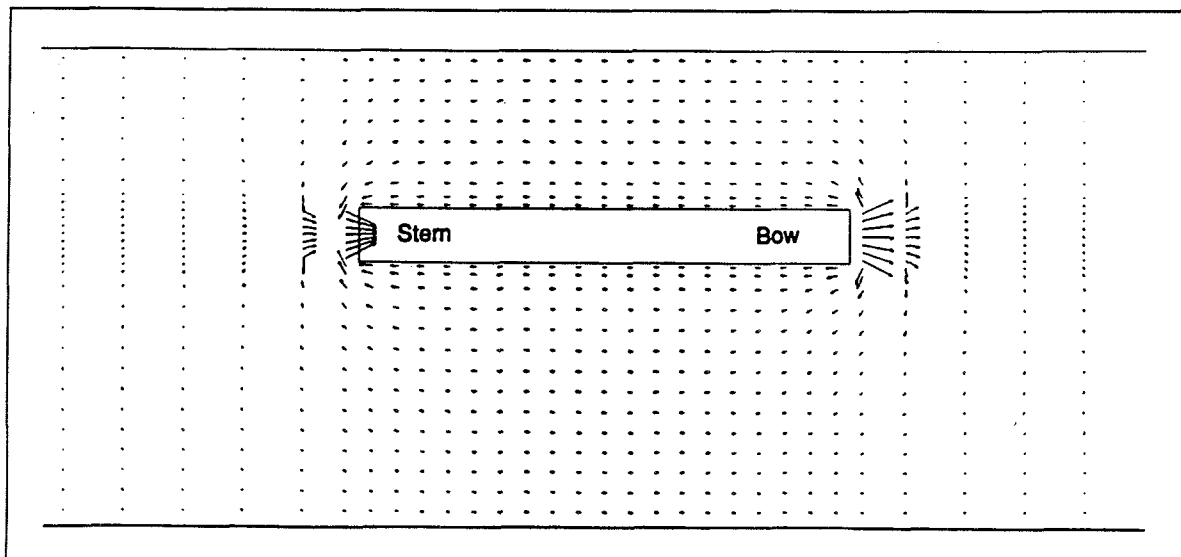


Figure 3. Velocity vectors produced by STREMR, potential flow

modeled a no-island scenario to establish base conditions. The strength of the source/sink used in these figures was 11.5 fps.

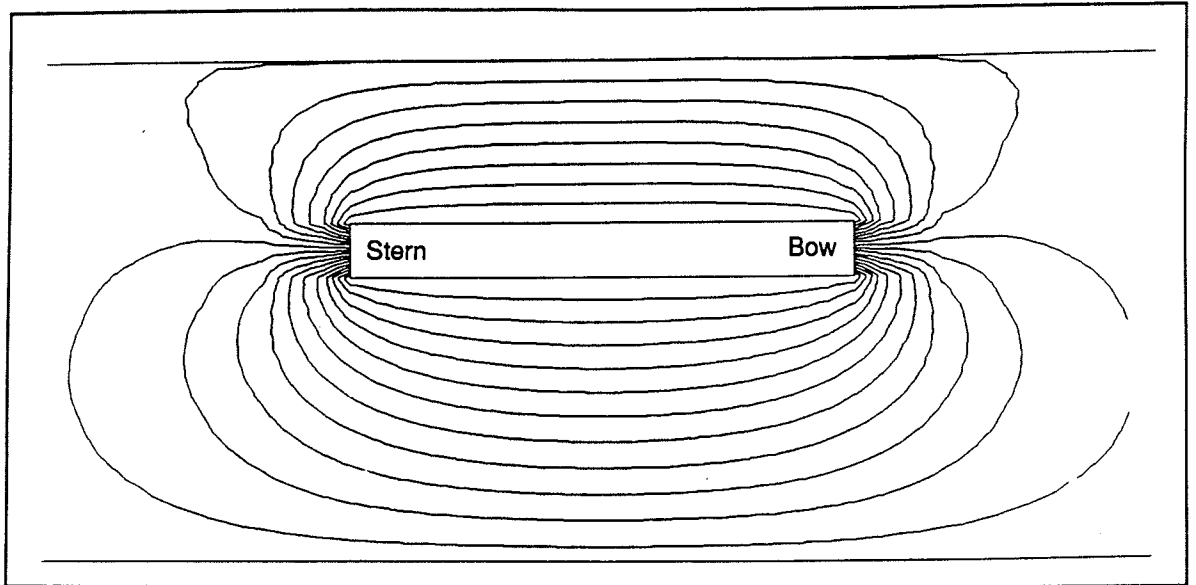


Figure 4. Streamlines produced by STREMR, potential flow

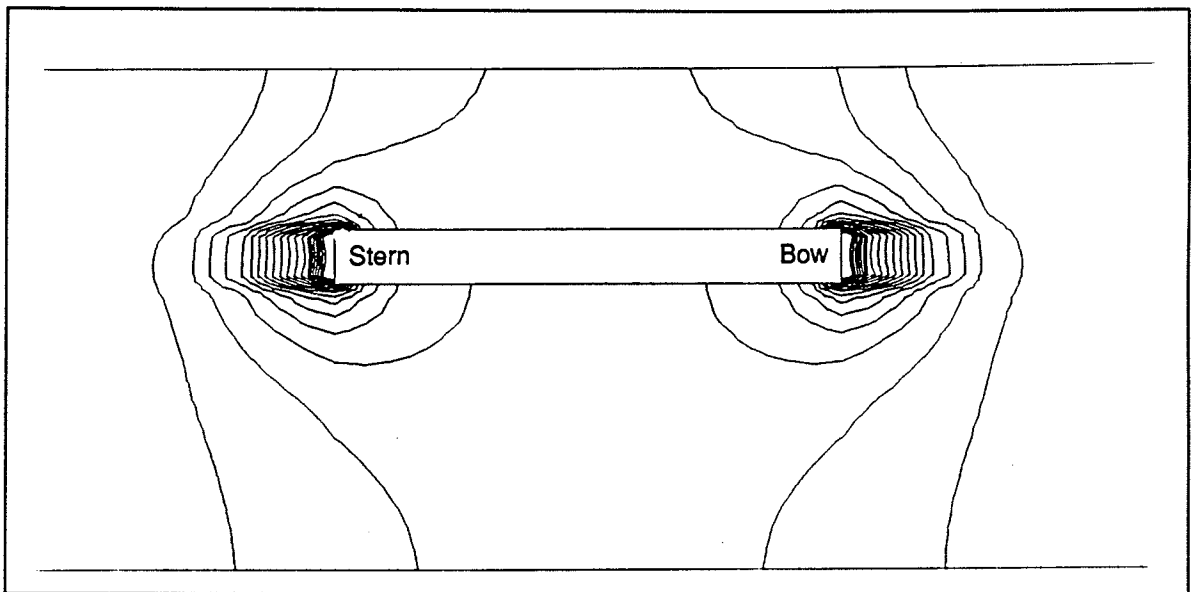


Figure 5. Velocity contours produced by STREMR, potential flow

VTS

Having determined that the potential flow solution and the application of flux boundaries at the bow and stern are qualitatively reasonable in the assessment of the flow field, it was then necessary to determine the strength of the source/sink required to accurately model the magnitude of the return current.

For lack of better data (prior to acquisition of the LDV), existing physical model data were used in verification of these results. These data were obtained from a VTS, which uses a video camera to keep a frame-by-frame account of the path of floating light bobbers during the passage of the tow. The system then calculates a vector based on the bobbers' path and speed and downloads the information to an AutoCAD plot. The accuracy of this method is limited by the number of frames it can "grab" per second, the scale effects regarding momentum due to the size of the floating bobbers, and some inherent rounding errors due to the selection of scales and the system clock. Additionally, in order for the vectors from the VTS to be compared to STREMR results, the assumption must be made that the surface currents are representative of the depth-averaged return currents (may or may not be true). Based on these drawbacks, absolute magnitudes of the vectors could not be compared. However, the physical model test results are graphically represented on the cross-section plots of each of six test conditions comparing STREMR data with two theoretical methods (Figures 6-11). It can be seen on the plots that STREMR results based on an upper and lower strength of source/sink bound the data on most tests. This analysis concluded that the assumptions regarding the strength of source/sink were on the right track, but due to the variability in the VTS data, the absolute magnitudes could not be confirmed.

The physical model tests for the island study were intended to examine trends in peak currents and to be used for the relative comparison of currents in the main channel to those in an area behind an island as the length of this island channel increased from zero to an infinite length. To this end, it was successful. The physical model tests concluded, for the channel width and tow length tested, that an island of roughly 300 ft or less had an insignificant effect on the magnitude and distribution of the return currents across the entire width of channel (riverbank to riverbank). An island length of roughly 2,100 ft or greater rendered the backwater area ineffective and the flow conditions equivalent to those of a channel with a width equal to that between the island and far riverbank. Similar comparisons were made in STREMR. Figures 12-21 show the changes in the flow field as an island was added and then lengthened. Figures 14 and 15 contain a 300-ft island, and it can be seen that the streamlines and velocity contours are essentially no different from the conditions in the channel with no island (Figures 12 and 13). At an island length of 1,510 ft, the velocity contours began to exhibit symmetric shapes on either side of the tow (Figure 19), and at an island length of 3,005 ft (Figures 20 and 21), the back channel area contained no significant currents. These comparisons further increased the confidence in the STREMR results.

Analytical Methods

Again, these tests did not get the modeler any closer to a decision regarding the appropriate strength of the source and sink to use as the boundary conditions in STREMR. The STREMR results were compared to those calculated using the uniform distribution method of Schijf and the distributed

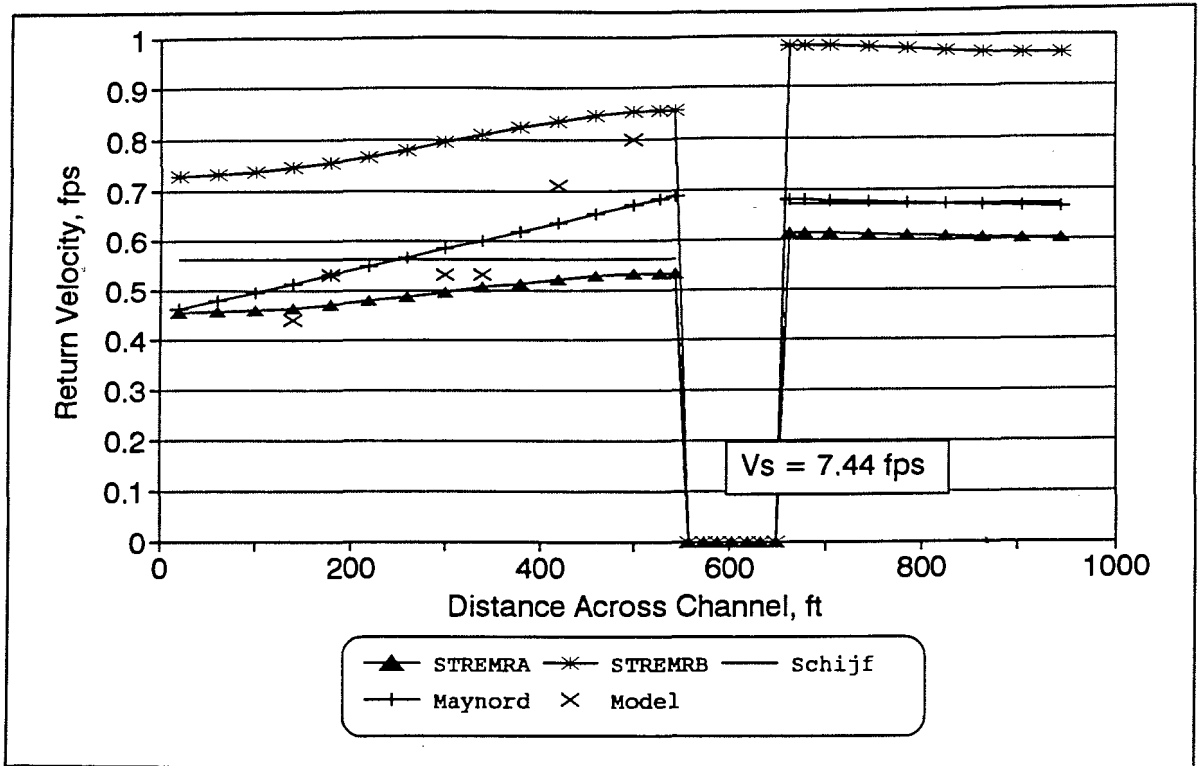


Figure 6. Comparison of methods, $V_s = 7.44$ fps

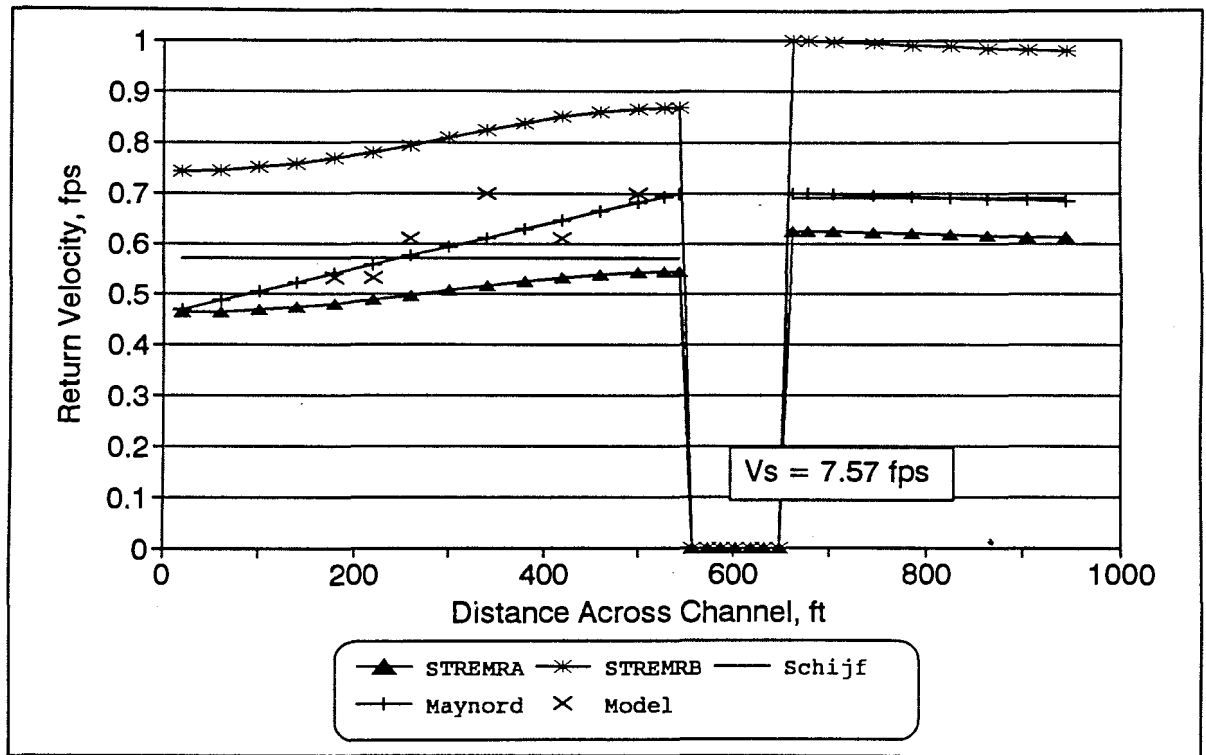


Figure 7. Comparison of methods, $V_s = 7.57$ fps

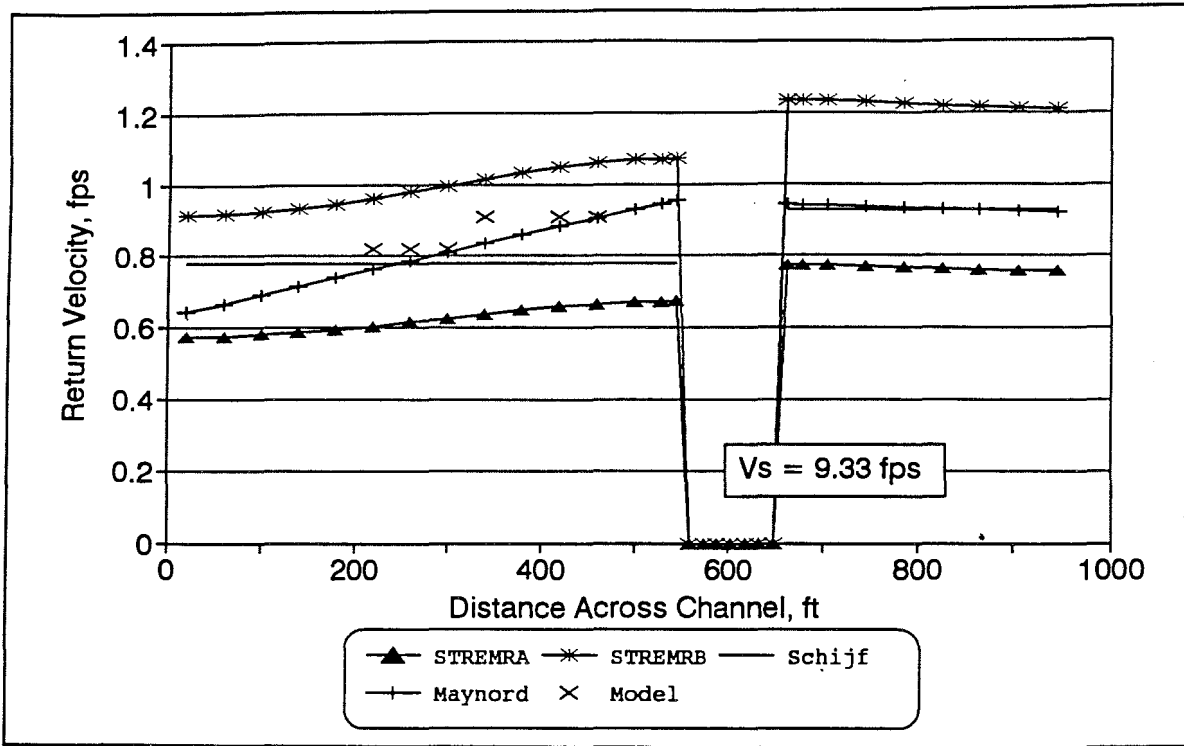


Figure 8. Comparison of methods, $V_s = 9.33$ fps

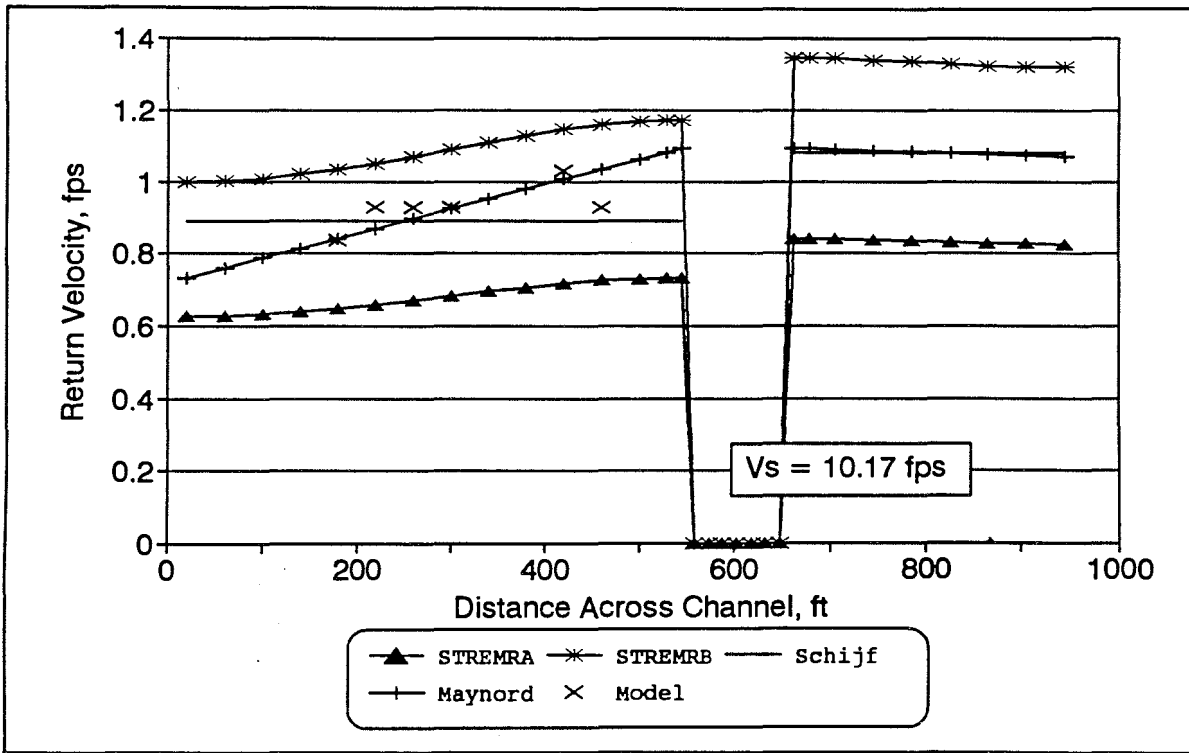


Figure 9. Comparison of methods, $V_s = 10.17$ fps

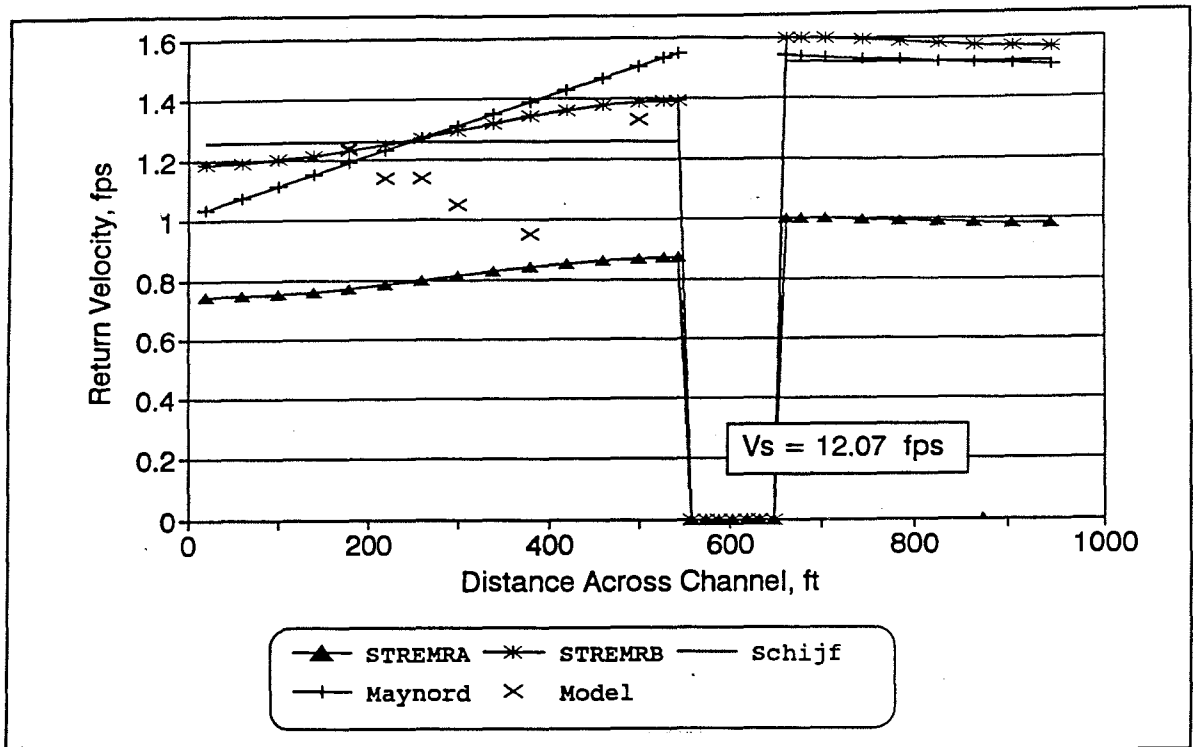


Figure 10. Comparison of methods, $V_s = 12.07$ fps

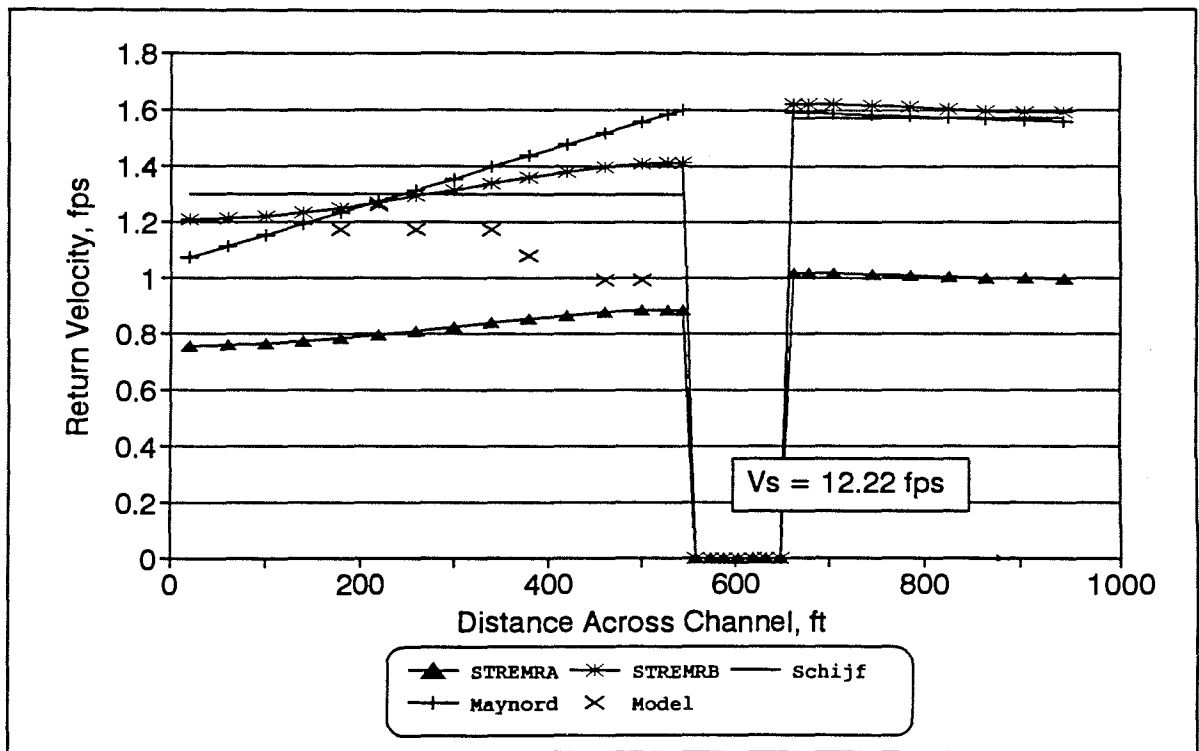


Figure 11. Comparison of methods, $V_s = 12.22$ fps

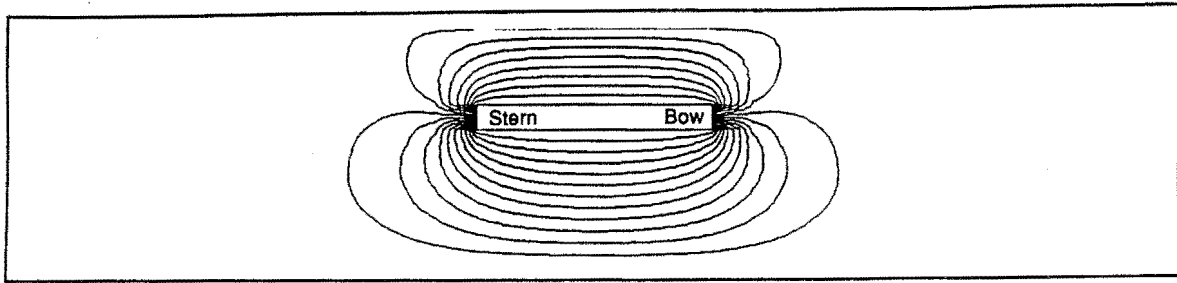


Figure 12. Streamlines, no-island condition

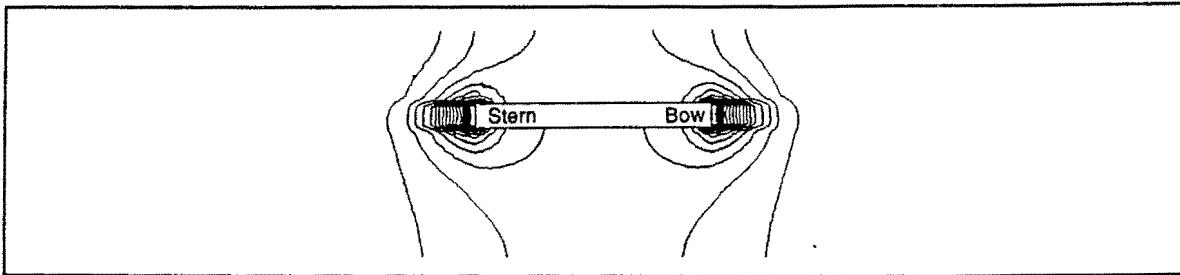


Figure 13. Velocity contours, no-island condition

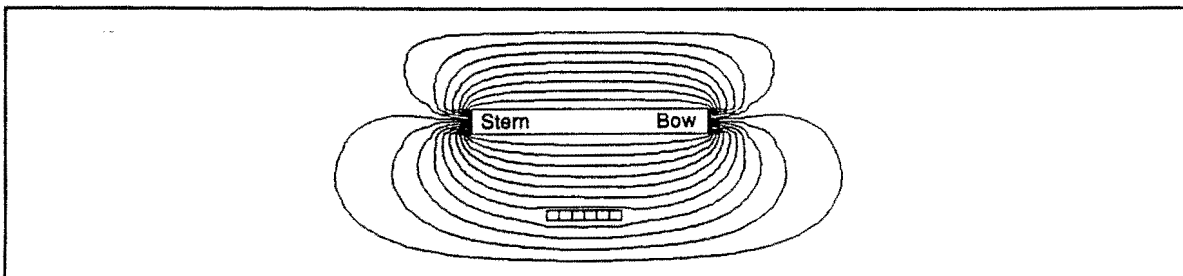


Figure 14. Streamlines, island length = 300 ft

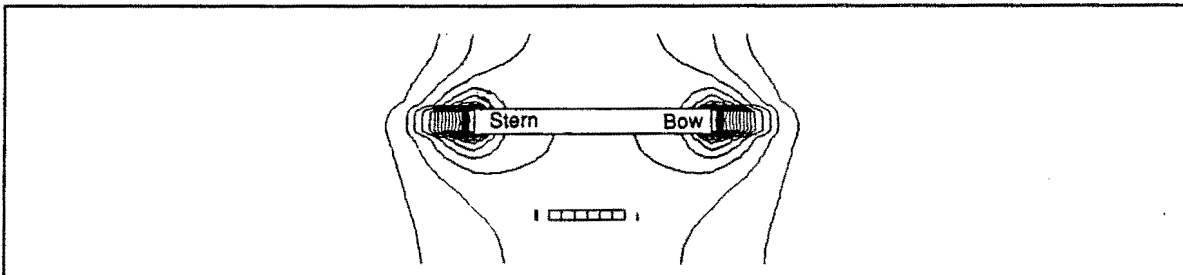


Figure 15. Velocity contours, island length = 300 ft

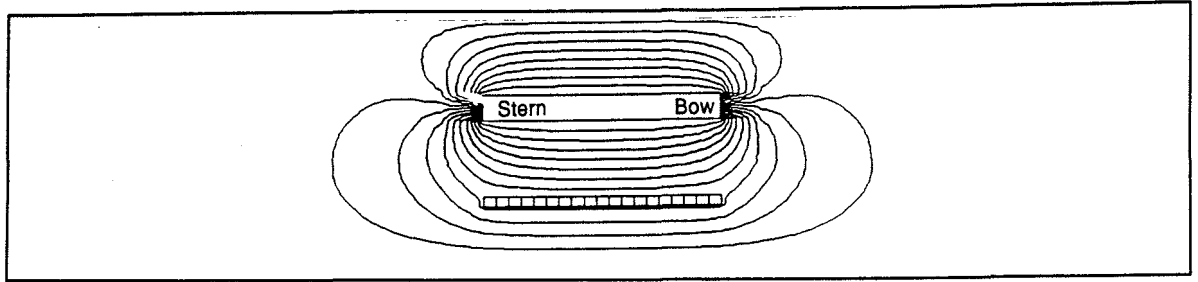


Figure 16. Streamlines, island length = 950 ft

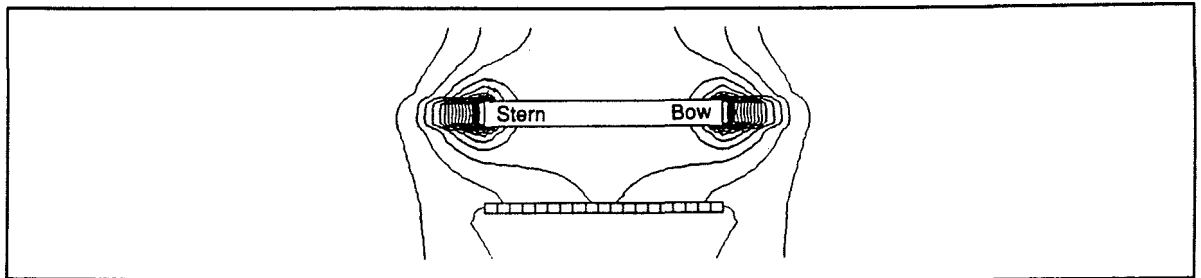


Figure 17. Velocity contours, island length = 950 ft

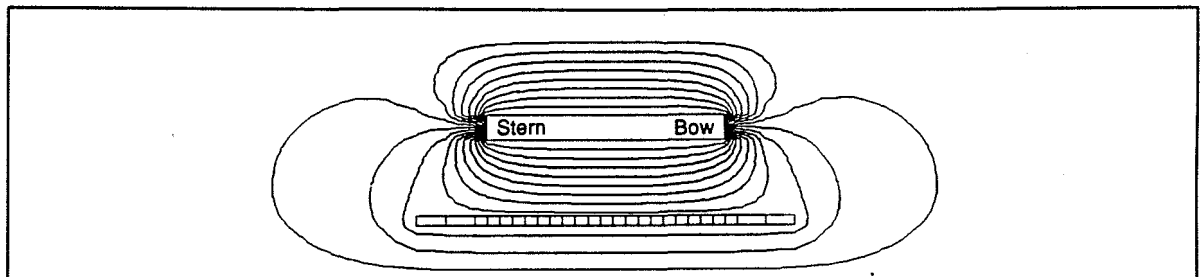


Figure 18. Streamlines, island length = 1,510 ft

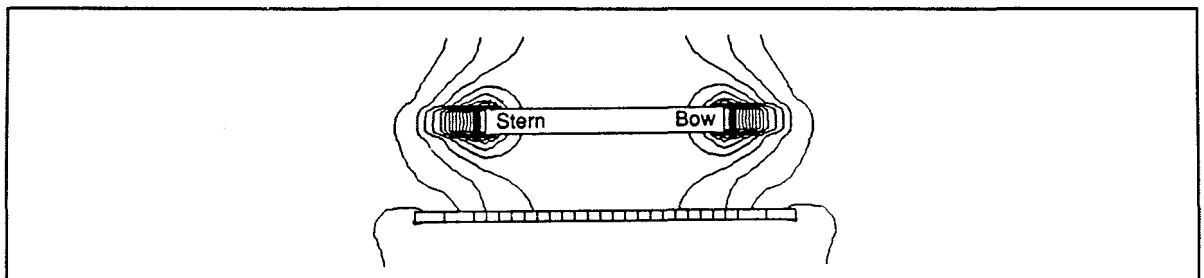


Figure 19. Velocity contours, island length = 1,510 ft

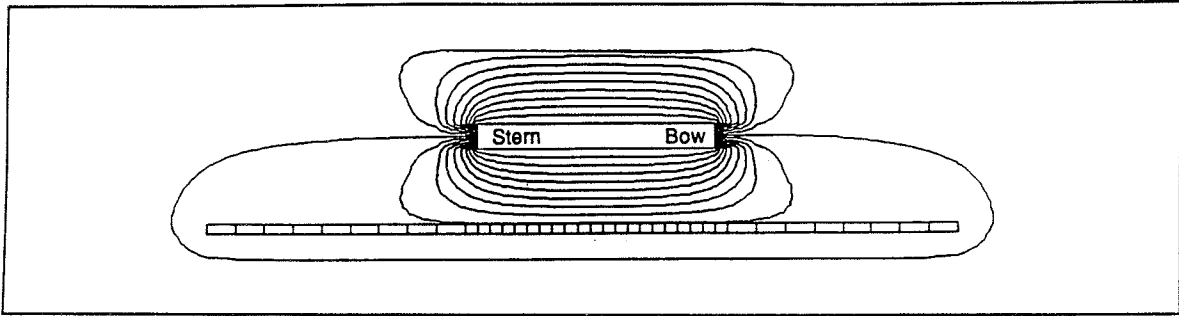


Figure 20. Streamlines, island length = 3,005 ft

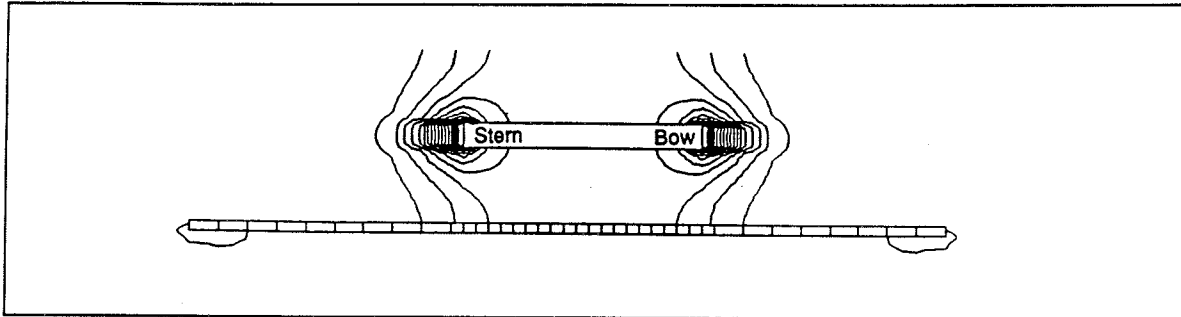


Figure 21. Velocity contours, island length = 3,005 ft

method of Maynard. While these are based on one-dimensional approximations and some empiricism, they have been used by many researchers; therefore, a level of confidence exists about the validity of the assumptions and the outcome of the results.

The Schijf method (previously described) was used to determine the average return current for each of the six tests in Figures 6-11. This is represented by a straight line on either side of the tow. Maynard's method modifies the Schijf results by distributing the return current across the section. For all these tests the distribution was linear, and likewise, is plotted in Figures 6-11. The upper limit (or 95 percent of the actual boat speed) and the lower limit (or 60 percent of the actual boat speed) boundary velocities were simulated in STREMR for each test, and the results along the midlength of the tow were superimposed on these figures as well. As can be seen from the cross-section plots, the upper and lower limits roughly bounded both the theoretical and experimental results. Finally, the weighted average return current on either side of the tow was determined from the STREMR output for each test, and those values were compared to the corresponding Schijf value (which is also representative of the average value from Maynard's method).

Figures 22 and 23 show the relationship between boat speed and average return current for the upper and lower limits used in STREMR and the Schijf

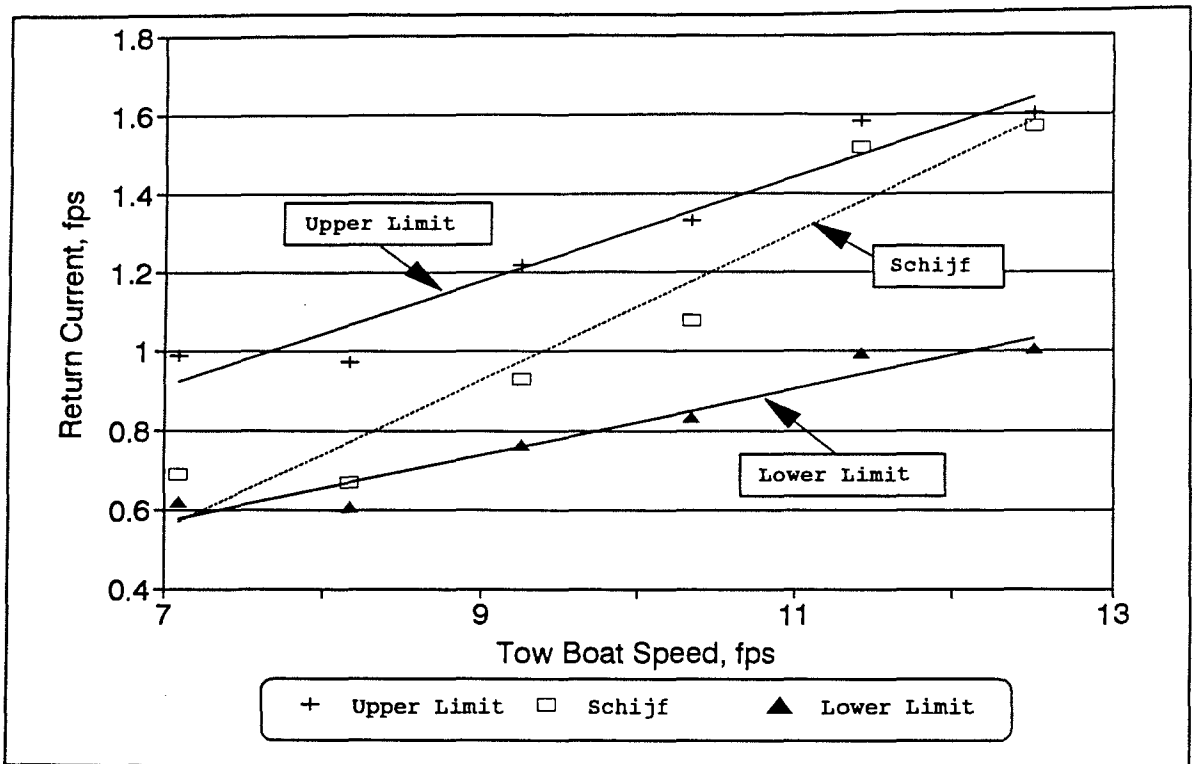


Figure 22. Comparison of average return currents, port

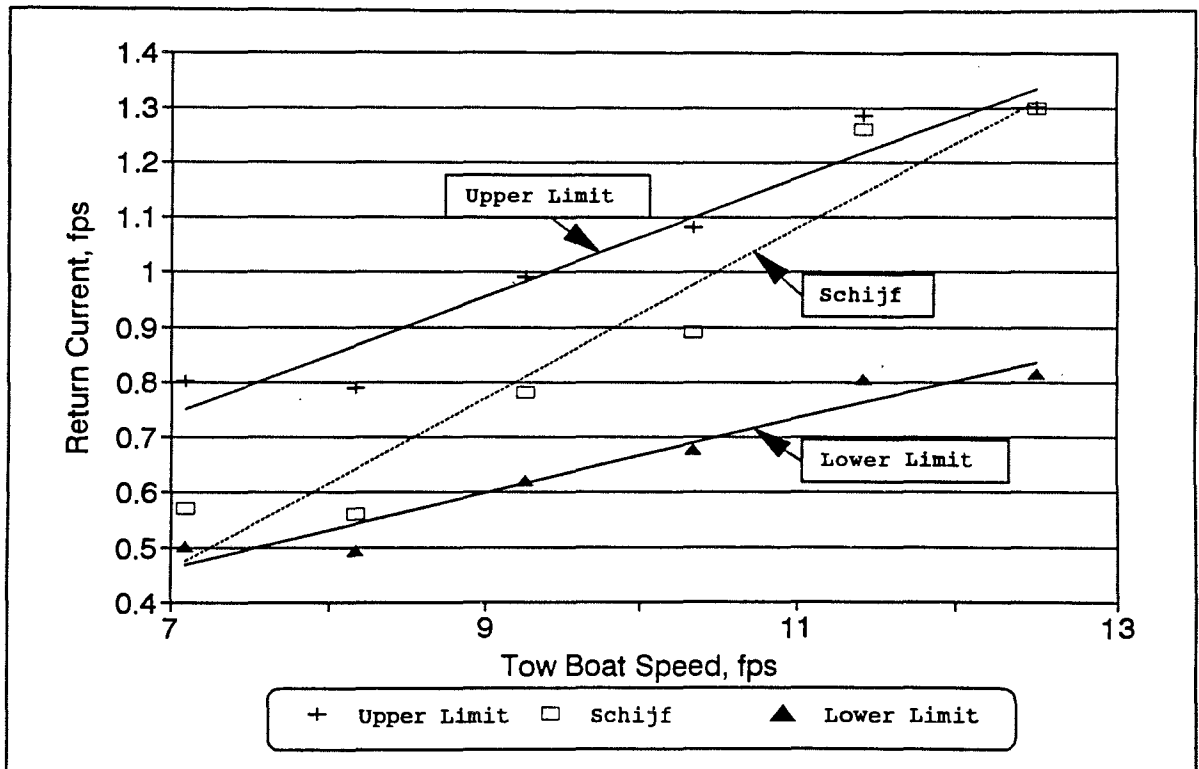


Figure 23. Comparison of average return currents, starboard

values. The lines represent a best fit through each of the six points. As seen in these graphs, the Schijf values approach the upper limit approximation used in STREMR as the boat speed increases. Researchers have concluded (and developed empirical coefficients to compensate) from test data that the Schijf approximation tends to underestimate the actual value of return current at slow boat speeds, but more closely estimates the correct value as the boat speed approaches its limit speed. (For this situation, the limit speed was approximately 15 fps.) Based on this analysis and without better experimental data to verify the magnitude of the return currents, it is concluded that the method of choice for the determination of the strength of the source/sink should be based on the upper limit methodology described in the section, "Boundaries."

LDV

The LDV is capable of collecting model velocities at accuracies far exceeding those of existing experimental techniques. The data collected are ideally suited for the verification of numerical results. However, actual quantitative values were not compared at this time because data from the LDV were obtained following completion of the CHI work initiative. In fact, the grid used in STREMR for the CHI work unit represents a 965-ft-wide by 15-ft-deep channel with a 105-ft-wide by 950-ft-long tow placed off-center in the channel, while the LDV data were collected in a flume representing a 400-ft-wide by 20-ft-deep channel and a 105-ft-wide by 390-ft-long tow placed in the channel center. This did not prohibit a comparison between techniques of general trends in the data.

The LDV provided 2-D velocity components in the longitudinal (streamwise or u -component) direction and transverse (crosswise or v -component) direction for the model situation described in the preceding section. The LDV was placed at a depth 60 percent from the surface at three locations: mid-channel between barge's edge and bank, one-quarter distance from the bank, and three-quarters distance from the bank (closer to the tow). Test results are shown in Figures 24-26. For these figures, u is positive in the direction opposite of tow movement, and v is positive in the direction away from the tow. Several observations are noted. The peaks in the v -component (both in a negative and positive sense) corresponded with the passing of the bow and stern, respectively. As the location of the measurement moved toward the tow's edge, the magnitude of these peak components increased. The return current (u -component) peaked at approximately midlength of the tow, and likewise, though less dramatically, its peak diminished with distance from the tow. It should also be noted that velocity data after passage of the stern (beyond approximately 50 sec) are due to a reflective wave in the flume and should not be interpreted as tow response data.

Three lines of longitudinal grid cells near the bank, near midchannel, and near the tow were selected for evaluation of u - and v -components in the STREMR model. These represent in space what the LDV data represent in

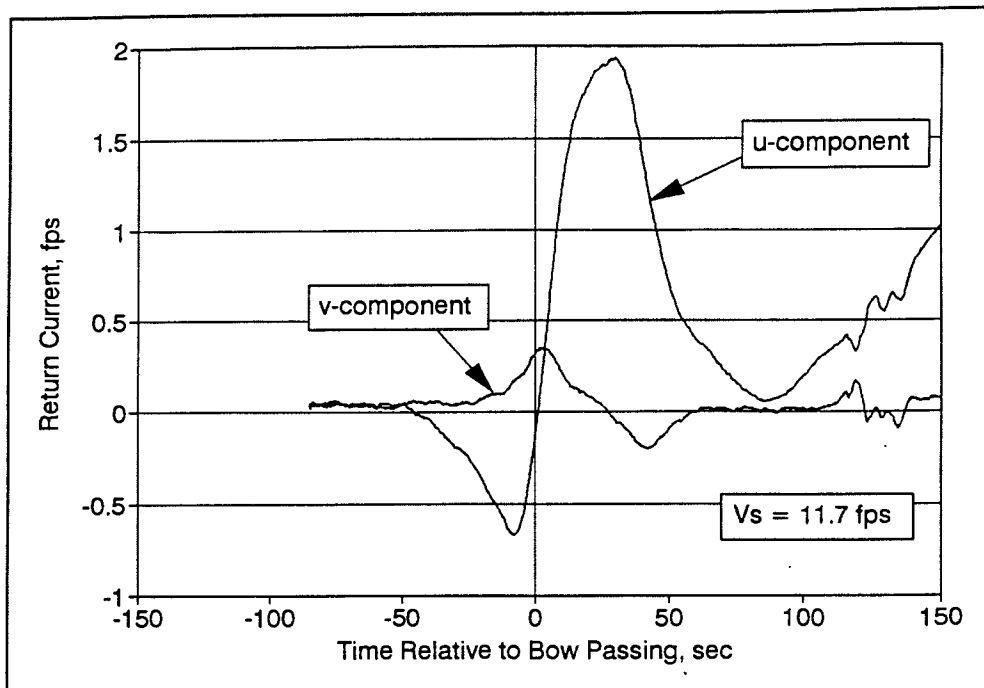


Figure 24. LDV velocities (prototype) one-fourth distance from bank to tow's edge

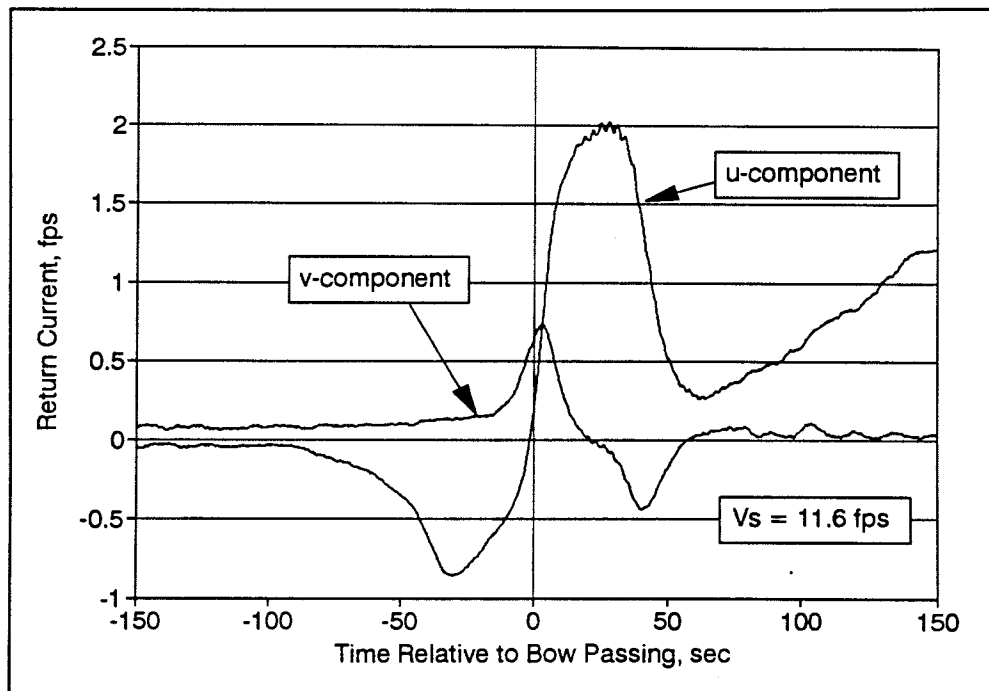


Figure 25. LDV velocities (prototype) one-half distance from bank to tow's edge

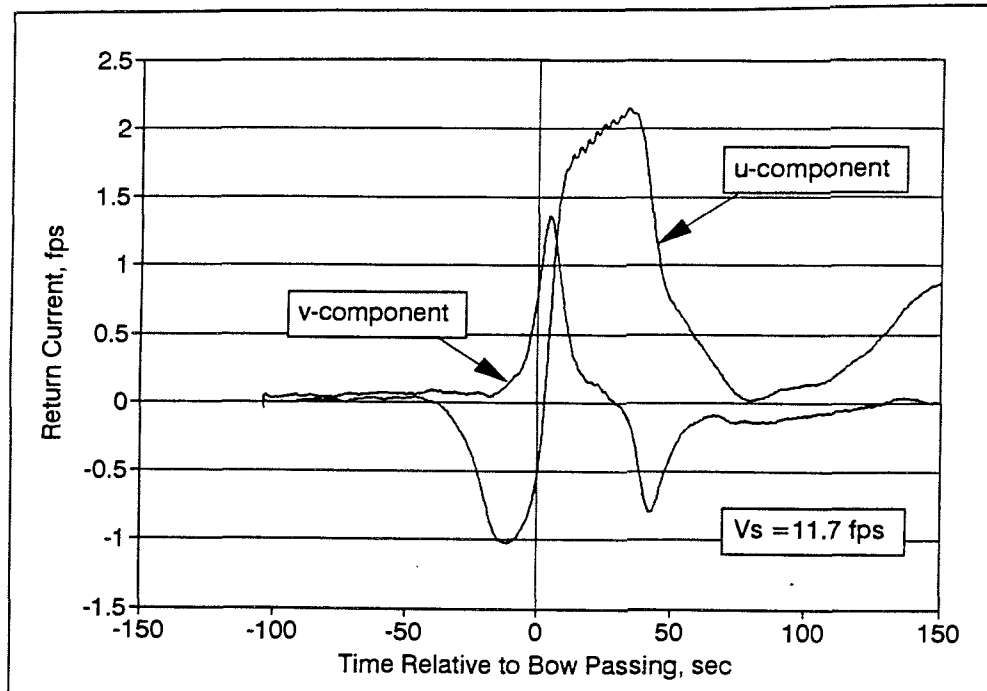


Figure 26. LDV velocities (prototype) three-fourths distance from bank to tow's edge

time. Space and time are related by the speed of the tow. Keeping in mind that these data represent a different geometry and direction of tow, Figures 27-29 contain the results of this evaluation. For these figures, positive u is in the direction of tow movement and positive v indicates movement toward the tow. As in the LDV data, v -component velocities are at a peak near the bow and stern. Comparing the vector plot in Figure 3 with these plots, it is obvious that near the corners of the barges as the velocities turn away from the bow and toward the stern, the v -components peak. It also follows that the magnitude of this component will decrease with distance from the tow. Likewise, at midlength of the tow, the return velocity contains no v -component and the u -component is at a maximum. These trends are identical to those observed in the physical model.

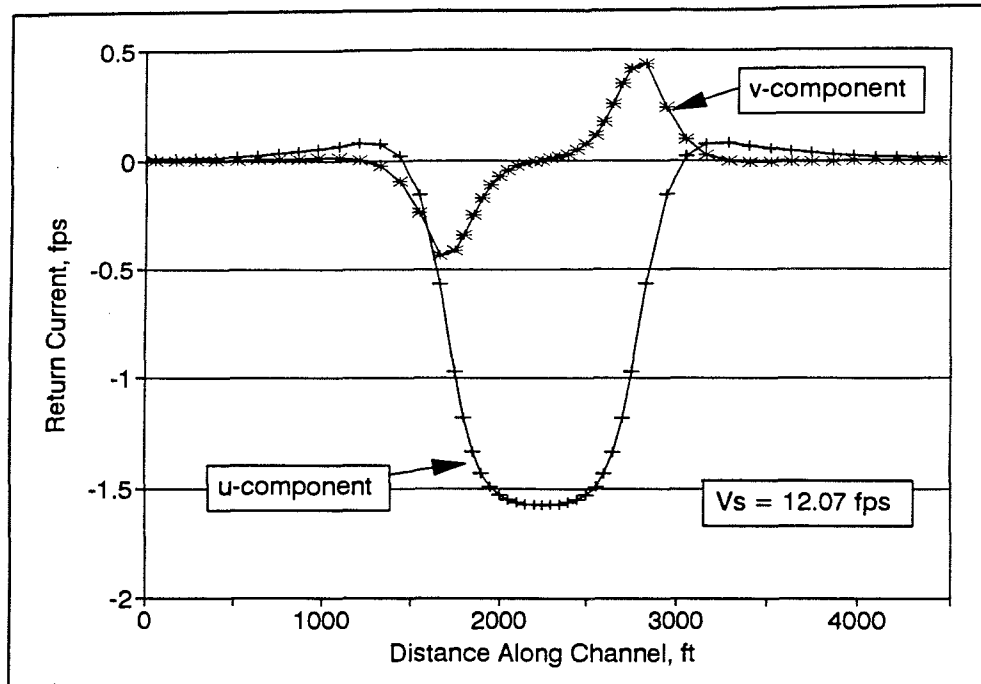


Figure 27. STREMR velocities near the bank, port side

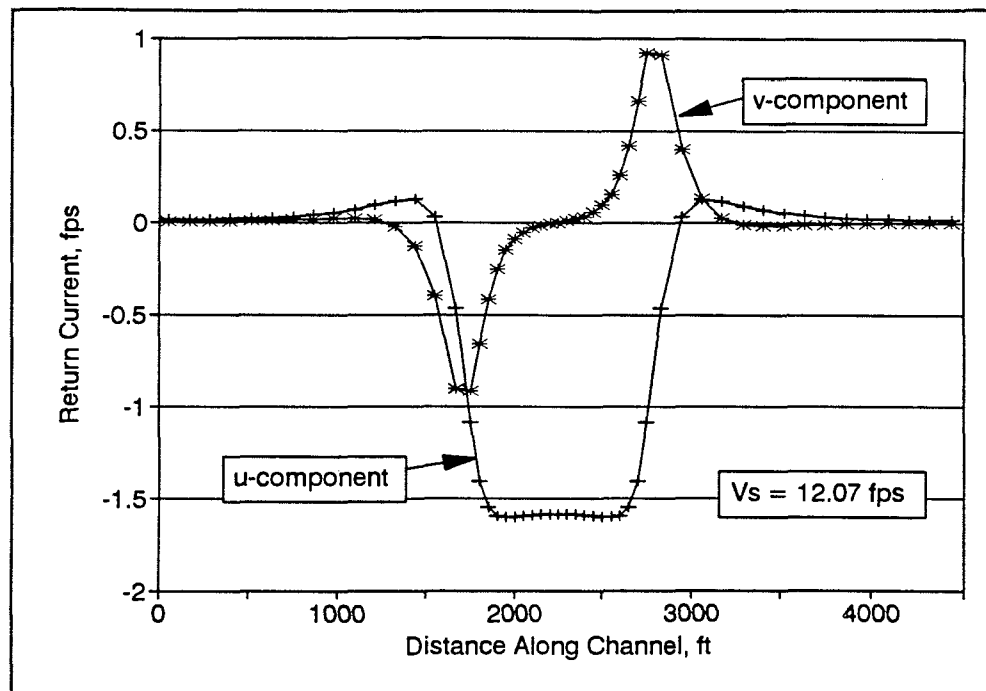


Figure 28. STREMR velocities near midchannel, port side

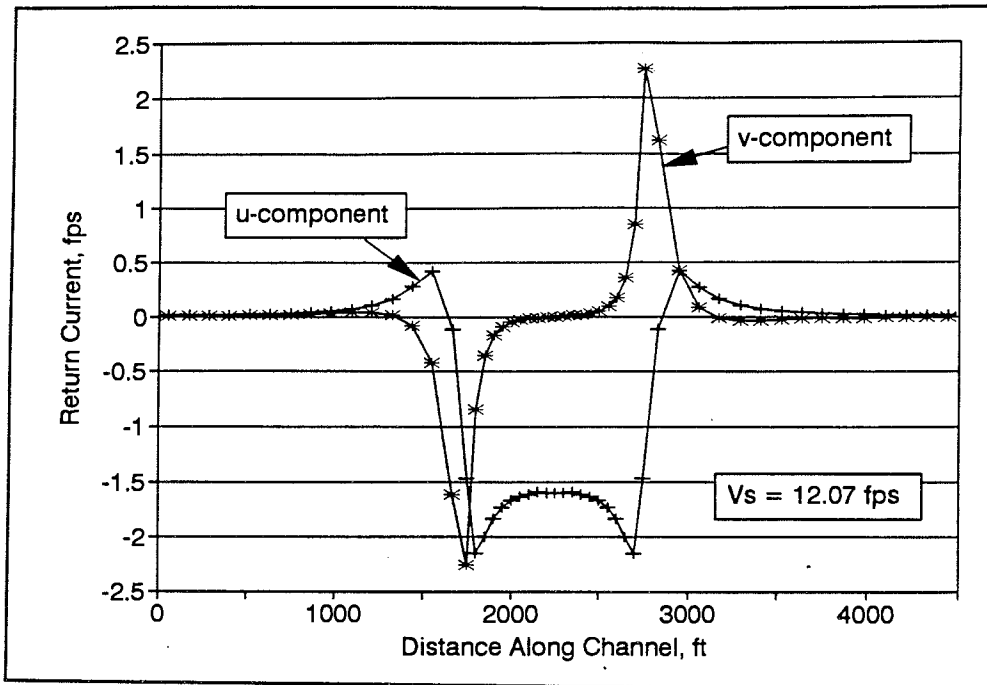


Figure 29. STREMR velocities closer to tow, port side

5 Summary

STREMR is an effective tool for approximating the flow field due to a moving tow at a specified location in a navigation channel. Velocities calculated using the discretized potential flow solution of the depth-averaged flow equations in STREMR provide a detailed determination of distribution as opposed to the single point solution of the Schijf equations. Advantages of STREMR over the traditional one-dimensional solution of the Schijf equations are summarized in Table 1. Bear in mind that both models are based on the same theoretical solution, that is, Bernoulli's energy equation for irrotational flows. This method is recommended as an improvement over the existing methodologies in the evaluation of far field tow induced currents. However, more research is needed to verify the model and evaluate any potential improvement in the solution by modeling the problem in three dimensions and/or using different two-dimensional methodologies. Additional verification with LDV data is needed to determine the source/sink strength relation with tow speed. This verification will be conducted and presented in future reports.

References

- Bernard, Robert S. (1989). "Explicit numerical algorithm for modeling incompressible approach flow," Technical Report REMR-HY-5, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Bernard, Robert S. (1993). "STREMR: Numerical model for depth-averaged incompressible flow," Technical Report REMR-HY-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
- Jansen, P. Ph., and Schijf, J. B. (1953). *Eighteenth International Navigation Congress*, Rome. Permanent International Association of Navigation Congresses, Brussels, Belgium, Section 1, Communication 1, 175-197.
- Le Mehauté, Bernard. (1976). *An introduction to hydrodynamics and water waves*. Springer-Verlag, New York.
- Maynard, Stephen T. (1990). "Velocities induced by commercial navigation," Technical Report HL-90-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

**Table 1
Comparison of STREMR and Schijf Equation**

STREMR	Schijf
Determines entire flow field (bow current, return current, displacement current)	Gives cross-sectional average return current
Calculates discrete values at any grid cell (flow distribution)	Calculates constant value across one section
Can model irregular channels	Models only uniform channel, specifically, rectangular channel
Gives longitudinal and transverse components of velocity	Gives only longitudinal value of velocity
Provides visualization products (stream potential lines, velocity vector plots, etc.)	Provides no visualization products

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13. ABSTRACT (Maximum 200 words) <p>In shallow-draft waterways, commercial towboats and barges generate complex currents as they move through the waterway. The flow, in general, moves from bow to stern as the tow moves forward. The current acting in the direction opposite tow movement and generally parallel to the bank is called the return current. The magnitude of the return current is generally determined using an analytical approach based upon the energy equation along a single streamline. This method gives only one, average value of the longitudinal component of the return current at a section mid-distance along the length of the tow for the entire width of the cross section. It is based on several assumptions including a uniform section, nonviscous flows, negligible ambient current, and center-line placement of the vessel.</p> <p>This study explored the use of a two-dimensional numerical model, STREMR, for the solution of the irrotational (potential) flow equations in the modeling of the vector field produced by a tow. The intent was not to develop a code for moving boundary problems nor to investigate the highly three-dimensional forces near the tow, but to determine the appropriate methodology and the potential applicability of using an existing tool in the determination of the tow-induced currents in a natural river. Successful use of this type approach could lead to the determination of tow-induced currents in irregular channels, with tows having off-center sailing lines, and in rivers with ambient currents.</p>				
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