Return Velocity and Drawdown in Navigable Waterways

by Steve Maynord

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Preface

The work described in this report was conducted at the U.S. Army Engineer Waterways Experiment Station (WES) during the period June 1995 to September 1995. This investigation was sponsored by Headquarters, U.S. Army Corps of Engineers (HQUSACE), under the Navigation Hydraulics Research Program as part of the Civil Works Investigation Work Unit, "Vessel Generated Forces and Protection," under HQUSACE Program Monitor Mr. Sam Powell.

The study was accomplished in the Hydraulics Laboratory (HL) under the direction of Mr. Richard A. Sager, Acting Director; Mr. Robert Athow, Acting Assistant Director; and Dr. Larry L. Daggett, Acting Chief, Navigation Division (HN). The study was conducted and the report was written by Dr. S. T. Maynord, Navigation Effects Group, HN.

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

Background

A vessel moving in a navigation channel displaces water and creates a flow of water (return velocity) alongside the vessel in a direction opposite that of the vessel. The magnitude of the return velocity is primarily dependent on vessel speed, channel cross section, and the submerged cross-sectional area of the vessel. The return velocity is also accompanied by a lowering of the water level alongside the vessel, drawdown, as well as other navigation effects shown in Figure 1. Return velocity and drawdown have been extensively studied in prismatic cross sections and confined or restricted channels, i.e., those having a low blockage ratio N, the ratio of channel cross-sectional area to vessel cross-sectional area. Previous studies (Permanent International Association of Navigation Congresses (PIANC) 1987, Schijf 1949) have addressed the channel stability aspects of return velocity and drawdown in

![Diagram of navigation effects](image)

*Figure 1. Navigation effects: A = return velocity; B = drawdown; C = propeller jet; D = wake flow; E = bow wave; and F = slope supply flow*
confined channels. In other studies (Blaauw and van der Knaap 1983, Tothill 1966), a primary concern of drawdown has been the resulting lowering or squat that the vessel experiences when drawdown occurs. In confined channels, vessel speeds can be limited by vessel squat when depth/draft ratios are low.

In a general sense, return velocity and drawdown are analogous to pier or obstruction effects in a river. For piers that are small relative to the size of the river, large effects are found near the pier and negligible effects near the bank. If the pier took up a greater portion of the river, the effects would be large near the pier and significant near the bank. Finally, as the pier begins to dominate the cross section, the effects near the pier and near the bank are similar in magnitude. Because return velocity and drawdown follow these trends, mathematical decay functions whose shape varies with the vessel cross-sectional area relative to the cross-sectional area of the river are used to describe the distribution of return velocity and drawdown between the vessel and the bank line. For a large vessel size relative to the river, the decay functions should collapse to an almost uniform distribution from bank to vessel.

Return velocity and drawdown are of interest in assessing the effects of navigation on environmental concerns for large navigable waterways. Channel stability and vessel squat impacts due to return velocity and drawdown are often small in large waterways like the Ohio and Mississippi where blockage ratios become large. One exception is areas where vessels travel near bank lines such as in lock approaches. The analytical techniques for estimating return velocity and drawdown developed for confined channels are not directly applicable to large waterways because many basic assumptions used in their development are not met in large waterways.

Objective and Scope

This study develops techniques for estimating return velocity and drawdown from commercial vessels operating in navigable waterways and compares them to model and prototype data. Confined channel methods are modified to extend their application to large riverine navigation systems. The results are incorporated into the PC program NAVEFF with this report serving as the documentation. This study does not address other navigation effects such as waves or propeller flows shown in Figure 1. This report presents a modification and an expansion of the results presented in Maynord and Siemsen (1991) and uses data from shallow draft navigation on the Ohio, Illinois, and Upper Mississippi Rivers.
2 Application of Confined Channel Methods to Large Waterways

Previous Confined Channel Studies

An excellent review of techniques to determine squat, drawdown, and return velocity in confined channels is presented by Blaauw and Van der Knaap (1983). Only the most pertinent studies are discussed in the following paragraphs.

Schijf’s (1949) conservation of energy approach is frequently used in determining return velocity and drawdown in confined channels. The basic assumptions required in this approach are: uniform trapezoidal or rectangular cross section, uniform return current velocity from vessel to bank line, uniform drawdown from vessel to bank line, friction losses disregarded, uniform or negligible ambient velocity; and vessel on channel center line. Considering all motions relative to the vessel, continuity requires that

\[ VA_c = A_w (V + V_r) \]

where

- \( V \) = vessel speed
- \( A_c \) = undisturbed channel area
- \( A_w \) = disturbed channel area around midsection of vessel excluding \( A_w \)
- \( V_r \) = average return velocity

For convenience, symbols and abbreviations are listed in the notation (Appendix A).
$A_m = \text{submerged cross-sectional area of the vessel at the midsection}$

Conservation of energy requires that

$$\frac{V^2}{2g} + h = \frac{(V + V_r)^2}{2g} + (h - z)$$

(2)

where

$g = \text{gravitational acceleration}$

$h = \text{undisturbed average water depth}$

$z = \text{average water-level drawdown}$

The unknown quantities $V_r$ and $z$ can be determined from Equations 1 and 2. Differentiation of Equations 1 and 2 leads to a maximum speed (called the critical or limiting speed $V_L$) which can not be exceeded by a self-propelled vessel and has been verified in both model and prototype investigations. PIANC (1987) presents a coefficient $\beta$ that varies with $V/L_s$ in the Schijf equations to improve agreement between observed and computed return velocity and drawdown. The energy equation is rewritten as

$$\frac{V^2}{2g} + h = \frac{\beta (V + V_r)^2}{2g} + (h - z)$$

(3)

Gates and Herbich (1977) included the displacement thickness from boundary layer concepts to determine effective vessel draft and beam improving the agreement between Schijf equations and prototype measurements of vessel squat. Inclusion of boundary layer concepts partially addresses the assumption requiring that friction losses be disregarded.

Bouwmeester et al. (1977) reported that Schijf (1949) cannot be used even approximately for $N$ greater than about 33 because water-level drawdown and return velocity are greatly nonuniform. Many tows in large waterways have a value of $N$ greater than 33.

PIANC (1987) documented techniques for using the Schijf (1949) equations in channel stability investigations of prismatic channels. Schijf is recommended for $B/B_o$ from 2 to 12, where $B_o$ is the channel width and $B$ is the beam of the vessel. Additionally, the ratio of channel width to vessel length $L$ can be a significant factor in defining the ratio of maximum water-level drawdown to average water-level drawdown and maximum return velocity to average return velocity. Channels having a large ratio $L/B_o$ will have a
well-defined return velocity and drawdown time-history during the time the
tow is adjacent to a given point on the bank.

Modification of Confined Channel Methods to
Large Waterways

Some of the six basic assumptions for applying the Schijf equations are
often not met in large waterways. The ambient and return velocities and the
water-level drawdown are not uniform, the cross section is not prismatic, and
the vessel is not on the channel center line. The equations determine average
values of return velocity and drawdown. Maximum values near the shore are
of the most interest for both channel bank stability and environmental
concerns. Environmental interests often also require the variation in return
velocity and drawdown between vessel and shoreline. The techniques
presented here predict, at any given point between vessel and shoreline, the
maximum deviation from ambient conditions due to return velocity and draw­
down during the tow passage.

A major problem that must be overcome in evaluating asymmetric channels
found in large waterways like the Ohio, Mississippi, or Illinois Rivers is how
to handle tows off the channel center line. One technique assumes a mirror
image on each side of the tow and computes average return velocity and draw­
down. This is satisfactory until the tow gets near one bank line and far from
the other resulting in a substantial amount of the return flow passing around
the front of and beneath the tow. Then, the return current predicted on the
side near the bank using the mirror image channel is much larger than actually
occurs.

A second problem with the Schijf equation is in certain asymmetric channel
shapes. Any channel with wide shallow areas on either or both channel sides
is particularly subject to overestimating the return velocity at high vessel
speeds. This problem becomes significant when tow speeds exceed about
90 percent of Schijf $V_L$ for the total section and when the ratio of maximum
depth to average depth exceeds about 1.3. Fortunately most tows are
traveling at less than 0.9 $V_L$, normally from 50 to 75 percent of $V_L$.

Large Waterways Studies

Hochstein and Adams (1989) documented a technique for estimating return
velocity on the upper Mississippi River that is used by Environmental Science
and Engineering (ESE) (1981) and Simons et al (1988) and on the Ohio River
by U.S. Army Engineer District, Huntington (1980). The average return
velocity is defined as
\[ V_r = V[(aB_r - B_r + 1)^{0.5} - 1] \]  

where \( a = (N/(N-1))^2 \).

For vessel speeds less than 0.65\( V_L \), where \( B_r \) is a coefficient defined as \( B_r = 0.3 \exp(1.8V/V_L) \) and for vessel speeds equal to or greater than 0.65\( V_L \), \( B_r = 1 \). From Maynord and Siemsen (1991), the Schijf and Hochstein average return velocity equations give similar results for vessel speeds equal to 50 to 60 percent of Schijf \( V_L \). In Equations 5 through 7, Hochstein presents a method for determining the return velocity distribution. A channel/tow width factor is defined as

\[ \alpha = \max (1, 0.114 \frac{B_o}{B} + 0.715) \]  

The maximum return velocity \( V_m \) at the vessel is determined from

\[ V_m = \alpha V_r \]  

For \( \alpha = 1 \), the distribution of velocity is uniform from vessel to bank line. For \( 1 < \alpha < 1.5 \), the distribution of return velocity is linear. For \( \alpha \geq 1.5 \), the distribution of return velocity is linear. For \( \alpha \geq \), the distribution of return velocity from vessel to bank line is defined as

\[ V_r(Y) = V_m \exp (-Y/k) \]  

where

\[ V_r(Y) = \text{maximum return velocity during tow event at distance } Y \text{ from center line of vessel} \]

\[ k = B_{side}/(\alpha\{1-\exp[-F(\alpha)\alpha]\}) \]

\[ B_{side} = \text{distance from vessel center line to shoreline} \]

\[ F(\alpha) = 0.42 + 0.52 \ln \alpha \]
ESE(1981), Simons et al. (1988), and USAED Huntington (1980) results showed that the Hochstein equations (Equations 4 through 7) underestimate measured return velocity.

Maynord and Siemsen (1991) presented a method for estimating return velocity in large waterways. Average return velocity is computed using Schijf (1949) without the correction factor. To handle tows navigating off the channel center line in asymmetric channels, the average return velocity is then proportioned on each side of the vessel using the following equation developed from physical model studies reported in Maynord (1990)

\[
\frac{V_{rs}}{V_r} = C_1 SKEW + C_2
\]  

(8)

where

\[
V_{rs} = \text{average return velocity for each side of vessel}
\]

\[
SKEW = \frac{A_v}{2A_{side}}
\]

\[
A_{side} = \text{cross-sectional area from tow center line to bank line}
\]

Maynord and Siemsen (1991) used coefficients of \(C_1 = 0.36\) and \(C_2 = 0.64\) in Equation 8. The ratio \(\alpha'\) of the maximum return velocity on each side of the tow \(V_{r_{2m}}\) to \(V_{rs}\) is determined from

\[
\frac{V_{r_{2m}}}{V_{rs}} = \alpha' = \max [1, 0.024N_{side} + 0.734]
\]  

(9)

where \(N_{side} = 2A_{side}/A_m\).

Note the similarity between Hochstein's Equations 5 and 6 which use a width ratio and Equation 9 which uses an area ratio. As the area ratio \(N_{side}\) increases, the distribution of return velocity becomes nonuniform. From Equation 9, \(N_{side}\) less than 11 gives \(\alpha' = 1\) and the distribution of return velocity between vessel and shoreline is uniform. The return velocity distribution from tow to bank line is determined from

\[
\frac{V_r(Y)}{V_{r_{2m}}} = \exp \left[-C \left(1 - \frac{B_{side}}{B_{side} - B} \right)\right]
\]  

(10)

where
$C = 1.2(\alpha' - 1)$ \hfill (11)

$V_r(Y)$ is the maximum return velocity during the tow event for a given distance $Y$ from the vessel center line. $V_r(Y)$ is linearly added to ambient currents for upbound tows and subtracted from ambient currents for downbound tows. $Y$ must be greater than $B$, because from $Y = 0$ to $Y = B$ the velocity is also affected by flow under the barges which can be considerably larger than the return velocity. Based on a limited data set used in Maynord and Siemsen (1991), the Hochstein method underestimated the measured return velocities while the Maynord and Siemsen (1991) method overestimated the measured return velocities.

An obvious limitation of these distribution equations is that the distribution does not vary with the shape or local depth of an asymmetric cross section, although both methods do address a vessel off the channel center line. For the remainder of this report, Equations 1, 2, and 8 through 11 are referred to as the 1991 analytical method.
3 Return Velocity and Drawdown Data Sources, Errors, and Analysis

Prototype data on navigation effects have been collected on the Upper Mississippi, Illinois, and Ohio Rivers. One major limitation of these data is that only a few points were collected between the vessel and the bank line, primarily in the near-bank zone. Consequently, these data can not provide a verification of the velocity distribution shape and the return velocity magnitude outside the near bank zone. Physical model studies of reaches on the Upper Mississippi River were conducted where return velocity and drawdown were measured from shore to vessel to define the distribution of return velocity and drawdown. The physical model tests simulated a reach of the Illinois River near Kampsville and the Mississippi River near Clark's Ferry where the Illinois State Water Survey (ISWS) (Bhowmik, Soong, and Xia 1993a,b) conducted prototype measurements of tow-induced return velocity and drawdown. The physical model was verified by comparing model and prototype results for six tow events in each river reach. Agreement was reached between model and prototype return velocity and drawdown by reducing the physical model draft. Details of the Kampsville and Clark's Ferry physical model studies and the data used herein are provided in Maynord and Martin (1996a,b).

As with many data collection efforts, collection of return velocity and water level drawdown data is not an easy task in either the physical model or the prototype. Some error sources are specific to either model or prototype or applicable to both. Errors in instrumentation along with details of other potential error sources in the physical model testing are discussed in the physical model reports.

Instrument error in the ISWS prototype tests must be considered in using prototype data because of the environmental conditions found in the prototype. Electromagnetic velocity meters were used in the ISWS prototype studies and can be subject to a variety of problems. Radio interference can result in highly erratic readings. Drift can accumulate around the sensor head and modify readings in a manner that is not obvious to the person conducting the
tests. Nevertheless, the electromagnetic velocity meter is the best available prototype technique for this type of measurement. Wave data collected in the ISWS tests were frequently missing due to instrument malfunction.

Tow length and width are relatively easy to determine in the field as long as the tow is comprised of the standard 10.7 by 59.5 (35- by 195-ft) barges. When chemical barges are present, their nonuniformity of length and width can be a problem. Tow length is important because the length and time of passage past a given point are often used to determine the tow speed in prototype tests. Tow draft may also contribute to the data scatter. Tows are assumed to draft 2.7 m (9 ft) if loaded and 0.6 m (2 ft) if unloaded unless contact with the towboat captain indicates otherwise. Mixed tows further complicate the issue.

Also the vertical location of velocity measurements is considered. Variations caused by this effect are not as significant as it might first appear since tow-induced return velocity profiles are generally uniform. The boundary layer resulting from tow passage does not have sufficient time to completely develop into the typical velocity profile found in a fully developed open channel flow. Therefore, velocity changes near the surface should be uniform down to the point where the boundary layer has developed. Results from the ISWS tests provided in Maynord and Martin (1996a) suggest that only meters 1001 and 998 (Figure 2) in the trip 1 data should not be used in the comparison with the 1991 analytical method because of the boundary layer influence.

One of the greatest causes of data variability is determining the tow impact from the time-history of the parameter of interest. The difficulty of this task increases as the magnitude of the tow impact decreases, because it becomes more difficult to distinguish the tow impact from the natural variations present in the river. The first task in defining the tow impact is defining the ambient velocity prior to tow passage which can be a problem as there are some long period variations in the ambient velocity due to several factors such as changes in the regulating gates at the locks and dams. The next task is defining the maximum deviation from ambient conditions. In the ISWS tests, the maximum (or minimum) value from an 11-sec moving average was selected during the time the tow was adjacent to the meter. This smoothing technique eliminated the normal variations present in turbulent flow while also defining the maximum value. The difference between the maximum value and the ambient was the tow impact.
Note: Meters 998, 999, and 1000 are mounted on a platform at 0.31, 1.22, and 2.44 m above the bottom, respectively. The velocity meters are two dimensional electromagnetic meters. Details of the meter descriptions can be found in Bhownik, Soong, and Xia (1993a).

Figure 2. Cross section of the Illinois River at the Kampsville site for trip 1
Return Current Comparisons with 1991 Analytical Method

Tow speed used in application of the analytical methods was equal to the sum of vessel speed relative to the ground and the ambient velocity. Ambient velocity was positive for unbound tows and negative for downbound tows. Data were limited to tows with a length at least 40 percent of the channel width to eliminate the tow length effects measured in physical model tests of the Clark's Ferry reach being studied on the Mississippi River (Maynord and Martin 1996b).

A scatterplot of observed return velocity versus the predicted return velocity using the 1991 analytical method (Figure 3) was developed from the Kampsville physical model data. The 1991 analytical method under predicts return velocity observed in the physical model for most of the tests.

Comparison of the 1991 analytical method to the ISWS data required determining the draft, beam, and length to use for some unusual tow configurations having a mixture of loaded, unloaded, and partially loaded barges. The approach for this report selected the beam, draft, and length of the section having the maximum cross-sectional area.

A scatterplot (Figure 4) of observed prototype return velocity versus the predicted return velocity from the 1991 analytical method was developed from ISWS Kampsville prototype test data. As in the physical model, prototype data were limited to tows with a length greater than 40 percent of the channel width. N less than or equal to 51 was used to agree with the limits of the physical model data. Meters 998 and 1001 from trip 1 were excluded because their close proximity to the boundary (0.31 m) led to boundary layer effects. As in the physical model, the 1991 analytical method under predicts observed prototype return velocity for most tests.
Figure 3. Observed physical model return velocity versus computed return velocity using 1991 analytical method

1995 Analytical Method

Based on the underprediction of both physical model and prototype results, the 1991 analytical method must be reexamined. The physical model data from Kamps ville and Clark’s Ferry provided an opportunity to evaluate each part of the 1991 method. The maximum return velocity \( V_r(Y) \) during the tow event for each meter is the value extracted from the model and prototype data. The \( V_r(Y) \) data from the eight physical model meters from the Kamps ville and Clark’s Ferry physical model data were averaged to determine the return velocity representative of the entire cross section \( V_r \). Since \( V_r(Y) \) is the maximum return velocity during the tow event at \( Y \), \( V_r \) is a cross-sectional average of these maximums. The ratio \( V_r/Schijf \) \( V_r \) (from Eq’s 1 and 2) was compared for upbound versus downbound vessels to determine if the average channel velocity is the correct velocity to use in determining the velocity of the tow relative to the water. A likely alternative is the velocity where the tow is operating which is generally greater than the average channel velocity.
The average Vr/Schijf Vr for upbound tows was higher than the average ratio for downbound tows when using the average channel velocity to determine the vessel speed through the water. When the average channel velocity was increased by 20 percent and then used to determine the speed through the water, upbound and downbound tows gave the same average ratio. This finding tends to confirm the use of the velocity where the tow operates when determining the tow speed through the water. The 20-percent increase is consistent with the actual velocity that occurs in the deeper areas where the tow is operating.

The Schijf return velocity, calculated using Equations 1 and 2 with the 20-percent increase in $V_{avg}$, under predicted the observed cross-sectional average of the maximum $V_r$ from the physical model. To correct this under-prediction, an effective draft and beam were determined by adding the displacement thickness to the draft and twice the displacement thickness to the beam of the vessel as recommended by Gates and Herbich (1977). Displacement thickness is determined from the Prandtl-Schlichting skin friction.
equation for a smooth flat plate at zero incidence (Schlichting 1968). Displacement thickness $\delta_1$ is determined from the skin friction equation according to

$$\delta_1 = \frac{0.292 L}{(\text{Log}(R_f))^2.58}$$

(12)

where

$L =$ total barge length

$R_f = \frac{V_{\text{disp}} L}{v}$

$V_{\text{disp}} = V_g + V_{\text{amb}} + \text{Schijf} V_r$

$V_g =$ vessel speed over the ground

$V_{\text{amb}} =$ positive for upbound tows and negative for downbound tows

$\nu =$ kinematic viscosity of water

While this significantly improved the comparison between observed average $V_r$ and $V_r (\text{Schijf})$, the error between the two was a function of the ratio of vessel speed to the critical or limiting speed ($V_L$) from Equations 1 and 2. Dependence with $V/V_L$ is consistent with the findings of Schijf (1949). The observed physical model data were used to develop a correction factor based on $V/V_L$ which provided good agreement between observed average $V_r$ and Schijf $V_r$. Schijf $V_r$ is calculated using the effective draft and beam in the Schijf equation. Average $V_r$ is calculated from

$$V_r = V_r (\text{Schijf}) (1.9 - 1.29V/V_L)$$

(13)

The computed $V_r$ from Equation 13 is not allowed to be less than the return velocity from the Schijf equation and $V/V_L$ should be from 0.35 to 0.9. The comparison between observed $V_r$ from the Kampsville and Clark’s Ferry physical models and computed $V_r$ using Equation 13 is shown in Figure 5. Since $\delta_1$ is computed using $V_r$ from equations 1 and 2, the solution does not require iteration with Equation 13.

The next step is evaluating the relationship in Equation 8 that proportions the return velocity on each side of the vessel. The return velocity for each side of the vessel $V_r$ was determined for each test using the Kampsville and Clark’s Ferry physical model data. $V_r$ was normalized by the observed
average $V_r$ (which represents the entire cross section) and tested against various parameters such as SKEW used in Equation 8. The best fit was found using the relation between distance from vessel to shoreline $B_{side}$ and total channel width $B_{total}$. For $B_{side}/B_{total}$ from 0 to 0.5

$$\frac{V_r}{v_r} = 1.65 - 1.3 \frac{B_{side}}{B_{total}}$$

(14)

For $B_{side}/B_{total}$ from 0.5 to 1.0
\[
\frac{V_n}{V_r} = 1.35 - 0.7 \frac{B_{\text{side}}}{B_{\text{total}}} \quad (15)
\]

Equations 14 and 15 are plotted against observed data from the Kampsville and Clark's Ferry physical models in Figure 6 along with rectangular flume data from a previously unpublished data set.

Figure 6. \( \frac{V_n}{V_r} \) versus \( \frac{B_{\text{side}}}{B_{\text{total}}} \) using physical model data

The third step is defining \( \alpha' = \frac{V_{\text{ref}}}{V_r} \) which defines the uniformity of the return velocity distribution between vessel and shoreline. Previous attempts at this relation using physical model data were only approximate because scale effects were not eliminated from the data as has been done in the Maynord and Martin (1996a,b) physical model data. Only the physical model data from the Kampsville model were used in the analysis of \( \alpha' \) because of the likely influence of dikes from the Clark's Ferry model. The
physical model data were used to determine $V_{rms}$ at $(Y-B)/(B_{side}-B) = 0$. Various parameters were tested against $\alpha'$, and $N_{side}$ provided the best agreement with observed data. $V_{rms}/V_r$ is plotted against $N_{side}$ in Figure 7 and is described by the equation

$$\frac{V_{rms}}{V_r} = \alpha' = 0.75 N_{side}^{0.18}$$

Figure 7. $V_{rms}/V_r$ versus $N_{side}$ using physical model data

The final step was determining $C$ in Equation 10 which describes the shape of the return velocity distribution. One requirement of $C$ is that it must equal zero for $\alpha' = 1$. The $C$ that best defines the shape of the return velocity distribution in the physical model data from Kampselle and Clark’s Ferry is defined by
The revised equations presented above will be referred to hereafter as the 1995 analytical method. A scatterplot of the Kampsville physical model data versus the 1995 analytical method (Figure 8) shows an improved comparison of observed versus predicted return velocity. Individual test plots for the Kampsville physical model are shown in Figures 9 to 13. The six plots on each figure for individual tests having varying speed, position, upbound versus downbound, etc. In the test number, the K stands for Kampsville and L or H for low or high flow. R or L stand for right or left of the channel thalweg and U or D stand for upbound or downbound. If neither R or L appear before U or D, the tow is on the channel thalweg. The last three numbers give the vessel speed relative to the ground in model meters per second which can be converted to prototype values for the 1:25 Kampsville model by multiplying by 25^{1/2} = 5. Details of each test are given in Table 1.

On some of the physical model tests, the exponential type equation given by Equation 10 underpredicts the return velocity at the bank. Other data sets will be examined to see if this trend is repeated. A scatterplot of the Clark’s Ferry physical model data versus the 1995 analytical model is shown in Figure 14 for N less than 52. Figure 15 provides a scatterplot of tests conducted with pool 572.7 in the Clark’s Ferry section which resulted in N of about 85. The tests in Figure 15 addressed the open river portion of the Upper Mississippi River where large channel cross sections result in large blockage ratios. The 1995 analytical method, derived from physical model data, was then evaluated using the ISWS data. Scatterplots of prototype data from Kampsville and Clark’s Ferry are shown in Figures 16 and 17, respectively. Individual plots for the ISWS prototype data at Kampsville are shown in Figures 18 to 21. Each of the 24 plots in Figures 18 to 21 represent an individual prototype tow with the towboat name given in the upper right-hand corner. Plots where there are two or more points at the same distance from the tow are locations where velocity meters were placed at different vertical positions. Details of the prototype tests are provided in the Table 2 report. Note that the Kampsville prototype data do not show evidence of an increase near the bank.
Figure 8. Observed Kampsville physical model return velocity versus computed return velocity using 1995 analytical method.
Figure 9. Observed Kampsville physical model return velocity versus computed return velocity using 1995 analytical method for individual tests: KLU335, 488, 640, 354 and KLD506 and 659 (Continued)
e. Test KLD506

Figure 9. (Concluded)

F. Test KLD659
Figure 10. Observed Kampsville physical model return velocity versus computed return velocity using 1995 analytical method for individual tests: KLRU49, KLRD49, KLLU49, KLLD51, KL1U46, and KL1U61 (Continued)
e. Test KL1U46

F. Test KL1U61

Figure 10. (Concluded)
Figure 11. Observed Kampsville physical model return velocity versus computed return velocity using 1995 analytical method for individual tests: KL1U76, KLEU49, KLEU67, KHEU38, KHEU56, and KHOU38 (Continued)
e. Test KHEU56

Figure 11. (Concluded)

f. Test KHOU38
Figure 12. Observed Kampsville physical model return velocity versus computed return velocity using 1995 analytical method for individual tests: KHOU53, KHOD50, KHOD66, KHRU38, KHRD66, and KHLU38 (Continued)
e. Test KHRD66

f. Test KHLU38

Figure 12. (Concluded)
Figure 13. Observed Kampsville physical model return velocity versus computed return velocity using 1995 analytical method for individual tests: KHL66, KHOU27, KHOD64, LU38Q2, and LD58Q2 (Continued)
e. Test LD58Q2

Figure 13. (Concluded)
### Table 1
Physical Model Experimental Conditions

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<th>Vessel Beam, m</th>
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<th>Effective Draft, m</th>
<th>Vessel Power, Hp</th>
<th>Vessel Speed Relative to Ground, m/sec</th>
<th>Ambient Velocity, m/sec</th>
<th>Direction, 1 = Upbound 2 = Downbound</th>
<th>Channel Area Left of Vessel, m²</th>
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<th>Ambient Velocity, m/sec</th>
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Figure 14. Observed Clark's Ferry physical model return velocity versus computed return velocity using 1995 analytical method for $N < 52$. 
Figure 15. Observed Clark's Ferry physical model return velocity versus computed return velocity using 1995 analytical method for N = 85
Figure 16. Observed Kampsville prototype return velocity versus computed return velocity using 1995 analytical method
Figure 17. Observed Clark's Ferry prototype return velocity versus computed return velocity using 1995 analytical method.
Figure 18. Observed Kampsville prototype return velocity versus computed return velocity using 1995 analytical method for individual tests: M/V Mr. Abdo, Floyd Blaske, Sugar (13), W. C. Norman (13), ContiKarla, and Rambler (Continued)
e. M/V Conti Karla

f. M/V Rambler

Figure 18. (Concluded)
Figure 19. Observed Kampsville prototype return velocity versus computed return velocity using 1995 analytical method for individual tests: M/V Mlawrce, ChaLehman, Jeffboat, Ardyce Randl, Mr. Paul (15), and Marget 0 (15) (Continued)
e. M/V Mr. Paul (15)

f. M/V Marget O (15)

Figure 19. (Concluded)
Figure 20. Observed Kampsville prototype return velocity versus computed return velocity using 1995 analytical method for individual tests: M/V Mr. Lawre (15), Al Smith, Dixie Patrit, Orleanian, Pat Breen, and Dixie Expre 1 (Continued)
e. M/V Pat Breen

Figure 20. (Concluded)
Figure 21. Observed Kampsville prototype return velocity versus computed return velocity using 1995 analytical method for individual tests: M/V Night 1401, Irving Crown, Thurston Mon, Olmstead, Jack D. Wofford, and Dixie Expre 2 (Continued)
e. M/V Jack D. Woffod

Figure 21. (Concluded)

f. M/V Dixie Expre 2
### Table 2
Kampsville Prototype Experimental Conditions

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<th>Test Number</th>
<th>Vessel Beam, m</th>
<th>Total Length of Barges, m</th>
<th>Effective Draft, m</th>
<th>Vessel Power, Hp</th>
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### Table 2 (Concluded)

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<th>Vessel Power, Hp</th>
<th>Vessel Speed Relative to Ground, m/sec</th>
<th>Ambient Velocity, m/sec</th>
<th>Direction, 1 = Upbound 2 = Downbound</th>
<th>Channel Area Left of Vessel, m²</th>
<th>Distance from Left Bank to Vessel m</th>
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<th>Total Channel Width, m</th>
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5 Development of 1995 Analytical Method for Prediction of Water-Level Drawdown

To compute water-level drawdown at position Y from the center line of the vessel, the average return velocity, as determined from Equation 13, was used in Equation 2 to determine the average drawdown \( z \) for the section. The difficulty at this point is that the number of drawdown distributions in the physical model was limited. Therefore, return velocity distributions were used to determine how the drawdown varied on either side of the tow and across the section. The drawdown on either side of the tow was determined from the same equations used for return velocity in Equations 14 and 15.

For \( B_{\text{side}}/B_{\text{total}} \) from 0 to 0.5

\[
\frac{Z_{n}}{z} = 1.65 - 1.3 \frac{B_{\text{side}}}{B_{\text{total}}} \tag{18}
\]

For \( B_{\text{side}}/B_{\text{total}} \) from 0.5 to 1.0

\[
\frac{Z_{n}}{z} = 1.35 - 0.7 \frac{B_{\text{side}}}{B_{\text{total}}} \tag{19}
\]

The maximum drawdown at \((Y-B)/(B_{\text{side}}-B) = 0\) is
\[
\frac{Z_{im}}{Z_{rs}} = \alpha_{\text{draw}} \tag{20}
\]

where \( \alpha_{\text{draw}} \) is a function of \( \alpha' \) defined by Equation 16.

The distribution of \( Z(Y) \) is defined as

\[
\frac{Z(Y)}{Z_{im}} = \exp \left[ C \left( \frac{Y-B}{B_{\text{side}}-B} \right) \right] \tag{21}
\]

where \( Z(Y) \) is the maximum water-level drawdown during the tow event at distance \( Y \) from the vessel center line and \( C \) is defined by Equation 17. \( \alpha_{\text{draw}} \) is the primary factor that establishes the slope of the drawdown distribution.

Based on the Kampsville and Clark's Ferry physical model drawdown data and detailed drawdown measurements for the WC Norman tow in the Kampsville physical model, \( \alpha_{\text{draw}} \) is defined by

\[
\alpha_{\text{draw}} = \alpha' \cdot 0.5 \tag{22}
\]

Scatterplots of observed physical model drawdown from Kampsville and Clark’s Ferry versus computed drawdown using the 1995 analytical drawdown method are shown in Figures 22 and 23, respectively. Comparison of the analytical method with detailed drawdown data from the WC Norman tow in the Kampsville physical model is shown in Table 3. The physical model-based 1995 Analytical Drawdown method was then tested for agreement with the prototype data which was taken at a single-wave gauge at the Kampsville site on the Illinois River. The wave data from ISWS were collected at 10 samples/sec. To be consistent with the return velocity analysis, an 11-sec moving average was used to smooth the wave data before extracting the ambient and changed water level from the record. Drawdown measurements based on only a staff gage reading were not used in this comparison. A scatterplot of drawdown for the ISWS prototype data is shown in Figure 24.
Figure 22. Observed Kampsville physical model drawdown versus computed drawdown using 1995 analytical method
Figure 23. Observed Clark's Ferry physical model drawdown versus computed drawdown using 1995 analytical method
### Table 3
**Observed Versus Computed Drawdown for WC Norman Test**

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Note: (-) No value was available.

$^1$ These values are drawdown.

![Diagram](image.png)

**Figure 24.** Observed Kampsville prototype drawdown versus computed drawdown using 1995 analytical method
Since the Kampsville and Clark's Ferry field data were used to verify the Kampsville and Clark's Ferry physical models which were then used to produce data used in the development of the 1995 method, comparison of the analytical method to the same field data is not independent. Two field data sets were used to provide an independent comparison with the 1995 analytical method. The first data set was return velocity data taken by ESE (1981) at one section on the Mississippi River and one on the Illinois River. A scatterplot of all ESE return velocity data meeting the limitations of the 1995 method is shown in Figure 25. The second data set comes from data collected at four sites on the Ohio River by the U.S. Army Engineer District, Louisville, whose cross sections are shown in Figures 26 through 29 and data on Tables 4 through 7. Scatterplots for all four sections are shown in Figures 30 and 31 for return velocity and drawdown, respectively. Scatter is large, but the trend around the line of perfect agreement is correct for all three scatterplots.
Figure 25. Observed ESE prototype return velocity versus computed return velocity using 1995 analytical method.
Figure 26. Cross section for ORL tests 89192-89196, French Island (Factor for converting feet to metric is 3.048 and square feet to square meters is 0.0929)
Figure 27. Cross section for ORL tests 89198-89203 — Ellis Island (Factor for converting feet to meters is 3.048 and square feet to square meters is 0.0929)
Figure 28. Cross section for ORL tests 90172-90179 (Factor for converting feet to meters is 3.048 and square feet to square meters is 0.0929)
Figure 29. Cross section for ORL tests 90191-90195 (Factor for converting feet to meters is 3.048 and square feet to square meters is 0.0929)
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Chapter 6  Comparison of 1995 Analytical Method with Independent Field Data
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Note: To convert to metric, multiply by these factors:
- feet x 0.3048 to obtain meters
- feet² x 0.0929 to obtain square meters
- horsepower x 745.7 to obtain watts
- inches x 0.0254 to obtain meters

(Sheet 3 of 3)
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(Sheet 1 of 3)

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| 89201004 | 52 | 898 | 9 | 999 | 9.03 | 1.8 | 1.0 | 8100 | 410 | 20460 | 1020 |
| 89201005 | 105 | 882 | 2 | 999 | 13.1 | 1.8 | -1.0 | 9800 | 410 | 20460 | 1020 |
| 89202001 | 105 | 702 | 9 | 999 | 10.6 | 1.8 | -1.0 | 10700 | 445 | 20460 | 1020 |
| 89202003 | 210 | 1167 | 9 | 999 | 10.4 | 1.8 | -1.0 | 14200 | 575 | 20460 | 1020 |
| 89202004 | 175 | 1129 | 2 | 999 | 7.94 | 1.8 | -1.0 | 15600 | 640 | 20460 | 1020 |
| 89202005 | 105 | 1115 | 9 | 999 | 11.5 | 1.8 | -1.0 | 14600 | 595 | 20460 | 1020 |
| 89202006 | 104 | 395 | 2 | 999 | 15.2 | 1.8 | -1.0 | 12900 | 520 | 20460 | 1020 |
| 89202007 | 41 | 96 | 5 | 999 | 12.5 | 1.8 | -1.0 | 16600 | 690 | 20460 | 1020 |

Chapter 6  Comparison of 1995 Analytical Method with Independent Field Data
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Note: To convert to metric, multiply by these factors:

- feet x 0.3048 to obtain meters
- feet² x 0.0929 to obtain square meters
- horsepower x 9809.5 to obtain watts
- inches x 0.0254 to obtain meters

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9999 means data not recorded or meter malfunction.

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Note: To convert to metric, multiply by these factors:
feet x 0.3048 to obtain meters
feet² x 0.0929 to obtain square meters
horsepower x 9809.5 to obtain watts
inches x 0.0254 to obtain meters

Chapter 6  Comparison of 1995 Analytical Method with Independent Field Data
### Table 7
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9999 means data not recorded or meter malfunction.

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Note: To convert to metric, multiply by these factors:
- feet x 0.3048 to obtain meters
- feet² x 0.0929 to obtain square meters
- horsepower x 9809.5 to obtain watts
- inches x 0.0254 to obtain meters

Description of items in database:
First line:
1. Test name
2. Vessel beam, feet
3. Length of barges, feet
4. Draft of barges, feet
5. Towboat power, horsepower
6. Vessel speed relative to ground, feet/second
7. Ambient velocity = Discharge/total channel area, feet/second
8. Upbound = 1.0, Downbound = -1.0
9. Channel area left of tow center line, feet²
10. Distance from left bank to tow center line, feet
11. Total channel area, feet²
12. Total water surface width, feet

Next 1, 2, or 4 lines:
1. Distance from left bank to velocity meter, feet
2. Maximum (upbound) or minimum (downbound) velocity alongside tow, feet/second
3. Ambient velocity at this meter, feet/second
4. Local depth at meter, feet
5. Distance from meter to bottom, feet

Next 1 line:
1. Distance from left bank to wave gauge, feet
2. Water-level drawdown, inches
3. Local depth at wave gauge, feet

(Sheet 4 of 4)
Figure 30.Observed ORL prototype return velocity versus computed return velocity using 1995 analytical method.
Figure 31. Observed ORL prototype drawdown versus computed drawdown using 1995 analytical method
Chapter 7: Program NAVEFF

The 1995 analytical method for return velocity and drawdown was programmed in QuickBASIC 4.5 language as shown in the program listing in Figure 32. The program prompts for metric or english units and then requests the following:

a. Total channel top width in meters or feet.

b. Distance from tow center line to left bank in meters or feet (when facing downstream).

c. Total channel cross-sectional area in square meters or square feet.

d. Channel cross-sectional area from tow center line to left bank.

e. Tow draft in meters or feet.

f. Total barge width in meters or feet.

g. Total barge length in meters or feet. In determining the displacement thickness used to determine effective draft and beam, a single temperature of 17 °C is used because of lack of sensitivity to temperature.

h. Average channel velocity in meters/sec or ft/sec. The program applies a factor of 1.2 to the average channel velocity to determine the vessel speed relative to the water.

i. Vessel speed relative to ground in meters/second or feet/second.

j. Direction of travel U or u for upbound, D or d for downbound.

The program then outputs $V_r(Y)$ in m/sec or ft/sec and $z(Y)$ in meters or feet at five points on each side of the tow. The five points are equally spaced and begin at one tow width away from the vessel center line and end at the shoreline. The program then prompts for a new vessel speed using the same channel and tow geometry. The program will indicate if the speed entered
'PROGRAM NAVEFF.BAS-BASED ON SCHIJF FOR ENTIRE CHANNEL
'AND 1995 WES REPT ON RETURN VELOCITY AND DRAWDOWN
REM THIS PRINTS OUT ALL DATA AND GIVES A VISUAL PICTURE
CLS
SCREEN 9
COLOR 11, 4
LINE (700, 600)-(0, 0), 4, BF
PRINT
PRINT TAB(12); "PROGRAM NAVEFF.BAS-SCHIJF METHOD PLUS EMPIRICISM"
PC = 0
PRINT
PRINT "  EXPERIMENTAL DATA USED IN DEVELOPMENT LIMITED TO THE FOLLOWING:
PRINT "  BLOCKAGE RATIO LESS THAN 85"
PRINT "  DISTANCE ON SIDE OF VESSEL GREATER THAN 10% OF TOTAL CHANNEL WIDTH"
PRINT "  AND GREATER THAN VESSEL BEAM"
PRINT "  VESSEL LENGTH GREATER THAN 40% OF CHANNEL WIDTH"
PRINT "  RETURN VELOCITY AND DRAWDOWN LIMITED TO ONE BEAM WIDTH AWAY"
PRINT "  FROM VESSEL CENTERLINE OUT TO THE SHORELINE"
PRINT "  VESSEL SPEED RELATIVE TO WATER SHOULD BE 0.35-0.9*LIMIT SPEED"
FOR I = 1 TO 10
PRINT
NEXT I
PRINT TAB(25); "Press SPACE BAR to Continue"
SLEEP
CLS
FLAG1$ = "N"
FLAG2$ = "N"
5 INPUT "ENGLISH OR METRIC UNITS (E OR M) ", uni$
IF uni$ = "E" OR uni$ = "e" THEN FLAG1$ = "Y"
IF uni$ = "M" OR uni$ = "m" THEN FLAG2$ = "Y"
IF FLAG1$ = "Y" OR FLAG2$ = "Y" THEN GOTO 7
GOTO 5
7
8
INPUT "ENTER TOTAL CHANNEL TOP WIDTH ", BTOTAL
INPUT "ENTER DISTANCE FROM TOW CENTERLINE TO LEFT BANK ", BLEFT
INPUT "ENTER TOTAL CHANNEL AREA ", ATOTAL
INPUT "ENTER AREA LEFT OF TOW CENTERLINE ", ALEFT
INPUT "ENTER BARGE DRAFT ", D
INPUT "ENTER TOTAL BARGE WIDTH ", B
IF B < BLEFT AND B < BTOTAL - BLEFT THEN GOTO 9
PRINT "DISTANCE FROM VESSEL CENTERLINE TO BANK MUST BE > VESSEL BEAM"
GOTO 8
9
INPUT "ENTER TOTAL LENGTH OF BARGES ", L
INPUT "ENTER AVERAGE CHANNEL VELOCITY, + FOR UBOUND, - FOR DOWN ", VAM
10 INPUT "ENTER TOW SPEED RELATIVE TO GROUND ", VG
V = VG + 1.2 * VAM
GRAV = 32.16
FLAG$ = "N"
IF uni$ = "M" THEN GRAV = 9.805
IF uni$ = "m" THEN GRAV = 9.805
LUNIT$ = "FEET"
VUNIT$ = "FEET/SEC"
AUNIT$ = "SQ FT"
IF uni$ = "M" OR uni$ = "m" THEN LUNIT$ = "METERS"
IF uni$ = "M" OR uni$ = "m" THEN VUNIT$ = "M/SEC"
IF uni$ = "M" OR uni$ = "m" THEN AUNIT$ = "SQ M"
'
' SET WATER VISCOSITY = 0.0000011 M**2/SEC FOR TEMP = 17 DEG C

Figure 32. Listing for PC program NAVEFF (Sheet 1 of 12)
VNU = .0000011
IF LUNIT$ = "FEET" THEN VNU = VNU * 3.28 * 3.28

' COMPUTE GEOMETRIC FACTORS
',
AM = B * D
BRIGHT = BTOTAL - BLEFT
ARIGHT = ATOTAL - ALEFT
NSIDEL = 2 * ALEFT / AM
NSIDER = 2 * ARIGHT / AM
SKEWL = ATOTAL / 2 / ALEFT
BLB = BLEFT / BTOTAL
IF BLB > .9 OR BLB < .1 THEN FLAG$ = "Y"
SKEWR = ATOTAL / 2 / ARIGHT
BRB = BRIGHT / BTOTAL
IF BRB > .9 OR BRB < .1 THEN FLAG$ = "Y"
IF FLAG$ = "N" THEN GOTO 20
CLS
PRINT "WARNING, THE DATA ENTERED FOR THE WIDTH ON ONE SIDE OF THE TOW ";
PRINT "IS LESS THAN 10% OF THE TOTAL CHANNEL WIDTH. THIS IS OUTSIDE THE";
PRINT "LIMITS OF THE EXPERIMENTAL DATA."
FOR I = 1 TO 15
PRINT NEXT I
PRINT TAB(25); "Press SPACE BAR to Continue"
SLEEP
CLS
IF L >= .4 * BTOTAL THEN GOTO 14
CLS
PRINT "WARNING, THE DATA ENTERED FOR THE VESSEL LENGTH ";
PRINT "IS LESS THAN 40% OF THE TOTAL CHANNEL WIDTH. THIS IS OUTSIDE THE";
PRINT "LIMITS OF THE EXPERIMENTAL DATA."
FOR I = 1 TO 15
PRINT NEXT I
PRINT TAB(25); "Press SPACE BAR to Continue"
SLEEP
CLS
14

20 H = ATOTAL / BTOTAL
N = ATOTAL / AM
En = N
IF N < 85 THEN GOTO 30
CLS
PRINT "WARNING, THE BLOCKAGE RATIO IS GREATER THAN 85, WHICH IS OUTSIDE "
PRINT "THE LIMITS OF THE EXPERIMENTAL DATA."
FOR I = 1 TO 15
PRINT NEXT I
PRINT TAB(25); "Press SPACE BAR to Continue"
SLEEP
CLS
30
REM 'SOLVE SCHIJF EQUATION FOR DISPLACEMENT CALCULATION
',
Z = .01

Figure 32. (Sheet 2 of 12)
40  SCHIJF = (1 + N * Z / H) / (N - 1 - N * Z / H)
    ZT = (V ^ 2 / 2 / GRAV) * ((SCHIJF ^ 2) + 2 * SCHIJF)
    U1 = V * SCHIJF
    IF ABS((ZT - Z) / ZT) < .00001 THEN GOTO 50
    IF Z > 20 THEN GOTO 100
    Z = ZT
    GOTO 40

50  REM
    REM COMPUTE DISPLACEMENT THICKNESS
    REM
    VDISP = V + U1
    RL = VDISP * L / VNU
    DISP = .292 * L / (.43429 * LOG(RL)) ^ 2.58
    DE = D + DISP
    BE = B + 2 * DISP
    N = ATOTAL / DE / BE
    REM 'SOLVE SCHIJF EQUATION FOR RETURN VELOCITY
    Z = .01

51  SCHIJF = (1 + N * Z / H) / (N - 1 - N * Z / H)
    ZT = (V ^ 2 / 2 / GRAV) * ((SCHIJF ^ 2) + 2 * SCHIJF)
    U1 = V * SCHIJF
    IF ABS((ZT - Z) / ZT) < .00001 THEN GOTO 52
    IF Z > 20 THEN GOTO 100
    Z = ZT
    GOTO 51

52  REM
    REM 'SOLVE SCHIJF EQUATION FOR LIMIT SPEED USING NEWTON RAPHSON
    VLO = V

54  RTEM = VLO ^ 2 / GRAV / H
    FV = 1 - 1 / N + .5 * RTEM - 1.5 * RTEM ^ (1 / 3)
    FPV = VLO / GRAV / H - (VLO ^ (-1 / 3)) / (GRAV * H) ^ (1 / 3)
    VLN = VLO - FV / FPV
    IF ABS((VLO - VLN) / VLO) < .0001 THEN GOTO 55
    VLO = VLN
    GOTO 54

55  VL = VLN

58  VLIMRAT = V / VL
    PRINT
    IF VLIMRAT < .35 THEN GOTO 59
    PRINT "WARNING******** SPEED LESS THAN 0.35*LIMIT SPEED ********

59  IF VLIMRAT < .9 THEN GOTO 61
    PRINT "WARNING******** SPEED GREATER THAN 0.9*LIMIT SPEED ********

61  ' APPLY CORRECTION FACTOR
    CF = 1.78 - 1.07 * VLIMRAT
    IF CF < 1 THEN CF = 1
    U1 = CF * U1
    ZT = (V + U1) ^ 2 / 2 / GRAV - V ^ 2 / 2 / GRAV
    PRINT
    REM COMPUTE a(ALF) AND AVERAGE Vr FOR EACH
    REM SIDE OF TOW
    VFACTL = 1.65 - 1.3 * BLB
    IF BLB > .5 THEN VFACTL = 1.35 - .7 * BLB
    VFACTR = 1.65 - 1.3 * BRB
    IF BRB > .5 THEN VFACTR = 1.35 - .7 * BRB

Figure 32. (Sheet 3 of 12)
VRAL = U1 * VFACTL
VRAR = U1 * VFACTR
ZSL = ZT * VFACTL
ZSR = ZT * VFACTR
ALFL = .75 * NSIDEL .18
ALFR = .75 * NSIDER .18
IF ALFL < 1 THEN ALFL = 1
IF ALFR < 1 THEN ALFR = 1
ZALFL = ALFL .5
ZALFR = ALFR .5
VRLM = ALFL * VRAL
VRRM = ALFR * VRAR
ZSML = ZALFL * ZSL
ZSMR = ZALFR * ZSR

PRINT TAB(22); "DATA SHOWN IS THE INPUT DATA"
PRINT PRINT " CHANNEL TOTAL AREA "; USING "#####.#"; ATOTAL;
PRINT " "; AUNIT$;
PRINT " AREA LEFT OF TOW "; USING "#####.#"; ALEFT;
PRINT " "; AUNIT$;
PRINT " TOTAL WIDTH "; USING "#####.#"; BTOTAL;
PRINT " "; LUNIT$;
PRINT " DISTANCE, LEFT BANK TO TOW "; USING "#####.#"; BLEFT;
PRINT " "; LUNIT$;
PRINT " TOW WIDTH " USING "#####.#"; B;
PRINT " "; LUNIT$; " DRAFT " USING "#####.#"; D;
PRINT " "; LUNIT$;
PRINT " TOW LENGTH "; USING "#####.#"; L;
PRINT " "; LUNIT$;
PRINT " TOW SPEED RELATIVE TO GROUND "; USING "#####.#"; VG;
PRINT " "; VUNIT$;
PRINT " AVERAGE CHANNEL VELOCITY(+UPBOUND,-DOWN) "; USING "#####.#"; VAM;
PRINT " "; VUNIT$;
PRINT
FOR I = 1 TO 10
PRINT NEXT I
PRINT TAB(25); "Press SPACE BAR to Continue"
SLEEP
CLS
IF ARIGHT > ALEFT AND VRRM > VRLM THEN VRRM = VRLM
IF ALEFT > ARIGHT AND VRLM > VRRM THEN VRLM = VRRM

COMPUTE RETURN VELOCITY AND DRAWDOWN DISTRIBUTION
,
PRINT PRINT TAB(15); "COMPUTED RETURN VELOCITY AND DRAWDOWN DISTRIBUTION"
PRINT PRINT TAB(15); "DISTANCE" TAB(37); "RETURN" TAB(54); "DRAWDOWN"
PRINT TAB(15); "FROM TOW CL" TAB(37); "VELOCITY"
PRINT TAB(15); LUNIT$ TAB(37); VUNIT$ TAB(54); LUNIT$
PRINT FOR J = 1 TO 2
IF J = 2 THEN GOTO 60
ALF = ALFL: VRM = VRLM

Figure 32. (Sheet 4 of 12)
ZALF = ZALFL; ZSM = ZSML
BSIDE = BLEFT
GOTO 70
60 ALF = ALFR; VRM = VRRM
ZALF = ZALFR; ZSM = ZSMR
BSIDE = BRIGHT
70 C = 3! * LOG(1 / ALF)
   ZC = 3! * LOG(1 / ZALF)
   ,
   YLAST = 0
FOR I = 1 TO 5
   IF J = 1 THEN dum = -BSIDE
   IF J = 2 THEN dum = B
   Y = (dum + (I - 1) / 4 * (BSIDE - B))
   YY = ABS(Y)
   YY = VRM * EXP(C * (YY - B) / (BSIDE - B))
   ZY = ZSM * EXP(ZC * (YY - B) / (BSIDE - B))
   LOCA$ = " "
   IF J = 1 AND I = 1 THEN LOCA$ = " LEFT BANK"
   IF J = 2 AND I = 5 THEN LOCA$ = " RIGHT BANK"
   IF (I = 1) AND (J = 1) THEN VYQL = VY: ZLQ = ZY
   IF (I = 1) AND (J = 2) THEN VYQR = VY: ZRQ = ZY
   PRINT LOCA$;
   PRINT TAB(15); USING "#####.#"; Y;
   PRINT TAB(30); USING "########.###"; YY;
   PRINT TAB(45); USING "###########.###"; ZY
   YLAST = Y
NEXT I
NEXT J
FOR I = 1 TO 5
   PRINT
NEXT I
PRINT TAB(25); "Press SPACE BAR to Continue"
SLEEP
GOTO 130
100 PRINT "SPEED EQUAL TO OR GREATER THAN VLIMIT"
GOTO 10
130 CLS
PRINT " ENTER 1 FOR A PRINTOUT OF THE INPUT DATA AND RESULTS"; PRN1
IF PRN1 = 1 THEN GOSUB PAPER
PRINT " ENTER 1 FOR A VISUAL DISPLAY OF THE RESULTS"; ANS1
IF ANS1 = 1 THEN GOSUB PICTURE
CLS
160 PRINT " ENTER 1 FOR A NEW VESSEL SPEED OR 2 TO QUIT"; ANS2
IF ANS2 = 1 THEN CLS : GOTO 10 ELSE CLS : END
PICTURE:
CLS
SCREEN 9
REM ADJUSTMENT FACTOR
RAT = 560 / BTOTAL
DMAX = (.75) * ((ALEFT / BLEFT) + (ARIGHT / BRIGHT))
DMRAT = DMAX * RAT
SELECT CASE DMRAT
CASE IS > 60

Figure 32. (Sheet 5 of 12)
\[ m = 1 \]
\[ \text{CASE 40 TO m = 2} \]
\[ \text{CASE 26 TO m = 3} \]
\[ \text{CASE 20 TO m = 4} \]
\[ \text{CASE 1 TO m = 5} \]
\[ \text{END SELECT} \]

\[ \text{REM BARGE} \]
\[ DM = D * m \]
\[ BLRAT = BLEFT * RAT \]
\[ BRRAT = BRIGHT * RAT \]
\[ DRAT = D * RAT * m \]
\[ DRTOT = 4.6 \]
\[ \text{IF } \text{AUNITS} = "\text{SQ FT}" \text{THEN } DRTOT = 3.28 \text{ * DRTOT} \]
\[ DT = (\text{DRTOT} - D) \]
\[ DTRAT = DT * RAT * m \]
\[ \text{brat} = B * RAT \]
\[ \text{BLRATA} = \text{BLRAT} + 40 \]
\[ \text{brbc} = \text{BLRATA} - (\text{BRAT}) / 2 \]
\[ \text{brtr} = \text{BRTR} \]
\[ \text{bltr} = \text{brrc} \]
\[ \text{LINE} (\text{bltc}, \text{bltr})-(\text{brbc}, \text{brbr}), \ B \]
\[ \text{LINE} (40, 160)-(600, 160) \]

\[ \text{REM FRAME WORK} \]
\[ \text{RAT} = 560 / \text{BTOTAL} \]
\[ \text{BLRAT} = \text{BLEFT} * \text{RAT} \]
\[ \text{BRRAT} = \text{BRIGHT} * \text{RAT} \]
\[ \text{IF } \text{VYQL} > \text{VYQR} \text{THEN } \text{VYQ} = \text{VYQL ELSE } \text{VYQ} = \text{VYQR} \]
\[ \text{IF } \text{QL} > \text{QR} \text{THEN } \text{Q} = \text{QL ELSE } \text{Q} = \text{QR} \]
\[ \text{IF } \text{VYQ} < .2 \text{THEN } \text{VRAT} = 350: \text{VP} = .2 \]
\[ \text{IF } (\text{Q} < .1) \text{AND } (\text{Q} < .2) \text{THEN } \text{DRAT} = 700: \text{DP} = .1 \]
\[ \text{PRINT } \text{VP}; " \text; \text{PRINT } \text{TAB(33); } " \text{RETURN VELOCITY} \text{PRINT } \text{TAB(12); } " \text{LEFT"; } \text{TAB(60); } " \text{RIGHT} \text{PRINT } \text{VP} = \text{.5} \]
\[ \text{IF } \text{uniS} = "\text{m}" \text{OR } \text{uniS} = "\text{M}" \text{THEN } \text{PRINT } \text{"M/SEC} \text{PRINT } \text{" 0 "}; \text{LEFT} " \text{< 0"; } \text{TAB(60); } " \text{0 } \text{ "}; \text{BRIGHT} \text{PRINT } \text{TAB(36); } " \text{DRAWDOWN} \]

Figure 32. (Sheet 6 of 12)
PRINT " M"
ELSE PRINT "F/SEC"
PRINT " 0 " ; BLEFT ; " < 0" ; TAB(60) ; " 0 > "; BRIGHT
PRINT TAB(36) ; "DRAWDOWN"
PRINT " FT"
END IF
PRINT
PRINT DP
LINE (40, 5)-(40, 160)
LINE (40, 80)-(600, 80)
LINE (600, 5)-(600, 160)
LINE (40, 290)-(600, 290)
LINE (35, 10)-(45, 10)
LINE (35, 150)-(45, 150)
FOR I = 1 TO 8
PRINT NEXT I
REM XSECTION
DMAX = (.75) * ((ALEFT / BLEFT) + (ARIGHT / BRIGHT))
DLEFT = ((2 * ARIGHT) / BRIGHT) - (DMAX / 2)
DRIGHT = ((2 * ARIGHT) / BRIGHT) - (DMAX / 2)
BRRAT = BRIGHT * RAT
DLRAT = DLEFT * RAT
DRRAT = DRIGHT * RAT
DMRAT = DMAX * RAT
SELECT CASE DMRAT
CASE IS > 60
  m = 1
CASE 40 TO 60
  m = 2
CASE 26 TO 39
  m = 3
CASE 20 TO 25
  m = 4
CASE 1 TO 19
  m = 5
END SELECT
DLRAT = DLRAT * m
DRRAT = DRRAT * m
DMRAT = DMRAT * m
BLP1C = DLRAT / 2 + 40
BLP2C = BLEFT * RAT + 40 + BLP2C
BRP1C = BRRAT / 2 + 40 + BLP2C
BLPIR = DLRAT + 160
BLP2R = DMRAT + 160
BRPIR = DRRAT + 160
LINE (1, 152)-(30, 152)
LINE (30, 152)-(40, 160)
LINE (40, 160)-(BLP1C, BLPIR)
LINE (BLP1C, BLPIR)-(BLP2C, BLP2R)
LINE (BLP2C, BLP2R)-(BRPIR, BRPIR)
LINE (BRPIR, BRPIR)-(600, 160)
LINE (600, 160)-(610, 152)
LINE (610, 152)-(640, 152)
LINE (BLP2C, 150)-(BLP2C, 5)

Figure 32. (Sheet 7 of 12)
DLRAT = DLEFT * RAT
DRRAT = DRIGHT * RAT
DMRAT = DMAX * RAT
PRINT TAB(30); "BED CROSS-SECTION"
PRINT "Bed Depth & Barge Draft are Increased by a Factor of"; m;
PRINT "for Display Purposes"
PRINT TAB(10); "Barge Location and Size are to Scale(hit space bar to continue)

REM PROP
IF BTOTAL < 150 THEN
DIM PX(15), PY(15)
IF PC = 0 THEN
FOR I = 1 TO 12
READ PX(I)
READ PY(I)
NEXT I
DATA 10,13,15,17,20,20,24,27,28,30,30,28,28,24,20,20,18,16,15,12,14,10,10,13
PC = 1
END IF
FOR I = 1 TO 11
LINE (PX(I) + BLRAT + 20, PY(I) + 140)-(PX(I + 1) + BLRAT + 20, PY(I + 1) + 14)
NEXT I
END IF

REM DRAWDOWN & VELOCITY LEFT SIDE
ALF = ALFL: VRM = VRLM
ZALF = ZALFL: ZSM = ZSML
BSIDE = BLEFT
C = 3! * LOG(1 / ALF)
ZC = 3! * LOG(1 / ZALF)

REM Y=DISTANCE VY=VELOCITY ZY=DRAWDOWN
REM YL(I)-YLC(I) VYL(I)-VYL(I) ZL(I)-ZLR(I)
FOR I = 1 TO 5
dum = -BSIDE
Y = (dum + (I - 1) / 4 * (BSIDE - B))
YL(I) = -Y
YLC(I) = (BLRAT + 40) - (RAT * YL(I))
YY = ABS(YL(I))
VYL(I) = VRM * EXP(C * (yy - B) / (BSIDE - B))
VYL(I) = 80 - (VYL(I) * VRAT)
ZL(I) = ZSM * EXP(ZC * (yy - B) / (BSIDE - B))
ZLR(I) = ZL(I) * DRRAT + 85
NEXT I

REM DRAWDOWN & VELOCITY RIGHT SIDE
ALF = ALFR: VRM = VRRM
ZALF = ZALFR: ZSM = ZSMR
BSIDE = BRIGHT
C = 3! * LOG(1 / ALF)
ZC = 3! * LOG(1 / ZALF)

REM Y=DISTANCE VY=VELOCITY ZY=DRAWDOWN
REM YR(I)-YRC(I) VRR(I)-VYRR(I) ZR(I)-ZRR(I)
FOR I = 1 TO 5
dum = B
YR(I) = (dum + (I - 1) / 4 * (BSIDE - B))
YR(I) = YR(I) * RAT + BLRAT + 40

Figure 32. (Sheet 8 of 12)
yy = ABS(YR(I))
VYR(I) = VRM * \exp(C \times (yy - B) / (BSIDE - B))
VYRR(I) = 80 - (VYR(I) \times VRAT)
ZR(I) = ZSM * \exp(2C \times (yy - B) / (BSIDE - B))
ZRR(I) = ZR(I) \times DRAT + 85
NEXT I

REM LOAD LINES INTO LINES.1 FILE
OPEN "LINES.1" FOR OUTPUT AS #1
FOR I = 1 TO 5
  IF I = 1 THEN
    PRINT #1, "BM";
    PRINT #1, USING "###"; YLC(I);
    PRINT #1, ";
    PRINT #1, USING "###"; VYLR(I);
  END IF
  IF I > 1 < 5 THEN
    PRINT #1, ";"
    PRINT #1, USING "###"; YLC(I);
    PRINT #1, ";"
    PRINT #1, USING "###"; VYLR(I);
  END IF
  IF I = 5 THEN
    PRINT #1, ";"
    PRINT #1, USING "###"; YLC(I);
    PRINT #1, ";"
    PRINT #1, USING "###"; VYLR(I)
  END IF
END I
FOR I = 1 TO 5
  IF I = 1 THEN
    PRINT #1, "BM";
    PRINT #1, USING "###"; YLC(I);
    PRINT #1, ";"
    PRINT #1, USING "###"; ZLR(I);
  END IF
  IF I > 1 < 5 THEN
    PRINT #1, ";"
    PRINT #1, USING "###"; YLC(I);
    PRINT #1, ";"
    PRINT #1, USING "###"; ZLR(I);
  END IF
  IF I = 5 THEN
    PRINT #1, ";"
    PRINT #1, USING "###"; YLC(I);
    PRINT #1, ";"
    PRINT #1, USING "###"; ZLR(I)
  END IF
END I
FOR I = 1 TO 5
  IF I = 1 THEN
    PRINT #1, "BM";
    PRINT #1, USING "###"; YRC(I);
    PRINT #1, ";"
    PRINT #1, USING "###"; VYRR(I);
  END IF
  IF I > 1 < 5 THEN
    PRINT #1, ";"
    PRINT #1, USING "###"; YRC(I);
    PRINT #1, ";"
    PRINT #1, USING "###"; VYRR(I);
  END IF
  IF I = 5 THEN
    PRINT #1, ";"
    PRINT #1, USING "###"; YRC(I);
    PRINT #1, ";"
    PRINT #1, USING "###"; VYRR(I)
  END IF
END I

Figure 32. (Sheet 9 of 12)
PRINT #1, USING "###"; VYRR(I);
END IF
IF I = 5 THEN
PRINT #1, "M";
PRINT #1, USING "###"; YRC(I);
PRINT #1, ",";
PRINT #1, USING "###"; VYRR(I)
END IF
NEXT I
FOR I = 1 TO 5
IF I = 1 THEN
PRINT #1, "BM";
PRINT #1, USING "###"; YRC(I);
PRINT #1, ",";
PRINT #1, USING "###"; ZRR(I);
END IF
IF 1 < I > 5 THEN
PRINT #1, "M";
PRINT #1, USING "###"; YRC(I);
PRINT #1, ",";
PRINT #1, USING "###"; ZRR(I);
END IF
IF I = 5 THEN
PRINT #1, "M";
PRINT #1, USING "###"; YRC(I);
PRINT #1, ",";
PRINT #1, USING "###"; ZRR(I)
END IF
NEXT I
CLOSE #1

REM DRAW LINES THROUGH POINTS
OPEN "LINES.1" FOR INPUT AS #1
LINE INPUT #1, LVEL$
DRAW "X" + VARPTR$(LVEL$)
LINE INPUT #1, LDRAW$
DRAW "X" + VARPTR$(LDRAW$
LINE INPUT #1, RVEL$
DRAW "X" + VARPTR$(RVEL$)
LINE INPUT #1, RDRAW$
DRAW "X" + VARPTR$(RDRAW$)
CLOSE #1
SLEEP
RETURN

PAPER:
CLS
PRINT "INSURE YOUR PRINTER IS ON WITH PAPER IN IT"
FOR I = 1 TO 4
LPRINT
LPRINT TAB(12); "PROGRAM NAVEFF.BAS-SCHIJF METHOD PLUS EMPIRICISM"
LPRINT TAB(12); "PROGRAM NAVEFF.BAS-SCHIJF METHOD PLUS EMPIRICISM"
LPRINT "EXPERIMENTAL DATA USED IN DEVELOPMENT LIMITED TO THE FOLLOWING:"
LPRINT "BLOCKAGE RATIO LESS THAN 85"
LPRINT "DISTANCE ON SIDE OF VESSEL GREATER THAN 10% OF TOTAL CHANNEL WIDTH"
LPRINT "AND GREATER THAN VESSEL BEAM"
LPRINT "VESSEL LENGTH GREATER THAN 40% OF CHANNEL WIDTH"
LPRINT "RETURN VELOCITY AND DRAWDOWN LIMITED TO ONE BEAM WIDTH AWAY"

Figure 32. (Sheet 10 of 12)
LPRINT " FROM VESSEL CENTERLINE OUT TO THE SHORELINE"
FOR I = 1 TO 8
LPRINT
NEXT I
LPRINT TAB(25); "DATA SHOWN IS THE INPUT DATA"
LPRINT
LPRINT " CHANNEL TOTAL AREA "; USING "#####.#"; ATOTAL;
LPRINT " "; AUNIT$;
LPRINT " AREA LEFT OF TOW "; USING "#####.#"; ALEFT;
LPRINT " "; AUNIT$;
LPRINT " TOTAL WIDTH "; USING "#####.#"; BTOTAL;
LPRINT " "; LUNIT$;
LPRINT " DISTANCE, LEFT BANK TO TOW "; USING "#####.#"; BLEFT;
LPRINT " "; LUNIT$;
LPRINT " TOW WIDTH "; USING "#####.#"; B;
LPRINT " "; LUNIT$; " DRAFT "; USING "#####.#"; D;
LPRINT " "; LUNIT$;
LPRINT " AVERAGE CHANNEL VELOCITY(+=UPBOUND,-=DOWN) "; USING "#####.#"; VAM;
LPRINT " "; VUNIT$;
LPRINT
IF VLIMRAT > .35 THEN GOTO 255
LPRINT " WARNING******** SPEED THRU WATER LESS THAN 0.35*LIMIT SPEED ********
255 IF VLIMRAT < .9 THEN GOTO 257
LPRINT " WARNING******** SPEED THRU WATER GREATER THAN 0.9*LIMIT SPEED ********
257 REM
FOR I = 1 TO 5
LPRINT
NEXT I
LPRINT TAB(15); "COMPUTED RETURN VELOCITY AND DRAWDOWN DISTRIBUTION"
LPRINT
LPRINT TAB(15); "DISTANCE"; TAB(37); "RETURN"; TAB(54); "DRAWDOWN"
LPRINT TAB(15); "FROM TOW CL"; TAB(37); "VELOCITY"
LPRINT TAB(15); LUNIT$; TAB(37); VUNIT$; TAB(54); LUNIT$
LPRINT
FOR J = 1 TO 2
IF J = 2 THEN GOTO 260
ALF = ALFL; VRM = VRLM
ZALF = ZALFL; ZSM = ZSML
BSIDE = BLEFT
GOTO 270
260 ALF = ALFR; VRM = VRRM
ZALF = ZALFR; ZSM = ZSMR
BSIDE = BRIGHT
270 C = 3! * LOG(1 / ALF)
2C = 3! * LOG(1 / ZALF)
,
YLAST = 0
FOR I = 1 TO 5
IF J = 1 THEN dum = -BSIDE
IF J = 2 THEN dum = B
Y = (dum + (I - 1) / 4 * (BSIDE - B))
YY = ABS(Y)
VY = VRM * EXP(C * (YY - B) / (BSIDE - B))
ZY = ZSM * EXP(2C * (YY - B) / (BSIDE - B))

Figure 32. (Sheet 11 of 12)
exceeds the Schijf return velocity and prompts for a new speed. At the end of each tabular output, the program produces a screen image of the cross section, tow, and computed return velocity and drawdown.

Example Problem (based on WC Norman tow on Kamps ville trip 1 field data):

a. Determine return velocity and drawdown distribution for a navigation channel having a 359-m top width and 1,309-sq-m cross-sectional area. The tow is 222 m from the left bank which results in a cross-sectional area left of the tow of 800 sq m. The barges draft 2.74 m, have a total beam of 32 m, and a total length of barges of 238 m. The downbound tow travels at 2.9 m/sec relative to ground against an average ambient velocity of 0.49 m/sec.

b. Solution: Enter an "m" to indicate the use of metric units followed by the geometric factors. Enter an average channel velocity of -0.49 m/sec, since this is a downbound tow. Enter a vessel speed relative to ground of 2.9 m/sec. The vessel length is used to ensure the ratio of vessel length/channel width exceeds 0.4 and to compute the displacement thickness to determine the effective draft and beam of the vessel. The program output is shown in Figure 33.
PROGRAM NAVEFF.BAS—SCHIJF METHOD PLUS EMPIRICISM

EXPERIMENTAL DATA USED IN DEVELOPMENT LIMITED TO THE FOLLOWING:

- BLOCKAGE RATIO LESS THAN 85
- DISTANCE ON SIDE OF VESSEL GREATER THAN 10% OF TOTAL CHANNEL WIDTH
- VESSEL LENGTH GREATER THAN 40% OF CHANNEL WIDTH
- RETURN VELOCITY AND DRAWDOWN LIMITED TO ONE BEAM WIDTH AWAY FROM VESSEL CENTERLINE OUT TO THE SHORELINE

DATA SHOWN IS THE INPUT DATA

<table>
<thead>
<tr>
<th>CHANNEL TOTAL AREA</th>
<th>AREA LEFT OF TOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1309.0 SQ M</td>
<td>800.0 SQ M</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOW WIDTH</th>
<th>DISTANCE, LEFT BANK TO TOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>359.0 METERS</td>
<td>222.0 METERS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOW LENGTH</th>
<th>DRAFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.0 METERS</td>
<td>2.74 METERS</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TOW SPEED RELATIVE TO GROUND</th>
<th>AVERAGE CHANNEL VELOCITY (+=UPBOUND, -=DOWN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.90 M/SEC</td>
<td>-0.49 M/SEC</td>
</tr>
</tbody>
</table>

COMPUTED RETURN VELOCITY AND DRAWDOWN DISTRIBUTION

<table>
<thead>
<tr>
<th>DISTANCE FROM TOW CL METERS</th>
<th>RETURN VELOCITY M/SEC</th>
<th>DRAWDOWN METERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEFT BANK</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-222.0</td>
<td>0.155</td>
<td>0.049</td>
</tr>
<tr>
<td>-174.5</td>
<td>0.185</td>
<td>0.053</td>
</tr>
<tr>
<td>-127.0</td>
<td>0.220</td>
<td>0.058</td>
</tr>
<tr>
<td>-79.5</td>
<td>0.263</td>
<td>0.064</td>
</tr>
<tr>
<td>-32.0</td>
<td>0.313</td>
<td>0.070</td>
</tr>
<tr>
<td>32.0</td>
<td>0.364</td>
<td>0.079</td>
</tr>
<tr>
<td>58.3</td>
<td>0.324</td>
<td>0.084</td>
</tr>
<tr>
<td>84.5</td>
<td>0.289</td>
<td>0.075</td>
</tr>
<tr>
<td>110.8</td>
<td>0.257</td>
<td>0.071</td>
</tr>
<tr>
<td>137.0</td>
<td>0.229</td>
<td>0.067</td>
</tr>
</tbody>
</table>

RIGHT BANK

Figure 33. Output from PC program NAVEFF
8 Results and Conclusions

The recommended 1995 analytical method presented herein is based on conservation of energy plus empiricism to define the distribution of return velocity and drawdown. The 1995 analytical method is summarized to compute the following:

a. Schijf return velocity and drawdown using Equations 1 and 2.

b. Average return velocity using Equation 13.

c. Compute average return velocity on each side of the vessel using Equations 14 and 15.

d. \( \frac{V_{rm}}{V_n} = \alpha' \) using Equation 16.

e. C using Equation 17.

f. \( V_r(Y) \) using Equation 10. \( V_r(Y) \) is linearly added to or from ambient currents.

g. \( z(Y) \) using Equations 18 through 22.

The 1995 analytical method should be limited to:

a. N less than 85. While the vast majority of the data had \( N < 52 \), the limited data from the Clark's Ferry pool 572.7 physical model tests for \( N \) of about 85 resulted in significant scatter but exhibited the correct trend about the line of perfect agreement.

b. Tow length greater than 40 percent of the channel width.

c. Distance on both sides of tow center line equal to or greater than 10 percent of the total channel width.

d. Distance \( Y \) from the tow center line greater than tow width \( B \).

e. Vessel speed equal to 35 to 90 percent of the limiting speed.
f. The predictive method presented herein, is applicable to river reaches that can be characterized by a single cross section. One would not expect these techniques to provide valid results at the end of an island or in other areas where the cross section varies rapidly.

Areas of needed research for this method are more data for N greater than 52, variable tow length less than 0.4 times the channel width, and better data supporting the distribution of water-level drawdown. Future versions of the NAVEFF model will include propeller jet effects as well as short-period wave activity.
References


Maynard, S. T., and Martin, S. K. (1996a). "Physical model study of navigation effects on Illinois River at Kampsville, IL" (technical report in preparation), U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.


U.S. Army Engineer District, Huntington. (1980). "Gallipolis Locks and Dam Replacement, Ohio River, Phase 1, advanced engineering and design study, General Design Memorandum; Appendix J, Volume 1, environmental and social impact analysis," Huntington, WV.
Appendix A

Notation

\(A_c\) Undisturbed channel area

\(A_w\) Disturbed channel area around midsection of vessel

\(A_m\) Submerged cross-sectional area of vessel at midsection

\(\beta\) Coefficient that varies with \(V/V_L\) in the Schijf equations to improve agreement between observed and computed return velocity and drawdown.

\(B_o\) Channel width

\(B\) Beam of vessel

\(B_{side}\) Distance from vessel center line to shoreline

\(g\) Gravitational acceleration

\(h\) Undisturbed average water depth

\(L\) Vessel length

\(N\) Ratio of channel cross-sectional area to vessel cross-sectional area

\(V\) the vessel speed

\(V_L\) Maximum speed (called the critical or limiting speed)

\(V_r\) Average return velocity

\(V_{rm}\) Maximum return velocity

\(V_{rs}\) Average return velocity for each side of vessel

\(V_{rms}\) Maximum return velocity on each side of the tow
$V_r(Y)$ Maximum return velocity during tow event
$Y$ Distance from center line of vessel
$z$ Average water-level drawdown
$Z_{rs}$ Average drawdown for each side of vessel
$Z_{um}$ Maximum drawdown for each side of vessel
$Z(Y)$ Maximum water-level drawdown during tow event
# Return Velocity and Drawdown in Navigable Waterways

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**Abstract:**
An analytical method for estimating return velocity and drawdown is developed based on physical model study data for the Kampsville reach, Illinois River and the Clark's Ferry reach, Mississippi River. The analytical method uses conservation of energy plus empiricism to define the distribution of maximum return velocity and maximum drawdown during the tow event. The method is compared to prototype return velocity and drawdown data from two sites on the Illinois River, two on the Mississippi River, and four on the Ohio River.

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- Drawdown
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- Navigation
- Tows

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