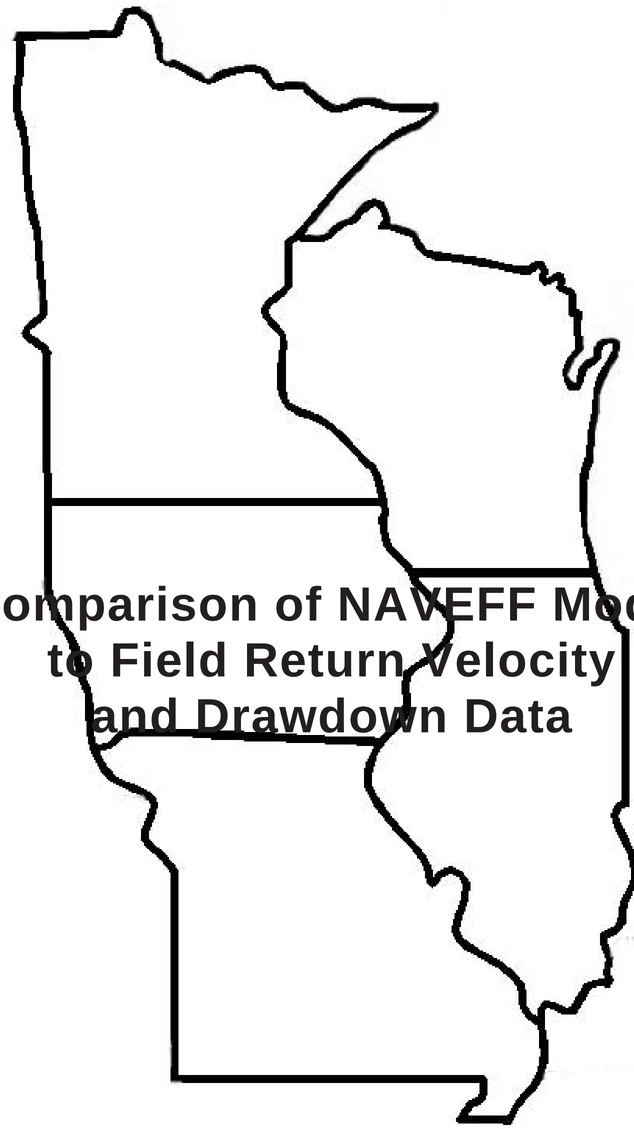
ENV Report 14

Interim Report For The Upper Mississippi River - Illinois Waterway System Navigation Study



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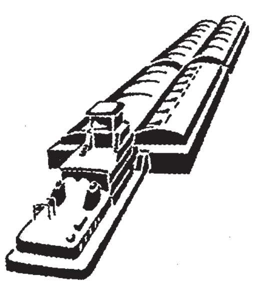

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Comparison of NAVEFF Model to Field Return Velocity and Drawdown Data

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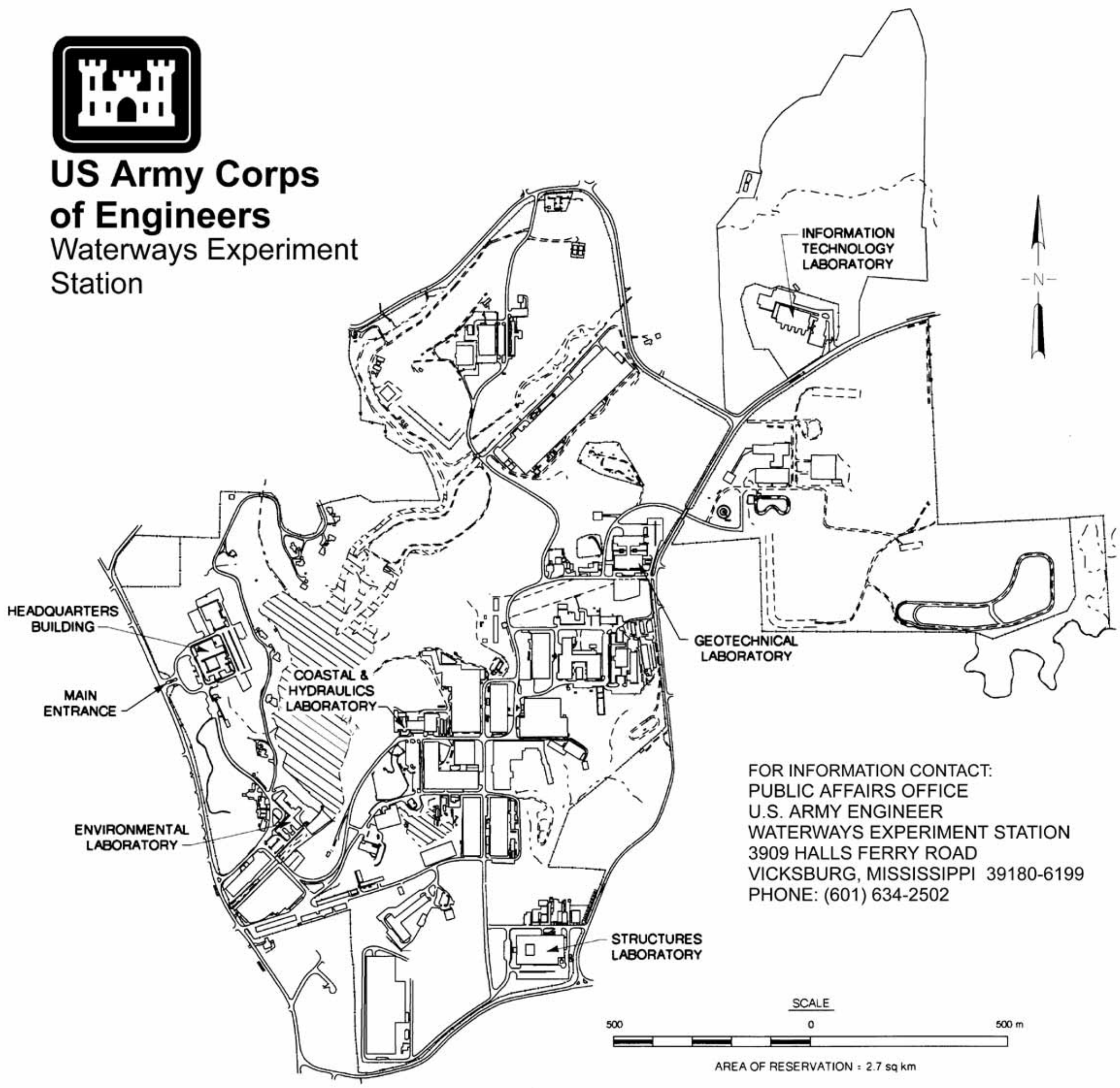

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Contents

Preface

The work reported herein was conducted as part of the Upper Mississippi River - Illinois Waterway (UMR-IWW) System Navigation Study. The information generated for this interim effort will be considered as part of the plan formulation process for the System Navigation Study.

The UMR-IWW System Navigation Study is being conducted by the U.S. Army Engineer Districts of Rock Island, St. Louis, and St. Paul under the authority of Section 216 of the Flood Control Act of 1970. Commercial navigation traffic is increasing, and in consideration of existing system lock constraints, will result in traffic delays which will continue to grow into the future. The system navigation study scope is to examine the feasibility of navigation improvements to the Upper Mississippi River and Illinois Waterway to reduce delays to commercial navigation traffic. The study will determine the location and appropriate sequencing of potential navigation improvements on the system, prioritizing the improvements for the 50-year planning horizon from 2000 through 2050. The final product of the System Navigation Study is a Feasibility Report which is the decision document for processing to Congress.

The study was performed during 1995 - 1998 by personnel of the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, a complex of five laboratories of the U.S. Army Engineer Research and Development Center (ERDC). The study was under the direction of Dr. James R. Houston, Director, CHL; Mr. Charles C. Calhoun, Jr., Assistant Director, CHL; and Mr. C. E. Chatham, Jr., Chief of the Navigation and Harbors Division (NHD), CHL. The NAVEFF studies were conducted by Dr. S. T. Maynord, Navigation Branch, NHD.

At the time of publication of this report, the Commander of ERDC was COL Robin R. Cababa, EN, and the Acting Director was Dr. Lewis E. Link, Jr. This report was prepared and published at the WES complex of ERDC.

1 Introduction

Background

The NAVEFF model reported in Maynord (1996b) is an analytical/empirical model for estimating the maximum return velocity and drawdown that occurs across a river section during passage of shallow draft navigation. The analytical part of the model makes use of the one dimensional energy equation along with mass conservation to define the average return velocity and drawdown during vessel passage. By basing the NAVEFF model on conservation laws, the model can be applied to a wide range of cross-section sizes without having to collect verification data for all channel sizes as would be required for a purely regression based approach. The empirical part of the model proportions the average return velocity and drawdown on each side of the vessel depending upon the vessels position in the cross section. An exponential decay function is used to define the return velocity and drawdown distribution between the vessel and the shoreline.

While most of the prototype return velocity and drawdown data taken on the Upper Mississippi River System (UMRS) by the Illinois State Water Survey (ISWS) and WES have been taken in the region near the shore, the NAVEFF model was based on data from a physical model which was first verified against prototype data in the near shore region and then used to collect data in the physical model from the shoreline to the center of the tow.

The empirical data used to develop the NAVEFF model resulted in the following limitations:

1) Blockage ratio N = Channel cross-sectional area/vessel cross-sectional area < 85. This limitation poses no significant problem for evaluating tow effects on the UMRS because magnitude of drawdown and return velocity for N>85 is negligible for even high speed tows.

2) Total barge length > 0.4 times the channel width. Comparisons of return velocity for various tow lengths (Maynord and Martin, 1998) show that, over the majority of the cross-section, return velocity decreases as the tow length/channel width falls below 0.4. Stated otherwise, NAVEFF will give a conservative estimate for tows that are short relative to the channel width.

3) Centerline of tow must be greater than 10 percent of channel width away from shoreline.

4) Predictions valid from shoreline to one vessel width away from vessel centerline.

5) River reaches where cross section is not changing rapidly.

In addition to the above limitations, the NAVEFF model has not been evaluated in bends because of lack of data in these reaches. In mild bends where tows can travel through without flanking/maneuvering resulting in a skewed tow, the method presented herein should be valid. When the tow is skewed with respect to the centerline, the effective width of the tow increases to an amount that is not known and the model is not valid. However, when the tow is skewed because of flanking/maneuvering through the bend, the speed of the tow relative to the water is generally low which results in low, many times insignificant, values of return velocity and drawdown.

The empirical part of the NAVEFF model was developed based on physical model investigations of the Illinois River near Kampsville (Maynord and Martin, 1997) and the Mississippi River near Clark's Ferry (Maynord and Martin, 1998). Both physical models were adjusted and verified against field data collected by the Illinois State Water Survey (ISWS). The NAVEFF model compared favorably to physical model and field data from Kampsville and Clark's Ferry (Maynord, 1996b) since this was the data used to develop the model. The physical model return velocity from the Kampsville model (Maynord and Martin, 1997) used to develop the NAVEFF model ranged up to 1.0 m/sec and drawdown from the Kampsville model ranged up to 0.35 m. Prototype return velocity data compared to NAVEFF in Maynord (1996b) ranged up to 0.4 m/sec while prototype drawdown ranged up to 0.1 m.

Independent data were also used in Maynord (1996b) to test NAVEFF. Return velocity data from field tests on the Illinois River and the Mississippi River were used from Environmental Science and Engineering (1981) and were found to provide fair agreement with the NAVEFF model (Maynord, 1996b). Return velocity and drawdown data were collected at four sites on the Ohio River by the US Army Engineer District, Louisville. The NAVEFF model provided a reasonable prediction of both return velocity and drawdown (Maynord, 1996b) on the four Ohio River sites.

Some investigators prefer to look at a variety of methods for estimating parameters such as return velocity and drawdown. Other methods that are available for estimating return velocity and drawdown include Hochstein and Adams (1989), an earlier version of the approach used in NAVEFF and provided in Maynord and Siemsen (1991), Mazumder et al (1993), Bhowmik et al (1995), and Bhowmik et al (1998).

Objective

The objective of this study is to compare the NAVEFF model to additional return velocity and drawdown field data from the UMRS and the Gulf Intracoastal Waterway that were not used in development of the model. Of particular interest is the use of field data in which enough velocity meters were used to test the shape of the exponential distribution used in the NAVEFF model to define the return velocity distribution across the channel. In addition to return velocity and drawdown, the maximum water-level drawdown from NAVEFF model was compared to observed squat from deep draft ships on the St Lawrence Seaway.

Approach

The NAVEFF model was tested against the following data:

(1) ISWS data on the Illinois River near McEvers Island (Bhowmik et al, 1994a), the Mississippi River near Apple River Island (Bhowmik et al, 1994b), and the Mississippi River near Goose Island (Bhowmik et al, 1994c)

(2) Waterways Experiment Station data on the Mississippi River at Pool 8 and the Illinois Waterway at Lagrange, (Pratt and Fagerburg, draft).

(3) Gulf Intracoastal data reported in Zhang et al (1993)

(4) Ship squat data on the St Lawrence Seaway reported in Tothill (1966)

To evaluate the goodness of fit of the NAVEFF model to the observed data, two error measures are used from Maynord (1996a). The mean relative error (MRE) is a measure of the dispersion of the predictions and is defined as

$$MRE = \frac{\Sigma \left| \frac{CALCULATED - OBSERVED}{OBSERVED} \right|}{n} \tag{1}$$

Where n = number of observations. The second error measure, mean trend error (MTE), is defined as

$$MTE = \frac{\Sigma \frac{CALCULATED - OBSERVED}{OBSERVED}}{n}$$

MRE and MTE become percentages when multiplied by 100. MRE is similar to Willmott's (1982) mean absolute error (MAE) but is divided by the individual observed value to provide a relative error. MTE is similar to Willmott's mean bias error (MBE) but is also divided by the individual observed value to provide a relative error measure. Willmott points out that these relative error measures (MRE and MTE) have problems because they are unbounded and are strongly affected by small observed values. An alternative to MRE and MTE that is not as affected by individual low observed values is to divide the difference between observed and computed by the average observed value rather than the individual observed value as used herein. Evaluation of MRE and MTE is as follows:

1) If MRE is low, MTE will also be low, and the model is accurately predicting observed results and dispersion is low.

2) If MRE is not low, MTE is used to determine if the model follows a trend of high or low prediction. Positive MTE indicates over prediction, negative MTE, under prediction. If MTE is low but MRE is high, the average trend of the model is correct but the dispersion is large.

The difference measures of MRE and MTE are used in lieu of the frequently used correlation coefficient r or r^2 . The author has observed cases where correlation coefficients and difference measures such as MRE give opposite findings regarding how well a model fits observed data. Willmott (1982) also questions whether Ar@ or Ar^2 A should be used at all. Willmott states AThe main problem is that the magnitudes of r and r^2 are not consistently related to the accuracy of the prediction, i.e., where accuracy is defined as the degree to which model-predicted observations approach the magnitudes of their observed counterparts.@ Willmott states that they should not be part of an array of model performance measures and recommends difference measures such as MBE and MAE. If this study had been to compare different models to a selected data set, absolute difference measures MBE and/or MAE would have been used in the evaluation. In this study, a single model (NAVEFF) was compared to several different data sets. Because the magnitude of return velocity and drawdown differed in the data sets, relative difference measures MRE and MTE were chosen for this evaluation.

2 Comparison with ISWS Data

Field Data Description

General. The ISWS collected velocity, water-level, and suspended sediment data before, during, and after vessel passage at 2 sites on the Illinois Waterway and 3 sites on the Mississippi River between 1989 and 1995 (Bhowmik et al. , 1998). Velocity data were collected with electromagnetic velocity meters and recorded at a rate of 1 sample/sec. An 11 second moving average was used to smooth the velocity data before extracting the return velocity from the time history of velocity. The water level data were collected with a wave gage manufactured at the ISWS and were recorded at a rate of 10 samples/sec. No mention was made in the Bhowmik et al (1998) regarding any smoothing or moving average of the water level data before the drawdown was extracted from the time history of water level. Details of the three sites used in this analysis (the other two were used in Maynord, 1996b) are shown in Table 1.

Table 1. Details of ISWS Field Sites from Bhowmik et al (1998)

Site/river	Date(s)	Average Ambient Vel, m/sec	Channel top width, m	Average Depth, m	# of Tows	# of Working Velocity Meters
McEver's Island/ Illinois	5/15/89-5/19/89	0.27	230	3.37	12	5
Apple River/ Mississippi	5/14/95-5/25/95	0.81	400	5.16	25	7
Goose Island trip 1/ Mississippi	8/20/90-8/29/90	1.13	418	6.04	15	8
Goose Island trip 2/ Mississippi	7/15/91-7/25/91	0.83	403	5.49	37	13

Data collected by the ISWS appear to be accurate in spite of the difficulty in collecting this type of data. Return velocity data are almost certain to exhibit considerable scatter. Velocity meters are placed in an environment where it is difficult to insure consistency because of debris moving down the river or external electronic interference. Separation of tow influence from ambient conditions is always a challenge because the ambient stage and velocity in the river vary over time scale of a tow event. Maynord and Martin (1998) examined variations in ambient velocity prior to passage of a tow and found that the ambient velocity, after removing short period turbulent fluctuations, varies +- 15 percent about the mean ambient velocity during a 100 sec time period which is comparable to the passage time for a tow. Combination of the various sources of error leads to significant variability in the measured data. The only criticisms of the data collected by the ISWS was the lack of electronic recording wave gages at McEver=s Island site that were used at the other sites, the need for a greater period of water level measurement before the tow arrived, and the use of only one wave gage.

The field data from the three ISWS sites were screened first to eliminate data not meeting the requirements for blockage ratio being less than 85 and tow length being greater than 40 percent of the channel width. The ISWS collected tow event data for any tow passing the site during the observation period. Many of the tows for which data were collected were small or unloaded and produced return velocity or drawdown that could not be discerned from the ambient fluctuations. This initial screening reduces the data set to the largest tows which are the tows having the most impact on the waterway. This is important because the tow impact can only be extracted from the data record if the impact is significantly greater than the ambient fluctuations. The tow event data that were eliminated were generally tows that produced effects that were so small the effect could not be discerned from the ambient fluctuations.

A second screening was done to eliminate mixed tows which can be difficult to accurately define the vessels effective cross-sectional area and length. This basically reduced the data set to 2- or 3-wide by 3-, 4-, or 5-long tows with all barges having the same draft. The next screening was done to eliminate velocity meters that appeared unreliable or those which were less than one vessel width away from the vessel centerline. Reliability was determined herein based on how the ambient velocity from a meter compared to its neighboring velocity meters. The argument behind rejecting velocity meters based on ambient velocity is that if a meter can not provide a reliable estimate of ambient velocity, that meter can provide no useful information. All return velocity data were taken directly from the ISWS reports which used a 11 sec moving average to determine the maximum return velocity. Although the final data set was greatly reduced from the original number of tows, the data set was adequate to evaluate the NAVEFF model since the model is primarily based on physical laws rather than purely regression. As stated before, the majority of tows removed from the data set were small or unloaded tows that produce tow effects that are difficult to extract from normal variations in the ambient conditions.

The final screening was conducted regarding the drawdown data. Only data based on an electronic recording wave gage were used in the analysis. The original data files were obtained from the ISWS and a 11 second moving average was used to smooth the data just as the ISWS used an 11 sec moving average with the return velocity data. This smoothing removes short period wave activity and any electronic variations that are not part of the tow induced drawdown process. Staff gage data were not used because it was not known whether the staff gage values reflected only drawdown or drawdown plus any short period wave activity. The maximum drawdown resulting from the smoothing process was often less than the drawdown reported in the ISWS reports. The fact that the 11 sec moving average drawdown values are less than the drawdown values in the ISWS reports suggest to this author that a portion of the ISWS drawdown values can not be attributed to vessel induced drawdown because drawdown is a long period event. The quoted accuracy of the wave gages in the ISWS reports was 0.015 m which is 59% of the average of all drawdowns shown in the following paragraphs. The Apple River experiments and both Goose Island Experiments had only one electronic recording wave gage whereas the McEvers Island experiments had a staff gage. The manner in which these screening efforts affected the individual sites are presented in the following paragraphs.

Apple River Island on Mississippi River. Screening of the 25 tows from Bhowmik et al (1994b) resulted in the use of the following tows. Drawdown from the smoothing process is shown if a recording wave gage was used. The other pertinent data can be found in the ISWS report.

Cooperative Ambassador, drawdown not analyzed because staff gage used
Christine Bailey, drawdown not analyzed because staff gage used
Herman Pott, drawdown not analyzed because staff gage used
Dell Butcher, 0.027 m
T.S. Kunsman, 0.040 m
Trojan, 0.012 m
Cooperative Mariner, 0.067 m

One of the seven working velocity meters, MMB527/332 (Marsh McBirney Model #527, serial number 332) was rejected because the ambient velocity was about 64 percent of two adjacent velocity meters.

Goose Island on the Mississippi River Trip 1. Screening of the 15 tows from Bhowmik et al (1994c) resulted in the use of the following tows. Drawdown from the smoothing process is shown if a recording wave gage was used. The other pertinent data can be found in the ISWS report.

Sierra Dawn, data not available
Dell Butcher, 0.020 m
Dare Carlton, data not available
T.R. Beesber, 0.053 m
Kevin Michael, 0.021 m
Twin City, 0.041 m

None of the 8 working velocity meters from trip 1 were rejected.

Goose Island on the Mississippi River Trip 2. Screening of the 37 tows from Bhowmik et al (1994c) resulted in the use of the following tows. Drawdown from the smoothing process is shown if a recording wave gage was used. The other pertinent data can be found in the ISWS report.

Ardyce Randall, 0.020 m
Scarlet Knight, 0.021 m
James F. Neal, 0.030 m
Frank T. Heffelfinger(1), data not available
Queen City, data not available
Helen M Clements(2), 0.015 m
Frank T. Heffelfinger(2), 0.024 m
Conti-Karla, 0.033 m

Cooperative Mariner, 0.026 m
Hornet, 0.034 m
Sam M. Fleming, 0.041 m
Kevin Michael, 0.024 m
A.M. Thompson, 0.027 m
Badger, data not available
Dell Butcher, 0.025 m

None of the 13 working velocity meters from trip 2 were rejected.

McEvers Island on the Illinois River. Screening of the 12 tows from Bhowmik et al (1994a) resulted in the use of the following tows. No drawdown data were used because all tests used a staff gage for measurement of water level.

R.W. Naye
Mobil Leader
Cooperative Vanguard
Marvin Norman
Illini
Thurston B. Morton
Clarence G. Frame

Two of the five working meters were rejected. Meter MMB511/1000 (0.91 m above bed) was rejected because it had an ambient velocity which was about 60 percent of meter MMB511/999. Meter MMB 511/999 was placed directly below the rejected meter at 0.15 m above the bed. Meter S4/071(0.91 m above bed) was rejected because it was the meter farthest from the bank yet had an ambient velocity of only 16 percent of the average channel velocity. The magnitudes of the rejected meters would indicate that either they were not operating properly or there was some local phenomenon, such as an upstream bathymetry feature, affecting the output. One would not expect a one-dimensional approach like NAVEFF to predict correct magnitudes where local conditions introduce abnormalities.

Results

Apple River Island on Mississippi River. Results for return velocity for each of the 7 tow events are shown on Figures 1 and 2. A scatterplot of all return velocity data is shown in Figure 3. The MRE is 0.53 and the MTE is 0.37. Results for drawdown for the 4 tow events having drawdown data are shown in the Figure 4 scatterplot. The MRE and MTE are 0.69.

Goose Island Trip 1 on Mississippi River. Results for return velocity for each of the 6 tow events are shown on Figures 5 and 6. A scatterplot of all return velocity data is shown in Figure 7. The MRE is 0.38 and the MTE is 0.21. Results for drawdown for the 4 tow events having drawdown data are shown in the Figure 8 scatterplot. The MRE is 0.30 and the MTE is 0.003.

Goose Island Trip 2 on Mississippi River. Results for return velocity for each of the 15 tow events are shown on Figures 9-12. A scatterplot of all return velocity data is shown in Figure 13. The MRE is 0.51 and the MTE is 0.33. Results for drawdown for the 12 tow events having drawdown data are shown in the Figure 14 scatterplot. The MRE is 0.47 and the MTE is 0.44.

McEvers Island on Illinois River. Results for return velocity for each of the 7 tow events are shown on Figures 15 and 16. A scatterplot of all return velocity data is shown in Figure 17. The MRE is 0.35 and the MTE is 0.02. No wave gage drawdown data were available for McEvers Island.

Error Measures for All Data. Combining all ISWS return velocity data resulted in a MRE of 0.48 and a MTE of 0.29. Combining all ISWS drawdown data resulted in a MRE of 0.48 and a MTE of 0.40.

Exponential Decay Function

The Goose Island Trip 1 and 2 data provide the best field data to evaluate the shape of the exponential decay function for return velocity because eight velocity meters were spaced over about 220 m on one side of the waterway. Based on the plots of return velocity versus distance from vessel for each tow shown in Figure 5-6 and 9-12, the exponential decay function provides a good fit of the data.

Data Variability

As shown in the scatterplots and the values of MRE and MTE, there is significant scatter in the observed versus computed values. A portion of this scatter is due to the fact that NAVEFF does not account for many factors that could affect the prediction that were not included in the model. For example, the rake angle of the bow of the barges is difficult to obtain while taking field measurements. In developing NAVEFF it was assumed that this angle did not vary enough to warrant it's inclusion in NAVEFF. The one-dimensional formulation of NAVEFF means that a single cross section is used to describe the waterway whereas local variations in bathymetry could have an impact on measured return velocity. Vessels skewed only a few degrees relative to the channel axis could have an effective beam greater than the actual beam of the vessel. The writer believes that one of the main sources of scatter between observed and computed return velocity and drawdown is the difficulty in extracting the tow influence from the fluctuating ambient velocity or water level. The stage and ambient velocity in the river has fluctuations occurring at the same relatively low frequency as the tow. This makes it almost impossible to extract only the tow influence.

To analyze the data variability, the Goose Island Trip 2 data were analyzed for consistency of return velocity from tow events that should have resulted in similar values because of their similar size, draft, length, and position in the channel. Thirteen tows were 3X5, loaded, downbound, and traveling at about the same position in the river, with the sailing line varying from 49-101 m (160-330 ft) from the right bank in a channel about 400 m (1300 ft) wide. Thirteen velocity meters were used in the Goose Island Trip 2 tests. Only eight of the thirteen velocity meters had enough data (7 or more tow events) to conduct the analysis.

The primary difference between these thirteen tows was their speed which varied from 2.6 to 3.9 m/sec (8.4 to 12.8 ft/sec). The return velocity from each of the thirteen tows had to be normalized to make the thirteen tows comparable. The differences in tow speed were normalized by multiplying the maximum observed return velocity at each velocity meter by the ratio of the computed average return velocity from Jansen and Schijf (1953) for the Queen City tow to the computed return velocity for the given tow. The Queen City was chosen because it was the tow having speed closest to the average speed of the thirteen tows. This normalization converted all the observed maximum return velocities to the Queen City vessel speed which was 3.3 m/sec. The normalized maximum return velocity is shown in Table 2. To insure understanding of the normalization process, two examples are given. In example 1, the maximum return velocities (normalized) in Table 2 for the Queen City are the same actual return velocities as plotted in Figure 10 since the Queen City was the basis for the normalization and return velocities were not affected. In example 2, since the speed of the Ardyce Randall (2.9 m/sec) was less than the Queen City (3.3 m/sec), the Ardyce Randall return velocities had to be increased to be comparable to Queen City. The maximum return velocities (normalized) in Table 2 for the Ardyce Randall differ from Figure 9 actual return velocities by the ratio of the computed return velocities shown in Table 2, column 2, or 0.175/0.142 = 1.23. Meter M834, which is the Table 2 and Figure 9 velocity meter closest to the tow, has the highest actual return velocity near the tow of about 0.233 m/sec as shown in Figure 9. The corresponding value in Table 2 has a value of 0.233*1.23 = 0.287 m/sec.

Since the tows were similar and speeds were normalized, the maximum return velocity should be constant for a given velocity meter. The last three rows are the mean normalized return velocity, the standard deviation, and the standard deviation/ mean which is sometimes called the coefficient of variation (CV). Results show that the average CV for the 8 velocity meters is 34 percent. Under the best conditions of a single velocity meter placed and not moved and relatively constant flow rate, significant scatter exists in the data. This finding is not a criticism of the ISWS data collection but shows how difficult it is to obtain consistent tow effects data. This author expects any return velocity data set to show similar variability.

3 Comparison with WES Mississippi River and Illinois Waterway Data

Field Data Description

Velocity and water-level data were collected by WES on the Mississippi River and Illinois Waterway during 1995 and 1996 (Pratt and Fagerburg, draft). The most difficult aspect of comparing NAVEFF with the WES data was that many of the field data collection sites were near the ends of islands. NAVEFF, being a one-dimensional model, is not applicable to areas where the cross-sectional area and width is changing rapidly. The Pool 26 data on the Mississippi River were collected near island ends and were not used in the comparison. The cross-section at the velocity or water level probe location was used in NAVEFF to make the comparison. A second difficulty was that vessel speed, which is the most sensitive parameter, was determined from passage times at cross-sections that were several miles apart rather than speed at the measurement section. The data used in the comparison is shown in Table 3. Return velocity and drawdown data were filtered using a Fast Fourier Transform (FFT) to eliminate short period effects not caused by the tow. The 11 sec moving average used in the ISWS data and the FFT used with the WES data result in very similar smoothing of the data. Tows not meeting the NAVEFF limitations given in the Introduction are not shown in Table 3.

Results

Mississippi River at Pool 8. Main channel ranges 1 and 3 were used in the analysis. A scatterplot of observed versus computed drawdown is shown in Figure 18. MRE and MTE for drawdown are 0.43 and 0.31, respectively. One of the shortcomings of the difference measures MTE and MRE is that one or two data points having a small observed value and a large computed value will significantly affect the value of MRE and MTE, particularly when the sample size is small. As an example, removal of the one Pool 8 data point labeled as an outlier in Table 3 resulted in MRE and MTE for drawdown of 0.19 and 0.06, respectively. Outlier is defined herein as observed/computed < 0.5 or greater than 2.0. Removal of outliers was done only for the WES UMRS data not to make the WES data look better but to show the significance of outliers on the chosen error measures MRE and MTE.

Illinois Waterway at Lagrange. Scatterplots of observed versus computed return velocity and drawdown are shown in Figures 19 and 20, respectively. Using all data points, MRE and MTE for return velocity are 0.36 and 0.25, respectively. Without the two points on Lagrange return velocity labeled as outliers in Table 3, MRE and MTE for return velocity are 0.26 and 0.13, respectively. Using all data points, MRE and MTE for drawdown are 0.33 and 0.11, respectively. Without the three points on Lagrange drawdown labeled as outliers in Table 3, MRE and MTE for drawdown are 0.20 and -0.04, respectively.

Error Measures for All WES UMRS Data. Since there was no return velocity analysis on Pool 8, the Lagrange return velocity error analysis represents all WES UMRS data. Using all data points, MRE and MTE for drawdown are 0.35 and 0.15, respectively. Omitting the three outliers and combining all drawdown data resulted in a MRE of 0.22 and a MTE of 0.01.

4 Comparison with Gulf Intracoastal Waterway Data

Field Data Description

Zhang et al (1993) conducted measurements of return velocity and drawdown on the Gulf Intracoastal Waterway (GIWW) at the Aransas National Wildlife Refuge. Only loaded vessels were used in the comparison because it is not known whether to use the beam, draft, and length of the unloaded barges or the towboat which will often have a larger cross-sectional area but of much less length. Because the data were presented in dimensionless ratios that were not always consistent, required input for the NAVEFF model could only be determined for 6 of the 10 loaded tows as shown in Table 4. All data were taken at site two and all tows were assumed to travel down the center of the channel.

Results

Observed versus computed return velocity and drawdown are shown in Table 4. Scatterplots of observed versus computed return velocity and drawdown are shown in Figures 21 and 22, respectively. MRE and MTE for return velocity are 0.36 and 0.25, respectively. MRE and MTE for drawdown are 0.32 and -0.23, respectively.

5 Comparison with Ship Squat Data from St. Lawrence Seaway

Field Data Description

Tothill (1966) conducted measurements of deep draft ship squat on the Caughnawaga Section of the St Lawrence Seaway. In restricted channels like the Caughnawaga Section, vessel squat generally correlates well with water level drawdown. The cross-section was trapezoidal with a 72.3 m bottom width and 1V:1.8H side slopes. Input data for NAVEFF are shown in Table 5. The vessels used in the comparison were limited to those having an average draft greater than 7.3 m or average squat greater than or equal to 0.46 m. The data were further restricted to vessels having near zero initial trim by using fore draft/aft draft from 0.97 to 1.03. Fifty-four ships met these criteria out of Tothill's data base of 190 ships. Vessels in the data set had a minimum depth/ draft ratio of 1.14. The beam shown in Table 5 is 98 percent of the actual beam to account for the actual sectional area of the ship. Vessels were assumed to travel in the middle of the channel and the V_w shown in Table 5 is the vessel speed relative to the water.

Results

The comparison of observed average ship squat versus the maximum water level drawdown from NAVEFF is shown in Figure 23. While NAVEFF provides a conservative estimate of the vessel squat for most of the vessels, the amount of conservatism is not excessive. MRE and MTE were 0.23 and 0.18, respectively.

6 Discussion of Results and Conclusions

The ISWS data at Goose Island trip 2 show that for vessels that appear similar in all respects, the scatter in the data is large. The standard deviation of the observed return velocity averaged 34 percent of the return velocity for data that were taken at one cross-section at one flowrate and by velocity meters placed in the channel and left in their initial position. If the variability resulting from other flows, other cross-sections, other meter placement, and other velocity meters is introduced, the scatter becomes quite large. The deviation of observed versus computed return velocity and drawdown also arises from factors not used in NAVEFF, such as the skewness of the tow. The difficulty of extracting the vessel influence from ambient deviations will always contribute heavily to the scatter in the data.

Examination of the ISWS data presented in the scatterplots and the MTE shows that the NAVEFF model for return velocity tends to over predict by an average of 29 percent when all data are considered. The NAVEFF model for drawdown tends to over predict by an average of 40 percent when all data are considered. Concern about this amount of over prediction of drawdown should be tempered by the fact that the accuracy of the wave gage (stated as 0.015 m) is a substantial percentage of many of the drawdown measurements, such as those on Apple River (average drawdown = 0.04 m) and Goose Island (average drawdown = 0.03 m).

Examination of the individual tow event plots shows that the exponential decay function correctly fits the shape of the observed data in the majority of the tow events. This is particularly evident in the ISWS Goose Island Trip 1 and 2 plots where a large number of velocity meters extend over a 200 m width of the channel. Since drawdown data were only collected at one wave gage near the shoreline, additional data are needed to verify the distribution of drawdown between shoreline and vessel.

Examination of the WES UMRS data show that the NAVEFF model for return velocity tends to over predict by an average of 25 percent when all data are considered. The NAVEFF model for drawdown tends to over predict by an average of 15 percent when all data are considered. The error measures used herein are subject to a significant influence from data where the observed value is low and the calculated value is high. Removal of outliers (2 of 23 points in return velocity, 3 of 47 points from drawdown) from the data reduced the average over prediction of return velocity to 13 percent and of drawdown to 1 percent. Similar reductions in the error measures of the ISWS data would be expected by removal of outliers.

Examination of the GIWW data presented in the scatterplots and the MTE shows that the NAVEFF model for return velocity tends to over predict by about 25 percent. The NAVEFF model for drawdown tends to under predict by about 23 percent. The GIWW data were the only drawdown data suggesting significant under prediction by NAVEFF.

Examination of the Tothill (1966) data for ship squat in a confined channel show that maximum water level drawdown from the NAVEFF model provided a fair estimate of the average ship squat with an average over prediction of 18 percent.

The data presented herein show that the NAVEFF model tends to over predict return velocity by 25-29 percent when considering all data. The data presented herein for drawdown are mixed, with the ISWS showing an average over prediction of 40 percent, the WES UMRS data showing 15 percent, and the GIWW data showing an under prediction of 23 percent. Based on all of the comparisons of drawdown, the writer concludes that the over prediction of drawdown is no more than the 25-29 percent demonstrated by the return velocity over prediction. The overprediction of both return velocity and drawdown is probably less if the exaggerated influence of outliers is removed from the error measures.

Based on these comparisons and the need for some conservatism in parameters that are so difficult to measure, NAVEFF as presented in Maynord (1996b) is recommended for estimating return velocity and drawdown. Additional comparisons to ship squat data are needed before conclusions can be drawn regarding the applicability of NAVEFF.

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Table 2. Variability of Maximum Return Velocity Data

Tow	Calculated Return Velocity*, m/sec	Maximum Measured Return Velocity Normalized to Speed of Tow “Queen C”, m/sec								
		M1001**	M1130	M1131	M999	M1000	M642	M332	M071	M834
A Randl	0.142	-	0.068	0.064	0.097	0.038	0.118	0.202	-	0.287
S Knight	0.148	0.072	-	-	0.065	0.085	0.158	0.134	-	-
J Neal	0.226	0.072	0.042	0.066	0.034	0.043	0.089	0.151	0.085	0.133
Hefing1	0.133	-	0.063	0.080	0.046	0.042	0.207	0.149	-	-
Queen C	0.175	0.057	0.054	0.068	-	0.159	0.138	0.160	-	0.246
Clem2	0.123	0.081	0.057	0.074	-	-	0.305	-	0.134	0.249
Conti K	0.185	0.067	0.063	0.067	0.071	-	0.173	0.073	0.143	0.157
Coop M	0.139	-	-	-	0.064	0.089	0.173	-	-	0.222
Hornet	0.157	0.076	-	0.072	-	0.077	0.109	0.202	0.086	0.197
K Mich	0.142	0.047	0.074	0.076	-	-	0.150	0.192	0.077	-
A Thom	0.137	-	0.101	0.127	-	-	0.160	-	0.130	0.104
Badger	0.200	0.055	0.047	0.064	0.056	0.052	0.083	0.143	0.140	0.137
Dell B	0.148	0.135	0.069	-	-	-	0.130	0.059	0.068	-
Mean		0.073	0.064	0.076	0.062	0.073	0.151	0.147	0.108	0.192
S		0.025	0.016	0.019	0.020	0.040	0.051	0.049	0.031	0.063
CV		0.349	0.257	0.245	0.325	0.550	0.339	0.335	0.291	0.328

* return velocity calculated using Jansen and Schijf (1953)
** Velocity meter having serial number 1001

Table 3. WES UMRS Return Velocity and Drawdown Data

Pool	Month	Rng	Tow Name	Total Area sq m	Area Left* sq m	Total WS m	WS dist left m	Barge Width m	Barge Length m	Draft m	Velocity to grnd m/s	average ambient m/s	dir	WAVE dist to LB LD m	prot total drawdown m	computed total drawdown m	Velocity dist to LB LD m	prot return velocity m/sec	computed return velocity m/sec
8	Nov	1	B05	2742	1667	516	330	32	297.3	2.7	2.2	0.61	u	1.6	0.049	0.047	--	--	-
8	Nov	3	B05	1891.8	859.1	425.5	198.8	32	297.3	2.7	2.5	0.71	u	1.6	0.098	0.073	--	--	-
8	Sept	1	B02	2017.9	1037.7	439	250	32	119	2.7	2.3	0.25	u	4	0.014	0.043**	-	--	-
8	Sept	1	B05	2017.9	980.2	439	189	32	237.8	2.7	3.4	0.25	d	4	0.056	0.063	-	--	-
8	Sept	3	B01	1459.7	604.5	414.6	188.4	32	297.3	2.7	1.9	0.31	u	1.2	0.038	0.045	--	--	-
8	Sept	3	B02	1459.7	604.5	414.6	188.4	32	119	2.7	2.3	0.31	u	1.2	0.048	0.058	--	--	-
8	Sept	3	B03	1459.7	855.2	414.6	226.2	32	297.3	2.7	2.2	0.31	d	1.2	0.021	0.029	--	--	-
8	Sept	3	B05	1459.7	855.2	414.6	226.2	32	237.8	2.7	2.9	0.31	d	1.2	0.062	0.052	--	--	-

* channel area on port side of vessel centerline

** outlier in MTE/MRE analysis defined as observed/calculated , <0.5 or >2.0.

Table 3. Completed

Pool	Month	Rng	Tow Name	Total Area sq m	Area Left* sq m	Total WS m	WS dist left m	Barge Width m	Barge Length m	Draft m	Velocity to grnd m/s	average ambient m/s	dir	WAVE dist to LB LD m	prot total drawdown m	computed total drawdown m	Velocity dist to LB LD m	prot return velocity m/sec	computed return velocity m/sec
LG	July	2	B02	634.1	329.3	155.2	75.1	16.5	162	2.7	3.3	0.49	u	4.5	0.30	0.25	4.5	0.575	0.50
LG	July	2	B04	634.1	304.8	155.2	80.1	32	118.9	2.7**	1.7	0.49	d	4.5	0.034	0.034	4.5	0.185	0.287
LG	July	2	B05	634.1	304.8	155.2	80.1	32	118.9	2.7**	2.8	0.49	d	4.5	0.16	0.121	4.5	0.31	0.45
LG	July	2	B06	634.1	329.3	155.2	75.1	16.5	162	2.7	2.8	0.49	u	4.5	0.162	0.14	4.5	0.357	0.33
LG	July	3	B02	651.9	351.3	157.5	68.1	16.5	162	2.7	3.3	0.48	u	4.5	0.34	0.22	4.5	0.558	0.45
LG	July	3	B05	651.9	300.6	157.5	89.4	32	118.9	2.7**	2.7	0.48	d	4.5	0.077	0.116	4.5	0.315	0.445
LG	July	3	B06	651.9	351.3	157.5	68.1	16.5	162	2.7	2.65	0.48	u	4.5	0.14	0.11	4.5	-	-
LG	July	4	B02	651.9	351.3	157.5	68.1	16.5	162	2.7	3.3	0.48	u	4.5	0.218	0.22	4.5	--	--
LG	July	4	B04	651.9	300.6	157.5	89.4	32	118.9	2.7**	1.7	0.48	d	4.5	0.040	0.033	4.5	--	--
LG	July	4	B05	651.9	300.6	157.5	89.4	32	118.9	2.7**	2.6	0.48	d	4.5	0.13	0.095	4.5	--	--
LG	July	4	B06	651.9	351.3	157.5	68.1	16.5	162	2.7	2.5	0.48	u	4.5	0.10	0.10	4.5	--	--
LG	July	5	B02	616.3	307.2	152.9	82.1	16.5	162	2.7	3.3	0.5	u	4.5	0.35	0.29	4.5	0.486	0.53
LG	July	5	B04	616.3	309.1	152.9	70.8	32	118.9	2.7**	1.7	0.5	d	4.5	0.046	0.037	4.5	-	-
LG	July	5	B06	616.3	307.2	152.9	82.1	16.5	162	2.7	2.5	0.5	u	4.5	0.148	0.12	4.5	0.274	0.28
LG	Sept	2	B02	604.9	298.8	150.9	70.5	32	297.3	2.6	2.0	0.4	u	4.5	0.248	0.17	4.5	0.65	0.57
LG	Sept	2	B03	604.9	298.8	150.9	70.5	32	297.3	2.7	1.6	0.4	u	4.5	0.162	0.124	4.5	0.63	0.49
LG	Sept	2	B04	604.9	298.8	150.9	70.5	32	297.3	2.7**	1.8	0.4	u	4.5	0.162	0.145	4.5	0.66	0.53
LG	Sept	2	B09	604.9	298.8	150.9	70.5	32	154	2.7**	2.3	0.4	u	4.5	0.21	0.23	4.5	0.60	0.68
LG	Sept	2	B10	604.9	306.1	150.9	80.4	21.4	115	1.3**	2.1	0.4	d	4.5	0.071	0.044	4.5	0.112	0.21
LG	Sept	2	B12	604.9	298.8	150.9	70.5	32	178	2.7**	2.1	0.4	u	4.5	0.077	0.074	4.5	--	--
LG	Sept	3	B02	602.5	325.5	141.3	76	32	297	2.6	2	0.38	u	1.3	0.12	0.19	4.5	0.558	0.66
LG	Sept	3	B03	602.5	325.5	141.3	76	32	297	2.7	1.45	0.38	u	1.3	0.155	0.12	4.5	0.571	0.51
LG	Sept	3	B04	602.5	325.5	141.3	76	32	297	2.7**	1.8	0.38	u	1.3	0.183	0.16	4.5	0.65	0.58
LG	Sept	3	B09	602.5	325.5	141.3	76	32	154	2.7**	2.2	0.38	u	1.3	0.181	0.21	4.5	0.496	0.67
LG	Sept	3	B10	602.5	277	141.3	65	21.4	115	2.7**	2.75	0.38	d	1.3	0.045	0.081	4.5	0.254	0.28
LG	Sept	3	B12	602.5	325.5	141.3	76	32	178	1.3**	2.1	0.38	u	1.3	0.106	0.080	4.5	0.31	0.25
LG	Sept	4	B02	602.5	325.5	141.3	76	32	297.3	2.6	2	0.38	u	1.3	0.049	0.17***	12.2	--	--
LG	Sept	4	B03	602.5	325.5	141.3	76	32	297.3	2.7	1.4	0.38	u	1.3	0.106	0.11	12.2	--	--
LG	Sept	4	B04	602.5	325.5	141.3	76	32	297.3	2.7**	1.7	0.38	u	1.3	0.167	0.14	12.2	--	--
LG	Sept	4	B09	602.5	325.5	141.3	76	32	154	2.7**	2.1	0.38	u	1.3	0.142	0.19	12.2	--	--
LG	Sept	4	B10	602.5	277	141.3	65.3	21.4	115	2.7**	3.4	0.38	d	1.3	0.064	0.14***	12.2	--	--
LG	Sept	4	B12	602.5	325.5	141.3	76	32	178.4	1.3**	1.7	0.38	u	1.3	0.055	0.058	12.2	--	--
LG	Sept	5	B02	607.2	272.1	160.4	64.9	32	297.3	2.6	2	0.41	u	4.5	0.055	0.16***	4.5	--	--
LG	Sept	5	B03	607.2	272.1	160.4	64.9	32	297.3	2.7	1.4	0.41	u	4.5	0.093	0.095	4.5	--	--
LG	Sept	5	B04	607.2	272.1	160.4	64.9	32	297.3	2.7**	1.7	0.41	u	4.5	0.15	0.125	4.5	0.31	0.46
LG	Sept	5	B09	607.2	272.1	160.4	64.9	32	154	2.7**	2.1	0.41	u	4.5	0.190	0.175	4.5	0.27	0.55***
LG	Sept	5	B10	607.2	335.1	160.4	95.5	21.4	115	2.7**	3.4	0.41	d	4.5	0.106	0.127	4.5	0.12	0.35***
LG	Sept	5	B12	607.2	272.1	160.4	64.9	32	178.4	1.3**	1.7	0.41	u	4.5	0.052	0.051	4.5	0.13	0.179

* channel area on port side of vessel centerline
** Tow with mixed loaded and unloaded barges
*** outlier in MTE/MRE analysis defined as observed/computed <0.5 or >2.0.

Table 4. GIWW Drawdown and Return Velocity Data.

Tow Name	Area, m^2	Width m	Beam m	Length m	Draft m	Speed m/sec	Obs Draw, m	Comp Draw, m	Obs V_r, m/sec	Comp V_r, m/sec
Norah	389	119	16.5	181	2.90	2.17	0.18	0.11	0.52	0.40
Expres	326	107	16.5	167	2.90	1.66	0.12	0.08	0.33	0.40
C Law	326	107	16.5	84	2.29	2.59	0.20	0.15	0.45	0.46
W Eag	326	107	12.2	150	2.44	2.37	0.13	0.09	0.29	0.31
Irene	326	107	16.0	81	2.75	1.63	0.11	0.07	0.38	0.34
Bill M	325	107	16.5	142	2.68	2.35	0.12	0.15	0.21	0.53

Table 5. Observed Ship Squat and NAVEFF Maximum Water Level Drawdown

Name of Vessel	Length m	Beam m	Lock Fore m	Draft Aft m	Observed Fore m	Squat Aft m	VW m/sec	Computed Maximum Drawdown m	Water Surface Width m	Total Area sq m
Carl Trautwein	155.18	20.91	7.65	7.71	0.46	0.46	3.53	0.60	105.18	814.71
Cape Breton Miner	207.93	22.41	7.53	7.68	0.43	0.37	3.02	0.41	105.18	814.71
Cate Brovig	159.45	20.30	7.56	7.59	0.37	0.43	3.18	0.40	105.18	814.71
Seaway Queen	218.60	21.52	7.50	7.50	0.27	0.21	2.68	0.30	105.18	814.71
Venus	178.96	21.80	7.77	7.71	0.43	0.37	3.09	0.43	105.18	814.71
Arrow	167.38	20.30	7.44	7.53	0.37	0.43	3.09	0.36	105.18	814.71
Linda	128.96	17.04	7.65	7.71	0.34	0.37	3.31	0.34	105.49	821.13
Venture	177.74	21.52	7.41	7.56	0.70	0.73	3.94	0.95*	105.49	821.13
Atlantic Duke	161.28	20.91	7.68	7.71	0.82	0.40	3.76	0.77*	105.18	814.71
Anna Katrin Fritzen	162.20	20.61	7.68	7.71	0.49	0.34	3.44	0.54	105.18	814.71
Silverweir	152.44	20.03	7.68	7.56	0.49	0.30	3.49	0.52	105.18	811.46
Inverewe	159.76	20.61	7.26	7.47	0.73	0.85	3.85	0.74*	105.18	814.71
Skrim	150.00	18.23	7.65	7.56	0.46	0.27	3.44	0.42	105.18	814.71
Scott Misener	208.84	21.52	7.01	7.10	0.52	0.43	3.27	0.42	105.49	821.13
Umberto D'Amato	132.32	18.23	7.71	7.71	0.30	0.18	3.04	0.31	106.10	833.95
Arna	155.79	19.73	7.74	7.62	0.27	0.09	2.68	0.27	106.10	833.95
Polarglimt	149.39	19.12	7.74	7.71	0.34	0.15	2.92	0.30	106.10	833.95
Argo Navis	152.74	19.12	7.56	7.53	0.46	0.58	3.44	0.45	106.10	833.95
Ilice	160.67	20.61	7.68	7.71	0.64	0.52	3.71	0.70*	105.49	817.97
Bernd Leonhardt	147.87	18.23	7.77	7.77	0.24	0.18	3.18	0.36	104.88	800.21
Silver Isle	222.56	22.41	7.68	7.68	0.00	0.40	3.35	0.62	104.88	800.21
Menihek Lake	217.99	22.41	7.59	7.68	0.55	0.40	3.04	0.43	105.18	808.21
Beltana	152.44	19.73	5.40	5.55	0.58	0.49	4.29	0.63	104.88	800.21
Lake Winnipeg	222.56	22.41	7.65	7.71	0.30	0.27	2.41	0.27	104.88	800.21
Seaway Queen	218.60	21.52	7.70	7.71	0.27	0.27	2.55	0.29	104.88	800.21
Lawrencecliffe Hall	222.56	22.41	7.74	7.68	0.21	0.21	2.66	0.33	104.88	800.21
Morvang	157.93	19.12	7.77	7.77	0.49	0.34	3.53	0.54	104.88	800.21
La Loma	150.61	18.81	7.65	7.62	0.49	0.21	3.04	0.33	104.88	800.21
Saguenay	222.56	22.41	7.65	7.74	0.37	0.30	2.77	0.34	105.18	809.88
Hera	123.48	17.93	7.13	7.04	0.52	0.40	3.80	0.51	105.18	809.88
Holthill	148.48	18.54	7.68	7.68	0.30	0.15	2.91	0.30	105.18	809.88
Quebecois	222.56	22.56	7.59	7.68	0.21	0.15	2.01	0.19	105.49	824.29
Ontario Power	217.07	22.41	7.71	7.68	0.49	0.43	3.09	0.44	105.49	824.29
Wheat King	169.82	21.80	7.68	7.74	0.64	0.40	3.49	0.60	105.79	830.98
Lawrencecliffe Hall	222.56	22.71	7.71	7.77	0.37	0.24	2.77	0.34	105.79	827.54
White River	166.46	20.61	7.62	7.65	0.46	0.34	3.45	0.51	105.79	830.98
Scott Misener	208.84	21.52	7.68	7.65	0.46	0.46	3.27	0.48	105.49	821.13
Cape Breton Miner	207.93	22.41	7.56	7.71	0.52	0.70	3.35	0.57	105.49	821.13
Philip R. Clarke	197.26	20.91	7.50	7.62	0.43	0.30	3.31	0.45	106.10	837.21
Atlantic Duke	161.28	20.91	7.71	7.77	0.37	0.24	2.73	0.30	106.10	837.21
Eshkol	135.37	17.32	6.10	6.16	0.61	0.61	4.60	0.73*	106.10	837.21
Quebecois	222.56	22.56	7.50	7.71	0.24	0.15	2.15	0.21	106.10	833.95
Guido Donegaui	165.55	20.61	7.71	7.71	0.34	0.30	2.73	0.29	106.10	833.95
Montrealais	222.56	22.56	7.62	7.71	0.49	0.43	3.27	0.51	106.10	838.88
Patignies	182.93	22.56	7.68	7.71	0.46	0.58	3.22	0.48	106.10	838.88
Capetan Costis I	156.10	17.32	7.71	7.71	0.21	0.12	2.28	0.17	106.40	848.55
Ferder	151.22	20.91	7.65	7.68	0.43	0.34	3.31	0.44	106.40	848.55
Quebecois	222.56	22.56	7.53	7.68	0.27	0.12	2.50	0.26	107.62	879.50
Forward	134.76	17.04	7.68	7.77	0.21	0.27	3.40	0.34	107.01	863.23
Jarosa	186.59	22.41	7.68	7.62	0.37	0.37	3.13	0.41	107.01	863.23
Don De Dieu	222.56	22.56	7.71	7.71	0.30	0.30	2.33	0.23	107.01	866.49
Silver Isle	222.56	22.41	7.29	7.38	0.52	0.40	3.53	0.59	106.40	843.71
Silver Sea	160.98	20.61	7.71	7.71	0.30	0.24	3.44	0.50	106.40	843.71
Oriental Clipper	174.09	22.41	7.62	7.59	0.40	0.30	3.13	0.42	106.40	843.71

* Velocity > 90% of the limiting speed

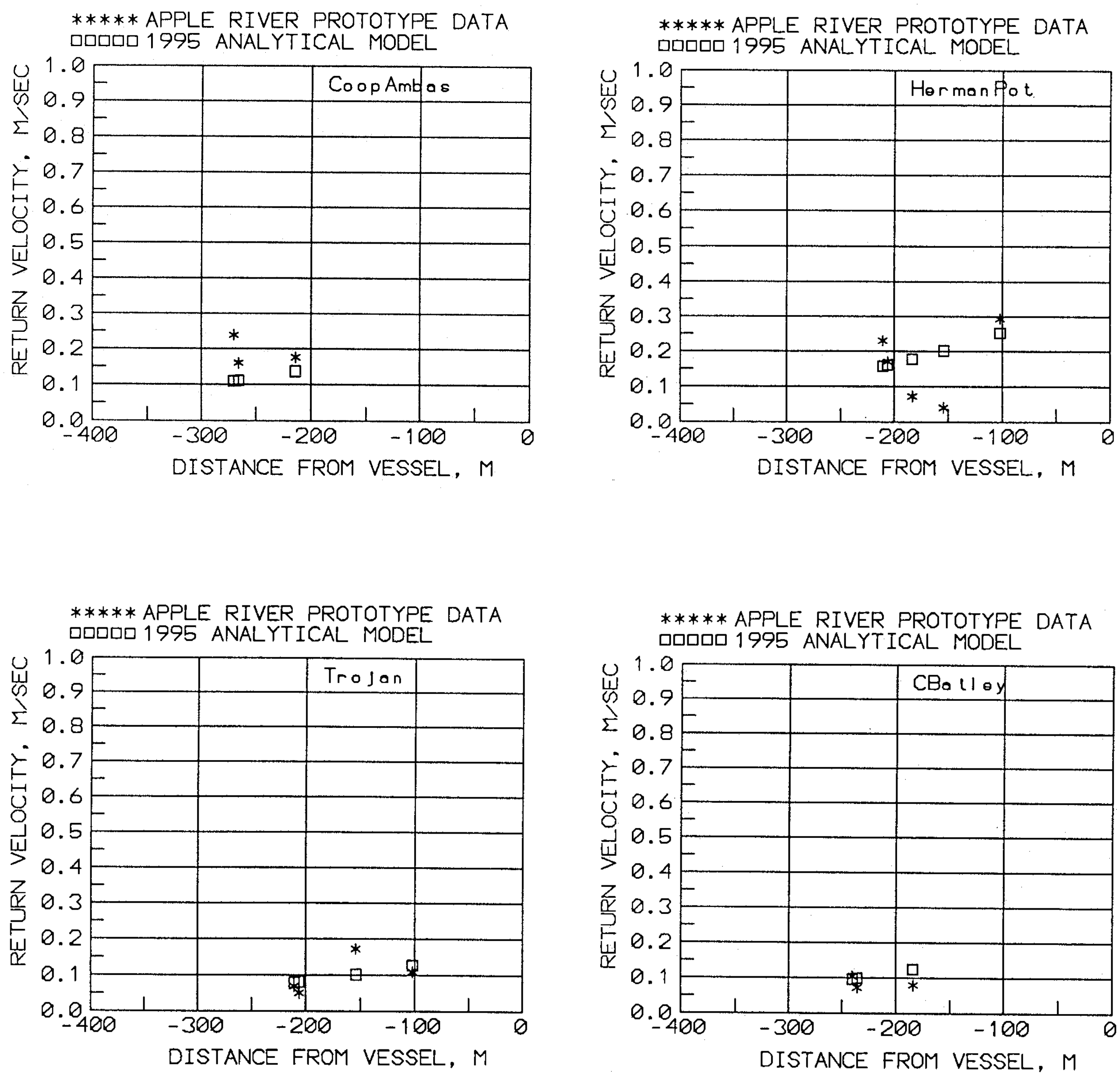

Figure 1. Observed versus computed return velocity at Apple River Island for Coop Ambassador, Herrman Pott, Trojan, and Christine Bailey

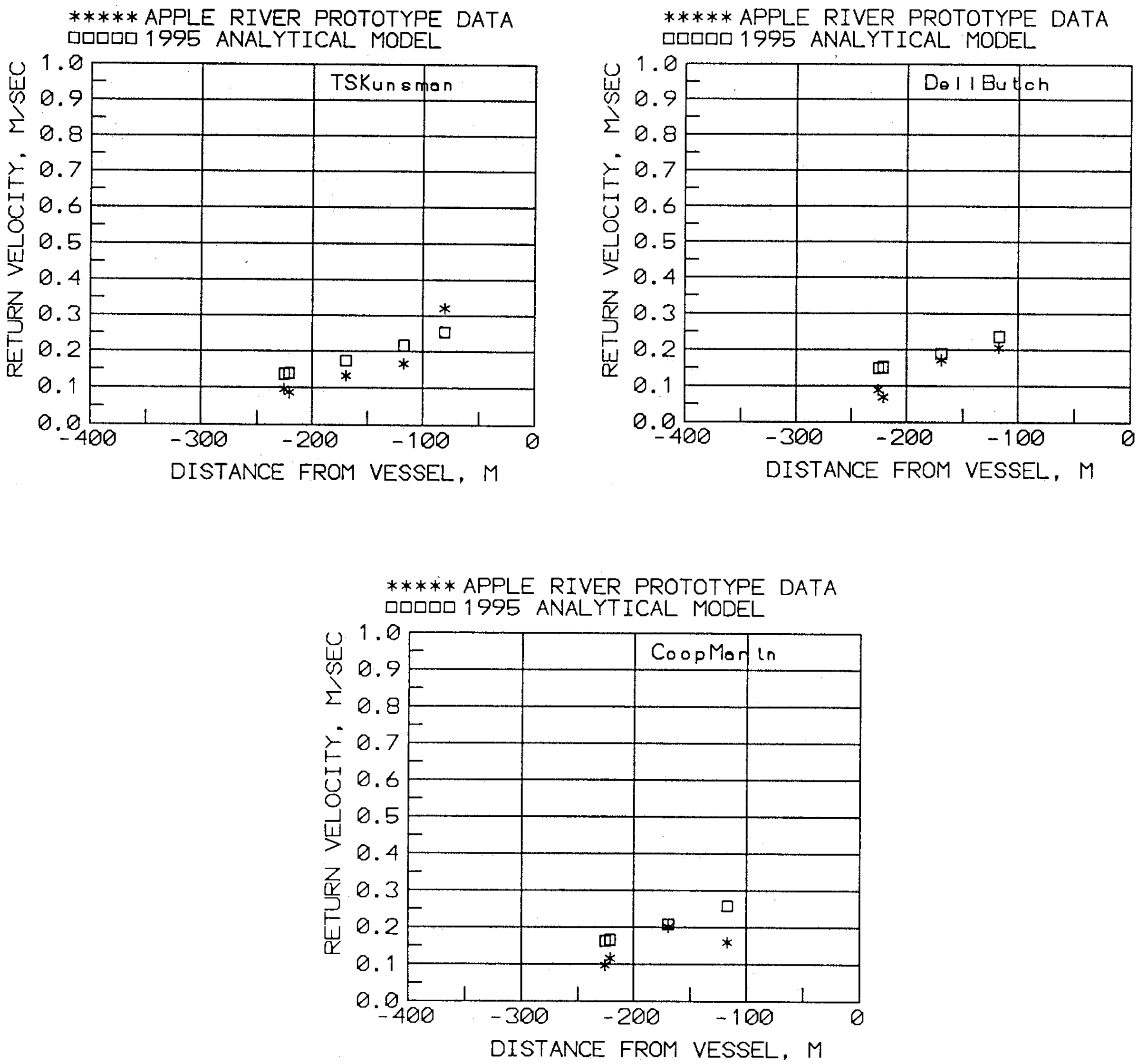

Figure 2. Observed versus computed return velocity at Apple River Island for T. S. Kunsman, Dell Butcher, and Coop Mariner

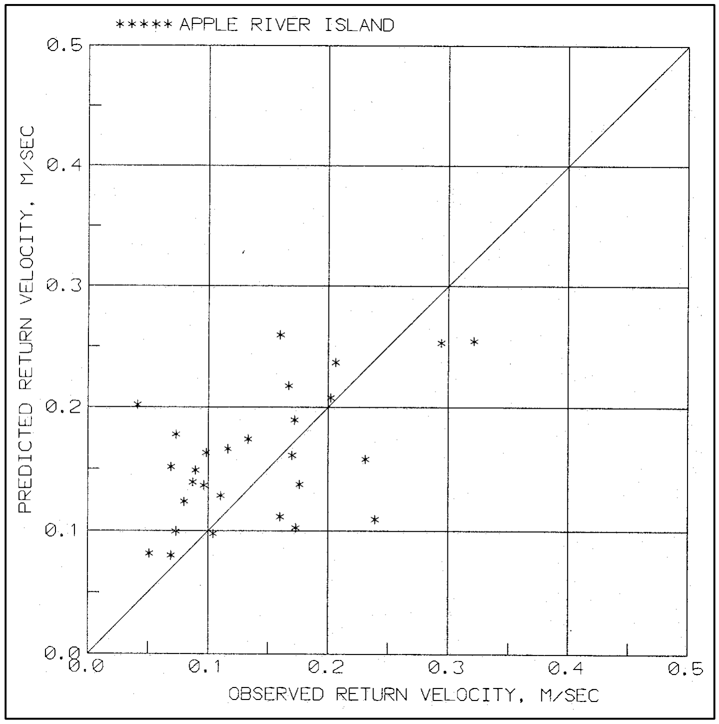

Figure 3. Observed versus computed return velocity at Apple River Island for all data

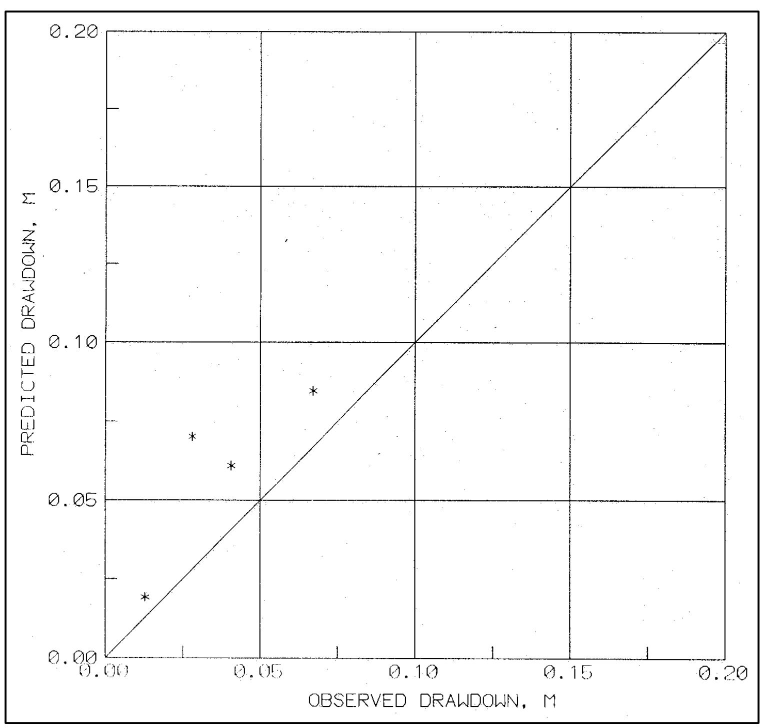

Figure 4. Observed versus computed drawdown at Apple River Island for all data

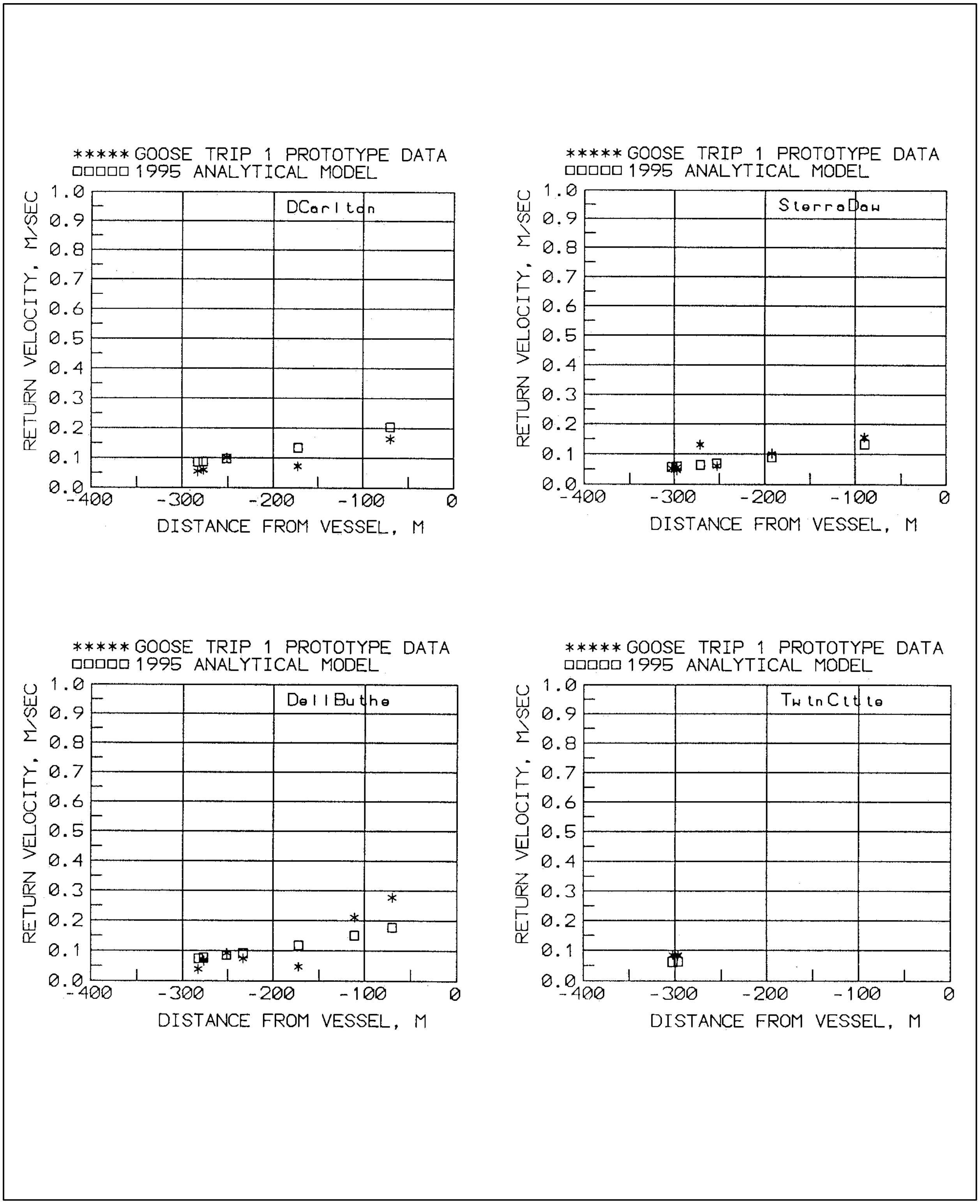

Figure 5. Observed versus computed return velocity at Goose Island Trip 1 for Dare Carlton, Sierra Dawn, Dell Butcher, and Twin City

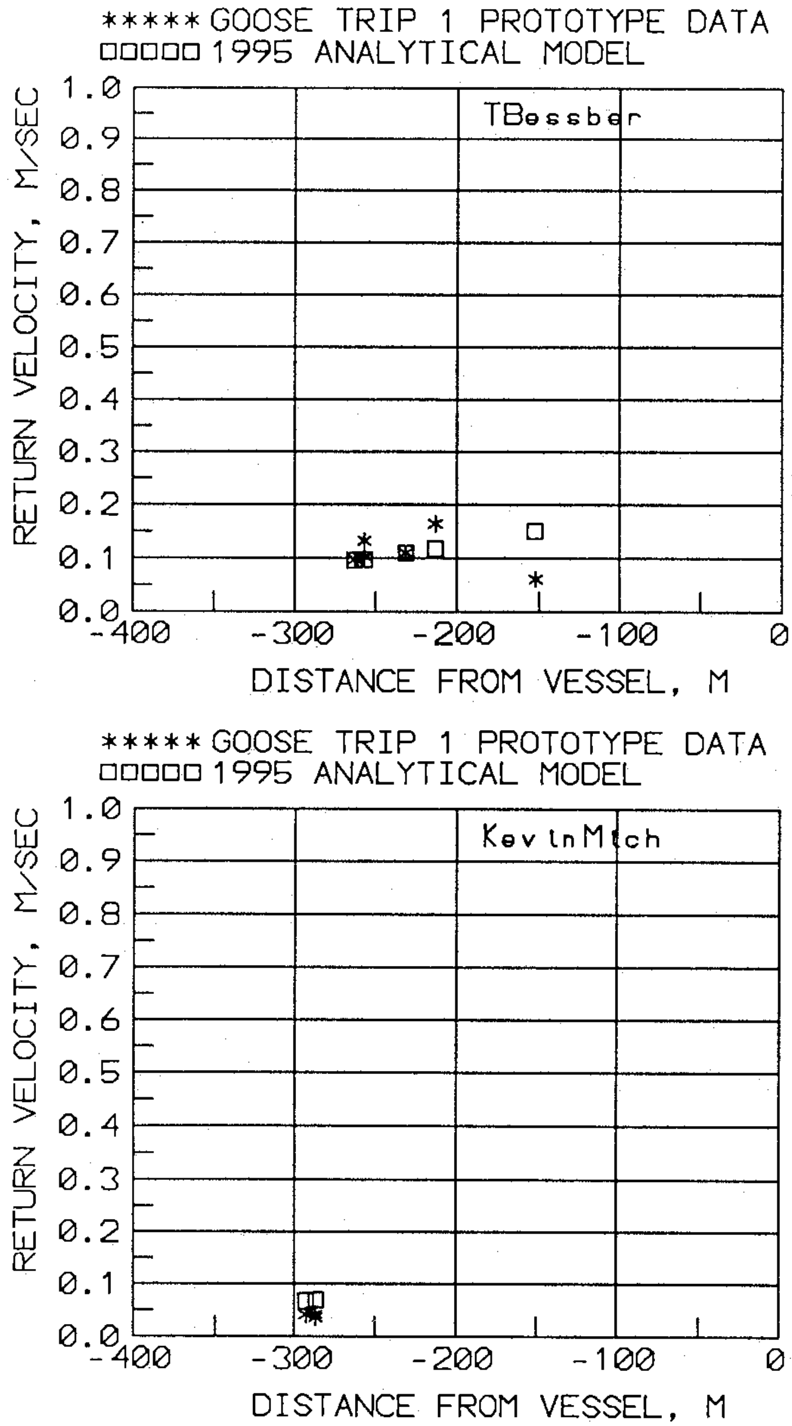

Figure 6. Observed versus computed return velocity at Goose Island Trip 1 for T. R. Beesber and Kevin Michael

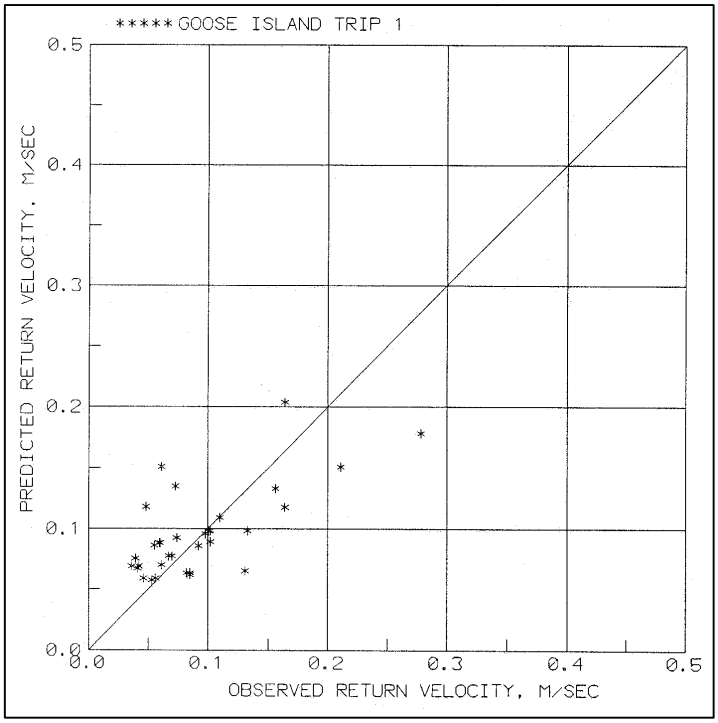

Figure 7. Observed versus computed return velocity at Goose Island Trip 1 for all data

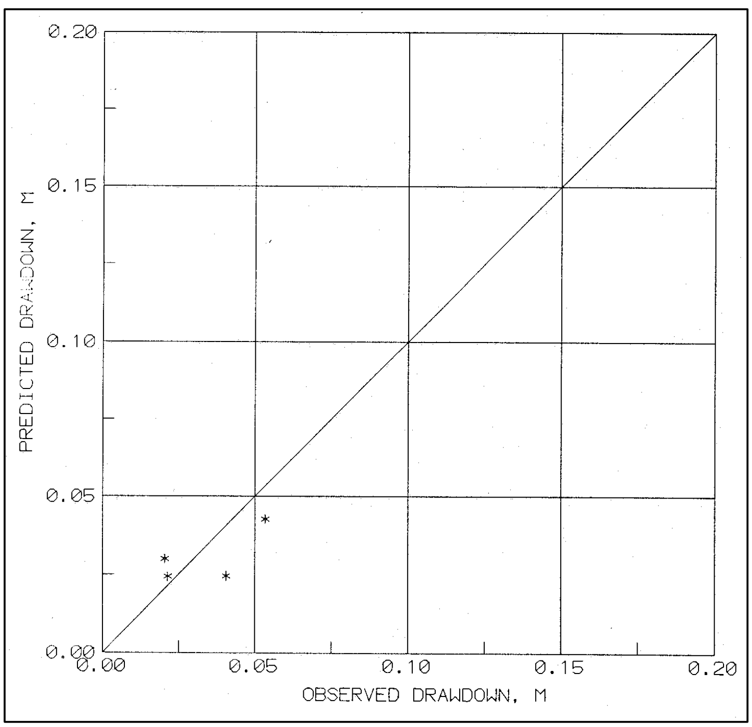

Figure 8. Observed versus computed drawdown at Goose Island Trip 1 for all data

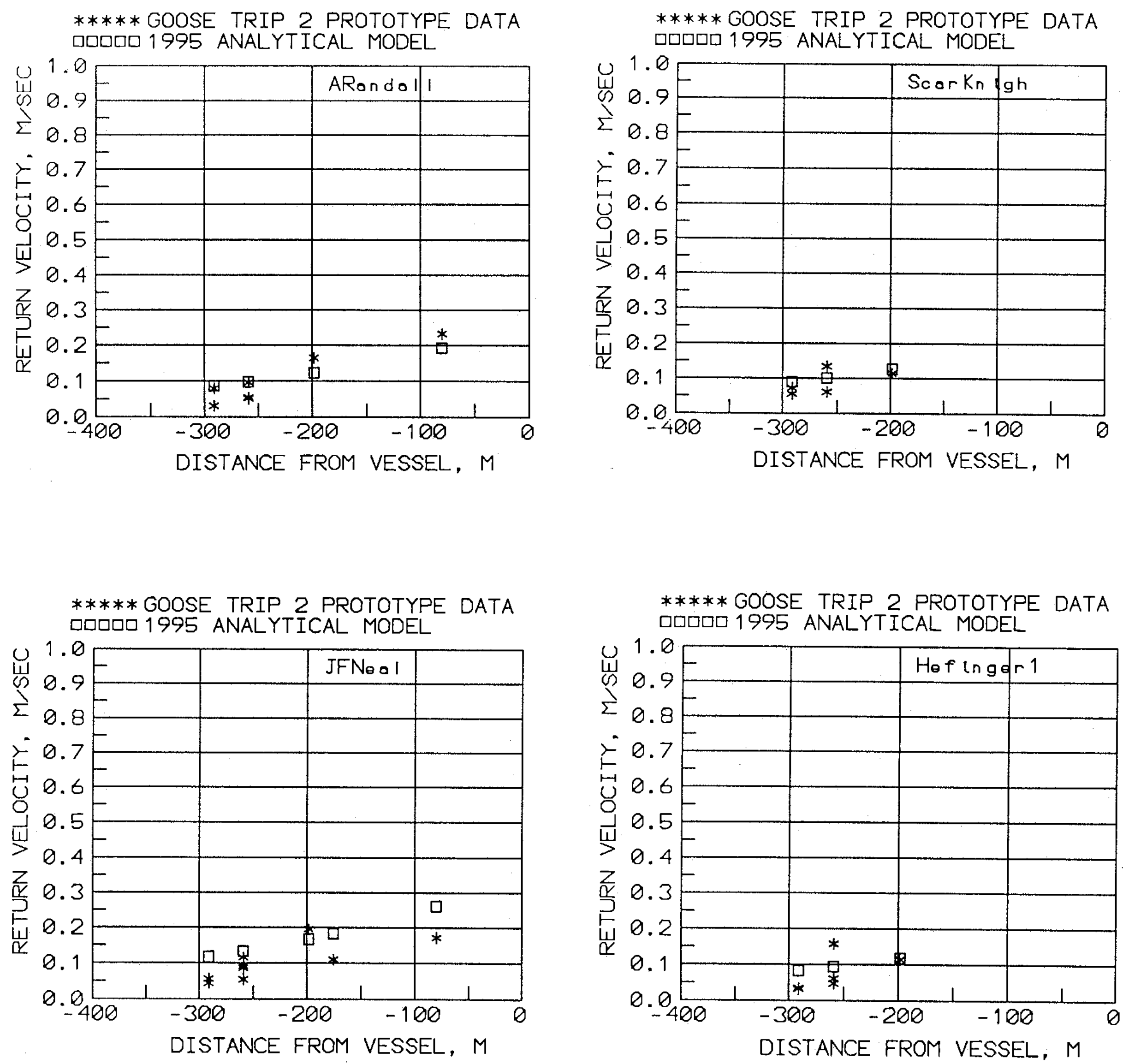

Figure 9. Observed versus computed return velocity at Goose Island Trip 2 for Ardyce Randall, Scarlet Knight, James F. Neal, and Frank T. Heffelfinger

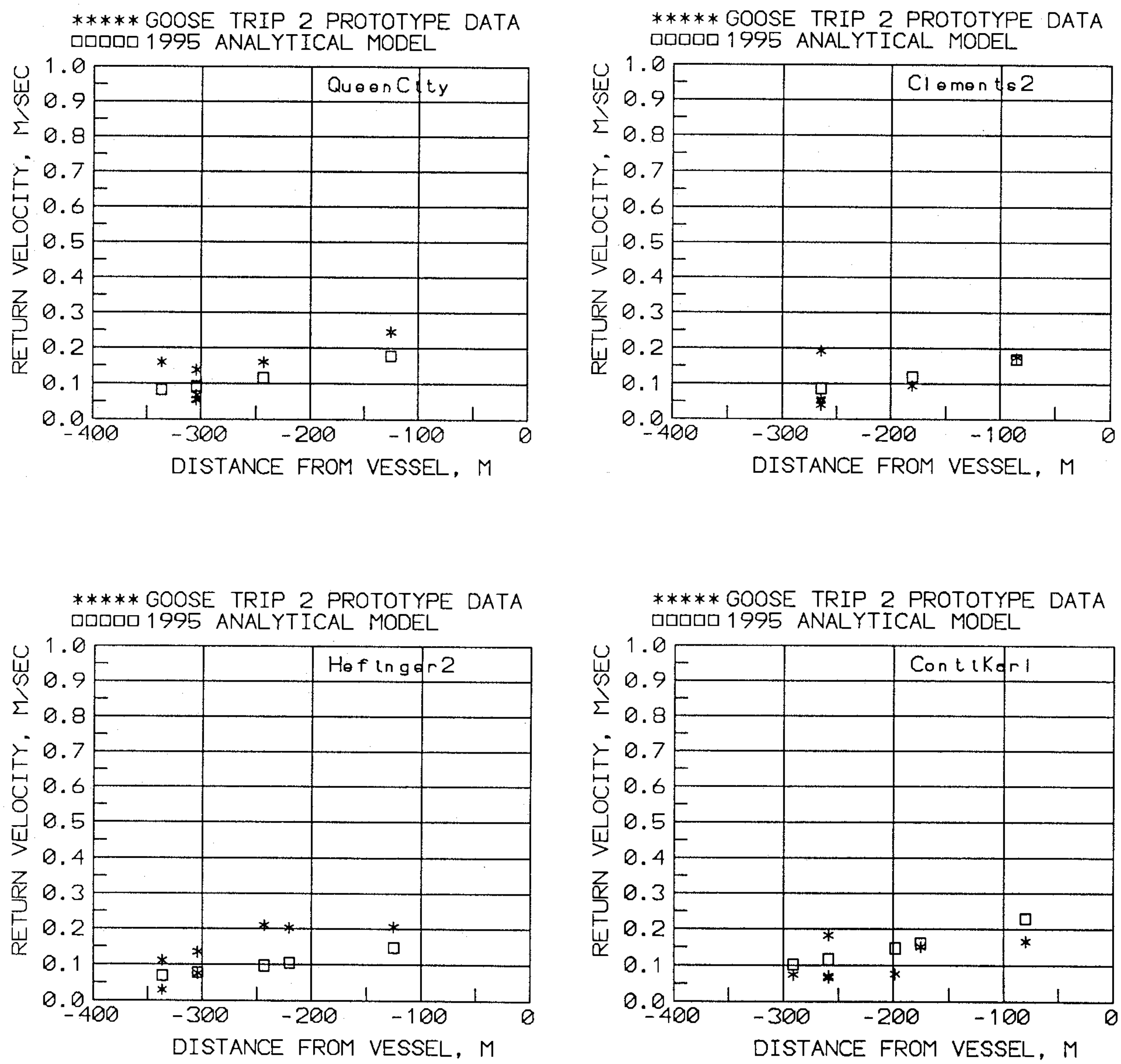

Figure 10. Observed versus computed return velocity at Goose Island Trip 2 for Queen City, Helen M. Clements (2), Frank T. Heffelfinger (2), and Conti-Karla

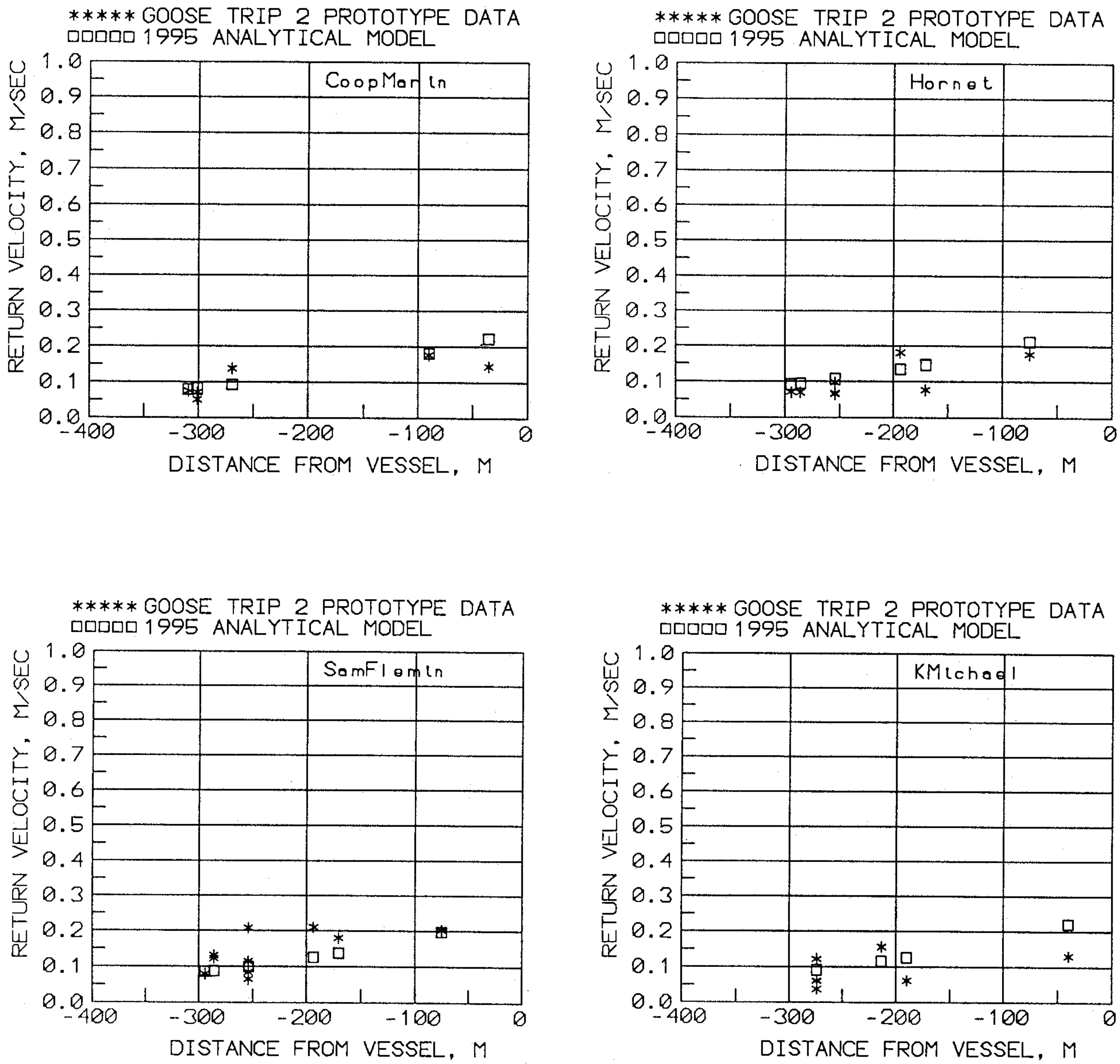

Figure 11. Observed versus computed return velocity at Goose Island Trip 2 for Coop Mariner, Hornet, Sam M. Fleming, and Kevin Michael

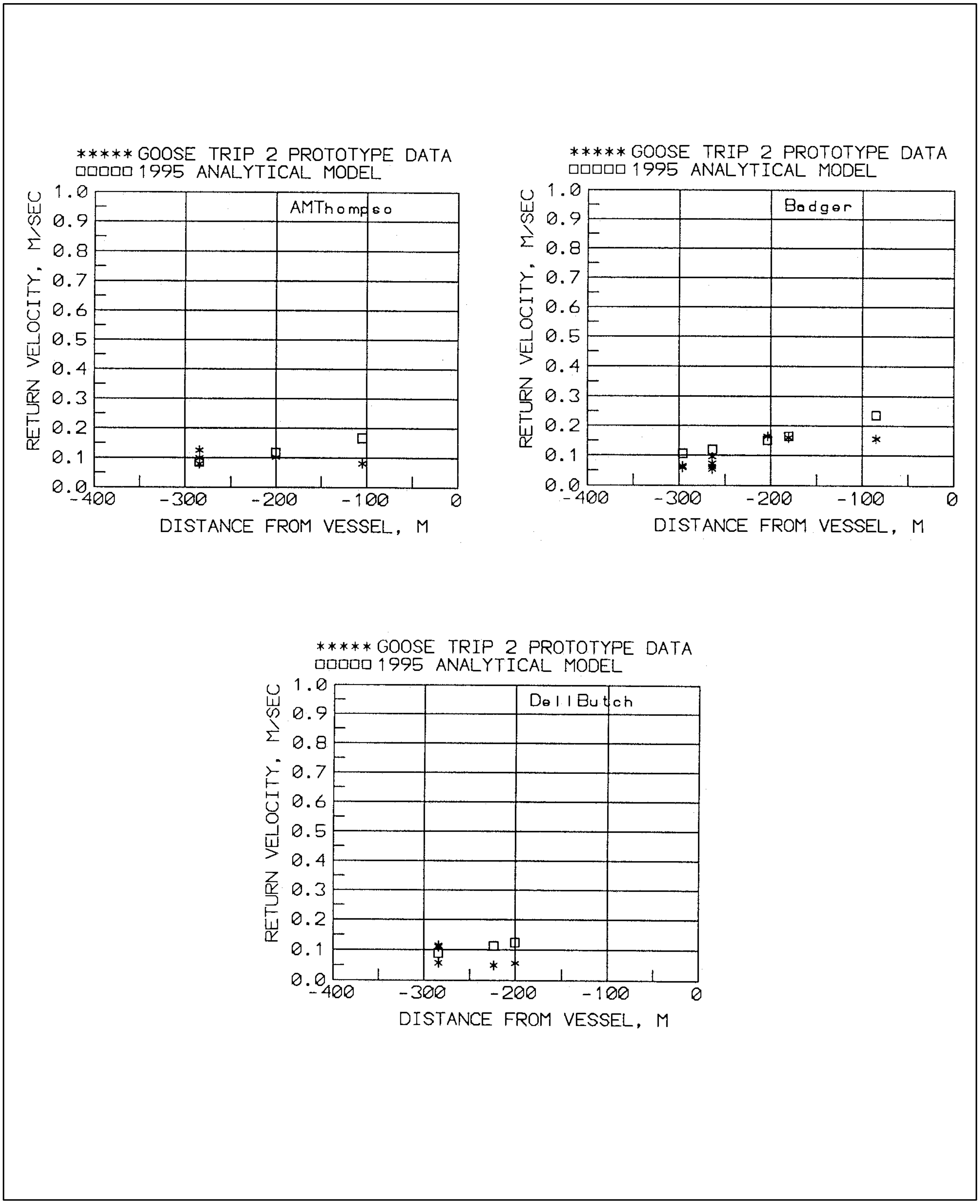

Figure 12. Observed versus computed return velocity at Goose Island Trip 2 for A. M. Thompson, Badger, and Dell Butcher

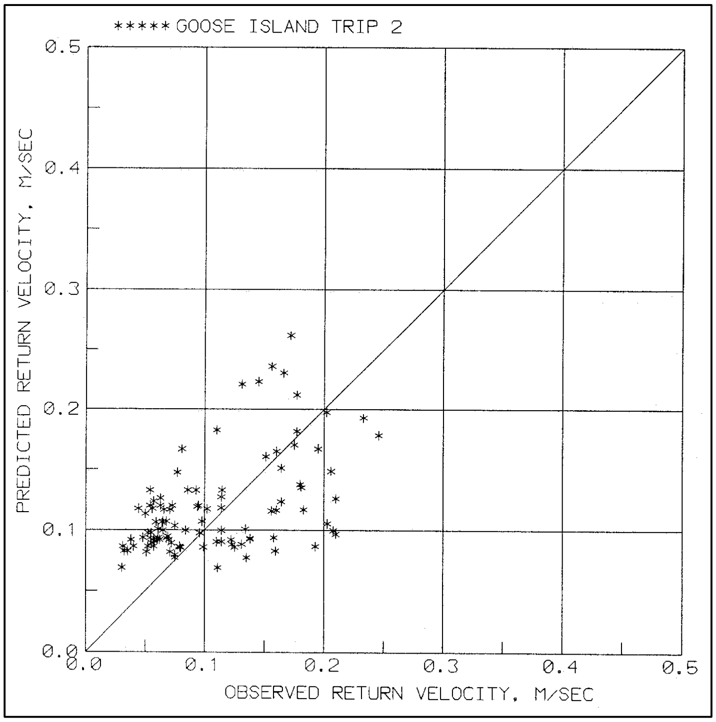

Figure 13. Observed versus computed return velocity at Goose Island Trip 2 for all data

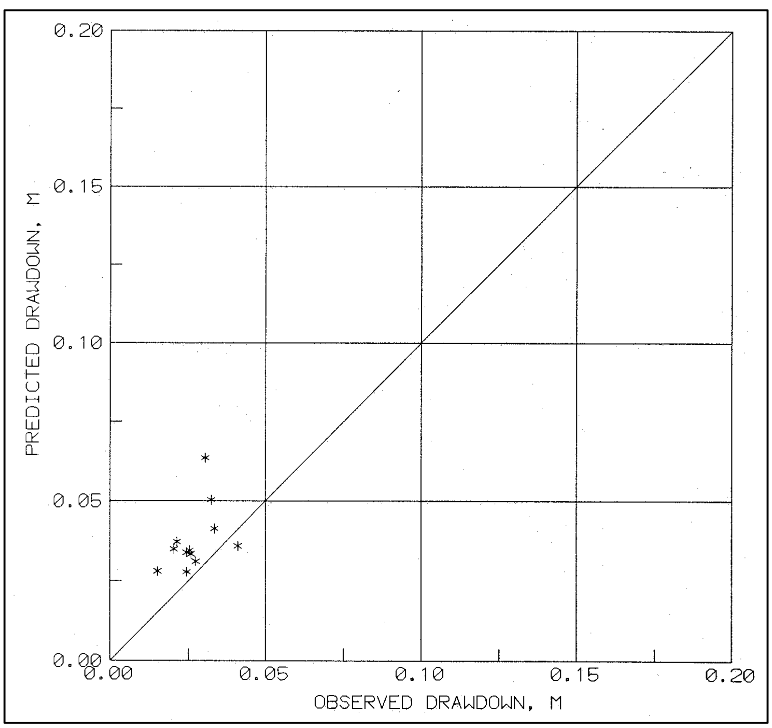

Figure 14. Observed versus computed drawdown at Goose Island Trip 2 for all data

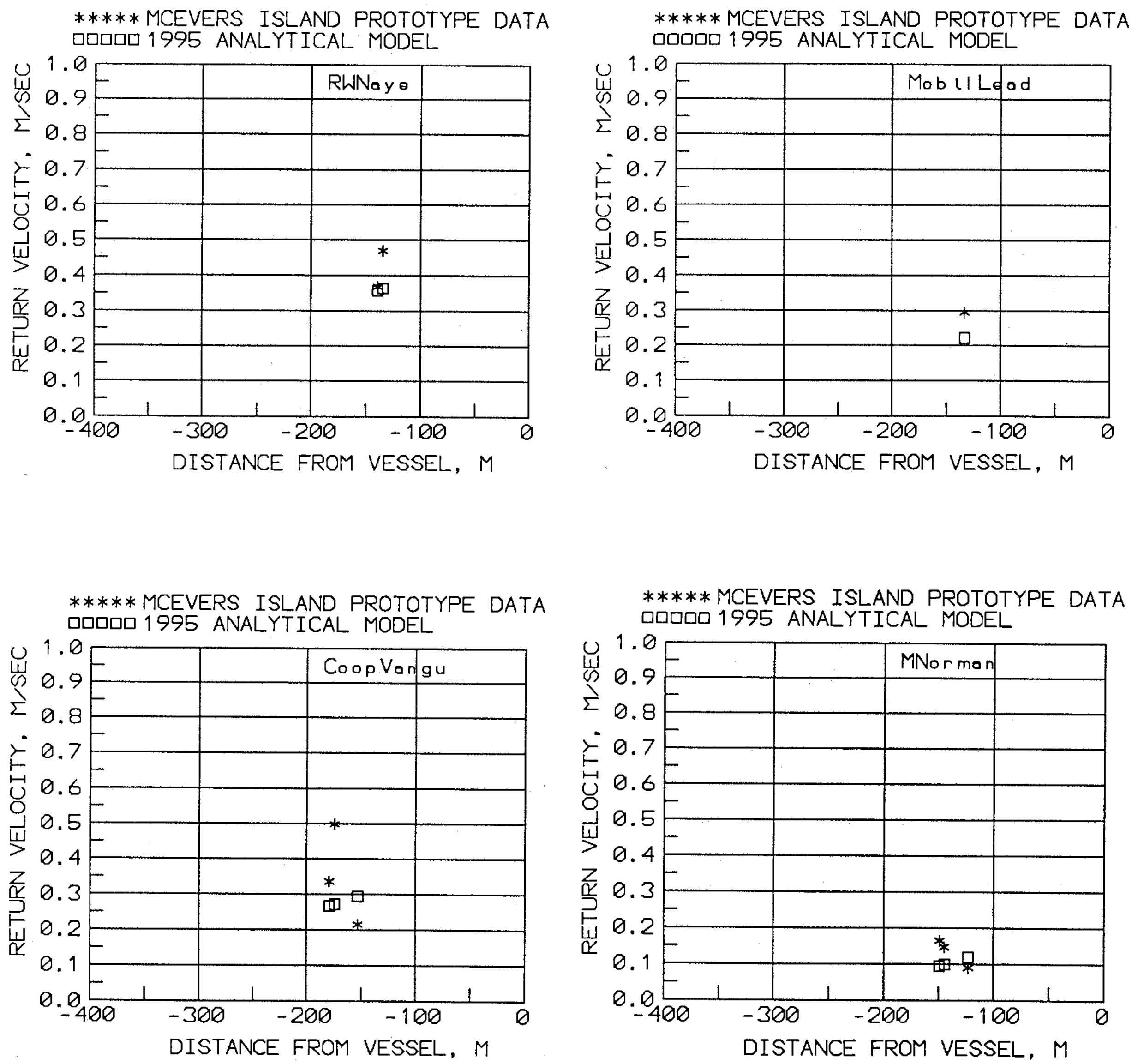

Figure 15. Observed versus computed return velocity at McEver's Island for R. W. Naye, Mobil Leader, Coop Vanguard, and Marvin Norman

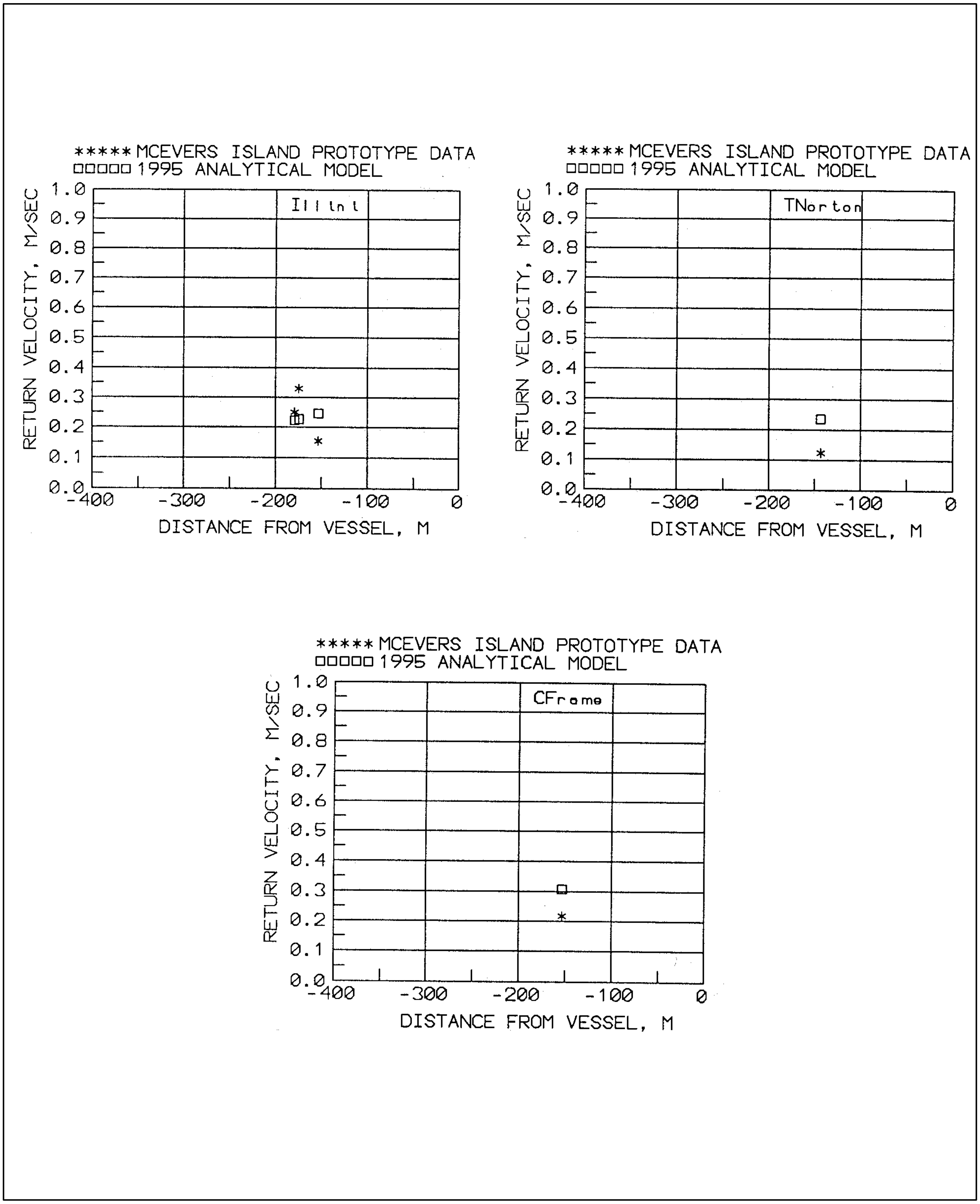

Figure 16. Observed versus computed return velocity at McEver's Island for Illini, Thurston B. Norton, and Clarence G. Frame

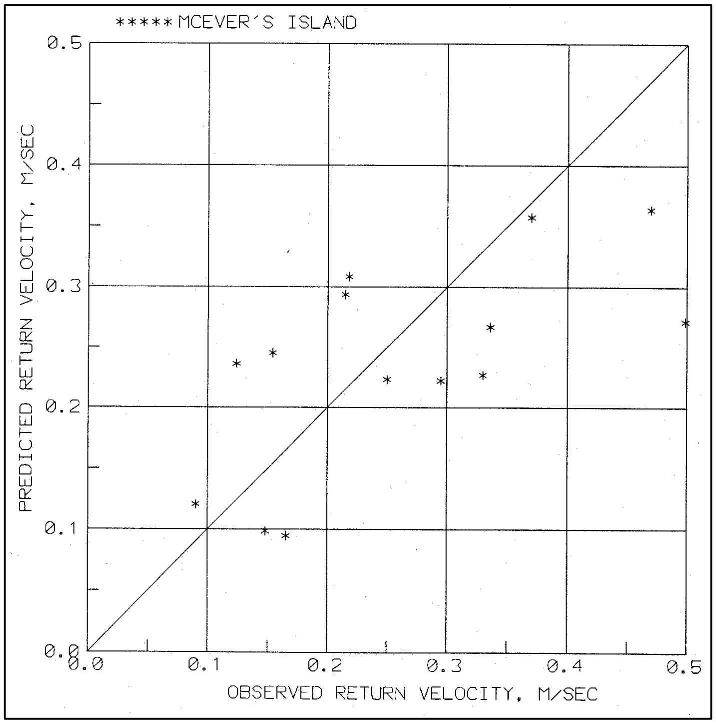

Figure 17. Observed versus computed return velocity at McEver's Island for all data

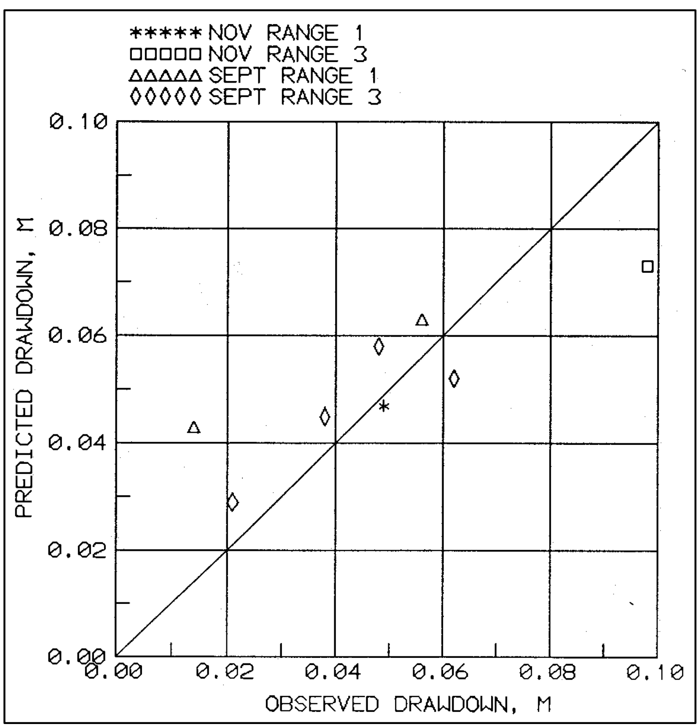

Figure 18. Observed versus computed drawdown at Pool 8 for all data

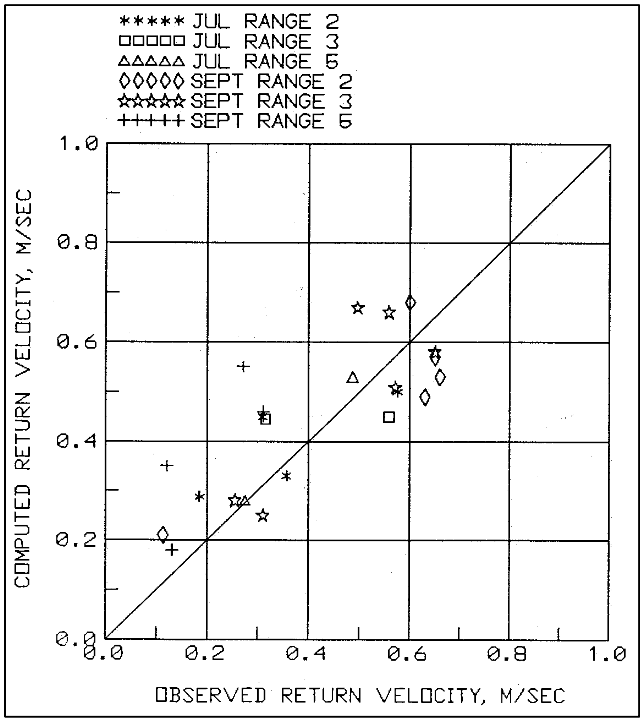

Figure 19. Observed versus computed return velocity at LaGrange for all data

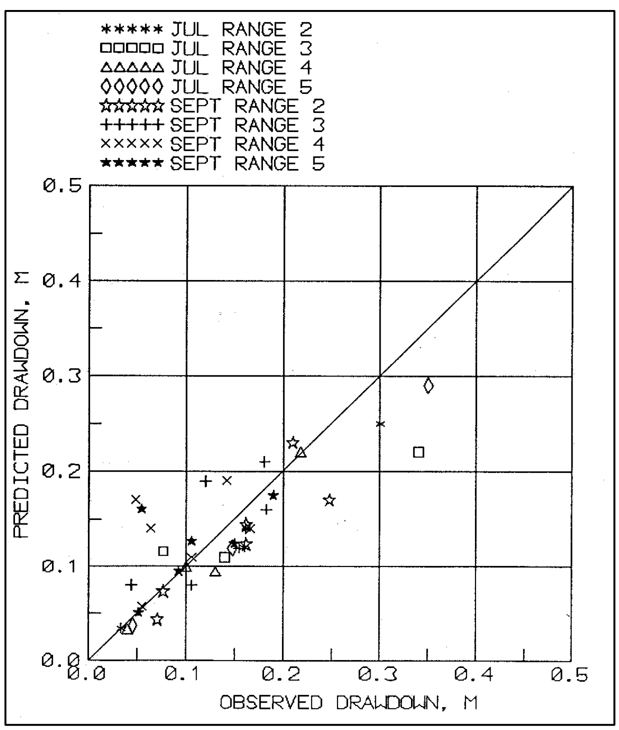

Figure 20. Observed versus computed draw-down at LaGrange for all data

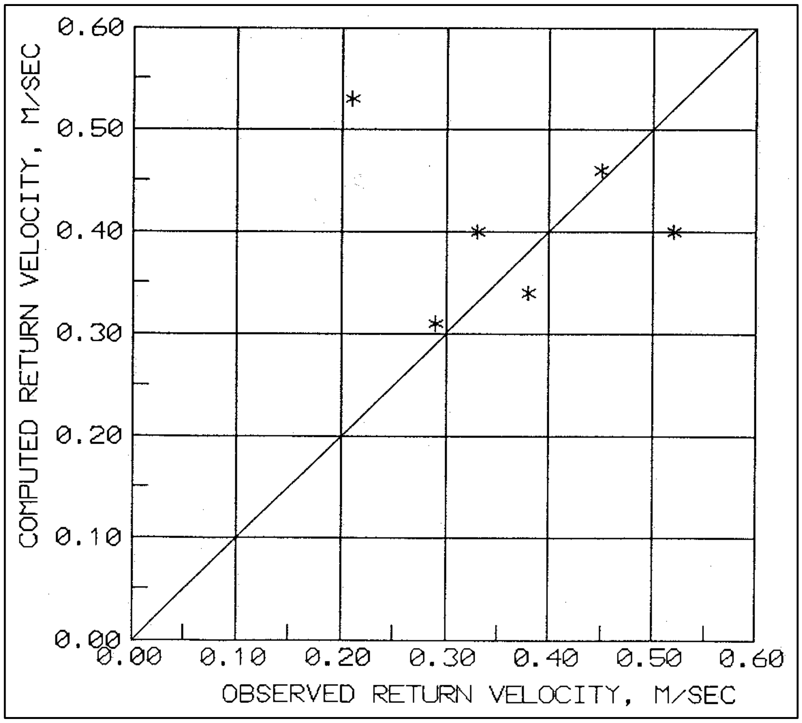

Figure 21. Observed versus computed return velocity for GIWW

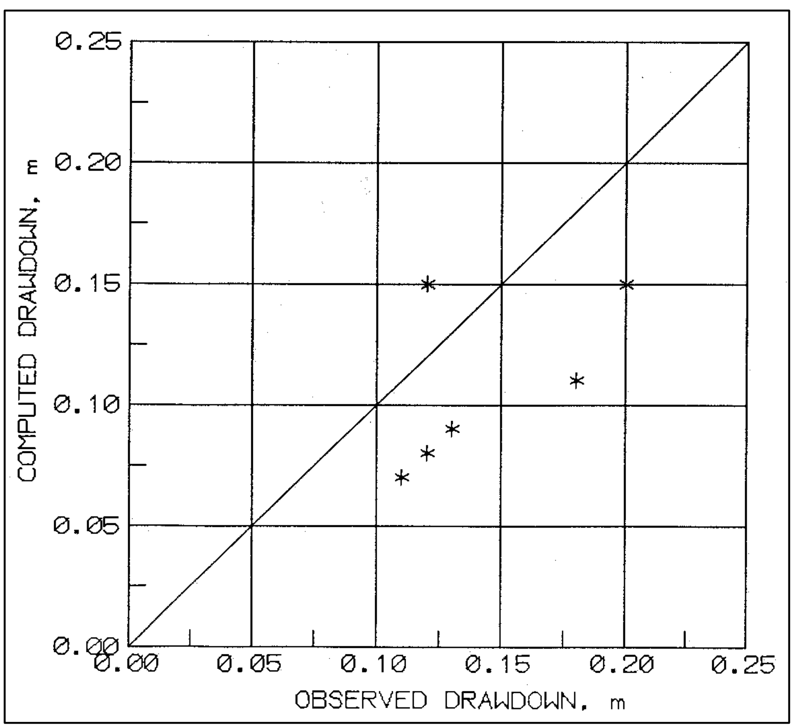

Figure 22. Observed versus computed drawdown for GIWW

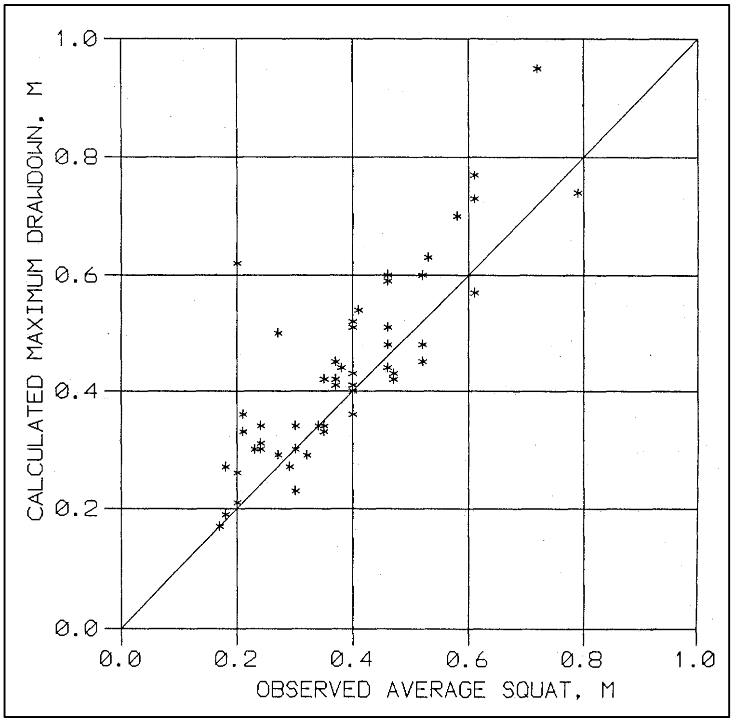

Figure 23. Observed average ship squat versus computed maximum drawdown for St. Lawrence Seaway data

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13. ABSTRACT ***(Maximum 200 words)***

The NAVEFF model is a one-dimensional model using conservation of energy and mass to determine return velocity and drawdown resulting from passage of vessels in a navigable river or channel. The NAVEFF model incorporates empirical exponential decay relations to provide the distribution of the maximum return velocity and maximum drawdown between the vessel and the shoreline. The NAVEFF model is compared herein to data that were not used in the development of the model from sites on the Mississippi River, Illinois Waterway, and Gulf Intracoastal Waterway. The observed prototype data are shown to exhibit considerable scatter based on comparison of similar vessels. Based on the comparisons of observed and computed values, the NAVEFF model overpredicts maximum return velocity and drawdown by an average of about 25 percent. Detailed return velocity measurements between vessel and shoreline at one site on the Mississippi River support the use of the exponential decay of return velocity between vessel and shoreline.

14. SUBJECT TERMS
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