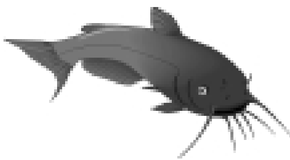
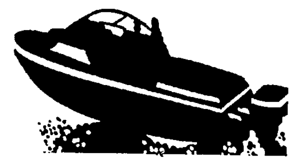
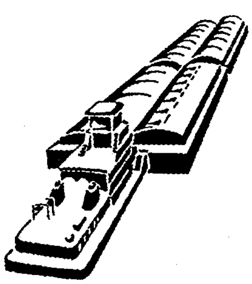
ENV Report 15

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





Wave-Height Predictive Techniques for Commercial Tows on the Upper Mississippi River - Illinois Waterway System



September 1999

US Army Corps of Engineers

Rock Island District
St. Louis District
St. Paul District

Upper Mississippi River - Illinois Waterway System Navigation Study

ENV Report 15
September 1999

Wave-Height Predictive Techniques for Commercial Tows on the Upper Mississippi River - Illinois Waterway System

by Sandra K. Knight

U.S. Army Engineer Research and Development Center
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Interim report

Prepared for U.S. Army Engineer District, Rock Island
Rock Island, IL 61204-2004
U.S. Army Engineer District, St. Louis
St. Louis, MO 63103-2833
U.S. Army Engineer District, St. Paul
St. Paul, MN 55101-1638

U.S. Army Corps of Engineers Cataloging-in-Publication Data

Knight, Sandra K.
Wave-height predictive techniques for commercial tows on the upper Mississippi River-Illinois Waterway System / by Sandra K. Knight ; prepared for U.S. Army Engineer District, Rock Island, U.S. Army Engineer District, St. Louis, U.S. Army Engineer District, St. Paul.
54 p. : ill. ; 28 cm.
“ENV report 15"
Includes bibliographic references.
1. Illinois Waterway (Ill.) -- Navigation -- Research. 2. Waves -- Mississippi River. 3. Towing -- Mississippi River. 4. Mississippi River. 5. Illinois Waterway (Ill.) 6. Navigation -- Mississippi River. I. United States. Army. Corps of Engineers. Rock Island District. II. United States. Army. Corps of Engineers. St. Louis District. III. United States. Army. Corps of Engineers. St. Paul District. IV. U.S. Army Engineer Research and Development Center. V. Upper Mississippi River-Illinois Waterway System Navigation Study. VI. Title. VII. Title: Interim report for the Upper Mississippi River-Illinois Waterway System Navigation Study.
TA7 W3499 R5U7 ENV rept.15 1999

Contents

List of Figures

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 that 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 work was performed by personnel of the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC), during 1996-1997. The study was under the direction of Dr. James R. Houston, Director, CHL; Mr. Charles C. Calhoun (retired), Assistant Director, CHL; and Mr. C. E. Chatham, Jr., Chief, Navigation and Harbors Division (NHD), CHL. Experiments for this study were conducted by Drs. Stephen T. Maynord and Sandra K. Knight, NHD, with assistance from Ms. Sheila Knight and Mr. James Sullivan. The analysis and preparation of this report was done by Dr. Knight.

At the time of publication of this report, Dr. Lewis E. Link was Acting Director of ERDC, and COL Robin R. Cababa, EN, was Commander.

1 Introduction

Background

Physical model studies and prototype data have been collected and analyzed as part of the Upper Mississippi River-Illinois Waterway System (UMRS) Navigation Feasibility Study for the purpose of developing a vessel-wave predictive tool for commercial tows. The approach used was to examine existing analytical techniques for predicting wave heights produced by vessels, determine their suitability and applicability to the vessels and waterways of the UMRS, and modify/validate them with physical model and available prototype data.

Purpose of Model Development

The analytical model selected and validated for prediction of wake waves in this study has been incorporated into an existing software package, NAVEFF (Maynord 1996), developed at the U.S. Army Engineer Research and Development Center (ERDC) to systemically evaluate physical effects produced by navigation traffic. NAVEFF also contains an analytical approach for quantifying return current and drawdown for a given set of traffic characteristics and channel conditions. As a part of the environmental studies for the Navigation Feasibility Study, this model will be used to predict physical effects at transects along the main channel of the UMRS for variable traffic conditions. These physical effects will be coupled with biological models and sediment models to determine potential impacts of increased traffic.

The predictive equations related to physical effects of commercial tows will also be coupled with a methodology for sizing riprap bank protection in lock approaches, canals, and narrow waterways. Results of this analysis regarding wave-predictive equations and riprap design guidance found in Martin (1997) will be incorporated into guidance for Corps of Engineers field offices. It is important, because of the spatial and temporal scope of the UMRS project and the potential application by field offices, that the analytical approaches in NAVEFF are not only accurate but are computationally simple and make use of attainable input data.

2 Predictive Wave Equations for Commercial Towboats with Barges

The hull of a moving vessel creates a pressure disturbance on the water surface generating waves. The vessel creates transverse and diverging waves intersecting at peaks that form a distinct pattern in deep water (Verhey and Bogaerts 1989). The shape of the vessel hull and the speed of the vessel dictate the magnitude of these waves known as secondary waves. Figure 1 is a diagram showing this wave pattern. The hull-formed waves are typically deepwater waves with periods of 1 to 3 sec. These waves should not be confused with the long-period shallow-water wave, drawdown, generated by the displacement of water by the vessel.

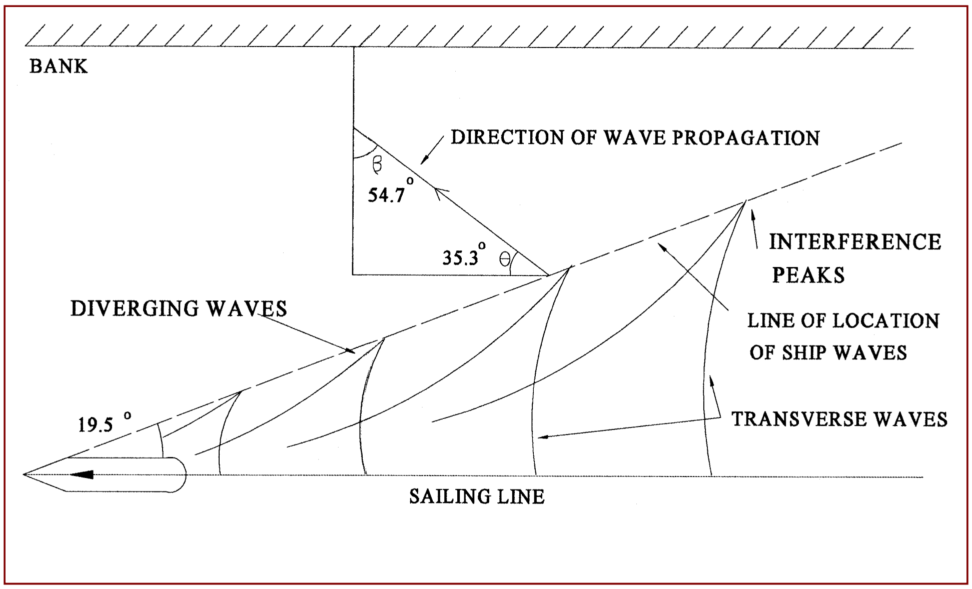


Figure 1. Ship-wave angles and definition sketch

A number of predictive equations have been developed for the prediction of secondary waves from a moving vessel. Many of these are presented in Sorensen (1997). These equations come in a variety of forms predicting wave height as a function of various independent variables such as blockage ratio, vessel draft, beam width, vessel length, hull entrance length, channel width, and displacement volume to name a few. All predictive equations include vessel speed. Many include hull form or shape factors empirically obtained from data, and some related magnitude to distance from the vessel.

Review of these equations led to the selection of the analytical approach developed by the Delft Hydraulics Laboratory and presented as guidance in the Permanent International Association of Navigation Congresses (PIANC) on the design of flexible revetments on inland waterways (PIANC 1987). There were several reasons for adopting this approach: (a) analysis of wave data collected at ERDC (Martin 1997) correlated well with the approach; (b) a relationship was needed for the UMRS study that related wave height to distance from the vessel; (c) the coefficient is a function of hull form and could be determined empirically from existing data; and (d) the parameters required for the solution are easily obtained.

The equation predicts the maximum secondary wave height, H_{max}, produced by commercial tows such that,

$$H_{max} = \alpha_1 h \left(\frac{s}{h} \right)^{-0.33} \left(\frac{V_w}{\sqrt{gh}} \right)^{\alpha_2} \tag{1}$$

where

H_{max} = maximum trough to following crest

α_1 = coefficient regarding hull type and draft

h = depth of water

s = distance between vessel s edge and the point of interest

V_w = speed of vessel relative to water

α_2 = exponent experimentally determined to be between 2.67 and 4.0

g = gravitational acceleration

The last term in the equation, the Froude number, is based on vessel speed and water depth and defined as

$$Fr = \frac{V_w}{\sqrt{gh}} \tag{2}$$

For typical hydraulic studies, the dimensionless Froude number generally utilizes a current velocity and a characteristic length-of-channel depth near the point of interest. Vessel draft or length might be appropriate characteristic lengths if the vessel were in a confined or shallow channel or if designing vessel hull forms, respectively. If one were describing the Froude number for purposes of evaluating shear stresses near the shore because of vessel-generated currents, one might select the peak return current and water depth during drawdown to describe the dimensionless Froude number. In the case of predicting the decay of waves in a channel, as they diverge from a moving vessel, the most appropriate characteristic velocity is vessel speed, and the length is water depth at the vessel. The latter is what was selected for this study.

Equation 1 was based on empirically fitting the dimensionless values of H_{max}/h, s/h, and Fr to data collected in both model and field studies. Literature suggests that wave height is inversely proportional to the cube root of the distance from the sailing line, thereby setting the exponent for s/h at -1/3 (Sorensen 1997; Verhey and Bogaerts 1989; Havelock 1908). This relationship was assumed to be valid for this study and is demonstrated in the analysis section.

Previous research at the Delft by Blaauw et al. (1984) had determined α_2 to be 2.67, but PIANC (1987), Verhey and Bogaerts (1989), and Boeters, van der Knaap, and Verheij (1995) recommended a value of 4.0. When α_2 is set at any value other than 2.67, the depth of water becomes a weighting factor in the prediction of the vessel wave height, thereby invalidating the deepwater assumption. Hochstein and Adams (1989), Gates and Herbich (1977), and Sorensen (1997) relate wave height to the square of the vessel speed. Using an exponent of 2.67 makes the equation closer to these relationships.

The values of α_1 , the hull form coefficient, were based on different types of vessels. In Blaauw et al. (1984) for push tow units, the recommended values for α_1 for loaded and unloaded vessels were 0.8 and 0.35, respectively. In the references from PIANC (1987) and Boeters, van der Knaap, and Verheij (1995), the coefficient for α_1 was determined to be 1.0. In both PIANC (1987) and Verhey and Bogaerts (1989), loaded pushtow units were not regarded as a significant source of secondary waves primarily because of their speed. Figure 2 shows the comparison of maximum secondary wave height of data collected in Martin (1997) compared with calculated values of the maximum secondary wave height using two different methods: (a) Blaauw et al. (1984) with α_1 equal 0.8 and α_2 equal to 2.67, and (b) Verhey and Bogaerts (1989) with α_1 equal 1 and α_2 equal 4.0. Some of the scatter in this figure can be attributed to the fact that the coefficients were not developed for this data set.

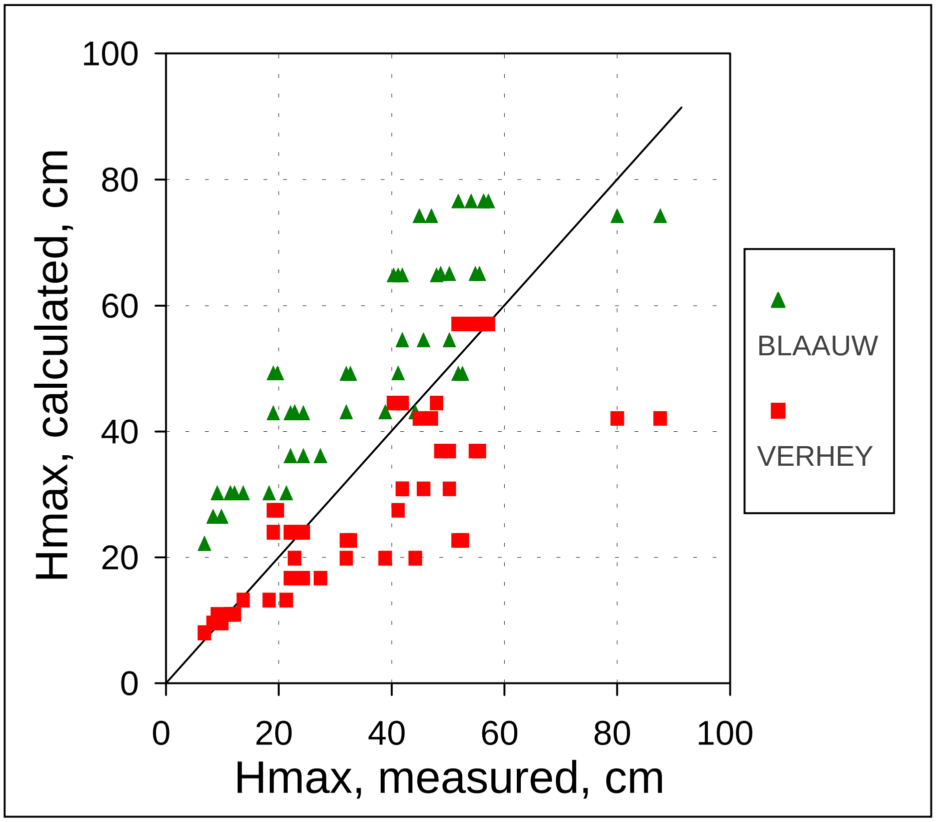


Figure 2. Comparison of measured with calculated values of secondary waves using two methods and Fiscal Year 1993 (FY93) data set

According to all the references using Equation 1, the validity is generally restricted to deepwater conditions and nonbreaking waves. These conditions are defined as an *Fr* less than 0.7 and H_{max}/h less than approximately 0.6, respectively. Sorensen (1966) confirms this stating the *Fr* should be less than 0.6 or 0.7 to qualify as a deepwater condition. The definition for deepwater or shallow-water waves is actually a function of the ratio of water depth to wave length and based on wave celerity. A shallow-water wave is generally described as one that "feels" the bottom. The *Shore Protection Manual* (1984) and LeMehaute (1976) suggest that the wave length to wave depth should be greater than 0.5 to be classified as a deepwater wave; from 0.05 to 0.5 is the transition zone; and less than 0.05 is considered a shallow-water wave.

Though not described as limitations in the references, data collected and used in the Dutch research were based on sailing line distances of less than or equal to 100 m and generally were taken in a flume of constant depth laterally across the channel.

3 Development of a Commercial Tow-Wave Predictive Equation for the UMRS

Development of the predictive tools in NAVEFF, though independent of the actual distribution of tows on the UMRS, was conducted in such a manner as to characterize a wide range of conditions that actually exist or could occur. Actual configuration type and frequency of prototype vessels on the UMRS are included in the physical effects analysis for the environmental impacts using the system model NAVEFF. Inputs to this analysis were based on historical fleet characteristics for each pool. Although there is an almost infinite combination of towboats and barge configurations on the UMRS, the historical data were used to aggregate the length, width, drafts, and speed of the vessels to give 27 likely combinations. Additionally, both directions (upbound and downbound), two types of towboat propulsion (kort-nozzle and open-wheel), and three tow positions (sailing lines) were selected to make a total of 324 potential computations of physical effects using NAVEFF at each cross section for each discharge condition. Details regarding the selection of these variables and the economic analysis regarding probability of occurrence of each of the vessel characteristics in each pool will be described in a separate report on the system model.

Available Data

Coefficients for typical U.S. inland commercial towboats with barges had not been developed prior to this analysis. Two physical model data sets and four prototype data sets from the UMRS study were available to evaluate waves produced by commercial tow traffic. Wave data were collected at 25 Hz in a physical model at ERDC under various vessel-operating conditions and at various lateral locations in two different channel models. The first data set was taken in a 1:25-scale model depicting a UMRS cross section of the Illinois River at Kampsville, IL (Maynord and Martin 1997). Another data set was obtained from a 1:30 scale model of the Mississippi River at Clark s Ferry (Maynord and Martin 1998). Additionally, prototype data were collected by the Illinois State Water Survey (Bhowmik et al. 1996) at four sites on the UMRS. Because of missing information, or in the case of some of the prototype events, nonstandard tow configurations, several events were eliminated leaving 241 data points for development of the coefficient α_1 in Equation 1. Another data set collected at ERDC in a 1:25 scale physical model of a trapezoidal section in 1993 (Martin 1997) was used for verification of the results. This data set included 52 events for loaded three-wide by five-long barge trains pushed by a towboat. In all data sets, a tow consists of a towboat and barges with each barge being 59.4 m long and 10.7 m wide. Descriptions of data-collection techniques and details of the analysis for each data set are found in the literature cited.

The 241 events used to develop the predictive equation, both prototype and model, included a wide range of tow characteristics and wave measurements. Tow configurations varied from a one-wide by one-long barge train to a three- by five-long barge train with most events (158) falling in the latter group. Vessel drafts ranged from 0.61 to 2.74 m. Some events were upbound and some downbound. The distance, s, ranged from 14 to 332 m with many data points in excess of 100 m. Vessel speeds relative to the water ranged from approximately 1.5 to 5 m/sec. Water depths at the gauge varied from less than 1 to 12 m. Depth at the sailing line ranged from 4 to 13 m.

Data Limitations

Though there are limitations and variability in model or prototype data sets, both were necessary to develop predictive equations. Field data can be variable because of a number of factors. Limitations in accuracy of the instrumentation, as well as the inability to monitor and/or control the natural fluctuations in river currents and wind conditions, can contribute to the variability of measured physical effects. It is often difficult to distinguish, particularly during windy conditions or during high flows, the actual hydrodynamic effects produced by the vessel versus those naturally occurring. In the prototype data, there can also be inaccuracies in recording tow draft, tow position, and tow speed, all of which contribute to the magnitude of the measured wave height or vessel-induced currents. For instance, a tow recorded as fully loaded is generally assumed to have a 2.74-m draft for a particular configuration. In reality, the tow often contains a slightly mixed combination of barge shapes and drafts.

In the physical model, there is a better opportunity to conduct controlled experiments, varying each contributing parameter with more accuracy. Physical models have the advantage of systematically testing each independent variable and evaluating a range of conditions outside the bounds of those that can be captured during a field-data-collection exercise. There are limitations to the physical model. In the experiments conducted at ERDC in the navigation effects research facility for the UMRS study, some of the major limitations deal with scale effect, flume length, and the inability to reproduce a river bend. Descriptions of these limitations can be found in Maynord and Martin (1997 and 1998).

Analysis of Time-History Data

To separate long-period wave responses from the time-history wave data, a Fourier transform method was used. Essentially, the data are transformed from the time domain to the frequency domain; low-frequency data are filtered out; and the remaining high frequency data are converted back to the time domain (Press et al. 1986). These higher frequency waves, or secondary waves, were filtered from the UMRS time-history data using a maximum frequency of 2 Hz and minimum frequency of 0.25 Hz. Figure 3 shows typical time-histories for an event beginning with the unfiltered event, the long-period response, and the short-period wave response. Wave heights were measured as trough to crest, upward crossing the still-water level. Each wave height and period in an event were measured for each filtered time-history response.

Characterization of vessel waves has not been researched to the same extent as wind-driven coastal waves. For engineering design purposes, a characteristic wave height is often selected that statistically represents the wave spectrum. In coastal design, the significant wave height, Hs, is frequently selected, which is defined in the *Shore Protection Manual* (1984) as the average of the highest one-third of the waves. The waves produced by a vessel typically ramp up to a peak and then return to background conditions over a short period of time. On commercial tows, there is sometimes a double peak because of the stern waves, and an event lasts several minutes.

In the literature on vessel-produced waves, an often used characteristic wave is the maximum wave, H_{max}, that occurs during the event. Since it was unclear as to what would be the best characteristic wave height to develop for vessel waves, the analysis of each event included several different statistical representations of the waves in addition to H_{max}. From each filtered time-history event, a computer program was written not only to extract H_{max} but other statistical values including the average of the highest three waves, H_3, the average of the highest five waves, H_5, the average wave height for the event, the total number of waves per event, and the average wave period during an event. In the extraction program, an event was defined as all waves that occur above 20 percent of H_3. This had been recommended by Dr. Robert Sorensen, Lehigh University, as one possible way to focus on the more significant waves.

Figures 4-11 show the distribution of samples and the cumulative frequency distribution of the UMRS data sets for maximum wave height (Figures 4-7) and wave period (Figures 8-11). Maximum wave heights for all data (Figures 4, 5, 8, and 9) were recorded from approximately 4 to 40 cm with periods ranging from approximately 1 to 3 sec. The mean wave height was approximately 12 cm. Figures 6, 7, 10, and 11 give the distribution of wave height and period for prototype events only. As shown, maximum recorded peak wave heights for prototype data were less than 25 cm and for all data up to 40 cm. Prototype period appears to be closer to 1.5 sec as opposed to the mean period of all data of 2 sec. Appendix A is a summary of pertinent data extracted from the time-histories for each event.

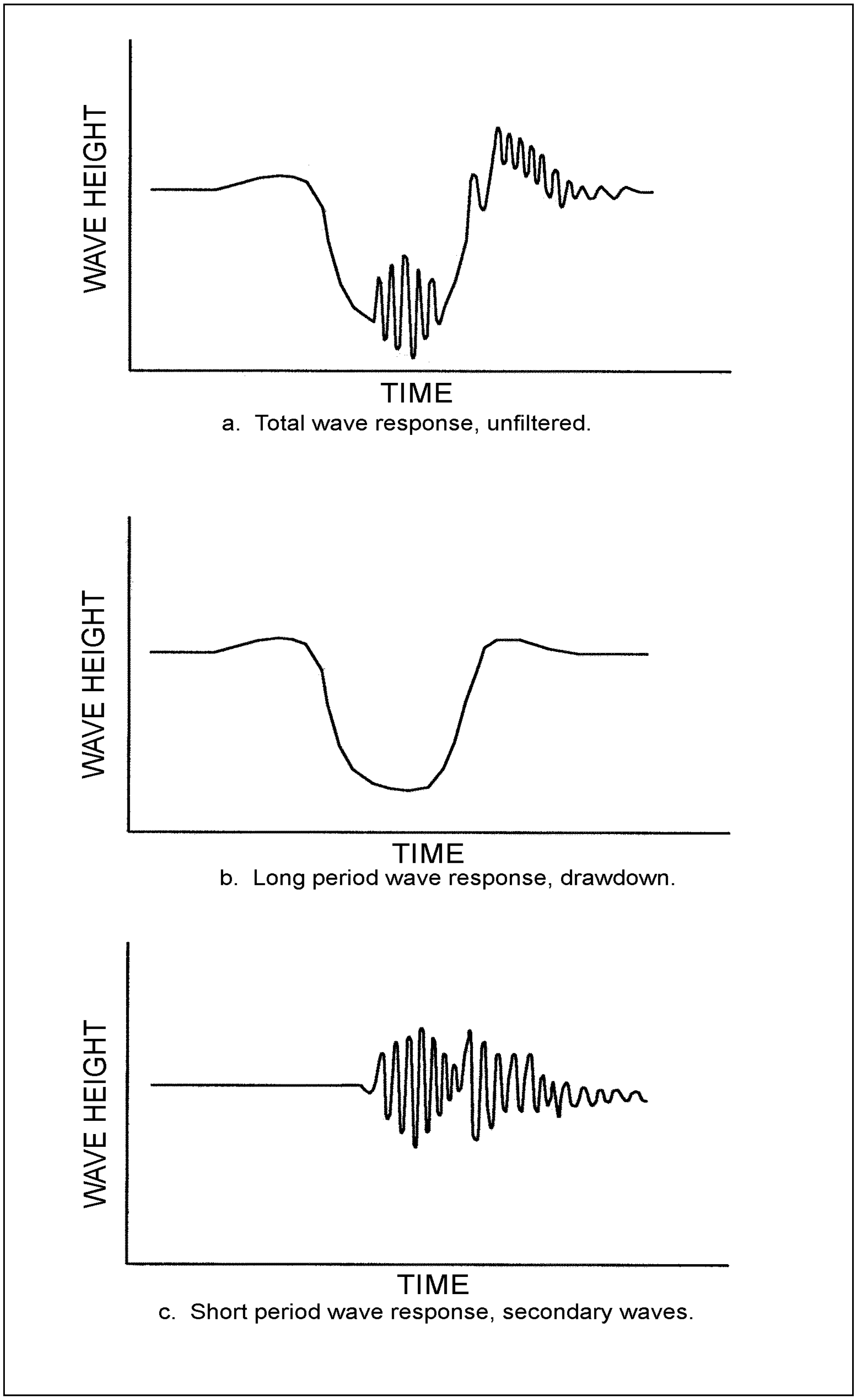


Figure 3. Typical time-history wave response for a tow in a confined channel

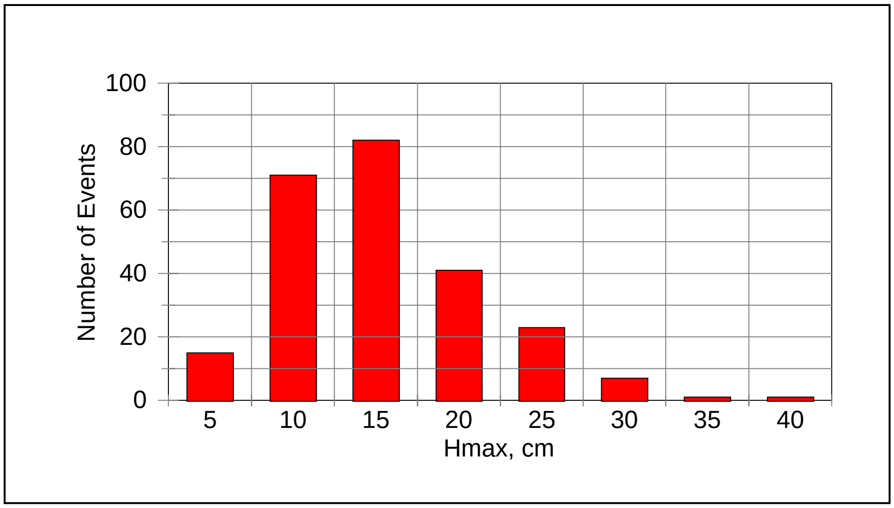


Figure 4. Relative frequency distribution of maximum wave height, all UMRS data

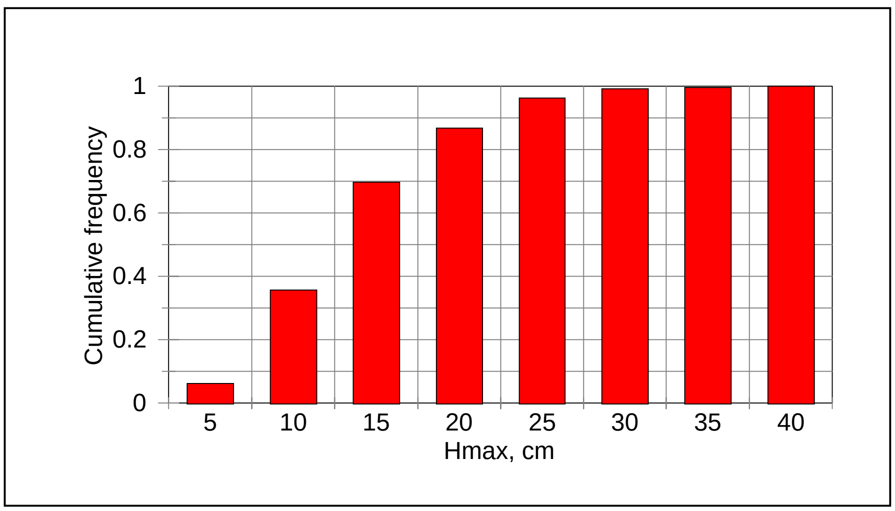


Figure 5. Cumulative frequency distribution of maximum wave height, all UMRS data

Development of Coefficients

As stated, Equation 1 assumes deepwater criteria are met. Attenuation, wave breaking, refraction, and other complex phenomena in the very nearshore are not described by this equation. All data used in the development of the coefficients met the criterion of having Froude numbers less than 0.7. All but two events met the nonbreaking wave criterion of wave height to depth at the gauge point less than 0.6. Assuming wave lengths on the order of 6 m, water depth should be

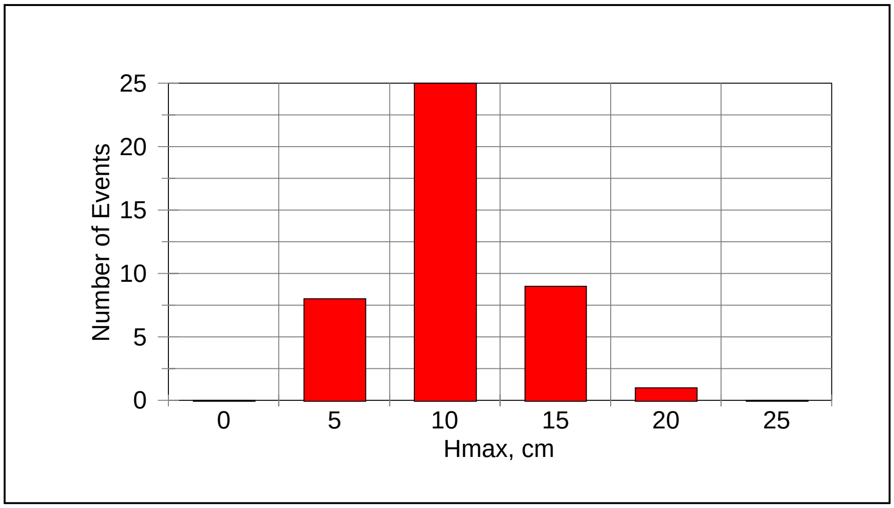


Figure 6. Relative frequency distribution of maximum wave height, ISWS data only

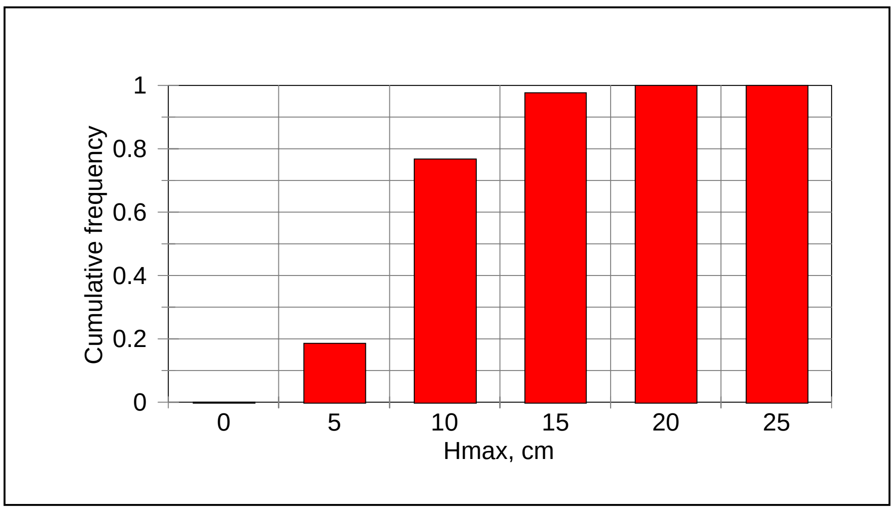


Figure 7. Cumulative frequency distribution of maximum wave height, ISWS data only

greater than approximately 3 m to meet the deepwater criterion established in LeMeHaute (1976). It appears that there could be conditions at depths less than this that would actually be classified as transitional waves. Violation of these criteria as waves approach the nearshore may explain some of the scatter in the data.

It was assumed that wave height diminishes with distance from the sailing line. To demonstrate the validity of using *s* to the -1/3 power in Equation 1, maximum wave height and sailing line for a set of data collected at a constant vessel speed, 3.5 m/sec, for three-wide fully loaded vessels is shown in Figure 12. The theoretical curve represented in the figure is based on α_1 of 0.8 and

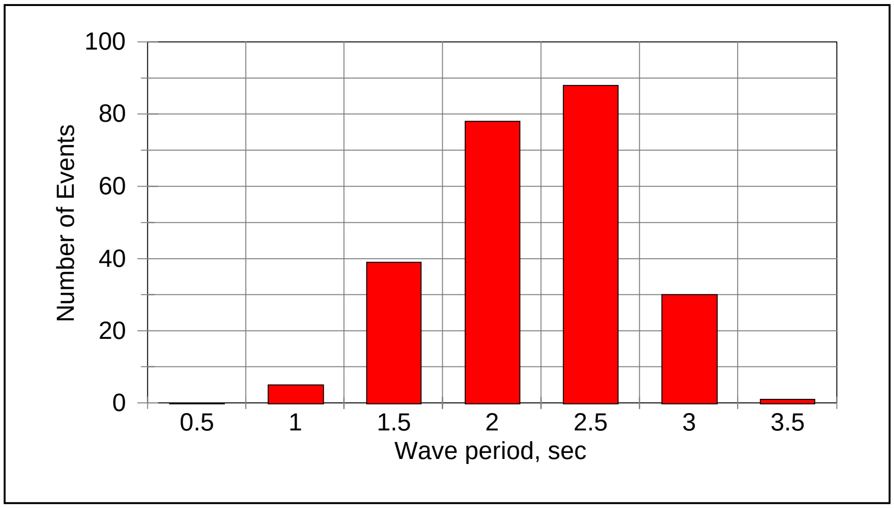


Figure 8. Relative frequency distribution of wave period, all UMRS data

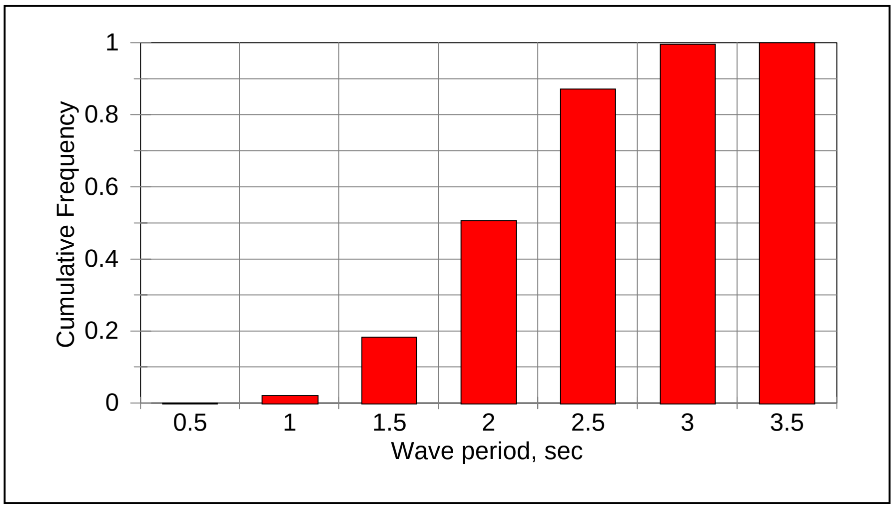


Figure 9. Cumulative frequency distribution of wave period, all UMRS data

α_2 of 2.67. All data did not have a strong correlation to distance from the vessel. In some instances, wave gauges may not have been located at the precise location to capture peak wave heights because of interference peaks. This, likewise, may explain some scatter in the data. However, based on the literature, the exponent of -1/3 was not changed. Data were also analyzed to determine if at 100 or more m away from the vessel, the predictive equation still trended in the same pattern as data at less than 100 m from the vessel. Checks were made to ensure that reflections because of proximity to shore or depth at the gauge were not biasing results or invalidating the predictive equation.

In the original analysis by the author, both α_1 and α_2 were obtained through a statistical regression using a multiplicative model. Using the independent

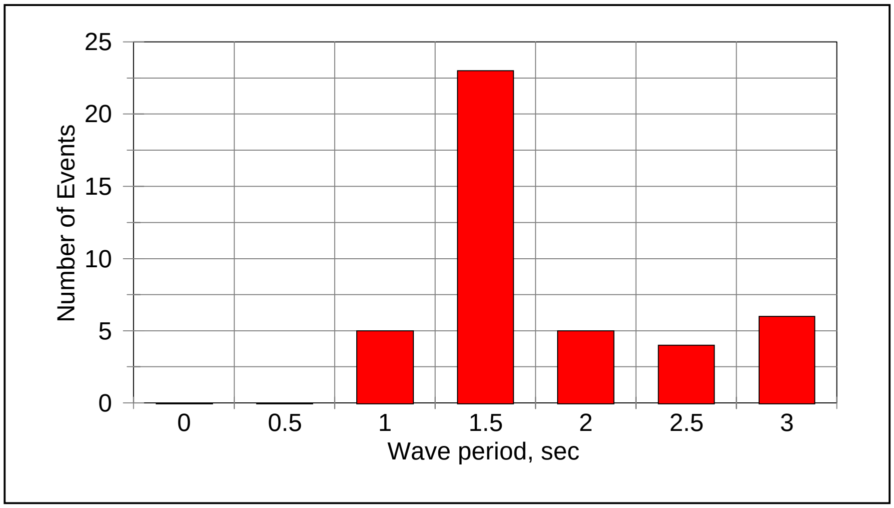


Figure 10. Relative frequency distribution of wave period, ISWS data only

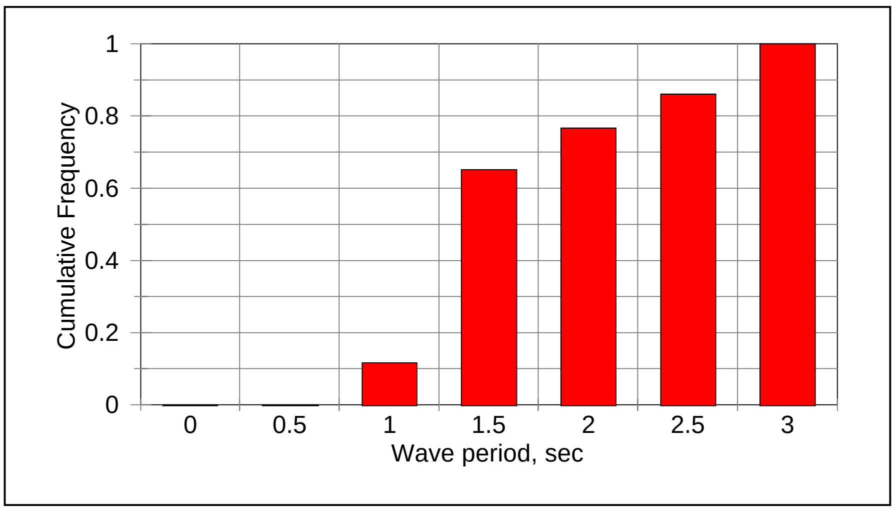


Figure 11. Cumulative frequency distribution of wave period, ISWS data only

variables from the experimental data, a statistical software package, STATGRAF, was used to select the values of both α_1 and α_2 that best fit the dependent variable, wave height. Following this analysis, α_2 was set at 2.67 for several reasons: (a) experimentally fitting both did not produce better correlations and only appeared to complicate the development of the predictive tool; (b) as was stated before, fixing α_2 at 2.67 was felt to be more theoretically reasonable because of the deepwater assumption; and (c) this value more closely followed the exponential relationship to vessel speed of other methods.

The analysis was then focused on the determination of α_1, the hull coefficient. A linear regression model in the spreadsheet package Quattro Pro version 6.01 for Windows was used for all remaining analyses. The best fit value of α_1 was determined from the analysis by fitting the independent variables, sailing

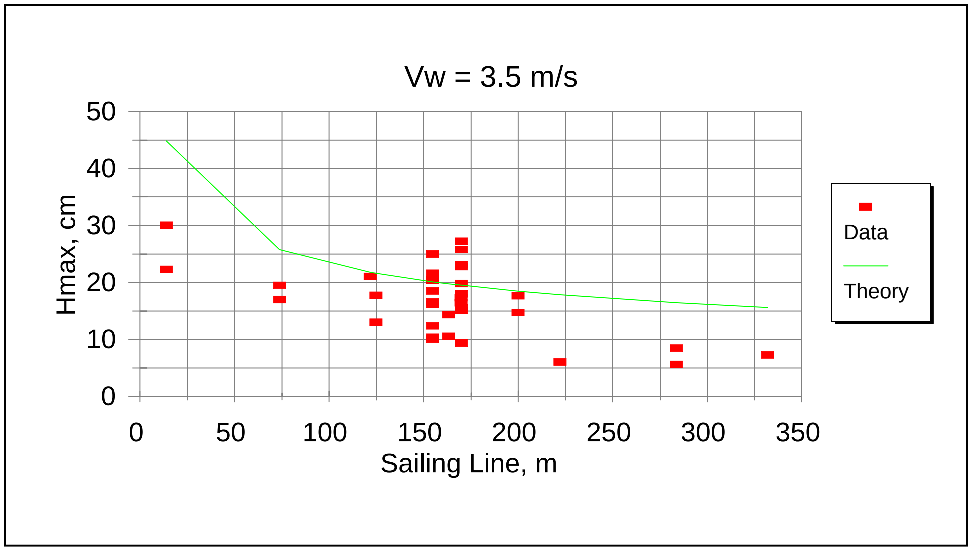


Figure 12. Relationship of maximum wave height to sailing line, *Vw* = 3.5 m/s, three-wide loaded vessels

line and vessel speed, on the right-hand side of Equation 1, to the dependent variable, wave height.

To evaluate goodness of fit, a method used by Maynord (1998) to analyze return currents and drawdown on the UMRS was adopted for this study. Maynord (1998) does not recommend use of the standard correlation coefficient, but suggests using terms called the mean relative error, MRE, and the mean trend error, MTE. These are defined as follows:

$$MRE = \frac{\sum \left| \frac{\text{Calculated} - \text{Observed}}{\text{Observed}} \right|}{n} \tag{3}$$

$$MTE = \frac{\sum \frac{\text{Calculated} - \text{Observed}}{\text{Observed}}}{n} \tag{4}$$

MRE when multiplied by 100 represents the average percent variation, error band, on either side of data that perfectly fits the model (MRE = 0). MTE multiplied by 100 is the average percentage the model overpredicts (positive value) or underpredicts (negative value) observed values when all data are considered. A low value of both MTE and MRE indicates the model is accurately predicting observed results.

To determine the best hull shape coefficient(s) for the UMRS data, the vessel events were aggregated according to different criteria to determine what parameters had the most effect on the outcome. To begin with, all 241 UMRS events were used, and α_1 in Equation 1 was determined through regression analysis to be 0.59 for measured values of H_{max}. The comparison of measured and calculated values is shown in Figure 13. In the plot, prototype data are distinguished from model data so that one can get the feel for the variability and range of values from each type of data. The value of MRE was 0.372 and MTE, -0.105.

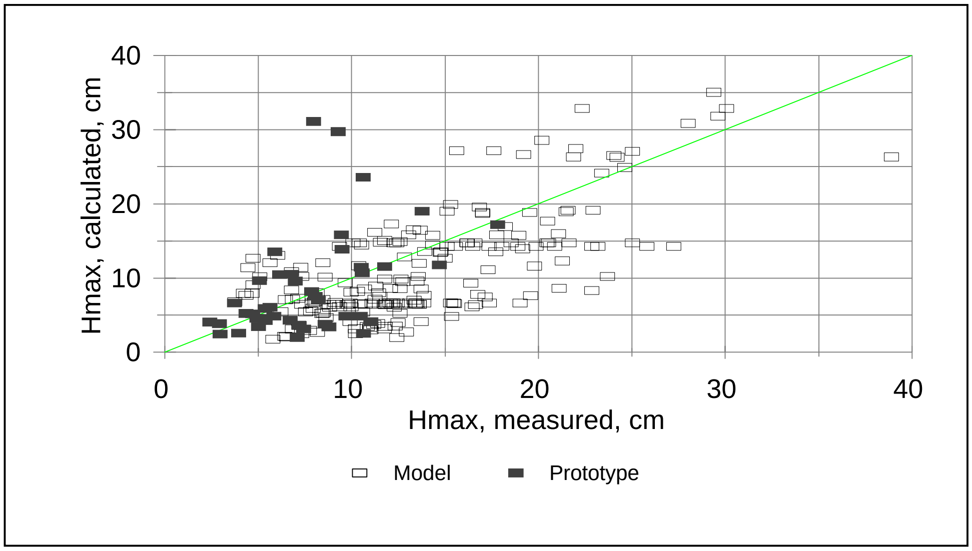


Figure 13. Comparison of measured with calculated values of H_{max}, all UMRS data, $\alpha_1 = 0.59$

Data were then extracted and analyzed according to vessel draft, length, width, direction of travel, and submerged cross-sectional area. Prototype data sets were compared with physical model data sets. Table 1 contains a summary of the different data sets used to obtain α_1 and the number of observations on which the regression was based. MTE and MRE were not calculated for all different coefficients.

Only one data set, the Clark s Ferry physical model data, was extensive enough to evaluate the effects of tow length on variability of wave height. Wave data collected in the Clark s Ferry model for events related to configurations of three by four, three by three, three by two, and three by one were not consistent with data collected for the three by five tows. The analysis of these data yielded higher values of α_1 than other tests. Errors in the data collection or analysis could not be ascertained. The same data set had been used to extract the long- period drawdown, and no abnormalities were noted in the magnitude of these data (Maynord and Martin 1998). It is possible that an error occurred in either the conversion to prototype units or in the analog-to-digital conversion of the

Table 1
Summary of Computed Hull Coefficients for Different Aggregated Data Sets

Data	Number of Observations	α_1
All UMRS data	241	0.591
All loaded	204	0.642
All unloaded	27	0.444
All loaded 3 x 5	129	0.624
All prototype	43	0.371
Prototype loaded 3 x 5	17	0.511
Prototype loaded 3 x 4	7	0.668
Kampsville model loaded 3 x 5	32	0.646
Kampsville model loaded 3 x 4	15	0.614
Clark s Ferry model loaded 3 x 5	81	0.623
Clark s Ferry model loaded 3 x 4	15	0.988
Clark s Ferry model loaded 3 x 3	8	0.718
Clark s Ferry model loaded 3 x 2	8	0.706
Clark s Ferry model loaded 3 x 1	8	0.862
Loaded 1 x 3	8	0.504
Loaded 3 x 3	8	0.72
All upbound	108	0.557
All downbound	133	0.643
All data with area less than 30 m^2	40	0.456
All data with area between 30 and 65 m^2	7	0.56
All data with area greater than 65 m^2	194	0.660
Prototype data with area greater than 65 m^2	28	0.606
FY93 data set	52	0.582

signal. Evaluating the coefficients for the one to four barge lengths in this data set indicates that a single-barge tow and a four-barge tow produce higher peak conditions than the two- and three-barge tows. In an unpublished analysis of tow length by the author, results of a numerical study suggest that under the same operating and channel conditions, a single barge-length vessel can produce peak values of return current and drawdown higher than longer tows near the vessel. Comparing magnitudes at some distance away from the tow, the effects increase as tow length increases. Tows with four and five barges had similar peak values. Similar conclusions were drawn from physical model studies by Maynord and Martin (1998). Because of the questionable nature of this data set, tow length was not considered as a pertinent factor for adjusting the coefficients. However, the Clark s Ferry data were not discarded since they only constitute approximately 16 percent of the total number of events. Any error associated with this assumption only leans to a more conservative approach.

The most obvious trends in coefficients were related to width, draft, and cross-sectional area of the vessel. Loaded vessels yielded a coefficient of 0.642 compared with unloaded, 0.444. This fits well with the Blaauw et al. (1984) recommendation of 0.8 for loaded and 0.35 for unloaded push tows. The wider barge train (three-wide) resulted in a higher coefficient, 0.72, than the narrowest barge train (one-wide), 0.50. Since area incorporates both width and draft, this analysis was deemed most appropriate. Small areas (less than 30 m^2) include three configuration types: (a) two-wide, empties, (b) one-wide, loaded or empties, and (c) three-wide, empties. The intermediate area (30-65 m^2) covers two-wide loaded configurations. Over 65 m^2 would pertain to a three-wide loaded tow. Coefficients of α_1 obtained from the regression were 0.456, 0.560, and 0.660, respectively. Using the area approach would provide a predictive method suitable for mixed draft fleets or other odd configurations and barge sizes, as well as standard sizes.

Verification

The coefficients developed for the UMRS data were verified using the FY93 data set. The three-wide by five-long loaded events were used from the UMRS, making it comparable with the other, yielding an α_1 equal 0.62. The FY93 data set yielded a value of 0.58. This gives an approximate 6 percent error per prediction. Using the value of 0.58 to calculate maximum wave height and comparing it with measured values in the FY93 data set resulted in an MRE of 0.409 and MTE of 0.294. Again using the FY93 data set and a coefficient of 0.62 to compare calculated with measured values yields slightly higher values of MRE and MTE of 0.461 and 0.382, respectively. Figure 14 compares measured values of H_{max} from the FY93 data with computed values using the 0.62 coefficient. A summary of pertinent data for each event is included in Appendix B in English units. Methodologies for data collection and analysis of these data are found in Martin (1997).

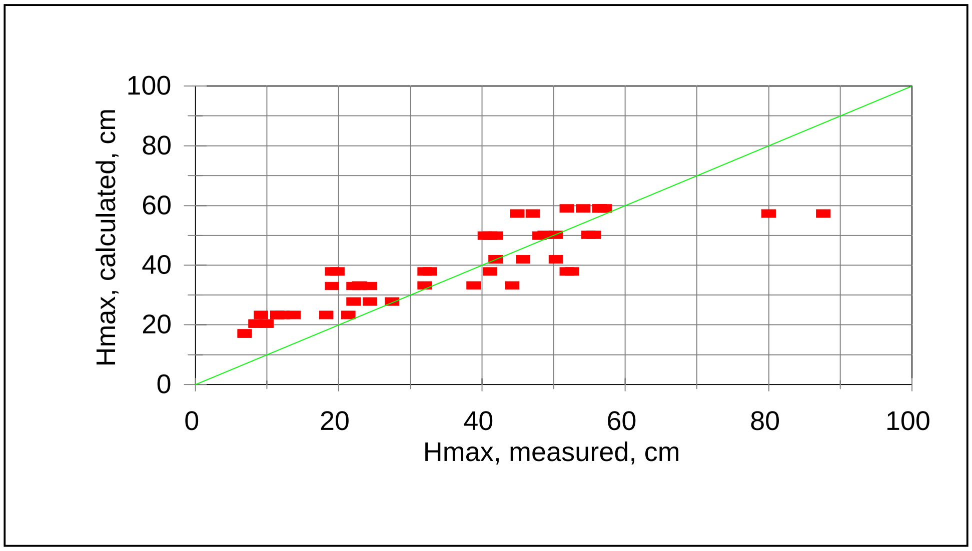


Figure 14. Comparison of measured with calculated values of secondary waves, using FY93 data α_1 –0.62

4 Development of a Time-History Associated with Commercial Vessels

To evaluate potential resuspension of sediments because of vessel wake waves, a time-history of the event was needed. From the analysis, the average wave period was approximately 2 sec, and the number of significant waves in the wave train (those greater than approximately 20 percent of the average highest three waves during the event) was on the order of 75. However, when reevaluating the actual wave files, it was determined that the actual duration of the events produced by commercial tows was longer than what was represented by the number of waves above the 20-percent H_3 value. There were several reasons for this discrepancy. First, the program to extract number of waves did not account for the interspersion of smaller waves between larger ones and therefore would stop counting as soon as the criteria were met. Second, because of the length of the physical model flume, only the peak and a portion of the time-history data could be captured before reflections in the flume interfered with the data. Finally, defining the vessel event in this manner truncates the event, particularly for higher peak values. When for instance a maximum wave of 30 cm is produced, all waves less than 6 cm are removed from the time- history. Reexamination of the time-history data indicated that an event might better be described as the number of waves above a minimal value. This would ensure that the entire event was captured above a critical threshold.

After examination of the field data, a generic time-history pattern was developed to be used with the predicted peak to generate the sequence and duration of the wave events. The duration of most prototype events was on the order of 400 sec, and the minimum measurable wave height above background noise was on the order of 2 cm. Upon calculating the peak event, H_{max}, the time history can be generated according to the diagram in Figure 15 showing the number of waves, N_i, versus the wave height, H. H_{max} occurs at N_i of approximately 25 and transitions again at N_i of 75. H_{LOW} is defined as the greater of 20 percent of H_{max} or 5 cm. For this analysis, each wave represented a wave period of 2 sec, so the whole event is 400 sec with the most significant part of the event occurring in less than 2.5 min. As can be seen, the maximum wave occurs early in the time-history, then tapers to background conditions. Figure 16 shows this generic

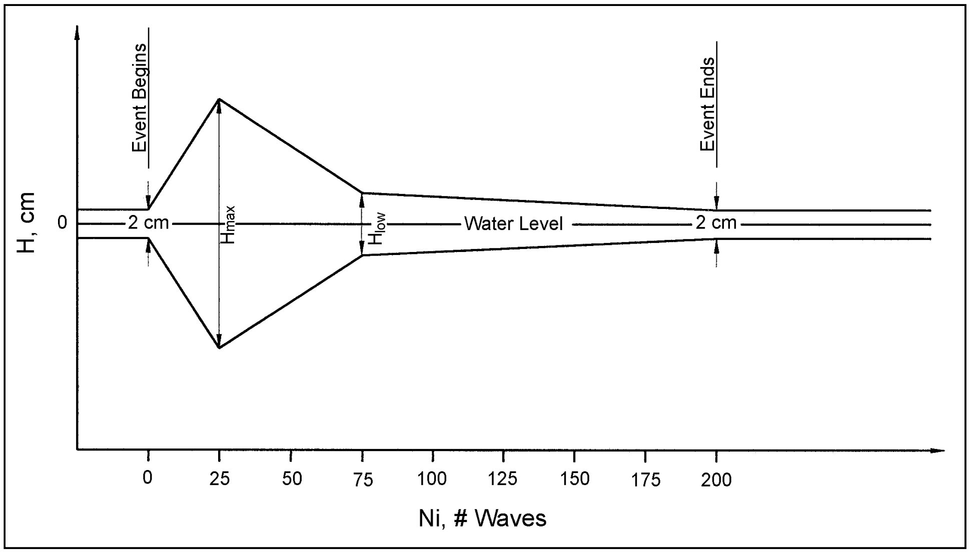


Figure 15. Generic time-history based on H_{max}

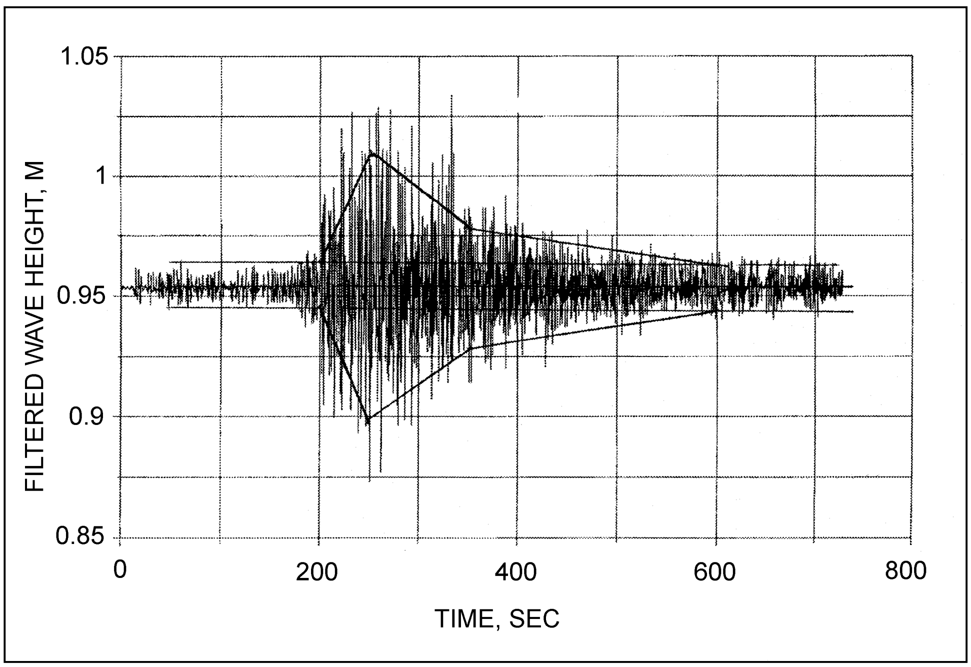


Figure 16. Generic time-history plotted on actual time-history of events caused by *Dixie Patriot*

time-history plotted on top of an actual vessel-wake response collected from the *Dixie Patriot* during the Kampsville field-data-collection exercise. The tow was pushing a one-wide by three-long fully loaded barge train at a speed relative to the water of 2.19 m/sec and at a distance of 161 m from the wave gauge.

5 Recommendations for Prediction of Commercial Tow-Wake Waves

Based on the review of the literature, the analysis conducted, and factoring out depth, the following equation is recommended for prediction of maximum secondary wave height

$$H_{max} = \alpha_1 s^{-0.33} \left(\frac{V_w}{\sqrt{g}} \right)^{2.67} \quad (5)$$

where $\alpha_{1,}$ is a function of the submerged cross-sectional area of the barges, such that:

If Area $\leq$30 m^2, (2 wide-E, 1 wide-F/E, 3 wide-E)
$\alpha_1 = 0.5$

If 30 m^2 <Area< 65 m^2 (2 wide-F)
$\alpha_1 = 0.6$

If Area 65 m^2 (3 wide-F)
$\alpha_1 = 0.7$

Coefficients were raised to the nearest tenth over those determined from the analysis and shown in Table 1. The same limitations apply to vessel Froude number and depth as Equation 1, and the method is valid for distances from 10 to approximately 335 m. Comparisons of measured with calculated values of H_{max} are found in Figures 17-19 for each three cross-sectional areas, respectively.The MRE using this methodology was 0.363, and the MTE was -0.0168.

To generate an approximate time-history of each maximum wave event, use the diagram in Figure 15. This method for predicting and generating a time-history of secondary waves is recommended for use in evaluating sediment resuspension because of vessel passage in areas where actual wave data are not

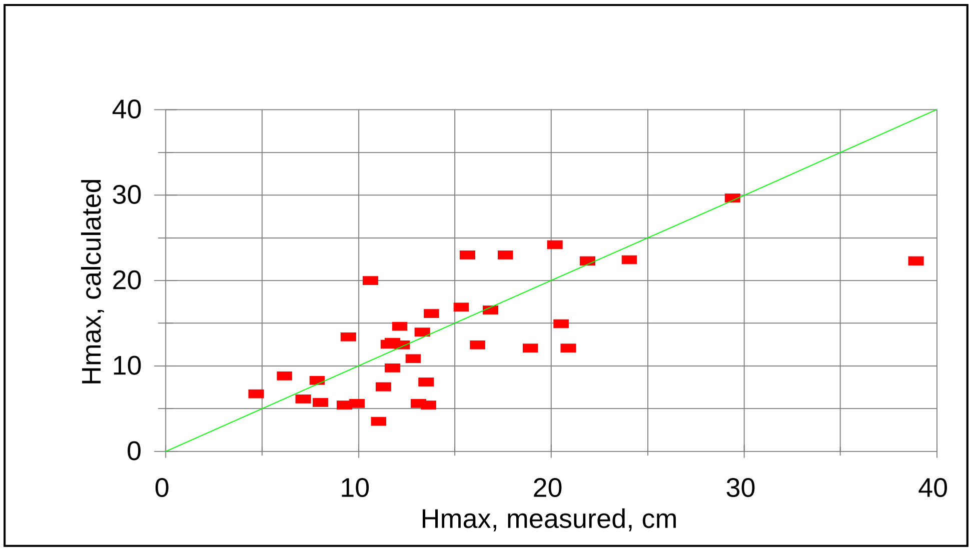


Figure 17. Comparison of measured with calculated values of H_{max}, tow cross-sectional area less than 30 m^2, $\alpha_1 = 0.5$

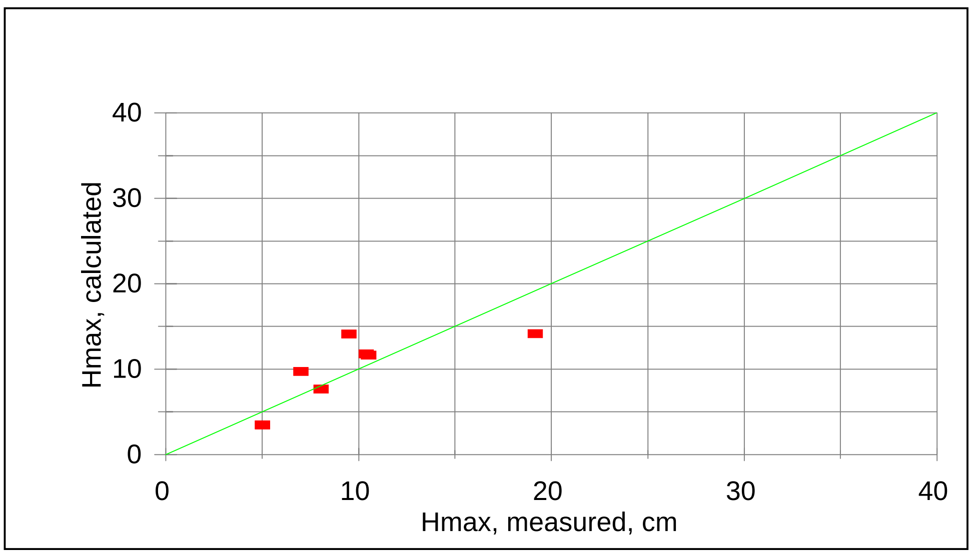


Figure 18. Comparison of measured with calculated values of H_{max}, tow cross-sectional area between than 30 m^2 and 65 m^2, $\alpha_1 = 0.6$

available. This methodology was used in modeling the systemic effects of boat waves on the nearshore environment for the UMRS.

In summary, both a method for predicting wave height and the time-history associated with it have been developed for commercial tows on the UMRS system. The wave-height model was based on the development of coefficients related to the hull cross-sectional area using an extensive data set of commercial tows. It has been verified to an independent data set and compares well with

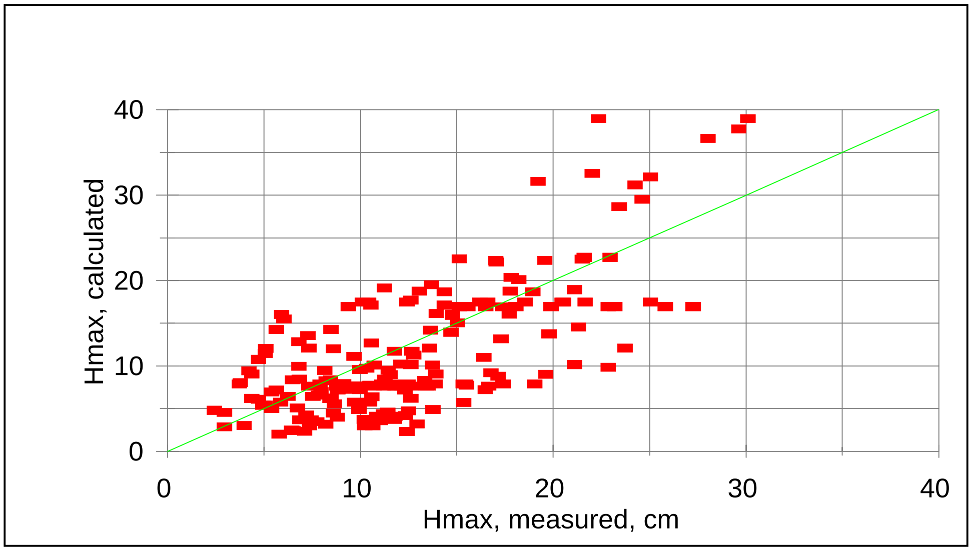


Figure 19. Comparison of measured with calculated values of H_{max}, tow cross-sectional area greater than 65 m^2, $\alpha_1 = 0.7$

coefficients found in the literature. Based on the statistical analysis, the model tends to underpredict by less than 2 percent when considering all data. The model, however, is felt to conservatively estimate wave heights since coefficients were rounded up to the nearest tenth and since analysis of prototype data alone tended to produce lower coefficients (See Table 1).

The predictive model developed herein can be applied to both the UMRS study to evaluate environmental impacts or used to estimate wave height for design of bank protection. These wave height formulas have been programmed into the system model NAVEFF to evaluate literally hundreds of miles of river, one cross section at a time, and predict physical effects. The predicted wave heights from NAVEFF have been coupled with the generic time-history and the available bottom sediments to predict resuspension in the nearshore. Economic traffic forecasts and probable fleet characteristics along with biological models related to aquatic macrophytes, mussels, and fate of transported sediments will be coupled with this analysis to evaluate environmental impacts of planning alternatives for the Navigation Feasibility Study.

The results of these equations are also appropriate for bank protection design. The methodology for design of bank protection considers both maximum drawdown and maximum secondary wave height. A conservative approach is incorporated in the selection of vessel speed to predict either drawdown or wave height and in safety factors for sizing stone (Martin 1997).

References

Bhowmik, N. G., Soong, D. S., Adams, J. R., Xia, R., and Mazuder, B. S. (1996). "Physical changes assoicated with navigation traffic on the Illinois and Upper Mississippi rivers," Draft report prepared for the Environmental Management Technical Center, Illinois State Water Survey, Champaign, IL.

Blaauw, H. G., van der Knaap, F. C., de Groot, M. T., and Pilarczyk, K. W. (1984). "Design of bank protection of inland navigation fairways," Delft Hydraulics Laboratory Publication No. 320, Delft, The Netherlands, presented at the International Conference on Flexible Armoured Revetments Incorporating Geotextiles, London, England.

Boeters, R. E., van der knaap, F. C., and Verheij, J. J. (1995). "Behavior of armour layers of riprap bank protections along navigation channels." *River, coastal and shoreline protection, erosion control using riprap and armourstone*. C. Thorne, S. Abt, F. Barends, S. Maynord, and K. Pilarczyk, ed., John Wiley, Chichester, England, 163-176.

Gates, E. T., and Herbich, J. B. (1977). "Mathematical model to predict the behavior of deep-draft vessels in restricted waterways," TAMU-SG-77-206, Texas A&M Ocean Engineering Program, College Station, TX.

Havelock, T. H. (1908). "The propagation of groups of waves in dispersive media, with application to waves on water produced by a traveling disturbance." *Proceedings of the Royal Society of London.* Series A, 81, 398-430.

Hochstein, A. B., and Adams, C. E. (1989). "Influence of vessel movements on stability of restricted channels," *Journal of Waterway, Port, Coastal, and Ocean Engineering*, American Society of Civil Engineers, 115(4), 444-465.

Le Mehaute, B. (1976). *An introduction to hydrodynamics and water waves.* Springer-Verlag, New York, 212-228.

Martin, S. K. (1997). "Physical model studies for riprap design of tow-induced forces," Technical Report CHL-97-7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Maynord, S. T. (1996). "Return velocity and drawdown in navigable waterways," Technical Report HL-96-7, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

__________. (1998). "Comparison of NAVEFF model to field return velocity and drawdown data," Interim Report for the Upper Mississippi River-Illinois Waterway System Navigation Study, Draft Environmental Report, prepared for U.S. Army Corps of Engineers, Rock Island, St. Louis, and St. Paul Districts.

Maynord, S. T., and Martin, S. K. (1997). "Physical forces study, Kampsville, Illinois Waterway," Interim Report for the Upper Mississippi River-Illinois Waterway System Navigation Study, ENV Report 3, prepared for U.S. Army Corps of Engineers, Rock Island, St. Louis, and St. Paul Districts.

__________. (1998). "Physical forces study, Clarks Ferry, Mississippi River," Interim Report for the Upper Mississippi River-Illinois Waterway System navigation study, ENV Report 5, prepared for U.S. Army Corps of Engineers, Rock Island, St. Louis, and St. Paul.

Permanent International Association of Navigation Congresses. (1987). "Guidelines for the design and construction of flexible revetments incorporating geotextiles for inland waterways," Report of Working Group 4 of the Permanent Technical Committee, supplement to Bulletin No. 57.

Press, W. H., Flannery, B. P., Teukolsky, S. A., and Vetterling, W. T. (1986). "Fourier transform spectral methods." *Numerical recipes: The art of scientific computing*. Chapter 12, Cambridge University Press, New York, 381-453.

Shore Protection Manual. (1984). 4th ed., 2 Vol, U.S. Army Engineer Waterways Experiment Station, U.S. Government Printing Office, Washington, DC.

Sorensen, R. M. (1966). "Ship waves," Ph.D. diss., University of California, Berkeley.

__________. (1997). "Prediction of vessel-generated waves with reference to vessels common to the Upper Mississippi River System," Interim Report for the Upper Mississippi River-Illinois Waterway System Navigation Study, ENV Report 4, prepared for U.S. Army Corps of Engineers, Rock Island, St. Louis, and St. Paul Districts.

Verhey, H. J., and Bogaerts, M. P. (1989). "Ship waves and the stability of armor layers protecting slopes," Publication No. 428, Delft Hydraulics Laboratory, The Netherlands.

Appendix A
Secondary Wave Data on the Upper Mississippi River - Illinois Waterway System for Commercial Towboats

SECONDARY WAVE DATA ON UMRS FOR COMMERCIAL TOWBOATS

Tow/Test Name	Data Series	Pool Elev NGVD	Q cms	Va m/s	Vs m/s	Dir. u/d	Vw m/s	Tow Conf.	Draft m	barge width m	barge length m	Tow cross-sec area	Channel Top width m	WG to Shore m	s Edge tow to WG	Depth @WG m	Depth @Tow m	Hmax cm	H3 cm	H5 cm	Ave period sec
lcuu40	Clarks	546.0	690	0.32	4.08	u	4.40	3X5	0.91	32	297.25	29.12	614.8	82.1	155.0	3.98	5.24	17.62	16.61	15.61	2.64
lcuu40	Clarks	546.0	690	0.32	4.08	u	4.40	3X5	0.91	32	297.25	29.12	614.8	175.6	170.1	2.86	5.24	21.88	20.25	18.85	2.63
lcud47	Clarks	546.0	690	-0.3	4.72	d	4.40	3X5	0.91	32	297.25	29.12	614.8	82.1	155.0	3.98	5.24	15.65	15.45	14.48	2.13
lcud47	Clarks	546.0	690	-0.3	4.72	d	4.40	3X5	0.91	32	297.25	29.12	614.8	175.6	170.1	2.86	5.24	38.92	31.23	28.54	2.30
lcud38	Clarks	546.0	690	-0.3	3.82	d	3.50	3X5	0.91	32	297.25	29.12	614.8	82.1	155.0	3.98	5.24	16.17	15.34	14.37	1.96
lcuu31	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	0.91	32	297.25	29.12	614.8	82.1	155.0	3.98	5.24	12.28	10.67	10.21	2.08
lcuu31	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	0.91	32	297.25	29.12	614.8	175.6	170.1	2.86	5.24	20.89	17.85	16.77	2.57
lcud38	Clarks	546.0	690	-0.3	3.82	d	3.50	3X5	0.91	32	297.25	29.12	614.8	175.6	170.1	2.86	5.24	18.91	16.78	15.86	2.14
lcud29	Clarks	546.0	690	-0.3	2.92	d	2.60	3X5	0.91	32	297.25	29.12	614.8	82.1	155.0	3.98	5.24	9.93	9.00	8.29	1.92
lcud29	Clarks	546.0	690	-0.3	2.92	d	2.60	3X5	0.91	32	297.25	29.12	614.8	175.6	170.1	2.86	5.24	9.28	8.77	8.34	1.95
lcuu22	Clarks	546.0	690	0.32	2.28	u	2.60	3X5	0.91	32	297.25	29.12	614.8	175.6	170.1	2.86	5.24	13.64	12.03	11.38	2.47
lcuu22	Clarks	546.0	690	0.32	2.28	u	2.60	3X5	0.91	32	297.25	29.12	614.8	82.1	155.0	3.98	5.24	13.12	12.60	12.19	2.74
hcu416	Clarks	551.5	1627	0.51	4.16	u	4.67	3X5	2.13	32	297.25	68.16	627.0	86.2	155.0	5.50	6.92	29.64	28.87	28.50	2.99
hcu416	Clarks	551.5	1627	0.51	4.16	u	4.67	3X5	2.13	32	297.25	68.16	627.0	183.8	170.0	4.54	6.92	28.04	25.26	23.79	2.92
chd472	Clarks	572.7	2317	-0.3	4.77	d	4.45	3X5	2.13	32	297.25	68.16	624.5	89.9	163.4	12.00	13.40	22.02	21.16	20.39	2.36
chd472	Clarks	572.7	2317	-0.3	4.77	d	4.45	3X5	2.13	32	297.25	68.16	624.5	169.2	170.0	11.00	13.40	25.05	24.11	23.45	2.21
chu408	Clarks	572.7	2317	0.32	4.08	u	4.40	3X5	2.13	32	297.25	68.16	624.5	89.9	163.4	12.00	13.40	19.23	19.14	17.87	2.48
chu408	Clarks	572.7	2317	0.32	4.08	u	4.40	3X5	2.13	32	297.25	68.16	624.5	169.2	170.0	11.00	13.40	24.24	21.58	20.73	2.65
hcd477	Clarks	551.5	1627	-0.5	4.77	d	4.26	3X5	2.13	32	297.25	68.16	627.0	86.2	155.0	5.50	6.92	24.63	21.74	20.89	2.14
hcd477	Clarks	551.5	1627	-0.5	4.77	d	4.26	3X5	2.13	32	297.25	68.16	627.0	183.8	170.0	4.54	6.92	23.42	23.05	22.70	2.12
DRayJr	Clarks	549.4	2351	0.83	3.00	u	3.83	3X5	2.13	32	297.25	68.16	622.1	59.3	149.7	2.16	6.30	21.51	20.81	19.75	2.90
DRayJr	Clarks	549.4	2351	0.83	3.00	u	3.83	3X5	2.13	32	297.25	68.16	622.1	232.8	148.3	4.90	6.30	15.12	14.90	14.32	2.86
hcd318	Clarks	551.5	1627	0.51	3.18	u	3.69	3X5	2.13	32	297.25	68.16	627.0	86.2	155.0	5.50	6.92	18.23	15.27	14.23	2.26
hcu318	Clarks	551.5	1627	0.51	3.18	u	3.69	3X5	2.13	32	297.25	68.16	627.0	183.8	170.0	4.54	6.92	13.68	12.83	12.46	2.59
chd382	Clarks	572.7	2317	-0.3	3.82	d	3.50	3X5	2.13	32	297.25	68.16	624.5	89.9	163.4	12.00	13.40	10.55	9.87	9.60	2.32
lcvucd	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	614.8	15.0	222.1	2.10	5.24	6.05	5.42	4.94	2.07
lc2u31	Clarks	546.0	690	0.32	3.18	u	3.50	3X2	2.13	32	118.90	68.16	614.8	82.1	155.0	3.98	5.24	10.41	9.69	9.38	2.24
lc3d38	Clarks	546.0	690	-0.3	3.82	d	3.50	3X3	2.13	32	178.35	68.16	614.8	175.6	170.1	2.86	5.24	15.14	13.88	13.19	2.11
lcvuaf	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	614.8	115.1	122.0	4.54	5.24	21.10	20.08	19.15	2.36
lc1d38	Clarks	546.0	690	-0.32	3.82	d	3.50	3X1	2.13	32	36.25	68.16	614.8	82.1	155.0	3.98	5.24	10.09	9.86	9.49	2.03
lru318	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	614.8	181.7	284.0	2.97	4.83	5.63	5.05	4.61	1.66
llu318	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	614.8	175.6	125.1	2.86	4.88	13.07	11.56	10.86	1.99
lcvuaf	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	614.8	190.7	155.0	3.10	5.24	12.42	11.39	10.74	2.18
lcvucd	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	614.8	13.6	332.1	1.20	5.24	7.29	7.13	6.79	2.54
lrd382	Clarks	546.0	690	-0.32	3.82	d	3.50	3X5	2.13	32	297.25	68.16	614.8	181.7	284.0	2.97	4.83	8.47	7.95	7.54	2.43
lc3u31	Clarks	546.0	690	0.32	3.18	u	3.50	3X3	2.13	32	178.35	68.16	614.8	175.6	170.1	2.86	5.24	9.37	8.62	7.92	2.39
chd382	Clarks	572.7	2317	-0.32	3.82	d	3.50	3X5	2.13	32	297.25	68.16	624.5	169.2	170.0	11.00	13.40	17.37	15.66	15.14	2.15
lc4u31	Clarks	546.0	690	0.32	3.18	u	3.50	3X4	2.13	32	237.80	68.16	614.8	82.1	155.0	3.98	5.24	18.54	17.11	16.45	2.29
llu318	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	614.8	82.1	200.0	3.98	4.88	14.79	14.47	14.06	2.29
lcvube	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	614.8	331.7	14.0	5.00	5.24	30.09	27.37	26.15	2.64
lcvube	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	614.8	223.1	14.0	5.18	5.24	22.35	21.97	21.62	2.40
lc1d38	Clarks	546.0	690	-0.32	3.82	d	3.50	3X1	2.13	32	36.25	68.16	614.8	175.6	170.1	2.86	5.24	27.25	21.84	19.02	2.47
lc3d38	Clarks	546.0	690	-0.32	3.82	d	3.50	3X3	2.13	32	178.35	68.16	614.8	82.1	155.0	3.98	5.24	21.66	20.13	18.83	2.51

SECONDARY WAVE DATA ON UMRS FOR COMMERCIAL TOWBOATS

Tow/Test Name	Data Series	Pool Elev NGVD	Q cms	Va m/s	Vs m/s	Dir. u/d	Vw m/s	Tow Conf.	Draft m	barge width m	barge length m	Tow cross-sec area	Channel Top width m	WG to Shore m	s Edge tow to WG	Depth @WG m	Depth @Tow m	Hmax cm	H3 cm	H5 cm	Ave period sec
lc1u38	Clarks	546.0	690	0.32	3.18	u	3.50	3X1	2.13	32	36.25	68.16	614.8	175.6	170.1	2.86	5.24	18.07	17.51	16.62	2.70
lld382	Clarks	546.0	690	-0.32	3.82	d	3.50	3X5	2.13	32	297.25	68.16	614.8	82.1	200.0	3.98	4.88	17.72	14.41	13.33	1.77
lc4d38	Clarks	546.0	690	-0.32	3.82	d	3.50	3X4	2.13	32	237.80	68.16	614.8	175.6	170.1	2.86	5.24	25.83	21.68	20.03	2.29
lc1u38	Clarks	546.0	690	0.32	3.18	u	3.50	3X1	2.13	32	36.25	68.16	614.8	82.1	155.0	3.98	5.24	25.04	21.20	19.23	3.07
chu318	Clarks	572.7	2317	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	624.5	169.2	170.0	11.00	13.40	16.49	14.39	13.60	2.32
lc2d38	Clarks	546.0	690	-0.32	3.82	d	3.50	3X2	2.13	32	118.90	68.16	614.8	82.1	155.0	3.98	5.24	16.61	16.03	15.49	2.06
chu318	Clarks	572.7	2317	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	624.5	89.9	163.4	12.00	13.40	14.37	13.19	12.24	2.11
lrd382	Clarks	546.0	690	-0.32	3.82	d	3.50	3X5	2.13	32	297.25	68.16	614.8	43.1	74.0	2.97	4.83	17.02	16.44	16.06	1.96
lc3u31	Clarks	546.0	690	0.32	3.18	u	3.50	3X3	2.13	32	178.35	68.16	614.8	82.1	155.0	3.98	5.24	16.20	14.51	13.24	2.61
lcu318	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	614.8	82.1	155.0	3.98	5.24	20.55	17.56	16.40	2.30
lld382	Clarks	546.0	690	-0.32	3.82	d	3.50	3X5	2.13	32	297.25	68.16	614.8	175.6	125.1	2.86	4.88	17.78	17.63	15.65	1.86
lc2d38	Clarks	546.0	690	-0.32	3.82	d	3.50	3X2	2.13	32	118.90	68.16	614.8	175.6	170.1	2.86	5.24	15.57	15.10	14.02	1.69
lcu318	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	614.8	175.6	170.1	2.86	5.24	23.20	18.28	16.63	2.15
lc4u31	Clarks	546.0	690	0.32	3.18	u	3.50	3X4	2.13	32	237.80	68.16	614.8	175.6	170.1	2.86	5.24	22.86	17.05	15.31	2.37
lc2u31	Clarks	546.0	690	0.32	3.18	u	3.50	3X2	2.13	32	118.90	68.16	614.8	175.6	170.1	2.86	5.24	19.88	18.56	15.89	2.53
lc4d38	Clarks	546.0	690	-0.32	3.82	d	3.50	3X4	2.13	32	237.80	68.16	614.8	82.1	155.0	3.98	5.24	20.46	18.45	17.19	2.24
lru318	Clarks	546.0	690	0.32	3.18	u	3.50	3X5	2.13	32	297.25	68.16	614.8	43.1	74.0	2.97	4.83	19.56	18.02	17.11	2.30
hcd382	Clarks	551.5	1627	-0.51	3.82	d	3.31	3X5	2.13	32	297.25	68.16	627.0	183.8	170.0	4.54	6.92	21.30	20.82	19.65	2.11
hcd382	Clarks	551.5	1627	-0.51	3.82	d	3.31	3X5	2.13	32	297.25	68.16	627.0	86.2	155.0	5.50	6.92	15.03	13.59	12.80	2.23
hcu273	Clarks	551.5	1627	0.51	2.73	u	3.24	3X5	2.13	32	297.25	68.16	627.0	86.2	155.0	5.50	6.92	13.64	10.79	9.97	2.34
hcu273	Clarks	551.5	1627	0.51	2.73	u	3.24	3X5	2.13	32	297.25	68.16	627.0	183.8	170.0	4.54	6.92	19.80	18.69	17.71	2.61
lcd337	Clarks	546.0	690	-0.32	3.37	d	3.05	3X5	2.13	32	297.25	68.16	614.8	82.1	155.0	3.98	5.24	23.73	17.32	15.54	2.01
lcd337	Clarks	546.0	690	-0.32	3.37	d	3.05	3X5	2.13	32	297.25	68.16	614.8	175.6	170.1	2.86	5.24	11.77	10.27	9.49	1.92
lcu273	Clarks	546.0	690	0.32	2.73	u	3.05	3X5	2.13	32	297.25	68.16	614.8	175.6	170.1	2.86	5.24	12.67	11.64	11.32	2.06
lcu273	Clarks	546.0	690	0.32	2.73	u	3.05	3X5	2.13	32	297.25	68.16	614.8	82.1	155.0	3.98	5.24	13.59	12.56	11.70	1.90
JDWofford	Clarks	549.4	2351	-0.83	3.70	d	2.87	3X4	2.13	32	237.80	68.16	622.1	232.8	73.3	4.90	6.20	17.30	15.65	14.82	2.15
JDWofford	Clarks	549.4	2351	-0.83	3.70	d	2.87	3X4	2.13	32	237.80	68.16	622.1	59.3	224.7	2.16	6.20	13.91	13.66	13.24	2.55
lcvdcd	Clarks	546.0	690	-0.32	3.18	d	2.86	3X5	2.13	32	297.25	68.16	614.8	13.6	332.1	1.20	5.24	19.05	16.89	15.31	2.59
lcvdaf	Clarks	546.0	690	-0.32	3.18	d	2.86	3X5	2.13	32	297.25	68.16	614.8	190.7	155.0	3.10	5.24	21.11	18.83	16.01	1.80
lcvdbe	Clarks	546.0	690	-0.32	3.18	d	2.86	3X5	2.13	32	297.25	68.16	614.8	331.7	14.0	5.00	5.24	21.61	19.63	18.93	2.01
hcd337	Clarks	551.5	1627	-0.51	3.37	d	2.86	3X5	2.13	32	297.25	68.16	627.0	183.8	170.0	4.54	6.92	22.86	18.05	16.59	1.99
lcvdbe	Clarks	546.0	690	-0.32	3.18	d	2.86	3X5	2.13	32	297.25	68.16	614.8	223.1	14.0	5.18	5.24	22.95	21.64	19.89	1.89
lcvdcd	Clarks	546.0	690	-0.32	3.18	d	2.86	3X4	2.13	32	237.80	68.16	614.8	15.0	222.1	2.10	5.24	19.61	15.87	14.67	2.30
lcvdaf	Clarks	546.0	690	-0.32	3.18	d	2.86	3X5	2.13	32	297.25	68.16	614.8	115.1	122.0	4.54	5.24	16.40	15.32	13.89	1.84
hcd337	Clarks	551.5	1627	-0.51	3.37	d	2.86	3X5	2.13	32	297.25	68.16	627.0	86.2	155.0	5.50	6.92	12.61	12.21	11.88	1.90
hcu228	Clarks	551.5	1627	0.51	2.28	u	2.79	3X5	2.13	32	297.25	68.16	627.0	86.2	155.0	5.50	6.92	11.44	9.58	8.75	2.05
hcu228	Clarks	551.5	1627	0.51	2.28	u	2.79	3X5	2.13	32	297.25	68.16	627.0	183.8	170.0	4.54	6.92	16.77	13.53	12.24	2.38
lc4d29	Clarks	546.0	690	-0.32	2.92	d	2.60	3X4	2.13	32	237.80	68.16	614.8	175.6	170.1	2.86	5.24	11.78	10.20	9.62	2.05
lc1d29	Clarks	546.0	690	-0.32	2.92	d	2.60	3X1	2.13	32	36.25	68.16	614.8	82.1	155.0	3.98	5.24	7.92	7.69	7.37	1.92
lcd292	Clarks	546.0	690	-0.32	2.92	d	2.60	3X5	2.13	32	297.25	68.16	614.8	175.6	170.1	2.86	5.24	12.18	10.88	10.40	2.03
lc4d29	Clarks	546.0	690	-0.32	2.92	d	2.60	3X4	2.13	32	237.80	68.16	614.8	82.1	155.0	3.98	5.24	11.13	10.63	9.78	2.03
lrd292	Clarks	546.0	690	-0.32	2.92	d	2.60	3X5	2.13	32	297.25	68.16	614.8	43.1	74.0	2.97	4.83	10.72	10.51	9.73	1.71
lld292	Clarks	546.0	690	-0.32	2.92	d	2.60	3X5	2.13	32	297.25	68.16	614.8	175.6	125.1	2.86	4.88	11.26	10.40	10.10	1.91

SECONDARY WAVE DATA ON UMRS FOR COMMERCIAL TOWBOATS

Tow/Test Name	Data Series	Pool Elev NGVD	Q cms	Va m/s	Vs m/s	Dir. u/d	Vw m/s	Tow Conf.	Draft m	barge width m	barge length m	Tow cross-sec area	Channel Top width m	WG to Shore m	s Edge tow to WG	Depth @WG m	Depth @Tow m	Hmax cm	H3 cm	H5 cm	Ave period sec
lld292	Clarks	546.0	690	-0.32	2.92	d	2.60	3X5	2.13	32	297.25	68.16	614.8	82.1	200.0	3.98	4.88	16.48	14.00	13.24	2.02
lc3d29	Clarks	546.0	690	-0.32	2.92	d	2.60	3X3	2.13	32	178.35	68.16	614.8	175.6	170.1	2.86	5.24	11.20	10.30	9.80	2.03
lc2d29	Clarks	546.0	690	-0.32	2.92	d	2.60	3X2	2.13	32	118.90	68.16	614.8	175.6	170.1	2.86	5.24	8.79	8.58	7.99	2.24
lrd292	Clarks	546.0	690	-0.32	2.92	d	2.60	3X5	2.13	32	297.25	68.16	614.8	181.7	284.0	2.97	4.83	7.54	6.48	5.65	1.84
chd292	Clarks	572.7	2317	-0.32	2.92	d	2.60	3X5	2.13	32	297.25	68.16	624.5	169.2	170.0	11.00	13.40	16.64	15.86	15.44	2.29
chd292	Clarks	572.7	2317	-0.32	2.92	d	2.60	3X5	2.13	32	297.25	68.16	624.5	89.9	163.4	12.00	13.40	15.51	15.08	14.57	2.32
lcd292	Clarks	546.0	690	-0.32	2.92	d	2.60	3X5	2.13	32	297.25	68.16	614.8	82.1	155.0	3.98	5.24	11.85	11.64	11.09	2.01
lc1d29	Clarks	546.0	690	-0.32	2.92	d	2.60	3X1	2.13	32	36.25	68.16	614.8	175.6	170.1	2.86	5.24	13.50	13.13	12.57	2.22
lc3d29	Clarks	546.0	690	-0.32	2.92	d	2.60	3X3	2.13	32	178.35	68.16	614.8	82.1	155.0	3.98	5.24	12.22	10.89	9.98	1.80
lc2d29	Clarks	546.0	690	-0.32	2.92	d	2.60	3X2	2.13	32	118.90	68.16	614.8	82.1	155.0	3.98	5.24	15.32	13.17	12.47	2.04
lcu228	Clarks	546.0	690	0.32	2.28	u	2.60	3X5	2.13	32	297.25	68.16	614.8	82.1	155.0	3.98	5.24	12.08	11.73	10.70	2.09
lcu228	Clarks	546.0	690	0.32	2.28	u	2.60	3X5	2.13	32	297.25	68.16	614.8	175.6	170.1	2.86	5.24	12.66	11.95	11.34	2.00
lc2u22	Clarks	546.0	690	0.32	2.28	u	2.60	3X2	2.13	32	118.90	68.16	614.8	175.6	170.1	2.86	5.24	10.73	9.92	9.32	2.38
chu228	Clarks	572.7	2317	0.32	2.28	u	2.60	3X5	2.13	32	297.25	68.16	624.5	89.9	163.4	12.00	13.40	10.49	9.77	9.26	1.82
llu228	Clarks	546.0	690	0.32	2.28	u	2.60	3X5	2.13	32	297.25	68.16	614.8	175.6	125.1	2.86	4.88	6.84	6.26	5.94	1.71
lc3u22	Clarks	546.0	690	0.32	2.28	u	2.60	3X3	2.13	32	178.35	68.16	614.8	175.6	170.1	2.86	5.24	9.08	8.77	8.46	2.22
lc4u22	Clarks	546.0	690	0.32	2.28	u	2.60	3X4	2.13	32	237.80	68.16	614.8	82.1	155.0	3.98	5.24	15.47	15.02	14.60	2.20
chu228	Clarks	572.7	2317	0.32	2.28	u	2.60	3X5	2.13	32	297.25	68.16	624.5	169.2	170.0	11.00	13.40	11.83	8.60	7.83	2.09
lru228	Clarks	546.0	690	0.32	2.28	u	2.60	3X5	2.13	32	297.25	68.16	614.8	181.7	284.0	2.97	4.83	6.24	5.90	5.54	2.33
lc1u29	Clarks	546.0	690	0.32	2.28	u	2.60	3X1	2.13	32	36.25	68.16	614.8	82.1	155.0	3.98	5.24	13.88	12.48	11.75	2.85
lru228	Clarks	546.0	690	0.32	2.28	u	2.60	3X5	2.13	32	297.25	68.16	614.8	43.1	74.0	2.97	4.83	13.75	13.21	12.33	2.12
lc4u22	Clarks	546.0	690	0.32	2.28	u	2.60	3X4	2.13	32	237.80	68.16	614.8	175.6	170.1	2.86	5.24	9.83	9.11	8.42	2.16
lc3u22	Clarks	546.0	690	0.32	2.28	u	2.60	3X3	2.13	32	178.35	68.16	614.8	82.1	155.0	3.98	5.24	17.39	13.48	12.16	2.30
llu228	Clarks	546.0	690	0.32	2.28	u	2.60	3X5	2.13	32	297.25	68.16	614.8	82.1	200.0	3.98	4.88	9.98	9.75	9.29	1.94
lc2u22	Clarks	546.0	690	0.32	2.28	u	2.60	3X2	2.13	32	118.90	68.16	614.8	82.1	155.0	3.98	5.24	12.46	12.00	11.64	2.48
lc1u29	Clarks	546.0	690	0.32	2.28	u	2.60	3X1	2.13	32	36.25	68.16	614.8	175.6	170.1	2.86	5.24	13.42	10.84	9.86	2.61
hcd292	Clarks	551.5	1627	-0.51	2.92	d	2.41	3X5	2.13	32	297.25	68.16	627.0	86.2	155.0	5.50	6.92	10.60	9.47	8.74	1.87
hcd292	Clarks	551.5	1627	-0.51	2.92	d	2.41	3X5	2.13	32	297.25	68.16	627.0	183.8	170.0	4.54	6.92	12.61	11.61	11.13	1.90
lcd247	Clarks	546.0	690	-0.32	2.47	d	2.15	3X5	2.13	32	297.25	68.16	614.8	82.1	155.0	3.98	5.24	12.49	11.10	10.74	1.71
lcd247	Clarks	546.0	690	-0.32	2.47	d	2.15	3X5	2.13	32	297.25	68.16	614.8	175.6	170.1	2.86	5.24	11.41	10.38	9.64	1.73
Conti-Nan	Clarks	546.0	673	-0.32	2.41	d	2.09	3X5	2.13	32	297.25	68.16	614.8	58.1	185.9	3.70	5.00	11.81	10.40	9.59	1.82
Conti-Nan	Clarks	546.0	673	-0.32	2.41	d	2.09	3X5	2.13	32	297.25	68.16	614.8	226.7	112.1	3.40	5.00	13.75	11.97	11.08	1.88
PearlB	Clarks	549.4	2351	-0.83	2.87	d	2.04	3X4	2.13	32	237.80	68.16	622.1	232.8	123.3	4.90	6.40	11.20	9.18	8.58	1.92
PearlB	Clarks	549.4	2351	-0.83	2.87	d	2.04	3X4	2.13	32	237.80	68.16	622.1	59.3	174.7	2.16	6.40	10.98	10.54	10.11	1.89
KevinMich	Clarks	546.0	673	-0.32	2.31	d	1.99	3X4	2.13	32	237.80	68.16	614.8	226.7	127.1	3.40	5.18	10.85	8.94	7.98	1.93
KevinMich	Clarks	546.0	673	-0.32	2.31	d	1.99	3X4	2.13	32	237.80	68.16	614.8	58.1	170.9	3.70	5.18	10.21	9.75	9.47	1.88
hcd247	Clarks	551.5	1627	-0.51	2.47	d	1.96	3X5	2.13	32	297.25	68.16	627.0	183.8	170.0	4.54	6.92	11.05	9.93	9.03	1.94
hcd247	Clarks	551.5	1627	-0.51	2.47	d	1.96	3X5	2.13	32	297.25	68.16	627.0	86.2	155.0	5.50	6.92	6.85	6.09	5.79	1.60
CoopAmb	Clarks	546.0	673	-0.32	2.22	d	1.90	3X5	2.13	32	297.25	68.16	614.8	226.7	182.1	3.40	5.00	12.93	10.12	9.35	2.10
CoopAmb	Clarks	546.0	673	-0.32	2.22	d	1.90	3X5	2.13	32	297.25	68.16	614.8	58.1	115.9	3.70	5.00	11.77	11.52	10.99	1.96
DValentine	Clarks	546.0	673	-0.32	2.14	d	1.82	3X5	2.13	32	297.25	68.16	614.8	58.1	135.9	3.70	5.10	8.20	8.08	7.98	1.87
DValentine	Clarks	546.0	673	-0.32	2.14	d	1.82	3X5	2.13	32	297.25	68.16	614.8	226.7	162.1	3.40	5.10	7.35	6.89	6.72	1.88
lcd202	Clarks	546.0	690	-0.32	2.02	d	1.70	3X5	2.13	32	297.25	68.16	614.8	82.1	155.0	3.98	5.24	6.44	5.92	5.75	1.53

SECONDARY WAVE DATA ON UMRS FOR COMMERCIAL TOWBOATS

Tow/Test Name	Data Series	Pool Elev NGVD	Q cms	Va m/s	Vs m/s	Dir. u/d	Vw m/s	Tow Conf.	Draft m	barge width m	barge length m	Tow cross-sec area	Channel Top width m	WG to Shore m	s Edge tow to WG	Depth @WG m	Depth @Tow m	Hmax cm	H3 cm	H5 cm	Ave period sec
lcd202	Clarks	546.0	690	-0.32	2.02	d	1.70	3X5	2.13	32	297.25	68.16	614.8	175.6	170.1	2.86	5.24	6.53	5.89	5.27	1.59
KEllen	Clarks	546.0	673	-0.32	1.92	d	1.60	3X5	2.13	32	297.25	68.16	614.8	58.1	120.9	3.70	5.10	12.43	10.83	9.61	2.00
KEllen	Clarks	546.0	673	-0.32	1.92	d	1.60	3X5	2.13	32	297.25	68.16	614.8	226.7	177.1	3.40	5.10	5.79	5.66	5.46	2.10
DixieExpress	Kampsville	420.0	329	-0.29	3.40	d	3.11	1X2	1.52	10.7	178.35	16.26	316.0	45.0	129.7	3.60	4.10	4.45	4.00	3.68	1.88
DixieExpress	Kampsville	420.0	329	-0.29	3.40	d	3.11	1X2	1.52	10.7	178.35	16.26	316.0	80.0	94.7	4.10	4.10	4.74	4.28	3.88	1.79
KHEU56	Kampsville	427.0	1281	0.71	2.82	u	3.53	3X5	0.61	32	297.25	19.52	362.4	38.9	155.0	3.70	6.25	11.78	11.48	11.06	2.50
KHEU56	Kampsville	427.0	1281	0.71	2.82	u	3.53	3X5	0.61	32	297.25	19.52	362.4	40.5	96.0	4.05	6.25	20.51	18.10	16.58	2.62
KLEU67	Kampsville	419.4	180	0.175	3.34	u	3.52	3X5	0.61	32	297.25	19.52	315.0	91.0	22.0	3.90	3.93	20.19	19.04	16.50	1.94
KLEU67	Kampsville	419.4	180	0.175	3.34	u	3.52	3X5	0.61	32	297.25	19.52	315.0	48.0	65.0	3.40	3.93	15.32	14.31	13.13	2.08
KHEU38	Kampsville	427.0	1281	0.71	1.91	u	2.62	3X5	0.61	32	297.25	19.52	362.4	38.9	155.0	3.70	6.25	8.04	7.12	5.94	1.77
KHEU38	Kampsville	427.0	1281	0.71	1.91	u	2.62	3X5	0.61	32	297.25	19.52	362.4	40.5	96.0	4.05	6.25	4.69	3.90	3.52	2.04
KLEU49	Kampsville	419.4	180	0.175	2.43	u	2.61	3X5	0.61	32	297.25	19.52	315.0	91.0	22.0	3.90	3.93	12.84	10.14	9.40	1.49
KLEU49	Kampsville	419.4	180	0.175	2.43	u	2.61	3X5	0.61	32	297.25	19.52	315.0	48.0	65.0	3.40	3.93	11.30	9.83	9.15	1.78
KL1U76	Kampsville	419.4	180	0.175	3.81	u	3.99	1X3	2.29	10.7	178.35	24.50	315.0	91.0	32.7	3.90	3.93	29.39	22.28	20.06	2.56
KL1U76	Kampsville	419.4	180	0.175	3.81	u	3.99	1X3	2.29	10.7	178.35	24.50	315.0	48.0	75.7	3.40	3.93	24.05	20.83	18.25	2.34
Burton	Kampsville	421.8	413	0.54	2.93	u	3.47	1X3	2.29	10.7	178.35	24.50	317.1	30.0	102.7	4.20	4.66	13.32	12.62	12.25	2.36
Burton	Kampsville	421.8	413	0.54	2.93	u	3.47	1X3	2.29	10.7	178.35	24.50	317.1	275.0	89.7	2.00	4.66	12.15	10.38	9.94	2.14
KL1U61	Kampsville	419.4	180	0.175	3.03	u	3.21	1X3	2.29	10.7	178.35	24.50	315.0	48.0	75.7	3.40	3.93	11.55	10.96	10.54	2.01
KL1U61	Kampsville	419.4	180	0.175	3.03	u	3.21	1X3	2.29	10.7	178.35	24.50	315.0	91.0	32.7	3.90	3.93	16.85	16.06	15.08	2.23
KL1U46	Kampsville	419.4	180	0.175	2.28	u	2.46	1X3	2.29	10.7	178.35	24.50	315.0	91.0	32.7	3.90	3.93	13.52	12.59	11.56	1.70
KL1U46	Kampsville	419.4	180	0.175	2.28	u	2.46	1X3	2.29	10.7	178.35	24.50	315.0	48.0	75.7	3.40	3.93	7.13	6.35	6.05	1.56
Lawrence	Kampsville	421.8	413	0.54	2.56	u	3.10	3X5	1.75	32	297.25	56.00	317.1	30.0	119.0	4.20	4.66	10.39	10.22	9.96	1.72
Lawrence	Kampsville	421.8	413	0.54	2.56	u	3.10	3X5	1.75	32	297.25	56.00	317.1	80.0	69.0	4.66	4.66	19.17	15.65	14.11	1.61
KHOU53	Kampsville	427.0	1281	0.71	2.67	u	3.38	3X5	2.29	32	297.25	73.28	362.4	38.9	155.0	3.70	6.25	14.78	12.99	12.30	2.62
KHOU53	Kampsville	427.0	1281	0.71	2.67	u	3.38	3X5	2.29	32	297.25	73.28	362.4	40.5	96.0	4.05	6.25	14.35	13.45	12.52	2.48
KLU640	Kampsville	419.4	180	0.175	3.18	u	3.36	3X5	2.29	32	297.25	73.28	315.0	86.0	84.0	3.60	3.93	11.24	9.80	9.21	1.96
KLU640	Kampsville	419.4	180	0.175	3.18	u	3.36	3X5	2.29	32	297.25	73.28	315.0	59.0	54.0	3.70	3.93	17.04	16.39	15.43	1.91
KLD659	Kampsville	419.4	180	-0.175	3.32	d	3.15	3X5	2.29	32	297.25	73.28	315.0	86.0	84.0	3.60	3.93	13.93	13.22	12.69	1.88
KLD659	Kampsville	419.4	180	-0.175	3.32	d	3.15	3X5	2.29	32	297.25	73.28	315.0	59.0	54.0	3.70	3.93	18.95	13.61	12.00	1.67
KLLU49	Kampsville	419.4	180	0.175	2.45	u	2.63	3X5	2.29	32	297.25	73.28	315.0	48.0	140.0	3.40	3.93	6.48	6.13	5.94	1.61
KLLU49	Kampsville	419.4	180	0.175	2.45	u	2.63	3X5	2.29	32	297.25	73.28	315.0	91.0	97.0	3.90	3.93	8.17	7.27	6.97	1.37
KHLU38	Kampsville	427.0	1281	0.71	1.91	u	2.62	3X5	2.29	32	297.25	73.28	362.4	38.9	65.0	3.70	6.01	4.73	4.69	4.32	2.05
KHOU38	Kampsville	427.0	1281	0.71	1.91	u	2.62	3X5	2.29	32	297.25	73.28	362.4	40.5	96.0	4.05	6.25	4.22	3.51	3.17	2.16
KHOU38	Kampsville	427.0	1281	0.71	1.91	u	2.62	3X5	2.29	32	297.25	73.28	362.4	38.9	155.0	3.70	6.25	3.77	3.28	2.85	1.55
KHRU38	Kampsville	427.0	1281	0.71	1.91	u	2.62	3X5	2.29	32	297.25	73.28	362.4	40.5	46.0	4.05	6.25	5.09	4.67	4.46	1.97
KLU488	Kampsville	419.4	180	0.175	2.43	u	2.61	3X5	2.29	32	297.25	73.28	315.0	86.0	84.0	3.60	3.93	10.33	9.57	8.95	1.69
KLRU49	Kampsville	419.4	180	0.175	2.43	u	2.61	3X5	2.29	32	297.25	73.28	315.0	59.0	14.0	3.90	3.93	12.62	10.86	9.67	1.50
KLU488	Kampsville	419.4	180	0.175	2.43	u	2.61	3X5	2.29	32	297.25	73.28	315.0	59.0	54.0	3.70	3.93	12.76	11.70	11.23	1.56
KLRU49	Kampsville	419.4	180	0.175	2.43	u	2.61	3X5	2.29	32	297.25	73.28	315.0	80.0	130.0	2.30	3.93	8.46	8.32	8.25	1.74
LU38Q2	Kampsville	418.0	625	0.69	1.90	u	2.59	3X4	2.29	32	237.80	73.28	306.2	79.7	84.0	3.18	3.50	9.98	8.70	8.00	1.85
LU38Q2	Kampsville	418.0	625	0.69	1.90	u	2.59	3X4	2.29	32	237.80	73.28	306.2	56.5	54.0	3.26	3.50	9.68	9.32	8.68	2.10
KHLD66	Kampsville	427.0	1281	-0.71	3.28	d	2.57	3X5	2.29	32	297.25	73.28	362.4	38.9	65.0	3.70	6.01	12.10	11.30	10.78	1.94
KHOD66	Kampsville	427.0	1281	-0.71	3.28	d	2.57	3X5	2.29	32	297.25	73.28	362.4	40.5	96.0	4.05	6.25	11.53	11.12	10.93	1.89

SECONDARY WAVE DATA ON UMRS FOR COMMERCIAL TOWBOATS

Tow/Test Name	Data Series	Pool Elev NGVD	Q cms	Va m/s	Vs m/s	Dir. u/d	Vw m/s	Tow Conf.	Draft m	barge width m	barge length m	Tow cross-sec area	Channel Top width m	WG to Shore m	s Edge tow to WG	Depth @WG m	Depth @Tow m	Hmax cm	H3 cm	H5 cm	Ave period sec
KHLD66	Kampsville	427.0	1281	-0.71	3.28	d	2.57	3X5	2.29	32	297.25	73.28	362.4	40.5	186.0	4.05	6.01	8.82	8.53	8.29	1.85
KHOD66	Kampsville	427.0	1281	-0.71	3.28	d	2.57	3X5	2.29	32	297.25	73.28	362.4	38.9	155.0	3.70	6.25	11.76	10.42	9.53	2.00
Wofford	Kampsville	420.0	329	0.29	2.22	u	2.51	3X5	2.29	32	297.25	73.28	316.0	80.0	84.0	4.10	4.10	17.16	15.74	14.59	2.06
Wofford	Kampsville	420.0	329	0.29	2.22	u	2.51	3X5	2.29	32	297.25	73.28	316.0	45.0	119.0	3.60	4.10	13.47	11.95	11.49	2.09
ND58Q	Kampsville	421.8	413	-0.49	2.90	d	2.41	3X4	2.29	32	237.80	73.28	317.1	66.5	55.5	4.40	4.66	4.36	4.26	3.99	1.51
ND58Q	Kampsville	421.8	413	-0.49	2.90	d	2.41	3X4	2.29	32	237.80	73.28	317.1	80.6	82.5	4.30	4.66	9.13	6.56	5.63	1.40
WCNorman	Kampsville	421.8	413	-0.49	2.90	d	2.41	3X4	2.29	32	237.80	73.28	317.1	30.0	92.0	4.20	4.66	7.34	6.70	6.31	1.30
ND58Q	Kampsville	421.8	413	-0.49	2.90	d	2.41	3X4	2.29	32	237.80	73.28	317.1	30.5	91.5	3.06	4.66	9.78	8.44	7.56	1.40
ND58Q	Kampsville	421.8	413	-0.49	2.90	d	2.41	3X4	2.29	32	237.80	73.28	317.1	102.5	19.5	4.70	4.66	6.80	5.82	5.56	1.33
ND58Q	Kampsville	421.8	413	-0.49	2.90	d	2.41	3X4	2.29	32	237.80	73.28	317.1	139.6	23.5	4.66	4.66	7.34	6.70	6.31	1.30
ND58Q	Kampsville	421.8	413	-0.49	2.90	d	2.41	3X4	2.29	32	237.80	73.28	317.1	17.6	145.5	2.90	4.66	7.83	7.49	6.85	1.39
WCNorman	Kampsville	421.8	413	-0.49	2.90	d	2.41	3X4	2.29	32	237.80	73.28	317.1	80.0	42.0	4.66	4.66	6.80	5.82	5.56	1.33
KLLD51	Kampsville	419.4	180	-0.175	2.52	d	2.35	3X5	2.29	32	297.25	73.28	315.0	48.0	140.0	3.40	3.93	8.42	7.48	6.68	1.79
KLLD51	Kampsville	419.4	180	-0.175	2.52	d	2.35	3X5	2.29	32	297.25	73.28	315.0	91.0	97.0	3.90	3.93	7.96	7.66	7.31	1.41
KLD506	Kampsville	419.4	180	-0.175	2.50	d	2.33	3X5	2.29	32	297.25	73.28	315.0	59.0	54.0	3.70	3.93	13.34	12.45	11.70	1.48
KLD506	Kampsville	419.4	180	-0.175	2.50	d	2.33	3X5	2.29	32	297.25	73.28	315.0	86.0	84.0	3.60	3.93	12.31	10.26	9.65	1.42
KLRD49	Kampsville	419.4	180	-0.175	2.43	d	2.26	3X5	2.29	32	297.25	73.28	315.0	80.0	130.0	2.30	3.93	15.35	11.27	9.70	1.60
KLRD49	Kampsville	419.4	180	-0.175	2.43	d	2.26	3X5	2.29	32	297.25	73.28	315.0	59.0	14.0	3.90	3.93	8.60	7.96	7.35	1.24
LD58Q2	Kampsville	418.0	625	-0.69	2.90	d	2.21	3X4	2.29	32	237.80	73.28	306.2	79.7	84.0	3.18	3.50	8.49	8.05	7.62	1.62
LD58Q2	Kampsville	418.0	625	-0.69	2.90	d	2.21	3X4	2.29	32	237.80	73.28	306.2	56.5	54.0	3.26	3.50	9.38	9.09	8.67	1.64
KHOD64	Kampsville	427.0	2094	-1.15	3.20	d	2.05	3X5	2.29	32	297.25	73.28	362.4	40.5	96.0	4.05	6.25	9.94	9.42	8.70	2.15
KHOD64	Kampsville	427.0	2094	-1.15	3.20	d	2.05	3X5	2.29	32	297.25	73.28	362.4	38.9	155.0	3.70	6.25	12.34	11.14	10.55	1.96
Rambler	Kampsville	421.8	413	-0.54	2.48	d	1.94	3X4	2.29	32	237.80	73.28	317.1	80.0	42.0	4.66	4.66	8.66	6.82	6.00	1.45
Rambler	Kampsville	421.8	413	-0.54	2.48	d	1.94	3X4	2.29	32	237.80	73.28	317.1	30.0	92.0	4.20	4.66	7.20	6.90	6.72	1.47
KHOD50	Kampsville	427.0	1281	-0.71	2.52	d	1.81	3X5	2.29	32	297.25	73.28	362.4	40.5	96.0	4.05	6.25	7.74	7.15	6.87	1.71
KHOD50	Kampsville	427.0	1281	-0.71	2.52	d	1.81	3X5	2.29	32	297.25	73.28	362.4	38.9	155.0	3.70	6.25	10.23	9.91	9.15	1.76
CMariner	ProApple	582.0	1537	-0.81	4.66	d	3.85	3X4	2.74	32	237.80	87.68	400.0	4.7	209.3	0.20	6.10	17.83	16.41	15.55	1.77
DelBtch	ProApple	582.0	1537	-0.81	4.33	d	3.52	3X5	2.74	32	297.25	87.68	400.0	4.7	209.3	0.20	6.10	5.91	5.82	5.61	1.29
Kusman	ProApple	582.0	1537	-0.81	4.15	d	3.34	3X4	2.74	32	237.80	87.68	400.0	4.7	209.3	0.20	6.10	14.71	13.65	12.78	1.56
Trojan	ProApple	582.0	1537	-0.81	2.68	d	1.87	3x3	2.74	32	178.35	87.68	400.0	4.7	194.3	0.20	6.40	10.66	9.34	8.49	1.42
Sunflower1	ProClarks1	549.5	2351	-0.83	5.59	d	4.76	1x1	0.61	10.7	36.25	6.53	622.2	22.9	221.8	3.00	5.90	9.30	9.04	8.46	1.17
Sunflower2	ProClarks1	549.6	2351	-0.83	5.60	d	4.77	1x1	1.52	10.7	36.25	16.26	622.2	22.9	196.8	3.00	5.90	7.99	7.33	6.94	1.17
VolState	ProClarks1	549.6	2351	0.83	3.51	u	4.34	3X5	0.61	32	297.25	19.52	622.2	22.9	211.1	3.00	5.90	10.63	10.04	9.49	1.49
AmBeauty1	ProClarks1	549.5	2351	0.83	3.23	u	4.06	3X5	0.61	32	297.25	19.52	622.2	22.9	236.1	3.00	5.40	13.78	13.72	13.47	1.75
Hornet	ProClarks1	549.6	2351	0.83	2.97	u	3.80	3X4	0.61	32	237.80	19.52	622.2	22.9	241.1	3.00	5.30	9.47	8.77	8.00	1.84
HMClements	ProClarks1	549.6	2351	0.83	2.51	u	3.34	3X4	0.61	32	237.80	19.52	622.2	22.9	221.1	3.00	5.70	11.78	10.66	10.08	2.18
CJErickson	ProClarks1	549.6	2351	0.83	2.37	u	3.20	3X5	0.61	32	297.25	19.52	622.2	22.9	211.1	3.00	5.90	6.16	5.70	5.39	2.03
SierDawn	ProClarks1	549.6	2351	-0.83	3.33	d	2.50	3X4	2.64	32	237.80	84.48	622.2	22.9	231.1	3.00	5.60	4.36	3.96	3.84	0.94
DButcher2	ProClarks1	549.6	2351	-0.83	3.24	d	2.41	3X4	2.74	32	237.80	87.68	622.2	22.9	261.1	3.00	5.10	4.95	4.29	3.81	1.13
PearlB	ProClarks1	549.4	2351	-0.83	2.87	d	2.04	3X4	2.74	32	237.80	87.68	622.1	22.9	211.1	3.00	5.90	7.44	7.01	6.77	1.00
CoopVang	ProClarks1	549.6	2351	-0.83	2.69	d	1.86	3X2	2.74	32	118.90	87.68	622.2	22.9	211.1	3.00	5.90	2.96	2.53	2.37	1.20
Beeseker	ProGoose1	468.0	2856	-1.13	3.58	d	2.45	3X5	2.74	32	297.25	87.68	418.0	35.0	247.0	0.59	7.50	9.70	8.21	7.54	1.20
KevinMc	ProGoose1	468.0	2856	-1.13	2.91	d	1.78	3X5	2.74	32	297.25	87.68	418.0	35.0	277.0	0.59	9.00	7.11	6.67	6.28	1.16

SECONDARY WAVE DATA ON UMRS FOR COMMERCIAL TOWBOATS

Tow/Test Name	Data Series	Pool Elev NGVD	Q cms	Va m/s	Vs m/s	Dir. u/d	Vw m/s	Tow Conf.	Draft m	barge width m	barge length m	Tow cross-sec area	Channel Top width m	WG to Shore m	s Edge tow to WG	Depth @WG m	Depth @Tow m	Hmax cm	H3 cm	H5 cm	Ave period sec
Fleming	ProGoose2	465.0	729	0.66	2.67	u	3.33	3X5	2.74	32	297.25	87.68	403.0	16.7	270.3	2.50	7.70	10.58	7.70	6.79	2.65
James	ProGoose2	466.0	1808	-0.83	4.05	d	3.22	3X5	2.74	32	297.25	87.68	403.0	12.1	279.9	1.30	7.70	5.07	4.16	3.80	2.69
Karla	ProGoose2	465.0	729	-0.66	3.46	d	2.80	3X5	2.74	32	297.25	87.68	403.0	12.1	279.9	1.30	7.70	3.73	3.59	3.45	2.61
Hornet	ProGoose2	465.0	729	-0.66	3.14	d	2.48	3X5	2.74	32	297.25	87.68	403.0	16.7	270.3	2.50	7.70	5.86	5.67	5.56	0.99
Scarlet	ProGoose2	466.0	1808	-0.83	3.20	d	2.37	3X5	2.74	32	297.25	87.68	403.0	12.1	279.9	1.30	7.70	5.38	4.44	3.83	2.49
Dbutch2	ProGoose2	465.0	1880	-0.84	3.19	d	2.35	3X5	2.74	32	297.25	87.68	403.0	16.7	300.3	2.50	8.10	2.42	2.18	2.05	2.67
Michael	ProGoose2	465.0	729	-0.66	2.94	d	2.28	3X5	2.74	32	297.25	87.68	403.0	16.7	290.3	2.50	7.90	8.60	8.03	7.63	0.94
Ardyce	ProGoose2	466.0	1808	-0.83	3.11	d	2.28	3X5	2.74	32	297.25	87.68	403.0	12.1	279.9	1.30	7.70	2.94	1.89	1.61	2.87
Mariner	ProGoose2	465.0	729	-0.66	2.89	d	2.23	3X5	2.74	32	297.25	87.68	403.0	16.7	285.3	2.50	7.80	7.22	6.76	6.58	0.71
Thompson	ProGoose2	465.0	1880	-0.66	2.86	d	2.20	3X5	2.74	32	297.25	87.68	403.0	16.7	300.3	2.50	8.10	8.80	6.87	6.08	2.51
DixExprs	ProKamps	419.7	329	-0.29	3.40	d	3.11	1X2	1.52	10.7	118.90	16.26	315.0	9.1	165.6	0.90	3.90	6.79	6.56	6.44	1.34
DixExpr2	ProKamps	419.7	329	0.29	2.58	u	2.87	1X2	2.74	10.7	118.90	29.32	315.0	9.1	185.6	0.90	3.70	7.87	7.70	7.46	1.28
DixiPtrt	ProKamps	419.7	329	-0.29	2.48	d	2.19	1X3	2.74	10.7	178.35	29.32	315.0	9.1	160.6	0.90	3.90	11.05	10.53	10.16	1.10
PatBreen	ProKamps	419.7	329	-0.29	2.29	d	2.00	3X5	1.52	32	297.25	48.64	315.0	9.1	134.9	0.90	4.40	5.03	4.94	4.85	0.92
MrPaul2	ProKamps	420.4	413	0.58	2.25	u	2.83	3X5	1.61	32	297.25	51.52	316.2	11.3	102.7	1.00	4.20	7.00	6.67	6.44	1.24
FlydBlsk	ProKamps	420.1	413	0.36	2.18	u	2.54	3X4	1.63	32	237.80	52.16	316.0	11.3	87.7	1.00	3.97	8.05	7.12	6.90	2.39
MrLwrnce	ProKamps	420.4	413	0.58	2.56	u	3.14	3X5	1.75	32	297.25	56.00	316.2	11.3	137.7	1.00	4.40	10.53	10.32	10.05	1.73
Margare2	ProKamps	420.4	413	-0.58	3.83	d	3.25	3X4	2.03	32	237.80	64.96	316.2	11.3	102.7	1.00	4.20	9.50	8.81	8.01	1.39
Sugarlnd	ProKamps	420.4	413	0.36	1.88	u	2.24	3X4	2.29	32	237.80	73.28	316.2	11.3	142.7	1.00	4.50	5.08	4.61	4.31	1.16
ALSmith	ProKamps	420.5	772	-0.58	2.80	d	2.22	2X4	2.48	32	237.80	79.36	316.2	11.3	112.7	1.00	4.30	10.48	9.31	8.80	1.28
WlmCNrmn	ProKamps	420.4	413	-0.36	2.90	d	2.54	3X4	2.74	32	237.80	87.68	316.2	11.3	110.7	1.00	4.30	8.23	7.48	7.19	1.14
JckDWfrd	ProKamps	419.7	329	0.29	2.22	u	2.51	3X5	2.74	32	297.25	87.68	315.0	9.1	154.9	0.90	3.90	5.65	5.18	4.95	1.26
Olmstead	ProKamps	419.7	329	0.29	2.19	u	2.48	3X5	2.74	32	297.25	87.68	315.0	9.1	154.9	0.90	3.90	5.39	4.99	4.71	1.30
Jeffboat	ProKamps	420.4	413	0.36	1.84	u	2.20	3X5	2.74	32	297.25	87.68	316.2	11.3	87.7	1.00	3.97	4.72	4.43	4.32	1.07
Rambler	ProKamps	420.4	413	-0.36	2.48	d	2.12	3X4	2.74	32	237.80	87.68	316.2	11.3	110.7	1.00	4.30	6.73	5.96	5.58	1.29
ArdcRandall	ProKamps	420.4	772	-0.58	2.36	d	1.78	3X5	2.74	32	297.25	87.68	316.2	11.3	127.7	1.00	4.40	3.98	3.87	3.79	1.01

Appendix B
Fiscal Year 1993 Wave Data in Full-Scale Units from Model Data

FY93 Wave Data in Full Scale Units From Model Data

Test Series	Bottom Width bw ft	Depth h ft	cot a left bank	Tow Position S ft	Barge Width Bs ft	Barge draft d ft	Boat Speed fps	Inst. Dist. from left bank, ft	Barge Edge to Inst. s, ft	Draw-down Zmax ft	Max Wave Hmax ft	Sec. Wave Hi ft	Wave Period Ti sec
NR93	400.00	20.00	2.00	240.00	105.00	9.00	6.00		72.50	0.11	0.06		
NR93	400.00	20.00	2.00	240.00	105.00	9.00	6.00	113.75	72.50	0.11	0.05		
NR93	400.00	20.00	2.00	240.00	105.00	9.00	8.00	113.75	72.50	0.41	0.39		
NR93	400.00	20.00	2.00	240.00	105.00	9.00	8.00	113.75	72.50	0.36	0.27		
NR93	400.00	20.00	2.00	240.00	105.00	9.00	10.00	113.75	72.50	0.70	0.49	0.28	2.84
NR93	400.00	20.00	2.00	240.00	105.00	9.00	10.00	113.75	72.50	0.70	0.50	0.28	2.84
NR93	400.00	20.00	2.00	240.00	105.00	9.00	12.00	113.75	72.50	1.15	0.83	0.75	2.84
NR93	400.00	20.00	2.00	240.00	105.00	9.00	12.00	113.75	72.50	1.00	0.78	1.05	2.84
NR93	400.00	20.00	2.00	240.00	105.00	9.00	14.00	113.75	72.50	1.50	1.28	1.83	3.10
NR93	400.00	20.00	2.00	240.00	105.00	9.00	14.00	113.75	72.50	1.68	1.49	1.80	3.22
NR93	400.00	20.00	3.00	260.00	105.00	9.00	6.00	133.75	72.50	0.07			
NR93	400.00	20.00	3.00	260.00	105.00	9.00	6.00	133.75	72.50	0.08			
NR93	400.00	20.00	3.00	260.00	105.00	9.00	8.00	133.75	72.50	0.46	0.49		
NR93	400.00	20.00	3.00	260.00	105.00	9.00	8.00	133.75	72.50	0.46	0.45		
NR93	400.00	20.00	3.00	260.00	105.00	9.00	10.00	133.75	72.50	0.91	1.14	0.33	2.52
NR93	400.00	20.00	3.00	260.00	105.00	9.00	10.00	133.75	72.50	0.92	1.16	0.33	2.52
NR93	400.00	20.00	3.00	260.00	105.00	9.00	12.00	133.75	72.50	1.37	1.90	1.45	3.10
NR93	400.00	20.00	3.00	260.00	105.00	9.00	12.00	133.75	72.50	1.60	2.16	1.28	3.06
NR93	400.00	20.00	3.00	260.00	105.00	9.00	14.00	133.75	72.50	1.88	2.72	1.60	3.35
NR93	400.00	20.00	3.00	260.00	105.00	9.00	14.00	133.75	72.50	1.58	2.24	1.65	3.10
NR93	400.00	20.00	2.00	340.00	105.00	9.00	6.00	163.75	123.75	0.23	0.23		
NR93	400.00	20.00	2.00	340.00	105.00	9.00	6.00	163.75	123.75	0.23	0.26		
NR93	400.00	20.00	2.00	340.00	105.00	9.00	8.00	163.75	123.75	0.43	0.39		
NR93	400.00	20.00	2.00	340.00	105.00	9.00	8.00	163.75	123.75	0.43	0.38		
NR93	400.00	20.00	2.00	340.00	105.00	9.00	10.00	163.75	123.75	0.78	0.73	0.23	2.74
NR93	400.00	20.00	2.00	340.00	105.00	9.00	10.00	163.75	123.75	0.80	0.75	0.23	2.72
NR93	400.00	20.00	2.00	340.00	105.00	9.00	12.00	163.75	123.75	1.35	1.30	0.73	3.28
NR93	400.00	20.00	2.00	340.00	105.00	9.00	12.00	163.75	123.75	1.38	1.28	0.80	3.10
NR93	400.00	20.00	2.00	340.00	105.00	9.00	14.00	163.75	123.75	1.80	1.70	1.38	3.27

FY93 Wave Data in Full Scale Units From Model Data

Test Series	Bottom Width bw ft	Depth h ft	cot a left bank	Tow Position S ft	Barge Width Bs ft	Barge draft d ft	Boat Speed fps	Inst. Dist. from left bank, ft	Barge Edge to Inst. s, ft	Draw-down Zmax ft	Max Wave Hmax ft	Sec. Wave Hi ft	Wave Period Ti sec
NR93	400.00	20.00	2.00	340.00	105.00	9.00	14.00	163.75	123.75	1.90	1.80	1.38	3.37
NR93	400.00	20.00	2.00	340.00	105.00	9.00	10.00	163.75	123.75	0.78	0.62		
NR93	400.00	20.00	2.00	340.00	105.00	9.00	10.00	163.75	123.75	0.90	0.76		
NR93	400.00	20.00	3.00	360.00	105.00	9.00	6.00	183.75	123.75	0.17	0.13		
NR93	400.00	20.00	3.00	360.00	105.00	9.00	6.00	183.75	123.75	0.15	0.11		
NR93	400.00	20.00	3.00	360.00	105.00	9.00	8.00	183.75	123.75	0.23	0.40		
NR93	400.00	20.00	3.00	360.00	105.00	9.00	8.00	183.75	123.75	0.28	0.51		
NR93	400.00	20.00	3.00	360.00	105.00	9.00	10.00	183.75	123.75	0.60	0.94	0.23	2.74
NR93	400.00	20.00	3.00	360.00	105.00	9.00	10.00	183.75	123.75	0.75	1.15		
NR93	400.00	20.00	3.00	360.00	105.00	9.00	12.00	183.75	123.75	1.45	2.03		
NR93	400.00	20.00	3.00	360.00	105.00	9.00	12.00	183.75	123.75	1.53	2.16	0.90	3.13
NR93	400.00	20.00	3.00	360.00	105.00	9.00	14.00	183.75	123.75	2.63	3.45	1.65	3.63
NR93	400.00	20.00	3.00	360.00	105.00	9.00	14.00	183.75	123.75	2.74	3.56	1.50	3.66
NR93	400.00	20.00	2.00	190.00	105.00	9.00	6.00	88.75	48.75	0.37	0.46		
NR93	400.00	20.00	2.00	190.00	105.00	9.00	6.00	88.75	48.75	0.35	0.45		
NR93	400.00	20.00	2.00	190.00	105.00	9.00	8.00	88.75	48.75	0.43	0.34		
NR93	400.00	20.00	2.00	190.00	105.00	9.00	8.00	88.75	48.75	0.43	0.37		
NR93	400.00	20.00	2.00	190.00	105.00	9.00	10.00	88.75	48.75	0.97	0.99	0.38	2.74
NR93	400.00	20.00	2.00	190.00	105.00	9.00	10.00	88.75	48.75	0.98	0.94	0.30	2.74
NR93	400.00	20.00	2.00	190.00	105.00	9.00	12.00	88.75	48.75	1.78	1.84	1.08	3.13
NR93	400.00	20.00	2.00	190.00	105.00	9.00	12.00	88.75	48.75	1.86	1.79	1.05	3.10
NR93	400.00	20.00	2.00	190.00	105.00	9.00	14.00	88.75	48.75	1.60	1.41	1.55	3.53
NR93	400.00	20.00	2.00	190.00	105.00	9.00	14.00	88.75	48.75	1.78	1.56	1.48	3.37
NR93	400.00	20.00	3.00	210.00	105.00	9.00	6.00	108.75	48.75	0.25	0.26		
NR93	400.00	20.00	3.00	210.00	105.00	9.00	6.00	108.75	48.75	0.23	0.23		
NR93	400.00	20.00	3.00	210.00	105.00	9.00	8.00	108.75	48.75	0.38	0.42		
NR93	400.00	20.00	3.00	210.00	105.00	9.00	8.00	108.75	48.75	0.39	0.40		
NR93	400.00	20.00	3.00	210.00	105.00	9.00	10.00	108.75	48.75	0.85	1.04	0.38	2.63
NR93	400.00	20.00	3.00	210.00	105.00	9.00	10.00	108.75	48.75	0.85	1.07	0.40	2.60

FY93 Wave Data in Full Scale Units From Model Data

Test Series	Bottom Width bw ft	Depth h ft	cot a left bank	Tow Position S ft	Barge Width Bs ft	Barge draft d ft	Boat Speed fps	Inst. Dist. from left bank, ft	Barge Edge to Inst. s, ft	Draw-down Zmax ft	Max Wave Hmax ft	Sec. Wave Hi ft	Wave Period Ti sec
NR93	400.00	20.00	3.00	210.00	105.00	9.00	12.00	108.75	48.75	2.00	2.60	1.73	3.41
NR93	400.00	20.00	3.00	210.00	105.00	9.00	12.00	108.75	48.75	2.00	2.63	1.70	3.38
NR93	400.00	20.00	3.00	210.00	105.00	9.00	14.00	108.75	48.75	3.19	3.88	2.88	3.63
NR93	400.00	20.00	3.00	210.00	105.00	9.00	14.00	108.75	48.75	3.21	3.95	2.63	3.82
NR93	400.00	20.00	3.00	210.00	105.00	9.00	10.00	108.75	48.75	0.75	0.74		
NR93	400.00	20.00	3.00	210.00	105.00	9.00	10.00	108.75	48.75	0.88	1.04		
NR93	400.00	15.00	2.00	180.00	105.00	9.00	6.00	78.75	48.75	0.48	0.58		
NR93	400.00	15.00	2.00	180.00	105.00	9.00	6.00	78.75	48.75	0.48	0.50		
NR93	400.00	15.00	2.00	180.00	105.00	9.00	8.00	78.75	48.75	0.78	0.65		
NR93	400.00	15.00	2.00	180.00	105.00	9.00	8.00	78.75	48.75	0.70	0.63		
NR93	400.00	15.00	2.00	180.00	105.00	9.00	10.00	78.75	48.75	1.58	1.41	0.45	3.00
NR93	400.00	15.00	2.00	180.00	105.00	9.00	10.00	78.75	48.75	1.85	1.68	0.70	3.29
NR93	400.00	15.00	2.00	180.00	105.00	9.00	12.00	78.75	48.75	2.43	2.18		
NR93	400.00	15.00	2.00	180.00	105.00	9.00	11.50	78.75	48.75	2.15	1.92	1.35	3.27
NR93	400.00	15.00	3.00	195.00	105.00	9.00	6.00	93.75	48.75	0.28	0.40		
NR93	400.00	15.00	3.00	195.00	105.00	9.00	6.00	93.75	48.75	0.30	0.35		
NR93	400.00	15.00	3.00	195.00	105.00	9.00	8.00	93.75	48.75	0.68	1.03		
NR93	400.00	15.00	3.00	195.00	105.00	9.00	8.00	93.75	48.75	0.70	0.83		
NR93	400.00	15.00	3.00	195.00	105.00	9.00	10.00	93.75	48.75	1.60	1.69	0.60	2.92
NR93	400.00	15.00	3.00	195.00	105.00	9.00	10.00	93.75	48.75	1.83	2.01		
NR93	400.00	15.00	3.00	195.00	105.00	9.00	12.00	93.75	48.75	3.50	4.31	0.65	2.87
NR93	400.00	15.00	3.00	195.00	105.00	9.00	11.80	93.75	48.75	3.50	4.30	0.63	3.03
NR93	400.00	15.00	3.00	195.00	105.00	9.00	10.00	93.75	48.75	2.70	3.48		
NR93	400.00	15.00	3.00	195.00	105.00	9.00	10.00	93.75	48.75	2.68	3.50		
NR93	400.00	15.00	2.00	230.00	105.00	3.75	6.00	103.75	73.75	0.13	0.07		
NR93	400.00	15.00	2.00	230.00	105.00	3.75	6.00	103.75	73.75	0.13	0.10		
NR93	400.00	15.00	2.00	230.00	105.00	3.75	8.00	103.75	73.75	0.21	0.15		
NR93	400.00	15.00	2.00	230.00	105.00	3.75	8.00	103.75	73.75	0.20	0.14		
NR93	400.00	15.00	2.00	230.00	105.00	3.75	10.00	103.75	73.75	0.42	0.30		

FY93 Wave Data in Full Scale Units From Model Data

Test Series	Bottom Width bw ft	Depth h ft	cot a left bank	Tow Position S ft	Barge Width Bs ft	Barge draft d ft	Boat Speed fps	Inst. Dist. from left bank, ft	Barge Edge to Inst. s, ft	Draw-down Zmax ft	Max Wave Hmax ft	Sec. Wave Hi ft	Wave Period Ti sec
NR93	400.00	15.00	2.00	230.00	105.00	3.75	10.00	103.75	73.75	0.40	0.34		
NR93	400.00	15.00	2.00	230.00	105.00	3.75	12.00	103.75	73.75	0.58	0.42	0.75	2.90
NR93	400.00	15.00	2.00	230.00	105.00	3.75	12.00	103.75	73.75	0.46	0.40	0.63	2.61
NR93	400.00	15.00	2.00	230.00	105.00	3.75	14.00	103.75	73.75	0.83	0.71	1.38	3.21
NR93	400.00	15.00	2.00	230.00	105.00	3.75	14.00	103.75	73.75	0.63	0.52	1.35	3.32
NR93	400.00	15.00	2.00	230.00	105.00	3.75	14.90	103.75	73.75	0.94	0.84	1.70	3.32
NR93	400.00	15.00	2.00	230.00	105.00	3.75	14.90	103.75	73.75	0.96	0.88	1.78	3.34
NR93	400.00	15.00	3.00	245.00	105.00	3.75	6.00	118.75	73.75	0.15	0.11		
NR93	400.00	15.00	3.00	245.00	105.00	3.75	6.00	118.75	73.75	0.13	0.08		
NR93	400.00	15.00	3.00	245.00	105.00	3.75	8.00	118.75	73.75	0.19	0.20		
NR93	400.00	15.00	3.00	245.00	105.00	3.75	8.00	118.75	73.75	0.19	0.30		
NR93	400.00	15.00	3.00	245.00	105.00	3.75	10.00	118.75	73.75	0.43	0.57		
NR93	400.00	15.00	3.00	245.00	105.00	3.75	10.00	118.75	73.75	0.42	0.59		
NR93	400.00	15.00	3.00	245.00	105.00	3.75	12.00	118.75	73.75	0.70	0.92	0.73	2.80
NR93	400.00	15.00	3.00	245.00	105.00	3.75	12.00	118.75	73.75	0.72	0.99	0.80	2.84
NR93	400.00	15.00	3.00	245.00	105.00	3.75	14.00	118.75	73.75	0.99	1.36	1.58	3.27
NR93	400.00	15.00	3.00	245.00	105.00	3.75	14.00	118.75	73.75	0.97	1.40	1.33	3.21
NR93	400.00	15.00	3.00	245.00	105.00	3.75	14.90	118.75	73.75	1.13	1.57	1.88	3.25
NR93	400.00	15.00	3.00	245.00	105.00	3.75	14.90	118.75	73.75	1.16	1.60	1.85	3.35

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
September 1999

3. REPORT TYPE AND DATES COVERED
Interim report

4. TITLE AND SUBTITLE
Wave-Height Predictive Techniques for Commercial Tows on the Upper Mississippi River-Illinois Waterway System

5. FUNDING NUMBERS

6. AUTHOR(S)
Sandra K. Knight

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Research and Development Center
Waterways Experiment Station
3909 Halls Ferry Road, Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
ENV Report 15

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
See reverse.

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Physical model studies and prototype data have been collected and analyzed as part of the Upper Mississippi River-Illinois Waterway System (UMRS) Navigation Feasibility Study for the purpose of developing a vessel wave predictive tool for commercial tows. The approach used was to examine existing analytical techniques for predicting wave heights produced by vessels, determine their suitability and applicability to the vessels and waterways of the UMRS, and modify/validate them with physical model and available prototype data.

Based on the literature reviewed and the analysis, both a method of predicting the maximum secondary wave height produced by a moving commercial tow and the time-history associated with it are presented in this report. The wave-height model was based on the development of coefficients related to the hull cross-sectional area and relates maximum wave height to distance from sailing line and the vessel speed. This equation is appropriate for predicting maximum secondary wave height for the purposes of estimating ecological impacts as well as designing bank protection.

14. SUBJECT TERMS

Commercial tows	Secondary waves	Wake waves
Maximum wave height	Time history	
Navigation effects	Upper Mississippi River System Navigation Feasibility Study	
Predictive models	Vessel-generated waves	

15. NUMBER OF PAGES
54

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
UNCLASSIFIED

18. SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102