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Application of UNET Model to Vessel Drawdown in Backwaters of Navigation Channels

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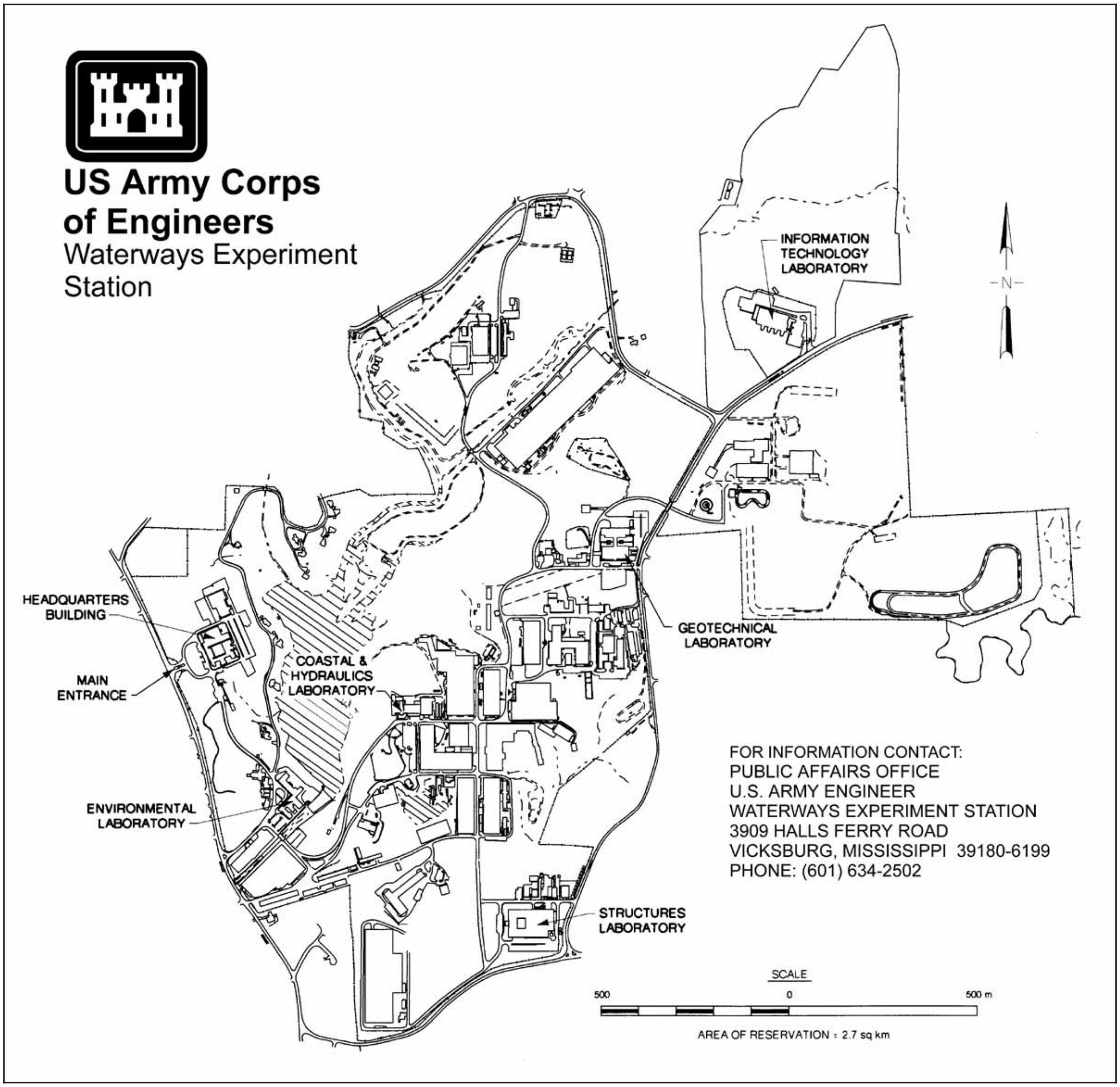

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Preface

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, Navigation and Harbors Division (NHD), CHL. The UNET studies were conducted by Dr. S. T. Maynord, Navigation Branch, NHD.

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

1 Introduction

Background

The Upper Mississippi River-Illinois Waterway System (UMR-IWWS) Navigation (Feasibility) Study will evaluate the justification of providing additional lockage capacity at sites on the UMR-IWWS while maintaining the social and environmental qualities of the river system. The navigation system feasibility study will be accomplished by executing the Initial Project Management Plan (IPMP) outlined in USACE (1994). The IPMP outlines Engineering, Economic, Environmental, and Public Involvement Plans.

The Environmental Plan identifies the significant environmental resources on the UMR-IWWS and probable impacts in terms of threatened and endangered species; water quality; recreational resources; fisheries; mussels and other macroinvertebrates; waterfowl; aquatic and terrestrial macrophytes; and historic properties. It considers system-wide impacts of navigation capacity increases while also assessing, in preliminary fashion, potential construction effects of improvement projects. The physical forces studies reported herein are part of the Environmental Plan. One of the physical forces created by commercial tows is water level drawdown that results from the large amount of area of the channel that is occupied by the tow. Drawdown lasts about as long as it takes for the vessel to pass a given point on the bank. While most of the other physical forces from the tow are confined to the main channel, drawdown can propagate along backwater channels large distances from the main channel.

Objective

The purpose of this study is to determine if the UNET model (Barkau, 1992) can be used to determine the variation of water level drawdown along the length of a backwater channel as a result of passage of commercial tows in the main channel.

Approach

A generic backwater channel layout was evaluated in a 1:30 scale physical model and measured water level changes and velocity were compared to the computed results from the one-dimensional unsteady flow model, UNET. The laboratory backwater is a highly idealized backwater but is a good test of UNET because it represents somewhat of a “worst case” since losses are minimal and reflections are large. To insure that the UNET model can be used for prototype conditions where losses are large and reflections are frequently small, the UNET model was then compared to measured water level and velocity changes on a backwater on the Lagrange Pool of the Illinois Waterway.

2 Physical Model Description

Similitude

Similarity of form resistance, flow patterns, and water surface changes in navigation models is best achieved when the ratio of inertia to gravitational forces is the same in model and prototype. This ratio, the Froude number F, is defined as

$$F = \frac{V}{\sqrt{gD}} \tag{1}$$

Where V is generally the vessel speed, g = gravitational constant, and D is a characteristic length such as depth, draft, or vessel length. The equations of hydraulic similitude, based on the Froude criteria, were used to express mathematical relations between the dimensions of hydraulic quantities of the physical model and prototype. General relations for transferring 1:30 scale model data to prototype equivalents are as follows:

Characteristic	**Dimension***	**Scale Relations Model:Prototype**
Length	$L_r=L_p/L_m$	1:30
Area	$A_r=L_r^2$	1:900
Velocity	$V_r=L_r^{1/2}$	1:5.477
Time	$T_r=L_r^{1/2}$	1:5.477
Discharge	$Q_r=L_r^{5/2}$	1:4929.5
Roughness Coefficient	$N_r=L_r^{1/6}$	1:1.763
Force	$F_r=L_r^3$	1:27000
Revolutions or frequency	$R_r=1/L_r^{1/2}$	5.477:1

*Dimensions are in terms of length.

However, viscous forces cannot be neglected in physical navigation models. If one is interested in the forces on a vessel as in typical towing tank studies, the relatively higher viscous forces in the physical model cause greater frictional resistance on the model vessel. If, as in this study, one is interested in the opposite problem of the forces the vessel imposes on the waterway, the relatively higher viscous forces in the model cause the model vessel to be effectively larger than the prototype vessel. Additional information on scale effects and model verification can be found in the Clark=s Ferry Report (Maynord and Martin, 1998). Both the Kampsville (Maynord and Martin, 1997) and the Clark=s Ferry studies showed the similarity of the shape of the return velocity and drawdown time histories. In the physical model used herein, the tow was only used to produce a drawdown typical of a vessel at the mouth of the backwater. The presence of viscous scale effects on the vessel was not important in this study because the UNET model being evaluated herein only simulates the backwater..

Model Flume and Appurtenances

The Navigation Effects Flume (Figure 1) is 125 meters (model) in length, 21.3 meters (model) in width, and has a maximum model depth of 1.22 meter. Unless noted, all units are in prototype equivalent. Ten pumps, each having an approximate discharge capacity of 0.16 cubic meters/second (model), recirculate flow through the flume. A sharp crested overflow weir at the upstream end of the flume evenly distributes the flow across the flume.

The 1:30 scale model of Clark=s Ferry on the Upper Mississippi River was modified by removing the dikes and adding a vertical wall left of the thalweg and adding a generic backwater as shown in Figure 2. The cross-section of the modified Clark=s Ferry reach at RM 468.2 and the dimensions of the backwater are shown in Figure 3. Additional information on the navigation effects flume can be found in the Upper Mississippi report for Clark=s Ferry (Maynord and Martin, 1998).

Instrumentation

Wave heights were measured using two capacitance type wave gauges manufactured at WES. Velocity measurements were taken using two Acoustic Doppler Velocimeters (ADV=s) (Kraus, Lohrmann, and Cabrera, 1994). Both of these probes were two-dimensional side-looking probes that measured velocity in the horizontal plane. The ADV=s take data approximately 5 cm from the transmit and receive transducers. The side-looking two-dimensional probes were needed for the shallow water in the backwater. The ADV=s use acoustic sensing techniques to measure flow in a remote sampling volume. No cables were in the water and the measured flow is relatively undisturbed by the presence of the probe. Data are available at an output rate of up to 25 Hz. The horizontal velocity range is +/- 2.5 m/s and there is no zero-offset in the velocity output. Data can be collected as close as 5 mm from a solid boundary. The ADV=s require particles of a certain size to be present in the water to measure the water velocity. Hollow glass spheres having a mean diameter of 10 microns and specific gravity slightly greater than 1 were used as the seed material in the model. Velocity measurements inside the backwater presented a difficult environment for the ADV=s because the seed tends to settle out because there was no flow in the physical model backwater. Once the meter cannot detect adequate seeding particles, the ADV gives extremely erratic data. If the lack of seed is momentary, the erratic data can be filtered out. If the seeding problem persists, the data become invalid and must be ignored. A wave gauge, a 2D ADV, and a 3D ADV are shown in Figure 4.

3 Physical Model Experimental Conditions and Results

General Description

All backwater experiments were conducted at a pool elevation of 546.0 with a tow that is a 3 wide by 5 long barge configuration and a simulated 2.74 m draft (all dimensions are in prototype quantities unless otherwise noted) moving along a sailing line 27 m right of the thalweg. One of the wave gages was located 4.8 m from the rear of the backwater channel and the other wave gage was located 9 m downstream of the mouth of the channel and 1.5 m away from the vertical wall forming the left bank of the channel as shown in Figure 5. Both ADV's were located at 60% depth below the surface in mid-channel of the backwater. In the backwater channel, one ADV was 9 m from the entrance and the other was 68.4 m from the entrance (Figure 5). An initial experiment was run to determine if the drawdown at the edge of the main channel was equal to the drawdown just inside the entrance of the backwater. The time history of the water level is equal in both locations as shown in Figure 6. Therefore only the wave gage in the main channel was used for further experiments. The positive wave at the beginning of the time history is an artifact of the physical model and is not as significant in prototype data. This hump is due to the rapid acceleration in the physical model which is required because of the short flume length. This rapid acceleration is possible in the model because of the additional power added by the towing carriage. The prototype accelerates much slower because of the more restricted power of the towboat and, in most cases, normally operates at a relatively steady rate of motion, i.e. no significant acceleration. Passage time of the bow of the tow at the mouth of the backwater in the physical model is equal to the time when the water level passes through zero just prior to the beginning of drawdown. The passage time of the stern of the barges is equal to the bow passage time plus the vessel length/vessel speed.

Experiment Series 1 - No Flow

The first series of physical model experiments were conducted with no flow in the physical model with 3 replicates. The vessel was operated at 3.95 m/s (87% of limiting speed), with propellers operating. Limiting speed is the maximum speed a self propelled vessel can travel relative to the water in a channel and depends on the channel area/vessel area and average channel depth. Limiting speed can be computed using Maynord (1996) and is equal to 4.54 m/sec for the channel and vessel used herein. The three replicate experiments were averaged and one of the three was selected as being most representative of the mean and was used to create a stage hydrograph (Figure 7) at the downstream end of the backwater for use in the UNET model.

Experiment Series 2 - Discharge=690 cms

The second series of physical model experiments were conducted with a discharge of 690 cms with 3 replicates. The experiments were run with a downbound tow with vessel speeds of 4.27 m/s (85% of limiting speed). The three replicate experiments were averaged and one of the three was selected as being most representative of the mean and was used to create a stage hydrograph (Figure 8) at the downstream end of the backwater for use in the UNET model.

4 UNET Model Comparison to Physical Model Experiments

UNET is a one-dimensional unsteady flow program that can simulate dynamic flow in a network of open channels. This model was created by Dr. Robert L. Barkau. For the UNET runs that follow, version 2.0 was used (Barkau 1992) because later versions did not allow the small time steps required in this simulation. UNET input had to be in English units but the discussion herein will remain in metric with the exception of pool elevation (NGVD) and river miles. All computations were in prototype dimensions.

The UNET model simulated the backwater only in both the physical model and Illinois Waterway applications. The boundary conditions on the end away from the main channel specified no flow. The boundary condition at the end connected to the main channel was a stage hydrograph that followed the time history of drawdown at the mouth of the backwater. Because the UNET model only simulates the backwater, the presence of flow in the main channel is not modeled. There are two input data files required to run UNET; these are described below.

Cross Section Input Data Description

The cross section input data file (Figure 9) is set up to contain cross-section input data for UNET. By using cross-section coordinates, any cross-section shape can be input into UNET. Just like most one-dimensional approaches, cross-section shape effects are incorporated into the hydraulic radius (= area/ wetted perimeter). The channel ›n: value was set to 0.025. This was based on scaling up the model ›n: values of about 0.014 for the plastic coated plywood and sheet metal boundaries of the model to its prototype equivalent. While 0.014 may seem high for prototype smooth boundaries like sheet metal or plastic coated plywood, the relatively small Reynold:s number in the model and the minimum resistance dictated by hydraulically smooth boundaries make this value correct. Mannings ›n: value for the left and right overbank was not important because flow was restricted to the backwater channel.

The UNET model must have a bottom elevation throughout the model, but particularly at the upstream end, that is below the minimum water surface elevation that occurs throughout the simulation. In the input file shown in Figure 9, the file is based on the physical model backwater. The first line of each cross section is identified by a cross section number, the number of ground points, the stations of the left bank and the right bank of the channel, and the length of the left overbank, right overbank, and channel reach. The next line is used to specify whether to write stage and flow hydrographs for the current cross section, to the UNET output file. The last line(s) specifies the elevation and station of each point in a cross section used to describe the ground profile. The cross sections are defined perpendicular to the direction of the flow. A cross section is required at representative locations along a river reach and at locations where changes occur in discharge, slope, shape, or roughness.

UNET Input Data File Description

The UNET input data file (Figure 10) is set up to contain job control parameters, initial and boundary conditions, and hydrograph specifications. The job control line specifies calculating maximum water surface profile, a time step, a time to cease computations, levee routines are disabled, an implicit weighting factor of 0.6 is used, and flow and stage data are output at hydrograph nodes at each time step to the UNET output file. The A-30MIN@ on Figure 10 is an output option and does not affect the computations.

In each experimental series, the initial flow conditions were set to zero. The upstream boundary connection is set in the UNET input data file using a 34 step inflow discharge hydrograph which for the physical model input was zero for all steps. The downstream stage hydrograph is a 34 step stage hydrograph. Both stage and discharge hydrographs use a time increment of 15 secs to discretize the hydrograph. The maximum number of iterations for Newton Raphson iteration scheme is set to 100. A stage tolerance is set to 3.05 x 10^{-6} m for convergence criteria.

Sensitivity Analysis for Physical Model Application

Barkau (1992) states “...any model application should be accompanied by a sensitivity study, where the accuracy and the stability of the solution is tested with various time and distance intervals.” The backwater channels investigated herein are relatively short and small Δx and ΔT can be used without having to worry about run time. Sensitivity experiments were conducted to determine the effect of distance between cross sections Δx and computational time step ΔT. The backwater channel Manning=s n value was 0.025 in all sensitivity runs with the exception of the runs used to evaluate Manning=s n effects and all sensitivity runs were based on Experimental Series 1 having no flow in the model and a vessel speed of 3.95 m/sec. The relationship between Δx, wave speed, and ΔT is generally expressed as the Courant number defined as

$$Courant\ No. = \frac{c\Delta T}{\Delta x} \tag{2}$$

where c is the wave speed = $(gd)^{1/2}$, g is the gravitational acceleration, and d is the depth. Courant numbers determined herein were based on an average depth in the physical model backwater of 2.44 m. The sensitivity runs for Δx of 4.9 m, 9.8 m, and 19.6 m and corresponding ΔT of 1 sec, 2 secs, and 4 secs are shown in Figure 11. All runs in Figure 11 have a Courant number of 1.0 and the magnitude of the initial computed water level drawdown is not affected by the increasing Δx and ΔT but reduced magnitude can be observed in the subsequent oscillations. Figure 12 shows the effect of a range of Courant #'s for Δx of 4.9 m. Results are similar to the previous Figure 11; almost no effect on the initial drawdown and differences in subsequent oscillations. The sensitivity of computed results to changes in Manning's n are shown in Figure 13. Again, the initial drawdown is not affected but subsequent oscillations show a small effect. This is almost certainly due to the relatively small channel velocity ($\leq$ 0.5 m/sec) that occurs during vessel induced drawdown events. All subsequent comparisons to physical model data are based on a Δx = 4.9 m, computational time step ΔT = 1.0 secs, Courant # = 1.0, and Manning's n = 0.025.

Results of Comparison to Physical Model

The downstream stage hydrograph used as input to the UNET model was created by using the physical model data collected at the entrance to the backwater channel. The data points for the hydrograph were picked off a moving average of the time history of water level every fifteen seconds from before the tow passed until the event was completed.

Computed water level drawdown from the UNET model at the upper end of the backwater for Experimental Series 1 with no flow is shown in Figure 14 versus the observed water level drawdown from the physical model. The initial rise and the initial drawdown were similar in magnitude and shape for computed versus observed. The computed peak magnitude for subsequent oscillations of the water level were larger than the observed peak values. The comparison of computed UNET velocity and the observed velocity data for Experimental series 1 with no flow are shown in Figures 15 and 16 for 9 m and 68 m from the backwater entrance, respectively. Positive velocities are toward the mouth of the backwater. Figure 15 is one of the physical model runs where lack of seeding caused the data after about 400 secs to not be valid. Velocities in both Figures 15 and 16 are in good agreement during the early portion of the vessel event but subsequent oscillations have computed values greater than observed values.

Computed water level drawdown from the UNET model at the upper end of the backwater for Experimental Series 2 with flow and a downbound tow is shown in Figure 17 versus the observed water level drawdown from the physical model. Good agreement is found between computed and observed water level throughout the event. The comparison of computed UNET velocity and the observed velocity data for Experimental series 2 with flow and a downbound tow are shown in Figures 18 and 19 for 9 m and 68 m from the backwater entrance, respectively. Figure 18 is another one of the physical model runs where lack of seeding caused the data after about 525 secs to not be valid. Velocities in both

Figures 18 and 19 are in good agreement during the early portion of the vessel event but subsequent oscillations have computed values greater than observed values.

For the backwater used in the physical model, both the physical model and UNET show that the maximum drawdown at the rear of the backwater is about 1.5-2 times the maximum at the mouth which results from the smooth boundaries, straight alignment, and vertical walls in the physical model. The agreement between UNET and the physical model is important because the physical model is a worst case in terms of the water level drawdown. While some of the physical model data was missing because of seeding problems, the comparison shows that the shape and magnitude of the initial wave of the drawdown event is correct. With few exceptions, the initial wave is the largest and most significant of all the wave events. No claims are made herein that UNET can simulate the complete time history of drawdown.

5 UNET Model Comparison to Illinois Waterway Backwater

Description of Illinois Waterway Backwater

To demonstrate the applicability of UNET to actual backwaters, UNET was compared to a backwater on the Lagrange Pool of the Illinois Waterway where measurements were taken in 1996 by Pratt and Fagerburg(draft). The prototype backwater channel (Figure 20) is on the left bank at River Mile 98.7 and connects the river to Panther Slough. At the connection to Panther Slough, a rectangular sheet pile structure having a sill width of about 9.1 m and sill elevation of about 0.8-0.9 m below the Lagrange normal pool elevation of 429.0. The “about” in the above sentence results because the width observation was based on similar independent estimates by two individuals who passed through the structure in a boat and the sill elevation estimate is based on bottom elevations taken upstream of the structure and the fact that the boat that passed through the structure had a known draft.

Bathymetry data and aerial photography were collected in about 1989 and resulted in an average channel top width of about 30 m along the length between the structure and the river. In 1993, the Illinois Waterway experienced a major flood. Four members of the 1996 field survey team independently estimated the channel top width to be from 12- 15 m wide during the field data collection. A fifth member of the field team collected GPS measurements that showed the top width to be 12 m in the middle of the reach between the structure and the river. Cross-sections were not collected during the 1996 field trip but depth checks at the water level and velocity measurement station near the structure and depths at sediment sampling points in the backwater showed the maximum depth during the 1996 trip was about 1.7 m. This depth is consistent with depths measured during the 1989 measurements. This disparity between the widths and the lack of cross-section data mean that this comparison will be more of a demonstration than a verification. Widths and depths upstream of the sheet pile structure are based on the 1989 measurements. One UNET model run will be conducted using widths in the reach below the sheet pile structure that are typical of the 1989 measurements to see how results are affected.

Pool elevation during the 1996 field measurements was 430.0 and flow rate in the backwater channel was near zero based on the velocity measurements which were less than 2 cm/sec. The upbound tow used in this demonstration of UNET, referred to as boat #2 in Pratt and Fagerburg (draft) is the M/V Tennessee which had a speed over ground $V_g = 1.8$ m/sec. The measured time history of water level at the mouth of the backwater (cross-section 0.00 in the UNET simulation, range 2 in the field data) is shown in Figure 21. Passage of the bow past the mouth of the backwater channel was at 10.14 hours for boat 2. Boat #2 was a loaded tow typical of the largest tows using the waterway having a length of about 340 m although the speeds were less than the fastest tows on the waterway. The measured time history of water level at the upper end of the backwater channel at cross-section 0.496 (range 1 in the field data) is shown in Figure 22 for boat 2. Cross-section names on Figure 20 refer to miles above the mouth of the backwater. Measured time history of velocity at UNET cross-section 0.496 is shown in Figure 23 for boat 2.

UNET Simulations of Illinois Waterway Backwater

The cross sections used in the Illinois Waterway backwater channel simulation are shown in Figure 24 and extended from the mouth to 2.0 miles upstream with the field measurement section at cross section 0.496. One of the limitations of applying the UNET model to actual backwaters is that most backwaters have a gradual decrease in depth all the way to zero whereas the UNET model must have a finite depth (a vertical wall) at the upstream end so that the depth will never be zero. A vertical wall reflects almost all of a wave whereas the mild slopes at the upstream end of an actual backwater reflect much less of the drawdown event compared to a vertical wall. The simulation used herein of the Illinois Waterway backwater has the measurement section far downstream of the upstream limit of the backwater so the reflection problems in UNET are not present. For backwaters where the water level is desired to be known where the backwater depth gradually diminishes to zero, it is recommended that the UNET simulation have a depth at the location of the actual upstream end of the backwater that is slightly greater than the drawdown and that the UNET simulation reach be extended far upstream of the actual upstream end of the backwater using the smallest depth that the model will run. This approximation will prevent the reflection problems at the location in the model that represents the actual upstream end of the backwater.

As in the physical model, none of the main channel of the Illinois Waterway was used in the UNET simulation. The drawdown time history from Figure 21 was discretized for input as the downstream stage hydrograph in the UNET model using a 30 sec time increment. While the 30 second discretization of a visual smoothing of the prototype time history did not capture all the variations in the prototype data, comparison of the observed data and the input downstream stage hydrograph in Figures 21 and 25 show a nearly identical shape.

Barkau (1992) states “...any model application should be accompanied by a sensitivity study, where the accuracy and the stability of the solution is tested with various time and distance intervals.” Sensitivity experiments were conducted to determine the maximum distance between cross sections Δx and computational time step ΔT. Courant numbers determined herein were based on a depth of 1.5 m. The sensitivity runs for Δx of 64 m, 32 m, 16 m, 8 m, and 4 m showed similar results for all Δx less than or equal to 32 m when comparing runs having the same Courant number. Sensitivity runs for ΔT were conducted with $\Delta x =$ 32 m for ΔT of 16 sec, 8 sec, 4 sec, 2 sec, and 1 sec giving Courant numbers of 2, 1, 0.5, 0.25, and 0.125, respectively. A time step of 16 secs (Courant number of 2) resulted in smearing (amplitude decreases, wavelength increases) of the drawdown time history compared to the observed time history. Time steps of 4 sec, 2 sec, and 1 sec (Courant numbers of less than 1) resulted in increasing oscillation of the computed time history which was not present in the observed data.

A time step of 8 sec, and Δx = 32 m, giving a Courant number of 1 and Manning's n = 0.030, resulted in computed water level drawdown that had a shape similar to the observed data and is plotted in Figure 25. The computed velocity from UNET is shown in Figure 26. The times in Figures 21-23 are the actual time of day the prototype data was measured. The time on the UNET plots like Figure 25 and 26 differ because UNET was run with a starting time of zero. Comparing Figures 22 and 25, a UNET time of 0.093 hours is equal to a prototype measurement time of 10.14 hours. The important time to note is the difference in time between passage of the minimum drawdown, equal to about 0.071 hours from both the observed data and the UNET calculations. The two input files for UNET are shown in Figures 27 and 28.

A Manning's n value of 0.030 was used in all previous runs. Two members of the 1996 field team looked at photographs of channels with known n values from Barnes (1967) and estimated that the n value for the backwater channel was from 0.026 to 0.035. Water level and velocity were computed for n = 0.026 and 0.035 and are shown in Figures 29 and 30, respectively. This range of n value had only a small impact on computed elevations and a larger impact on computed velocity. The small effect of n value changes is likely due to the low average channel velocity (less than or equal to 0.41 m/sec) that occurs as a result of the vessel drawdown.

A final sensitivity run was conducted using a channel bottom width that was twice the bottom width of the channel used in the previous sensitivity runs (depth over the bottom remained the same due to the similarity of depth measurements in 1989 and 1996) to determine the importance of the contraindication between the 1989 measurements and the 1996 field observations. The doubling of the channel width was only in the reach below the sheet pile structure and used Δx = 32 m, ΔT = 8 sec, and n = 0.030. Results showed that doubling the channel width increased the maximum drawdown at the measurement station by about 50 percent. The explanation for the increased drawdown lies in how the width was doubled. The side slopes were left alone and the doubling of width was placed in the middle of the channel. For cross-sections 0.057 to 0.496 (Figure 24), the hydraulic radius of the original cross-section was 1.13 m. The hydraulic radius of the wider channel was 1.32 m which was one of the causes of the increase in drawdown. Another possible cause of the increased drawdown is that the cross-section at the weir and upstream remained the same in both runs. The increased contraction (wave going upstream) or expansion (wave going downstream) at the weir could also contribute to the increased drawdown.

Application of UNET Model

Another use of the UNET model output is to determine the amount of flow or volume leaving the backwater during the passage of a commercial vessel.

UNET also has modelling features that allow simulation of a large backwater lake (storage area) connected to the main channel by a channel. Although data was not found to evaluate this configuration, results from this study show that the UNET model simulates a worst case physical model backwater and a prototype channel backwater and should be applicable to the backwater lake/connecting channel.

One of the inputs to UNET is the time history of drawdown at the mouth of the backwater which was measured in the two cases studied herein but is rarely known. The NAVEFF model (Maynord, 1996) can be used to estimate the maximum drawdown along the edge of the main channel. Table 1 provides a dimensionless time history of drawdown developed based on prototype data. Knowing the vessel speed and length and the maximum drawdown from the NAVEFF model, the dimensionless parameters in Table 1 define the duration and magnitude of the drawdown event. The dimensionless time parameter is time at any instant / total time required for the barges to pass a fixed point on the river. The dimensionless drawdown parameter is the drawdown at any instant / maximum drawdown during vessel passage.

Table 1
Dimensionless Drawdown Time History

Time Time for Tow Passage*	Drawdown Maximum Drawdown
0.00	0.00
0.25	-0.32
0.50	-0.63
0.75	-0.83
1.00	-1.00
1.25	-0.82
1.50	-0.55
1.75	-0.33
2.14	0.00

* Time for tow passage = (Total Length of Barges)/(Vessel Speed)

UNET provides an easy way to evaluate variation of water level in navigation backwater channels, but because it is a 1-D model, the effects of many of the channel features such as alignment must be lumped into the resistance coefficient. For more detailed study of drawdown effects, the HIVEL2D model (Berger, Stockstill, and Ott 1995) is a two-dimensional depth averaged model that can be used to determine the effects of various channel alignments, shapes, and does not require a vertical wall at the boundaries of the backwater. Although the 2-D model requires more effort to setup and run, it requires less experience on the part of the modeller because channel features such as alignment are part of the model rather than lumped into an empirical resistance coefficient which the user must specify. The advantage of UNET is that is easier to set up and run.

6 Discussion of Results and Conclusions

From the UNET simulations of the physical model and the Illinois Waterway backwaters, UNET can predict the magnitude and shape of the initial wave where there is a backwater channel with one opening into the navigation channel. The UNET model can not provide complete time history of water level change, particularly in the highly reflective environment used in the physical model. For environmental studies of field backwaters that are typically not highly reflective, the magnitude and shape of the initial wave is the primary issue. Water level predictions were generally better than velocity predictions, particularly in the Illinois Waterway backwater. The physical model represents a worst case condition because of the straight alignment, smooth boundaries and vertical walls. As observed in both the physical model and in the UNET model, drawdown in the backwater channel is greater at the upstream end of the backwater than at the mouth. The ratio of the drawdown at the rear over drawdown at the mouth is about 1.5-2. Actual backwaters will tend to respond differently because of the uneven alignment, rough boundaries, and because depths generally decrease gradually at the upstream end of the backwater which leads to a decay of drawdown with distance from the mouth. The Illinois Waterway had drawdown at 800 m from the mouth that was about 1/3 of the drawdown at the mouth.

Sensitivity experiments showed that the model performed well when using a Courant number of about 1. Smearing (decreased amplitude and increased wavelength) occurred for larger Courant numbers whereas numerical oscillation was present at lesser Courant numbers, particularly in the Illinois Waterway backwater channel. Sensitivity runs for the Illinois Waterway backwater showed that the maximum reach length that could be used between cross sections was about 32 m. Sensitivity experiments are required on all UNET simulations to determine the maximum reach length between cross sections. This can be accomplished easily in UNET using the XK card in the cross section input file which sets the maximum distance for interpolated cross sections.

For both the smooth laboratory backwater and the prototype backwater, n values consistent with those used for typical steady water surface profile computations were used in the UNET simulations and provided a reasonable fit of the unsteady drawdown event.

While the results with UNET are promising, it should be remembered that the UNET model has been compared to only one laboratory and one field backwater channel. Because backwaters vary in shape, alignment, roughness, length, connection to backwater lakes, etc, and drawdown events can vary in shape and magnitude, additional comparisons are needed to establish proper n values, time steps, and distance between cross-sections. To the author’s knowledge, data for other backwaters did not exist at the time of this study.

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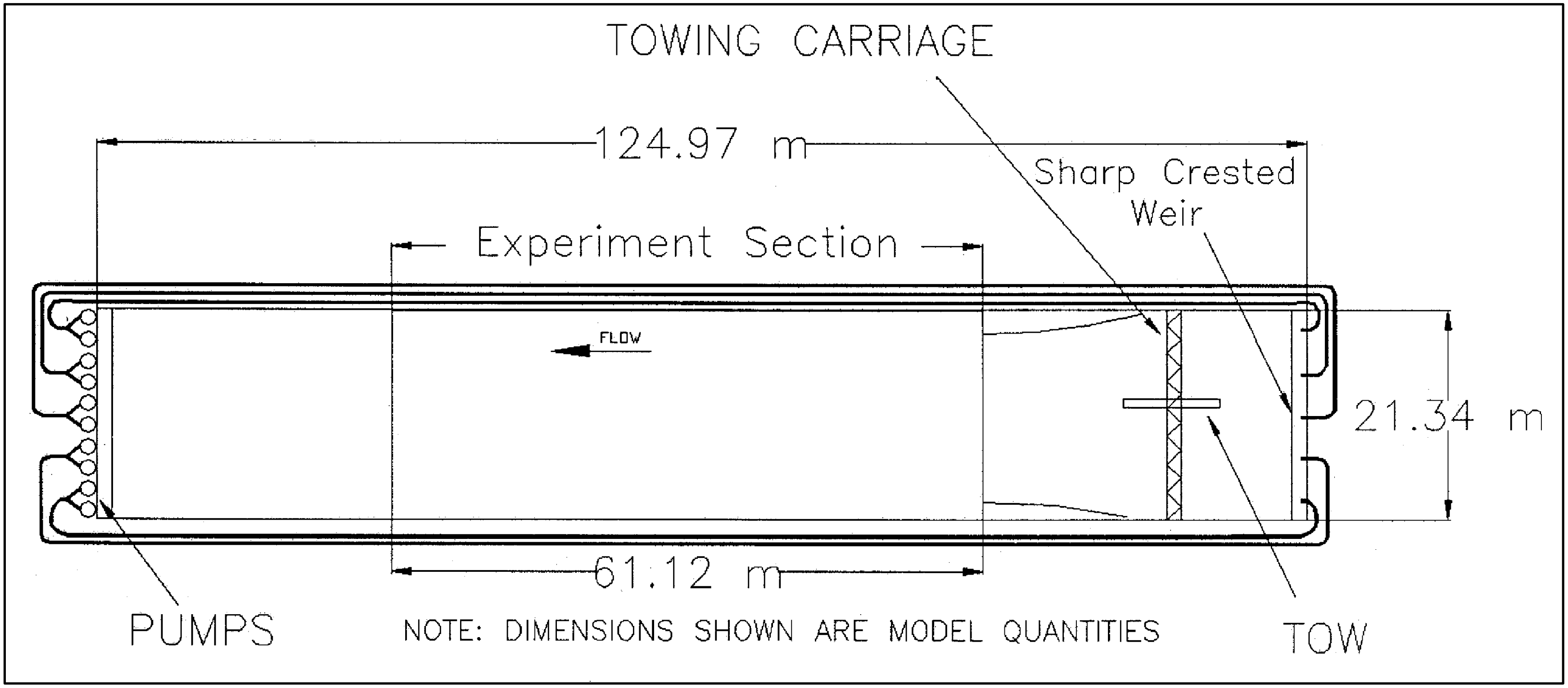


Figure 1. Layout of navigation effects flume

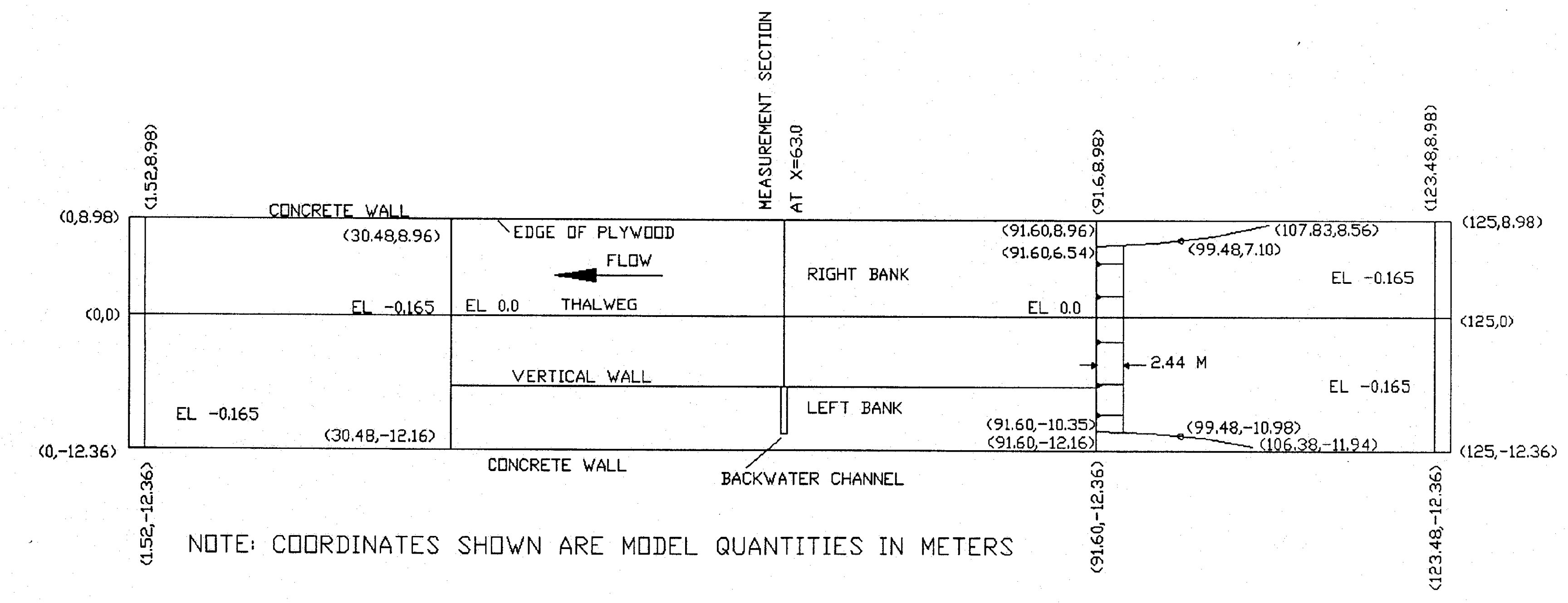


Figure 2. Flume dimensions and location of backwater

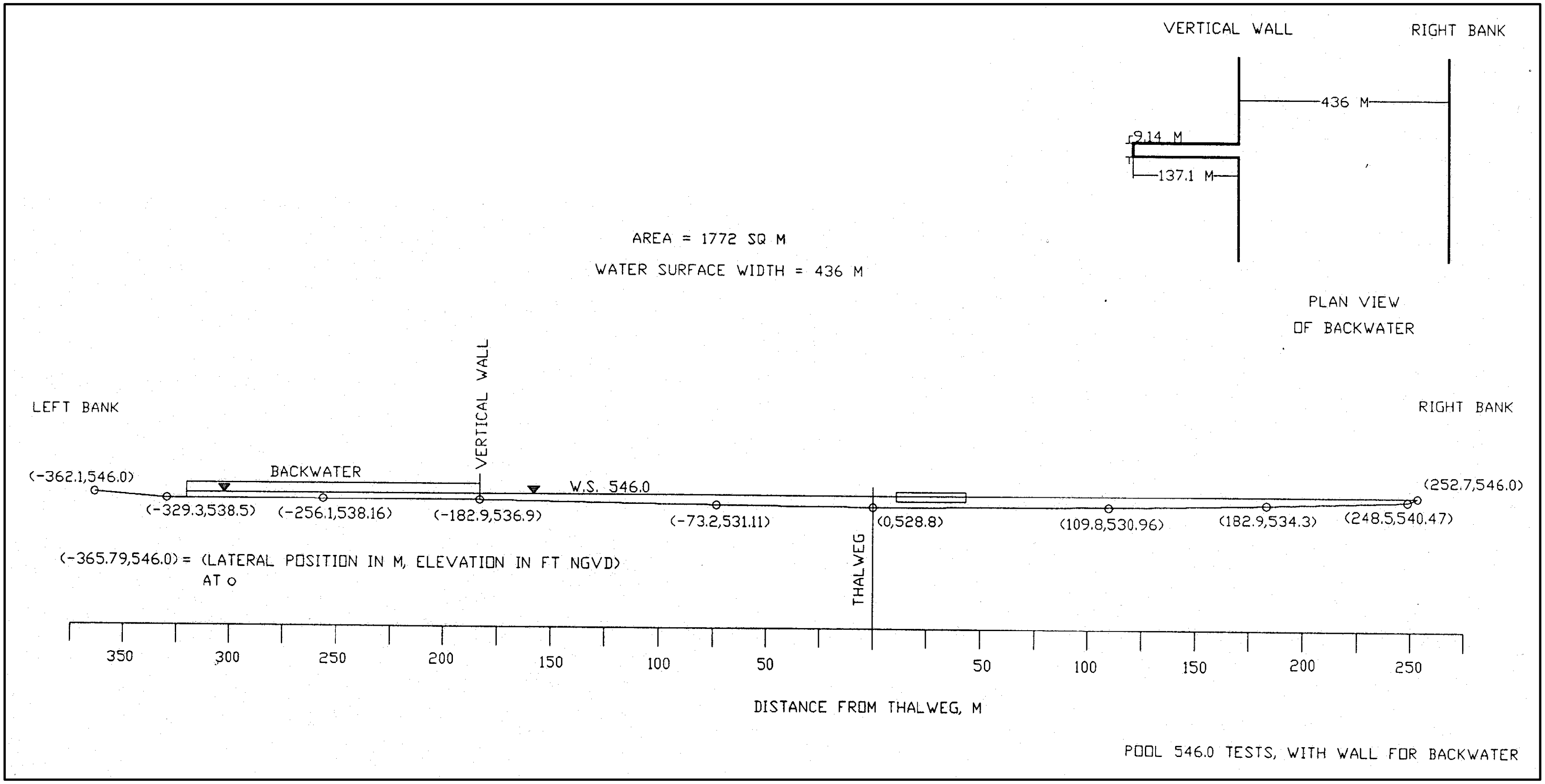


Figure 3. Channel cross-section used in backwater tests

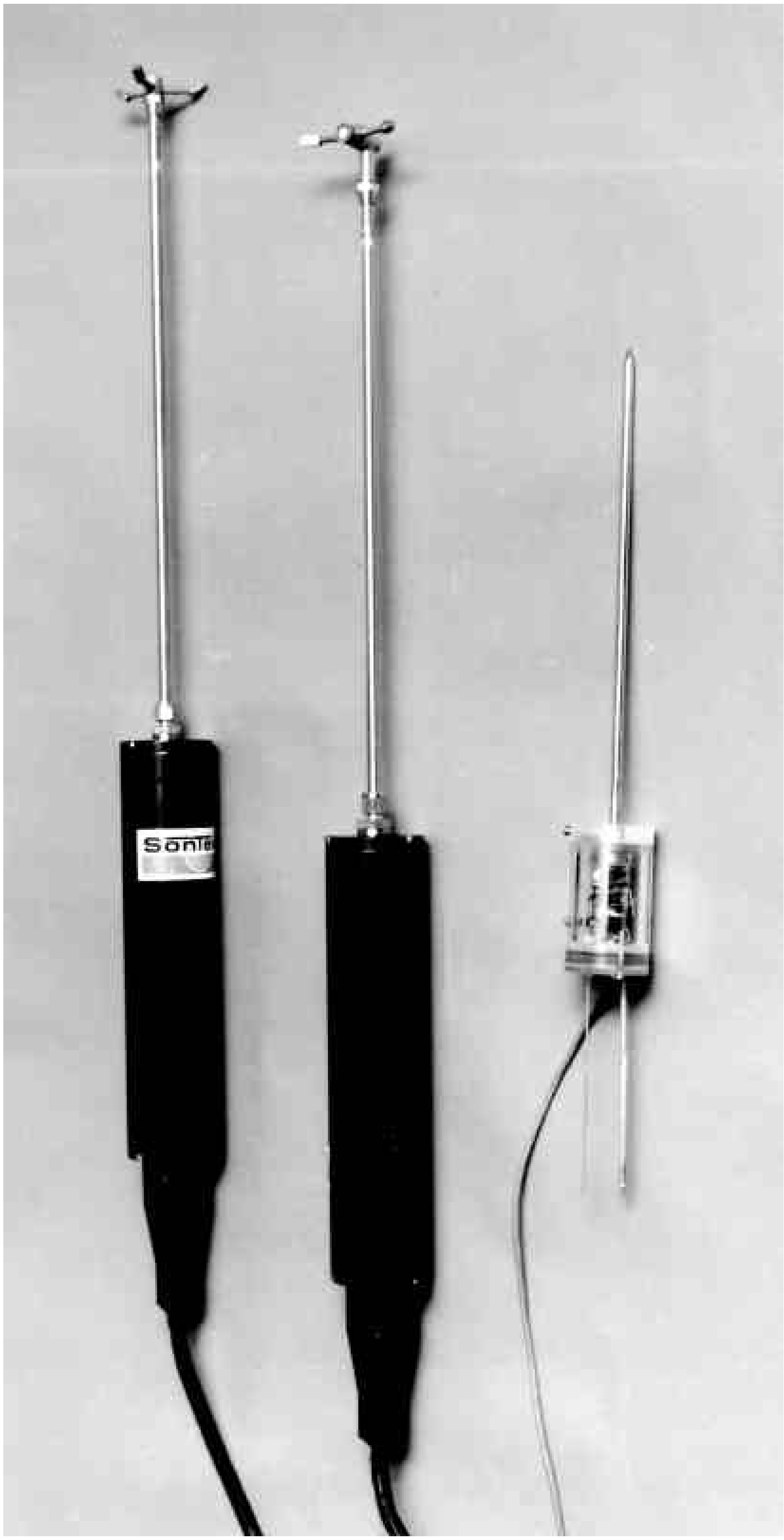


Figure 4. Wave gage and 2D and 3D velocity meters used in physical model backwater

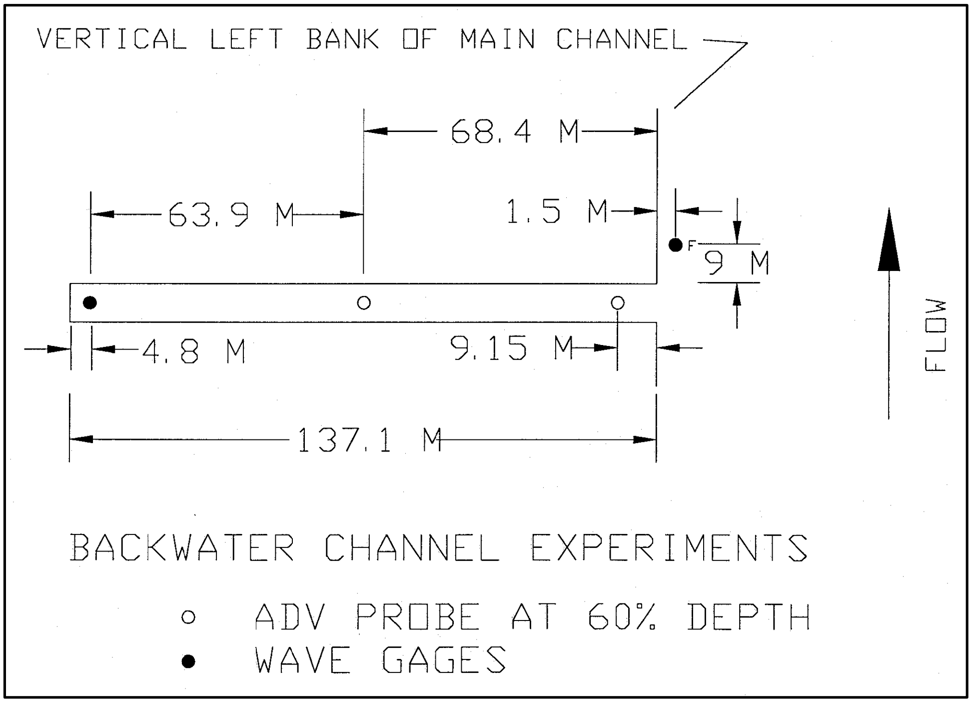
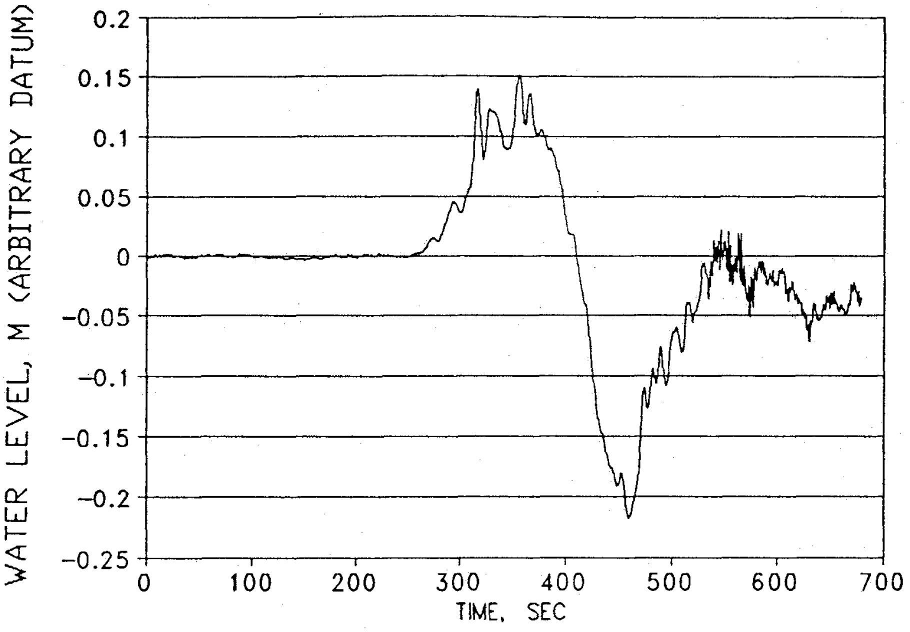
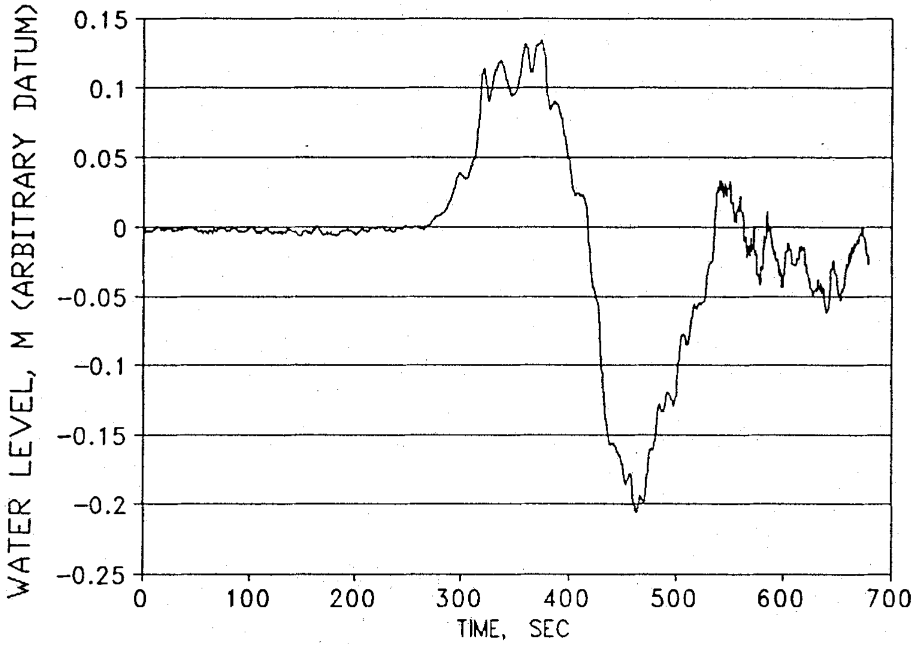


Figure 5. Plan view of physical model backwater and instrument locations



a. Wave gage located outside the backwater channel



b. Wave gage located inside the backwater channel

Figure 6. Comparison of drawdown, inside backwater versus edge of main channel

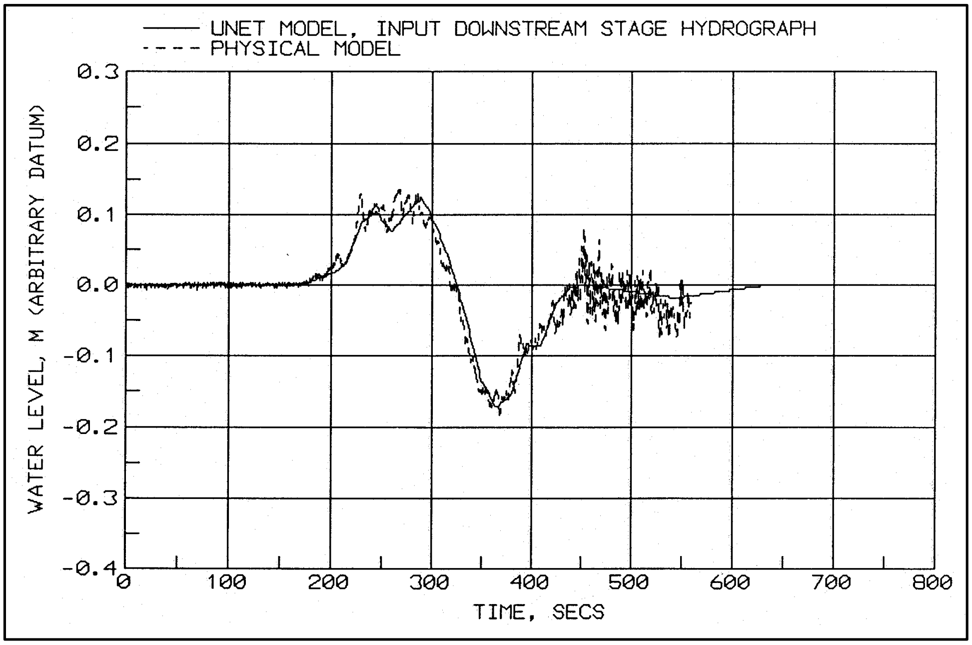


Figure 7. Water level from physical model and UNET input downstream stage hydrograph, mouth of backwater, no flow, vessel speed = 3.95 m/sec

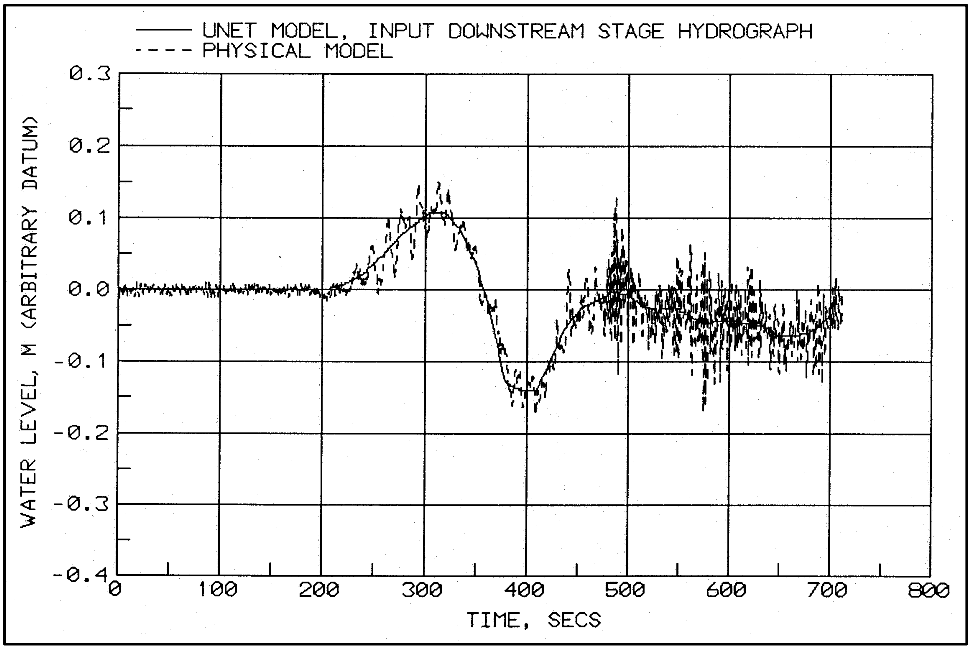
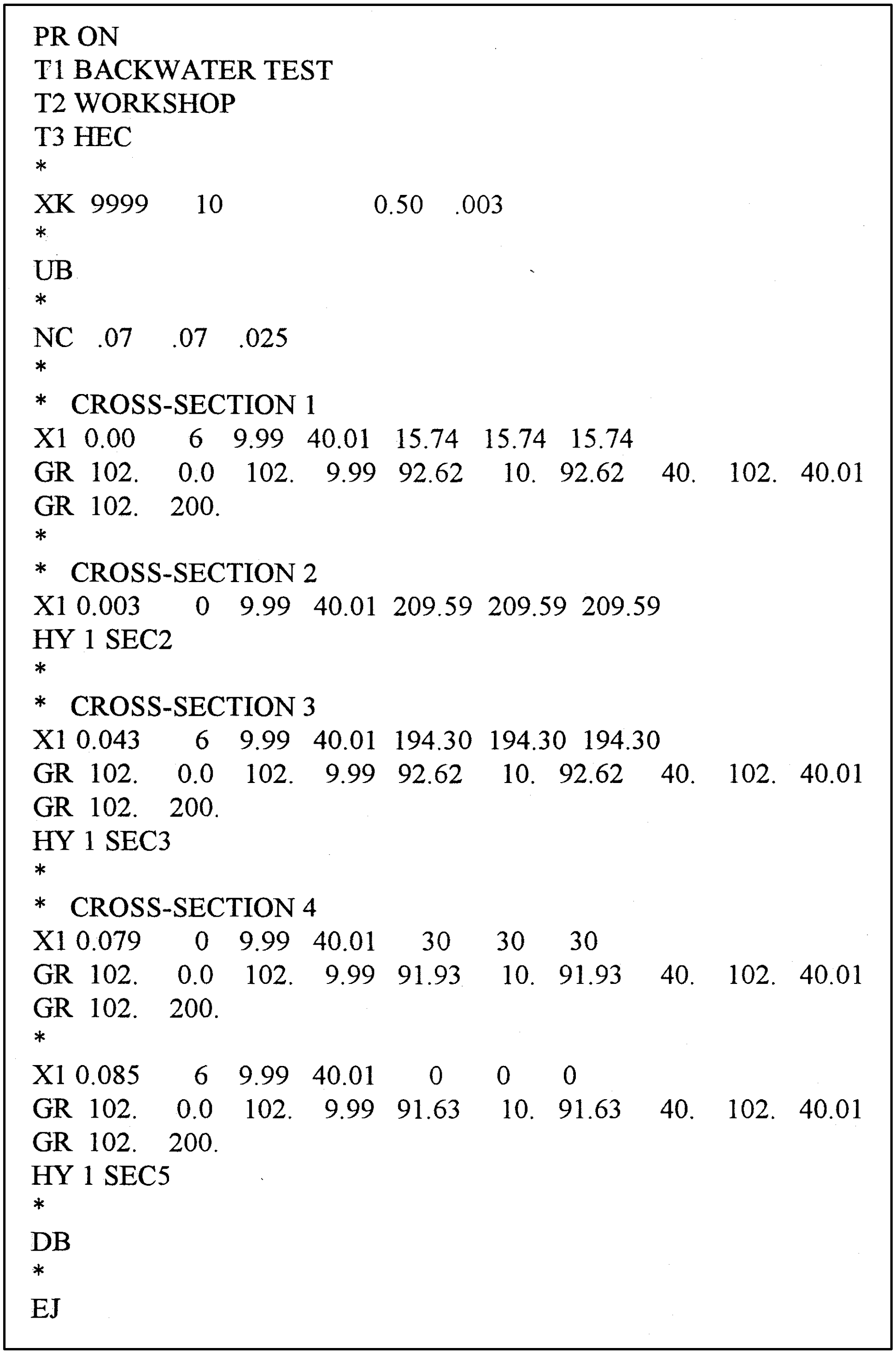


Figure 8. Water level from physical model and UNET input downstream stage hydrograph, mouth of backwater, with flow, vessel speed = 4.27 m/sec



```
PR ON
T1 BACKWATER TEST
T2 WORKSHOP
T3 HEC
*
XK  9999     10                0.50    .003
*
UB
*
NC   .07     .07    .025
*
*   CROSS-SECTION 1
X1  0.00      6    9.99   40.01   15.74   15.74   15.74
GR  102.    0.0    102.    9.99   92.62    10.   92.62    40.    102.   40.01
GR  102.    200.
*
*   CROSS-SECTION 2
X1 0.003      0    9.99   40.01  209.59  209.59  209.59
HY 1 SEC2
*
*   CROSS-SECTION 3
X1 0.043      6    9.99   40.01  194.30  194.30  194.30
GR  102.    0.0    102.    9.99   92.62    10.   92.62    40.    102.   40.01
GR  102.    200.
HY 1 SEC3
*
*   CROSS-SECTION 4
X1 0.079      0    9.99   40.01     30      30      30
GR  102.    0.0    102.    9.99   91.93    10.   91.93    40.    102.   40.01
GR  102.    200.
*
X1 0.085      6    9.99   40.01      0       0       0
GR  102.    0.0    102.    9.99   91.63    10.   91.63    40.    102.   40.01
GR  102.    200.
HY 1 SEC5
*
DB
*
EJ
```

Figure 9.   UNET Cross Section input file for physical model backwater

```
 WORKSHOP NO. 2
 BACKWATER
 UNET
*
*  Job control information
*
JOB CONTROL
 T  T  .01666666 .14 -6  F  0.6  T  T  -1  -30MIN
*
*
TIME INCREMENT
.0041667
*
INITIAL FLOW CONDITIONS
1 0.000
*
UPSTREAM FLOW HYDROGRAPH
1 34
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
```

Figure 10. UNET input data file for physical model backwater. Downstream stage hydrograph based on experiment series 1 having no flow and vessel speed = 3.95 m/sec (Sheet 1 of 3)

```
0.000
0.000
0.000
0.000
0.000
0.00
0.00
0.00
0.00
0.00
0.00
0.00
*
DOWNSTREAM STAGE HYDROGRAPH
1 34
100.0031
100.0006
100.0242
100.0515
100.0986
100.2932
100.3404
100.2498
100.3329
100.4110
100.2734
100.0862
99.84938
99.56174
99.43651
99.49354
99.72539
99.72291
99.91509
99.99072
100.0
99.99
99.98
99.97
99.96
```

Figure 10. (Sheet 2 of 3)

```
99.95
99.94
99.95
99.96
99.97
99.98
99.99
100.0
100.0
*
*
*  Set maximum number of iterations for Newton Raphson iteration scheme
*
MXITER = 100
*
*  Set stage tolerace to 0.00001 ft, for convergence criteria
*
ZTOL=0.00001
*
*
EJ
```

Figure 10. (Sheet 3 of 3)

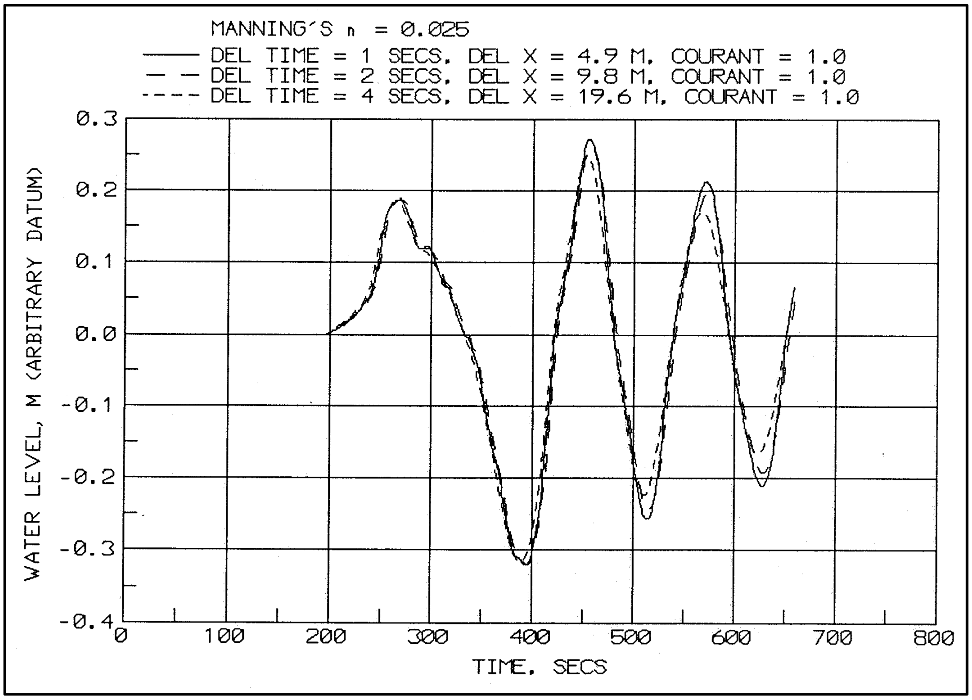


Figure 11. Water level from UNET model, upper end of physical model backwater. Courant # = 1.0, DEL time = 1, 2, and 4 secs

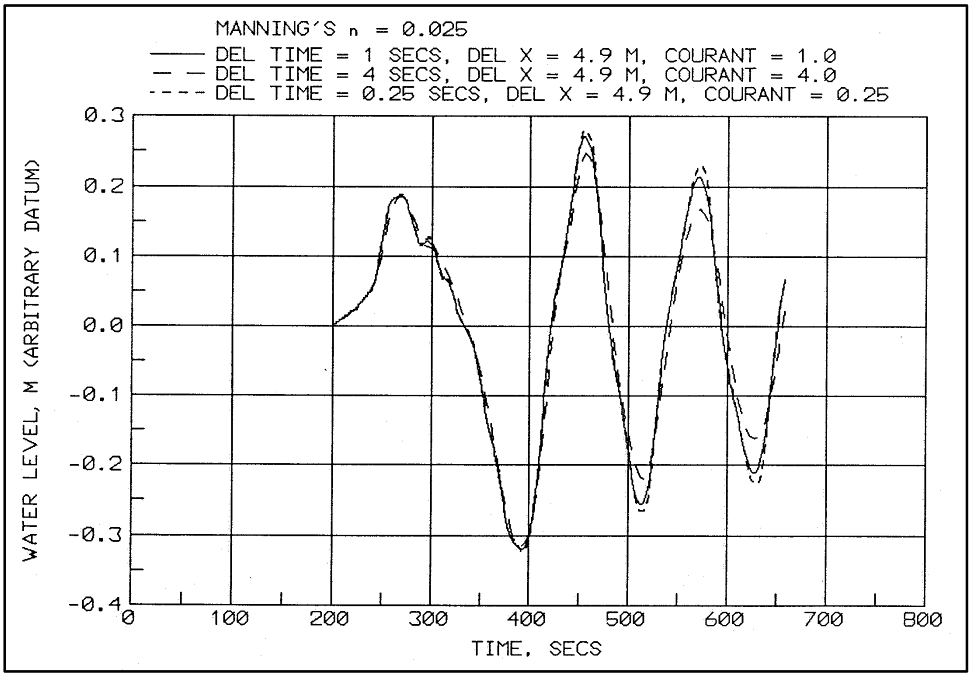


Figure 12. Water level from UNET model, upper end of physical model backwater. DEL X = 4.9 m, courant # = 1.0, 4.0, and 0.25

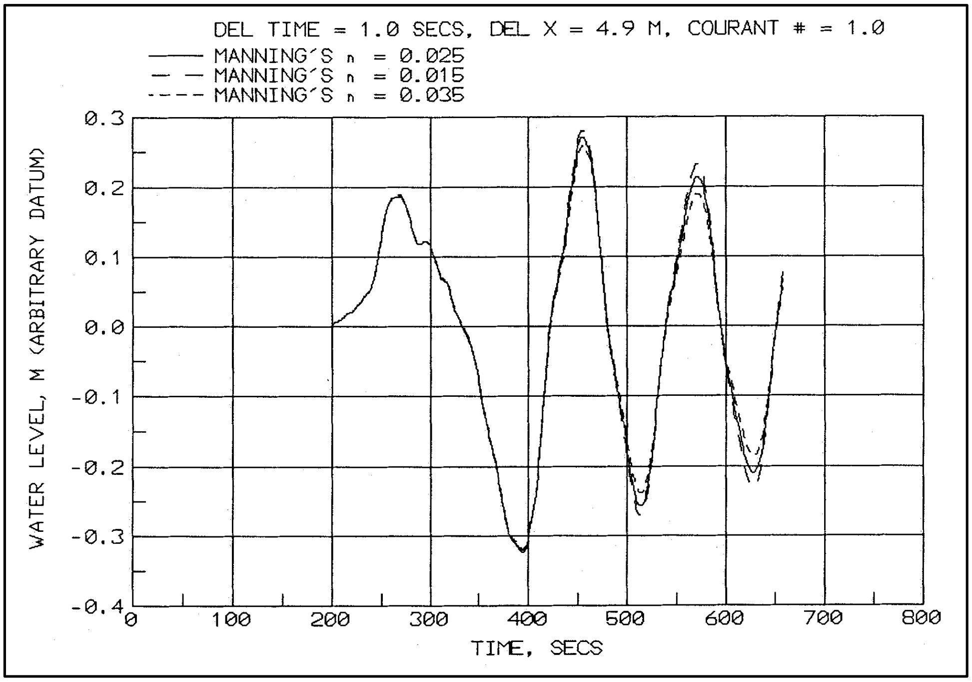


Figure 13. Water level from UNET model, upper end of physical model backwater. Manning's n = 0.025, 0.015, and 0.035

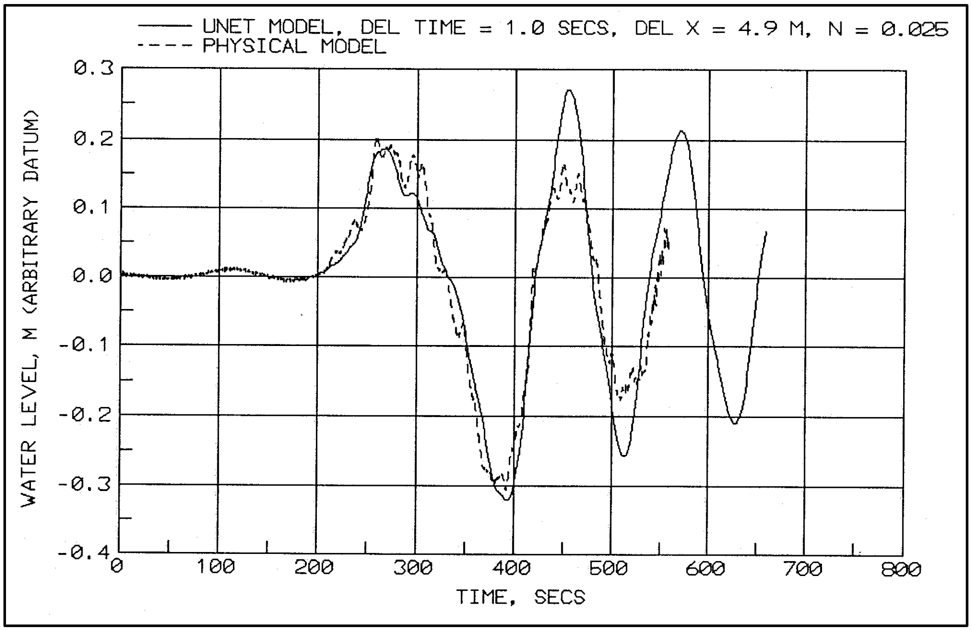


Figure 14. Water level from physical model and UNET model, upper end of backwater

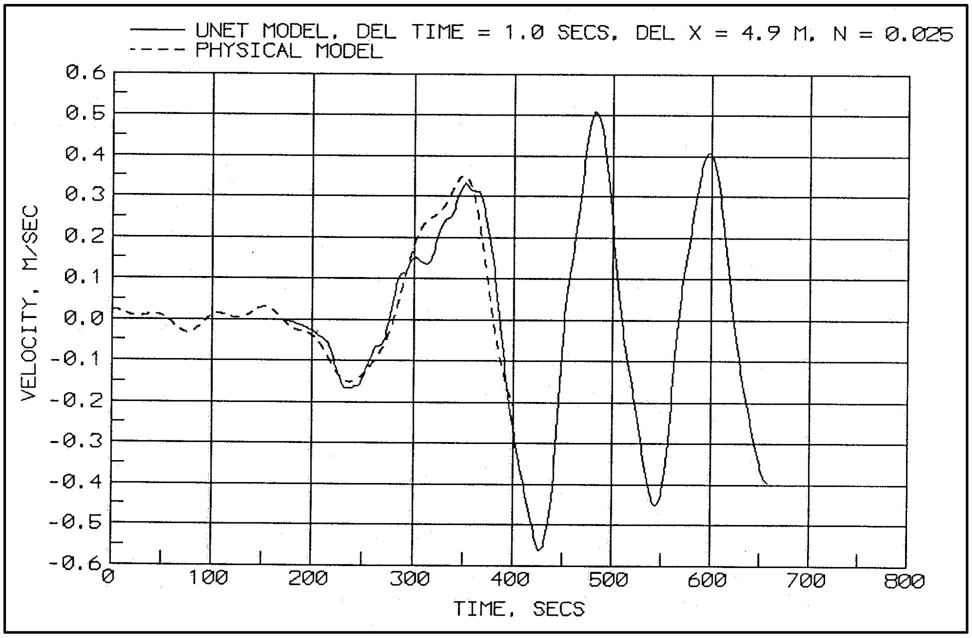


Figure 15. Velocity from physical model and UNET model, 9 m from backwater entrance

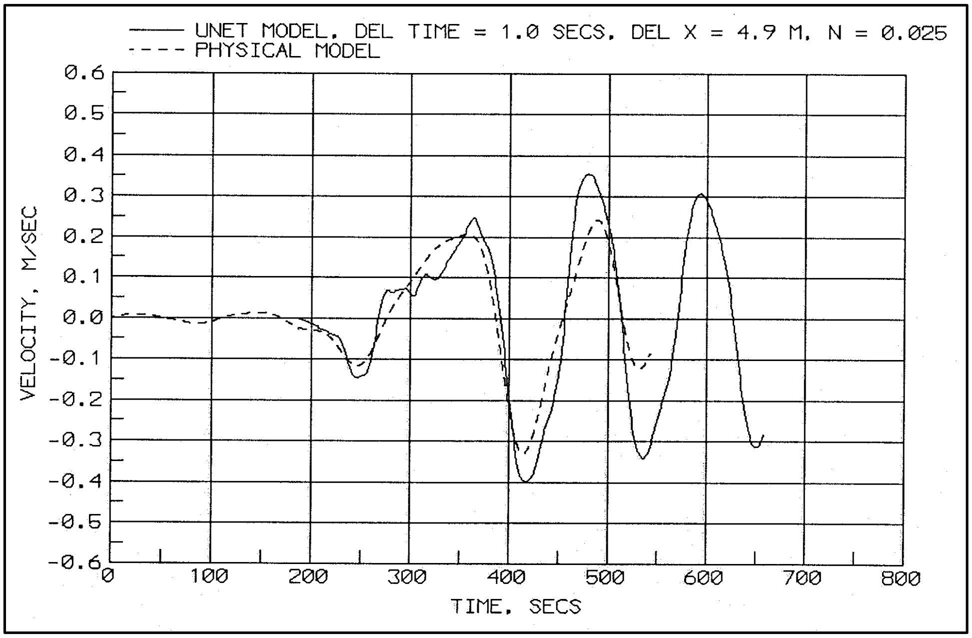


Figure 16. Velocity from physical model and UNET model, 68 m from backwater entrance

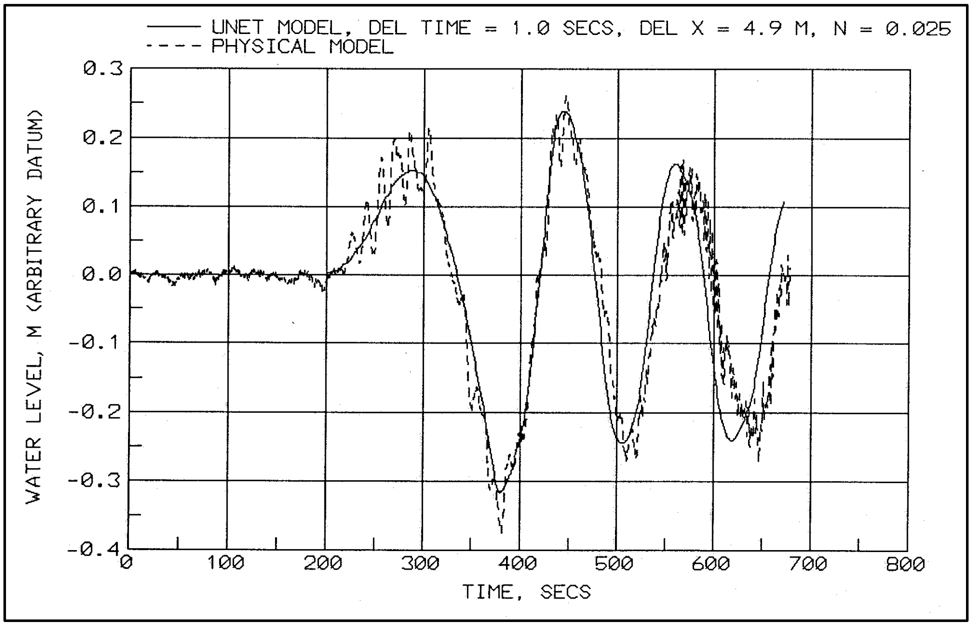


Figure 17. Water level from physical model and UNET model, upper end of backwater, downbound tow

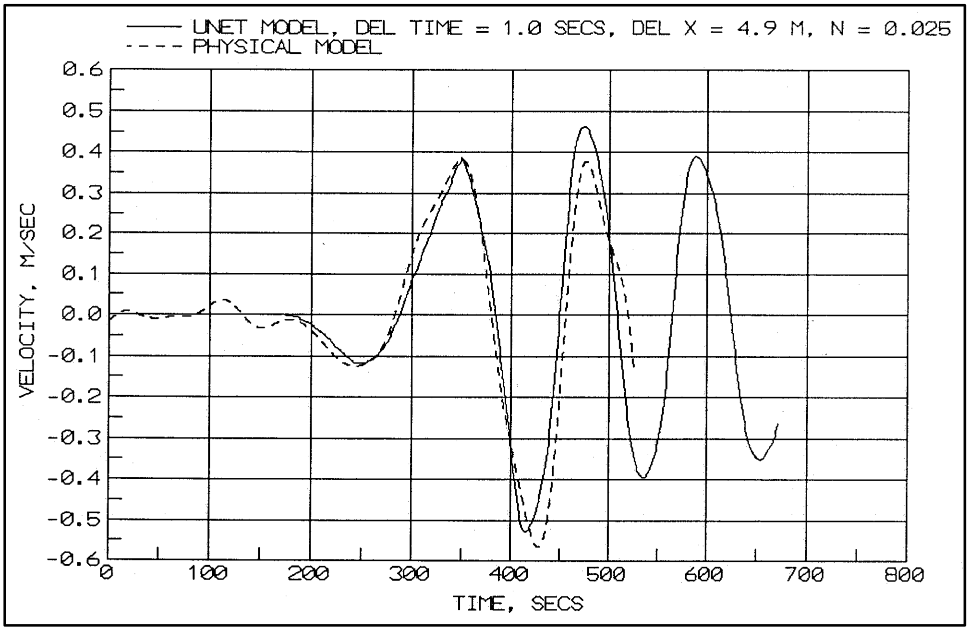


Figure 18. Velocity from physical model and UNET model, 9 m from backwater entrance, downbound tow

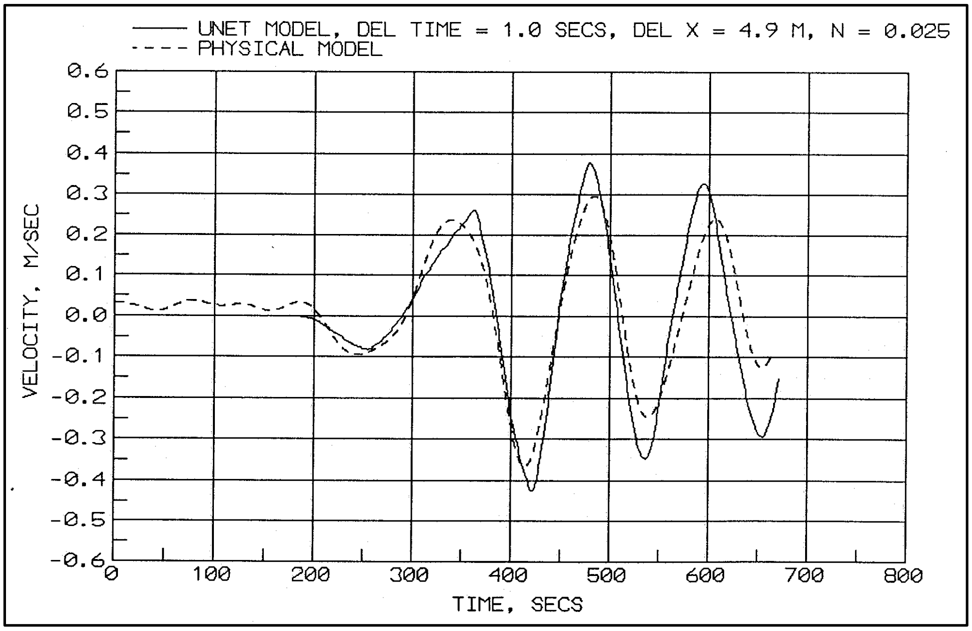


Figure 19. Velocity from physical model and UNET model, 68 m from backwater entrance, downbound tow

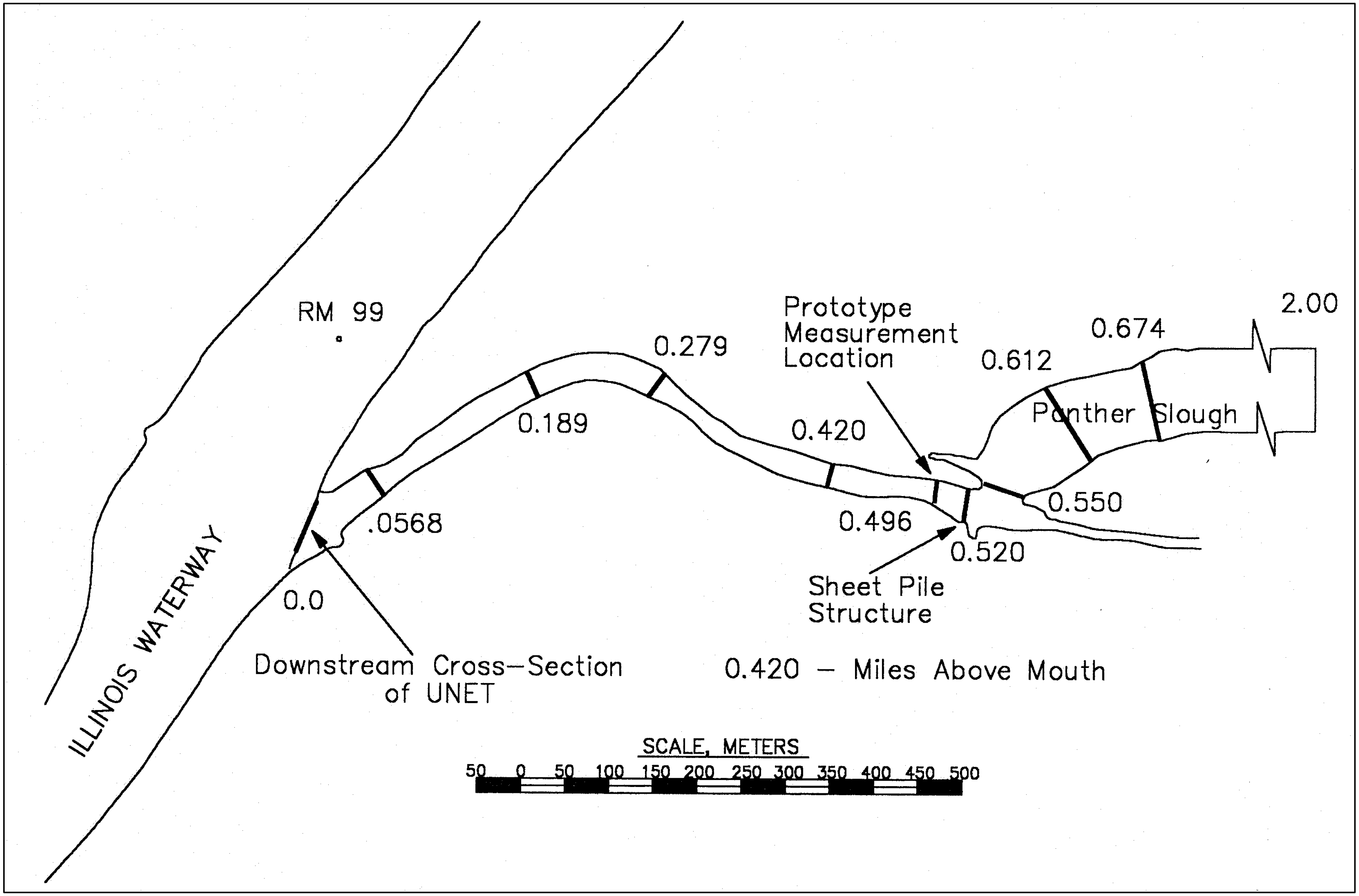


Figure 20. Illinois Waterway Backwater Channel cross-section locations for UNET simulation

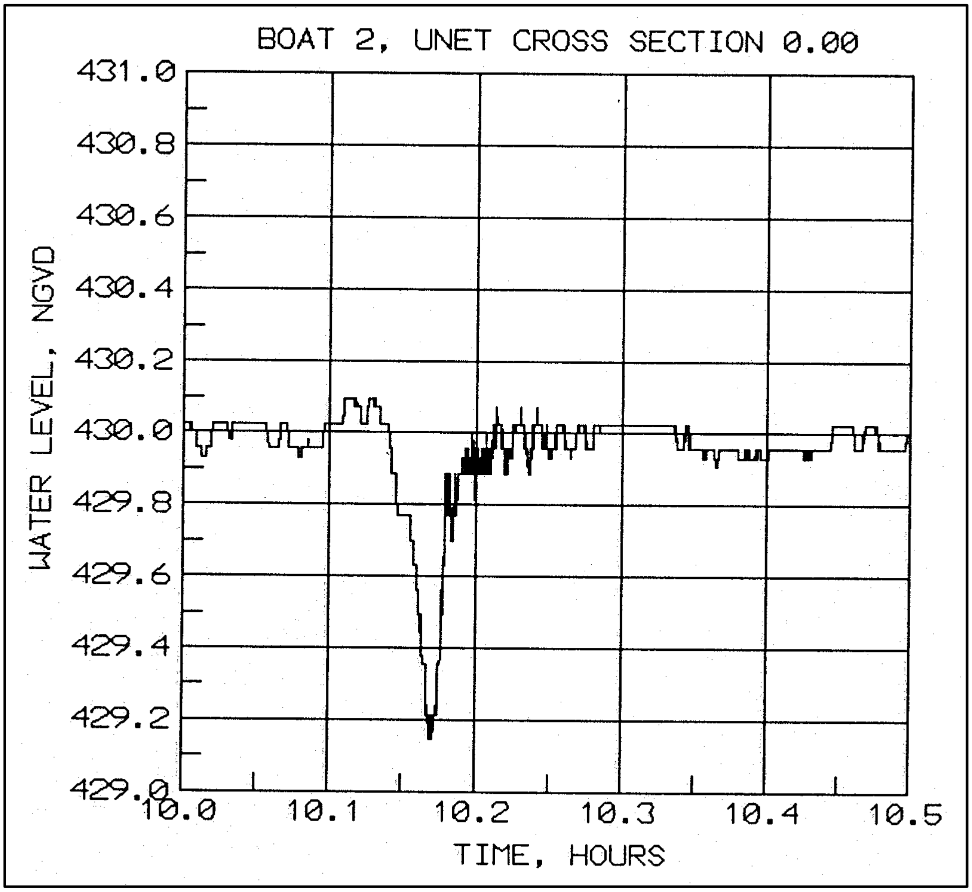


Figure 21. Observed water level, mouth of Illinois Waterway Backwater Channel, Boat 2, UNET Section 0.00

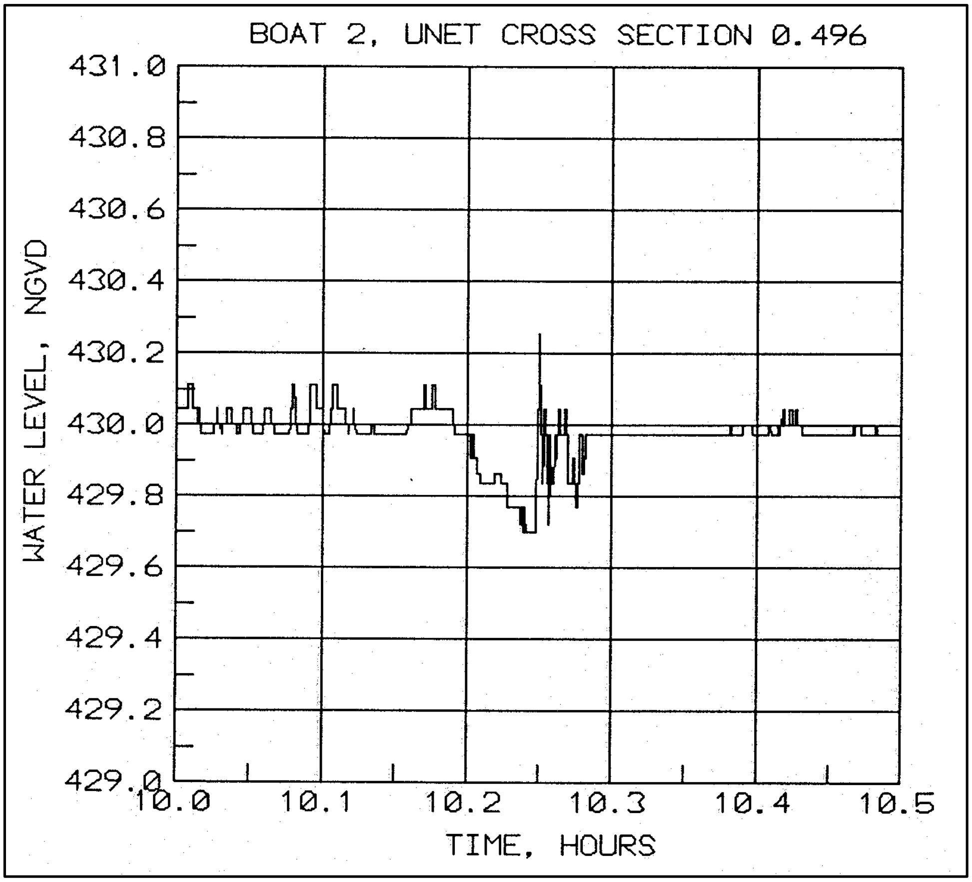


Figure 22. Observed water level, Illinois Waterway Backwater Channel, Boat 2, UNET Section 0.496

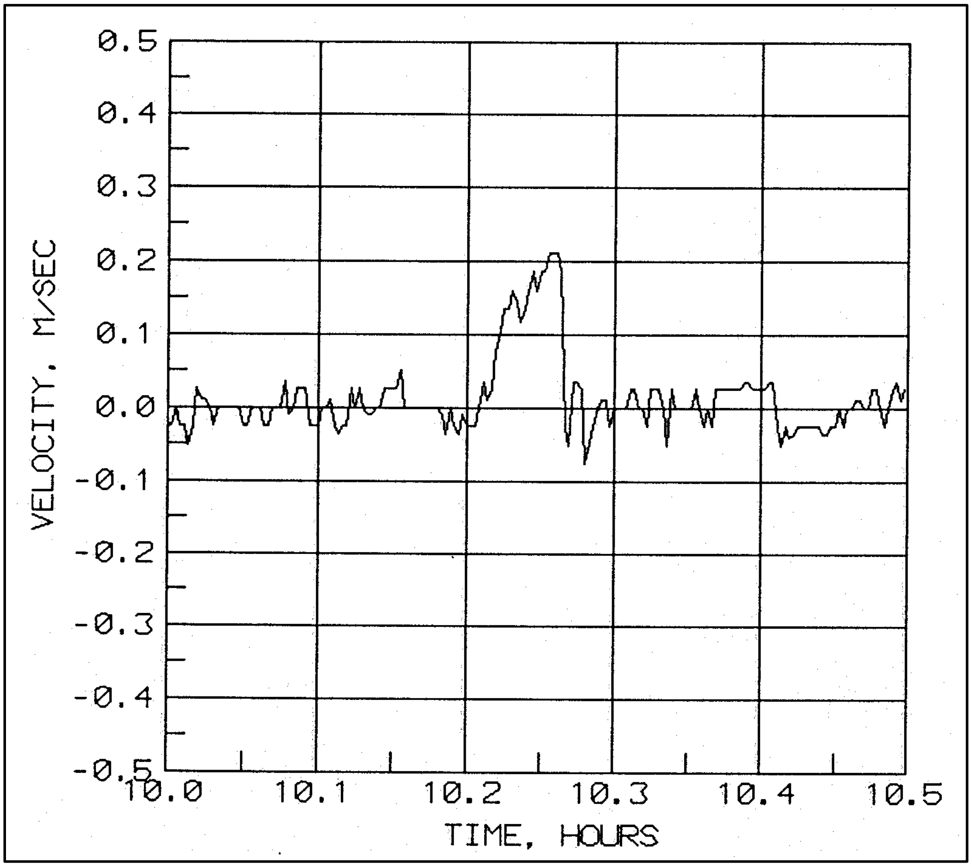


Figure 23. Observed velocity, Illinois Waterway Backwater Channel, Boat 2, UNET Section 0.496

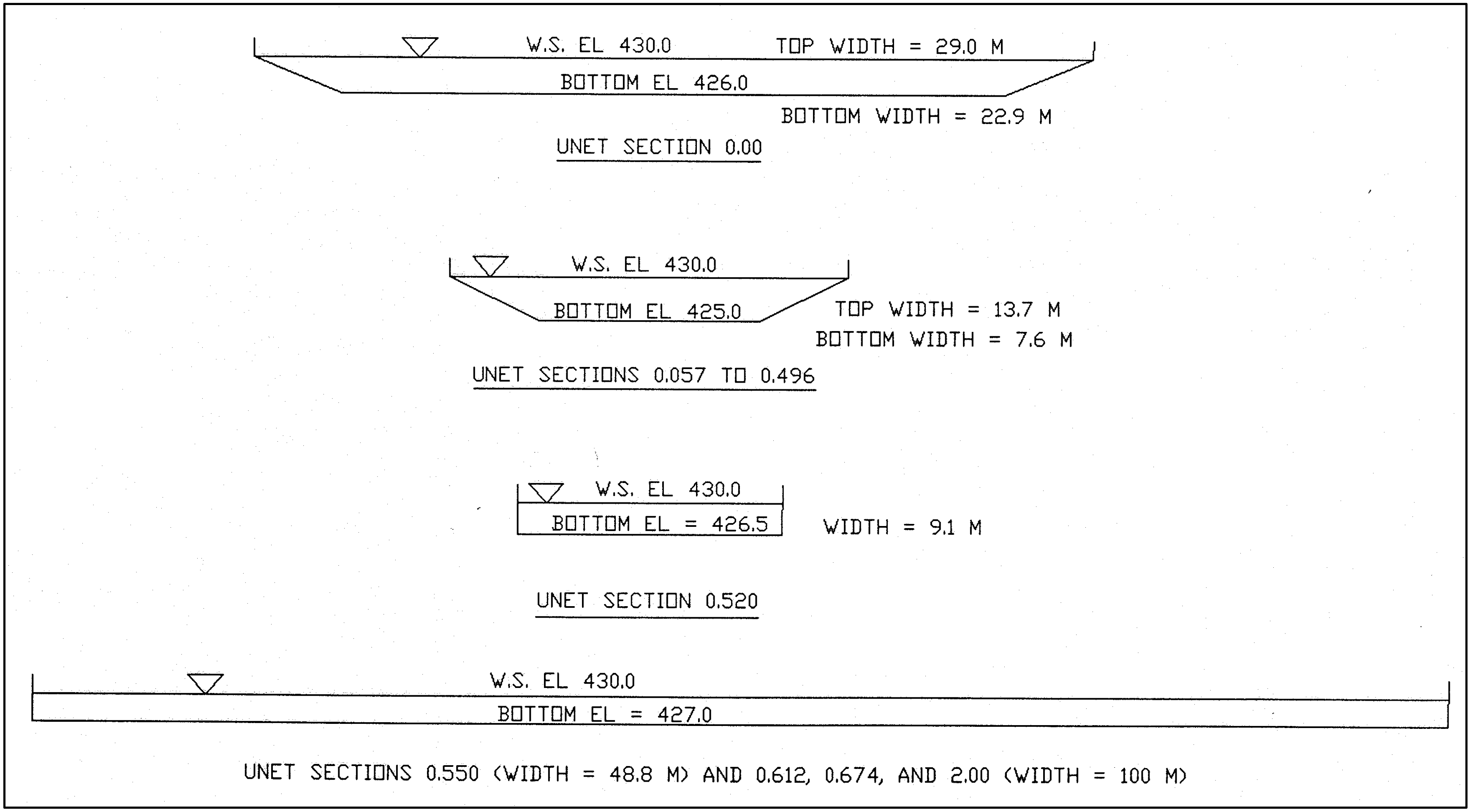


Figure 24. Cross sections used in UNET for Illinois Waterway

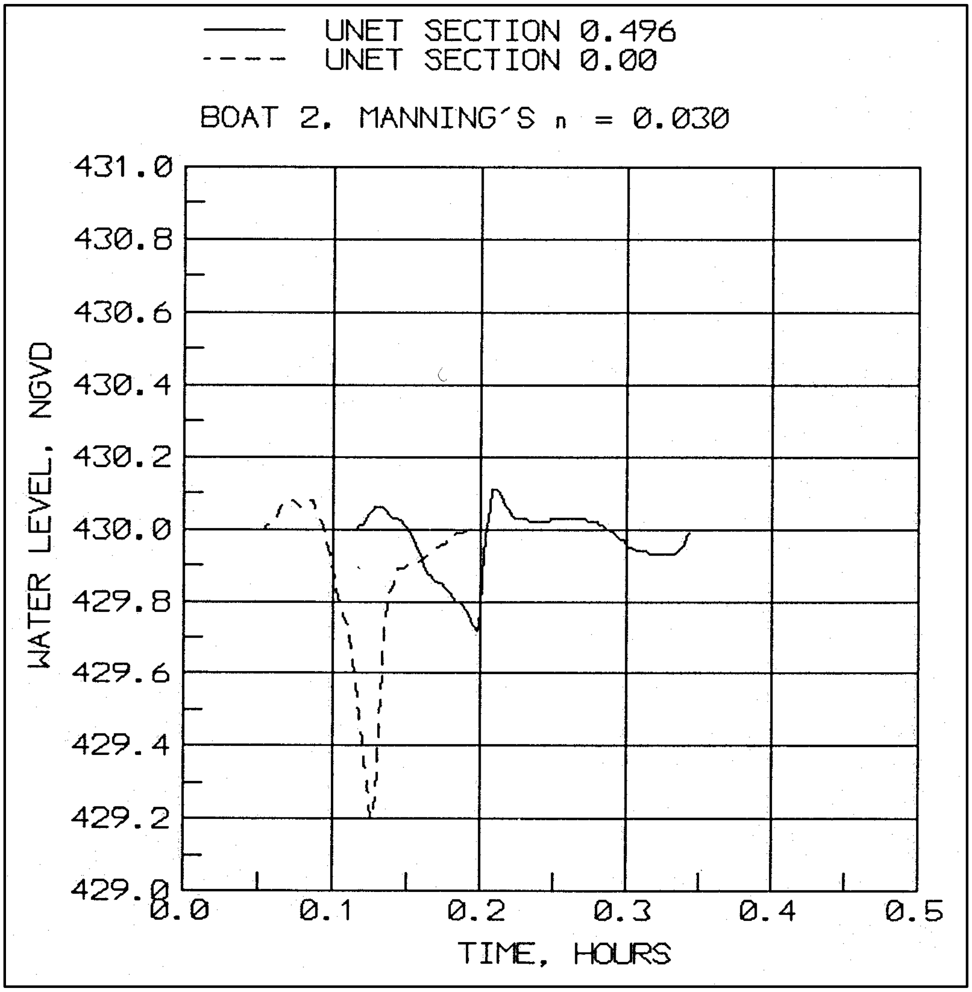


Figure 25. Computed water level, UNET model, Illinois Waterway Backwater Channel, dashed line is input downstream stage hydrograph

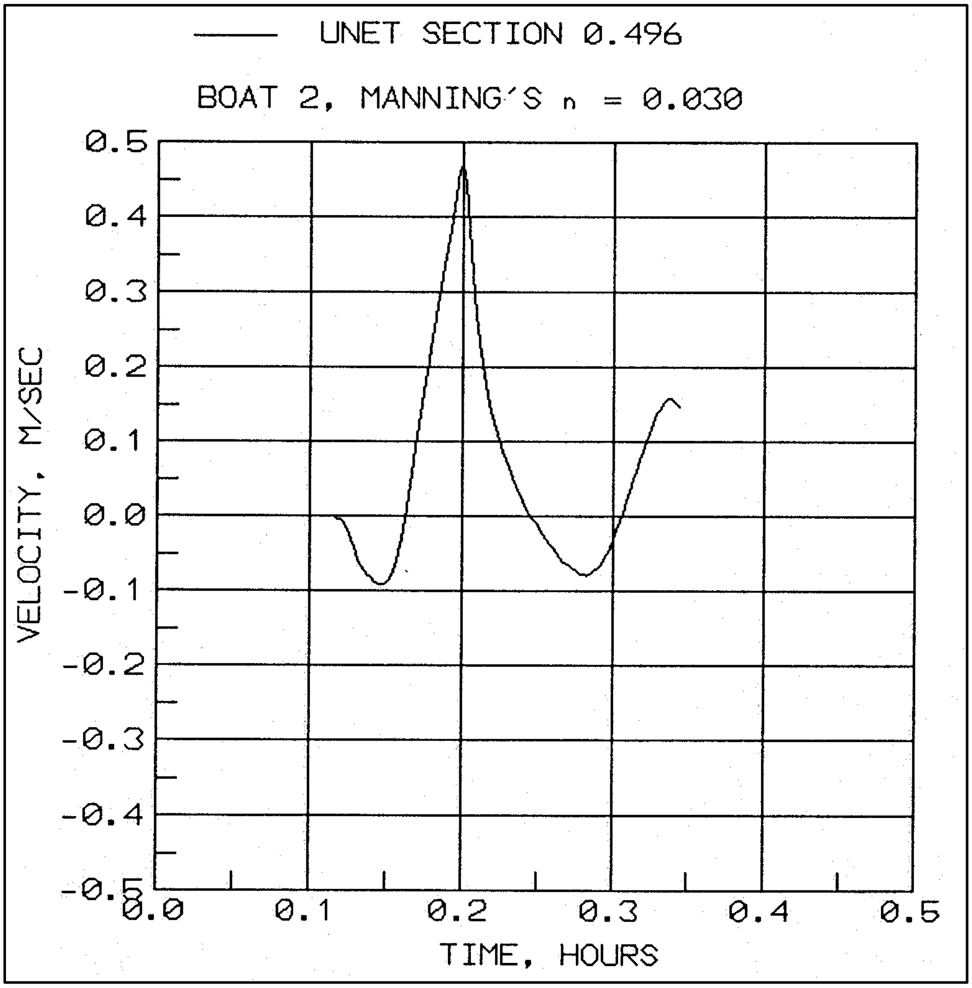


Figure 26. Computed velocity, UNET model, Illinois Waterway Backwater Channel

```
PR ON
T1 BACKWATER Experiment
T2 WORKSHOP
T3 HEC
*
XK   4.0     25                 0.25    0.02
*
UB
*
NC   .10     .10    .03
*
*   CROSS-SECTION 2.000
*
X1 2.000      6    9.99   338.1    7001    7001    7001
HY 2.000
GR  432.     0.0    432.    9.99  427.00     10.  427.00    338.   432.0  338.10
GR 432.0   400.0
*
*   CROSS-SECTION 0.674
*
X1 0.674      6    9.99   338.1     328     328     328
GR  432.     0.0    432.    9.99  427.00     10.  427.00    338.   432.0  338.10
GR 432.0   400.0
*
*
*
*   CROSS-SECTION 0.612
*
X1 0.612      0    9.99   338.1     328     328     328
*
*   CROSS-SECTION 0.550
*
X1 0.550      6    9.99   170.1     160     160     160
GR  432.     0.0    432.    9.99  427.00     10.  427.00    170.   432.0  170.10
GR 432.0   400.0
*
*   CROSS-SECTION 0.520 SHEET PILE STRUCTURE SECTION
*
X1 0.520      6    9.99   40.1     125     125     125
GR  432.     0.0    432.    9.99  426.50     10.  426.50     40.   432.0   40.10
GR 432.0   400.0
```

Figure 27. UNET Cross Section Input File for Illinois Waterway Backwater (Continued)

```
*
*   CROSS-SECTION 0.496 PROTOTYPE MEASUREMENT LOCATION
*
X1 0.496      8    9.99    55.1     400     400     400
HY 0.496
GR  432.     0.0    432.    9.99  430.00    10.  425.00    20.   425.0    45.0
GR 430.0    55.0    432.    55.1  432.00    100.

*
*   CROSS-SECTION 0.420
*
X1 0.420      0    9.99    55.1    745.    745.    745.
*
*   CROSS-SECTION 0.279
*
X1 0.279      0    9.99    55.1    475.    475.    475.
*
*   CROSS-SECTION 0.189
*
X1 0.189      0    9.99    55.1    700.    700.    700.
*
*   CROSS-SECTION 0.0568
*
X1 0.057      0    9.99    55.1    300.    300.    300.
*
*   CROSS-SECTION 0.0
*
X1  0.00      8    9.99   105.1     0.      0.      0.
HY 0.0
GR  432.     0.0    432.    9.99  430.00    10.  426.00    20.   426.0    95.0
GR 430.0   105.0    432.   105.1  432.00    200.
*
DB
*
EJ
```

Figure 27. (Concluded)

```
 WORKSHOP NO. 2
 BACKWATER
 UNET
*
*  Job control information
*
JOB CONTROL
 F  F  .13333367 .30 -6  F  0.6  T  T  -1  -30MIN
*
*
TIME INCREMENT
.0083333
*
INITIAL FLOW CONDITIONS
1 0.000
*
UPSTREAM FLOW HYDROGRAPH
1 21
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
0.000
*
```

Figure 28. UNET Input Data Description for Illinois Waterway Backwater (Continued)

```
DOWNSTREAM STAGE HYDROGRAPH
1 21
430
430
430.02
430.09
430.06
430.08
430.0
429.83
429.72
429.45
429.16
429.8
429.89
429.90
429.92
429.95
429.97
429.99
430.0
430.0
430.0
*
*
* Set maximum number of iterations for Newton Raphson iteration scheme
*
MXITER = 100
*
* Set stage tolerace to 0.00001 ft, for convergence criteria
*
ZTOL=0.00001
*
*
EJ
```

Figure 28. (Concluded)

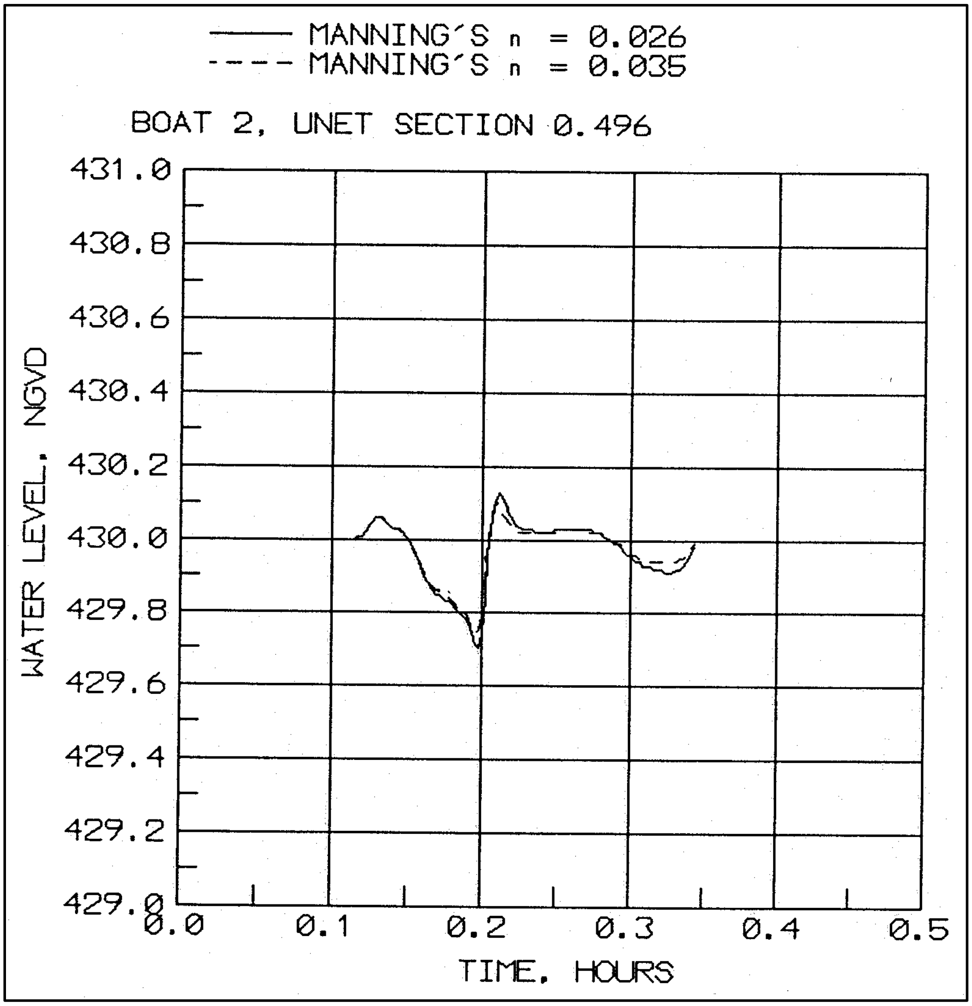


Figure 29. Computed water level, UNET model, Illinois Waterway Backwater Channel, Manning's n = 0.026 and 0.035

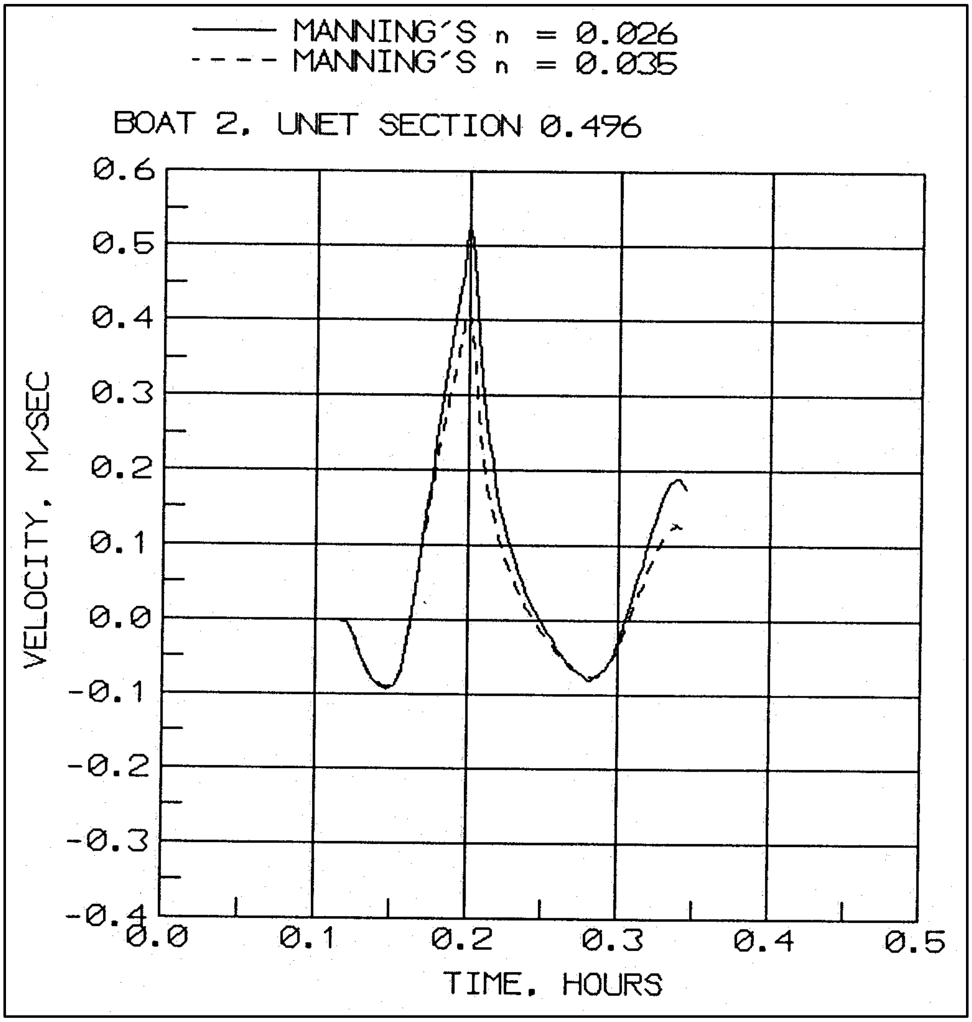


Figure 30. Computed velocity, UNET model, Illinois Waterway Backwater Channel, Manning's n = 0.026 and 0.035

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

Results of the one-dimensional unsteady flow model UNET were compared to measured water level and velocity changes in a backwater connected to a navigation channel. These changes resulted from passage of shallow-draft navigation in the navigation channel. Measurements used in the comparison were from a 1:30-scale physical model generic backwater and from an actual backwater of the Illinois Waterway. The UNET model covered only the backwater with the vessel-induced time-history of drawdown being the input boundary condition at the downstream end of the UNET model backwater. Based on the comparisons, the UNET model can predict the nagnitude and shape of the initial wave that travels up the backwater but subsequent reflections compare less facorably with the observed data. Water level predictions were generally better than velocity predictions, particularly in the Illinois Waterway backwater.

14. SUBJECT TERMS Backwaters Drawdown Environmental effects	Navigation Physical model	**15. NUMBER OF PAGES** 53 **16. PRICE CODE**

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