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Comparison of Surface Velocities in Micro-model and Prototype

Stephen T. Maynord*

*US Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Navigation Branch, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199; PH (601) 634-3284; FAX (601) 634-3218; email:Stephen.T.Maynord@erdc.usace.army.mil

Abstract

The micro-model is an extremely small-scale physical river model having a movable bed and varying discharge. The US Army Corps of Engineers is conducting an evaluation of the micro-model to determine its capabilities and limitations. As part of that evaluation, a comparison was made of surface velocities in model and prototype of a bend on the Mississippi River at Vicksburg, MS. The Vicksburg micro-model has a horizontal scale of 1:14400 and a vertical scale of 1:1200 for a distortion ratio of 12, which is typical of micro-models. Minimum channel width in the Vicksburg model was 5 cm and the entire model fits on a 1 m wide X 2 m long table. Velocity measurement in the micro-model, because of depths on the order of 1-2 cm, is practically limited to surface velocity. Surface velocities in the micro-model were measured using Particle Image Velocimetry (PIV) in the Vicksburg micro-model. Time-lapse photography and confetti are also used in the micro-model to determine surface current patterns. Comparable velocities were measured in the prototype bend of the river using recording Global Position System (GPS) units mounted on surface floats. Velocity magnitude from the model using PIV and prototype using GPS were compared at three cross-sections along the bend. Pathlines from both the PIV and confetti in the micro-model were compared to pathlines based on the GPS in the prototype.

Introduction

The micro-model is an extremely small-scale physical river model having a movable bed and varying discharge. Details of the model and its operation are provided in Gaines and Maynord (2001). Graf (1971) categorizes movable bed models (MBM) as either empirical (qualitative) or rational (semi-quantitative). While similarity laws are not followed closely in qualitative models, there are definite differences between the micro-model and most previous qualitative MBMs as follows:

1) Small size- The micro-model is one to two orders of magnitude smaller than most qualitative models. Minimum channel width is on the order of 3 cm with horizontal scale ratios of up to 1:20000.
2) Large Distortion- With a few exceptions, distortion ratios used in the micro-model are about twice that in most qualitative models. Micro-models commonly use distortions of 8-15.
3) Vertical scale and vertical datum determined as part of the calibration/verification rather than in model design. This is much easier in the micro-model than in other models because of the following item.
4) No correspondence of stage and discharge in micro-model and prototype- most qualitative models relate stage and discharge to a corresponding stage and discharge in the prototype.
5) Low stages run in micro-model- typical alluvial streams have dominant or channel forming discharges that are roughly at a bankfull stage. Maximum stages in the micro-model are about 2/3 of bankfull.
6) Verification of micro-model based on equilibrium bed- Previous qualitative models conduct verification by starting with a known bed configuration, running the subsequent hydrograph, and comparing the ending bed topography in model and prototype. The micro-model starts with an unmolded bed, runs a generic hydrograph for many repetitions until the bed reaches equilibrium, and compares the equilibrium bed to as many prototype hydrographic surveys as possible to see if the correct trends are reproduced.
7) The small size of the micro-model and the relatively heavy (heavy for plastic) bed material (SG=1.47) results in steep slopes in the micro-model. Water surface slopes of the few micro-models that have been measured are about 0.01 ft/ft. Steep slopes result in significant exaggeration of the Froude number.
8) The small model size and thus larger vertical scale ratio means that model sediment, when scaled to prototype dimensions using typical vertical scale, is 2-4 ft in diameter.
9) Similarity of friction is not present in the micro-model.
10) Micro-model uses porous dikes to solve exaggerated scour problems around dikes that occur in distorted models.

Based on these differences, this writer places the micro model in a third category in addition to Graf's two categories and defined as "totally empirical" because no similarity criteria are used in the micro-model.

The US Army Corps of Engineers is conducting an evaluation of the micro-model to determine its capabilities and limitations. One of the primary issues in this evaluation is whether the micro-model is a quantitative, qualitative, or simply a demonstration tool. The micro-model website states “Micro-modeling is an excellent engineering tool for evaluating and designing structures to improve navigation on the Mississippi River. It provides a means to optimize the design of structures such as dikes, bendway weirs and chevrons to greatly improve navigation conditions, while improving the environment and establishing biological diversity.” The statements about optimizing and design and the use for navigation studies suggest the micro-model is being used quantitatively. For the purpose of this evaluation, uses of MBMs are broken into the following four categories:

1) Demonstration, education, and communication- the micro-model has been widely successful in demonstration, education, and communication based on comments by the three Corps of Engineers Districts using the micro-model. The micro-model has been used to demonstrate to resource agencies the concepts used in river engineering including the general effects of structures placed in the river.
2) River Engineering- Qualitative- Almost every MBM is expected to be able to provide qualitative river engineering studies. In this type of study, the model only needs to be good enough to compare alternatives and show the correct prototype trends in the model. Stated otherwise, a qualitative river engineering model is often used to serve as a screening tool. A screening tool as defined herein is a tool to separate likely solutions from unlikely solutions. A screening tool is neither a tool for optimizing nor for design.
3) River Engineering- Quantitative- Examples of quantitative river engineering movable-bed studies are: a) determining dike or weir locations, lengths, heights, angles, and number; (b) estimating quantities for dredging; and (c) providing bed topography for another model, either physical or numerical. This category specifically excludes quantitative river engineering near structures, which is covered in the next category. Quantitative river engineering studies are a significant step beyond qualitative river engineering studies and can be used for optimizing and design.
4) Navigability/ Hydraulic Structures/ Flow Patterns- This use of a MBM involves studies such as navigation through and approaching a lock, bridge, or river confluence. It also includes flow details such as use of velocity measurements or confetti streaks to make conclusions about safe navigation or determination of changes in water surface elevations. The difference between quantitative river engineering and Navigability/Hydraulic Structure/Flow Details is less about the capabilities of the model and more about the consequences of the model being wrong. If a model wrongly predicts the dike characteristics of location, length, height, angle, etc in a channel away from hydraulic structures, the consequence is limited to the need for more river engineering. These wrong predictions rarely create an issue of safety. However, around structures such as locks, bridges, and confluences where safe navigation is essential, the consequence of wrong model predictions can be costly in terms of lives and dollars.

The first objective of this conference paper is to present a method for comparing velocity in micro-model and prototype. The second objective is to present results of such a comparison from the Vicksburg Front micro-model and prototype in order to address the capabilities of the micro-model in reproducing flow patterns. These results and other results of the evaluation will be used to determine if the micro-model can be used for the third and fourth categories given above.

Description of Vicksburg Front Micro-model

The Vicksburg Front micro-model was conducted to evaluate proposed channel improvement design alternatives and is shown in Figure 1. From Davinroy, Gordon, Rhoads, and Abbott (2000), “The Mississippi River along Vicksburg Front can be difficult to navigate under certain conditions, primarily for downbound traffic. An extremely sharp bend exists near the mouth of the Yazoo Diversion Canal, located between Miles 438 and 436. The proximity of the bend is located just upstream of the Railroad and Highway 80 and Interstate 20 bridge crossings at Mile 435.8. At the apex of the bend, the navigation channel becomes extremely narrow. The point of the adjacent middle bar off the right descending bank extends into the channel, making it difficult for a downbound tow to drive this bend at low to medium stage conditions”.

The Vicksburg micro-model had a horizontal scale ratio of 1:14400 and a vertical scale ratio of 1:1200, for a distortion of 12, which is typical of micro-models. Calibration of the model was based on the 1994 and 1997 prototype data. Concerning the base test (also serves as the calibration), Davinroy, Gordon, Rhoads, and Abbott (2000) note “During the calibration of the model, after a long series of successive hydrographs, there was a tendency for the side channel at Delta Landing to start to fill in with sediment and the middle bar at Mile 437 to develop into one dominant point bar. When this tendency was first observed in the model, successive hydrographs were run until the side channel was completely filled in with sediment. The sediment source was from the adjacent main channel during the peak flow of each hydrograph. This trend occurred after the 20th hydrograph, or after one hour of continous, successive flow hydrographs (each hydrograph was 3 minutes in duration). The side channel completely filled with sediment by the 28th hydrograph, or 84 minutes of continuos flow simulation. The side channel was re-formed in the model after this occurred to reflect the conditions of the river and the test was repeated. This tendency consistently occurred after an hour of flow simulation. Since this trend was not observed in the river, flow conditions for the base test and all alternative tests was established as 10 hydrographs per test, or 30 minutes of continuos flow simulation. Under these flow conditions, no filling of the side channel was observed."

Figure 2 shows pathlines from confetti streaks at high flow in the micro-model base test. Pathline is used for the various types of float visualization in this paper instead of streamline because most bends exhibit some degree of unsteadiness. Although discharges and water surface elevations are not given in the micro-model report, typical model stages at high flow are about +20 ft LWRP which is 6.1 m (20ft) above the Low Water Reference Plane (LWRP) which is the datum based on the water level which is exceeded 97% of the time. Bankfull stage along this portion of the Mississippi River is on the order of +9.1 m (30 ft) to +10.7 m (35 ft) LWRP.

Particle Image Velocimetry (PIV) in Vicksburg Micro-model
Subsequent to completion of the Vicksburg micro-model and as part of this evaluation, the model was rerun using PIV to determine surface velocities in the micro-model. The PIV techniques are described in Gaines (2002). Water level data collected during the PIV measurements averaged +5.95 m (19.5 ft) LWRP, which is in agreement with previous micro-model experience. Figures 3 and 4 show the pathlines and velocity vectors at high flow from the Vicksburg model PIV. Figure 5 shows both PIV and confetti pathlines from the micro-model and similar trends are shown. Mississippi River discharge corresponding to +5.95 m LWRP is about 17000 cms (600000 cfs) and average channel velocity is about 1.5 m/sec.

Prototype Surface Velocity using Global Positioning System (GPS) Receivers
The prototype surface flow visualization was conducted using floats with recording GPS units placed on the floats (Figure 6). The floats were 0.3-m diameter buoys with about 0.6-m long vanes suspended in the water which prevented significant influence of wind. The float shown in Figure 6 is the same design as used in the Vicksburg tests but has 0.9-m long vanes. The data was taken during 11-15 May 2000. Stage on the Vicksburg gage during testing was a mid-bank flow of 5.7-m (18.8-ft) LWRP on 11 May, 5.5-m (18.2-ft) LWRP on 12 May, 5.2-m (17.2-ft) LWRP on 13 May, and 4.9-m (16.2-ft) LWRP on 15 May. The majority of the measurements were made on 12 and 13 May during which average discharge was about 14170 cms (500000 cfs) and average channel velocity was about 1.3 m/sec. Flow out of the Yazoo River was low during these measurements.

Comparison of Surface Velocity at Cross Sections from GPS and PIV
Velocity data were taken from both the GPS field data and the PIV model data and plotted in Figures 7 to 9 for river miles 434.5, 437.5, and 439.5, respectively. The model velocities were scaled using the square root of the vertical scale ratio, which is the ratio for converting velocity in a Froude scale distorted model. Cross sections are plotted in Figures 10-12 for the micro-model base test, the 1994 and 1997 prototype used in the micro-model verification, and the 2000 prototype present when the GPS float study was conducted. The velocity across the cross-section has a greater magnitude in the model at all three river miles that is expected because the model discharge must be exaggerated to provide acceptable bed movement. Comments on each cross section are as follows: **River Mile 434.5-** The micro-model base test cross section at RM 434.5 is significantly higher than the bed in all three prototype surveys (Figure 10) and has the thalweg against the left descending bank whereas the prototypes have the thalweg about ¼-1/3 of the channel width away from the left bank. The velocity across the cross section (Figure 7) was different in micro-model and prototype GPS but was consistent with the differences in cross section shape with maximum in the micro-model near the left bank and maximum in the prototype about a third of the way from the left bank. **River Mile 437.5-** The micro-model base test cross section compared well with the 1994 and 1997 prototype surveys used in the verification (Figure 11). Due to the sedimentation problems in the base test on the right bank, the similarity of the side channel on the right bank suggests that the survey was taken shortly after the model channel was remolded in the micro-model. The most significant difference between the 2000 prototype survey and the

micro-model or 1994 and 1997 prototype surveys is the height of the middle bar which is about 3 m (10 ft) lower than the micro-model. The velocity plot at RM 437.5 (Figure 8) shows differences between micro-model and prototype. The GPS prototype data show a lesser velocity over the shallow area on the submerged middle bar and higher velocity in the deeper side channels. The PIV velocity from the micro-model shows about the same ratio of velocity over the middle bar to velocity on the left bank as the prototype GPS velocity. However, micro-model velocity ratio of left bank/right bank velocity was far greater than the prototype. **River Mile 439.5-** The micro-model base test cross section compared well with the 1994, 1997, and 2000 prototype surveys left of the island (Figure 12) except for the shallow area approaching the island. On the right side of the island, the micro-model was shallower than all three prototype surveys. The velocity plot in Figure 9 only covers the area to the left of the island. As at RM 437.5, flow at RM 439.5 is concentrated more on the left bank in the micro-model than in the prototype which likely explains the tendency for shoaling in the model along the right descending bank at Mile 437 that was not present in the prototype.

Comparison of Surface Velocity along Bend from GPS, PIV, and Confetti
The tracks from the GPS float measurements are shown on Figure 13 along with the PIV measurements. The confetti streaks were plotted along with the GPS tracks in Figure 14. Both the confetti and the PIV tracks from the model show the same tendency compared to the prototype data. At the beginning of the bend, the prototype currents begin deflecting to pass around the bend well before the flow does in the micro-model. About 1-2 channel widths upstream of the I-20 Bridge, the prototype GPS floats are crossing toward the left descending bank whereas the confetti and PIV in the micro-model are aligned with the banklines. Both model PIV and model confetti differ significantly from the prototype GPS data. Some of these differences, but not most, can be attributed to the lower middle bar height present during the 2000 prototype GPS tests. The differences are primarily the result of the skewed velocity distribution in the model shown at RM 439.5.

Analysis of Data and Summary
Comparison of the velocities across the cross-section in Figures 7 to 9 and pathlines in Figures 13 and 14 show differences between the micro-model and prototype. The differences in pathlines are most pronounced at Mile 437 which is also the location of incorrect shoaling in the model noted in the Davinroy, Gordon, Rhoads, and Abbott (2000) report. Differences in flow patterns are also significant at the I-20 Bridge. At the two upstream sections (RM 437.5 and 439.5), model flow is more concentrated on the left descending bank than in the prototype. Of the differences between micro-model and qualitative MBM in the Introduction, the large distortion and Froude number exaggeration are model parameters most closely tied to correct simulation of flow distribution. Zimmermann and Kennedy (1978) studied flow in bends of having a movable bed and concluded that distortion should be limited to 2 or 3 compared to the value of 12 used in the Vicksburg Front micro-model. Other factors, such as lack of similarity of friction and lack of correspondence of stage and discharge are also factors important in flow distribution. The comparison of velocity presented in this paper show that flow distribution in the Vicksburg Front micro-model is not similar to the prototype and likely because of these model distortions.

Acknowledgements
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Zimmermann, C. and Kennedy, J.F. 1978. "Transverse bed slopes in curved alluvial streams", ASCE Journal of the Hydraulics Division, Vol 104, No. HY1, January, pp 33-48.

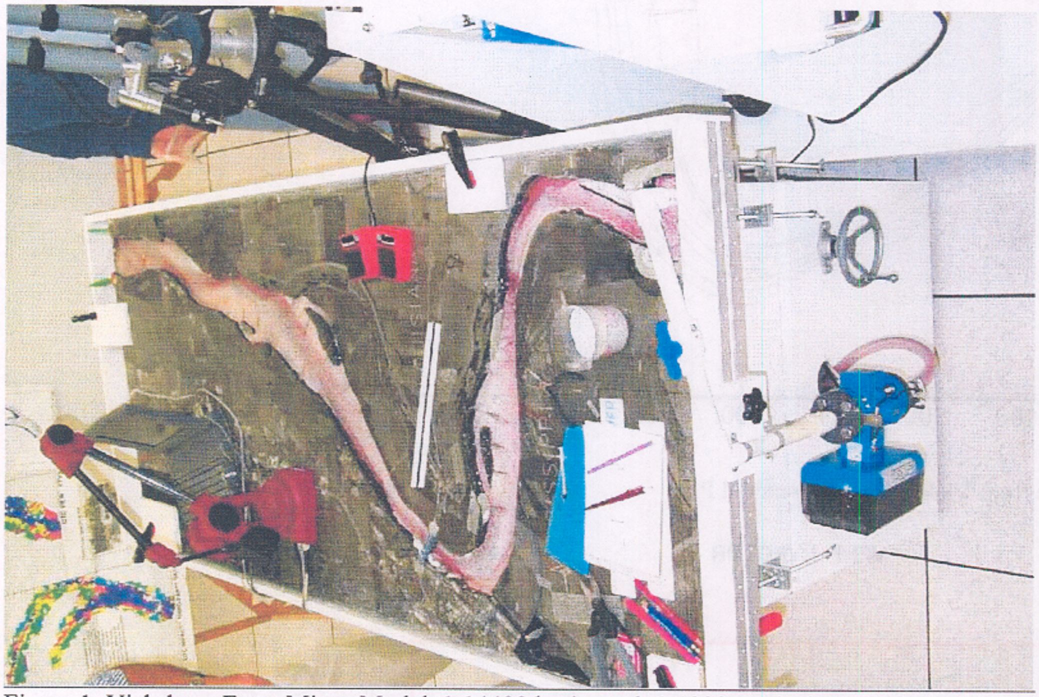

Figure 1. Vicksburg Front Micro-Model, 1:14400 horizontal, 1:1200 vertical.

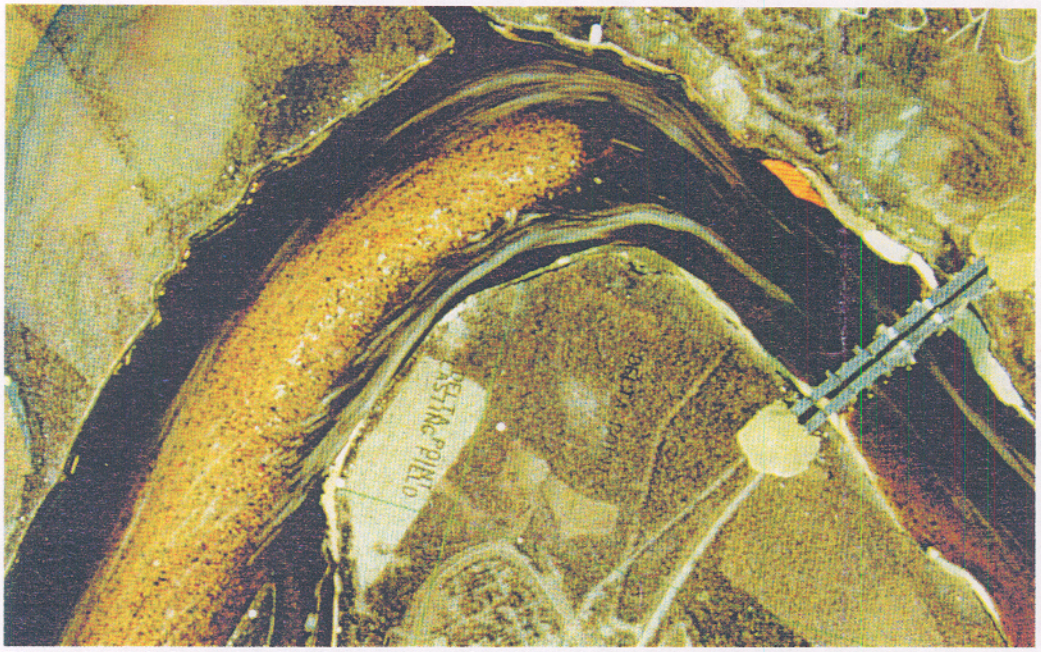

Figure 2. High flow visualization using confetti in Vicksburg Micro-model.

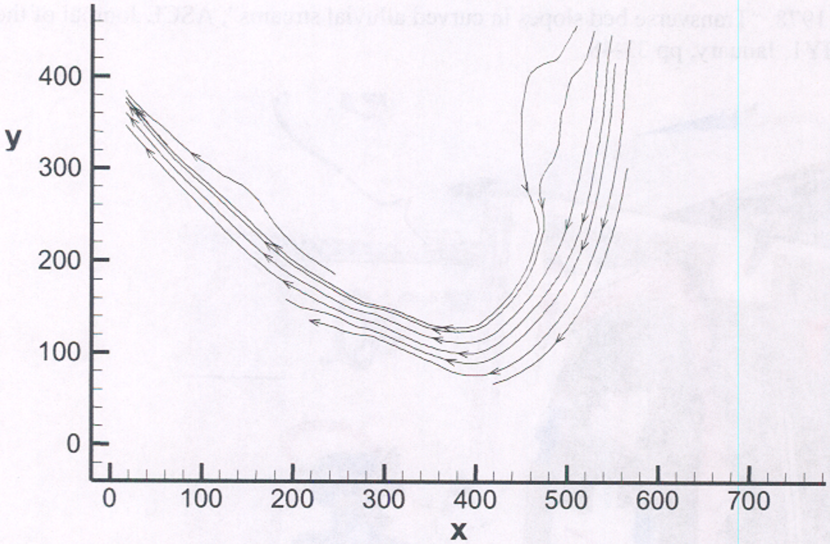

Figure 3. Pathlines from Vicksburg micro-model PIV.

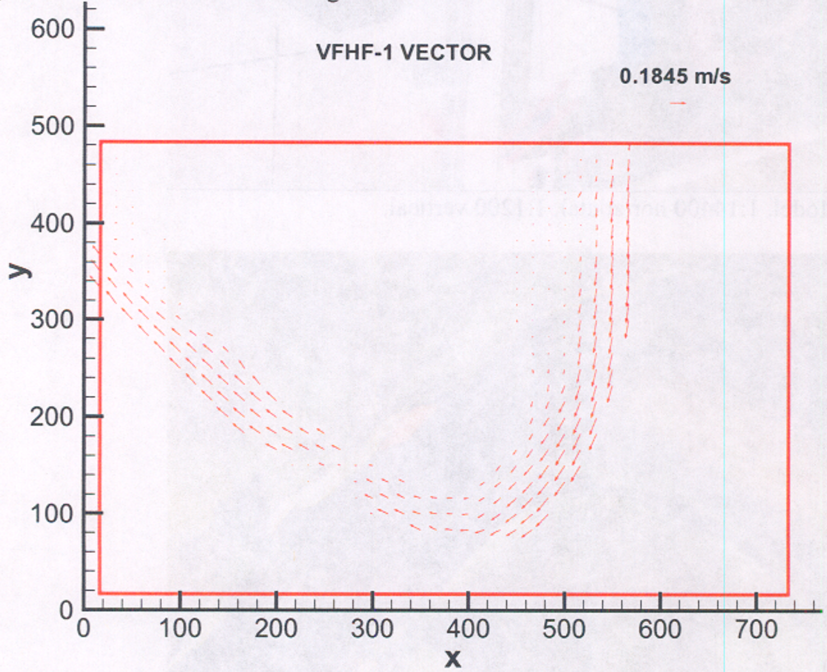

Figure 4. Velocity vectors from Vicksburg micro-model PIV.

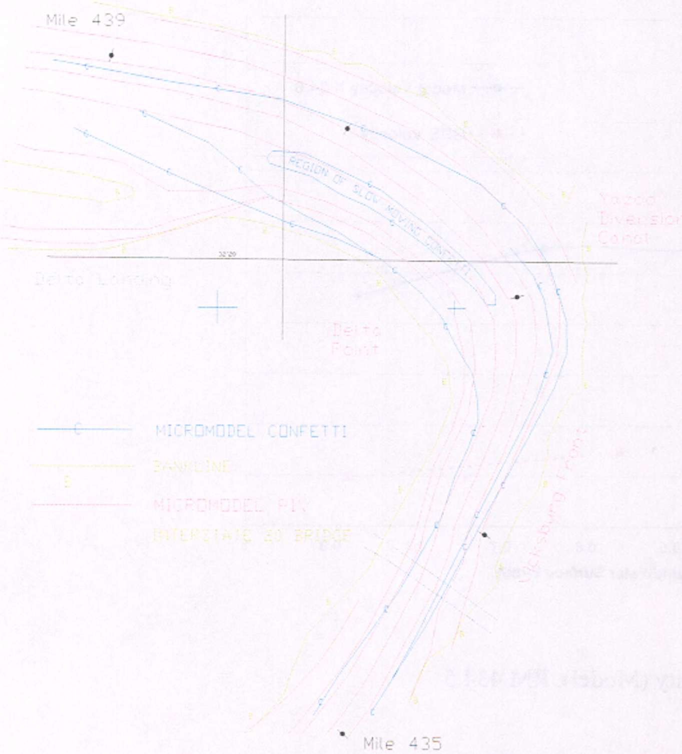

Figure 5. Comparison of PIV and Confetti Streaks in Vicksburg Micro-model

Figure 6. Float used in prototype data collection using GPS.

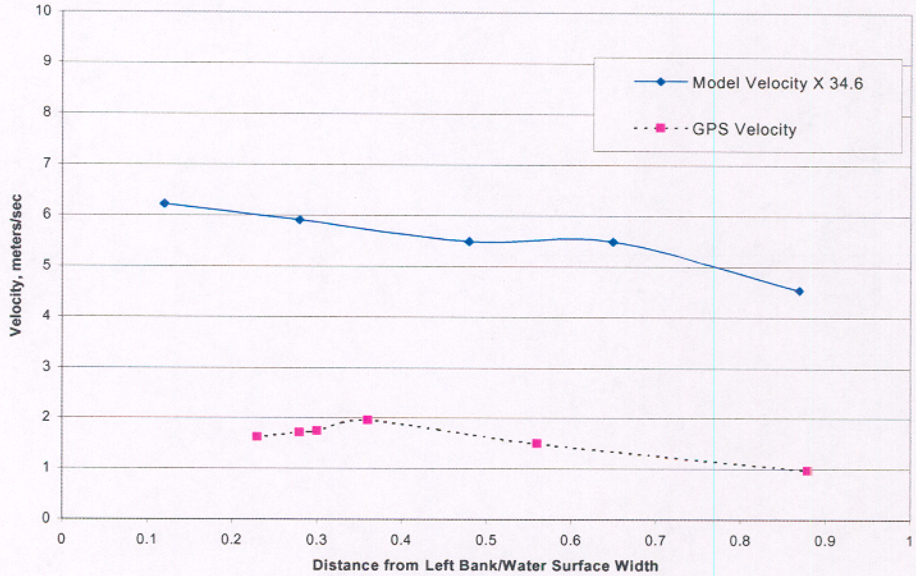

Figure 7. GPS Velocity (Field) versus PIV Velocity (Model), RM 434.5

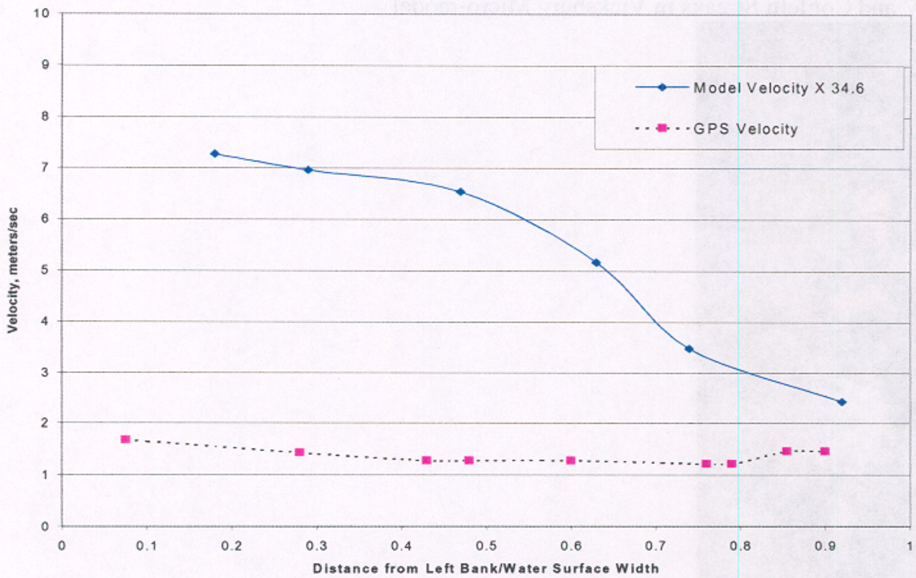

Figure 8. GPS Velocity (Field) versus PIV Velocity (Model) River Mile 437.5.

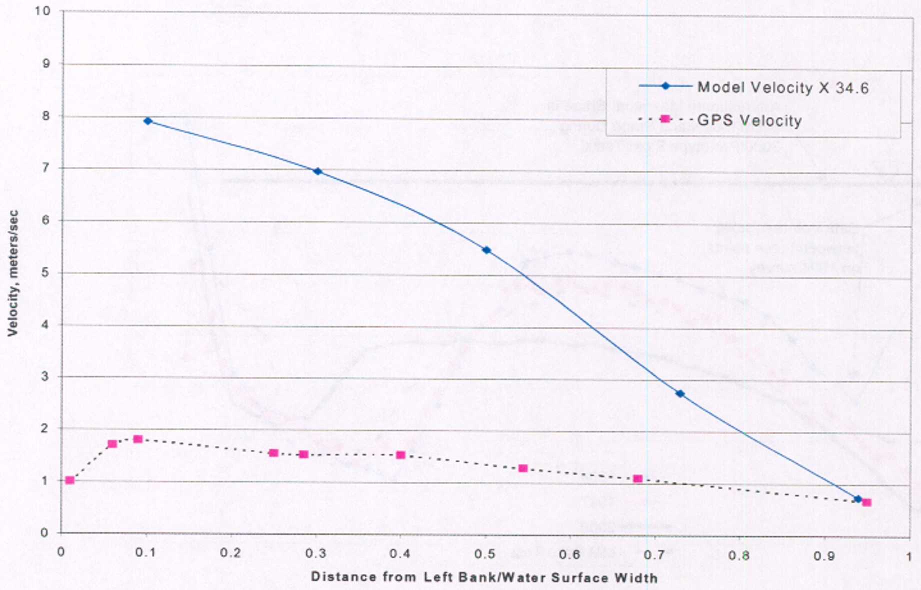

Figure 9. GPS Velocity (Field) versus PIV Velocity (Model), River Mile 439.5

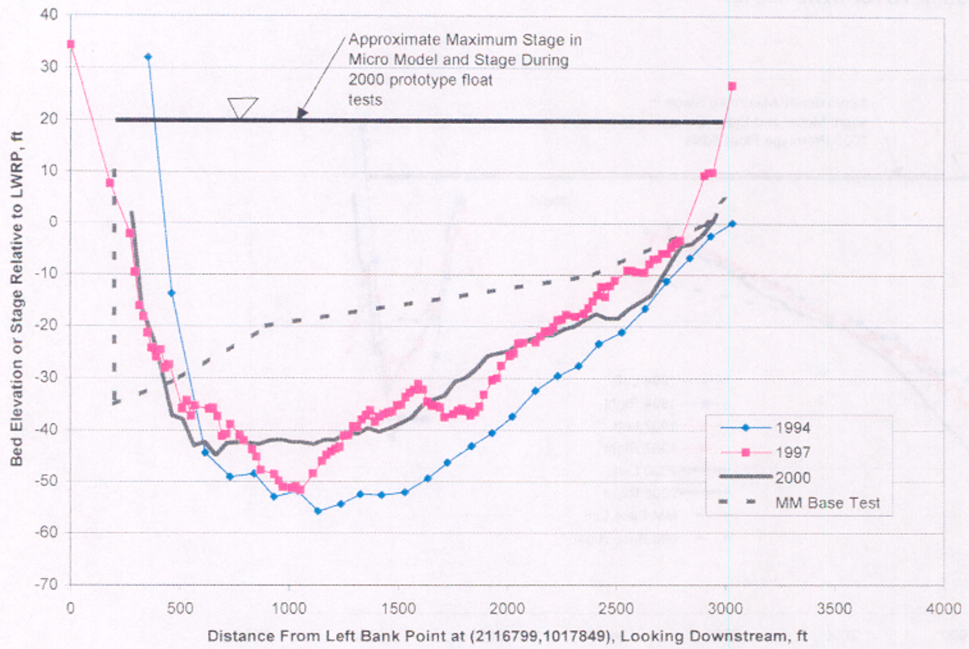

Figure 10. Cross Section at River Mile 434.5.

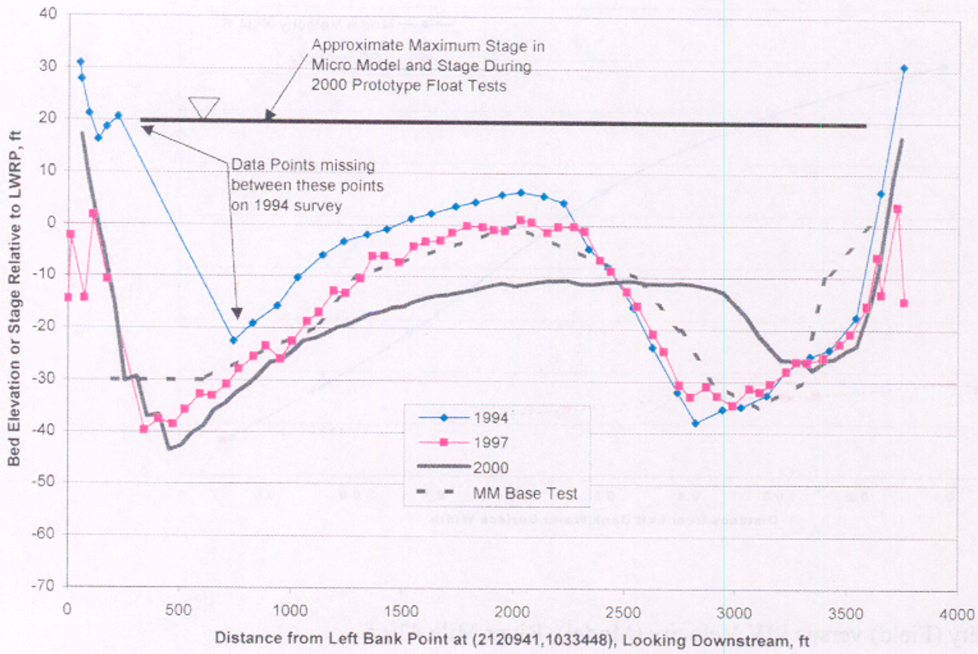

Figure 11. Cross Section at River Mile 437.5.

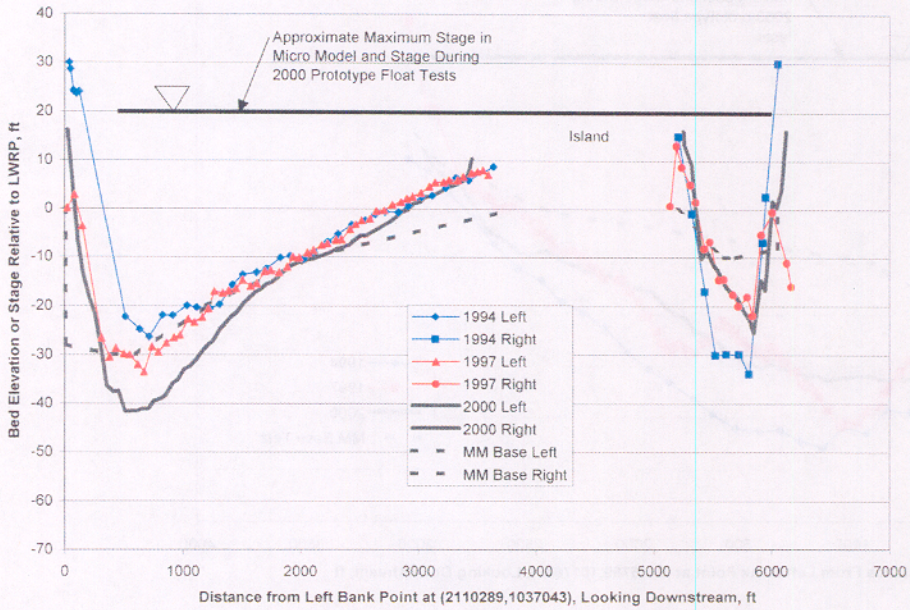

Figure 12. Cross Section at River Mile 439.5.

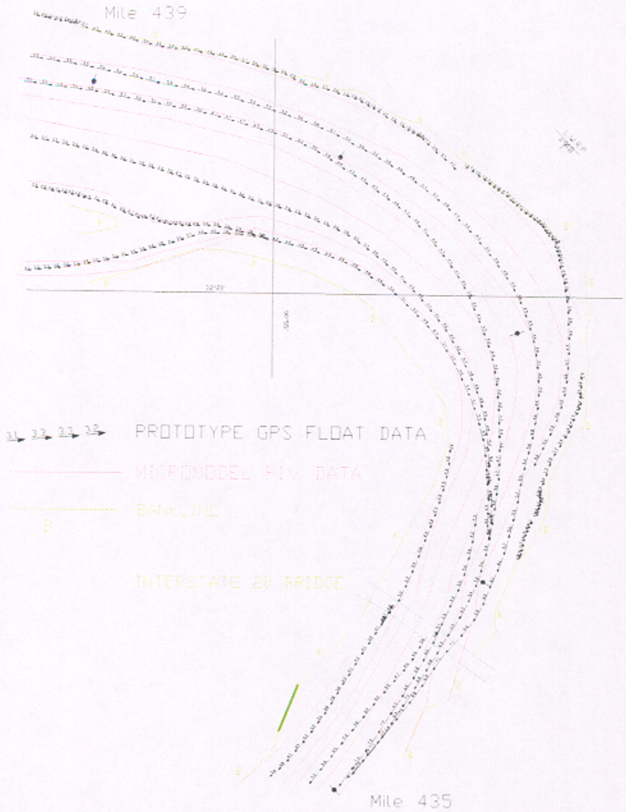

Figure 13. Comparison of PIV in Micro-model and GPS in Prototype

Figure 14.GPS/confetti