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JOINT VENTURE TEAM

EVALUATION REPORT

EVALUATION REPORT
PART I
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CEMVM-ED-H

25 SEP 2002

MEMORANDUM FOR
David C. Gordon, CEMVS-ED-HP
Stephen T. Maynord, CEERD-HC-N

SUBJECT: [redacted] of Micromodel Evaluation Report entitled: "Micromodel Capabilities and Expanded Applications," Micromodel Joint Venture Evaluation

1. Copies of the subject rough, preliminary, working draft report are provided for [redacted] The use of several qualifiers preceding "draft" intends to emphasize the very preliminary nature of the document as of this date. The document continues to be a "work-in-progress" and hard copy is provided only to facilitate your participation in the final editing process. The hard copy is also provided for you to update your respective Branch Chiefs (Mr. Claude Strauser and Mr. Tom Pokrefke) on the report status prior to their meeting in early October.

2. The intent of providing the hard copy of this incomplete draft is to allow each of us to view the document in its entirety. A secondary intent is to provide some form of evaluation document to the primary team members prior to the 30 September 2002 completion date set for the final draft. Although the team failed to produce a final draft prior to the 30 September 2002 deadline, the subject report draft "as-is" represents our best efforts to date.

3. [redacted] The document reflects approximately 200+ pages of comments, replies, and discussions. As you will no doubt realize, the report needs some editing. At present there is too much emphasis on the case study reporting (over 2/3 of the document). What needs to happen is to have each of the three primary team members put down their opinions in writing -- preferably in the form of short, one or two paragraph statements with justification(s) of how that opinion is supported. Until there are three written independent opinions, not rebuttals or comments, the document can't be completed "as-is." Having the three, individual written opinions will allow the team to focus on what is required to produce a final report.

4. I can be reached at (901) 544-3392 should you wish to discuss the report at any time.

Andy Gaines
CEMVM-ED-H

MICROMODEL CAPABILITIES AND EXPANDED APPLICATIONS

A Joint Venture Evaluation

For:

The US Army Corps of Engineers:

Mississippi Valley Division

Memphis District

St. Louis District

Engineer Research and Development Center

Preliminary Draft

By:

Roger A. Gaines, CEMVM

David C. Gordon, CEMVS

Stephen T. Maynord, ERDC

September 2002

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NOMENCLATURE

Symbol	Description
a	Acceleration; a constant
A	Area; dependent variable
A_0	Cross-sectional Area at elevation 0.0 Low Water Reference Plane
B	Channel Width (see also W), Width of structure (e.g., a pier); function
C	Chézy resistance coefficient
C'	Resistance coefficient
C_D	Drag coefficient; discharge coefficient
C_f	Friction coefficient, $(u_*/u)^2$
D	Particle diameter
D_S	Depth of local scour
D_{50}	Median particle diameter
D_*	Dimensionless particle number
e	Porosity
Fr	Froude number
f	Darcy-Weisbach resistance coefficient
f_b	Darcy-Weisbach resistance coefficient corrected for flume side-wall effects
G	Geometric distortion, x_r/y_r
g	Gravitational acceleration
g_S	Mass rate of sediment transport per unit width of flow
G_S	Total mass rate of sediment transport
H	Hydraulic Depth, Area divided by Top Width
H_L	Head loss
k_s	Roughness height
L	Length; flow length; wave length
L_N	Lohtin Number
m	Number of fundamental dimensions
M	Mass; a non-dimensional parameter
n	Kutter resistance coefficient; Number of variables

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N	A constant
P	Wetted perimeter
Q	Discharge; water discharge
q	Discharge per unit width of flow
q_B	Volumetric bed load transport rate per unit width of flow
q_S	Volumetric rate of sediment transport per unit width of flow
q_T	Volumetric total sediment transport rate per unit width of flow
R_h	Hydraulic radius
Re	Reynolds number
Re_*	Particle Reynolds number
R_p	Modified particle Reynolds number
R	number of dimensionless Π parameters
r_c	Radius
S	Slope
S_E	Energy Slope
S_f	Slope of energy grade line, friction slope
S_0	Bed slope
T	Time; Sedimentation Time; Temperature
TP	Thalweg Position
t	Hydraulic time
U	Streamwise flow velocity
u	Local velocity in x direction
u_*	Shear velocity
u_{*c}	Critical value of u_* associated with incipient motion of bed particles
v	Local velocity in *y* direction
∀	Volume
W	Width
We	Weber number
w	Local velocity in z direction; fall velocity of a sediment particle
x"	Independent Variable
x	Horizontal scale

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Y	Flow depth; vertical scale; water depth
y	Depth
y''	Dependent Variable
z	Distance
β_1	Bogardi regime coefficient
β	Roughness distortion factor
α	Angle
Γ	Flow circulation
γ	Unit weight of water
γ_s	Submerged unit weight of sediments
Δ	Ratio of Submerged Particle Density to Fluid Density $\left(\frac{\rho_s - \rho}{\rho}\right)$, an Increment
δ	Bedform height, boundary layer thickness
τ^*	Shields parameter
τ^*_c	Critical value of Shields parameter
μ	Dynamic viscosity
μ_f	Ripple Factor
υ	Kinematic viscosity
Π	Dimensionless pi parameter
π	Pi (3.1415)
ρ	Density
ρ_s	Density of sediment particles
σ	Stress; surface tension strength of water
τ	Shear stress
φ	Functional relationship among non-dimensional parameters
ω	Particle fall velocity; angular velocity
ζ	Channel Sinuosity

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SUBSCRIPTS

b	Value at solid boundary
p	Prototype
m	Model
r	Ratio
0	Value at the boundary, Value at Elevation of 0.0 (Low Water Reference Plane)
c	Corrected Value

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1. INTRODUCTION

1.1. RIVER ENGINEERING - Navigation Design, Past and Present

The advent of the steamboat in the early 19th century brought about a dramatic change in travel and commerce along our nation's inland waterways. With increased traffic, safety on the river became a vital concern for the crews, passengers, and cargo aboard the vessels (Figure 1-1). Early river engineering design was employed on major rivers such as the Mississippi and Missouri Rivers to ensure a safer, more dependable and deeper navigation channel. River engineering design involved the layout and construction of dike and revetment works, including willow mattress construction for the stabilization of eroding banks in bends, and wooden pile dike construction, for the management of sediment within the channel.

Figure 1-1 Early Steamboat Accident on the Mississippi River.

These early designs (Figure 1-2) relied heavily upon intuition, experience, and prior European construction. Learning from the mistakes and successes of this early American river engineering, an historical knowledge base was established. The knowledge base did not contain equations or complex design procedures. Instead, it involved real world

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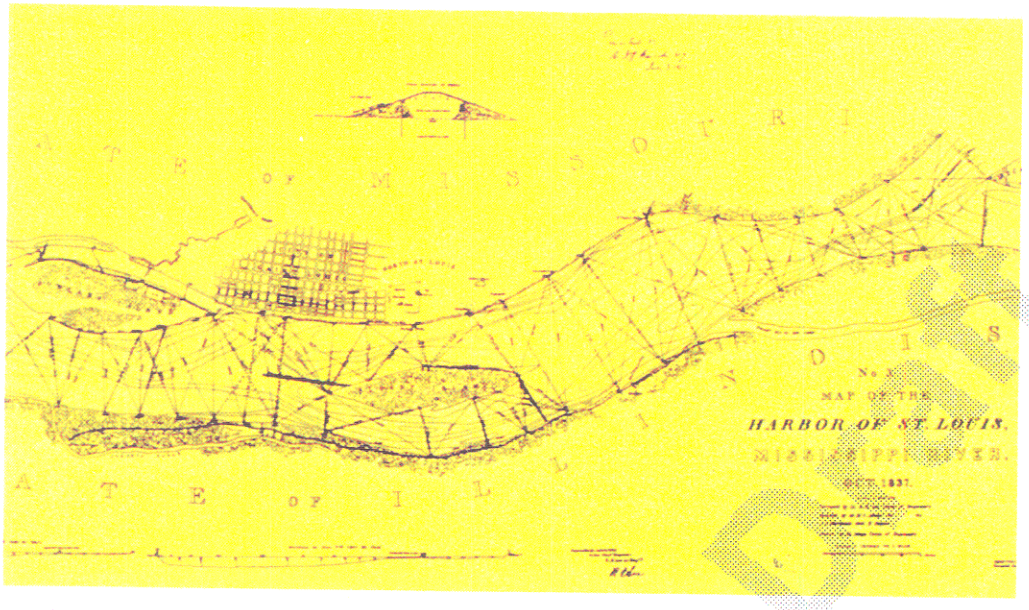

Figure 1-2 Early River Engineering Navigation Design on the Mississippi River, St. Louis Harbor, Robert E. Lee Map, Circa 1837.

results of both successful designs and failures in the actual river. A desire to work with the forces of nature rather than contend against them was always the underlying premise for design.

The problems that river engineers have dealt with in the past continue today. Frequent dredging, required in river reaches that repetitively shoal with sediment, is costly. River engineers are responsible for seeking design solutions that attempt to minimize dredging in an environmentally sensitive manner. River engineers have also been responsible for solving navigation alignment problems, such as in reaches upstream of bridges, harbors, locks and dams, etc. There are numerous bridge crossings, harbor entrances, and locks and dams on the rivers of the Inland Waterway Navigation System in the U.S. Normally, the river engineer's task has been to ensure a safe alignment or approach of the navigation channels through these types of structures.

Today, things have not radically changed from the way early river engineering was performed. Past historical knowledge combined with intuition and experience is still at the forefront of design (Figure 1-3). However, what has changed is the amount, type, and detail of river data now available for the engineer's use. Within the last decade, new technologies such as the multi-beam hydrographic survey system for the collection of

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Figure 1-3 Typical Modern Day Dike Design on the Mississippi River.

high-resolution bathymetry, and the acoustic Doppler systems for the measurement of flow, have greatly advanced the engineer's ability to "read" the river.

A more descriptive account of modern day river engineering can be taken from a navigation hydraulics workshop held at the Waterways Experiment Station in Vicksburg, Mississippi in 1989. River engineers from all over the country who were experienced in navigation design attended this conference. Individual projects on major rivers were rigorously discussed. These rivers included the Mississippi, Missouri, Arkansas, White, Columbia, and Ohio Rivers, to name a few.

What was clear from the onset of this workshop was that the designs being employed and constructed on the rivers of the U.S. were solely dependent upon each engineer's knowledge, experience, judgment, and familiarity with the prototype. In all cases, whatever the problem, time and time again the engineer relied heavily upon past historical knowledge and as much prototype information as possible. The prototype data was in the form of hydrographic surveys, photographs, conversations with pilots and landowners, field inspection, etc. Construction decisions were made from a summation of all of the above.

The basic river engineering procedure summarized at the conference involved:

1. Studying and understanding the problem at hand
2. Examining time and budget

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3. Collecting past and present prototype data
4. Formulating a list of conceptual design alternative plans
5. Presenting these plans with various interest groups, including the environmental, navigation, and the public community
6. Choosing a design that is the most acceptable with all of the above groups
7. Preparing plans and specs
8. Collecting pre-construction data
9. Performing field inspection of construction
10. Collecting post-construction data
11. Evaluating the reaction of the river after construction through data monitoring
12. Adding or modifying a design if required

To date numerical models have not provided the river engineer with predictions of the general three-dimensional bed response of the river. This is in part due to the complex nature of the three-dimensional bed response and a lack of equations to define that response. The river boundary is ever changing in dimensional shape due to the continual movement of water and sediment. Unlike other engineering fields such as highway or structural engineering, where static forces are more the norm and established scientific-based design procedures have been developed to deal with these forces, there is a lack of scientific design guidance within the field of river engineering. Thus, the river engineer has had no choice but to rely on following the basic procedure as described above for achieving design success.

However, in some cases, large physical movable bed models have been used to assist the engineer in the design process. In most other cases, they were not. The 1989 workshop underscored two common problems the engineer faced, time and cost. Budgets were constantly being reduced, which directly influenced every decision the river engineer made regarding a particular problem, from the amount and type of river data collected, to whether a model study was employed.

When time and budget permitted, and the river engineer wanted to obtain a general feel for the trends and tendencies of a particular problem, large movable bed models were used for design assistance. The three-dimensional nature of the models

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helped to sometimes fill the void created by the lack of available scientific design procedures available. The river engineer would use the model to observe the general bed response and in many cases the general surface flow patterns from a particular design. Minute details and exact replication of the river were not desired and were not expected from these models. The model gave the river engineer a general idea of how different design plans would affect the flow and bed response of the channel. The model served as another piece of data to help the engineer in making a final design decision.

Further detail was sometimes required when changes in fixed, hydraulic structures were proposed, such as changing the location of a navigation span for a new bridge or for modifying or changing the location of concrete lock structures. In these cases, the engineer would then, if budget and time permitted, choose to use an undistorted fixed-bed hydraulic structures model, or more recently, a mathematical simulator model, to study and predict localized effects produced by these proposed measures.

The final design and construction of remedial measures implemented in the river often varied significantly from the recommended plan of the model study. This was due to many factors including budget, unforeseen physical river changes, practicality of construction, political or environmental concerns, or a variety of other factors.

In the majority of designs on the Inland Waterway System, the river engineer would follow the procedure discussed previously. Rock dikes, revetments, and/or other types of structures would be conceptually formulated and then presented and discussed with the various interests groups. If the proposed plans were accepted, the river engineer would then proceed with final design and construction using a phased approach. The intent was to let the river respond gradually after the first construction phase, monitor the response, and then proceed into the next phase. The ultimate goal was the completion of the intended measure of improvement. Rational evaluations could then be made for each phase of the design, if required.

By utilizing this phased river engineering design and construction approach, a factor of safety was established. Through careful analysis the engineer was able to determine when any phase of design did or did not perform as anticipated. Rock structures and revetments could be cost-effectively modified in the river when required.

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Rock structures have been extended, re-angled, degraded, and in some cases removed as a result of the phased approach.

In summary, the river engineering design of the past and present in the United States is based upon a historical knowledge base. Intuition, experience, and observations of the river are the cornerstone of design. When budget and time is sufficient, models are sometimes used to supply additional data for river engineering decision-making. Due to the lack of scientific design parameters available to the river engineer, the majority of designs built within the Inland Waterway Navigation System are conducted by using the traditional phased-construction procedure.

1.2. DEVELOPMENT OF THE MICROMODEL

Historically, the Corps of Engineers has employed relatively large-scale loose-bed models in the analysis and design of river engineering structures on rivers within the inland waterway system. These large-scale models were used primarily for the purpose of improving navigation conditions in the channel such as reduced shoaling in shallow crossings and increasing channel width in tight bends by use of dikes and other training structures. The large-scale models had vertical distortion and employed an empirical model approach. The empirical approach utilized adjustments in model operation to produce a desired bed response that was similar in nature to the observed prototype response. Because the typical size of these models were large (some as long as 300 feet), significant resources were needed to construct, operate and maintain the models. In addition, typical model studies often took several years to complete.

Budget constraints imposed on the Corps of Engineers in the early nineteen nineties resulted in the large-scale models being cost prohibitive for their routine use. This was a disappointing development to engineers, especially those at the St. Louis District Corps of Engineers (MVS) because MVS in conjunction with the Waterways Experiment Station (WES) had obtained considerable success from the large-scale models. Bendway weirs, chevrons, and other river engineering structures on the Mississippi River all came about from the use of the large-scale models.

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Thus with the favor and experience of using the large-scale models, MVS looked for other economical alternatives for studying river engineering problems. After a great deal of research and experimentation, MVS developed an approach that uses much smaller models for analyzing channel response (Davinroy, 1994). This approach or methodology was referred to as micromodeling. A U.S. patent was granted to MVS in 1997 for the micromodel technology.

Once MVS had claims of success in using micromodels to study the Mississippi River, other districts contracted with MVS for model studies. The work performed by MVS included studies for the Memphis District (MVM), the Rock Island District (MVR), the Vicksburg District (MVK), the New Orleans District (MVN), the Mississippi Valley Division, and the Northwest Division. The work performed by MVS for these offices was unsolicited and based on the immediate needs of each respective office.

After a few contracted model studies with MVS, the Memphis and Rock Island Districts requested a technology transfer of micromodeling. MVS obliged this request under the approval of the Mississippi Valley Division and provided complete transfer of the technology. Transfer of the technology included:

1. Training of personnel in model operation, technique, and theory
2. Training of personnel in data collection equipment and procedures
3. Compilation of an equipment list required for micromodeling
4. Assistance in procuring flumes, inserts, control systems and support equipment
5. Participating in initial site visits and review of facility setup
6. Review and guidance in proposed studies

At present, three micromodel facilities have been established within the Corps of Engineers Mississippi Valley Division. These facilities are located in the St. Louis District (1994), the Memphis District (1998), and the Rock Island District (1999). By

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MVD policy the St. Louis District Applied River Engineering Center (AREC) is the established authority for micromodel technology within MVD. This policy also places responsibility on MVS to ensure that all micromodel studies are conducted in a consistent manner. This responsibility includes review of proposed model layouts, of the model calibration, and of the study reports. Approval for transfer of the micromodel technology to other offices resides at the Mississippi Valley Division. Currently, only MVS, MVM, and MVR districts are approved by MVD for conducting micromodel studies.

1.3. JOINT VENTURE EVALUATION

In 1998 a joint venture team was chartered in order to evaluate a number of the issues pertaining to micromodels. This collaborative effort consisted of team members and technical advisors from the Mississippi Valley Division (MVD), the Engineer Research and Development Center (ERDC), the St. Louis District (MVS) and the Memphis District (MVM). A list of the joint venture (JV) team members and the technical advisors appears in Table 1-1.

The study effort assigned to the JV team included several broad goals. Within the context of advancing micromodel application, Corps of Engineers management sought to:

1. Establish a basic understanding of micromodel procedures,
2. Identify the micromodel's capabilities and any associated limitations, and
3. Determine how well the micromodels reproduce prototype conditions both during calibration and any predicted channel response to alternative structures.

The JV effort intended to furnish part of the basic knowledge necessary for making management decisions regarding micromodel technology. This was to be accomplished by defining a consistent approach for conducting micromodels and for analyzing their results and by defining areas of micromodel applicability (or capabilities and limitations). Acquiring the fundamental knowledge needed to investigate micromodel capabilities and limitations proved to be a daunting task because of the complexity associated with mobile boundary hydraulics, sediment transport, the empirical approach

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to loose-bed modeling, and the way in which river engineering studies are accomplished. In order to reduce the

Table 1-1 Joint Venture Team Members and Roles

Team Member	Office	Role
Roger A. Gaines	MVM	Project Manager and Team Leader
David Gordon[1]	MVS	Team Member
Stephen T. Maynord	ERDC	Team Member
Robert D. Davinroy[1]	MVS	Technical Advisor
Claude Strauser	MVS	Technical Advisor
Charles Nickles	ERDC	Technical Advisor
Tom Pokrefke	ERDC	Technical Advisor
Robert Occhipinti[2]	MVD	Technical Advisor
Dewey L. Jones	MVM	Technical Advisor

complexity, the study was divided into several components, each targeting a finite aspect of loose-bed modeling.

The JV study consisted of three principal components. Component A sought to establish a mechanism for comparing model results to prototype data in a consistent manner. Component B sought to explore boundary effects in the micromodels as they relate to model scale and scale distortion. Component C sought to assess micromodel repeatability at two scales and to analyze how well the micromodels reproduced the prototype data.

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[1] The original team member from MVS was Mr. Robert Davinroy. Mr. Gordon was subsequently substituted as the MVS team member by MVS MEMORANDUM dated 8 January 2001. Mr. Davinroy remained on the evaluation effort as an additional technical advisor from MVS.

[2] The original technical advisor from MVD was Mr. Malcolm Dove. Upon Mr. Dove's retirement, Mr. Occhipinti assumed the role of MVD technical advisor.

1.4. CONSULTANTS

1.4.1. General

Early in the JV study, three consultants provided an independent assessment of the proposed research and the micromodel methodology. Two of these consultants were from an academic background while the third had previous practical experience from the Mead Hydraulics Laboratory. Each of the three consultants had previous experience with loose-bed models. Table 1-2 lists the consultants.

The panel of consultants reviewed several past micromodel reports and then met at the MVS Applied River Engineering Center on May 18, 1999 to observe the micromodels first hand. The panel also participated in a round-table discussion of the proposed research while at the MVS lab. Each panelist provided a written report that documented their observations and outlined suggestions relative to the joint venture (JV) evaluation proposal. Appendix A contains copies of the individual reports.

Table 1-2 Panel of Consultants

Name	Affiliation	Role
Robert Ettema	Iowa Institute of Hydraulic Research, University of Iowa	Review previous micromodel reports, provide cursory assessment of micromodel approach, serve as continuing academic advisor through JV effort
Gary Parker	St. Anthony Falls Laboratory, University of Minnesota	Review previous micromodel reports, provide cursory assessment of micromodel approach
Warren Mellema	Private Consultant, formerly with Missouri River Division, Corps of Engineers Mead Hydraulics Lab	Review previous micromodel reports, provide cursory assessment of micromodel approach

The JV team selected one of the panelists, Dr. Robert Ettema, to continue as an advisor for the duration of the effort. Dr. Ettema provided his expertise in developing a

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framework for evaluating micromodels (Ettema, 2001) and by participation in various team meetings and discussions. Later, the IIHR was contracted separately to conduct a series of fixed-boundary (flat-bed) flume studies to investigate scale and distortion affects. The fixed-boundary flume studies are described more completely in subsequent sections and in Ettema and Muste (2002).

1.4.2. Consultants

The three consultants were asked to provide an assessment of the micromodel methodology and the proposed evaluation. The consultants reviewed previous micromodel reports and participated in a one-day conference at the MVS AREC. The conference (held May 18, 1999) provided the consultants with an opportunity to view active micromodels and to participate in a round-table discussion with the JV evaluation team regarding micromodeling and the evaluation proposal. Each of the consultants reviewed several reports. However, only one consultant (Parker, 1999) specified which reports were reviewed.

Each of the consultants that evaluated the micromodel methodology provided a written report of their opinions and observations. Copies of these reports are included in Appendix A. Conclusions made by each of the consultants are provided in the subsequent sections for the reader's convenience.

1.4.2.1 Robert Ettema (1999)

Ettema (1999) reviews a number of similarity considerations and identifies important non-dimensional parameters associated with loose-bed modeling. Ettema leads into his evaluation by providing general impressions about the proposed evaluation plan of study as follows (paraphrased):

> The proposed study will require a consistent theoretical framework based on similitude and laboratory-effect considerations. As is explained subsequently in this report, micromodel capabilities cannot be evaluated effectively without such a framework. Nor, for that matter, can the issues listed... be posed or answered appropriately in the absence of such a framework. Quite possibly such a framework remains to be developed

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early in the study. Also I [Ettema] would urge that the word "theoretical" not be thought of as being purely academic; the capabilities and possible extended application of micromodeling cannot be evaluated in an abstract or ad-hoc manner.

An important facet of the proposed study should be an evaluation of the levels of accuracy needed for designing river-training works. The target levels of accuracy and reliability obtainable with micromodels should be consistent with those levels. The early micro-scale models of the Mersey and Seine estuaries were useful in part because great accuracy was not needed in designing the channel-training structures modeled. It might also be added that the records are unclear as to the actual veracities of the models.

A simple truism in modeling is that model results are only as good as the knowledge of the people interpreting them. Usually, the more knowledgeable the modeler, the less exact need be the model; this goes for all hydraulic and computer modeling. Reynolds and Vernon-Harcourt used micro-scale models, but arguably both men also were among the most knowledgeable fluid mechanicians of their day. To be effective, the proposed study should evaluate the level of expertise needed to design and interpret micromodels.

Micromodeling is motivated in part by the substantial pressures imposed on Corps Districts to get engineering information in a timely and cost-effective manner. There is a risk that those pressures give rise to unrealistic estimates of the capabilities of micromodels. In my [Ettema], micromodel use is constrained to the single, but very significant, class of river-training applications for which approximate, information is sought regarding the impacts of relatively large-scale hydraulic structures (e.g. wing dams, dikes, bendway weirs) placed in relatively wide, essentially two-dimensional flow situations. For other applications, the modeling client must be in a position to stand the risks incurred with uncertain information accuracy.

In conclusion, Ettema (1999) states:

Micromodels have their place as a design aid for river engineering. They potentially can yield preliminary, qualitative, and approximate insights into the larger geometric-scale processes associated with flow and fluid-transport processes. Their wise use, though, requires due consideration of similitude criteria and consequent scale and laboratory effects. Additionally, their wise use requires a sound knowledge of the processes being modeled and of the appropriate levels of design accuracy and reliability needed for the river-training works whose performance they are simulating. As with all hydraulic models, the bottom line for micromodels is that the limits of their applicability fundamentally depends

on the extents to which they meet similitude considerations and on the level of risk the model user is prepared to assume.

1.4.2.2 Warren Mellema (1999)

Mellema (1999) offers the following observations regarding the potential uses of the micromodel. These discussions are based upon Mellema's "background, experience, and observations over the years and are not based on operating models at the scales and distortions used in micromodels."

1. Navigation Channel Design - Micromodels can probably be used to demonstrate general locations of scour and fill, however, the extent and level of these deposits and scour holes are probably not to scale and are not directly transferable to the prototype. This is particularly true in the scour mode and/or in locations where the sides and bed of the model are fixed.

2. Dredging Studies - The micromodel can probably be used to demonstrate the temporary impact of a dredge cut within a channel, however, there is no known way of transferring this to the prototype, because the time scale of the sediment transport along the bed of the model would be indeterminate.

3. Small Rivers - Bed Scour - If scour is the primary issue, an undistorted vertical scale is generally required. Scour tends to respond to the vertical scale only, and the underwater angle of repose of the bed material.

4. Outdraft Studies at Locks - This issue appears to be more directly related to surface velocities and structural and channel alignment, and therefore may be an area where a micromodel can be used as an indicator. Vertical distortion should be kept to a minimum.

5. Closure Structures - The impact of closing off major chutes, particularly those where considerable flow passes at normal discharges may have potential to be observed and evaluated in a micromodel. If however, the major transport mechanism in the chute consists of suspended sediment, the model must be capable of transporting and depositing suspended sediment at model velocities.

6. Build Islands out of Dredge Spoil - The model could potentially be used to demonstrate the impact of constructing islands out of dredge spoil, however, the stability and ultimate location of these deposits would probably not be directly transferable to the prototype.

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7. Side Channel Openings - Scour and deposition in side channels is highly dependent upon the sequence of flows to which they have been subjected (i.e. high flows may scour them out, low flows may result in low velocities and deposition). The impact of high flows passing through a chute can possible be demonstrated with such a model, however, since the model does not carry any significant material in suspension, it is doubtful if the deposition phase of the process can be demonstrated with any degree of reliability.

Mellema (1999) also provides the following summary and conclusions:

1. The micromodel technique represents a unique and innovative tool to evaluate and demonstrate alluvial channel processes. Its use as a design tool is being evaluated, and the proposed tests will provide valuable assistance in determining the applicability of the model for various river issues.

2. The highly distorted scales make transformation of model data to prototype conditions most difficult and in some cases indeterminate. This issue is being partially addressed in the proposed studies, but still may not fully answer all of the questions regarding this complex issue.

3. Investigations are encouraged to fully document all proposed studies, and gather all pertinent physical and hydraulic data in order to determine and compare model results with other studies and investigations. This is essential in order to gain confidence in model results.

4. Modelers should be careful not to unduly "force" the model to reproduce a set of river conditions. It is recognized that this can be accomplished physically by adjusting such things as slope, scales, etc., however, this complicates interpretation of model results when subjected to other flows. If the model is in fact a miniature river, it should have the same degrees of freedom as a river. If these degrees of freedom are constrained or removed, one no longer has a model of a river, but a laboratory flume waiting for a river to match it.

5. The micromodel constructed and applied to date obviously has an ability to demonstrate the impacts of how bed forms are formed in a micromodel environment, and as such, appears to be a great tool for demonstration purposes. Its use as a design aid is still being evaluated, and this entire experience should be a giant step forward in answering some of the issues surrounding its reliability as a design aid.

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1.4.2.3 Gary Parker (1999)

Parker (1999) suggests that the micromodel should be thought of as a process model rather than one that satisfies strict similitude. Parker gives the following reasons for this:

1. In addition to heavy distortion, the bed appears to be significantly tilted as well.
2. The bed sediment was selected because it appeared to perform well rather than because of any criterion involving similitude.
3. Although [Parker] did not obtain precise data, Parker was fairly sure that the Froude number in the micromodels is significantly higher than that prevailing in the corresponding field sites.
4. Model calibration was implemented by matching bed morphology rather than through strict similitude.

In light of the previous considerations, Parker suggests that micromodel results must be interpreted with care.

Parker suggested that a study of two models, one with conventional distortion (less than about four or five) and one with distortion commensurate with micromodels, could aid in the development of micromodels. For the two hypothetical models, detailed measurements of bed and water surface slope, flow velocity and sediment transport rate should be taken in addition to the model bathymetry. Parker further states:

> These comments are not meant to imply that micromodels are useless. It has recently been shown that self-formed meanders can develop up to the point of cut-off in a model not much larger that the micromodels...Although the shape of the bends are definable different from field-scale alluvial bends, most of the processes are clearly similar, including point bar formation, deep scour on the outside of banks and features that resemble scroll bars. All this is achieved in a flow that is also barely turbulent. The micromodel is thus a useful tool that is waiting to be verified further.
>
> It was encouraging to find that Davinroy had devised a means to reduce the exaggerated scour in micromodels. This was done by modeling an impermeable structure in the field as a permeable structure in the model. The permeability partly compensates for the exaggeration in scour

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depth due to the distortion. The physical basis for this empirical conclusion is sound: the permeability acts to suppress vertical velocities by allowing for a cross flow.

While I [Parker] was at the AREC,..heard...some rather cavalier disparagement of the principles of similitude. In particular I [Parker] heard the opinion that as long as the micromodel was able to reproduce the field bed morphology the precise criteria of similitude mattered not a whit. ... am sure that the statement was an exaggeration for the sake of making a point. It is, however, not particularly helpful. The laws of Newtonian physics apply to micromodels until someone can conclusively prove otherwise.

While I [Parker] strongly believe that the physical basis for micromodeling needs to be established further, I [Parker] am a strong supporter of the concept. Micromodels allow for a representation of the relevant river processes at a very low cost. They provide a tool for a comparative evaluation of various river countermeasures.

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2. LOOSE-BED RIVER MODELS

2.1. GENERAL

Loose-bed physical models provide a tool for the study and analysis of complex river problems. The term "loose-bed" is used herein to describe a physical model of river channels that has fixed alignment boundaries and a movable channel bottom or bed. Some of the earliest loose-bed models were small table-top sized models. These early models were used in the study of estuary and coastal sediment problems. As the loose-bed modeling gained more wide spread use in the early 1900's, the typical model size increased in order to reduce the scale distortions. Recent developments by the St. Louis District Corps of Engineers have returned to the small table-top models which are known as micromodels.

The micromodel is an extremely small-scale physical river model having a movable bed and varying discharge. The micromodel is described further in following sections. Micromodels are most commonly used to address river training activities for purposes of navigation and environmental effects. The micromodel is not used for more rigorous problems like rate of sediment transport. This report presents the results of an evaluation of the micromodel.

During this evaluation the reader is reminded of the statement that someone once said that you should never be afraid to try something new because amateurs built the ark and professionals built the Titanic. The micromodel provides a new empirical technique to loose-bed hydraulic modeling. However, simply having a channel with sediment and water flowing from one end to the other does not guarantee a model suitable for engineering design or analysis. M.S. Yalin, a recognized expert on physical movable bed models, said upon seeing the micromodel "Just because water runs downhill does not mean that you have a model." [3]

When water is run through a movable bed model and the model scours the bed near the outer bank of a bend, the flow crosses over to the opposite side of the channel prior to the following opposite bend, or an obstruction simulating a dike creates scour at

[3] In this light, criticisms of the WES models have also been made by other movable bed modeling experts.

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the end, those responses should not surprise an observer. The question that must be answered is to what extent does that model replicate the trends, locations, and magnitudes of response that are specific to the prototype reach being simulated. More importantly, how well will the model replicate changes to the system in a model calibrated to existing conditions and used to test alternatives? Evaluators must be open to new ideas while recognizing there are physical laws that govern similarity of flow and sediment transport in rivers.

Throughout this evaluation, the statement has been made that results from the micromodel should only be interpreted by someone knowledgeable in river engineering. This fact is also true for other types of models, but particularly for loose-bed models. No one has disputed this often repeated statement, and experience plays a major role in interpreting loose-bed model results. That statement does not change the need to test the veracity of results from the micromodel when operated according to a standard set of procedures.

As with any new approach, there is controversy regarding use of micromodels. As an example, some claim that micromodels are little more than demonstration tools while others claim that micromodels provide the same solution capabilities provided by any other loose-bed model. These opposing viewpoints may be at the extreme end of the spectrum. In all likelihood, the answer lies somewhere between the two extremes. Therefore, a balanced view becomes necessary. The present evaluation attempts to provide a balanced presentation of the facts.

2.2. SCOPE OF STUDY

In an evaluation of any engineering material or tool, it is helpful to have (1) a generally accepted test or measure and (2) generally accepted limits or criteria for that test. Item (1) can be stated as "How good is this tool?" Item (2) can be stated as "How good is good enough?" In movable bed models, whether physical or numerical, neither question has been fully answered. The objective of this evaluation of the micromodel is to address "How good is this tool?" The complete answer to the second question "How good is good enough?" is beyond the scope of this evaluation. However, an important

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aspect of the second question is the consequence of the model being wrong. While environmental concerns and navigation are of equal importance, the required accuracy of navigation predictions is generally greater than environmental predictions. For example, environmental studies can be successful by showing the creation of diversity of depth and velocity even if the location is not properly simulated. Navigation studies generally need to be more precise in predicting location in order to achieve safe navigation.

At the beginning of this evaluation, Gary Parker of the University of Minnesota served as a short-term consultant to recommend approaches to use in this effort. He suggested that the micromodel be compared to a large model having minimum distortion. Construction and operation of such a model was beyond the scope of the present investigation. Had the evaluation been able to construct and operate a model according to the classical approach of Einstein and Chien (1954) or Yalin (1965), using such a model as a standard of comparison would have been a valuable approach. Lacking such a model, the evaluation focuses on how the micromodel compares to the prototype, the effects of deviations of the micromodel from currently accepted movable bed modeling criteria, and a series of flume tests to determine the effects of various distortions.

Evaluating the micromodel in light of it's ability to reproduce prototype behavior and it's agreement (or departure) from important similarity criteria requires the consideration of whether results are qualitative or quantitative. Previous published micromodel reports state that the model results are qualitative. However, the MVS Applied River Engineering Center micromodel website states that:

> Micromodeling 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 suggest that the micromodel provides some level of quantitative results. The past use of flow visualization in the micromodel to assess navigation conditions also implies a level of "quantitativeness." The current

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investigation attempts to address the quantitative versus qualitative nature of micromodel results.

2.3. AN HISTORICAL PERSPECTIVE

According to the Oxford English Dictionary, citations for the word "model" extend back to 1575. The original sense of the term concerned representation of something larger. The stated definition is "Something that accurately resembles something else" or "A simplified or idealized description or conception of a particular system, situation, or process ... that is put forward as a basis for calculations, predictions, or further investigation."

Vollmers (1989) states that the German BROCKHAUS encyclopedia defines "scientific" model as:

> Simplified reproduction of the original representing only those properties thought to be important. These simplifications are meant to obtain a model that can be overlooked or mathematically calculated or is appropriate for experimental investigations. Technical models serve most of all ... as scientific objects of experiments (model tests).

These definitions of a "model" seem fairly straightforward, yet there are many variants when considering specific properties, processes, or experimental investigations. In fact, the way a model approach is defined depends largely on the laboratory conducting the study. Many publications address the various model types and applications. Model types range from detailed models of hydraulic structures (e.g., ASCE, 2000) to fairly simplistic process models (e.g., Parker, 1998). Physical sediment modeling entails use of a scaled model to replicate flow and transport processes. Model sophistication depends upon specific study requirements.

Various authors (Yalin 1971, Bogardi 1974, Kobus 1980, Graf 1984, Kamphuis 1991) characterize physical models into categories depending on their intended use or on the method employed for model development. In general, physical models have been classified into two broad categories; those based on "empirical" methods and those based on "rational" methods. Models utilizing the empirical approach have been described as

being purely qualitative and some references suggest that they are of limited use (USBR, 1980). The rational approach to physical modeling is fairly direct. Similitude principles provide a means for maintaining constant proportions between physical phenomenon in a model and its prototype. The physical processes in a model must replicate those processes observed in the prototype. Successful extension of model results to the prototype requires adherence to certain model "rules" or criteria.

Strict adherence to similitude relationships requires that all governing parameters provide consistent relationships between model and prototype. In order to achieve similar behavior between model and prototype, all geometric, kinematic and dynamic processes should be the same. Similitude relationships and dimensional analysis provide a mechanism to help identify important engineering variables that describe the physical relationships necessary to produce geometric, kinematic, and dynamic similarity. Froude, Reynolds, and Weber numbers, derived from dimensional analysis, are of primary concern for models with a free surface. Derivations and definitions of Froude, Reynolds and Weber numbers as well as other dimensionless parameters appear in most basic hydraulics texts as well as in many other publications (ASCE 1942, Janna 1981, Vennard 1981, French 1985, and ASCE 2000). Various articles discuss similitude and dimensional analysis as related to physical sediment models (Einstein and Chien 1956, Snamenskaya 1969, Yalin 1971 and 1986, Suga 1973, Watt 1973, Bogardi 1974, Garde and Ranga Raju 1974, Onishi 1975, Gujar 1981, Gehrig 1981, Kobus 1984, and Shen 1986).

Physical models rarely replicate all flow processes. This is particularly true of physical sediment models. One distinct disadvantage of physical modeling is that both model and prototype exist on the same planet Therefore, gravitational forces, model to prototype, are almost never scaled (some limited work with centrifuges as in Kobus (1984) may be the exception). Additionally, the model fluid is usually water in both the model and prototype. Hence, viscous forces cannot be appropriately scaled. A number of well-known hydraulic laboratories have established model design procedures (both published and unpublished). However, adherence to similitude criteria for the remaining properties of Froude number, sediment mobility, Reynolds number, and roughness

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characteristics often depends more on a modeler's experience and intuition than on a rigorous procedure. An alternative viewpoint defines similarity based on the model's ability to reproduce the prototype's bathymetric response after an extensive calibration and verification phase. Such an approach implies that some similarity criteria may often be of minor importance (Vollmers, 1989). However, similarity considerations can not be entirely abandoned because the same physical laws apply to both model and prototype.

Gaines (2002) provides a summary of previous physical movable bed model approaches. One item that should be perfectly clear to anyone who has read these previous studies is that strict adherence to similarity criteria is not done in many if not most loose-bed models. Most loose-bed models place primary importance on a calibration and/or verification phase. The calibration/verification phase involves adjusting the model to achieve observed prototype bathymetric trends.

Graf (1971) categorizes loose-bed models as explicit or rational models which are semi-quantitative and as implicit or empirical models which are qualitative. Graf (1971) places models developed using the regime theory in the qualitative class. The equilibrium approached employed by the micromodels places them under the umbrella of regime theory, yet there have been no models based upon the regime theory constructed at the small scales used in micromodels. Blench (1964) states that the time consuming verification phase can be shortened by application of regime relations. Present application of the micromodel technology does not consider regime relationships during model design.

2.3.1. Rational Loose-Bed Modeling

Graf (1974) credits Einstein and Chien (1954) with development of the rational method of loose-bed modeling. Yalin (1967) and the Delft Hydraulics Laboratory also developed methods that fall under Graf's category of a rational loose-bed model. The rational method is simply a more rigorous adherence to similarity criteria and generally requires large models to apply the method than used in the empirical approach. Rational models are characterized by low vertical scale distortion, low Froude number exaggeration, and equality of Shields parameter in model and prototype. Neither the

large-scale models nor the micromodels considered herein follow the rational method of loose-bed modeling.

2.3.2. Empirical Loose-Bed Modeling

Qualitative models place less reliance on similarity requirements. Warnock (1949) states,

> Instead of arranging the various hydraulic forces involved to meet definite requirements laid down in any law of similitude, the successful prosecution of a movable-bed model study requires that the combined action of the hydraulic forces bring about similitude with respect to the all-important phenomenon of bed movement, which is the essence of this type of model study.

Warnock (1949) also states that the verification of a qualitative loose-bed model is the basis for most of the confidence in the model.

Davinroy (1994), who developed the micromodel, uses morphological similarity in overall bed configuration, which is similar to Warnock (1949). Although less rigorous than rational loose-bed models, most qualitative models attempt to limit vertical scale distortion and Froude number exaggeration. Qualitative loose-bed models have a Shields parameter that is less than the prototype. Based on a review of the literature, the civil engineering profession accepts the qualitative loose-bed model as a useful tool in river engineering. Parker, in consulting on this evaluation, stated "In process models precise similitude is not sought. Rather, the model is adjusted so that the processes and patterns of morphology, such as the pattern of scour and fill, are reproduced as faithfully as possible. Because the same physical phenomenon are represented in the model as in the prototype, the model is still useful as a diagnostic tool." Parker also stated "They (process models) provide a tool for a comparative evaluation of various river countermeasures."

2.3.3. Empirically Based Rational Loose-Bed Modeling

Few model efforts comply with the full set of requirements described by Graf's (1974) rational model category. However, several laboratories utilize an empirical

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approach to achieve similarity of the major aspects required of the rational models, namely similarity of roughness, Froude number, and sediment mobility. Models in this category are generally those conducted in Europe and South Africia (Struiksma, 1980 and 1986, and Zwamborn, 1966 and 1967). Although the foregoing similarity conditions were sought, the model process utilized for these models involved a verification phase where the model was continually adjusted until the model adequately reproduced prototype bed response. As in the case of other model approaches described in this report, a visual assessment of the agreement between model and prototype served as the basis for determining whether the model is verified.

A synopsis of the European and South African model approaches is provided in Gaines (2002). Additional model approaches are also described in Gaines (2002).

2.3.4. Other Loose-Bed Modeling

Freeman (1929) discusses early studies by Reynolds and Vernon-Harcourt which were similar to the qualitative model but used Froude scale velocities in models with huge (greater than 20) vertical scale distortions. Vernon-Harcourt conducted a study of the Mersey estuary in England in a model with a vertical scale distortion of 60. Vernon-Harcourt discusses a verification process which involves a three-step process. Vernon-Harcourt's three-step process differs from the two-step process used in the micromodel and most loose-bed modeling. In most loose-bed models, adjustments are made in the model until it can reproduce a certain prototype condition. The model is then declared ready for prediction. Vernon-Harcourt adjusted his qualitative model until it reproduced a known prototype condition as in other loose-bed modeling. He then tested the model against a different set of changes in the prototype to see if it reproduced those known changes. If satisfactory in this hindcast, he then declared the model ready for prediction.

2.4. THE REALITY OF MODELING

Ackers (1987) poses the question that remains today when discussing the rational approach requiring equality of Shields parameter and other criteria stating "Yet many apparently successful models have been made of sand bed rivers and estuaries which did

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not follow those rules. Were those modelers deluding themselves as to the degree of simulation achieved, or is the academic approach to scale selection unnecessarily restrictive or even misleading?" Vollmers (1989) classification of modelers addressed this same concept in a slightly facetious manner at a 1987 NATO workshop (Shen 1990). Vollmers divided the workshop participants into two groups: 1) Theoreticians having published similarity laws but never run a movable bed model; and 2) practitioners using similarity laws to obtain initial data for their models, but who later on during the experiments are forced to accept numerous compromises that cannot be explained physically. If one concludes that only those studies having equal Shields parameter in model and prototype are valid, then most models including the micromodel are not valid. Past acceptance of model results where the Shields parameter was significantly less in the model than in the prototype demonstrates that valid studies have been conducted with inequality of the Shields parameter.

2.5. MODEL TYPES EVALUATED

The current investigation sought models based upon various approaches and at differing scales and distortions. Gaines and Maynord (2001) appealed to the engineering and academic communities for data on loose-bed models for inclusion in the evaluation. No entity provided model data outside the US Army Corps of Engineers. As a result, sixteen large-scale model studies conducted by the Waterways Experiment Station (WES) and fourteen micromodel studies conducted by the St. Louis and Memphis Districts were analyzed in an attempt to identify scale and distortion effects.

Conditions in alluvial streams are continuously changing and are affected by variations in hydrologic conditions, channel geometry, and sediment movement. The channel morphology and man-made features are additional factors influencing this change. Because of the complex spatial and temporal interaction of these and other factors, it is not possible to distinguish the cause effect relationship for each individual factor (Biedenharn, 1995). While it is not the intent of the present study to relate channel response to these factors, each of these factors has a direct influence on variations found in the prototype. Even with the most rigorous sediment model,

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variability in the prototype data causes problems when comparing model and prototype data. The problem becomes more acute when parameters that cause variability in the bathymetry are not included in the modeling process. For example, the micromodel does not simulate hydrograph variability that may be a major cause of variability in the prototype bathymetric data.

Although extensive data were available for study of prototype variability, accomplishment of present study goals required that only data associated with available model studies be analyzed. Not all model studies incorporated in the analysis utilized multiple prototype surveys for model verification/calibration. In particular, the verification process employed by the Waterways Experiment Station (WES) generally utilized only one prototype survey to assess model reproduction of prototype conditions (The WES models are also referred to as large-scale models). Their verification began with a specified prototype condition which was molded into the model bed. The model was then operated (and adjusted) to reproduce prototype discharges and sediment loads necessary to reproduce a second, later prototype bathymetry. Verification was assessed through a visual qualitative interpretation of model and prototype bathymetry. Franco (1978) provides further details of the WES verification procedure.

Contrasting this method of verification, micromodels employed an equilibrium sediment recycling approach, which utilized a number of prototype surveys in a calibration process. This process involved operating a model through a series of hydrograph cycles with adjustments to slope, discharge, and boundary conditions until prototype conditions were reproduced in the model. Where available, multiple prototype surveys were visually and qualitatively compared to model bathymetry in a manner similar to that used for the WES models to assess the state of model calibration. Where only one prototype survey was available, the comparison technique involved only the model and the single prototype bathymetric survey.

Both large-scale models and micromodels included herein utilized a visual assessment of the state of model calibration by comparing model bathymetry to prototype bathymetry. However, several noteworthy differences exist between model approaches used with the large-scale models and the micromodels.

2.5.1. Basic Methodology of WES Movable Bed Models

The large movable-bed models employed by the Corps of Engineers at the Waterways Experiment Station (WES) in Vicksburg, Mississippi, as stated previously, were classified as loose-bed models that used an empirical modeling approach. The models utilized relatively large horizontal scales (typically 1:120 to 1:600) and relatively low vertical distortion (typically 4 to 10 in the sand-bed models and 1.5 to 4 in the coal-bed models). By taking an empirical approach, the models did not utilize established, Froude similitude criteria during the design or operation of a model. Warnock (1949) stated that the primary step in the development of a movable-bed model involved the selection of suitable scales and bed material which would result in two phase, water and sediment, flow similar to the prototype. To accomplish this, a thorough knowledge of the characteristics of the prototype based upon hydraulic and hydrographic survey data was required. In addition, experience in the field of river mechanics and movable-bed hydraulic models was needed for proper model verification. Figure 2-1 is a typical movable-bed model used at WES.

The distortion or exaggeration of the vertical to horizontal scale ratio in the WES models was necessary to generate satisfactory bed movement in the models. Franco (1963) recommended that distortion should be as small as practical primarily because it tends to affect the relationship of velocity, width-depth ratio of the channel and curvature, and, consequently, the distribution of energy within the channel. Franco goes on to state that the effect of distortion on the performance of some structures such as sills or stilling basins can usually be eliminated by using the vertical scale to reproduce certain horizontal dimensions, particularly the dimensions in the direction of flow.

These models were used in both indoor and outdoor facilities. A rectangular channel flume composed of concrete or a combination of concrete and mortared brick was designed and constructed according to a chosen planform or bankline alignment of the prototype. WES also constructed some movable-bed models in flumes with fixed water systems in an effort to reduce model construction costs. The movable-bed portion of the model within the flume was then molded or formed from a chosen prototype

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Figure 2-1 Large Movable Bed Model at WES, Middle Mississippi River at Dogtooth Bend, Miles 39.2 to 20.2, Scales 1:400 Horizontal & 1:100 Vertical

survey. The molding process usually involved establishing comparative range lines or cross sections on the model at intervals consistent with hydrographic surveys (typically 4 feet apart on the model). The model bed was then interpolated and contoured between these sections by skilled technicians and model makers. Figure 2-2 is a photo illustrating the molding process and the contouring of the model bed.

Figure 2-2 Technicians molding or forming WES large-scale model

Franco (1978) presented guidelines for design, adjustment, and operation of physical sediment models at WES. Franco listed eight factors to be considered during model design. These factors were:

1. Discharge scale
2. Time Scale
3. Sediment type, rate, and method of sediment input
4. Supplementary slope
5. Entrance and exit conditions
6. Bank alignment and overbank roughness
7. Erosion resistant boundary(ies)
8. Regulating Structure elevation and condition.

In addition to the factors listed above, a ninth, very important factor integral to the model design was the adjustment of rails to provide a supplemental slope on the model to

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aid in achieving the desired mobility of the model bed material. Each of these nine factors are discussed in detail.

1. **Discharge Scale.** Discharge in the models were controlled through the use of a pump, weir or venturi meter, and associated valves. The ability to vary the discharge was required because the models used variable hydrographs. An important observation by Franco (1978) relates to the type of hydrograph used in model operation. Franco notes that many hydraulic laboratories operated physical models based on the dominant discharge concept where a single flow rate is used for all model simulations. He advocates use of a variable hydrograph because "most problems in alluvial streams result from changes in river stages and discharges…" (Franco, 1978).

   In selection of a discharge scale relation, care was taken to ensure that the model was operated very near the critical tractive force (or critical velocity) required to start movement, realizing that the prototype operated considerably above that range. Therefore, the model discharge scale had to be variable to provide the same relation of model sediment movement to that of the prototype for the range of flows and stages reproduced. To compensate for this exaggeration of energy and to prevent the bed from becoming abnormally mobile as compared to the prototype, the rate of increase in discharge was exponentially reduced in the model as compared to the prototype, such that as the maximum prototype discharge was approached, the discharge scale relation approached the Froude discharge scale factor for the model scales. Depending upon the particular model, the application of these applied discharge factors was different.

   An example of this exponential, non-linear model discharge scale relationship to the prototype was presented by Franco (1978) on a coal bed model with distortion of 1.5 (Figure 2-3). The graph shows that as the discharge of the model increased, the scale discharge ratios applied to represent the prototype increased exponentially. It should be noted that this plot is on semi-log graph paper resulting in an exponential (or power) relationship. Models are generally too small to develop the forces required to move typical model bed materials, especially at lower flows. The additional forces needed to move the sediment must be provided through discharge scale relations that are greater than the theoretical scale derived from the model horizontal and vertical scales. However, over the range of model discharges, there was always more distortion (increase) of low flow than high flows relative to the Froude criteria.

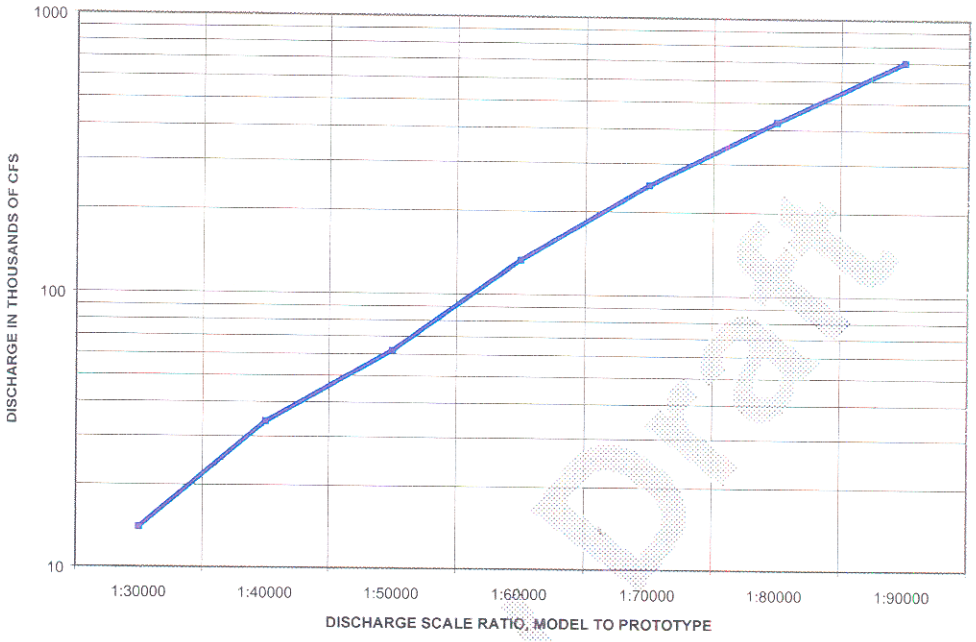

Figure 2-3 Discharge Relation Curve, WES Coal Bed Model, Scale 1:120 - 1:80

Prototype discharge hydrographs were simulated using distorted model discharges while maintaining the corresponding stage hydrographs in the model. This was accomplished by installation of a movable tailgate in the model exit area. For all intensive purposes, this tailgate was used to reproduce the portion of the river downstream of the modeled reach to create backwater and maintain selected stages in the model based on the stage hydrograph. This tailgate, in combination with the changing scale discharge releases at the upper end of the model, was moved upward or downward to maintain a desired model water surface elevation at a preselected location in the model. Figure 2-4 from Franco (1978) shows the discharge scale ratio versus stage from a sand bed model with a distortion of seven (7). The graph shows that as stages increased, the discharge scale ratio conversion to the prototype increased exponentially.

2. **Time Scale.** Franco (1978) noted that time scales in the WES models should be adjusted in order to reproduce sequences and durations of stage and discharge in the prototype. The time scale should indicate a relation between the time required for bed development in the model and in the prototype. The WES models utilized time scales between 5 and 10 minutes to equal one day in the prototype, depending on the bed material used. The vast majority of the models operated at WES used a time scale of 6 minutes equal to one, prototype day. These times were based primarily on prior model work.

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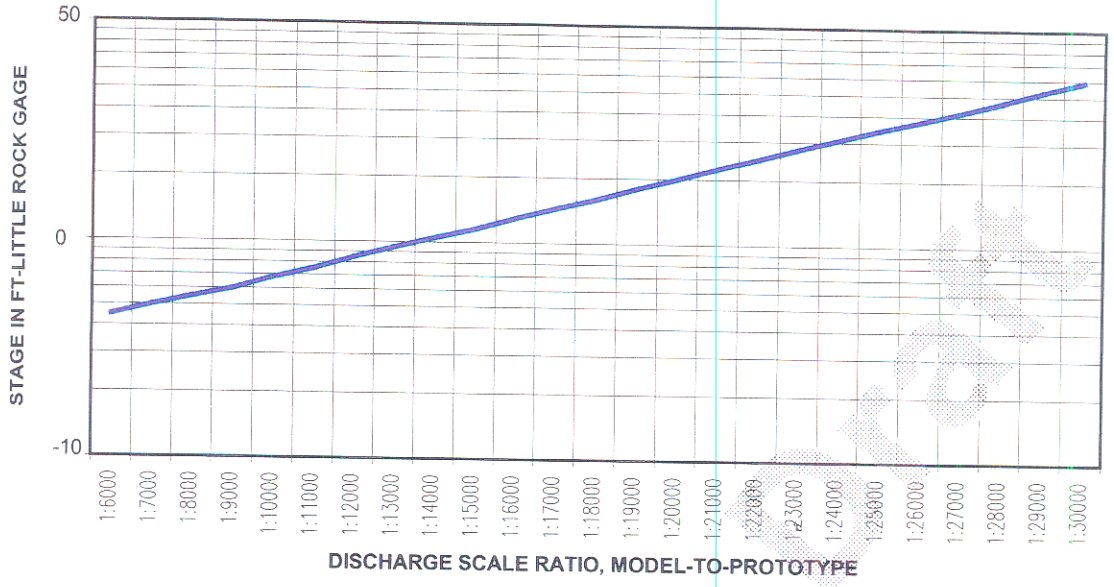

Figure 2-4 Discharge Relation Curve, WES Sand Bed Model, scale 1:250 - 1:36

Although a physical time sequence was used while model testing of alternatives, the model time was never used as a representation of the actual elapsed time one could expect sediment response changes to occur from a particular design alternative or plan. The primary reason for this was that so little was known about the actual sediment transport response time in the prototype. In addition, multiple, successive average model hydrographs were sometimes run for a particular design alternative to ensure that the full, ultimate model bed response to stability was achieved. The resultant bed configuration at the end of the hydrographs was always meant to represent the general trends of that particular design and was never meant to give the river engineer an estimate on the actual time it would take for the design response to fully develop in the prototype. This approach was taken based on making comparison of model results for alternative plans tested, and the realization that any plan constructed in the prototype would be subjected to stage and discharge hydrographs different those used in the model testing.

3. **Sediment Type, Rate, and Method of Sediment Input.** Model sediment was not sized according to the model scales because of physical limitations. Reducing particle sizes to smaller sizes would have required even larger model scales and would change the behavior of the model bed material from non-cohesive to cohesive. Foster (1975) described model sediments predominantly used in the WES models to be a 0.2 mm diameter for sand bed models (specific gravity of 2.65) and 4 mm diameter for crushed coal bed models (Specific gravity of 1.3). The sizes of these sediments equated to

approximately 1.5 inches to 9 inches in prototype diameter, depending upon the particular model that was in use. The Mississippi River is comprised mainly of sand and silts. Franco (1978) states "in natural streams, the size of bed material does not vary in direct proportion to the size of the river and tends to be larger in smaller streams".

The method of sediment input used in the WES models involved a procedure whereby bed material was manually introduced at the upper end of the model. The rate of transport of this material through the model was ultimately a function of the energy supplied by the model and was developed during the verification process. The immediate goal was to ensure that sufficient model bed material was available to enter the model if energy conditions were such to have that occur. While the ultimate goal was to establish equality in the amount of sediment introduced into the model as compared to the amount of sediment leaving the model, during verification the amount of material input to the model was independent of the amount of sediment extruded from the model. An agreement in model sediment budget, particularly during plan testing, would ensure that the channel bed would not degrade nor aggrade. This was one portion of the term "stability" of the model. The other portion of the "stability" term addressed the channel bed configuration. When the channel configuration was not changing significantly and the sediment input and output amounts were in agreement over consecutive hydrographs, the model was considered "stable." Adjustments to sediment input were made only during model verification based upon the modeler's visual observations. At the end of the verification phase, a model sediment-discharge curve was developed and provided input parameters for base and plan testing.

4. **Supplemental Slope.** Supplemental slope (also referred to as tilt) is the slope needed in addition to that resulting from the linear scales to produce adequate bed movement. Franco expressed supplemental slope as:

$$S_{su} = S_m - \left[S_p \frac{y_r}{x_r} \right]$$

where

S_{su} = supplemental slope,

S_m = total model slope required to mobilize the model bed sediment,

S_p = slope at full scale (prototype)

x_r = the horizontal scale ratio, and

y_r = the vertical scale ratio.

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For model studies conducted at the WES values for total slope were reported as:

S_m = 0.00065 to 0.0010 for 0.2 mm sand
0.00030 to 0.00050 for 4 mm crushed coal

Typically a model operates very near the critical tractive force while the prototype operates considerably above the critical level. Vertical distortion is an adaptation to increase tractive force in a model. The distortion of the discharge scale also aids in increasing the tractive velocity to accomplish the movement of model bed sediment. However, in most loose bed models supplementary slope is also required to develop the total necessary force for bed movement.

5. **Entrance and Exit Conditions.** The entrance condition was constructed and modified so as to dissipate excessive energy and bed scour resulting from the discharge introduction point at the upstream portion of the model. In addition, modifications were made to ensure the proper direction of flow into the model. Baffles or guide vanes constructed of concrete, screen, and other materials were used to accomplish this. The exit condition was constructed far enough downstream from the area of interest in the model study to ensure minimal negative model influence, and contained an adequately sized pit to collect the bed material extruded from the model.

6. **Bank Alignment and Overbank Roughness.** The accurate alignment of the banks in the model, or channel planform, was critical to the proper development of the resultant bed configuration. For this reason, it was necessary to acquire accurate maps, drawings, or photos of the prototype for accurate horizontal boundary conditions in the model. In addition, often some representation of overbank roughness, usually in the form of folded screen, was incorporated in the models to simulate overbank prototype roughness associated with vegetation, etc. The purpose of this folded screen was not to exactly model the prototype vegetation and roughness, but to provide some degree of increased flow resistance, as compared to the channel, on the overbank areas. In most WES models, a small, parallel portion of the floodplain or overbank was usually included in the model. However, some WES movable-bed models reproduced significantly large overbank areas.

7. **Erosion Resistant Boundaries.** There are many erosion resistant materials that occur in the prototype in the form of gravel and cobble bars, clay plugs, rock strata, sunken vessels, debris, etc. The WES models utilized several different materials in the model to simulate resistance to erosion including haydite, screen, gravel, and concrete. Figures 2-5 and 2-6 are photos illustrating some of the different materials used. In Figure 2-5, concrete was used to simulate both a rock feature and dikes in the model. In Figure 2-6,

haydite was used to simulate an erosion resistant bar (Boston Bar). The determination of erosion resistant boundaries in the model was usually made during model verification based upon either information obtained from the prototype or upon judgment made by the modeler.

In addition, pile dikes and rock structures of the prototype were represented in the model. Pile dikes were constructed using appropriately sized, based on the horizontal scale, cylindrical rods. Rock structures were typically constructed using small limestone or pea gravel with some type of cement binder to take into account the physical, scale distortion in the model. Figures 2-7 and 2-8 illustrate impervious structures used in the WES models.

8. **Regulating Structure Elevation and Condition.** Critical to the performance of the WES models was the amount of available information describing the condition of existing channel regulating structures in the prototype. This included basic information on dike elevation and dike length, dike type, pile or rock. During verification, as much information about the general condition of the dikes was necessary for successful completion of this effort.

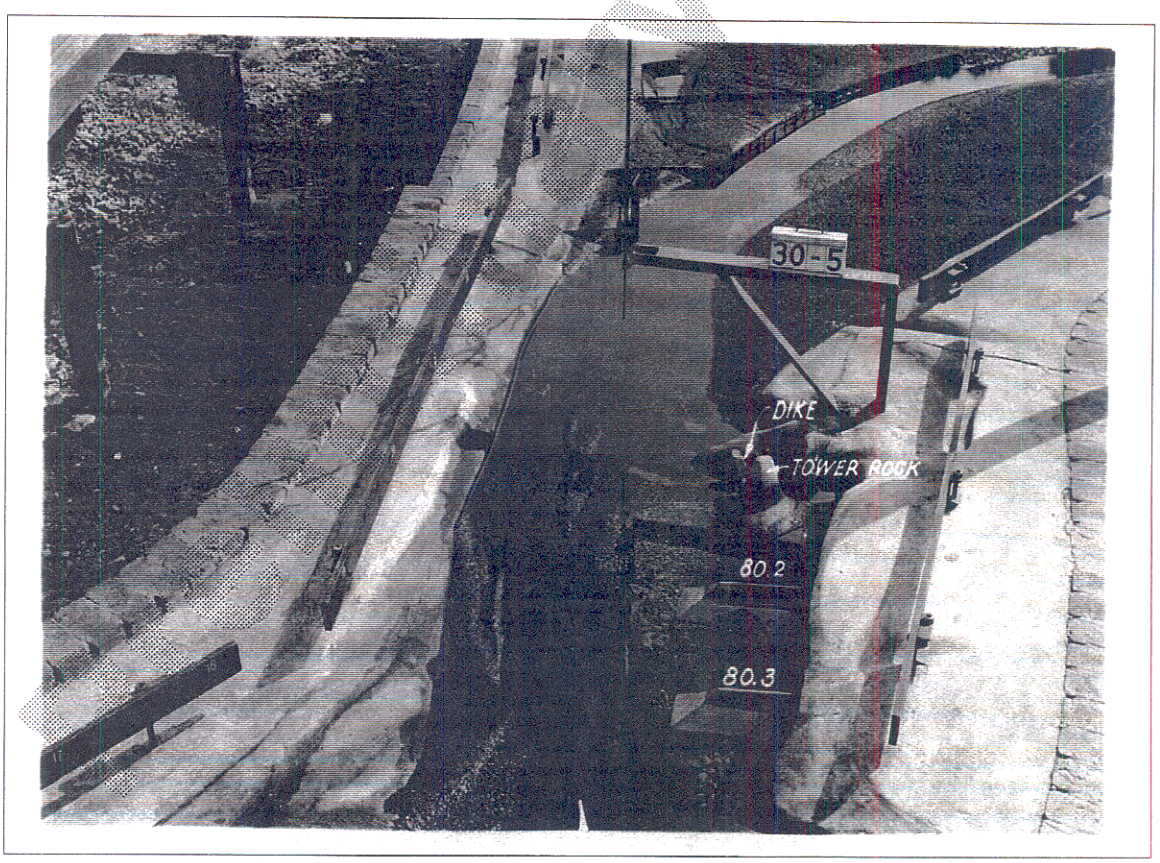

Figure 2-5 Tower Rock Bar Model Showing Concrete Formed Geologic Rock Feature (Tower Rock) and Concrete Formed Dikes.

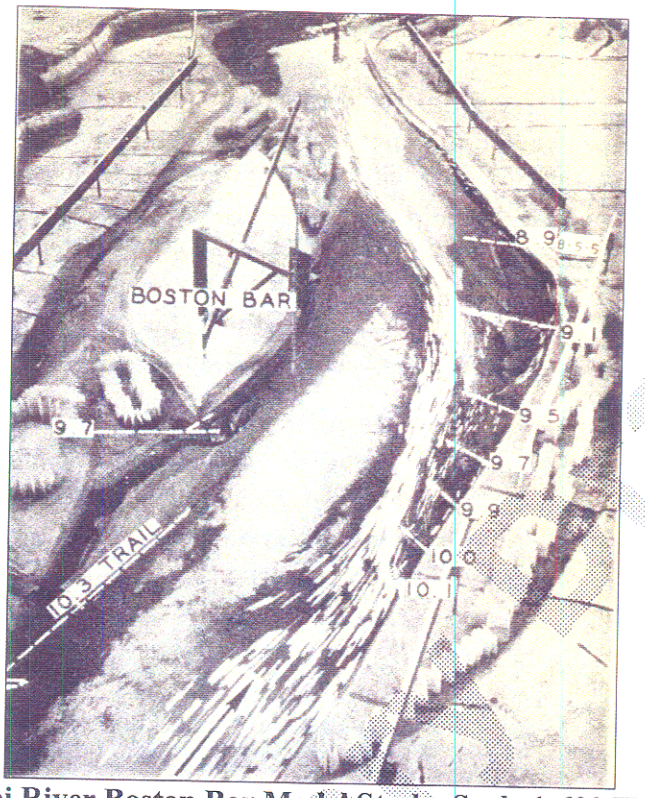

Figure 2-6 Mississippi River Boston Bar Model Study, Scale 1:600 H and 1:100 V. Boston Bar is at Left Center and was Constructed out of Erosion-Resistant Haydite.

Figure 2-7 Pea Gravel-Concrete Conglomerate Representing Bendway Weirs in the Dogtooth Bend Model

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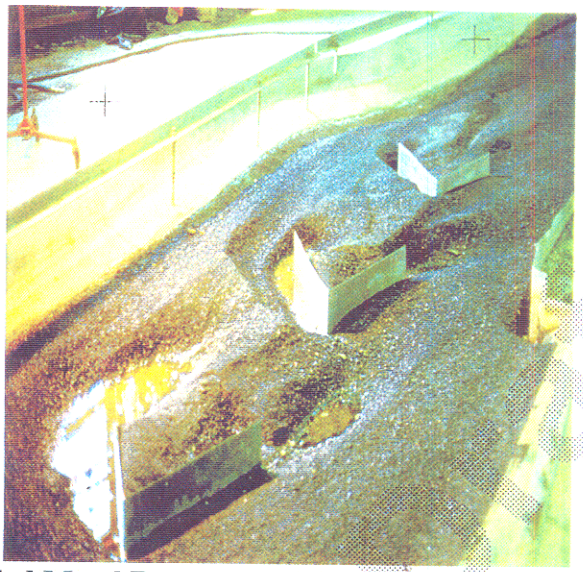

Figure 2-8 Thin-Walled Metal Representing Chevrons in the St. Louis Harbor Model

9. **Adjustments of Rails.** A series of adjustable rails were placed on either side of the model banks, and used to install the desired supplemental slope in the model. These rails were also used to hold the templates used in molding the initial model bed configuration and to survey the model at the end of tests. Elevations used to establish the supplemental slope were based on a fixed benchmark established and maintained for the specific model. That benchmark was related to prototype elevations and was the basis for all vertical measurements on the model. The rail adjustments to obtain the desired supplemental slope were made during the verification process and were then held constant throughout the duration of the model study. WES was able to use this approach because specific stages were maintained in the model, and areas of excessive or limited bed material movement could be identified during verification. Subsequently, the supplemental slope in the rails was increased or decreased as needed to obtain acceptable bed material movement. Figure 2-9 is a photo showing the location of rails for datum elevation adjustments.

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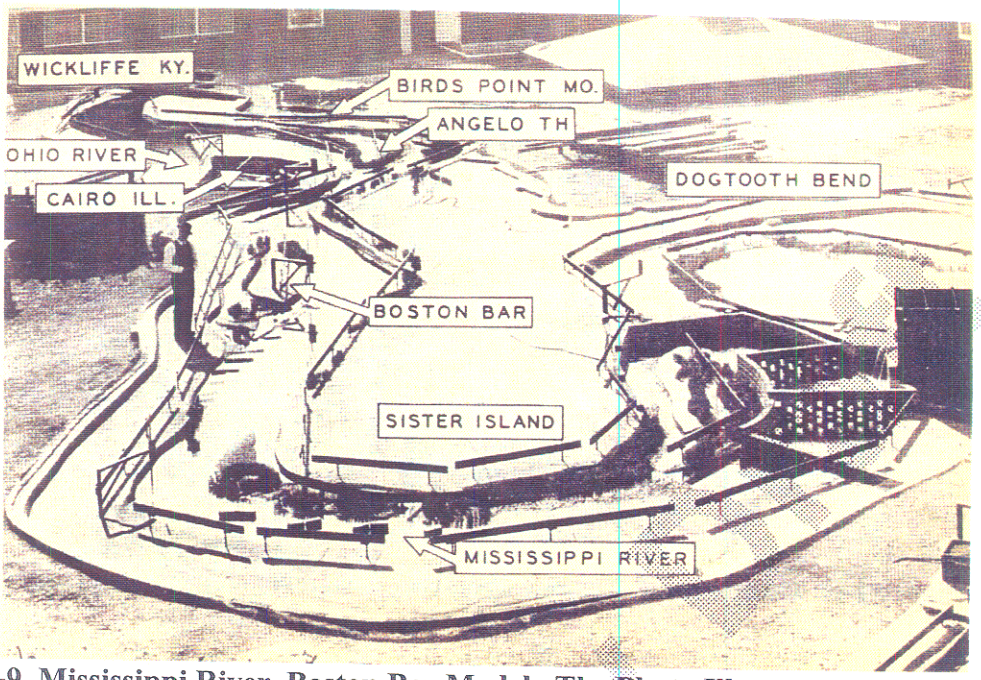

Figure 2-9 Mississippi River, Boston Bar Model. The Photo Illustrates the Use of an Adjustable Rail System for Localized Control of a Variable Datum.

Once the bed was molded, the model was ready for testing. The procedure at WES for the initial adjustment or calibration of the model bed behavior was termed "model verification" (Franco 1963). Each of the preceding nine parameters were adjusted during the verification phase of the model study. Franco (1963) states that the normal verification is an intricate process of adjusting the various hydraulic forces and model operating technique until the model demonstrates its ability to reproduce with acceptable accuracy the changes in bed formations that are known to have occurred in the prototype during a given period. Franco (1978) adds that the "principal considerations in the design of movable-bed models should be that the hydraulic forces developed be sufficient to move the material forming the bed in simulation of prototype sediment movement and that the model is capable of defining the problem at hand." With this as the focal objective, sediment movement was guided by the following considerations:

1. Model bed movement should occur during all flows that produce prototype bed movement.
2. During low flows, movement should be mostly in crossings with little or no movement in deep channels.

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3. During high flows, sediment movement should be fairly general throughout, but movement in bends and deeper channel areas will be greater than elsewhere.
4. Resultant bed conditions are dependent on the point of time in the hydrograph cycle when a survey is made (surveys made at the end of a high-flow period indicate deeper channels in bends and shallower crossings while surveys made at the end of a low-flow period indicate shallower channels in bends and deeper crossings).

During the verification a representation of the discharge and stage hydrographs are introduced and maintained in the model over a starting bed configuration that was molded to represent the actual prototype bathymetry that existed at the beginning of the hydrographs. The planform or bankline alignment of the model associated with this bed was constructed from available historical information as close to the era of time that the starting bed configuration was based upon. After the hydrograph was run, the model bed configuration was surveyed. The resultant bathymetry was visually compared in planform and elevation to a hydrographic prototype survey representative of prototype conditions occurring at the end of the historical hydrograph. The time duration of the historical hydrograph was kept relatively short, usually one prototype year. This was based on the premise that the model should be capable of reproducing prototype trends and tendencies that were documented between annual prototype surveys. Major changes in the bankline occurring in the prototype due to bankline recession could be incorporated into the model based on timing within the hydrograph, but this was an unusual case. Longer hydrograph durations were consider impractical from both a model operation and economic perspective (Derrick 2002).

After the stage and discharge hydrographs were run through the model and the ending bed configuration was compared to the prototype survey, the model was re-molded to the starting bed configuration and adjustments were then made as discussed earlier. The hydrograph was then again simulated and the process repeated as necessary until the modeler felt that similarity was achieved with the ending prototype survey. Special attention was given to the input of sediment to ensure that the model had sufficient (neither too much nor too little) bed material available.

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After the described process was complete, the model was considered verified. At this point, an "average annual design hydrograph" was developed in coordination with the study sponsor and used for all subsequent model runs. These stage and discharge hydrographs were based upon the particular problem at hand and were empirically determined usually by averaging a set of historical data. The average annual design hydrograph was then used to establish a base test condition in the model.

The model bed configuration at the end of verification or a particular prototype survey served as the starting bed configuration for the base test. Usually, multiple average annual hydrographs would be run through the model until bed stability was achieved (sediment equilibrium and relative channel configuration consistency). Once this occurred, the resultant model bed configuration formed the base test template bed. This base test bed configuration was the bed normally used for the starting bed configuration of all design alternative tests. When a particular design was installed in the model, two to three hydrographs were usually simulated, depending upon the channel response observed in the model. At the end of each hydrograph, the model was usually surveyed and then compared to the starting base test bed configuration. Sometimes additional hydrographs were simulated in a particular design alternative until model stability was achieved. Additional hydrographs were also simulated on plans of river training structures that involved progressive phases or stages of construction where the channel bed was allowed to react to a plan before another phase was installed and testing continued. When a new design was to be incorporated into the model, the bed was usually re-molded back to the starting base test bed configuration and the procedure repeated.

It was in the above manner that general conclusions were made on the effectiveness of particular design alternatives. Designs were always compared to the base test and not directly to the prototype. However, the desired improvements were also considered in this analysis. The river engineer then took these bed response indications from the model to assist in design and construction decisions for the prototype.

Flow visualization was also used in many movable-bed model studies at WES. Using time exposure or time lapse photography, confetti streaks or lighted drones were

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captured under certain flow conditions in the model usually during the base test and comparative design alternative tests. In the model study results, the flow visualization was used for a general indication of the relative effects of the main concentration of flow for a particular design as compared to the base test. Due to the fact that the model velocities were distorted above the theoretical values (based on Froude number similitude), this flow visualization provided general information only and was not used in designing testing plans or transfer of model information to the prototype. It was merely another indication of the plan effects. There was no way to relate the flow visualization in the WES models directly to any type of navigation condition or evaluation thereof. However, general assessments regarding the effect of flow patterns on navigation (identified by the model flow visualization) were made in some models (e.g. Dogtooth Bend and Greenville Bridge model studies). Figures 2-10 through 2-13 illustrate flow visualization used in some of the WES models.

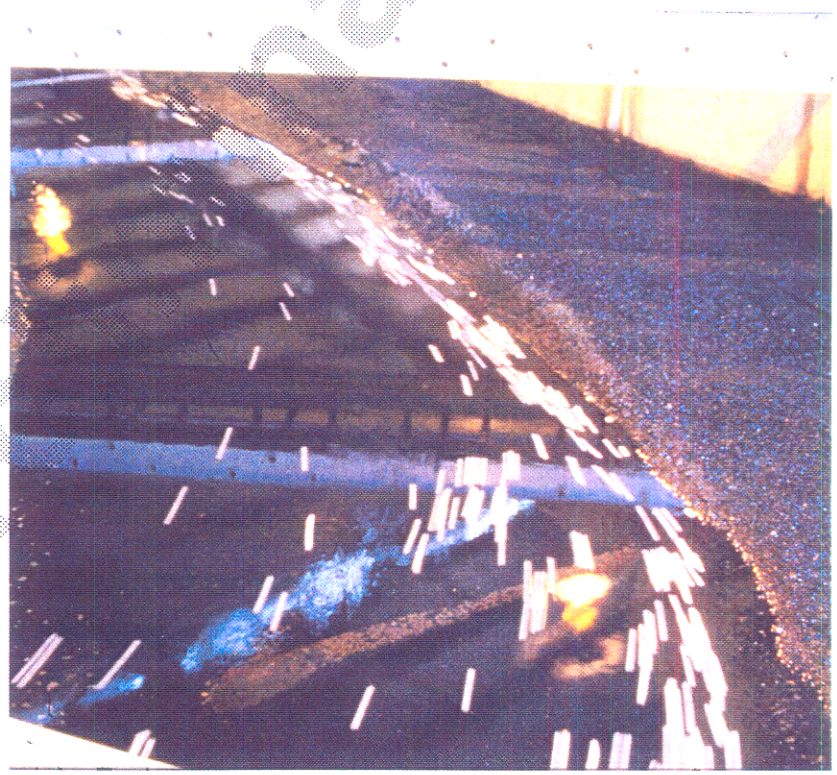

Figure 2-10 Flow Visualization of the Greenville Bridge Model, Lower Mississippi River, Vertical Scale Distortion of 3.6

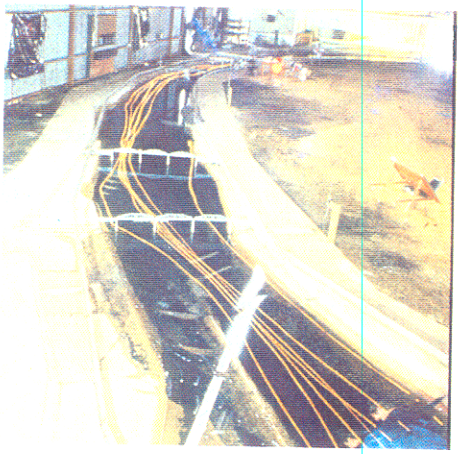

Figure 2-11 Flow Visualization of the St. Louis Harbor Model to Assess Flow Patterns through Multiple Bridge Crossings, Vertical Scale Distortion of 2.5

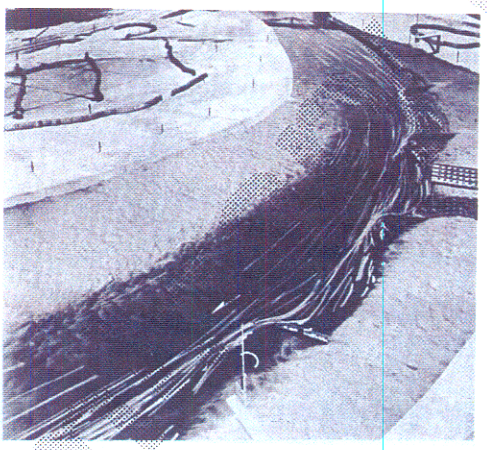

Figure 2-12 Flow Visualization of the Arkansas River Model, Vertical Scale Distortion of 4

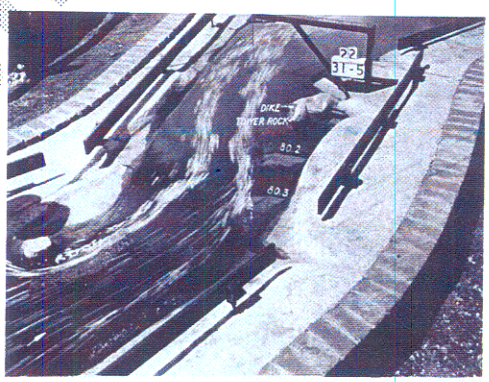

Figure 2-13 Flow Visualization of the Grand Tower Model, Middle Mississippi River, Vertical Scale Distortion of 4

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2.5.2. Basic Methodology of Micromodels

Davinroy (1994) developed an empirical modeling procedure utilizing small horizontal scales (e.g. as small as 1:20,000) and a relatively high degree of vertical distortion (e.g. distortions up to 1:20 were used) to study sedimentation problems primarily in the Mississippi and Missouri Rivers. Models resulting from this technique (called "micro modeling" by Davinroy) are known as micromodels. Since 1995, the approach has been used in modeling a variety of streams ranging in size from small tributaries to the Mississippi River (streams less than 90 feet wide to over 3000 feet wide, respectively) as described in eighteen published reports. Calibration of a micromodel begins by adjusting slope and sediment volume to produce a desired state of sediment mobility given a constant discharge. Two constant discharges, a lower and higher flow rate, define the lower and upper hydrograph limits, respectively. A cyclic hydrograph operation mimics stage and flow changes observed in the prototype. Such changes in flow and stage are noted by Davinroy (1994), Franco (1978), Zwamborn (1966), Vogel (1938), and Vogel and Dean (1932) as key to reproducing sediment behavior as observed in the prototype. Further description of general micromodel procedure is found in subsequent sections.

The micromodel approach begins by selecting horizontal scales based on physical constraints. The vertical scale, however, is not known *a priori* as it is established during initial calibration (recognizing that vertical scale is a dependent parameter). Micromodeling employs an equilibrium concept using sediment recirculation. The equilibrium concept implies the existence of a unique relationship between bed material physical characteristics, slope, discharge, depth, and boundary roughness. Determining model vertical scale as part of the calibration procedure acknowledges the relationship between flow depth and roughness and between sediment material and roughness.

Other investigators noted below have also acknowledged the dependency of depth on bed material characteristics. Jonte (1949) presents an iterative procedure for establishing the bed material and vertical scale for a particular model. The method described by Jonte attempts to relate model flow depth, slope, and discharge at operating conditions, prototype flow depth, slope, and discharge at a state of incipient bed mobility,

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and vertical distortion through a graphical technique to achieve a satisfactory choice of vertical scale and bed material composition. The method involves placing trial bed material in the model then operating the model at constant discharge until a stable bed is obtained. Slope, discharge and mean flow depth are then determined and compared to prototype conditions where the bed is at the point of motion. This process is repeated for a number of runs in order to establish the satisfactory combination of sediment material and vertical scale. Glazik (1978) and Gasser (1989) also suggest changing vertical distortion as part of model calibration.

The micromodel technique does not utilize established similitude criteria during the design or operation of a model. Instead, micromodeling seeks a form of morphologic similarity (Davinroy, 1994, Glazik, 1978, Hecker, 1989, and Snamenskaya, 1969) where overall bed configuration determines the degree of similarity between model and prototype. The morphologic parameters commonly considered in micromodeling are thalweg location and general bed-elevation trends. Further explanation of the micromodel procedure is provided in the following sections.

2.5.2.1 Operation and Calibration Procedures for Micromodels

The overall objective of a micromodel study is to evaluate as many alternatives as feasible, while keeping the time and cost to a minimum. In order to achieve the objective of the study the micro model must be properly constructed, setup, calibrated and operated. A fundamental premise of micro modeling is that the bed slope will adjust to an equilibrium condition given a specified channel alignment, sediment size, sediment size distribution and discharge. A second premise is that micromodel behavior will closely approximate the bathymetry of the prototype.

The first requirement of a micromodel study, as with any study, is to complete a search of the background of the reach under investigation. This search includes gathering historical materials including photographs, hydrographic surveys, geological data and any other pertinent information, which may be available. Particular attention should be given to any anomalies that may be present such as rock outcroppings or other tertiary

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limitations, either vertical or horizontal, which may affect the characteristic of the reach being studied.

The model itself consists of several major components: (1) the insert that simulates the banks of the river, (2) the flume base that holds the insert and houses the water reservoir, submersible pump and control valve, and (3) the computerized flow controller which provides communication between the computer and the control valve.

2.5.2.2 Micromodel Insert Layout

Once the background research has been completed, appropriate Computer Aided Drafting and Design (CADD) files and recent aerial photographs of the reach are compiled. Using this information, a reasonable horizontal scale can be chosen so that a river reach of 5 km to 15 km (depending on channel width) can be represented in the model. The model horizontal scale is determined by trial until the required reach fits within the flume base. The maximum horizontal dimensions of the flume are approximately 200 cm long by 90 cm wide. Therefore, in choosing a scale, consideration must be given to the minimum channel width acceptable for evaluating the particular problem to be studied. Consideration must also be given to building the Insert with sufficient length to account for entrance and exit conditions. The minimum main-channel width used in micromodels is typically around 35 mm to 40 mm.

After determining the limits of the study reach and establishing a workable scale, the channel bank lines of the river are digitized from the aerial photographs. These lines are typically located at the vegetation line or, where sufficient information exists, at the recognized top bank location. Bank lines are sometimes modified to permit adjustment of the model banks if channel realignment is to be considered during the study. The modified bank may consist of either a removable section in the insert or just a setback in the bank line that can be adjusted using oil-based modeling clay. A reference plane and grid is established on the insert using an appropriate coordinate system such as the Universal Transverse Mercator (UTM) or the State Plane Coordinate System (SPCS). The coordinate grid is added to the CADD file describing the model limits.

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Three identical scaled plots of the model insert are used to manufacture the physical insert. These plots have existing stream boundaries and other model features such as islands, grid lines, head gates, and tailgates clearly marked. Two of the aerial photographs are laminated and glued to two pieces of acrylic sheeting. The acrylic sheets are then glued to the upper and lower sides of a piece of 76 mm thick high-density polystyrene foam. The foam layer and upper acrylic layer are cut along the stream bank and island lines to form an open trough or channel. These cuts are vertical giving the channel a rectangular cross-section area. Modeling clay is used in some instances to add slope to the banks if required to achieve the desired bathymetric response. The manufacturer uses the third plot during construction of the insert. The head gate and tailgate structures are then constructed and placed within 100 mm to 300 mm from the beginning and end of the model, respectively. The tailgate consists of a fixed free overfall. The sides of the model channel are painted black to reduce the capture of extraneous data when surveying the model bed.

2.5.2.3 Micromodel Flume and Setup

The completed insert is placed within a table-size flume base that measures approximately three feet by 6 feet. Woodworker's clamps are used to secure the insert to the flume to prevent movement during model operation. Rotational jacks located within the flume base control the slope of the model in both the longitudinal and transverse directions. A 20 gallon reservoir with a small sedimentation chamber and submersible pump is located within the flume base along with an electronic control valve that controls flow to the model insert. Another reservoir is located outside and above the flume base to provide a constant head for flow. A magnetic flow meter is placed on the inlet line to monitor flow during operation of the model. The slope of the flume base is initially adjusted to approximately 0.01 in the longitudinal direction and zero in the transverse direction. The head gate and tailgate assemblies are adjusted to near mid-depth of the insert to control bed elevations. Existing prototype river training structures are simulated by galvanized steel mesh and placed within the insert at the proper locations, lengths and elevations. Because the vertical scale and shift are initially unknown, the first structure

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elevations placed in the model are visually set relative to the maximum water levels to produce a trial bed response. This bed response is then used in estimating the vertical scale and shift for setting structure elevations in subsequent runs. Sediment, consisting of a plastic Urea Type II is then added to the insert to about one-half the channel depth or approximately 1.5 inches. The material is randomly placed in the flume without molding by the modeler. Several different sizes of sediment can be combined to represent the bed material of the stream under investigation. Selection of model sediment gradation is based upon past experience with models of similar reaches of a stream and on the size of the model.

2.5.2.4 Micromodel Operation

The model is operated using a customized computer control system that simulates a hydrographic cycle. The cycle chosen can be either constant flow, sine wave, triangular or user defined. In addition to choosing a cycle, the duration of the cycle can also be specified. During these cycles water and sediment are introduced into the head-bay by a submersible pump and then transported along the bed of the model until it exits the tailgate and is discharged into the sediment chamber below. The submersible pump collects the sediment and again discharges it into the head-bay and the process is repeated. Through the use of the customized software, control valves and centrifugal pumps, a range of flows can be introduced into the model. The moving water and sediment are allowed to develop bed morphology similar to that in the river according to natural hydraulic principals. Once the process has begun, the hydrographic cycle continues until equilibrium conditions are reached. Equilibrium conditions generally refers to a state where the bed sediments move in a uniform manner throughout the cycle of operation and no sediment waves are observed moving along the bed of the model.

2.5.2.5 Micromodel Calibration

Calibration of the model usually begins by introducing a constant discharge to the head-bay of the insert. This flow begins to form the bathymetry of the bed given the channel alignment, the amount of sediment in the model and the tilt of the flume. After

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equilibrium conditions have been reached and the model bed has stabilized, the slope is adjusted by adding or removing sediment, increasing or decreasing the tilt of the flume, adjusting the tailgate elevation or a combination thereof. These adjustments are continued until the water surface is parallel to the reference plane established on the surface of the insert. Water surface elevations are measured using a mechanical three-dimensional digitizer. During the adjustment process guide vanes, roughness, non-erodible material and baffles are added, and fine-tuned as necessary, until a reasonable inlet flow distribution is achieved. It is especially critical that flow conditions into the study reach be defined properly, since it is here that the stage is set for bed development throughout the rest of the model.

The constant discharge is run at a high flow of approximately 9 l/min. to 12 l/min. to establish a high flow limit on the hydrographic cycle. The discharge is then changed to a flow of around 3 l/min. to 4 l/min. to ascertain a low flow limit on the cycle. High and low flow limits are determined when a desired level of sediment movement is observed in the model. The desired state of sediment mobility is based on the modeler's experience and judgment.

After establishing high and low flow conditions, unsteady flow is introduced in the form of either a sinusoidal or triangular wave. The sinusoidal mode opens and closes the control valve in a stepped sequence, which simulates a sine wave cycle, while the triangular mode does the same resulting in a linear opening and closing of the valve. This cyclic operation provides a mechanism for simulating the effects of the hydrographic cycle of the prototype. The cycle time can be set, at the modeler's discretion, at a low time scale, such as 2 to 3 min./cycle, or a high time scale, in the range of 10 to 15 min./cycle. Models are normally operated between 3 and 5 min./cycle. It should be noted that the time cycles in the model are not related to time scale in the prototype.

The vertical scale of the model is determined through a trial and error process during the calibration phase. All data is referenced to the coordinate plane on the surface of the insert, which is set at zero elevation. This plane must be shifted vertically toward the surface of the sediment bed so that the reference plane matches the prototype reference plane. The vertical offset between the model reference plane on the insert

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surface and the equivalent Low Water Reference Plane (LWRP) of the model is called the shift factor. The LWRP on the Mississippi River is based on a statistical analysis of historical river stages and is defined as the stage that is exceeded 97% of the time. Bathymetry collected in the prototype is normally converted from standard elevation data to LWRP format. Adjusting the shift moves all model elevation data vertically toward the model LWRP. Refinements to the shift and vertical scale continue until the model data approximates the prototype data and the model is considered to have geomorphologic similarity. After the shift and vertical scales are determined, water surface elevations are checked during constant discharges at low and high flow limits to determine the prototype stage conditions being modeled. Typically the maximum model flows represent +5.0 m to +6.0 m LWRP in the prototype; however, higher stages have been used on some models. Minimum model flows tend to be at the LWRP. Higher flows in the micromodel produce a greater energy level and result in excessive sediment movement. Entrance and exit conditions may be modified slightly, if necessary, to improve the ability of the model to reproduce prototype conditions.

After final adjustments are made to slope, sediment, vertical scale, and shift, the model is operated for several timed hydrographs to ensure that the model is in equilibrium. As stated earlier, equilibrium generally refers to a state where the bed sediments move in a uniform manner throughout the cycle of operation and no sediment waves are observed in the model. When it is established that equilibrium conditions exist, the model bed is surveyed using a three-dimensional laser.

Data collected are processed through a customized computer program that converts the model data to prototype coordinates. The data are then converted to hydrographic maps using CADD software and compared qualitatively to prototype surveys to determine general bathymetric trends. Thalweg location, deep pools, crossings and sandbar locations are some of the parameters currently used as a basis of comparison. When comparison reveals disagreement between the model survey and the prototype surveys, small adjustments are made by changing model tilt, entrance and exit conditions, and boundary conditions. This process is repeated until morphologic

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similarity between the model survey and the prototype surveys is such that the model is considered to be calibrated and baseline conditions exist.

Consistency between repeated model surveys and their comparison to prototype surveys indicates when model baseline conditions have been attained. The actual measure of how well the model data replicates the prototype data depends on the modeler's interpretation of the survey results. Generally it is evaluated on how well the converted model data visually reproduces the prototype survey data in both general elevation and location. The modeler is looking at bathymetric and flow trends as opposed to exact depths or velocities.

In reaches where prototype data are available, flow visualization provides a method of comparing surface flow conditions in the micromodel to prototype flow conditions. Prototype data, which may be available, consists of aerial photography containing ice floes, float data, or Acoustic Doppler Current Profiler (ADCP) data obtained through surface velocity and path measurements. Flow visualization in the model utilizes timed exposures during a constant flow to record the path of surface confetti. The method currently in use employs seeding the model with plastic urea, the same material used to compose the bed. When dry, the urea will float providing an excellent method of tracking surface flow patterns. The added sediment must be captured at the tailgate and removed from the model to avoid increasing the amount of sediment in the system, which would, in turn, increase the model slope and energy. Flow visualization serves as a mechanism for comparing flow paths, resulting from alternative designs, with baseline data.

2.5.2.6 Design Alternatives

Once baseline data have been established and the model is considered calibrated design alternatives may be applied to the model. The modeler prepares alternative design strategies and confers with pertinent technical personnel, as necessary, to reach stated study objectives. Proposed designs consist of possible structure locations, alignments, lengths and elevations. Each proposed design is placed within the model, and the model is operated through several hydrograph cycles until the bed is stabilized. The actual

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number of cycles depends on the relative magnitude of the changes induced by the alternative structures. Typically five or six five-minute cycles will bring the bed to equilibrium conditions.

Slight changes may require less time for the model to re-stabilize the bed while more drastic changes may require more time. Bed re-stabilization occurs when the model bathymetry obtains a new equilibrium condition. The new equilibrium condition exists when bed material transport remains relatively consistent over several hydrograph cycles and no sediment waves are observed in the model. The resultant bathymetry is surveyed using the laser scanner, and the data are compared qualitatively to baseline conditions. The effectiveness of the alternative is evaluated, a new alternative introduced into the model, and the process repeated.

2.5.2.7 Simulation of River Training Structures in the Model

The generalized impact on the riverbed imposed by dikes, weirs, closure structures, and other channel regulating structures in the prototype are highly desirable to the river engineering community. These type structures have been used extensively in both micromodels and large-scale models to mimic current conditions or to test new design alternatives.

During the calibration phase of either large-scale or micromodels, the existing dikes in the study reach are set in the model according to their actual elevations. Structure elevations in the WES models are set using the rail datum and vertical scale of the model. Structure elevations in the micromodel are set using the reference datum and the selected shift and vertical scale of the model. If dikes and other training structures are not set to their proper elevations, then the model bed will not respond correctly and calibration is adversely affected. Because prototype structure elevations are utilized to set model structure elevations, dikes in the model can be designed to an approximate elevation by setting their elevation relative to the existing structures in the model. Therefore, an approximate design elevation is obtained from the model for use by the modeler and designer in developing plans for construction in the river.

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One of the most important functions of movable bed models is the ability to make qualitative assessments on the three-dimensional effect of dike structures on the bathymetry of a river. An area of concern in the model's bathymetric response to these structures involves a realistic reproduction of scour patterns. The reproduction of scour in vertically distorted models requires special attention.

Because the model is geometrically smaller than the prototype, the turbulence associated with a solid boundary structure in the model is relatively greater than the turbulence associated with the same boundary structure in the prototype. Distortion of the vertical scale length also magnifies the disparity between model and prototype turbulence effects. The increased model turbulence, which exaggerates scour patterns, was evident on the early micromodel studies where solid boundary structures were used. This was also true for many past model studies at WES.

The exaggerated response typically observed around many of the dikes in the models was a large scour hole off the end of the dike which wrapped around the upstream side of the structure. This formation is the opposite of conditions observed in the river. Typically, a depositional pattern is located upstream of the dike while an area of scour or plunge pool is formed downstream when the dike is overtopped.

Two types of material, sheet metal and a cement-pebble conglomerate, were predominantly used in the WES models to represent dikes. In many cases, the response of the bed observed around these structures was not representative of what was actually occurring in the river. Figures 1 and 2 shows excessive scour around sheet metal structures and rock structures tested in the St. Louis Harbor model. Other structures, including the bendway weirs in the large-scale Dogtooth Bend Model, also exhibited increased scour. The scour that occurred off the ends of many of the structures was so great that the bottom of the concrete flume was exposed. Once the flume bottom was exposed, the bed was essentially armored, which then caused the scour to exaggerate laterally. This created a wider scour pattern that unrealistically represented the bed response of the prototype. Case studies of both models are presented later in this report and provide more description of the model studies.

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The same types of problems were noted early during the development of the micromodels, including the original work done at the University of Missouri-Rolla (UMR) (Davinroy, 1994). Impervious sheet metal (.01 inch) was first used to represent prototype rock dikes. As was the case of the WES models, the exaggerated scour of the models was accepted as a limitation of the model, with the underlying philosophy that as long as changes in the thalweg could be observed, one could still make general conclusions about the effectiveness of dikes in the model. However, this limitation would result in extreme difficulty during model calibration due to the inability to control the exaggeration of scour depths and the lateral extent of the scour created by the dikes.

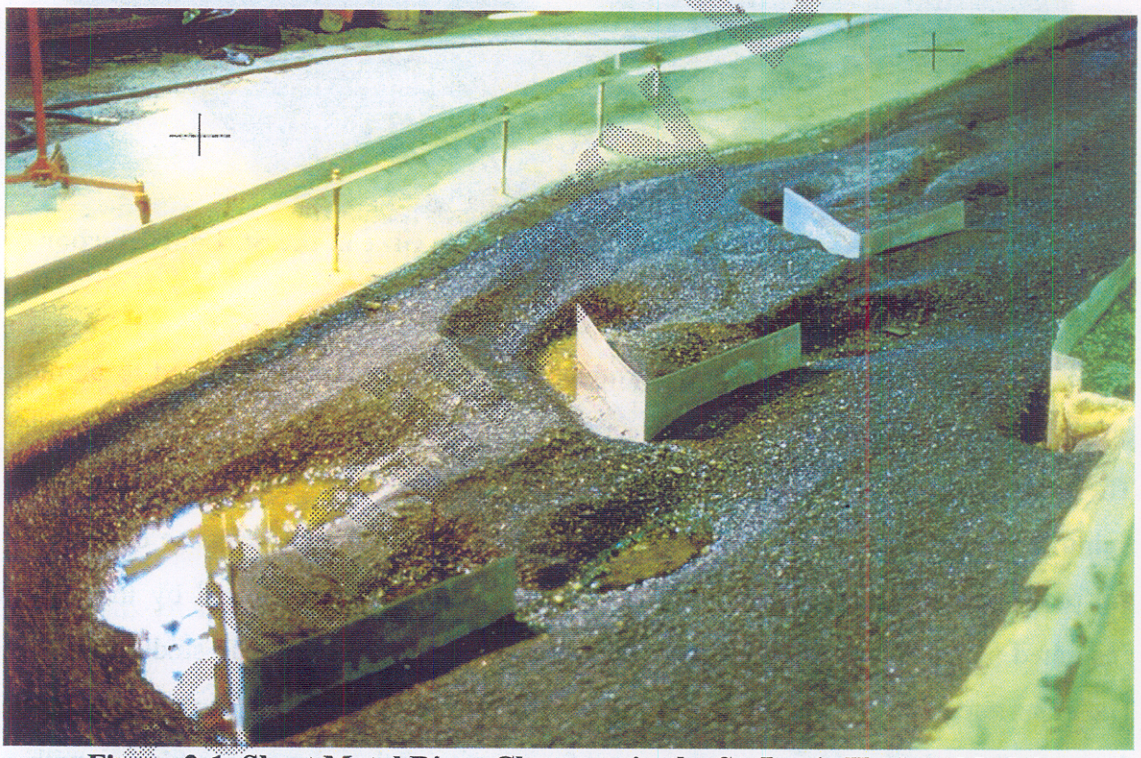

Figure 2-1 Sheet Metal River Chevrons in the St. Louis Harbor Model.

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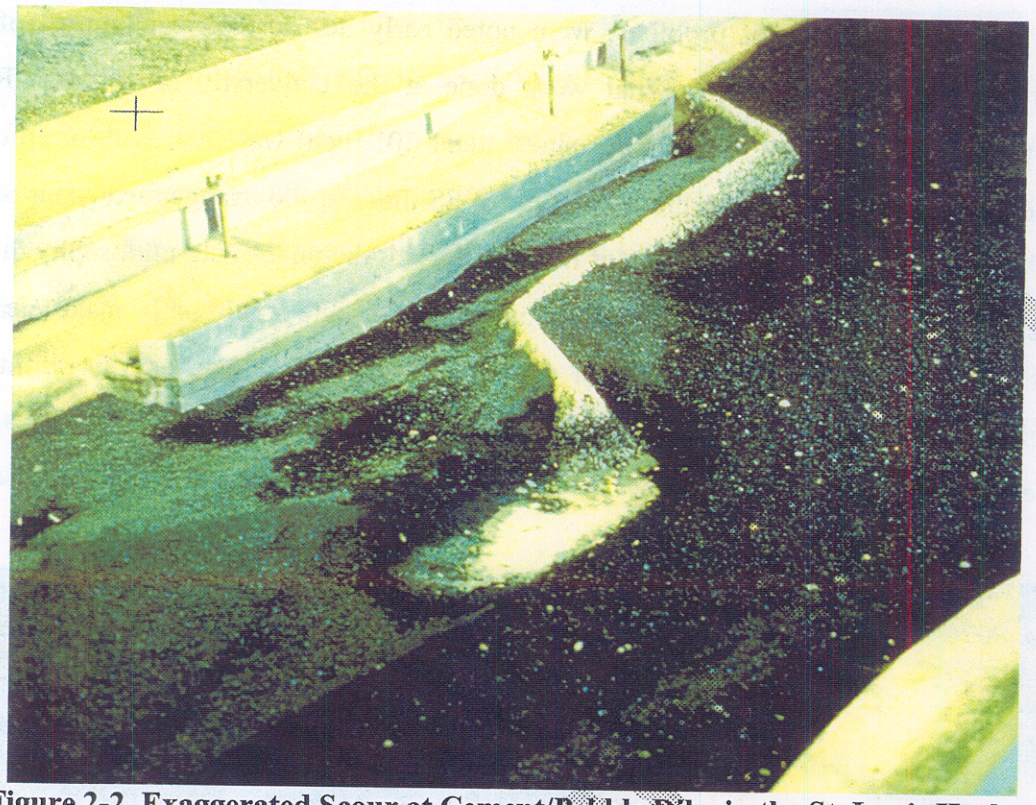

Figure 2-2 Exaggerated Scour at Cement/Pebble Dike in the St. Louis Harbor Model

Developed through flume experimentation, porous structures proved to be more effective in mimicking the bed response of solid dike structures observed in the river. The micromodel approach currently utilizes pervious steel mesh to represent prototype training structures to simulate scour patterns and the depositional response observed in the prototype. The use of porosity in the micromodel was reinforced by the effects generated by both impervious and porous structures observed in flume studies at IIHR. The experiments in a fixed bed flume showed that impervious structures radically distort the near flow field. However, the use of porous model structures combined with a movable bed greatly dampened this distortion. The porous structures enable a relative lowering of the forces and shear stresses traditionally applied to the model bed with solid structures. Structure porosity in models also introduces a presently unknown scale effect through altered flow distributions. The end result of using porous model structures is a reproduction of the bathymetric response around these structures that is comparable to the bathymetric response created by solid rock structures in the prototype.

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2.6. MICROMODELS CONTRASTED WITH OTHER LOOSE-BED MODELS

While similarity laws are not followed closely in qualitative models, there are differences between the micromodel and most previous qualitative models. The differences refer not only to the large-scale models conducted at WES but also to loose-bed models conducted in Europe, South Africa, and other laboratories in the United States. Specific differences between the micromodel and other loose-bed models are as follows:

1) Small size- The micromodel is one to two orders of magnitude smaller than most qualitative models. Minimum channel width is on the order of 1.5 inches with horizontal scales of up to 1:20000. Model depths as low as ½-inch are an order of magnitude less than the minimum of 2.5-inches recommended in Gujar (1981). There is no requirement for minimum Reynolds number used in the micromodel. The small model depths result in extreme distortion of relative roughness.

2) Large vertical scale distortion- With a few exceptions, distortion ratios used in the micromodel are about twice that in most qualitative models. Micromodels commonly use distortions of 8-15. Recommendations for maximum distortion in other qualitative models range from three to six or seven depending on the laboratory.

3) Vertical scale and vertical datum determined as part of the calibration rather than in model design. In converting model bed elevations to equivalent prototype elevations after a calibration test, various vertical scales and vertical datums are tried until the micromodel bed configuration most closely matches the prototype. This adjustment can be done in the micromodel because there is no similarity between model and prototype stages and discharges.

4) No correspondence of stage and discharge in micromodel to prototype stage and discharge - Although a distorted discharge scale is generally used, most qualitative models relate stage and discharge to a corresponding stage and discharge in the prototype.

5) Low stages run in micromodel- Typical alluvial streams have dominant or channel forming discharges that are roughly at a bankfull stage. Maximum stages in the micromodel are about 2/3 of bankfull. One positive feature of the low stages is that it reduces distortion effects.

6) Calibration of micromodel 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

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topography in model and prototype. The micromodel 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 micromodel and the relatively heavy (heavy for plastic) bed material (SG=1.47) results in steep slopes in the micromodel. Water surface slopes of the few micromodels that have been measured are about 0.01 ft/ft. This translates to about 53 ft/mile, which is about 100 times the slope of the Mississippi River. Steep slopes result in significant exaggeration of the Froude number. Froude number exaggeration will be discussed subsequently. Recent studies in the micromodel have experimented with material having SG = 1.2-1.3 which should reduce this problem.

8) The small model size and larger vertical scale ratio means that model sediment, when scaled to prototype dimensions using typical vertical scale, is 2-4 ft in diameter. The relatively large particle sizes coupled with small depths result in an extreme exaggeration of the relative roughness.

9) No similarity of friction in the micromodel. The micromodel methodology includes no provision for providing similarity in friction (or roughness) as done in some other qualitative model techniques. Reproduction of prototype stages in other models is one measure employed to achieve similar friction characteristics.

10) The micromodel uses porous dikes to solve exaggerated scour problems around dikes that occur in all distorted models. The porosity of these mesh structures reduces the turbulent effects and provides a corresponding reduction in shear stress at the model bed.

2.7. MODEL COMPARISONS

Successful model study results help define an acceptable level of morphologic similarity between the model and prototype. Because of the complexity that exists in loose-bed modeling deciding where to start is difficult. A logical place to start involves looking at previous model study results to help establish what defines an acceptable model. The current investigation thus began by considering previously completed models and their ability to reproduce prototype conditions. A comparison of model bathymetry to prototype bathymetry provided the basis of this analysis.

Although individual model study reports generally included a description of how the model reproduced prototype conditions, only one report was found to include a

systematic analysis of several models aimed at defining overall model accuracy (Franco, 1982). Franco's analysis utilized the same visual interpretation of model and prototype bathymetry used in model verification/calibration. Franco's report documented sand-bed model studies that utilized a slightly different approach than traditionally used at WES.

Instead of using the subjective methodology of comparing bathymetric data used during model calibration, the present investigation sought to utilize a quantitative approach in attempting to define morphologic similarity. A brief description of the methodology is described in Gaines, Gordon, and Maynord (2002). Gaines (2002) provides a more exhaustive description of the method.

2.7.1. Franco (1982)

In the early 1980's, Franco prepared a model-prototype comparison study of dike systems in connection with the Mississippi River Commission (MRC) potamology program. This study considered moveable-bed model studies conducted in seven of the most complex and troublesome reaches of the Mississippi River. The models included in this study were not typical of other sand-bed and coal-bed models used at WES.

Franco's (1982) comparison study intended to obtain some quick, general indications of the effectiveness of plans proposed for the improvement and stabilization of those reaches studied. Because of the limited time available, the model studies were conducted in an existing facility with little or no adjustment of the models and in some cases without a base test. Only a relatively short reach of the river including the problem was reproduced with little or no overbank areas because of the limited size and shape of the available facility. Horizontal scales varied with each reach and depended on its size and shape. According to Franco (1982) these models were much smaller and had a higher distortion of the linear scales than was considered desirable for studies of this type. Each of the studies considered utilized sand as the model sediment material.

Franco's analysis of the model results compared with developments in the river indicated that the types of models used predicted, at least qualitatively, most of the principal trends that actually occurred in the river with the plans tested. According to Franco (1982) the degree of accuracy of the models varied and depended to a

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considerable extent on the model adjustment, characteristics of the reach, flow conditions, and similarity between plan tested and actual construction.

Franco's comparison effort consisted of a visual appraisal of model bathymetric surveys and a number of prototype bathymetric surveys in a manner consistent with methods used in verifying other large-scale models. There was no attempt to quantitatively compare model and prototype bathymetry. Excerpts from Franco's (1982) report are included in Appendix D.

2.7.2. Gaines, Gordon, and Maynord (2002)

Gaines, Gordon and Maynord (2002) describe comparisons of the verification phase of thirty previous model study results using morphologic similarity. Only the verification or calibration model surveys were compared to the respective prototype surveys for these studies. Morphologic similarity was quantified in each of the model studies using difference calculations, mean square error (MSE) values, and morphologic parameter plots by range. The parameters used to define morphologic similarity are the thalweg location, the cross-section area, the top width, the hydraulic depth, and the ratio of width divided by the depth. These parameters, calculated for a number of Ranges within the model reach, provided a description of the hydraulic geometry and the channel planform. Gaines, Gordon and Maynord (2002) provide a case study example to define the methodology used in comparing morphologic similarity.

Average difference and MSE values between individual data sets provide a quantitative expression of overall parameter similarity. The magnitude of differences, calculated for the five morphologic parameters in the fourteen micromodels, are similar to those calculated for the sixteen large-scale models. For example, differences in cross-section area at 0.0 LWRP are -25 percent, -22 percent, and + 13 percent for the Kate-Aubrey large-scale model, the 1:8,000 micromodel and the 1:16,000 micromodel, respectively. The corresponding MSE values for these models were 0.331, 0.216, and 0.319, respectively. Values for all thirty model study results are included in Gaines, Gordon and Maynord (2002).

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A significant observation by Gaines, Gordon and Maynord (2002) is that the difference and MSE values do not adequately define how well a model actually reproduces the prototype and that a third method is required. The additional method is necessary because the difference and MSE values represent averaged reach conditions. The averaging of values over the reach may result in difference and MSE values that do not sufficiently describe the morphologic similarity. Therefore, a third method suggested by Gaines, Gordon and Maynord (2002) includes morphologic parameter plots by Range for model and prototype bathymetry. These plots provide a means to view the level of agreement between model and prototype data throughout the model reach, particularly in the specific reach pertaining to the problem under investigation.

Although the plots of morphologic parameters by Range do not provide a quantity that describes the level of similarity, the plots do provide a consistent way to present how well the model represents observed prototype conditions. Presentation of this information allows engineers and scientists that use the model results to understand how well the model reproduced the prototype (e.g. goodness of fit) which will aide in applying model results to develop prototype designs. An expression of "goodness of fit" may be obtained through statistical analysis of the data to develop confidence levels; however, additional data needs to be obtained from model and prototype to facilitate this analysis. Documentation of the necessary data from present and future model studies is discussed in subsequent sections.

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3. BASIC ENGINEERING ANALYSIS

3.1. GENERAL

ASCE (2000) presents the dimensionless parameters associated with flow of water and sediment in channels with a bed of cohesionless particles as

$$\Pi_A = f_A\left\{D\left(\frac{g(\rho_s-\rho)}{\rho\nu^2}\right)^{1/3}, \frac{\rho RS}{D(\rho_s-\rho)}, \frac{\rho_s}{\rho}, \frac{D}{R}, \frac{B}{R}, \frac{\sigma}{\rho g S R^2}\right\} \quad (3\text{-}1)$$

where D is a representative sediment particle size, R is the hydraulic radius, B is the width, S is the slope, σ is the surface tension, g is the gravitational constant, ρ_s is the sediment density, ρ is the density of water, and ν is the kinematic viscosity of water. The dependent variable A in Π_A might be flow resistance, thalweg sinuosity, sediment transport, or some other variable in alluvial channels. Scale distortions arise when these dimensionless parameters are not the same in model and prototype. However, some of the dimensionless ratios do not cause significant effects under certain conditions. For example, the last parameter on the right side of equation 1 will not be the same in model and prototype, but the effects of surface tension in model and prototype will be negligible if the model is large enough. The present investigation did not determine the effects of surface tension in micromodels. The first term on the right hand side is a particle density term, which shows that if a light weight material is used, the particle size in the model will be larger than in the prototype. The second term is the Shields parameter that is present in almost all loose-bed model criteria. The third term ρ_s/ρ is often ignored because density effects are addressed in the 1st and 2nd terms of the right side of the equation. The fourth term on the right hand side, D/R, is the relative roughness, which is almost never equal in model and prototype of sand bed streams. Relative roughness is often assumed to have negligible effects on results. However, Ettema et al (????) has shown significant scale effects of D/R on bridge pier scour. The micromodel has an extreme distortion of D/R which can be as low as 1/6 whereas the prototype values are 2 to 4 orders of magnitude less. The 5th term on the right side is the aspect ratio which is another term which can rarely be maintained the same in model and sand bed prototype

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rivers. The micromodel distortion of vertical scale and thus B/R is about twice as large as most previous loose-bed models.

A review of the literally hundreds of references on loose-bed modeling reveals that guidance for design and operation of loose-bed models consists of similar sediment mobility and flow patterns yielding similar bed configuration. As will be discussed subsequently, some of the techniques for insuring similar sediment mobility can adversely affect reproduction of flow patterns and thus bed configuration.

The numerous working model and research studies pertaining to model and prototype similarity provide insight into the present problem of evaluating micro-scale physical sediment models. However, a fundamental study of scale and scale distortion effects is necessary to establish the degree of flexibility possible without adversely impacting model results. Fixed-bed or rigid-boundary flume studies by the Iowa Institute of Hydraulic Research (IIHR) provided information regarding vertical distortion effects on separation and reattachment lengths (Ettema, 2002). A similar program of loose boundary flume experiments (Gaines, 2002) delineated possible deviations from similarity requirements. The flume experiments targeted a better understanding of the basic parameters associated with the far-field and near-field levels mentioned above. Williams (1970) performed related experiments when investigating the effects of flume width and water depth on sediment transport. The Williams (1970) study results supplement the flume data collected during the present research. Detailed measurements of localized flow features such as turbulent velocity fluctuations and point velocities are not required at this fundamental level.

Limits for model application and the acceptable deviations in similarity parameters are somewhat dependent on the variability in prototype conditions. The dependence lies in selection of prototype values to be used in assessing the similitude criteria (e.g. Froude number, roughness, sediment mobility). Prototype variability makes it difficult to define the level of agreement between model and prototype. Therefore, the level of expected accuracy (and similarity) from a model must be tempered with knowledge about prototype variability because this variability defines the basis for the similarity relationship between model and prototype bathymetry.

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Arguably, prototype variability is partly a function of man's ability to measure physical phenomena in the riverine environment. The true accuracy of prototype discharge measurements is unknown because the absolute volumetric flow rate cannot be determined. Buchanan and Somers (1969) suggest that capabilities for field measurement of discharge under ideal conditions is repeatable to within approximately +/-5 percent.

Accuracy of sediment discharge measurements, especially bed load which is highly dependent on flow depth, cannot be reliably estimated. In particular, the Mississippi River (and other large river systems) poses significant obstacles to measurement of sediment transport phenomena and even discharge data are difficult to obtain. For example, water discharge data for the Mississippi River is only periodically collected for relatively few locations.

The limited spatial (and temporal) definition of discharge (much less velocity distributions and sediment transport) makes the concept of similarity for a particular model reach problematic: what discharge should be used, what energy slope exists in the prototype, and what bathymetry is most representative? This leads to the conclusion that similitude in open rivers can not be defined in absolute terms.

3.2. FUNDAMENTAL CONCEPTS

Ettema (2000) assisted in developing a scheme for evaluating use of small-scale physical sediment models. Although his framework targeted investigations into veracity and limits of micromodel use, the concepts can be generalized to represent physical modeling as a whole.

Establishing an analysis framework begins by identifying important variables that are associated with the intended purpose of models. Thus, the purpose of physical sediment models must be expressed. Physical sediment models rarely attempt to replicate the full flow and sediment transport phenomena. These models usually target only a limited number of processes where model-to-prototype similarity can be achieved through a calibration or verification process. Those processes in turn mimic, to varying degrees, the degrees of freedom existing in alluvial rivers. The degrees of freedom describe the flexibility by which a river adjusts in response to flow and sediment loading

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and to external constraints imposed by the morphology of the banks (e.g., bed rock or rock outcrops).

Three principle freedoms are apparent from observation of most streams: adjustment in channel depth, adjustment in alignment, and adjustment in cross-section shape. The successful prosecution of a physical sediment model entails reproducing these natural adjustment tendencies. However, owing to the high degree of complexity and mostly unknown processes associated with lateral channel adjustment, such models typically employ a rigid (or nearly so) planform where meander migration and bank progression are restricted. Thus, the thalweg is constrained to the confines of the channel banks. This confinement partially limits channel response and the thalweg can adjust only within the channel. Thalweg alignment, therefore, retains a measure of freedom to adjust laterally, but the overall channel alignment and the banks may dictate thalweg location (e.g. at sharp bends, where the channel is narrow, or where banks are not susceptible to erosion). Where river training structures exist, a further reduction in thalweg positional freedom occurs, and in the extreme case, the channel behaves as a constricted reach with limited potential for adjustment of thalweg position. Distortion of various model parameters (i.e., vertical scale, slope, and roughness) produces further constricting effects.

The consequences of constricting the thalweg's ability to shift in response to water and sediment may pose problems in achieving successful model results. Because thalweg alignment is often a key component of physical sediment model studies, a reduced ability of the thalweg to move may create difficulties in model calibration and in applying model results to the prototype. This is especially true for highly distorted models whose primary objective is to estimate the position and number of flow-training structures necessary to constrain the channel thalweg alignment and its concomitant depth as described by Davinroy (1994, 1999) and Gaines and Maynord (2001).

3.2.1. Important Variables. The important engineering variables for most river training essentially relate to thalweg behavior. Table 3-1 provides a recapitulation of factors that influence model and prototype similarity. Consider then the possibilities for

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general thalweg behavior as depicted in Figures 3-1, 3-2 and 3-3 (Ettema, 2000). In Figure 3-1 Ettema depicts a hypothetical, unrestrained case where thalweg position is free to adjust vertically, laterally, and downstream within the channel banks. Principle variables that characterize this case are channel width (W), slope (S_o), sediment size (D), thalweg depth (Y_o), lateral thalweg position within the channel width (T_o), and sinuosity (ζ_o). Figure 3-2 depicts a hypothetical long constriction that results from multiple training structures. Principle variables characterizing the long contraction are channel width, slope, sediment size, thalweg depth, Y_1, lateral thalweg position, T_1, and sinuosity, ζ_1. Figure 3-3 illustrates a hypothetical short constriction resulting from a single training structure. Thalweg position for this case is considered partially fixed with freedom to move vertically and to a small degree laterally (freedom to adjust only in the approach to and exit from the cross-section containing the dike). Principle variables of interest for the short contraction are channel width, slope, sediment size, thalweg depth, Y_2, lateral thalweg position, T_2, and sinuosity, ζ_2. The contracted width, W', may also be of interest for the contracted cases (as in Figures 3-2 and 3-3) as Ettema presents the ratio of contracted width to the uncontracted width, termed the contraction coefficient (C_C), as a diagnostic parameter for general flow field similarity.

The variables defining thalweg depth, alignment, and sinuosity are dependent variables – their values depend on the independent variables that characterize flow, sediment transport, and boundary geometry. Ettema casts these independent variables in the form of non-dimensional parameters that describe the similarity conditions for physical sediment modeling. Variables that influence flow and bathymetry

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Table 3-1 Factors Influencing Model-to-Prototype Similarity Requirements

GEOMORPHIC/HYDROLOGIC				SEDIMENT			TRAINING STRUCTURE			
Stream	Width:	-variability		Bed Material	median size	D_{50}	Type	Abutment		
		-bankfull width			grainsize distribution			Dike/wingdam		
		- low flow width			density	ρ_s		Bendway weir		
	Channel:	-cross-section shape			cohesiveness			Lateral dike		
		-slope			non-erodible			Chevron		
		-depth		Particle	Incipient mobility	θ_c		Revetment		
	Thalweg:	-straight			State of mobility	θ, τ_*		Vane		
		-sinuous	ζ_s		Bed-forms:			Closure		
		-divided channel			- type					
	Bathymetry	Alignment Geometry			- magnitude		Character	Length	L	
		- radius of curvature	r_c		- wavelength	λ		Height/elevation		
		- central angle of bend	α		Sorting/Armoring			Number	N	
Hydraulic	Discharge:	-magnitude	Q		Fall Velocity	ω		Location		
		-variability						- straight reach		
		-duration	t	Transport	Equilibrium State			- bendway		
					-Equilibrium					
					- Dis-Equilibrium			-side channel		
	Flow Velocity:	- mean velocity	V, u, v		Rate	q_s		Spacing	l	
		- lateral distribution			Form of Transport:			Alignment	α	
		- secondary currents			- bed load		Detailed Features	Notches		
	Turbulence	- magnitude			- suspended load					
		- flow field	Re		Lateral Distribution					
		- boundary	Re*		Porosity	ε				
		- intensity								
	Flow Depth:	- main channel deoth	y, h, H							
		- lateral distribution								
	Fluid:	- Temperature	T							
		- density	r							
		- viscosity	n							
		- surface tension	σ							
	Roughness:	- bed	f_b							
		- banks	f_w							
		- total	f							

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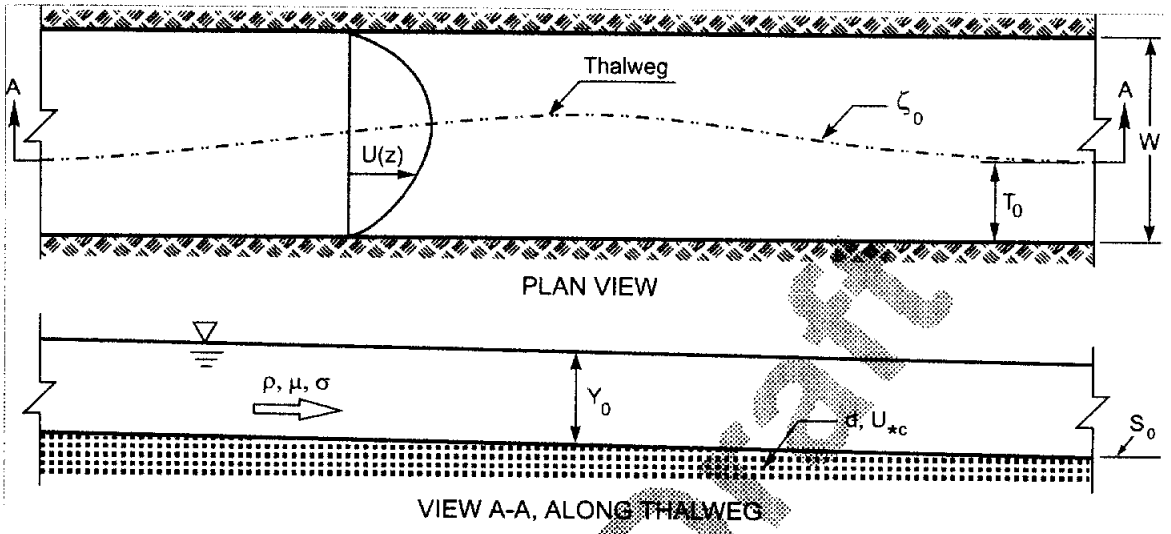

Figure 3-1 Hypothetical Flow, Sediment and Thalweg Alignment Along a Channel of Fixed Width (after Ettema, 2000).

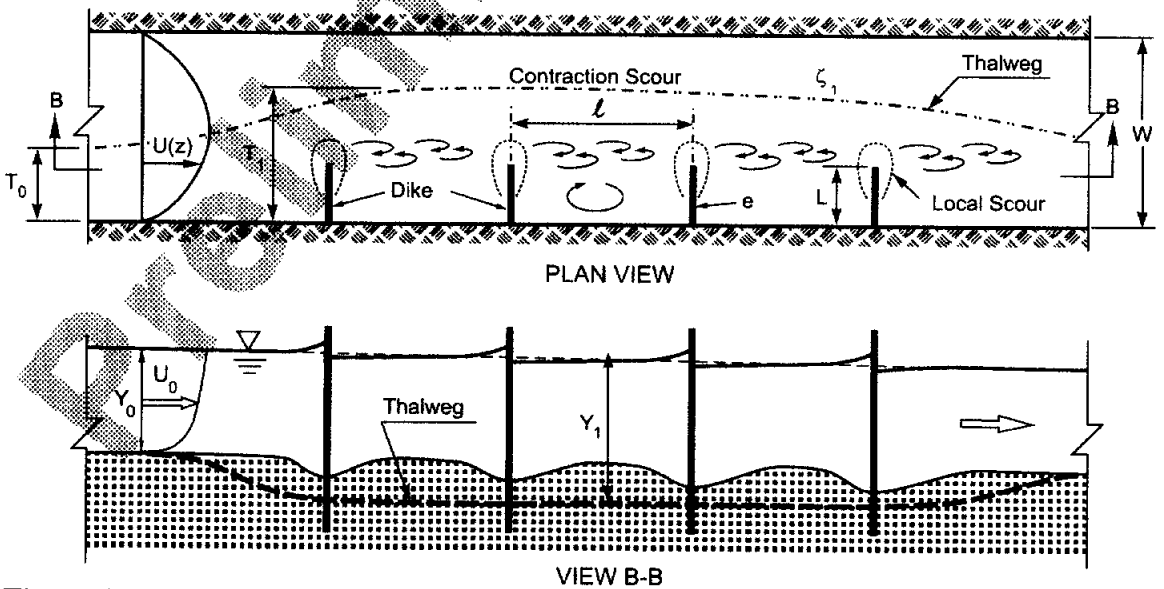

Figure 3-2 Hypothetical Flow, Sediment, and Thalweg Bathymetry Through a Long Constriction in a Channel of Fixed Width (after Ettema, 2000).

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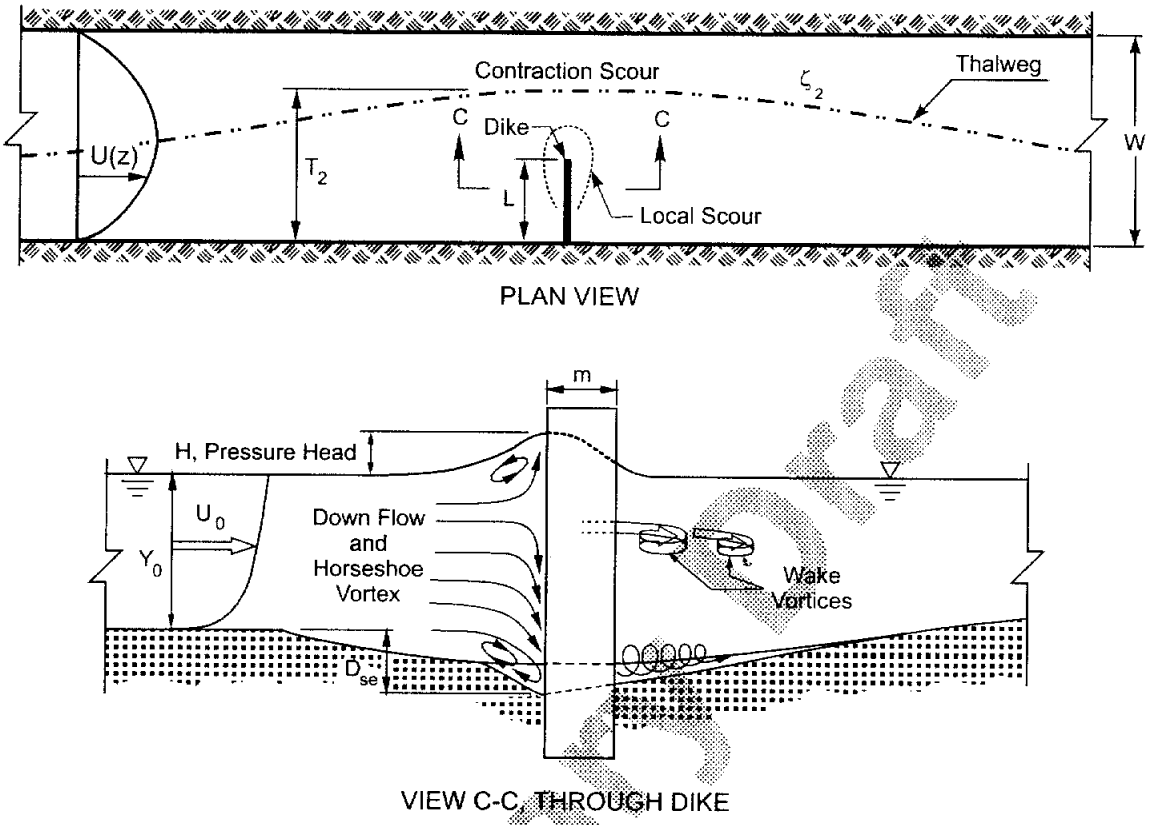

Figure 3-3 Hypothetical Flow, Sediment, and Thalweg Bathymetry Through a Short Constriction in a Channel of Fixed Width (after Ettema, 2000).

for micromodels, as shown in Figure 3-1, are

$$\rho, \sigma, \mu, S_0, u_{*0}, g, D, u_{*_c}, W$$

where ρ, σ, μ define fluid properties of density, surface tension, and dynamic viscosity, respectively; g is gravitational acceleration; u_*, u_{*c}, and D define sediment material characteristics of shear velocity, critical shear velocity, and representative particle size, respectively; and W is channel width. This is a slightly expanded list of variables as compared to those used by Yalin (1971). Ettema applied dimensional analysis with u_{*o}, D, and ρ as repeating variables to yield the following dimensionless combinations

$$S_0, \frac{u_{*0}}{u_{*c}}, \frac{(u_{*0})^2}{gD}, \frac{\rho u_{*0} D}{\mu}, \frac{\rho D {u_{*0}}^2}{\sigma}, \frac{W}{D}.$$

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When the channel is contracted as shown in Figures 3-2 or 3-3 Ettema includes additional variables of

$$\rho, \sigma, \mu, S_0, u_{*0}, g, D, u_{*_c}, W, L, l, e, m, N$$

where L is the constriction length, l is the spacing interval, e is the structure porosity, m is the structure thickness (parallel to flow), and N is the number of structures. Applying dimensional analysis as before, Ettema derives the following dimensionless parameters

$$S_0, \frac{u_{*0}}{u_{*C}}, \frac{(u_{*0})^2}{gD}, \frac{\rho u_{*0} D}{\mu}, \frac{\rho D u_{*0}{}^2}{\sigma}, \frac{W}{D}, \frac{L}{D}, \frac{l}{D}, \frac{m}{D}, e, N$$

Both of the preceding dimensionless combinations characterize flow and sediment movement near the bed. Ettema proposes an alternate arrangement of these combinations to provide insight into the local flow field at obstructions, such as a training structure. This operation produces the following set of dimensionless parameters that pertains to the overall flow field

$$S_0, \frac{u_{*c}}{u_{*0}}, \frac{(V)^2}{gL\sqrt{f}}, \frac{\rho V L}{\mu\sqrt{f}}, \frac{\rho L V^2}{\sigma\sqrt{f}}, \frac{W}{D}, \frac{L}{W}, \frac{l}{L}, e$$

where V is the mean flow velocity and f is the Darcy-Weisbach resistance coefficient. Ettema continues with the description of dependencies relating to micromodels with each dependent parameter, T, y, ζ, described as functions of various independent non-dimensional combinations. In brief, Ettema's relationships intend to describe reach morphology imposed by the constriction.

3.2.2. Consequences of Distortions. Ettema (2000) further describes scale effects that result from the relaxation of four common characteristic parameters: increased length scale, vertical distortion, inflated bed sediment size, and exaggerated slope.

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Ettema provides calculated examples exemplifying the effect of reduced lengths (with no distortion in the vertical dimension, e.g. $x_r=y_r$) on Reynolds and Weber numbers (viscous and surface tension effects, respectively). Ettema asserts that reduced lengths alter local flow patterns and pressure gradients around simulated hydraulic structures, along the river bed, and along the river banks.

Regarding vertical scale distortion, Ettema also uses generalized calculations to demonstrate that distortion of the vertical dimension results in scale effects. Specifically, vertical distortion alters the cross-channel flow distribution because viscous forces increase. This in turn indicates that sediment transport is altered, particularly in the vicinity of structures and the bank. Melville and Coleman (2000) indicate that there is a relationship between scour depth and flow depth at bridge piers and abutments. Because certain abutment arrangements mimic the effects of dikes, scour tendencies are similar near the riverward end. Therefore, the scour depth versus water depth relationship would indicate that vertical exaggeration also impacts depth of scour. Lateral extent of scour features, particularly evident in the vicinity of a structure, is increased at least partly because the angle of repose of bed sediment material remains unchanged irrespective of vertical distortion.

Yalin (1971) presents the concept that where scale restrictions are relaxed, a model is only "partly dynamically similar." Such a relaxed model adequately reproduces only those prototype properties within the similar regions described by the governing non-dimensional combinations. According to Yalin (1971), prediction of the behavior of properties outside those represented by imposed similarity requirements is not reliable and should be avoided.

As an example, consider the influence of flow width, B, on a channel having a trapezoidal cross-section (Figure 3-4). If the width-depth ratio, B/y (depth, y, is used in lieu of the hydraulic radius for the wide channel example), of the channel is very large, then the functional relationship A (Equation 3-1) in the central region of such a flow can be regarded as independent of B/y. Thus, if only the flow properties in the central region are of interest,

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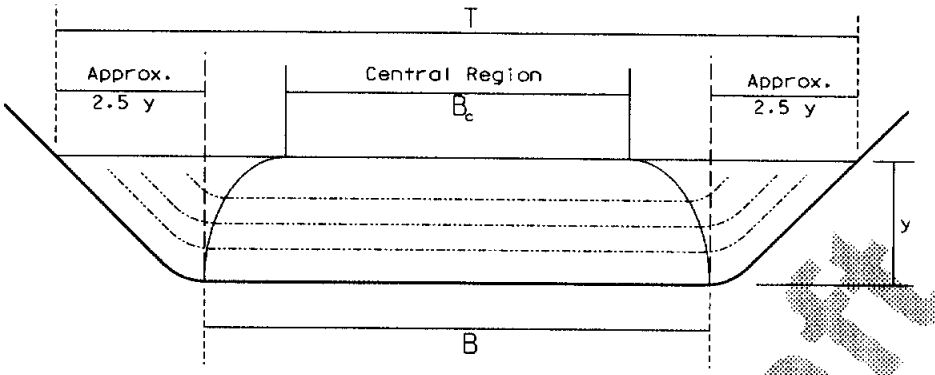

Figure 3-4. Regions within a Wide Channel

the requirement that

$$\frac{\left(\frac{B}{y}\right)_p}{\left(\frac{B}{y}\right)_m} = 1 \quad \text{or} \quad B_r = y_r$$

can be relaxed. This affords considerable economy by allowing the selection of different scales for width, B, and depth, y.

Vertical distortion results from selecting different scales for B and y. Large rivers typically have large width to depth ratios (three digits). As such, they behave as wide channels making it possible to consider them in basic two-dimensional terms. For wide channels, the central region depicted in Figure 3-4 exists. Where B/y is small the wide channel assumption fails, and the channel behaves in a more three-dimensional manner. The definition of a wide channel in this case varies, but Kuelegan (1938) suggests $B/y < 5$. Chow (1959) suggests that $B/y < 5$ to 10. Either case permits a degree of flexibility in selecting scales. However, certain bounds are implied.

Based upon data from published study reports, micromodels typically have flow widths of 1.5 to 8.3 inches and reach average hydraulic depths of 0.26 to 1.91 inches. The typical reach average values of width and depth in the micromodels are about 3.7 inches and 0.7 inches, respectively. These typical values of depth and width yield an

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average B/y of 5 for the micromodels[4]. By comparison, values of B/y for the Mississippi River are typically on the order of 50 for the Mississippi River at Memphis, TN for an equivalent water surface elevation of approximately +20 LWRP. Values of B/y for the large-scale models was not available for +20 LWRP as used in the micromodels. Therefore, values of B and y for a water surface elevation of 0.0 LWRP were used to make a relative comparison of prototype, large-scale, and small-scale model B/y values. The large scale models had average B/y that was 40 percent of the prototype B/y value at a water surface elevation of 0.0 LWRP; micromodels had average B/y that was 10 percent of the prototype B/y value at this water surface elevation.

Yalin (1992) discusses the long-standing debate regarding the relevance of cross-circulation. Cross-circulation is composed of two components, helicoidal flow and laterally oscillating flow. Helicoidal flow is induced by channel curvature and consists of a longitudinal fluid motion that also rotates as it moves downstream. Laterally oscillating flow is caused by the variation in channel curvature and is formed by fluid mass that shifts periodically left and right as it moves downstream. Yalin (1992) suggests that helicoidal flow is most prevalent in small meandering streams having small B/y values and that laterally oscillating flow is most prevalent in large meandering rivers having large B/y values. In this light, Yalin states the following conclusion: "it is not whether but when the cross-circulation is relevant (or prominent) - what is right for small B/y may turn out not to be so when B/y is large." The unknown factor in this case is when does cross-circulation (in the micromodel channels) become relevant. The answer to this lies in comparison of model results to prototype data.

Determining just how far the scales can be relaxed is an all important part of understanding loose-bed model design and operation. In loose-bed modeling, the modeler often fixes the degree of relaxation by selection of the vertical scale. In previous model approaches, vertical scale was selected during the initial model design. However, selection of vertical scale in the micromodeling approach occurs during the calibration phase.

[4] The values of B/y based on an equivalent prototype water surface elevation of +20 LWRP.

A priori selection of model vertical scale yields the advantage of assessing similarity criteria during model design. Accordingly, the Froude criterion provides an estimate of model discharges. Channel bathymetry serves to define gross sediment transport similitude, but similarity in sediment particle mobility is of secondary importance. This approach defines techniques employed in the sixteen large-scale models considered.

A disadvantage of selecting vertical scale prior to operating the model results from the lack of any means to allow the physical processes to establish the necessary distortions. Here distortions depict the interrelationship between the various distortions that occur at model scale. Specifying a vertical scale distortion fixes the linear dimension of depth, but other non-linear distortions occur in the model. For instance, Froude number is a function of the square root of depth. In reality, the selection of vertical scale should reflect all distortions that occur within the model and would no doubt result in a trial and error process to determine its optimum value (Jonte, 1949, Glazik, 1978, and Gasser, 1989).

Two parameters describing relative roughness, y/D, and relative sediment size, W/D, are impacted by changes in vertical scale. Ettema describes this effect in terms of u_{*c}/u_{*o} [critical value of shear velocity (u_{*c}) divided by the shear velocity relative to the flow field (u_{*o})]. Ettema suggests that approximate similarity based upon this ratio exaggerates the velocity head and associated pressure gradients. One mitigating factor regarding this distortion is that reduced relative roughness results in increased turbulence (e.g., reduced depth and the same or larger particle size (D) causes increased boundary layer influence), for all other factors held constant. Ettema's assessment in this regard further supports earlier discussions wherein the increase in turbulence from relative roughness was noted by other authors. As relates to bed form, Ettema suggests that a reduced W/y (or B/y) inhibits development of bed forms. This fact is noted from observation of models constructed with small widths and relatively large sediment sizes.

Slope distortion also occurs as a result of other distortions. Basing approximate similarity on sediment transport, which is a fundamental procedure for most physical

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sediment modeling, implies a similarity of u_{*c}/u_{*o}. Because u_* is a function of slope, a distortion in slope is essentially the same as vertical distortion with similar scale effects.

Kahn (1970) and Schuum and Kahn (1972) present a relationship between sinuosity and slope that indicates than when slope is increased, sinuosity increases up to a maximum then decreases. Therefore, distortion of slope in a model will likely affect the model's ability to faithfully reproduce sinuosity.

3.2.3. Sediment Mobility

Sediment mobility is quantified in most loose-bed model guidance by the Shields parameter. The Shields parameter represents the ratio of the forces tending to move the sediment to the ratio of the forces tending to keep the sediment at rest. The rational methods of Einstein and Chien (1956) and Yalin (1965) include the requirement that the Shields parameter in the model equal the value in the prototype. Einstein and Chien (1956) state that "no deviation from this equation is usually desired." Yalin (1965) states that the Shields parameter "is therefore the most important variable from the point of view of movement of bed material." Zwamborn (1966) notes that the rational approach "generally lead to completely impractical model scales." In Yalin (1971), an example using the Mississippi River and the classical approach yielded a model width of 10.25 m. This example was based on using the lightest possible sediment which would result in the smallest channel width.

Three techniques provide a means to increase sediment mobility in the model in order to achieve equal Shields parameter in model and prototype. In the Shields parameter, the water density, ρ, is fixed, prototype sediment density, ρ_s, is relatively constant, and the model particle size, D, cannot be scaled down due to particle cohesion problems. Sediment size will generally be about the same in model and prototype for sand bed alluvial streams. Therefore, if the model Shields parameter is to be increased or made equal to the prototype, the only parameters that can be varied in the model are ρ_s, R, and S. Adjustment of these three parameters leads to three techniques often used jointly in loose-bed models as follows:

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a. Lightweight sediment- Typical minimum specific gravity of model sediment has been about 1.05 but sediment this light has to be carefully handled and model flooding and startup are difficult. Walnut shells having a specific gravity of 1.3 have been used. Coal having a specific gravity of 1.3 is common. The plastic used in the micromodel having specific gravity of 1.48 is relatively heavy compared to other lightweight materials in use. The use of lightweight sediment has little direct effect on flow patterns but particle size is important in several aspects of model similarity. The model ratio of particle size to depth is larger than the prototype in all loose-bed models and Ettema (19??) has shown that a lack of similarity in this ratio can lead to problems with scour reproduction in models. Particle size also affects resistance which is important in reproducing correct water levels and flow patterns, particularly in bends.

b. Vertical scale distortion- Vertical scale distortion is the second technique used to achieve correct sediment movement. Horizontal scale/ vertical scale is referred to as distortion and values of up to 33 were used by Reynolds as reported in Freeman (1929). Vertical scale distortion results in attempting to model a prototype channel with a model that has an aspect ratio (width/depth) that is much less than the prototype. Knauss (1980) recommends distortion should not exceed 0.1 times the aspect ratio which is one of the more lenient recommendations for distortion. This limit of 0.1 times the aspect ratio is based on maintaining a wide central region in model that is not dominated by bank effects. For a typical Mississippi River section having an aspect ratio of 100, distortion would be limited to 10. This 0.1*aspect ratio limit does not address the dynamics of flow in bends which the literature suggests are most affected by distortion. Jaeggi (19??) concludes that morphological processes are highly dependent on width / depth and that a distorted model should be avoided. Glazik (1984) stated that distortion should be avoided in movable bed river models but that a value of 1.5 provided suitable results. Suga and Baba (1971) conducted bed evolution tests in a movable bed bend with distortions of 1, 3, and 5. The plotted profiles for distortions of 3 and 5 departed from the case with no distortion and did not vary in a consistent manner. Suga (1973) reports that distortions used in his lab's loose-bed model studies were five or less and concludes that distortion should not be used when scour depth and location are the main subjects. Foster (1975) presented cross section plots of velocity from a model with a distortion of three and an undistorted model of the St. Lawrence River. Foster concluded "The velocities in the distorted model shifted several hundred feet toward the outside of the bend from those in the undistorted model." Channel width in this reach was 1200-1500 ft. Zimmerman and Kennedy (1978) conducted research on curved channels to determine the transverse bed slope in bends and concluded distorted models can be used if distortion is limited to no more

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than 2 or 3. Chitale (19??) recommends limiting distortion to 6 or less. While these previous studies have recommended limitations on distortion, the regime theory requires distortion of models according to the equation

$$h_r^3 = L_r^2 \tag{1}$$

Using equation (1) and a typical micromodel L_r = 10000 in the micromodel results in h_r = 464 or a distortion of 21.5 which is generally greater than used in the micromodel. Note that as Lr increases, so does the distortion. Limits of applicability for equation (1) are unknown but no examples are found in the literature where regime theory has been applied in model design for scale ratios typically used in the micromodel. While no one would dispute that small channels generally have lower aspect ratios than large channels, what is not obvious is the subsequent conclusion that a model of a large channel must have a lower aspect ratio. A large channel often has multiple secondary current cells affecting flow and bed topography. A smaller channel or a distorted model of a larger channel may have only one much stronger cell affecting flow and bed topography, particularly in bends.

The rational approach of Yalin (1971) is based on the equality of Shields parameter and grain Reynolds number in model and prototype and results in

$$h_r^3 = \Delta\rho_r L_r^{3/2} \tag{2}$$

The rational approach also shows increasing distortion with increasing L_r. For typical minimum model depths and thus h_r recommended in the rational approach, equation (2) results in small allowable distortions.

The criteria for distortion fall into two categories of 1) distortion should be minimized and less than some value that ranges from 1.5 – 6 or 2) regime theory requires distortion but none of the applications of regime theory in the literature deal with L_r = 10000 typical of the micromodel. Studies of distortion in bends show pronounced effects on secondary flow intensity that are a result of distortion in the vertical scale dimension (Rocha, 1983).

c. Increase model slope- Increased model slope is the third technique used to achieve correct sediment movement. This leads to a Froude number in the model that is greater than the prototype which raises concerns about the ability of the model to reproduce flow patterns. Increased model slope is achieved by an increase in model discharge. ERDC coal bed models had

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discharge ratios (and Froude numbers) that were exaggerated at low flows but close to the flow required by equality of Froude number at high flows. In the Dogtooth bend micromodel at mid-bank flow, Davinroy (1994) reports that the Froude number in the micromodel was 6 times the Froude number in the prototype. Einstein and Chien (1956) allow some exaggeration of model Froude number but do not recommend a limit. In an example presented by Gujar (1981), a Froude number distortion of $F_m/F_p = 2.5$ was classified as large whereas 1.67 was classified as acceptable. Qingshen et al (1986) recommends a Froude number distortion of less than 2. Latteux (1986) reported a Froude number exaggeration of 2.5 was unsatisfactory but 2.2 provided acceptable results. Vollmers (1986) used Froude number exaggeration of 1.4 in the loose-bed model of the Elbe estuary which had a distortion of eight.

The earlier models of Reynolds in which distortions of up to 33 were conducted with tidal periods according to the Froude criteria (resulting in no distortion of the Froude number in the model). Tidal models require no distortion of Froude number to properly simulate the influence of waves. Without Froude number exaggeration, the Reynolds' model was slow with one simulation in the two feet wide by six feet long model lasting three weeks. Froude number exaggeration is based on the concept that Froude number has limited significance for low values typical of alluvial streams. A problem arises when the Froude number is exaggerated to the point where it is no longer insignificant in the model. Froude number distortion should be limited by not getting anywhere close to critical conditions at a Froude number of 1.0.

For example, a prototype Froude number of 0.5 and a Froude number distortion of 2.0 would result in a model Froude number of 1.0 and clearly be unacceptable. Sherenkov (1984) evaluated similarity of the recirculation zone below an abrupt channel expansion as a function of Froude number in a fixed-bed channel. Froude number effects were small, but not insignificant, up to a Froude number of 0.66. The length of the recirculation zone varied increasing by about 25% from a Froude number of 0.1 to 0.66. Between data points at a Froude number of 0.66 and 0.90, the recirculation length changed significantly. Sherenkov's best fit line started rapidly changing at a Froude number of about 0.75. Summarizing these findings, Froude number exaggeration has generally been limited to 2.0 or less and model Froude number, if exaggerated, should not exceed somewhere in the range of 0.66-0.75.

3.2.4. Performance Categories

Gaines (2002) summarizes several non-dimensional parameters and relationships that define sets of similarity conditions. These parameters and relationships describe flow and sediment motion in physical sediment models. Indeed, similarity relationships

mean little if the parameter being "simulated" is not understood in its full context. For example, there is a well known phenomena in rivers whereby a looped rating curve occurs; the so called hysterisis effect. Because all flow field and sediment transport similarity parameters (and processes) depend upon discharge, similarity must be viewed as variable; it too is a variable function that changes with time and location (Glazik, 1984, Gujar, 1981, and Gessler, 1971). As a result, similarity can be considered a risk problem. In this context varying levels of similarity relaxation are possible, with each level based upon the acceptable deviations allowable for the particular problem being modeled.

Melville and Coleman (2000) present a framework for bridge scour analysis according to five "scales" of scour processes (based on work by Parola, Hagerty, Mueller, Melville, Parker, and Usher, 1996). The spatial scales are as follows:

1. Catchment scale;
2. Stream section scale;
3. Bridge far-field scale;
4. Bridge near-field scale; and
5. Local scour scale.

Although these "scales" do not pertain directly to physical sediment modeling, *per se*, they illustrate the concept that analysis should begin with a focus on "macro" level phenomena with progressive refinements that more completely define detailed "micro" level features of the process. Such a scheme has merit in consideration of model-to-prototype similarity. For instance, focus on overall sediment transport and general bed response may be taken as a "macro" level phenomena (Parola et al. (1996) section scale) and similarity conditions are more relaxed (Ettema, 2000). Alternately, focus on local scour at a specific training structure, or the localized flow field response, may be categorized as a "micro" level phenomena (Parola et al. (1996) local scour scale) and similarity requirements are more restrictive. Thus, similarity conditions can be divided into categories that define the degree of flexibility that are permissible for the particular model objective. Using a similar scheme as the bridge scour analysis presented by

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Melville and Coleman, the following categories or levels of similarity relaxation are suggested:

1. Far-field;
2. Near-field;
3. Local-field; and
4. Detailed-field.

At the far-field level, only gross processes are significant as relates to physical sediment transport modeling. Here the dominant variables become those that influence general sediment movement, surface flow pattern and bathymetric response. The application of most physical sediment modeling fits within the confines of this category where an approximate intensity of sediment transport is achieved and the associated bathymetric response is evaluated by a calibration or verification process. Similarity requirements for this category are least restrictive. However, the permissible degree of relaxation and any associated effect remains largely undetermined from a quantitative standpoint.

Near-field similarity implies an increased attention to dimensionless parameters that describe both hydraulic and sedimentation phenomena. At this level, more attention is afforded the requirements of similarity as outlined by Zwamborn (1966), wherein three predominant similarity criteria are expressed. Here too, the permissible deviations in similarity are quantitatively undetermined. There are only subtle differences between model approaches at the far-field and near-field levels and some overlap is probable.

Local-field similarity introduces additional similitude requirements. The Einstein and Chien (1956) method for model design may be indicative of the types of similarity required at this level. At this level, requirements may dictate that the two-dimensional flow fields have greater similarity to the prototype than exists at the far- or near-field levels. A possible example for this level is where the model objective is to estimate the anticipated quantities of sediment extracted through a water intake. For this case, the width of the two-dimensional flow field has a major influence on the lateral distribution of velocity and of sediment -- the lateral distribution of velocity and particularly sediment

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impacts the quantity of sediment available for extraction. Permissible deviations in similarity are not determined for this level.

Detailed-field similarity invokes the strictest requirement for attaining similarity between the model and prototype. Conditions for this level are such that intensity and frequency of turbulent flow features become an important aspect of the model design. Vorticity and vortex shedding may also be of primary interest. This is the case for highly three-dimensional flow conditions such as exists at bridge piers or in the immediate vicinity of short contraction structures. Again, a quantitative description of flexibility in similarity requirements remains undetermined for this case.

An alternative approach to classify micromodel applicability stems from a consideration of the intended model purpose. There are four categories defined as follows:

1. Demonstration/Education/Communication
2. Qualitative Bathymetry Analysis and/or Assessment of General Surface Flow Patterns
3. Quantitative Bathymetry Analysis and/or Analysis of General Surface Flow Patterns
4. Quantitative Analysis of Scour and Deposition Patterns and/or Analysis of Detailed Flow Patterns

These four categories closely parallel the four levels described previously, but emphasize the increasing level of detail required of the model.

Determining the degree of relaxation permissible in the various similitude criteria at each of these levels or categories is highly desirable. However, establishing prototype values of the relevant similitude criteria for each category becomes increasingly complex as more constraints are imposed on the modeling process.

Each level of similarity relaxation deals with the degree of uncertainty associated with the use of physical models (or for mathematical models). Uncertainty primarily results from a lack of knowledge and understanding of complex river processes and responses. Uncertainty leads to a risk of failure and it is therefore critical to assess the

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risk and incorporate this knowledge in the final design. Broad categories of uncertainty include:

1. Model uncertainty results when simplified mathematical or small-scale physical models are used to describe the complex river behavior processes.
2. Parameter uncertainty results from difficulties in estimating model parameters such as roughness and channel forming discharges.
3. Randomness includes natural fluctuation in flow and sediment transport parameters.
4. Human error introduced through design and operation of the model and in the design and construction of the prototype structure.

Limits for model application are dependent upon the variability in prototype conditions. The values used in defining the various similitude criteria also depend on prototype variability. The level of expected accuracy (and similarity) from a model must, therefore, be tempered with knowledge about prototype variability.

Arguably, prototype variability is partly a function of man's ability to measure physical phenomena in the riverine environment. The true accuracy of prototype discharge measurements is unknown because the absolute volumetric flow rate cannot be determined. Buchanan and Somers (1969) suggest that capabilities for field measurement of discharge under ideal conditions is repeatable to within approximately +/-5 percent.

Accuracy of sediment discharge measurements, especially bed load, which is highly dependent on flow depth, cannot be reliably estimated. In particular, the Mississippi River (and other large river systems) poses significant obstacles to measurement of sediment transport phenomena and even discharge data are difficult to obtain. The limited spatial (and temporal) definition of discharge (much less velocity distributions and sediment transport) makes the concept of similarity for a particular model reach problematic: what discharge should be used, what energy slope exists in the prototype, and what bathymetry is most representative? This leads to the conclusion that similitude in open rivers cannot be defined in absolute terms.

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The lack of an absolute definition of similitude, however, does not preclude the use of loose-bed physical models. Past application of these models (documented by a long list of successful model study reports) proves their utility in solving complex riverine problems. Both large-scale and small-scale models provide information useful in developing problem solutions.

3.3. SCALE RATIO ANALYSIS

Gaines (2002) utilized reach-weighted morphologic parameter values calculated from previous model study results to investigate similarity relationships. Weighted values were utilized because preliminary calculations using arithmetic mean values indicated that isolated problem Ranges unduly influenced the calculation of average difference values. This influence would have also affected similarity calculations. For this reason, a sub-reach weighting procedure was applied to obtain representative reach values for each model and prototype morphologic parameter used in similarity calculations. The additional consideration of prototype to model scale ratios provided a significant improvement in the way model similarity could be analyzed.

Because measured model and prototype data were limited, the similarity analysis used scale ratios to investigate roughness, Shields parameters, and sediment transport similarity relationships. Gaines reported that the limited availability and/or lack of data severely restricted the investigation and precluded a definitive analysis of scale relaxation or distortion effects. Gaines suggested that future research should be directed at determining scale effects in the small-scale models because actual measured prototype and model data is necessary to more completely understand and interpret model results. Such research may lead to improved model design and operation and an expanded application of the models.

Gaines states that the scale ratio technique leads to a better understanding of how both large- and small-scale models met the similitude criteria. Evaluation of the Shields criterion through the scale ratios indicated that the small-scale models provided a degree of similarity on par with that provided by the WES models. However, Gaines developed the scale ratios based upon the assumption of Froude scaling. Although the WES models

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more closely approximate Froude scaling than do the micromodels, neither of the models in Gaines' analysis were based on a strict application of the Froude criterion.

Gaines found hydraulic and sedimentation time ratios to be greater in the large- and small-scale models than ratios reported by previous investigators (Zwamborn, 1966). Both large-and small-scale models were found to fall on a single curve visually fitted through the time scale data with small-scale model time ratios approximately one log cycle greater than the large-scale model time ratio values.

Roughness similarity was considered through use of the Chezy roughness ratio and/or the roughness distortion factor β. Gaines (2002) shows roughness in the large-scale models to represent a closer degree of similitude than the small-scale models. The large-scale model data also fall closer ideal similarity between slope distortion and roughness distortion than do the micromodels.

The small-scale model data presented by Gaines (2002) indicate that model roughness is lower than required for similitude and that the small-scale models have too much slope distortion. Corrected roughness and slope distortion factors were calculated by Gaines using the ripple factor. Gaines' corrected values for distortion indicate that micromodel vertical-scale distortion should be reduced approximately 25 to 30 percent in order to achieve better friction similarity. This observation has the greatest impact in selection of the vertical scale and in specifying model slope.

The scale ratio analysis suggests that there is sufficient latitude for adjusting small-scale operational techniques (e.g. through selection of a coarser model sediment material gradation and lower vertical scale distortion) in order to improve the roughness characteristics in the micromodel. The Shields criterion and the roughness and slope distortion factors provide a mechanism for balancing sediment mobility and boundary roughness effects in the model to achieve the desired sediment characteristics and model slopes.

While the scale ratio approach presented by Gaines is based on an approximation using limited available data, the methodology presented provides a tool for evaluating scale effects resulting in deviation from similitude requirements for the micromodel. Understanding these scale effects is a significant part of determining the veracity of the

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micromodel and in understanding the limitation of the micromodel. In this light, the principal scale ratio methodology developed by Gaines (2002) is included in Appendix C. Future efforts should include documentation of the parameters needed for using the scale ratio methodology to evaluate scale effects in the micromodels.

3.4. FLUME STUDIES

Investigation of scale and distortion effects in models of natural channels is complicated by the irregular influence of the channel alignment, bed deformation, and variable discharges. Therefore, the evaluation attempted to simplify the analysis of basic flow characteristics by using two separate flume studies. Each of the flume studies sought to examine specific aspects of how scale and scale distortion affected the overall hydraulic (and sediment in the case of loose-bed flumes) characteristics of the flow. Rigid boundary flume studies provided the strictest control of experimental parameters because boundary conditions were most nearly fixed. Loose boundary flume studies allowed for controlled testing but to a lesser degree than possible with the rigid boundary flumes because of possible deformations of in the channel bottom.

3.4.1. Fixed-Bed Flumes

The current investigation included flume experiments conducted under contract with Robert Ettema and Marian Muste at IIHR (Ettema and Muste, 2002). The IIHR flume experiments primarily consisted of a series of tests to identify the effects of scale and scale distortion at a single dike structure using fixed-bed (or flat-bed) flumes having rigid boundaries. The study also included several tests conducted in loose-bed flumes to investigate how bed deformation might influence interpretation of the fixed-bed flume results. The IIHR report provides the following summary.

> This study is part of an overall effort by the U.S. Army Corps of Engineers to evaluate the potential use and limits of very small hydraulic models (termed micromodels) for simulating flow and sediment-transport processes associated with alluvial-channel control. In particular, the study was conducted to determine scale-effect trends associated with selected important features of the flow field around a single dike or wing-dam

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placed on a fixed-bed channel. The flow features of interest are channel thalweg alignment (the path of maximum depth and usually velocity) of flow around a dike, and the flow-separation region formed immediately downstream of a dike. These features are of practical importance for channel control, especially in facilitating alluvial-channel use for navigation. USACE has made extensive use of micromodels to aid investigation of channel-control modifications, which commonly involve the placement of modification of dikes.

The following paragraphs describe the IIHR study and findings. These descriptions include paraphrases from the IIHR report.

The IIHR study's approach utilized flume experiments based on a similitude framework developed for evaluating the technical utility of hydraulic models for replicating flow and sediment movement around dikes in alluvial channels. The framework required that flume experiments be conducted to determine how horizontal- and vertical-length scales affect the flow field around a model of a single dike placed in a straight, fixed, flat-bed channel. Those experiments, conducted over a large range of length scales[5], sought to illuminate flow field trends uncomplicated by the influences of alluvial-bed deformation (local scour and bed forms). Brief experiments were also conducted with single dikes in a loose-bed channel, in order to determine how bed deformation affects the flow field around a dike. The experiments involved non-porous and porous dikes.

Because micromodels have mobile beds of model sediment, the main similitude consideration for IIHR experiments is similitude in intensity of bed-sediment movement. This consideration is the basis for the primary similitude criterion assumed for most mobile-bed hydraulic models. However, as other similitude considerations are not met, scale effects inevitably arise and become more severe as model scale increases. One scale effect is exaggeration of velocity heads associated with flow around a dike. Further scale effects arise with the use of vertically distorted models, and with amplified roughness of bed sediment. The results of the IIHR study show that the consequent distortions in the lateral and vertical distributions of flow, as well as exaggeration of

[5] Length scale = prototype length / model length

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velocity heads, affect the strength and dispersion of wake eddies and turbulence generated by a model dike in a fixed-bed flume. These consequences lead to increased distance, relative to dike length, for flow symmetry to re-establish downstream of a dike in a fixed bed channel. Commensurately, thalweg alignment and separation region in the vicinity of a dike may deviate from prototype values. Additional tests in loose-bed flumes at IIHR indicate a reduction in these effects result from deformation of the bed in the vicinity of the dike structures.

The results also show that, through the use of a porous dike, small-scale hydraulic models of dikes can be made to simulate thalweg alignment around a dike. Dike porosity partly compensates for the exaggerated velocity heads incurred by basing similitude primarily on intensity of bed-sediment movement. Dike porosity, however, disrupts the flow-separation region downstream of a dike. Further, the results show that local scour of the bed at a dike has a major influence on thalweg alignment and flow-separation in the vicinity of a dike. That influence can dominate, and offset, the scale effects described above, provided that scour depth and lateral extent do not grossly exceed scaled prototype values. Porous dikes are used in micromodels in order to reduce the depth and lateral extent of scour exaggeration.

3.4.2. Loose-Bed Flumes

Similar to the fixed-bed flume studies conducted by IIHR, a series of experiments were conducted by Gaines (2002) at the University of Missouri-Rolla (UMR) to explore scale and distortion effects on relative roughness, aspect ratio, sediment transport, shear velocity, separation/reattachment lengths, and equilibrium slope in loose-bed flumes. The kinematic and dynamic similitude involving sediment mobility and boundary roughness are identified as two primary considerations in the loose-bed flume studies at UMR.

The UMR flume studies also included experiments to assess the effects of a single training structure on channel response and the associated hydraulic response of the flow. Both solid and porous training structures were tested. The only results from the training structure experiments reported in Gaines (2002) pertain to the effects of channel size on

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the lateral and vertical contraction effects induced by the various training structures analyzed.

Interpretation of the surface flow patterns was not included in Gaines (2002). Because the effects of distortion include an exaggeration of velocity and Froude number in small-scale model channels, the surface flow patterns are influenced by the distortion. For this reason, surface flow patterns in the UMR flume experiments were interpreted during preparation of the present report. A report of the investigator's interpretation of the relevant flume data are included in Appendix B.

3.4.2.1 Sediment Mobility

Sediment mobility as a model similarity requirement involves three distinct relationships: the point of incipient particle mobility, the general state of sediment mobility, and the particle's suspension characteristics. Two dimensionless parameters provide the means for evaluating the particle mobility. The first is the Shields stress (τ^*)

$$\tau^* = \frac{\rho u_*^2}{g(\rho_s - \rho)D} = \frac{\tau_b}{\rho g \Delta D} = \frac{HS}{\Delta D}$$

where $\Delta = (\rho_s - \rho)/\rho$. The second dimensionless parameter is the particle Reynolds number Re_* also repeated for the reader's convenience

$$Re_* = \frac{u_* D}{\upsilon}$$

which can be shown in a modified form of particle Reynolds number as

$$R_p = \frac{\left(\sqrt{\Delta g D}\right) D}{\upsilon} .$$

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Garcia (2000) used R_p and τ^* to generate a Shields regime diagram useful for differentiating between alluvial and gravel bed rivers. This form of the Shields diagram provides a simplified mechanism for the design and operation of physical sediment models. Likewise, evaluating model limits can be accomplished by comparing and contrasting physical sediment model particle mobility data to prototype data through the diagram. In lieu of maintaining stringent similarity requirements between model and prototype for τ^* and R_p the Shields regime diagram can be used to assess whether model conditions are representative of the prototype. The Shields regime diagram is a useful technique for revealing whether model transport is in the same regime as exists in the prototype.

A first step in investigating the state of sediment mobility in the current investigation required establishing the point of incipient particle motion. Experiments were conducted using Kramer's weak-movement criteria to determine this point. Incipient mobility (IM) data determined for the Urea sediment material are shown on the Shields regime diagram, Figure 3-5, as four points identified as UMR 2" Flume PG IM (two points represented by solid diamond symbols), UMR 6" Flume PG IM (a single solid triangle symbol) and UMR 2" Flume PG IM (a single solid square symbol). These four incipient motion points for PlastiGrit fall well above the critical curve delineated by Brownlie's (1981) fit of Shields data. Additional data are needed to more completely investigate the reason for the high values of τ^* for the Urea Plastigrit sediment.

Shields stresses for flume experiments where sediment motion was greater than incipient motion are also shown in Figure 3-5. The experimental data for flume runs with higher sediment mobility are depicted by UMR 2" Flume (open diamond), UMR 6" Flume (open triangle), and UMR 12" Flume (open square) labels in the figure. A noticeable pattern in the UMR flume data is apparent from the figure. Each flow level used in the experiments produces a commensurate level of Shields stress regardless of flume size. This occurrence is a direct result of the pseudo Froude scaling approach used in establishing flow levels between the three flumes (e.g., $u_{*r} \cong 1$). The steady increase of τ^* with increasing depth (after all τ^* is a function of depth, H) suggests that vertical

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distortion may be a plausible means for obtaining closer model-to-prototype similarity as expressed by the Shields similarity criterion.

The τ^*, R_p data from the current investigation falls within the transitional zone as do most of alluvial sand-bed rivers at a state of bankfull discharge (Garcia, 2000). Garcia's prototype data and large flume data are depicted in Figure 3-5 as noted in the legend. The principal difference between Garcia's sand-bed river data and that of the UMR study was that the flume data fell below the suspension curve defined by $u_*=\omega$.

The Shields regime diagram further aids in assessing the state of sediment suspension between model and prototype. The curve where $\omega=u_*$ defines a condition of similarity expressed by Zwamborn (1966), wherein the ratio of shear velocity to the fall velocity between model and prototype is unity. The Shields regime diagram refers to the curve where $\omega=u_*$ for sand spheres as the transition between suspension and no-suspension of sediment particles. Of particular interest is the effect of particle shape on this curve. Data for sand disks are also shown in Figure 3-5 as labeled. The data for sand disks provides some insight regarding the effect of particle shape on similarity of particle suspension when plotted with $\omega=u_*$ (as shown by the dashed line on Figure 3-5).

Average fall velocity data obtained for four sizes of the PlastiGrit material (12/16, 16/20, 30/40, and 40/60) result in points that plot below the curve for sand spheres. A line visually fitted through the four PlastiGrit points appears to be parallel to and below the sand curve. This indicates that the PlastiGrit material provides a degree of relaxation in sediment mobility characteristics.

The delineation of the transition from ripple to dune bedforms on the Shields regime diagram (Figure 3-5) coincides with the lower transition zone ($Re^*=11.6$) as depicted by Garcia (2000). This would indicate that the flumes should exhibit bedforms as dunes. However, no bedforms were visible at any time during the experiments. A possible explanation for the lack of dunes (or even ripples) in the flumes stems from the consideration of particle shape and relative roughness on bedform development. No published data were found regarding the influence of particle shape on bedform development. Most bedform prediction methods found in the literature involve flow depth.

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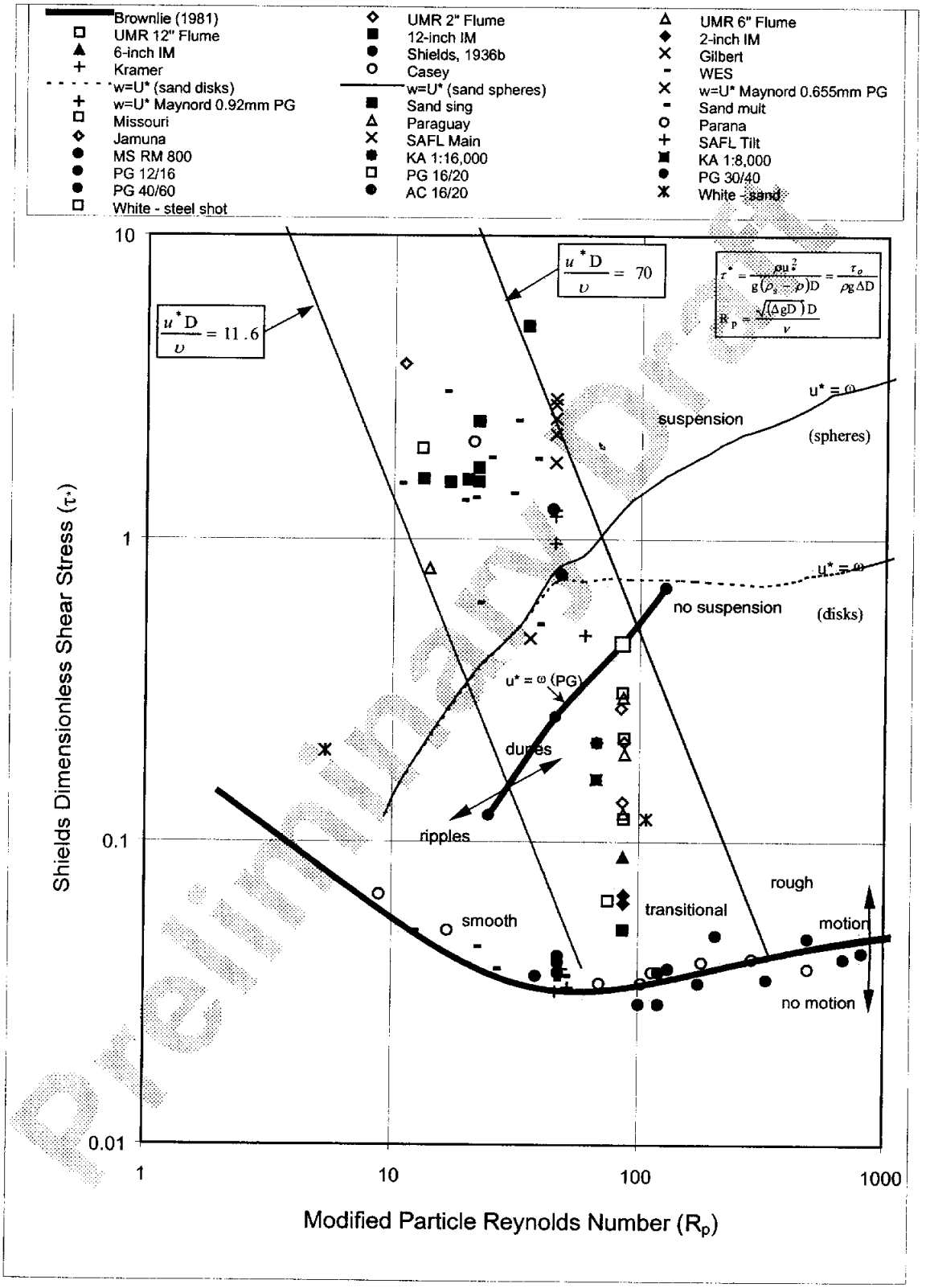

Figure 3-5 Shields Regime Diagram (after Garcia, 2000)

3.4.2.2 Roughness Relationships

A number of previous investigators identified boundary roughness as an important parameter in model design. Incorrect roughness in a model results in an inability to reproduce prototype stages. This implies a direct influence on velocity and sediment distributions. Investigation of roughness in small-scale channels (widths on the order of 2 inches) required collection of friction data as part of the UMR flume studies.

Experimental results from basic flume runs (no training structures) comprised the bulk of data used for this component of the investigation. Friction factor (f_b) values with side wall correction applied are shown in Table 6-2 of Gaines (2002). The side wall correction utilized for computing f_b compensates for the effect of a different boundary roughness along flume walls than exists along the bed.

The well known Moody diagram depicts friction factor (f) as a function of Re. Such a diagram is shown graphically in Figure 3-6 for data from Block B experiments. The data for the Williams (1970) experiments are also shown on this figure.

The data exhibit a similar trend to that observed in the Moody diagram. The curves for laminar flow, described by

$$f = \frac{64}{\mathrm{Re}}$$

and for the smooth boundary condition (described by the Blasius equations)

$$f = \frac{0.316}{\mathrm{Re}^{1/4}} \quad \text{for Re} < 10{,}000$$

$$\frac{1}{\sqrt{f}} = 2.0 \log_{10}\left(\frac{\mathrm{Re}\sqrt{f}}{2.51}\right) \quad \text{for Re} > 10{,}000$$

are shown in Figure 3-6 for reference.

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The experimental flume data can be grouped by relative roughness as depicted in the standard Moody Diagram (Gray, 2000). Lines shown in Figure 3-6 were visually fitted through the experimental data (The lines through the data reflect the third parameter of relative roughness). In Figure 3-6 data from Williams (1970) three largest flume widths (widths of 6, 12, 24 inches) indicate an upward trend in f_b with increasing

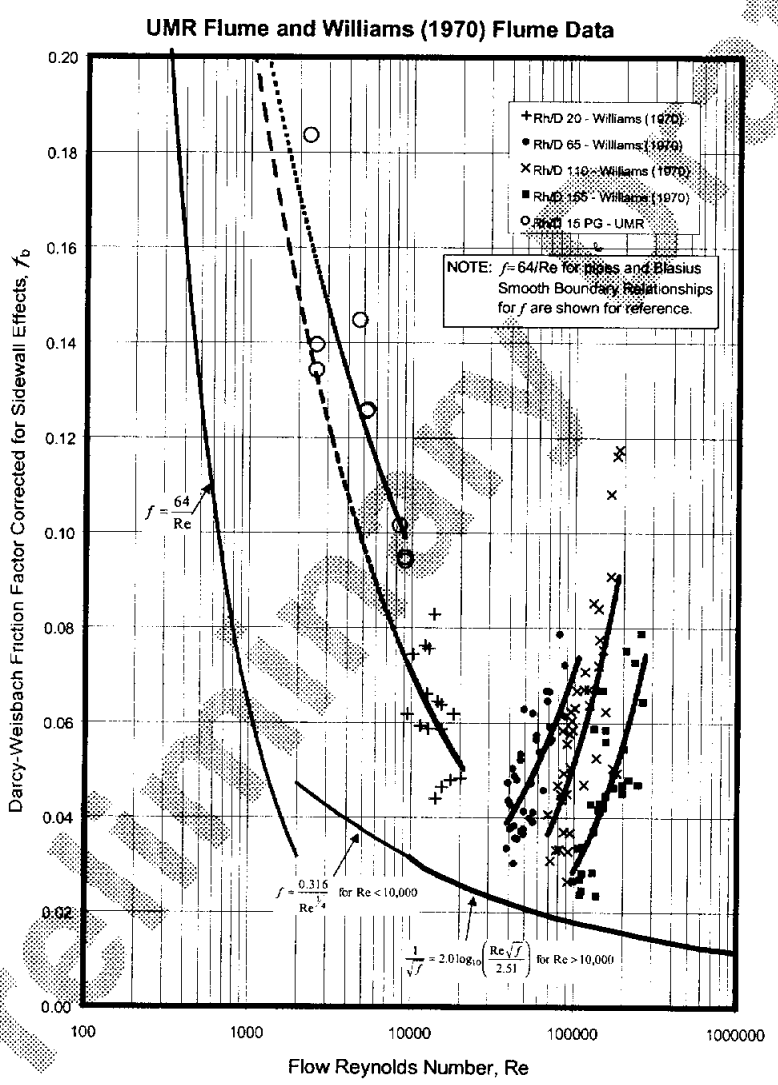

Figure 3-6 Moody Diagram for Flume Data

Re* while the smallest Williams flume (3 inches wide) and UMR flume experiments indicate a downward trend.

The data suggest that the experiments having the smallest relative roughness exhibited friction behavior as found in the laminar and transitional regions of the curve despite the fact that Re > 2000 which indicates that fully turbulent flow existed in the flumes. The line fitted to the UMR flume data closely resembles the shape of the laminar curve depicted by Equation (3-1). Therefore, flume width appears to play a role in the relationship between roughness and Reynolds number. One possible explanation for the change in trend derives from the fact that channel width to depth ratio plays a major role in reproduction of two dimensional flow characteristics.

Williams (1970) data, obtained for sand bed conditions, and the UMR flume data, obtained using the Urea PlastiGrit bed material, proved insufficient to assess possible relaxation of the roughness similarity criterion. The data suggest a relationship between f_b and the particle density as demonstrated by the relative position of relative roughness curves for the lowest sand bed experimental data and the PlastiGrit experimental data. Although the relative roughness curve shown in Figure 3-6 for R_h/D equal 20 is tenuous at best, the indications are that reduced particle density results in an increased friction factor, f, over sand given the same Reynolds Number , Re, and relative roughness, R_h/D.

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4. CASE-STUDIES

4.1. CASE STUDY DATA

Sixteen micromodel reports have been published to date. Several other micromodel studies have also been completed where no formal report was prepared. Table 4-1 provides a list of published micromodel studies.

Unfortunately, there are few examples of designs developed form micromodel studies that have been constructed in the prototype rivers. There are two main reasons for

Table 4-1. USACE Micromodel Investigations.

Investigation Name (River/Stream)	Horizontal Scale*	Distortion (Horz.:Vert.)	Objective/Description
Mouth of White River (Mississippi)	1:12000	10:1	Improved Navigation Alignment
Clarendon, AR (White)	1:4200	14:1	Improved Navigation Depths
Augusta, AR (White)	1:3600	20:1	Improved Navigation Depths
Vicksburg Front (Mississippi)	1:14400	12:1	Improved Navigation Alignment
Wolf Island (Mississippi)	1:7200	12:1	Evaluate features for Environmental Diversity
Memphis Front (Mississippi)	1:4800	8:1	Harbor Entrance
Sante Fe Chute (Mississippi)	1:7200	6:1	Improve Side Channel Depths/Alignment
Lock & Dam 24 (Mississippi)	1:9600	16:1	Corrected Currents Dangerous to Lock Approach
SEMO Port (Mississippi)	1:3600	6:1	Improved Navigation Depths at Port Entrance
Bolters Bar (Mississippi)	1:9600	16:1	Improved Navigation Depths
Savanna Bay (Mississippi)	1:4800	8:1	Improved Navigation Depths/Side Channel Protection
Marquette Chute (Mississippi)	1:9600	12.3:1	Side Channel Enhancement
Copeland Bend (Missouri)	1:3600	15:1	Environmental Enhancement
Ballard's Island (Illinois River)	1:3600	15:1	Side Channel Enhancement
Schenimann Chute (Mississippi)	1:4800	8:1	Side Channel Enhancement
Morgan City/Berwick Bay (Atchafalaya)	1:7200	6:1	Improved Navigation Depths & Alignment
New Madrid (Mississippi)	1:20000	17:1	Improved Navigation Depths

* Herein scale is model/prototype ratio

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this. First, the micromodel technology has only recently been developed. Second, funding constraints have prevented construction on many of the projects. Therefore, it is difficult to describe the model's ability to predict the bathymetry and flow patterns actually observed in the prototype in response to plans derived from model results.

Although 20 micromodel studies have been conducted by the St. Louis District, only five designs have been constructed. Of these five, only one design was constructed as modeled. The remaining four designs that resulted from micromodel studies were not fully constructed according to model recommendations or the construction has only recently been completed. For this reason a complete evaluation of the models ability to predict prototype response cannot be made. However, a cursory assessment of post construction conditions follows.

4.1.1. Big Creek (Case Study 1)[6]

The Big Creek micromodel study was initiated in 1995 and the structure that was designed during the study was constructed in 1997. Therefore, after nearly five years, a reasonable assessment of the project can be made. Unfortunately, due to the lack of prototype data before and after construction, a quantitative assessment is impossible. However, a qualitative description is described below through the use of numerous site visits and photographs of the reach.

Big Creek is a gravel bottom stream located in rural Lincoln County, Missouri, approximately 50 miles northwest of St. Louis. Shortly after a new bridge was constructed over the stream, an upstream lateral erosion problem developed that threatened the structure's southern abutment. Local reports indicated that the stream bank erosion rate increased severely after the new bridge was built. The misalignment of the bridge opening in respect to the stream planform, and the constriction of the stream caused by the width of the bridge opening, had led to severe bank erosion problems both upstream and downstream of the bridge crossing. County officials worried that further

[6] Gordon, D.C., Davinroy, R.D., "Bridge Abutment Erosion Problem Solved with a Small Scale Physical Sediment Transport Modeling Approach," 7th Federal Interagency Sedimentation Conference Proceedings, 2001.

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high water events and additional erosion on the bridge abutment could cause a catastrophic failure to the structure.

In 1995, county officials sought the expertise of the U.S Army Corps of Engineers to solve the problem and preserve the structure. To address the problem and design a solution, the Corps of Engineers decided to use a micromodel. This modeling technique allowed county officials and local farmers whose land was being affected by the erosion, to view the model and discuss possible remedial actions. The final design was the result of a cooperative engineering effort between the Corps of Engineers, Lincoln County Officials, and local landowners.

Through a cost share program in 1997, the Corps of Engineers and Lincoln County constructed a small rock structure in the stream to reduce the severe abutment erosion and realign the stream's thalweg. Since the construction of the small 30-foot rock dike, strategically located 600 feet upstream of the bridge, the river training structure has caused the thalweg of the stream to adjust and realign. The area of scour along the bridge abutment has been converted to a naturally depositional area. The vertically eroding bank located upstream of the bridge has experienced a new growth of natural vegetation and begun to revert back to a more natural slope. The stream thalweg now makes a smoother, more natural transition through the bridge opening. Photos taken before and after construction show the dramatic changes in the river regimen.

4.1.1.1 Background

Big Creek is a typical meandering gravel bed stream found in the central Missouri. The bed material consists of mainly gravels, sands, and silts. Courser gravels and cobbles exist, although their quantity and occurrence is significantly less. The approximate physical stream parameters of Big Creek are as follows:

1. Average Slope $\cong$ 6.4 ft/mile or 0.12 %
2. Average Channel Depth at Bankfull Flow $\cong$ 10 feet
3. Average Channel Width at Bankfull Flow $\cong$ 150 feet
4. Average Width to Depth Ratio $\cong$ 15
5. Deepest Channel Depth Encountered $\cong$ 19 feet

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4.1.1.2 Problem Description

In 1995, Lincoln County highway commissioners presented to the U.S. Army Corps of Engineers a very common problem that faces many local governments. Big Creek was rapidly eroding a bridge abutment and the nearby banklines at a bridge crossing for rural County Highway 729. The abutment was in danger of completely failing and threatening the structural integrity of the bridge

Historically, Big Creek had been a somewhat stable stream. However, with increased runoff from land use changes that have occurred in the basin and channel constriction of the stream at the bridge crossing, the tendency for lateral bank erosion had dramatically increased both upstream and downstream of the bridge. The aerial photo in Figure 1 shows the degree of bank erosion that has occurred. The lateral movement of the stream was more significant where adequate vegetation buffers were not maintained between the crop fields and the stream.

In the early 1990's, a new bridge crossing was constructed across Big Creek on Lincoln County Highway No. 729. The support for the 25 feet wide by 220 feet long concrete bridge consists of three sets of bridge piers and two earthen abutments. Since the new bridge was built, the stream channel upstream of the bridge had moved laterally in a southward direction approximately 100 feet. The lateral movement of the thalweg had caused a majority of the flow to be directed at the right descending bridge abutment. The scour experienced along this abutment had threatened the integrity of both the road and the bridge. Therefore, county road crews had to continuously repair this abutment for the temporary protection of the road and bridge. The low flow patterns through the bridge opening were orientated in a nearly parallel direction to the bridge crossing (Figure 4-1). Immediately downstream of the bridge opening, flow patterns were directed against the left descending bank.

Figure 4-1 shows a complete overview of the study conditions. Conditions of the stream in the vicinity of the bridge crossing were described as follows:

1. The right descending bank was actively eroding and did not contain any natural vegetation. This feature extended from the bridge abutment to a point 500 feet upstream of the bridge.

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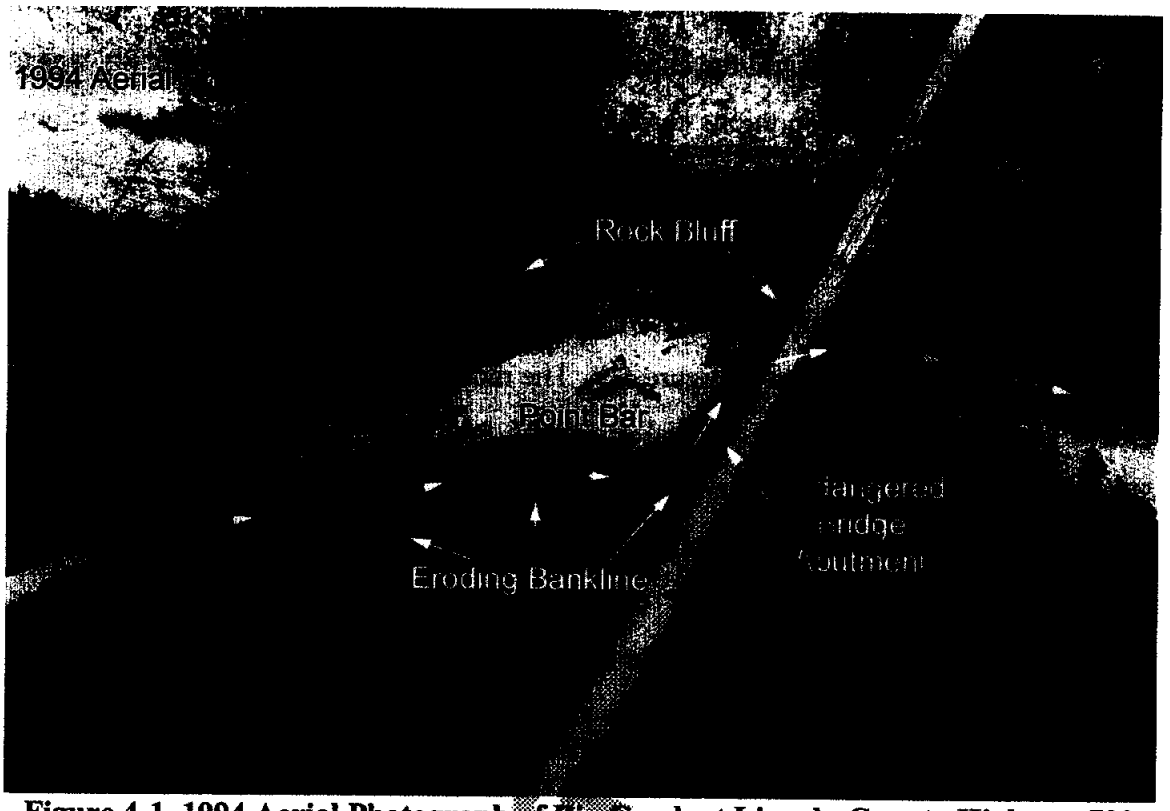

Figure 4-1 1994 Aerial Photograph of Big Creek at Lincoln County Highway 729

2. The banks, 500 feet upstream of the bridge, were heavily wooded and stable.
3. A large point bar was located along the left descending bank upstream of the bridge. The size and growth of the point bar was directly related to the migration of the right descending bank. This depositional area indicated that the majority of flow was concentrated along the right descending bank.
4. The left descending bank immediately upstream of the bridge was a wooded, natural rock bluff line. This condition was evident to a point approximately 400 feet upstream of the bridge.
5. The bridge crossing was severely misaligned with the channel thalweg.
6. Downstream of the bridge, the right descending bank was heavily vegetated. A small point bar was located along this bank. The majority of flow was concentrated along the left descending bank.
7. The left descending bank downstream of the bridge was vertical and devoid of vegetation. This condition was evident from the bridge to approximately 700 feet downstream to a small outcropping of trees.

The study was performed by the Corps of Engineers to address the existing sediment transport response occurring in the vicinity of the bridge crossing. This

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included investigating the bridge abutment erosion, the detrimental flow alignment through the bridge opening, and the excessive bank erosion. The goal of the study was to develop improved flow conditions through the bridge opening and protect the bridge abutments through the use of channel regulation structures.

4.1.1.3 Big Creek Micromodel

The model used for this study was constructed according to the high resolution 1994 aerial photograph shown in Figure 4-1. The model employed a horizontal scale of 1 inch = 50 feet, or 1:600, and a vertical scale of 1 inch = 10 feet, or 1:120, for a 5 to 1 distortion ratio. This distortion supplied the necessary forces required for the simulation of sediment transport conditions similar to those of the prototype (Davinroy).

The micromodel insert was constructed of water-resistant polystyrene and measured 6 feet long by 29 inches wide by 3 inches deep. The bed material used was granular plastic urea with a specific gravity of 1.4. The banks of the stream were formed with sheet metal inserts and the bridge abutments, dikes, and weirs were modeled with oil-based clay. In all model tests, an average design hydrograph was used. Each hydrograph was a repeatable triangular response representing low to high flows.

Data available from the prototype used for the calibration process included surveyed cross sections, contours surrounding the bridge crossing, aerial photographs, and on-site field inspections. Once the favorable comparison of several surveys of model tests to field survey data was made, the model was considered calibrated. This base test served as the comparison for all future tests, which represented the average expected sediment response of the prototype over an extended period of time. Observations and data collected from the base test indicated that the flow lines and sediment transport trends of the model and the prototype were very similar.

4.1.1.4 Recommended Solution

Several alternative design plans were tested in the model. The procedure for analyzing each alternative involved implementing the desired plan, running 5 consecutive design hydrographs, observing the sediment transport through the channel, and surveying the bed of the model. Through these tests, it was determined that the most cost-effective

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design solution to the problem was the implementation of a level crested 25 foot long dike at elevation top of bank, strategically placed 600 feet upstream of the bridge on the right descending bank. The model indicated that the structure redirected a majority of flow and shifted the thalweg toward the left descending rock bluff bank. The design also shifted the flow lines and the thalweg to a nearly perpendicular alignment to the bridge crossing which eliminated the scour against the right descending bridge abutment

The designers determined that a 30-foot long dike should be constructed in the river at the location specified by the model design alternative. The additional length was added to account for any stone launching off the end of the structure. The launched material would naturally armor the creek bed near the dike to reduce localized scour. The design also called for revetment to be placed on the right descending bank upstream and downstream of the dike as well as on the left descending bank adjacent to the dike. This measure would ensure bank stability throughout the area of constriction caused by the structure. The left descending vertical bank just downstream of the bridge would also be stabilized with revetment to protect the north bridge abutment from any back eddies that would develop from the new flow patterns.

The scope of the study focused primarily on reducing scour at the right descending abutment of the bridge crossing. Therefore, the lateral bank erosion problem downstream of the bridge along the left descending bank was not addressed.

4.1.1.5 Results

The recommended design was constructed in the summer of 1997. After the first high water event, the streambed demonstrated an began to react immediately. With the passing of each event, the bed configuration continued to develop. Figure 4-2 shows a 2001 aerial photograph of the reach (compare this photo with Figure 4-1). Figure 4-3 shows a photograph taken from the top of the bridge facing upstream before the construction of the dike. Figure 4-4 was taken from the same location 3 years after construction. The photos show a substantial shift of the thalweg from the right descending bank towards the left descending bank. The thalweg cut a new path through the depositional area, which isolated the remnants of the old point bar along the right

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descending bank. The right descending bank downstream of the dike has begun to naturally repair itself with vegetation. The area near the endangered bridge abutment has filled with sediment, which indicates that it is now a depositional area with slower velocities. Additional maintenance to the bank and bridge abutments after construction has not been required and only periodic monitoring of the streambed has been needed.

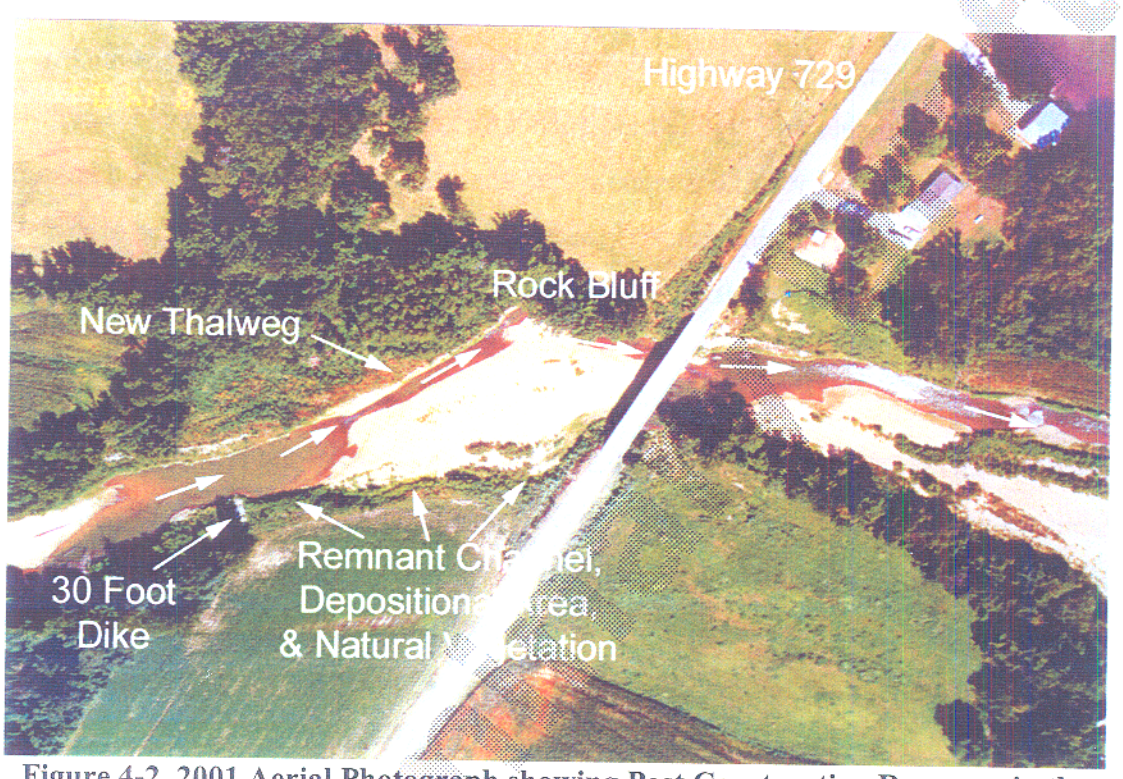

Figure 4-2 2001 Aerial Photograph showing Post Construction Response in the Stream

Before the project and model study began, a local contractor stated that a 50-foot dike should be built in approximately the same location as the constructed rock dike. A test of this design in the model indicated that it would produce excessive scour in the channel and would not properly realign the channel through the bridge crossing. Therefore, the model was very helpful in guiding the design team toward a more economical solution that ultimately resulted in successful project.

This project would not have been possible without the support of the farmers who own the land adjacent to the creek. These landowners had already lost land due to the lateral bank erosion caused by the new bridge and were extremely skeptical of any

structure designed to remedy the problem. In fact, they intended to deny access to the stream from for construction purposes. Only after engineers enabled the farmers to observe the micromodel in action did they accept the design and allow access to the construction site.

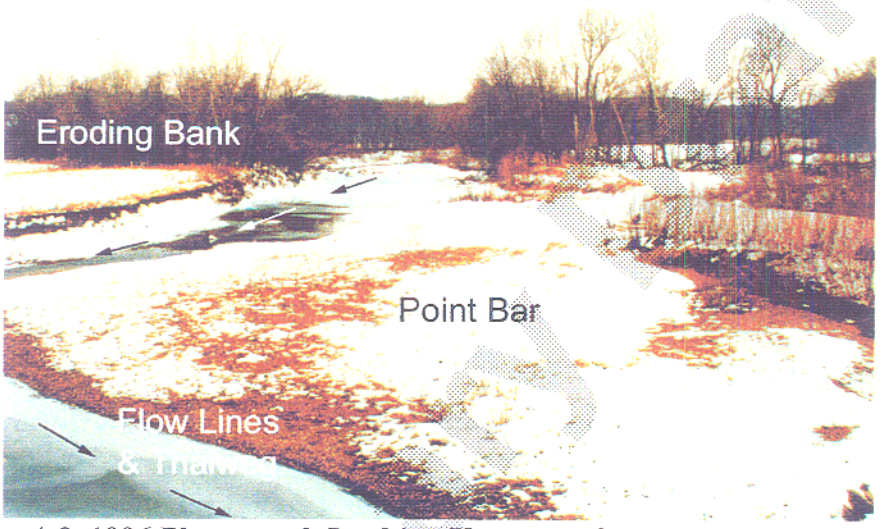

Figure 4-3 1996 Photograph Looking Upstream from the Bridge Crossing.

Figure 4-4 2000 Post Construction Photograph with the Same View as Figure 4-3

4.1.2. Lock and Dam 24 (Case Study 2)[7]

In 1996, micromodel methodology was used to evaluate dangerous outdraft flows at the upstream approach to Lock and Dam 24. A number of design alternatives and modifications were studied and tested to alleviate these adverse flow conditions at the Lock. The study area consisted of a 6.5-Mile reach of the Upper Mississippi River, between Miles 277.5 and 271.0 near Clarksville, Missouri (Figure 4-5).

The study recommended two structural changes for alleviating the outdraft problem. The first change involved a 200-foot extension of the existing rock dike structure located upstream from the lock chamber. The second recommendation was the construction of 4 bendway weirs placed along the left descending bank upstream of the existing dike. The design was intended to create a longer and wider area of slack water downstream of the dike to give tows a low velocity area to maneuver and therefore reduce the outdraft problem.

A majority of the project was constructed in 1998 and 2000. However, due to depth constraints, three of the weirs have not been constructed to their full design length. An initial evaluation of the micromodel study at has been made although the full design has not been fully implemented.

4.1.2.1 Problem Description

Outdraft has been defined as the condition whereby natural or man-induced crosscurrents developed in the river adversely affect a vessel while in a low-powered state. Outdraft conditions are experienced at all lock chambers on the Mississippi River. The degree and severity of outdraft is different at each location. Generally, it is caused by the lock chamber acting as an obstruction to flow, which causes current patterns to deflect around the chamber and head through the adjacent gate openings in the dam.

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[7] Davinroy, R.D., Gordon, D.C., Hetrick, R.D., "Navigation Study at the Approach to Lock and Dam 24, Upper Mississippi River, Hydraulic Micromodel Investigation," U.S. Army Corps of Engineers, St. Louis District, 1998.

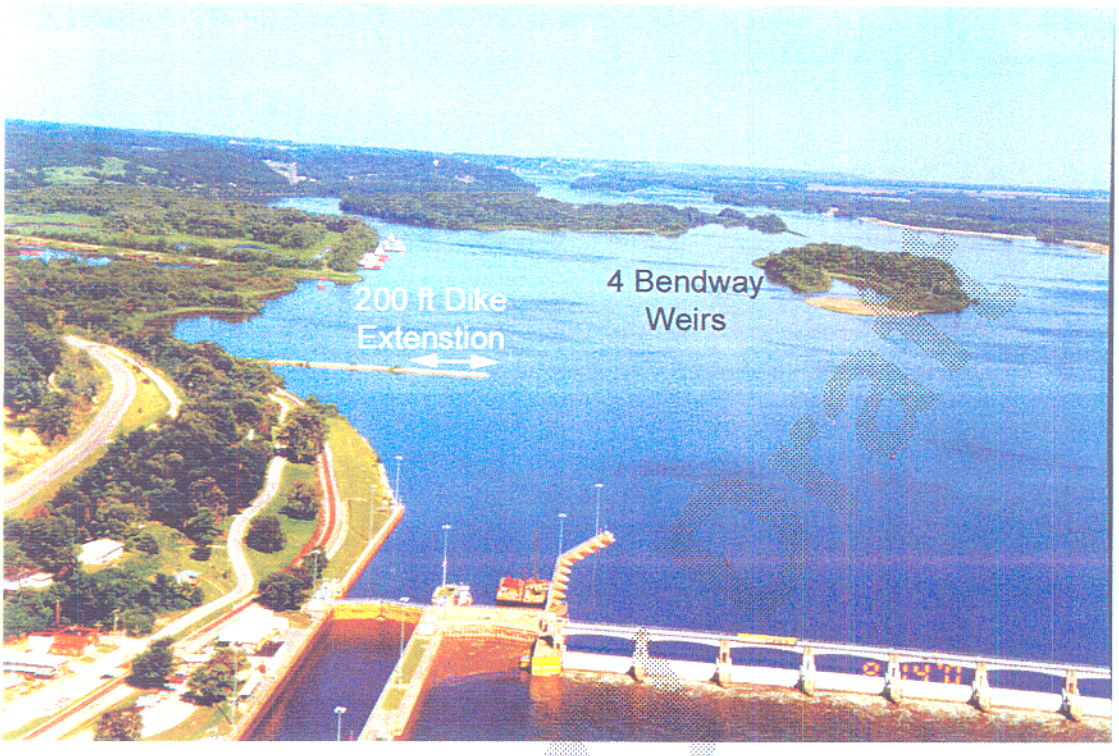

Figure 4-5 Lock and Dam 24 on the Upper Mississippi River

Severe outdraft at Lock and Dam 24 had existed since the dam was completed in 1940. Tows approaching the Lock from upstream usually experienced these detrimental crosscurrent patterns between the upper end of the landwall and the lock chamber. These currents had pulled vessels toward the riverwall and gate openings in the dam. Numerous accidents and near catastrophic events have occurred from this recurring problem. Figure 4-6 shows the consequences of an outdraft induced accident at Lock and Dam 24.

The flows that cause the outdraft became most prevalent when there was at least 30 feet of total gate opening on the dam. The greater the gate opening, the more severe the outdraft problem became. This normally occurred during high flow and open river conditions when the gates were completely out of the water. Flows equal to or exceeding this condition occurred approximately 48% of the time.

Outdraft at Lock 24 was magnified due to a combination of the existing river alignment and a rock bluff that extends along the right descending bank from the lock chamber to Mile 274.1. This protruding bluffline deflected currents and directed them

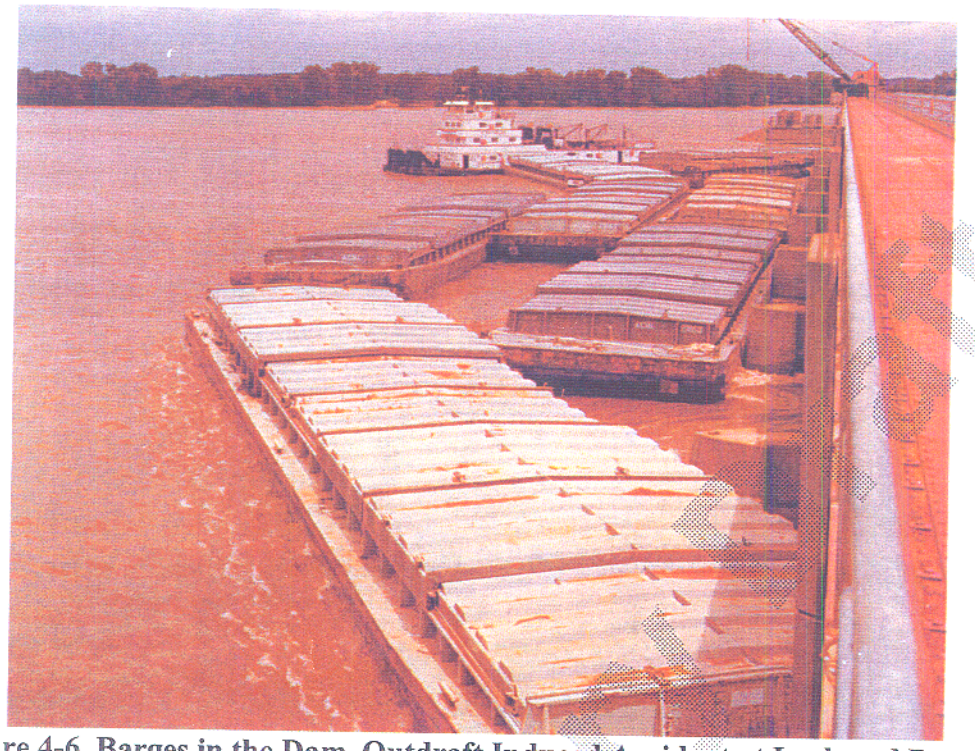

Figure 4-6 Barges in the Dam, Outdraft Induced Accident at Lock and Dam 24

toward the gate openings. Another factor contributing to the severity of outdraft is the location of the Lock and Dam in a river crossing.

Tows approaching the lock from upstream frequently utilize the services of a helper boat during most river conditions to enter the lock chamber. A helper boat assists the tow by pushing the head of the tow against the landwall while the tow pilot keeps the stern from drifting toward the riverwall. Figure 4-7 is a plan view aerial diagram describing the process of a tow entering the lock chamber with the assistance of a helper boat. If the pilot chooses not to use the helper boat, the tow must be aligned or the head of the tow checked into the landwall several times with the help of lock personnel. If the tow drifts and strikes the riverwall, its barges may become separated and carried into the dam.

In 1969, a stone dike was constructed upstream of the Lock and perpendicular to the right descending bank. This dike was later extended in 1971. The dike was constructed in an attempt to alleviate outdraft conditions and create a waiting or holding

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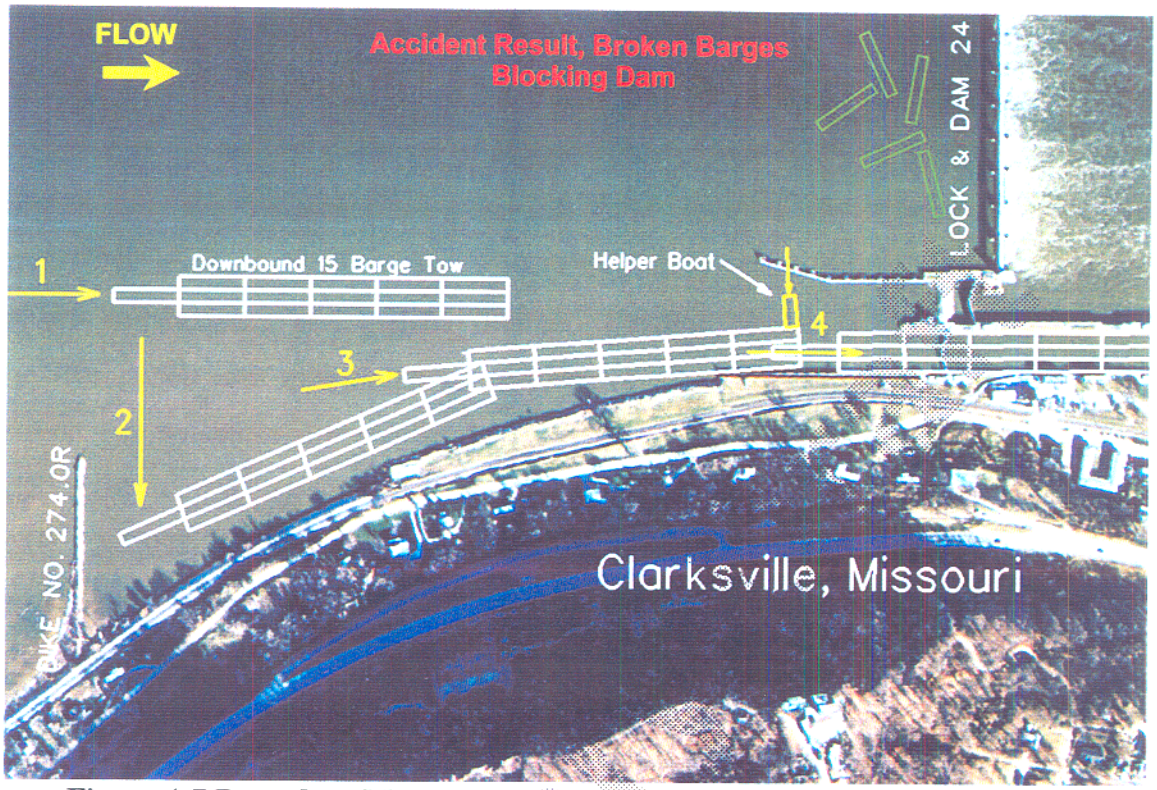

Figure 4-7 Procedure Most Downbound Tows Use to Navigate into Lock 24

area for tows approaching form upstream. The downstream eddy or flow shadow formed by the structure maintains a low velocity region. Model test results discussed later indicated that this dike location was crucial in the overall solution to the outdraft problem. Most tows approaching the lock will travel downstream of the dike and then back up into this region before making their final approach into the lock chamber. This allows the pilot to properly align the tow before entering the lock chamber. While within the dike shadow, the stern is positioned in the slack water near the bank, the bow is positioned out in the faster currents, and the entire tow is turned at a skewed angle. The pilot then proceeds toward the lock, usually with the assistance of the help boat.

Lock records have indicated that through the period between 1980 and 1991, 55 percent of downbound tows experienced outdraft of which 36 accidents occurred. Of these accidents, 23 involved damage to the Lock or Dam. The economic and safety impacts of this navigation problem are of great concern. In 1993, a detailed economic analysis was conducted by the St. Louis District In the Lock and Dam 24 Major

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Rehabilitation Report, the impacts of reducing delay times by eliminating outdraft were estimated at approximately $1,020,000 annually. For the twelve-year period in this study, the average cost for the repair of damages to the Lock and Dam as a result of outdraft was $12,877 per accident, while the cost per accident without outdraft was $1,841.

Another cost associated with the outdraft problem was transportation delays caused by the closure of the lock due to repair of the miter gates from collisions. An unscheduled half-day lock closure for repairing a leaf gate was estimated to increase transportation costs approximately $220,000. A two-day unscheduled lock closure for repair was estimated to increase transportation costs approximately $2,760,000. The greatest cost would result from an accident that causes major damages to the miter or tainter gates, resulting in a loss of pool. The minimum closure due to this occurrence was estimated to be 14 days with navigation delays estimated at approximately $82 million.

4.1.2.2 Study Purpose and Goals

The purpose of this study was to develop possible remedial measures to improve navigation conditions at Lock and Dam 24. This was accomplished by the utilization of a hydraulic micromodel.

The goals of this study were to:

1. Further investigate the flow mechanics causing the outdraft problem.
2. Evaluate a variety of remedial measures in the micromodel with the objective of identifying the most positive, economical, and environmentally friendly plan to alleviate the outdraft problem.
3. Communicate to other engineers, lockmasters, river industry personnel, biologists, and environmentalists the results of the micromodel tests and the plans for improvements.

4.1.2.3 Investigation of Outdraft Velocity Patterns

Historically, a somewhat modest amount of velocity data had been collected near the Lock. Traditional velocity measuring systems were used in an attempt to study outdraft. Unfortunately, the resolution of this data had limited the depiction or visualization of the outdraft flow patterns. With the more recent advancements of data

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collection and remote sensing methodologies, the opportunity existed in this study to obtain additional velocity data with greater resolution.

Figure 4-8 show velocity vectors surveyed upstream of the Lock during three consecutive days in April of 1982. Although the density or resolution of the data points was limited, the surveys showed that velocities near the lock chamber were directed toward the gate openings. The most severe skewed angles of velocity occurred just upstream of the riverwall. However, reliable velocity patterns that delineated the outdraft problem could not fully be determined from this data alone.

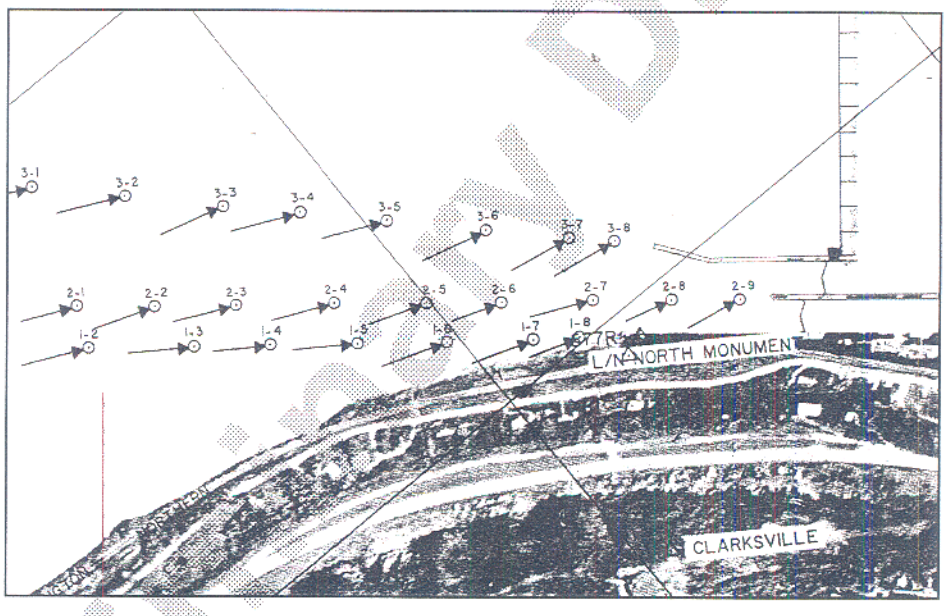

Figure 4-8 Velocity Vectors at Lock 24, Surveyed in April 1982.

Figure 4-9 displays velocity vectors that were collected using an ADCP in March of 1997 during open river conditions. Since the resolution of the historical data was limited, this data further characterized the velocity patterns. The data indicated that currents deflected off the right descending bank near the apex of the rock bluff protrusion and approximately 600 feet upstream of the end of the landwall. This discovery served a vital role in the eventual calibration of flow within the micromodel.

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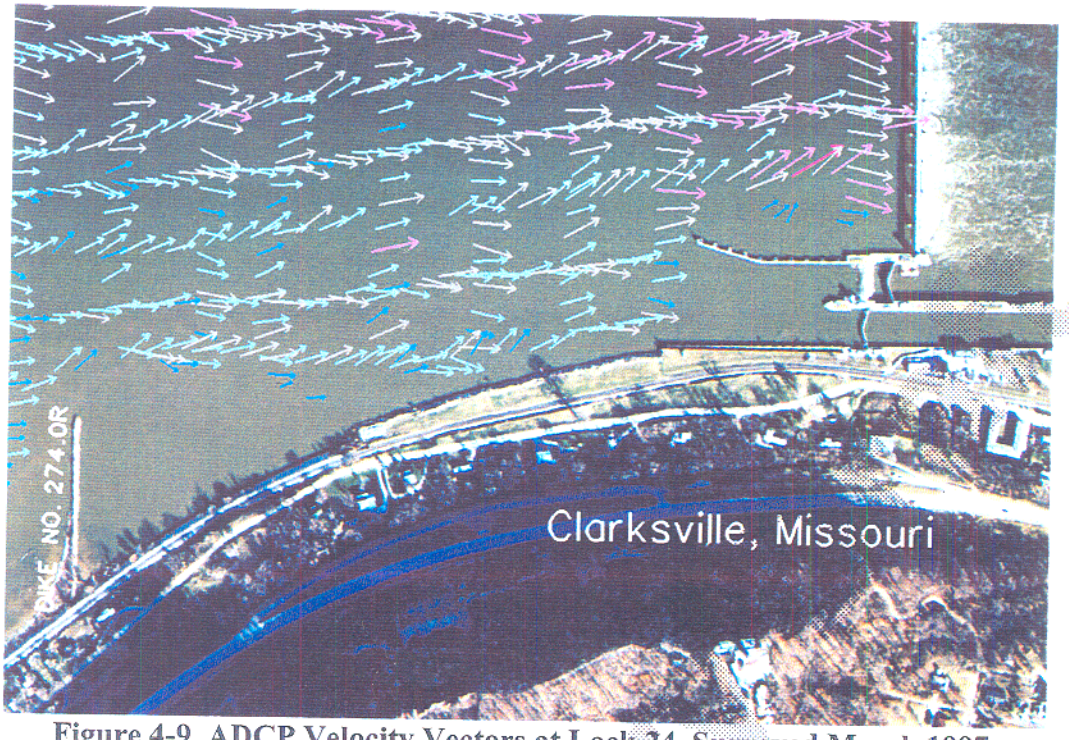

Figure 4-9 ADCP Velocity Vectors at Lock 24, Surveyed March 1997.

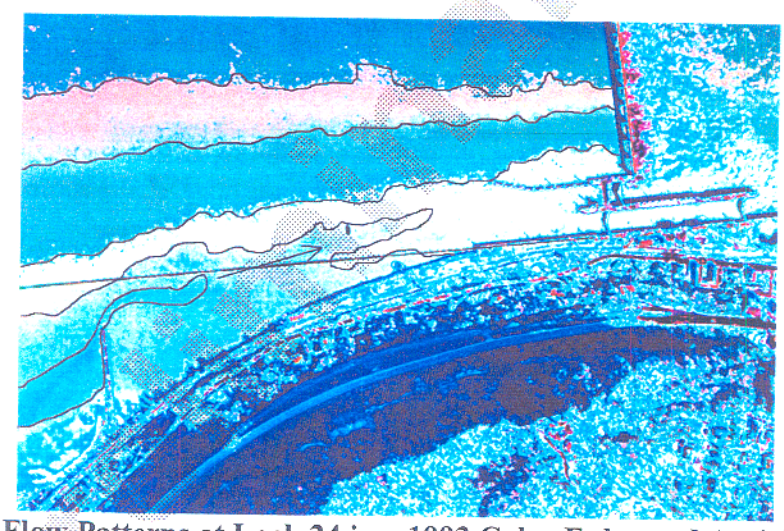

Figure 4-10 Flow Patterns at Lock 24 in a 1993 Color Enhanced Aerial Photograph

The remote sensing technique, combined with the ADCP data and the historic velocity data, enabled engineers to determine location and reason for outdraft current patterns. It was apparent that the rock bluff protrusion, located approximately 600 feet above the lock chamber, was the primary influence to the development of exaggerated

outdraft conditions upon downbound approaching tows. This observation was later shown in the flow visualization of the micromodel base test.

4.1.2.4 Lock and Dam 24 Micro model

The micromodel was constructed according to 1994 aerial photography of the study reach. The scales of the model were 1 inch = 800 feet, or 1:9600 horizontal and 1 inch = 50 feet, or 1:600 vertical for a 16:1 distortion ratio. The model was considered calibrated after it was concluded that the bathymetric patterns of the model were similar to those of the prototype. It was then determined that the flow patterns of the base test (Figure 7) were extremely similar to those shown in the prototype flow data.

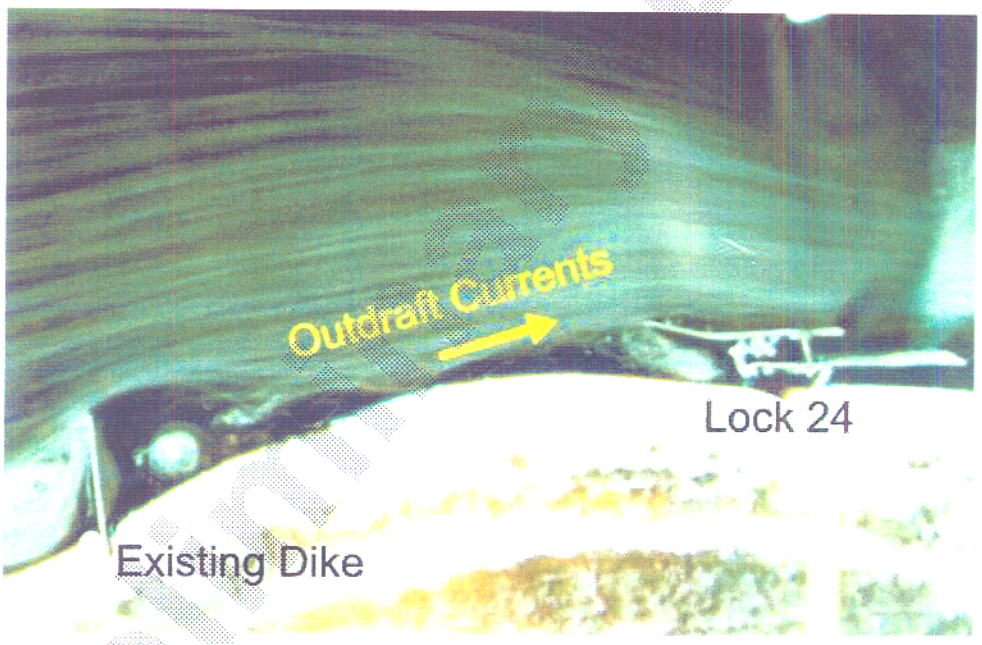

Figure 4-11 Micromodel Base Test Flow Visualization Showing Dangerous Outdraft Flow Patterns

Thirty alternative design plans were then tested in this study in an attempt to improve flow conditions at Lock and Dam 24. The effectiveness of each plan was compared to the base test conditions. Impacts or changes created by each alternative were evaluated by analyzing both the flow (using flow visualization) and sediment response of the model. A qualitative evaluation of the ramifications of each plan to both downbound and upbound tows was made during team participation meetings at AREC.

Engineers and navigation industry port captains and pilots carefully examined and discussed each alternative.

4.1.2.5 Recommended Solution

Using the model study test results as a guide, team representatives from the St. Louis District and river industry determined the most economical and practical solutions to the outdraft problem at the Lock. The team concluded that four bendway weirs upstream of the lock chamber off the left descending bank and a 200-foot extension of the existing dike at Mile 274.0R would result in the best possible measure at reducing or eliminating the outdraft problem. The weirs were designed to push flow towards the existing rock dike, making the elongated structure more effective at creating an area of slack water between the dike and the lock chamber. The resultant bathymetry from the model indicated that the thalweg shifted toward the right descending bank near the dike extension. Flow visualization in the model indicated that this design would create increased slack water between the dike and the lock chamber which would reduce the outdraft flow patterns (Figure 4-12, flow visualization). These patterns would provide favorable flow conditions for both upbound and downbound tows entering and leaving the lock chamber.

4.1.2.6 Results

The dike extension was constructed in 1998 while portions of the 4 bendway weirs were built in 2000 (Figure 1). Unfortunately, the contractor was unable to build the weirs to their designed length due to the lack of depth near the Missouri bank. The insufficient depths in the channel prevented full construction of these three structures. However, after a few high water events, the as-built structures should begin to scour the channel. Once sufficient depths are generated off the ends of the weirs, the remainder of the structures will be constructed. Until recently, Pool 24 had not experienced an extended duration of high flow that would rearrange the bathymetry of the riverbed to generate the proper depths for completion of the weirs.

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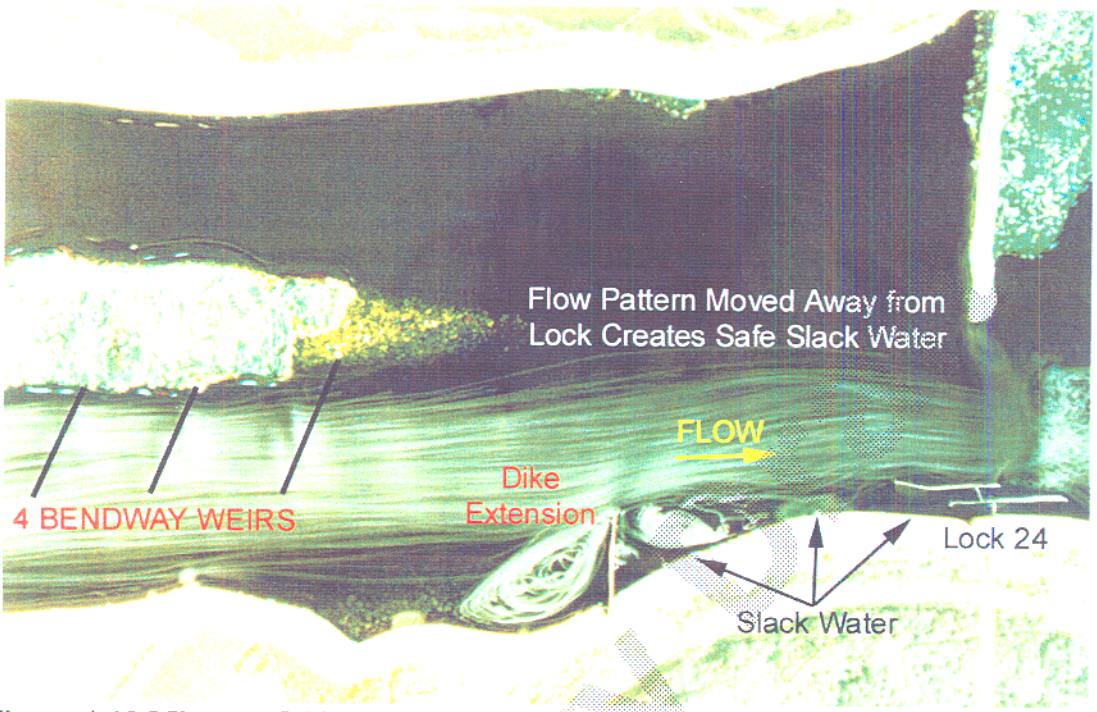

Figure 4-12 Micromodel Flow Visualization of the Recommended Remedial Design

Immediately after the dike extension was constructed, lock personnel and tow pilots reported positive results. The tow pilots have described a noticeable improvement in the flow patterns, which they say has significantly eased navigability into the lock chamber. Some pilots have even chosen not to accept assistance from the helper boat. Lock personnel also reported a decrease in drift entering the lock chamber, which may indicate that the higher flows are no longer directed toward the lock chamber. Post construction ADCP velocity data was collected in 2000 and is shown in Figure 4-13. Additional hydrographic survey data and ADCP data will continue to be collected to monitor the weirs and flow patterns.

4.1.2.7 Lock and Dam 24 (Case Study 2) Analysis of Results

The flow patterns discerned from the ADCP data collected in 2000 (Figure 4-13) clearly demonstrates distinctive similarities to those predicted by the micromodel flow visualization of the recommended design (Figure 4-12). This ADCP data compared to the preconstruction ADCP data (Figure 4-9) indicates that the dangerous flow patterns that had caused the outdraft problem have been dissipated. As also shown in the post construction data, the flow patterns in the model displayed a correction to the detrimental

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currents that had deflected off the right descending bank. The micromodel also correctly predicted the position and size of the eddy downstream of the dike. Although these methods of recording flow patterns are different, the similarities between the ADCP velocity vectors and the time elapsed stream lines from the model are clearly shown in these Figures.

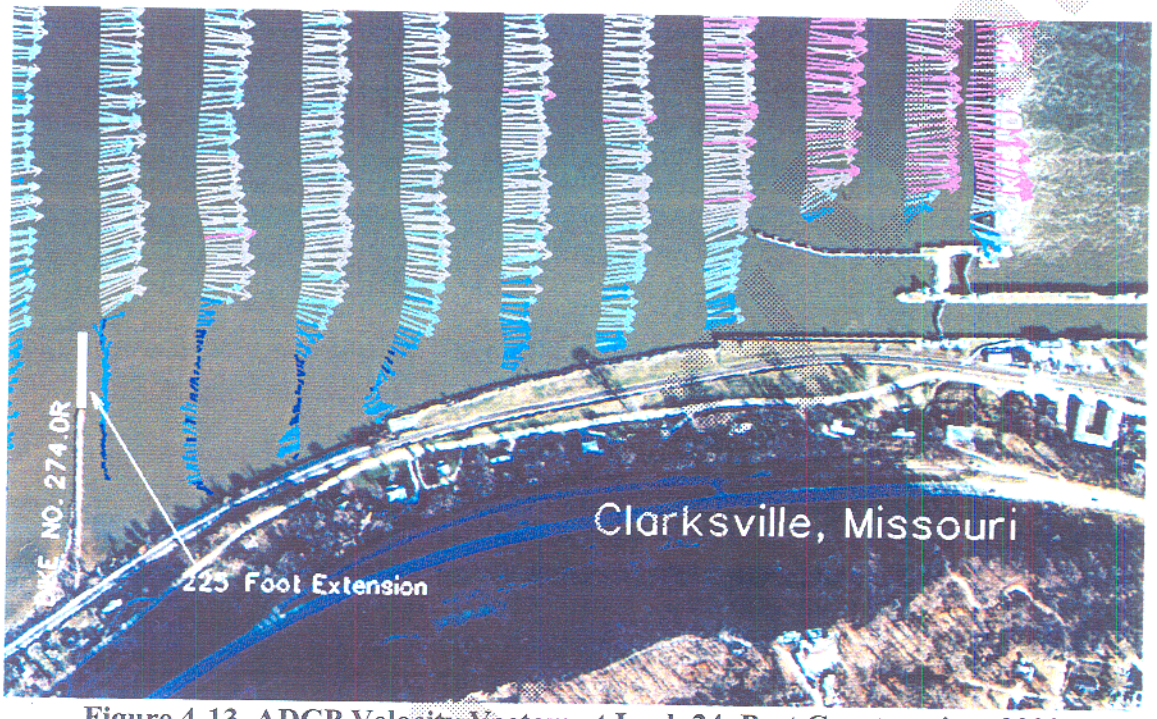

Figure 4-13 ADCP Velocity Vectors at Lock 24, Post Construction, 2000

4.1.3. Sante Fe Chute (Case Study 3)[8]

In 1996, biologists and engineers from the U.S. Fish and Wildlife Service, the Illinois Department of Natural Resources, the Missouri Department of Conservation, and the St. Louis District Corps of Engineers, ventured on a joint environmental effort to improve riverine habitat conditions within Sante Fe Chute on the Middle Mississippi River. This effort was made possible by the authority of the St. Louis District Avoid and Minimize Environmental Program.

[8] Gordon, D.C., Davinroy, R.D., "River Restoration Measures in Four Secondary Channels of the Mississippi River, An Interagency Success Story," ASCE Wetlands Engineering and River Restoration Conference Proceedings, 1998.

The agencies assembled a team of experts to formulize ideas and strategies for the purpose of developing aquatic diversity within the side channel at Mile 39. Design alternatives were tested by the team in the Micromodel at the AREC in St. Louis, Missouri. The use of the Micromodel enabled the team to address the complex sediment transport interaction problem between the side channel and the main navigation channel of the Mississippi River. Team members assembled at AREC on numerous occasions to jointly experiment with the Micromodel.

4.1.3.1 Problem Description

Sante Fe Chute was considered a high priority to the Corps partnering agencies for rehabilitation. The side channel parallels (Figure 4-14) the main river channel for approximately five miles and contains a dike and closure structure at the upper entrance. Compared to the main channel, bed elevations in the side channel are relatively high. At lower river stages, most of the bed becomes dry with isolated pockets of stagnant water that become disconnected from the main channel. Furthermore, depths throughout the reach are generally homogenous. Diversity, in the form of shallow and deep-water environments with areas of fast and slow flow, were desired to create important backwater habitat to support aquatic species. The team used a Micromodel to investigate structural designs to enhance the environmental diversity in the chute while ensuring navigable depths in the main channel.

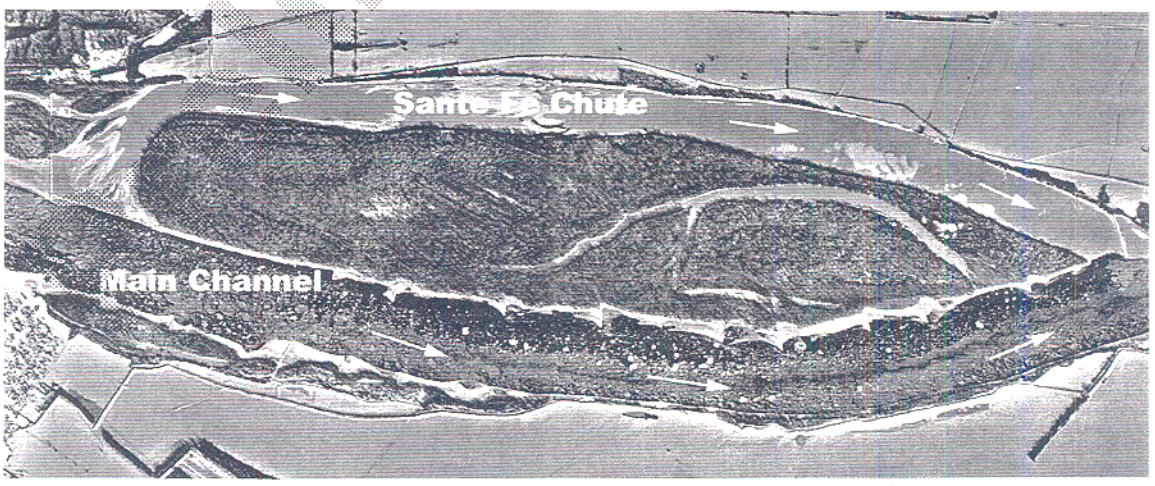

Figure4-14 Sante Fe Chute, Middle Mississippi River

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4.1.3.2 Sante Fe Chute Micromodel

The Micromodel was constructed according to 1994 aerial photography of the study reach. The scales of the model were 1 inch = 600 feet, or 1:7200 horizontal and 1 inch = 100 feet, or 1:1200 vertical for a 6:1 distortion ratio.

After the model was calibrated, team meetings were held in which various alternatives were conceptualized with the primary goal of creating diversity in bed elevations. Various modifications to existing river training works as well as other structural additions were tested in the model, including closure structure removal/modification, dredging, chevrons, and traditional dikes. Those designs that displayed promise in the model where then studied in greater detail using the established Micromodeling methodology. A total of seven structural design alternatives were model tested to study their impacts on bed development in both the side channel and main channel. The resultant bed configurations formed by each alternative were compared to the model base condition, whereby the most feasible and cost effective design alternative was selected.

It had long been believed by the agencies that the closure structure located at the upper entrance to the chute should be removed to restore flows to the backwater and remove or flush out much of the sediment that had accumulated. Model tests showed that this alternative would not have the desired effect. Additional bed load was able to enter the side channel, which ultimately decreased depths and filled in the only deep area of scour in the side channel. Navigable depths were also lost in the main channel adjacent to where the closure structure had been located.

The design eventually chosen by the team for implementation in the Mississippi River encompassed an alternating dike scheme that created sinuosity in both the flow and sediment patterns of the side channel (Figure 4-15). The alternative produced the most positive effects to the flow and streambed of the side channel in the most cost effective manner.

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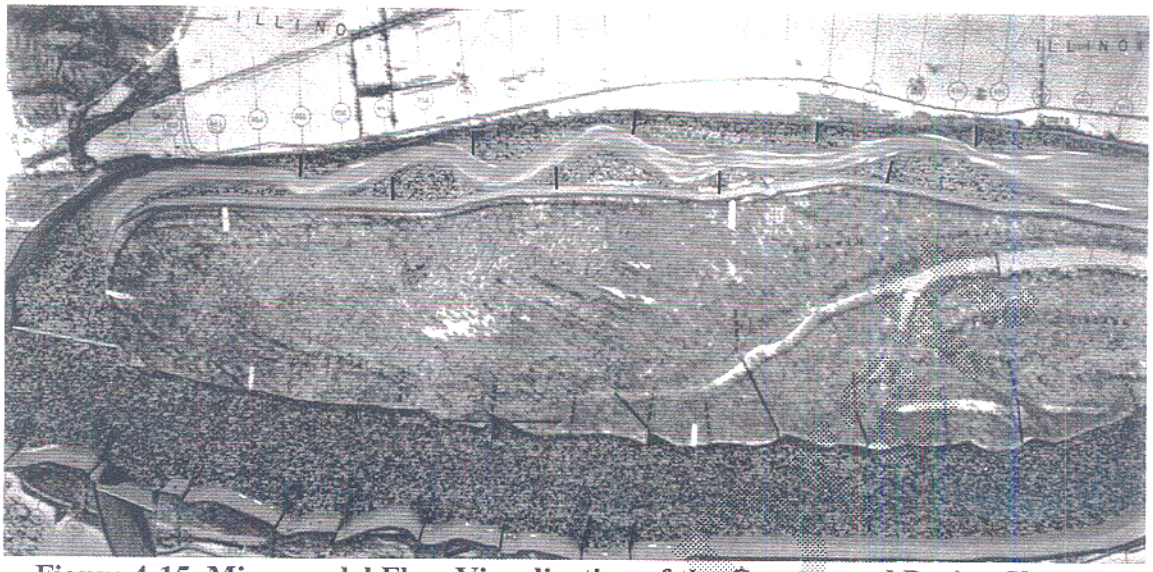

Figure 4-15 Micromodel Flow Visualization of the Constructed Design Shows a Sinuous Flow Pattern Created by Alternating Dikes in the Side Channel

Engineers then developed detailed construction plans and specifications with construction of the plan initiated shortly after completion of the model study in April of 1997 (Figure 4-16). However, due to funding constraints, the dikes were built significantly lower (10 feet) then recommended by the Micromodel study. Recent field monitoring of the design in the river has demonstrated that the riverbed has partially developed the predicted bed forms even with the structures at a lower elevation.

Through the use this Micromodel, it was possible for a team of biologists and engineers to develop a cost effective, reliable design solution to the first side channel restoration project on the Middle Mississippi River. The hours spent together on the Micromodel provided an invaluable dialect and understanding among the interagency team members and set precedence for additional environmental engineering efforts on the river.

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Figure 4-16 Two of the 7 Dikes Constructed in Sante Fe Chute

4.1.4. Morgan City/Berwick Bay (Case Study 6)[9]

In 1999, the Hydrologic Engineering Section of the U.S. Army Corps of Engineers, New Orleans District initiated a sedimentation and navigation improvement study of the Lower Atchafalaya River at Morgan City and Berwick, Louisiana. The purpose of the study was to evaluate a number of structural design alternatives and/or modifications for channel improvement on the Atchafalaya River between Miles 124.0 and 118.5. Micromodeling methodology was used to evaluate the sediment transport and hydrodynamic response trends that could be expected to occur in the river from various channel improvement design alternatives. These alternatives were conceptualized and submitted by members of a study team representing the New Orleans District, the St.

[9] Case study descriptions extracted from:
Gordon, D.C., Davinroy, R.D., "Sedimentation and Navigation Study of the Lower Atchafalaya River at Morgan City and Berwick, Louisiana, River Miles 124.0 to 118.5, Hydraulic Micromodel Investigation," U.S. Army Corps of Engineers, St. Louis District, 2001.

Gordon, D.C., Davinroy, R.D., Austin, J.W., "Small Scale Physical Sediment Transport Modeling Approach Used to Solve a Chronic Dredging Problem on the Atchafalaya River at Morgan City, Louisiana," 7th Federal Interagency Sedimentation Conference Proceedings, 2001.

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Louis District, and the Corps of Engineers Coastal and Hydraulics Laboratory. The primary goal was to qualitatively evaluate the impacts of these measures on the resultant bed configuration (sediment transport response) and hydrodynamic response (flow patterns) within the study reach.

4.1.4.1 Problem Description

The Atchafalaya River is a primary distributary channel of the Mississippi River in which the Corps of Engineers maintains a 12-foot deep by 125-foot wide navigation channel. The Berwick Bay reach, shown in the aerial photo in Figure 4-17, is located between Morgan City and Berwick, Louisiana. The reach is comprised of several branches of the Gulf Intracoastal Waterway System (GIW) that converge through this reach. This intersection of waterways results in congestion for commercial navigation traffic.

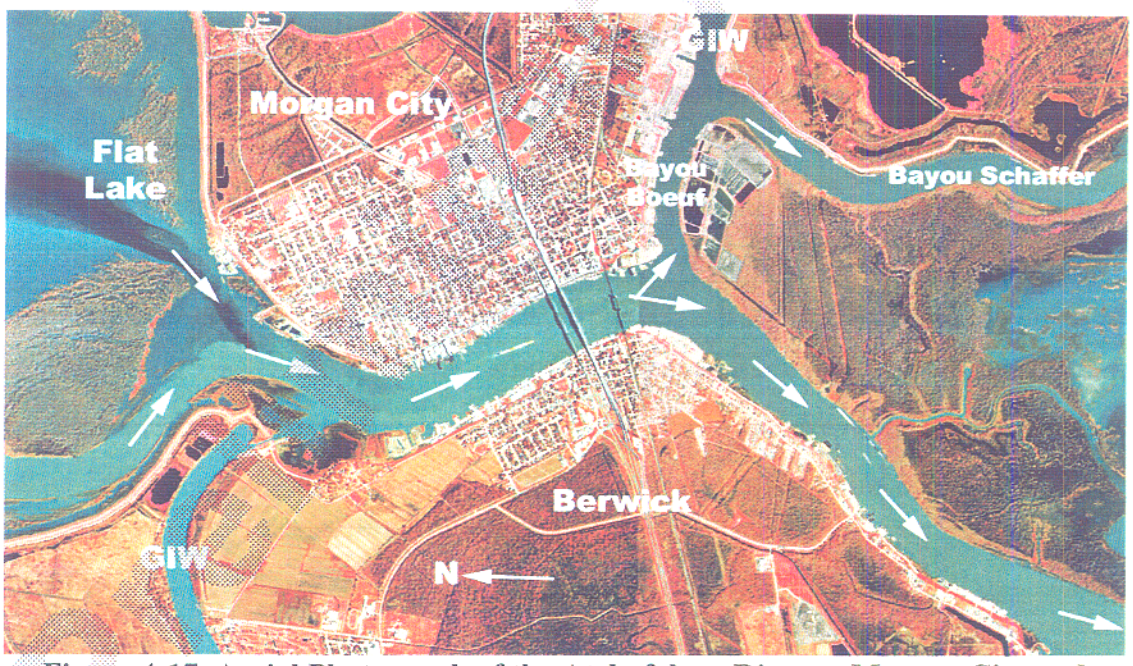

Figure 4-17 Aerial Photograph of the Atchafalaya River at Morgan City and Berwick, Louisiana

This particular stretch of river has been one of the most troublesome reaches on the Atchafalaya River in terms of dredging cost, frequency, and volume. The New Orleans District must maintain navigable depths between river banks within Berwick Bay

to ensure adequate depths for the ports, facilities, and boat docks that are located along the riverfronts of both cities. Although Berwick has sufficient depth to maintain navigation, Morgan City is faced with a large depositional area that accumulates enough sediment to halt navigation into the port facilities. The District currently dredges at this location approximately twice per year. Nearly one million cubic yards of material were removed from this site in 1999.

Another concern in this reach of river is safety. Berwick Bay contains three bridges that span the river in close proximity to each other. The two U.S. Highway 90 bridges contain adequate navigation span widths of 580 feet and 520 feet. However, the Southern Pacific Railroad Bridge contains a lift-span with an extremely narrow navigation width of approximately 320 feet. Until the establishment of a stringent traffic control system by the U.S. Coast Guard in 1974, this bridge was listed as the "most hit" in the United States.

Historically, the flow and direction of currents in this area have not been conducive to safe navigation through these bridge spans. While the navigation spans of the bridge crossings are located in the center of the channel, the thalweg and main concentration of flow are located near the right descending bank along the Berwick side of the river. Therefore, the direction of river currents tends to divert downbound vessels attempting to navigate through the center bridge spans toward the right descending bank. The misalignment of currents with the navigation spans has forced tow pilots to make precise adjustments to the position of their vessels well upstream of the bridges. A slightly misguided tow could easily collide with the many bridge piers located in the channel.

4.1.4.2 Study Purpose and Goals

The purpose of this study was to qualitatively assess the present day sediment transport and flow response trends of the Atchafalaya River. The primary goals were to evaluate design alternatives that would reduce the deposition and dredging associated with the reach, and to provide improved flow conditions for navigation through the bridge crossings. Improving flow conditions included examining ways to reduce

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velocities and generally redistribute flow patterns in the Atchafalaya River channel by the use of underwater weirs. Qualitative assessments of each design alternative included the examination on the ultimate effects to sedimentation, flow patterns, and navigation within the main channel of the Atchafalaya River.

4.1.4.3 Morgan City/Berwick Bay Micromodel

The Micromodel encompassed the Atchafalaya River channel between Miles 116.5 and 126.0 and was constructed according to the high-resolution aerial photography of the study reach shown in Figure 1. Portions of Flat Lake, Bayou Boeuf and Bayou Schaffer were also included in the model. The scales of the model were 1 inch = 600 feet, or 1:7200 horizontal, and 1 inch = 100 feet, or 1:1200 vertical, for a 6 to 1 distortion ratio. The model was calibrated to the 1999 multi-beam bathymetric survey shown in Figure 4-18. The Micromodel base test is shown in Figure 4-19. A comparison of cross sectional area between the Micromodel and the prototype revealed an average 8.2% difference.

Figure 4-18 Multi-Beam Bathymetry from the Atchafalaya River used to Calibrate the Micromodel

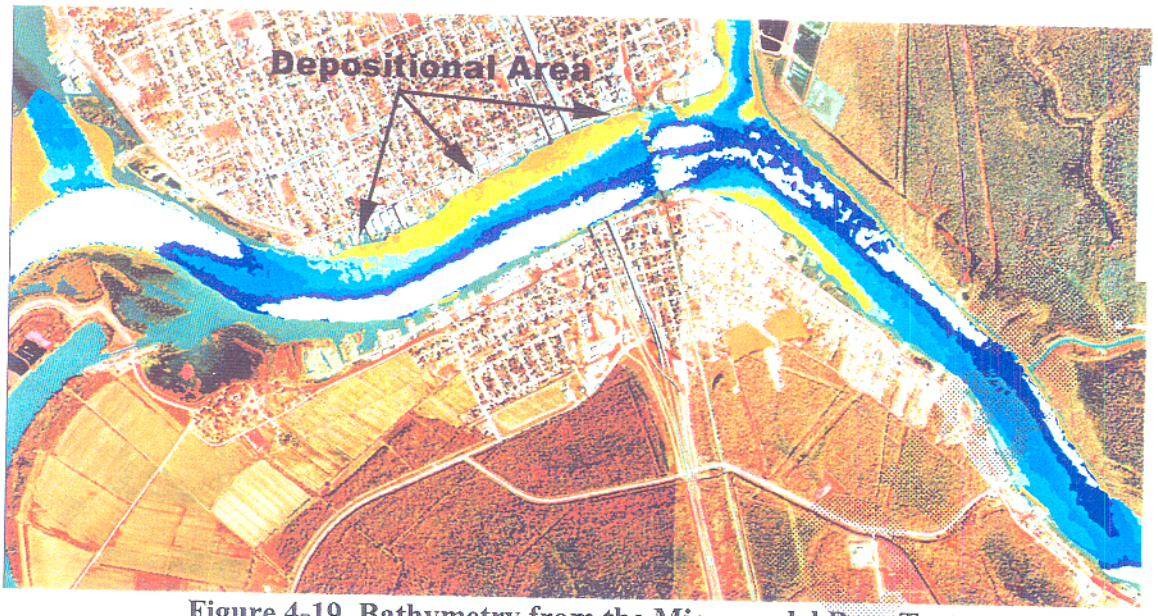

Figure 4-19 Bathymetry from the Micromodel Base Test

Flow visualization photographs were examined at both low flow and high flow to better assess the general surface current patterns associated with each design alternative. It was determined that the flow trends of the model base test, shown in Figure 4, were very similar to the prototype velocity vectors established from ADCP data. These photos then served as the comparative flow patterns for all design alternative tests. At both flow rates, the model demonstrated that most of the flow was concentrated along the right descending bank and to the right of the navigation spans which are located in the center of the channel.

Eleven design alternative plans were model tested to examine methods of modifying the sediment response trends that would minimize dredging and improve the flow patterns through the Berwick Bay reach. The impacts induced by each alternative design were assessed by qualitatively examining both the flow and sediment response of the model. The effectiveness of each design was evaluated by comparing the resultant bed configuration and flow patterns to those of the base test condition.

4.1.4.4 Recommended Solution

Examination of the model results indicated that the most effective design consisted of 10 bendway weirs located within a one-mile reach of river and at a depth of –20 feet below the low water stage. The resultant flow patterns and bathymetry

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developed by this design in the model are shown in Figures 4-20 and 4-21. The model results demonstrated that the design proved effective at reducing the elevations in a substantial portion of the depositional area along the left descending bank. The design also shifted the thalweg towards the center of the channel at the upstream portion of the reach (Figure 4-22). The weir field effectively created a smooth transition of the thalweg from the bend towards the middle of the channel and into the straight reach upstream of the bridges. The length, angle, position, and elevation of each weir placed in the micromodel were critical to achieving the desired bed forms and flow patterns.

Flow visualization demonstrated a significant redistribution of current patterns across the channel width. The design indicated that the flow patterns were more evenly distributed across the entire channel width and were no longer concentrated along the right descending bank with the recommended alternative.

Figure 4-20 Micromodel Base Test Flow Visualization

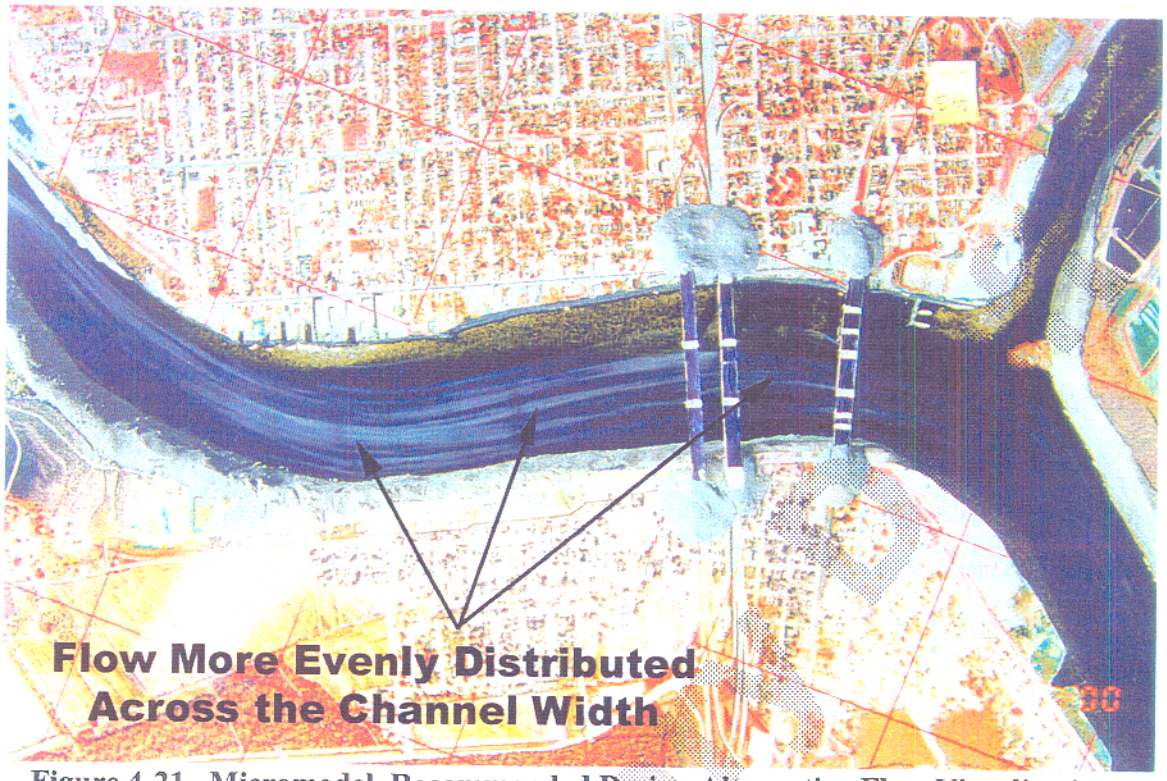

Figure 4-21 Micromodel Recommended Design Alternative Flow Visualization

Figure 4-22 Bathymetry Trends Developed by Bendway Weirs, Selected Alternative

4.1.4.5 Results

The historically complex nature of this reach of river has caused river engineers to use extreme caution when studying designs that significantly modify the flow patterns in this dangerous and busy reach of river. Therefore, the results of the Micromodel are being utilized in a three-dimensional numerical flow model at the University of Iowa to quantitatively evaluate the flow conditions induced by the bendway weir design. The results from this model will then be applied to a computer navigation simulator at the Corps of Engineer's Coastal and Hydraulics Laboratory in Vicksburg, Mississippi to study the effects of modeled flow conditions on tows navigating this reach of river. Construction of the design may begin only after these models are completed and approvals are obtained from the towing industry and the U.S. Coast Guard.

4.2. MOUTH OF THE WHITE RIVER (CASE STUDY 4) [10]

In 1997, micromodel methodology was used for a sedimentation and navigation improvement study of the Lower Mississippi River at the confluence of the White River (Mile 599). Various channel improvement design alternatives were qualitatively evaluated for improving detrimental flow conditions that affect tows navigating into the White River. The micromodel was used by the study team to assess the impacts of these measures on the resultant bed configuration (sediment transport response) and hydrodynamic response trends (general flow patterns) that could be expected to occur in the river within the study reach. The members of the study team represented the Memphis and St. Louis Districts, Mississippi Valley Division, and various representatives of the navigation industry. The team's recommended plan of seven bendway weirs near the confluence was constructed over two phases during the fall of 2001 and the winter of 2002. The Memphis District has already compiled extensive post-construction flow data and conducted interviews with tow pilots.

[10] Gordon, D.C., Davinroy, R.D., "Sedimentation and Navigation Study of the Lower Mississippi River at the White River Confluence, Miles 603 to 596, Hydraulic Micromodel Investigation," U.S. Army Corps of Engineers, St. Louis District, 1998.

4.2.1.1 Problem Description

The White River serves as an entrance to the McClellan-Kerr Arkansas River navigation system. The new Montgomery Point Lock and Dam is currently being constructed on the White River approximately 3000 feet upstream of the confluence with the Lower Mississippi River. There have been several navigation problems associated with the confluence of the two rivers. The present day alignment at higher river stages has been generally responsible for problems with tows entering or exiting the White River. Towing companies that typically navigate in and out of the White River were interviewed and all stated that they have had frequent problems with differing degrees of severity when entering or exiting the mouth of the White River. Indications were that the problem has existed for years, and may be getting more severe each year.

The strong velocities on the outside of this Mississippi River bend at the confluence create detrimental flow conditions for tows transiting into the White River (Figure 4-23). The bar encroaching out from the adjacent bankline at Smith Point has caused a narrower, deeper, and swifter Mississippi River channel in this area. The present alignment requires that tows navigate broadside to the high Mississippi River currents to get into the White River (Figure 4-24). This dangerous but necessary maneuver has swamped vessels and pushed tows into the banklines. Adding to the reported poor alignment is a strong eddy off the upstream point. This eddy creates additional navigation problems for some towboats at varying stages. The pilots have also mentioned that the sharp contrast or difference in depths between the Mississippi River and the White River as a possible navigation problem. The bathymetry of the reach is shown in Figure 4-25. Different methods of navigation are employed to help avoid the problems encountered. These methods include breaking tows and double tripping, using another boat for assistance, or using the upstream eddy as a guide for navigating into the mouth.

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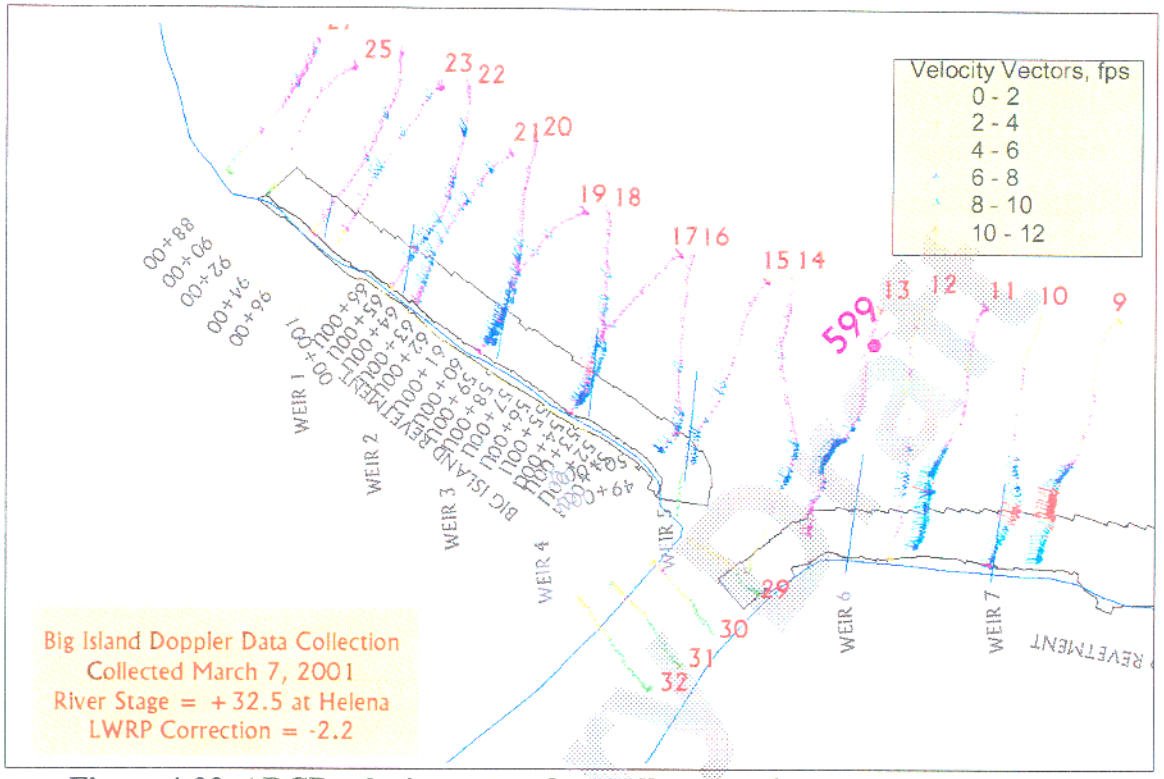

Figure 4-23 ADCP velocity vector data collected before construction of the bendway weirs. High velocity flows were located on the outside of the bend and near the White River confluence.

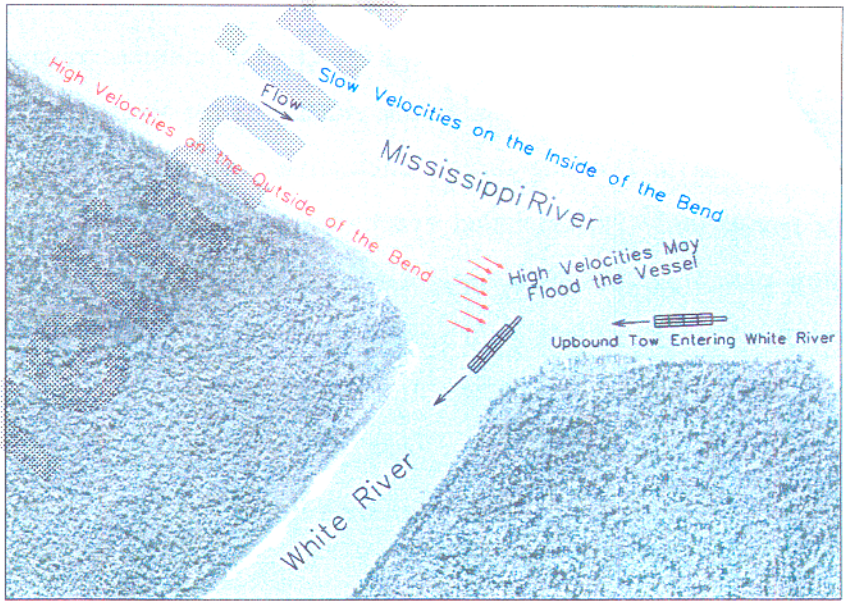

Figure 4-24 Diagram of the typical procedure employed by an upbound tow entering the mouth of the White River.

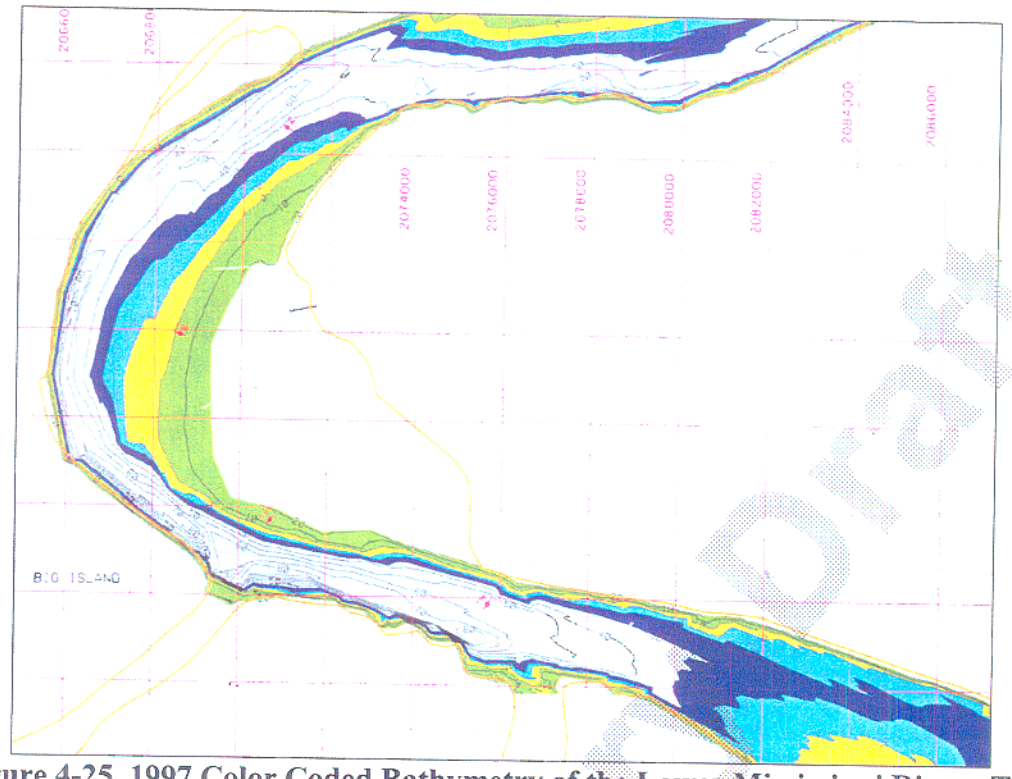

Figure 4-25 1997 Color Coded Bathymetry of the Lower Mississippi River. The white colors represent the deepest areas of the river on the outside of the bend.

4.2.1.2 Study Purpose and Goals

The purpose of this study was to assess the general sediment transport and flow response trends of the Mississippi River in the vicinity of the White River confluence. The primary goal was to evaluate design alternatives that would provide improved conditions for navigation. This included examining methods to reduce velocities and redistribute flow patterns in the Mississippi River main channel by the use of bendway weirs. Protection of the confluence with a dike structure, realignment possibilities, and reduction of the eddy were also evaluated. Assessments of these alternatives included a qualitative examination to the ultimate effects to sedimentation, flow patterns, and navigation within the main channel of the Mississippi River.

4.2.1.3 Mouth of the White River Micromodel

The micromodel insert encompassed the Mississippi River channel between Miles 605 and 587 and was constructed according to aerial photography of the study reach. The scales of the model were 1 inch = 1000 feet, or 1:12000 horizontal, and 1 inch = 100 feet,

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or 1:1200 vertical, for a 10 to 1 distortion ratio. Flow was not simulated in the White River because historic stage and flow records have indicated that the Mississippi River discharge dominates most of the year. The problems this study addresses have been evident mainly when the Mississippi River is at high stage. At this stage the White River, for purposes of this study, was considered a backwater area with no simulation of flow or sediment transport. The bed of the White River above the confluence was molded according to a 1996 hydrographic survey of the study reach.

The model was considered calibrated after it was concluded that the bathymetric patterns formed in the model were similar to those of the prototype. It was then determined that the flow patterns of the base test were similar to those shown in the prototype flow data. Figure 4 shows the flow visualization of the micromodel and a 1977 ice photo of the confluence area. Even though the modern day alignment has changed slightly since this time period, the ice in the photo gave a general representation of flow patterns within the study reach. The ice patterns showed that the flow in the Mississippi River was concentrated tightly along the right descending bankline upstream of the White River confluence. Flow deflected slightly off the downstream point of the confluence began to distribute across the channel before approaching the downstream crossing. The ADCP data in Figure 4-23 can also be compared to the photos shown in Figure 4-26.

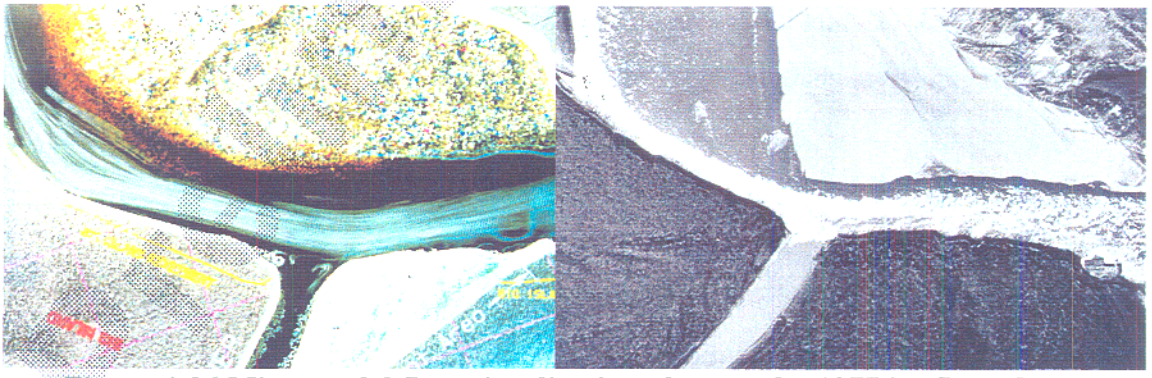

Figure 4-26 Micromodel flow visualization photo and a 1977 ice flow photo.

Ten alternative design plans were tested in the model to improve flow and navigation conditions at the confluence of the two rivers. The designs included traditional dikes, bank realignment, and bendway weirs. The effectiveness of each plan was evaluated by qualitatively comparing the resultant bed configuration and general

flow patterns to that of the base condition. A qualitative evaluation of the ramifications to both upbound and downbound tows was made during team participation meetings in St. Louis, Missouri. Engineers from the Memphis, St. Louis, Vicksburg, and Little Rock Districts, Mississippi Valley Division, Waterways Experiment Station, and those involved in the navigation industry carefully examined and discussed each alternative.

4.2.1.4 Recommended Solution

Using the model as a guide during alternative testing and team meetings, it was concluded that a set of 7 bendway weirs would accomplish the objectives set forth. Five of the weirs would be placed upstream of the confluence while the remaining two would be built downstream. It was determined that this design would effectively improve entrance conditions for tows navigating in and out of the White River. Tows that currently navigate this area are often subjected to high velocities in a deep channel near the confluence. The weirs in the model moved these higher velocities and depths toward the center of the channel and away from the confluence (Figure 4-27). An additional benefit of shifting and redistributing the higher velocities away from the confluence was a possible reduction of the dangerous eddies that form within the mouth of the White River at certain river stages. The model also showed that the bendway weirs widened the narrow navigation channel by removing a portion of the sandbar along the adjacent bankline. A wider channel would create safer conditions for the larger tows transiting the main Mississippi River channel.

4.2.1.5 Results

The construction of the weirs concluded in January 2002. Although the structures have not completely formed its resultant bed configuration or flow patterns, the initial impacts of the structures were noticed almost immediately. The tow pilots that regularly operate in the reach have reported significant improvements in the general flow patterns and the navigability of their vessels. Corps' engineers witnessed nearly vertical faces along the point bar adjacent to the weirs, which signified a widening of the channel. ADCP data in Figures 4-28 through 4-32 show plan view the resultant velocity vectors and velocity isovels before and after construction. The Figures clearly show that the

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higher velocity flows have been moved away from the bank and to the areas off the ends of the weirs near the center of the channel.

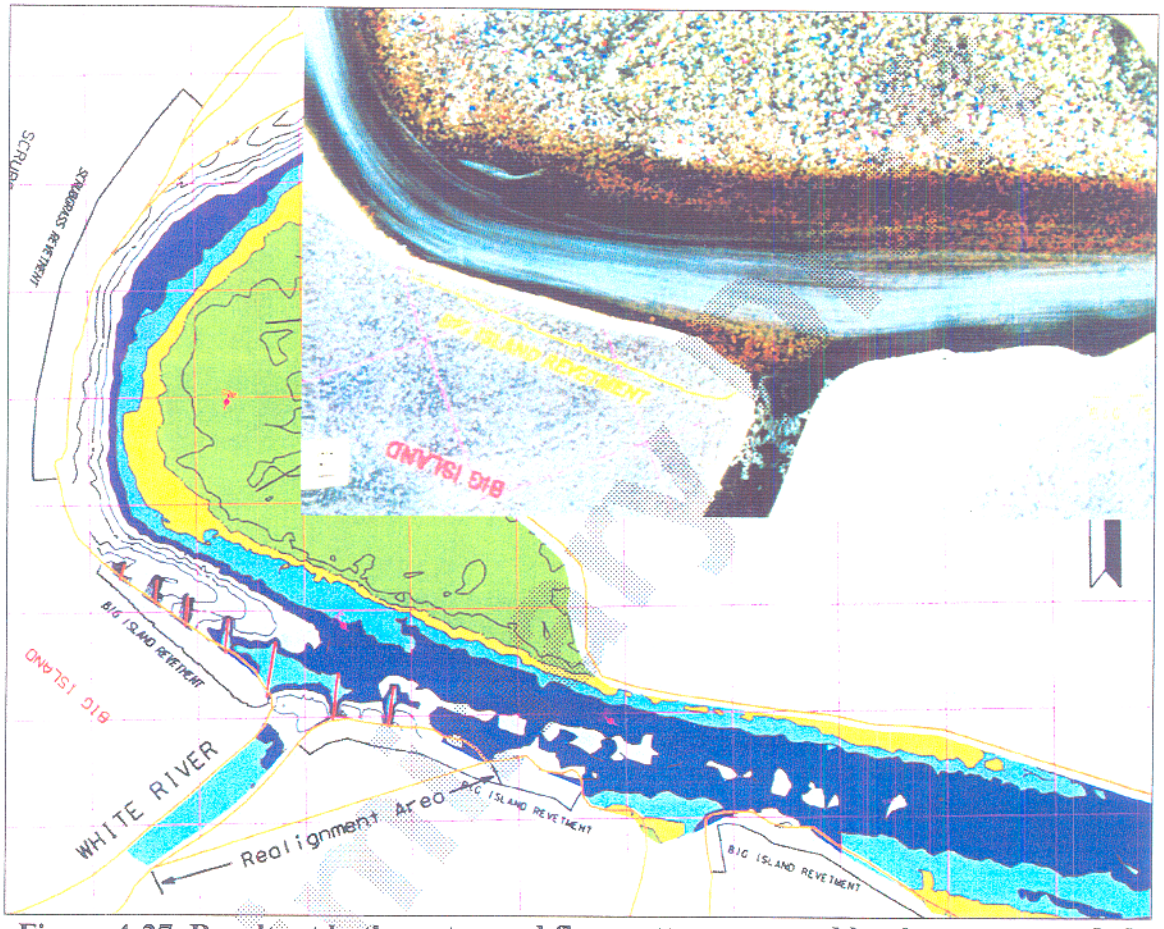

Figure 4-27 Resultant bathymetry and flow patterns created by the recommended bendway weirs in the micromodel. The model showed that the thalweg and highest flow patterns were shifted towards the center of channel as result of the design.

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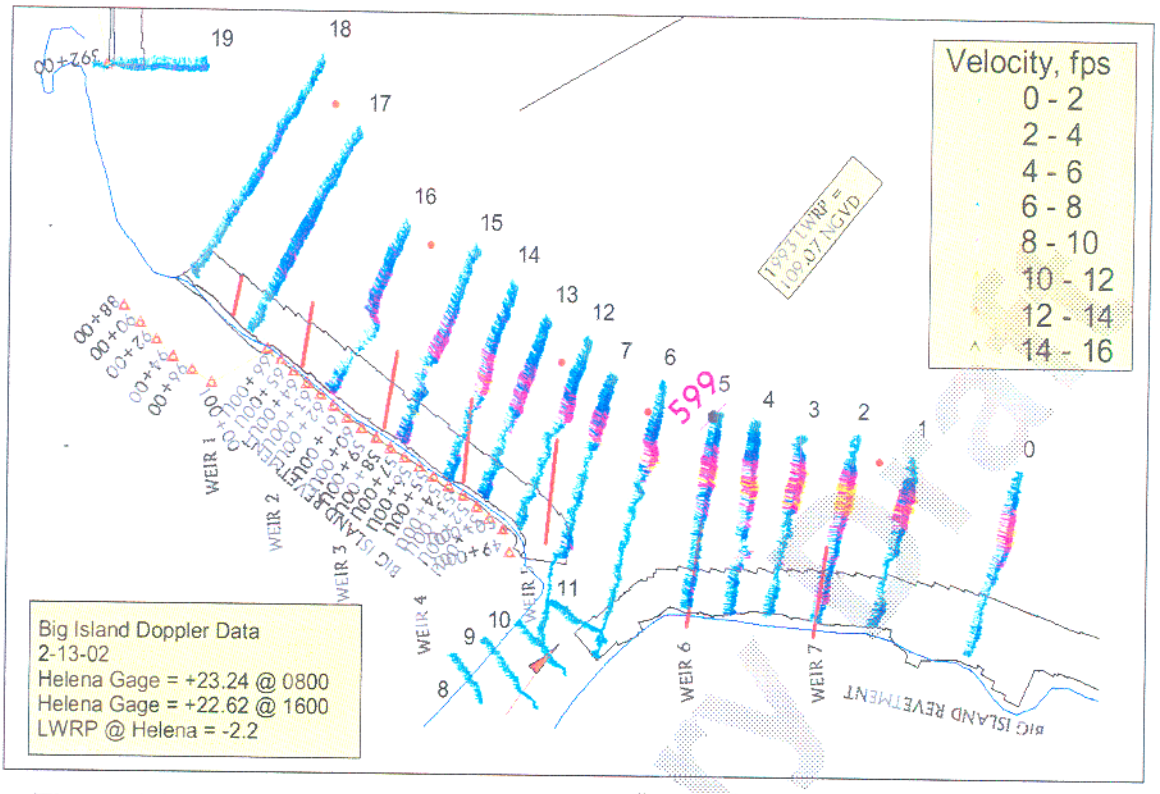

Figure 4-28 ADCP velocity vector data collected shortly after construction. The main flow is shown off the ends of the weirs and toward the center of the channel.

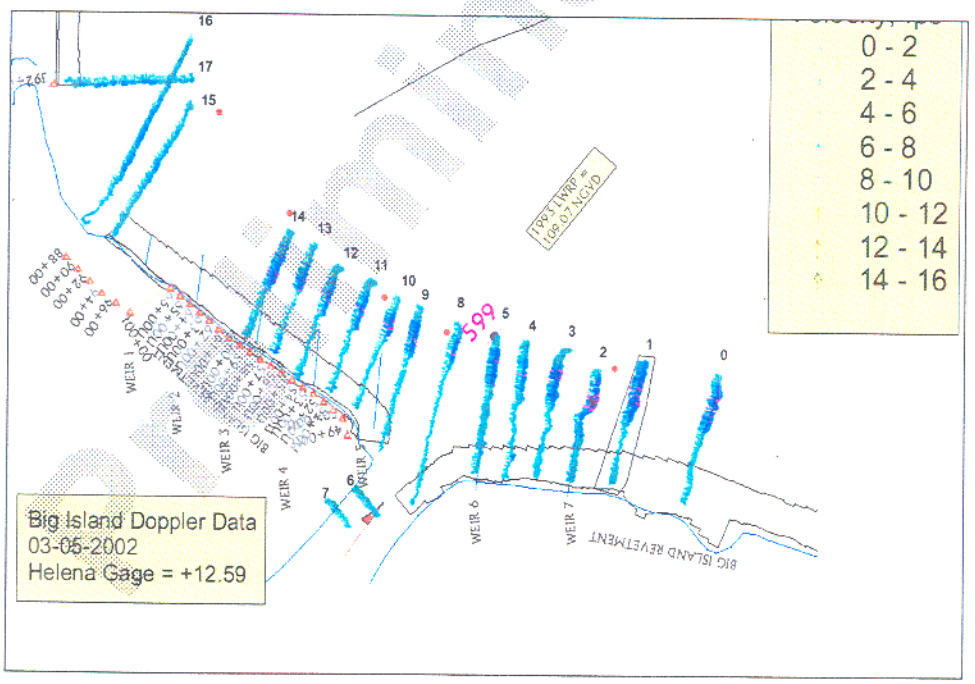

Figure 4-29 ADCP velocity vector data collected after construction. The main flow is shown off the ends of the weirs and toward the center of the channel.

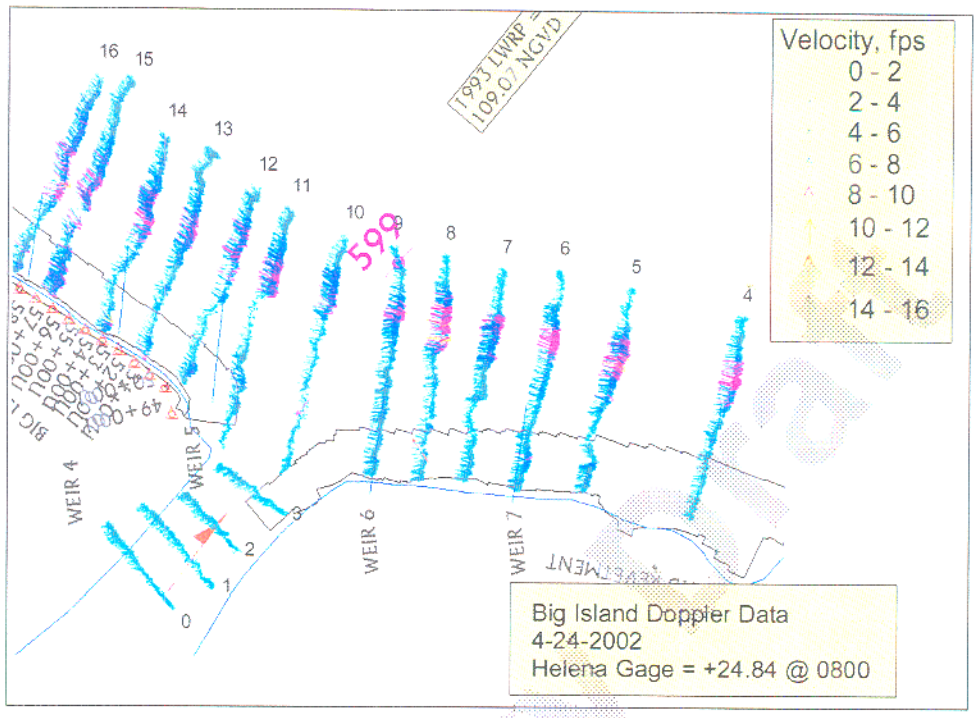

Figure 4-30 ADCP velocity vector data collected after construction. The main flow is shown off the ends of the weirs and toward the center of the channel.

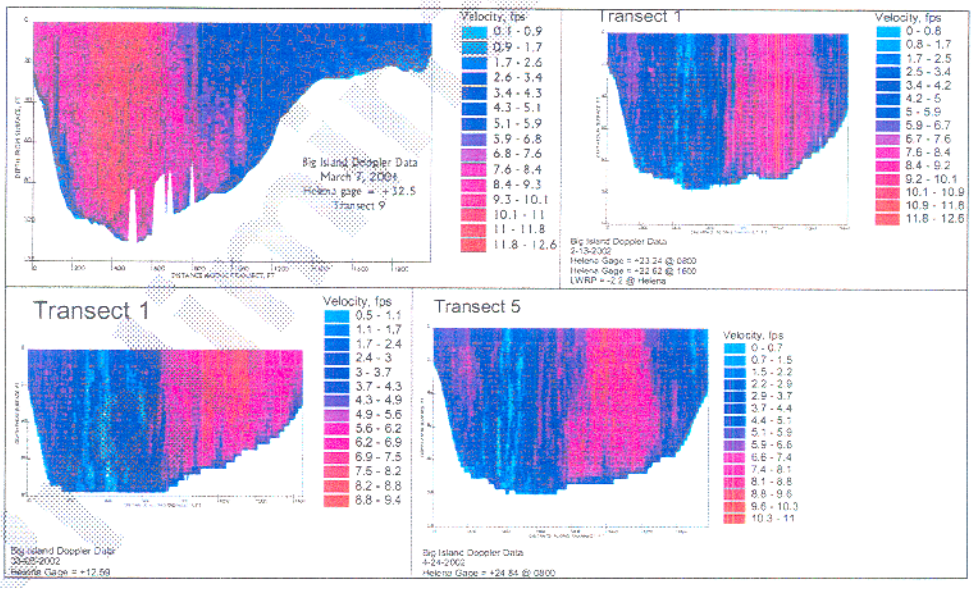

Figure 4-31 ADCP velocity isovels downstream of Weir 7 collected before construction (top left) and after construction (top right and bottom). The view is looking upstream and shows the high velocity flows have shifted to the area off the ends of the weirs and toward the center of the channel.

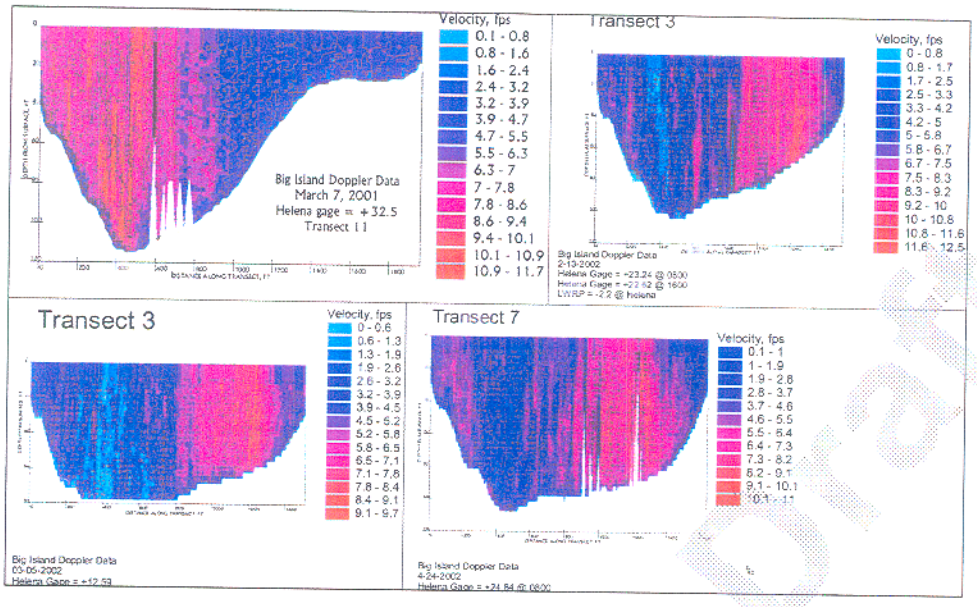

Figure 4-32 ADCP velocity isovels upstream of Weir 7 before construction (top left) and after construction (top right and bottom). The view is looking upstream.

4.3. GENERAL

Application of loose-bed physical models involves a qualitative assessment of model results relative to the prototype under consideration. This qualitative assessment includes a degree of subjectivity on the part of the modeler. Because individual opinions differ, loose-bed models are often the subject of controversy. The various empirical techniques (even the "rational" model design envisioned by Einstein and Chien involved a degree of empiricism) used in model calibration add to the controversy. Perhaps because of their deviation from "conventional" loose-bed model practices, micromodels are the subject of a large amount of criticism. One principle need then is to establish what defines an acceptable model output. In this case, the definition of acceptable is not absolute because it is site and situation specific.

Much of the support for micromodel use stems from past model study results. Therefore, case studies provide the primary basis of proponent views. While past model success plays an important role in evaluating the tool, there are some areas where opposing views exist. The opposing views arise primarily from comparison of model and prototype, from the extreme deviations in similarity criteria that exist in the micromodel

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and in interpretation of model results. Current micromodel methodology dispenses with any regard of similitude other than a similarity in channel bathymetry. Indeed, no simililitude criteria are used in micromodel design or operation. Nevertheless, Parker (1999) emphasized that the laws of Newtonian physics apply to micromodels just as they do to the prototype and similarity considerations can not be ignored. Micromodels must also be considered in light of their ability to reproduce the physical phenomena that drive the bed response.

4.4. PROPONENT VIEWPOINTS

Many of the critics to micromodeling have been experts familiar with typical hydraulic models that do not account for sediment transport. Therefore, their critique is directed at similitude criteria and typical parameters used in quantitative hydraulic modeling. However, the focus of all movable bed models is sediment transport and its pattern of formation in an alluvial river channel. These models are always considered qualitative. The critics also state that the micromodel is unsuitable for use in the design of river training structures. Whether or not this is a true statement, there are no alternative models, other tools, or guidance available to the engineer for designing these structures.

Overall knowledge of sediment transport is limited -- There are no equations or models that can accurately predict sediment transport rates or the resultant bathymetry of a river. Therefore, what guidance does the engineer have when designing river training structures? Traditionally, the only tools available were experience, intuition, and the large physical models. Today, the micromodel is the only additional tool available.

The micromodel is used mainly for qualitatively studying the relative effects of alternative designs on the riverbed. Many other tools are available for studying different types of problems, such as stage-discharge relationships. A complete study of rivers and their morphology requires many different tools in which the user must account for an array of interrelated parameters. The micromodel is a dedicated tool for the use of studying changes of in channel bathymetry. The micromodel, like all other models, can only be as useful as the knowledge of the modeler. Any problematic reach of river

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requires an experienced river engineer or designer to design the proper solution, whether or not a model is used.

Ettema (1999) states: "Micro-models have their place as a design aid for river engineering." He also states "As with all hydraulic models, the bottom line for micro-models is that the limits of their applicability fundamentally depend upon the extents to which they meet similitude considerations and on the level of risk the model user is prepared to assume." This risk is also assumed during the design of river training structures without a model. The risk the modeler takes is considerably less than the risk river engineers normally assume when most river training works are designed. These structures are usually designed without the aid of models or any other quantitative tools. The design process consists of a team of river engineers using only their experience and intuition with a limited amount of data to develop a completed design. There are no equations or specific guidelines to follow.

The design of most river training structures are conducted by experienced river engineers without the use of any type of model. The data used for design normally includes bathymetry and aerial photography. Sometimes flow data is obtained, such as velocity vectors from ADCP or ice data. However, most designs are initiated without the use of equations or any other quantitative or numerical aids. It is the experience and intuition of a team of river engineers that usually decides upon an initial concept as well as the final design that is eventually constructed in the river Most designs originated from empirical analysis by the designers.

Many times loose-bed models are used as a type of insurance to the engineer. They allow the user to first test a design in the protection of a laboratory setting without the risk of failure in the natural river environment. The model can give a design team additional confidence than just using their experience and intuition. For example, the original contract designer of the Big Creek project suggested that a 50-foot dike would solve the problem. However, the model suggested that a 25-foot dike would achieve the desired results and would therefore be the more economical solution.

As with all types of models, the micromodel requires the operator to have previous experience in the field of physical sediment transport modeling and in river

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engineering. The models simply help the river engineer and associated team members formulate plans and conceptual designs through a number of meetings and experiments. A model provides a means of studying and understanding the morphologic characteristics of a reach of river through the investigation of the data available and through the workings of the model. The model and data tend to complement each other and afford the modeler as well as others a greater clarity of the reach dynamics and characteristics.

Most dikes, weirs and river training structures are designed using the strictly qualitative approach of pure experience and intuition. However, this approach translates into a dimensional design during this process without any quantitative analysis. Therefore, a gray area exists between qualitative and quantitative analyses and the subsequent design processes. In the field of river engineering, there is an undefined point where a qualitative analysis must become quantitative. All sediment transport modeling overlaps this point. During a model study, the modeler must use quantitative reasoning to make a qualitative analysis. A completely qualitative or quantitative analysis does not exist.

In a sense, the model is quantitative because exact measurements are recorded and studied. However, the modeler must examine the measured data and translate it into qualitative thoughts and analysis. At some point during this process, a quantitative design solution must be extracted. Therefore, the points at which reasoning changes from quantitative to qualitative and back to quantitative occurs are blurred. This process not only occurs in the modeling process, but within any river engineering design process.

It is impossible to approach sediment transport and river engineering in a strictly quantitative sense. Every aspect of this field is of a qualitative nature because the current knowledge of the physical processes is limited. Therefore, the model must be considered quantitative. Yet, the modeler must analyze the model results in both a qualitative and quantitative sense because the final design solution requires specific dimensions and must therefore be quantitative. The modeler (or the designer) must therefore be the one to recognize the differences and select the appropriate way to use each type of analysis.

One area of concern in any model's response involves reproduction of scour patterns. The reproduction of scour in vertically distorted models requires special

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attention. The micromodel approach utilizes a pervious representation of prototype training structures to achieve scour patterns observed in the prototype. In this way, a favorable scour and depositional response can be achieved on a micro scale. In the early years of micromodel development, non-impervious sheet metal (.01 inch) represented prototype rock dikes. Observations of exaggerated scour when using solid structures in the movable bed models conducted by WES lead to the adoption of the non-pervious structures in the micromodel.

In previous experience with the WES models, two types of material were used to represent dikes, sheet metal and a cement-pebble conglomerate. In many cases, the response of the bed observed around these structures was not representative of what was occurring in the river. Figure one shows excessive scour around sheet metal structures and rock structures tested in the St. Louis Harbor model. In both cases, scour was so great that the bottom of the concrete flume was exposed. Once the flume bottom was exposed, the end result was armoring of the bed and an unrealistic bed response.

For typical dikes, an exaggerated response was observed as the scour hole off the end of the model dikes wrapped around and upstream of the structures. This was opposite of conditions observed in the river. Other structures, including Bendway Weirs, exhibited this pattern. In all tests, the inside scour occurring off the ends of the exposed the bottom of the concrete flume. The end result was an unrealistic bathymetric response as compared with the prototype.

These type problems were noted early on with the development of the micromodels, including the original work done at the University of Missouri-Rolla (UMR) (Davinroy, 1994). At first, as in the case of the WES models, the exaggerated scour of the models was accepted as a limitation of the model, with the underlying philosophy that as long as changes in the thalweg could be observed, one could still make general conclusions about the effectiveness of dikes in the model. Later, however, through flume experimentation, porous structures proved to be much more realistic and effective in mimicking the bed response of solid dike structures observed in the river.

Confidence in a model comes from the modeler's confidence in understanding the reach of river under study. If the reach is highly variable or if current construction has

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destabilized the river, then the modeler cannot have much confidence in understanding the mechanisms at work in the channel. The model is a tool which helps the modeler understand the dynamics in the reach. This learning process takes place mainly during the calibration phase when the modeler works with the model to achieve bathymetry trends similar to those of the prototype. By modeling the sediment transport and trying to get the model to form the appropriate bed conditions, the modeler learns dynamics at work in the river. Without this understanding, the model is useless. The experience the modeler builds while working with and studying a reach of river is invaluable. For example, it would not be recommended that one modeler calibrate the model while another modeler tests design alternatives after calibration. The intimate knowledge of a river reach that a modeler gains during calibration builds confidence in the modeler's recommended design alternative. Therefore, it is the modeler that must have the experience and judgment necessary to effectively operate a model. The model is the tool that the modeler uses to study a reach and then recommend a remedial design. If the engineer does not have the modeling tool available, then his past experience serves as the sole basis for designing a solution to a river engineering problem. This is often the case. Therefore, the model becomes necessary to build his/her confidence.

4.4.1. Micromodel Flow Visualization

The material contained in this section was the proponents response to viewpoints expressed in section 1.4.1.12 on the Vicksburg Front micromodel.

The flow visualization used in the Vicksburg Front Micromodel study employed time exposure photography. The camera settings were setup to capture streaks of hundreds of floating particles seeded on the surface of the water in the Micromodel. The end result showed the general trend of water flow in the model at the surface. Figures 4-33 and 4-34 illustrate flow visualization used in the Vicksburg Front Micromodel study.

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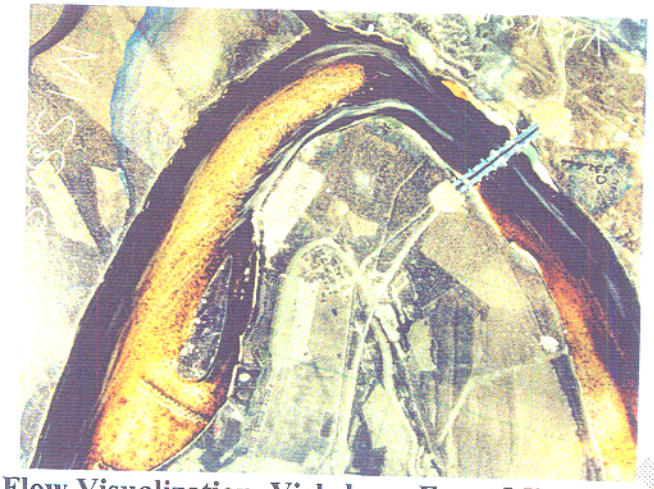

Figure 4-33 Flow Visualization, Vicksburg Front Micromodel, High Flow

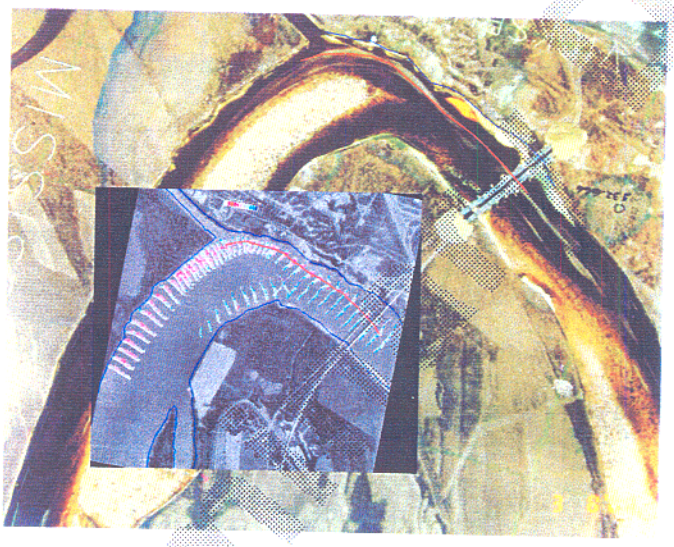

Figure 4-34 Flow Visualization, Vicksburg Front Micromodel, Low Flow Pathline Comparison with ADCP

The process does not represent the same physical phenomena as a GPS float survey conducted in the prototype for the following reasons:

1. Figure 4-35 is a map showing the GPS float survey. The seeding of floats in the GPS float survey of the prototype conducted by contractor for ERDS in Vicksburg Front did not represent individual floating particles captured throughout the reach under study. Instead, a comparatively small amount of floaters were introduced at the upper end of the study reach and at few other selected locations downstream and then the single paths tracked along the river.

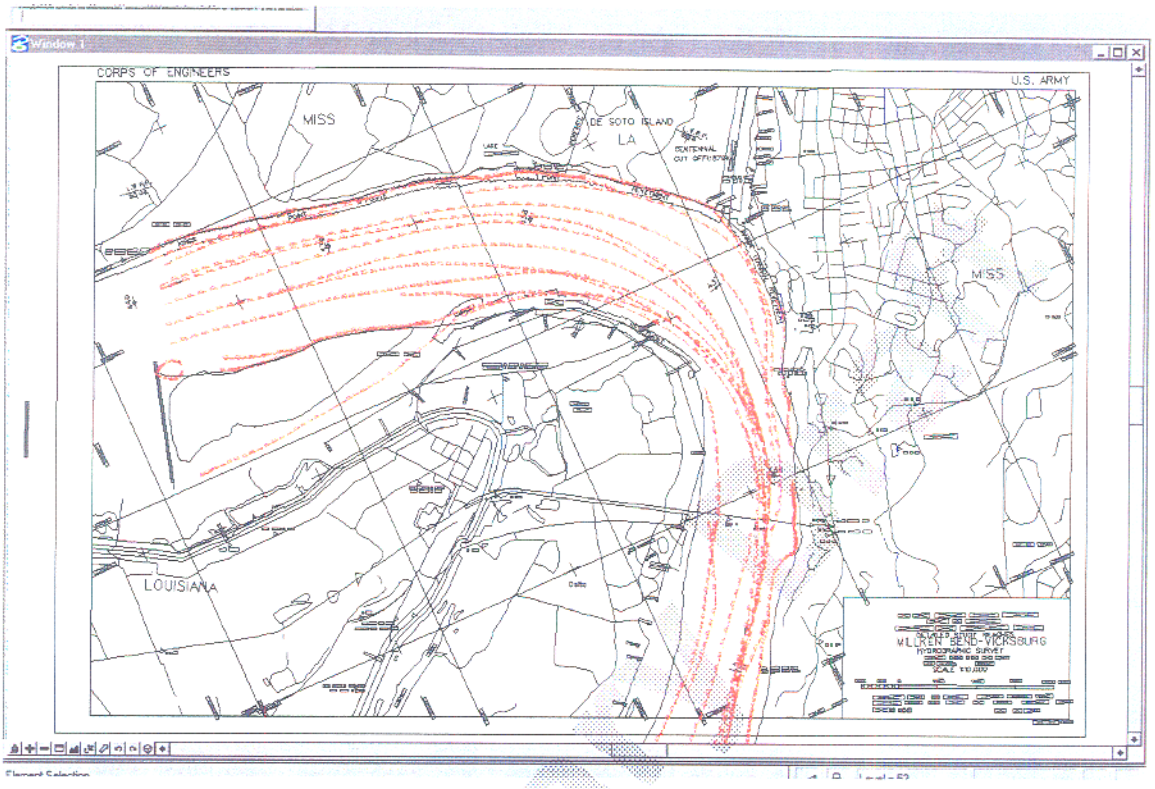

Figure 4-35 GPS Float Survey at Vicksburg Front

2. The confetti introduced in the Micromodel represented an instantaneous snapshot of hundreds of floaters throughout the study reach viewed in the photo frame, whereas the floaters introduced in the prototype represented a relatively small amount of floaters (under 20 according to the survey) placed in the water not as a snapshot but as individual float pathlines or tracks established over a relatively long data collection period of 5 days. For the purposes of the Vicksburg Front Micromodel Study, the seeding resolution was actually reduced somewhat in order to better define critical flow. In this manner, the main concentration of flow was visualized along the thalweg and matched up well with the ADCP data (Figure 4-24). In both the Micromodel and the ADCP, the direction of the main current was directed off the rock protrusion near Mile 436.5 L and directed toward the right descending side of the navigation spans of the bridges.

3. In the time exposure methodology used in the Micromodel, because of the high resolution of floaters, streaks were parallel and did not cross path lines. In this manner, relative flow distribution was captured, as observed in Vicksburg Front Micromodel study. In the GPS float survey of the prototype, because of the poor resolution established by the low seeding, pathlines were not parallel and crossed at numerous areas of the survey, including Mile 439.2 near the left descending bank, two areas near Mile 437.8 near the right descending bank in the side channel, one area at Mile 437 near the right descending side

of the channel, an area in the left descending side of the main channel at Mile 437.4, an area off the right descending bank at Mile 436.6, and multiple pathlines crossing in the main channel near Mile 435.4. In addition, many floats that were placed in their respective starting positions in close proximity with each other deviated in their directional pathlines by a wide margin.

As an example, two floats near the middle of the channel near Mile 439.3 were at the same relative point, yet the float pathlines that developed were not parallel and veered off from each other by as much as 500 feet. Another example was observed at the upper end of the reach in the main channel near Mile 439.8. Two floats in this location were placed within 80 feet of each other approximately 900 feet off the left descending bank, yet veered off from each other by as much as 720 feet near Mile 437. These two examples illustrate a great discrepancy in the direction of flow and would also influence the true recording of flow magnitude.

The above shortcoming of a discontinuous seeding in the float survey with low resolution is further verified in a particular flow visualization technique performed by WES in the St. Louis Harbor study in the early 1990s. Figures 4-36 and 4-37 are photographs illustrating a particular flow visualization method whereby reflective floating tracers were tracked using photographic time exposure. The flow and stage conditions observed in the two photos were exactly the same in the model, the only difference being that two different tests were done with floaters dropped in slightly different positions. In both tests, non-continuous, low resolution seeding was introduced in the most upstream part of the model and then tracked. This was the same method of seeding used in the prototype float survey at Vicksburg Front.

What is interesting to note is the fact that not only did the pathlines of flow cross in several locations, but the relative direction of flow was different in each photo, even though the flow conditions were exactly the same in the model. These tests verify that a float survey conducted in this manner is highly suspect in capturing true flow distribution and thus subject to erroneous interpretation of flow.

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Figure 4-36 Flow visualization at WES, St. Louis Harbor Study, 19.2 Feet Stage

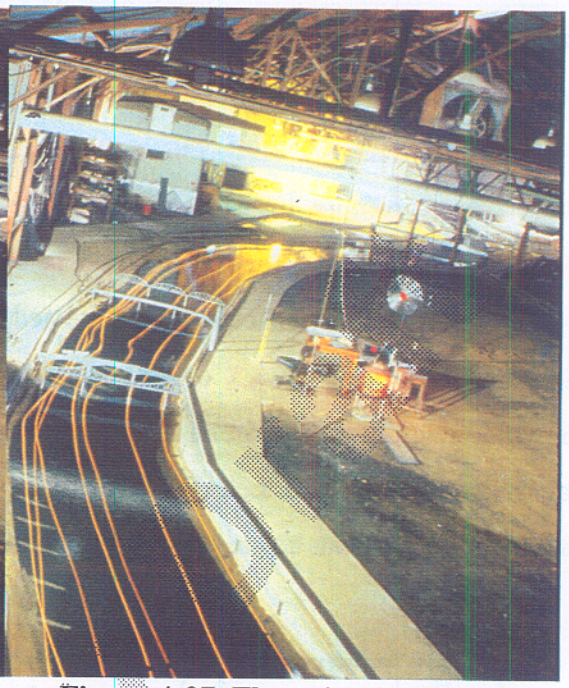

Figure 4-37 Flow visualization at WES, St. Louis Harbor Study, 19.2 Feet Stage

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4.4.2. Comparison of Acoustic Doppler Current Profile (ADCP) vs. Float Survey.

ADCP is a standard field data collection method of water flow used by USACE, USGS, and others. Hydroacoustic transducers are mounted on a vessel and generate pulses of sound at a known frequency. As the sound travels through the water, it is reflected in all directions by particulate matter (e.g., sediment, biological matter, bubbles). Some portion of the reflected energy travels back along the transducer axis toward the transducer where processing electronics measure the change in frequency. The Doppler shift is applied and thus the transducers reflect the velocity of the water along the axis of the acoustic beam. When tied to a compass and GPS, the three-dimensional direction of velocity is recorded. A vessel mounted with ADCP can thus collect near real-time velocity profile data at any given location of the river.

The particular vessel and ADCP system used to collect data through the Vicksburg Reach was the MV Boyer. The MV Boyer has a proven track record for collecting accurate velocity data with the ADCP. Calibration of velocity with the Price

Current Meter using the ADCP system of this vessel has been within 2% to 5 %, well within the accepted values and standards established by the USGS. **are these % for velocity or discharge????? These figures and previous para. are not consistent with many, many papers presented at the EWRI conference concerning velocity with ADCP!!!! Several of the USGS "experts" on ADCP expressed contrary positions!!!!**

A total of 56 transects were collected in the Vicksburg Front reach in October of 1999 during a stage of **XX** on the Vicksburg gage. Figure 4-38 is a plan view map showing magnitude and horizontal direction of the ADCP data collected along the transects at a depth of 5 feet. From this data, the main path line or concentration of flow along the thalweg can be clearly visualized and is shown in figure 4-39.

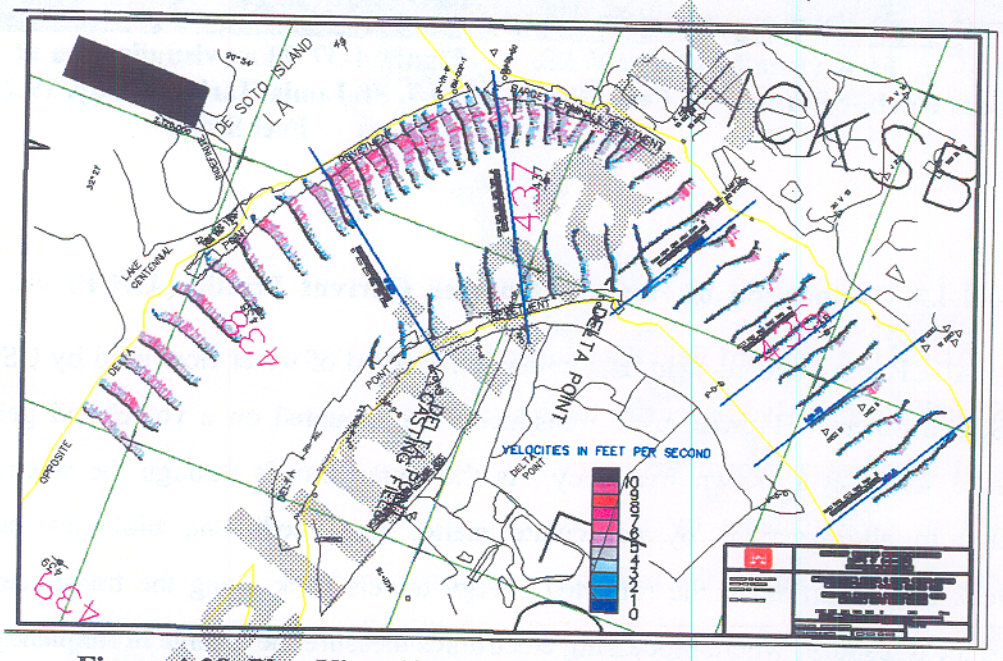

Figure 4-38 Plan View ADCP Velocity Profiles at 5 Feet Depth

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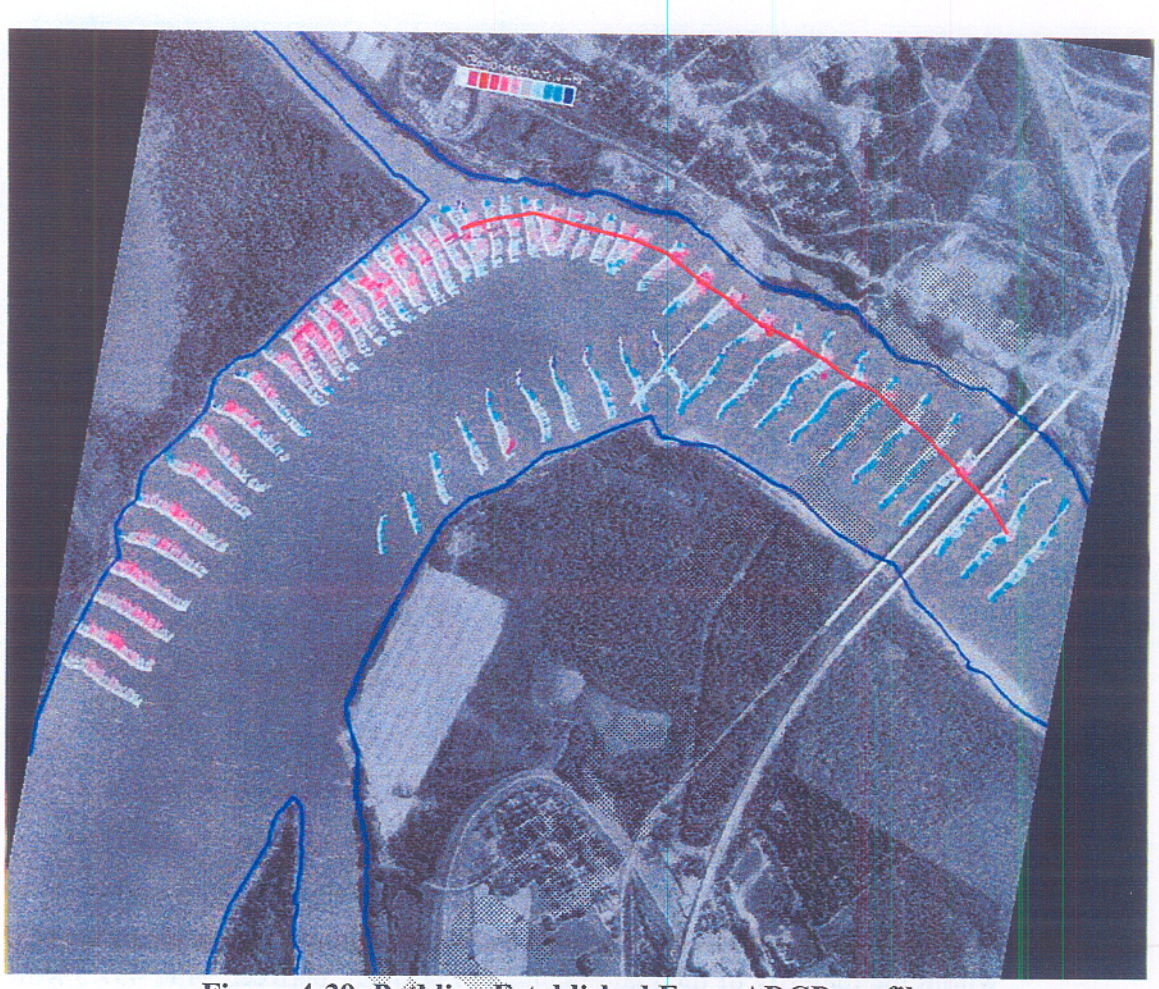

Figure 4-39 Pathline Established From ADCP profiles.

Figure 4-40 shows the plan view vector map of the ADCP prototype data superimposed on the GPS prototype float survey. Although each survey was taken at a different stage and flow condition, general comparisons and inferences can still be made about the characteristics of flow measured by the two methods of data collection. Results indicated some major differences that reinforce the observation that the float survey is highly suspect. These differences are described as follows.

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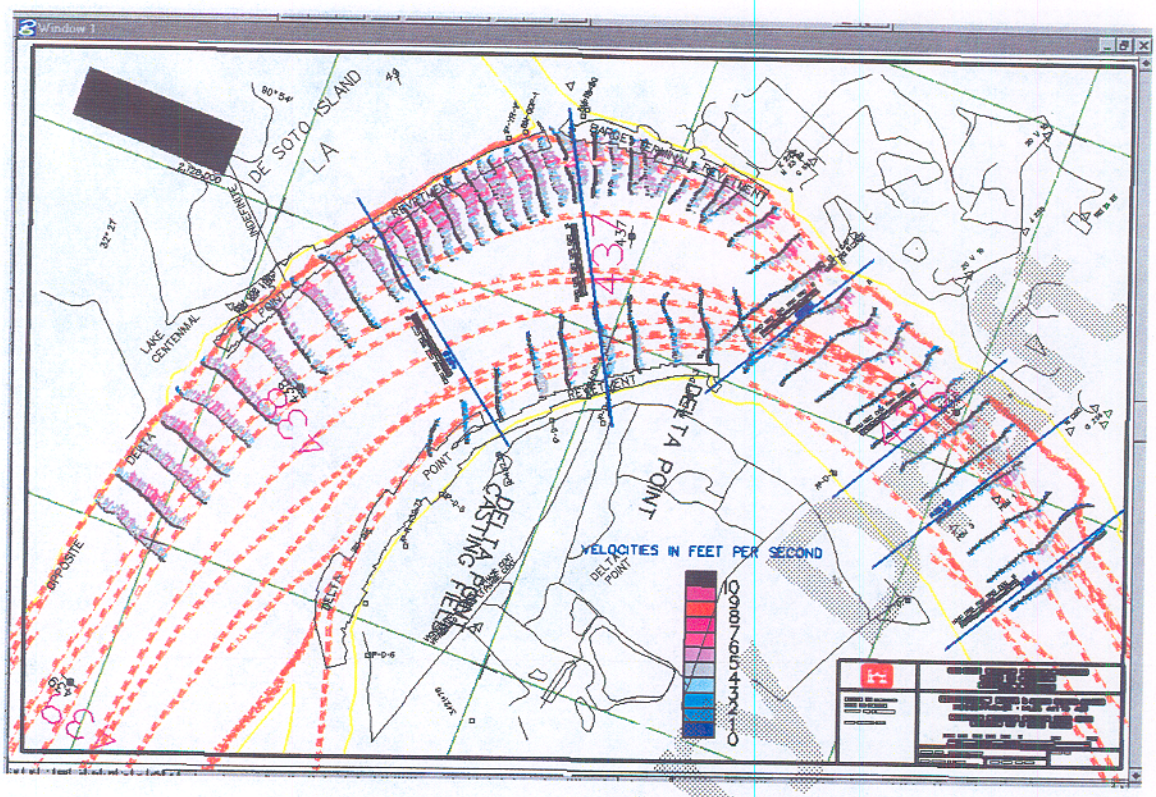

Figure 4-40 ADCP vs. GPS Float Survey

1. Except for a few floats hugging the left descending bank, no floats existed within the majority of the main navigation channel, between Mile 437.5 Mile 436.5 (Figures 4-41, 4-42, and 4-43). This was a very critical area for the Vicksburg Front Study and was accurately and clearly defined with the ADCP data but not with the float survey. The one critical float that was used in Maynard's paper showing a difference in direction of flow along the main channel between the float survey and the Micromodel was actually outside the main navigation channel in this critical reach (the float path line was over the shallow bar at delta point. The path line of this float was not parallel with the path line of the thalweg established by the ADCP transects. This fact, combined with the discussion generated previously that this particular float deviated substantially in path line direction from another float placed in almost nearly the same position, make the float survey highly suspect.

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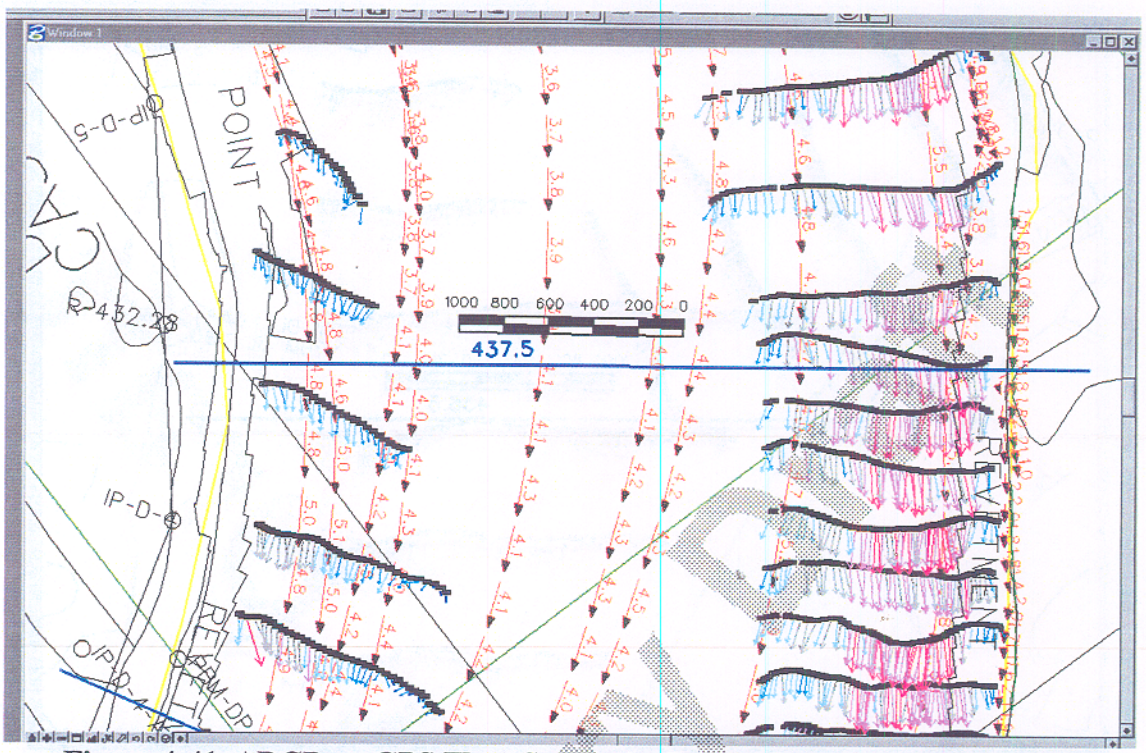

Figure 4-41 ADCP vs. GPS Float Survey in Critical Reach near Mile 437.5

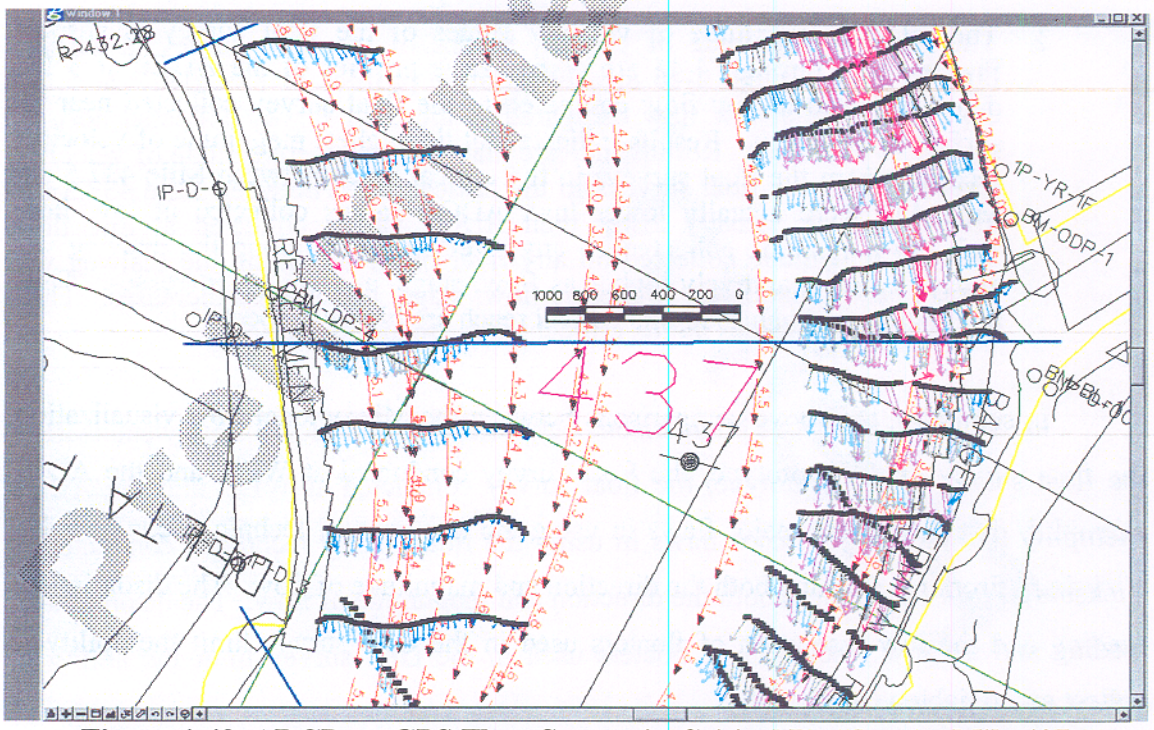

Figure 4-42 ADCP vs. GPS Float Survey in Critical Reach near Mile 437

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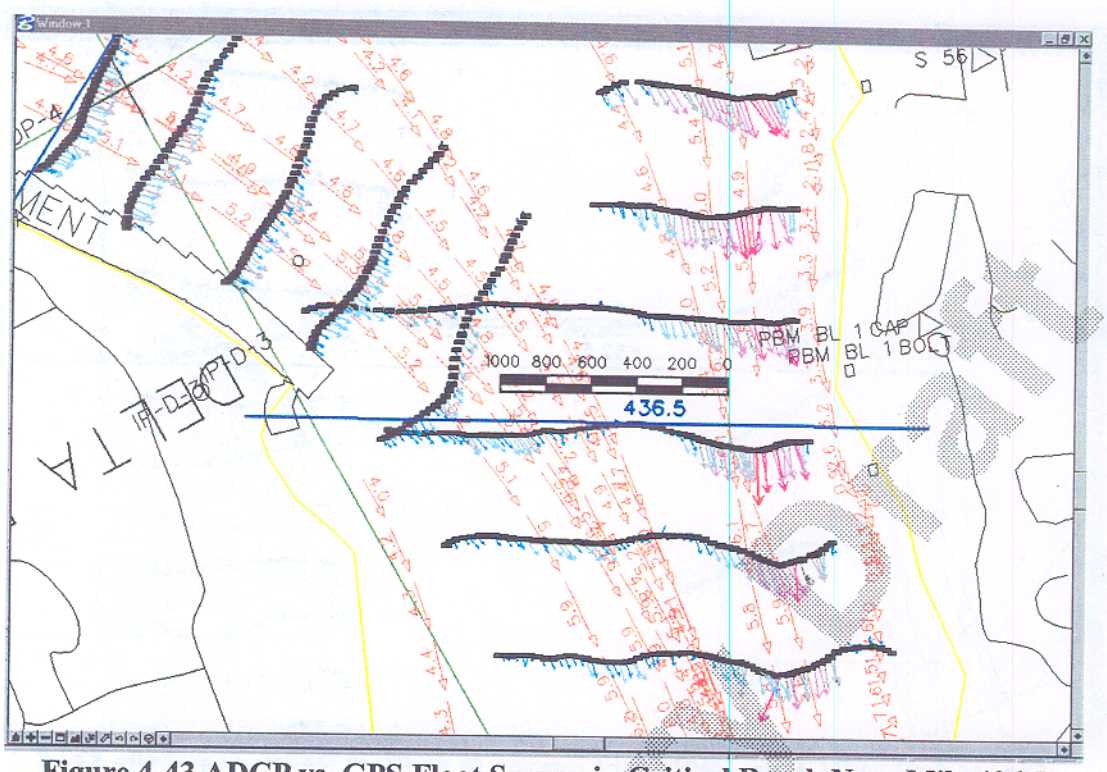

Figure 4-43 ADCP vs. GPS Float Survey in Critical Reach Near Mile 436.5

2. The relative magnitude of velocity values of the float survey is suspect. Figures 4-44 through 4-46 are comparative profiles of the ADCP at 5 feet depth collected at low flow compared to the float survey collected near the surface at high flow. Results indicate that the highest magnitude of velocities recorded from the float surveys in the critical reach between Mile 437.5 and Mile 436 were actually lower than ADCP values collected at low flow. Velocity magnitude collected on any river or stream along the thalweg will always be comparatively higher as flow, stage, and energy increases. Thus, the float survey values in this critical reach are highly suspect.

In summary, the above comparisons between the Micromodel flow visualization, the float survey of the prototype, the float survey conducted at WES, and the ADCP exemplify that there were major flaws in using the float survey technique conducted at Vicksburg Front for defining both the direction and magnitude of flow. The disontinuous seeding and the low resolution of floaters used in the GPS survey limit the ability to collect any reliable velocity data.

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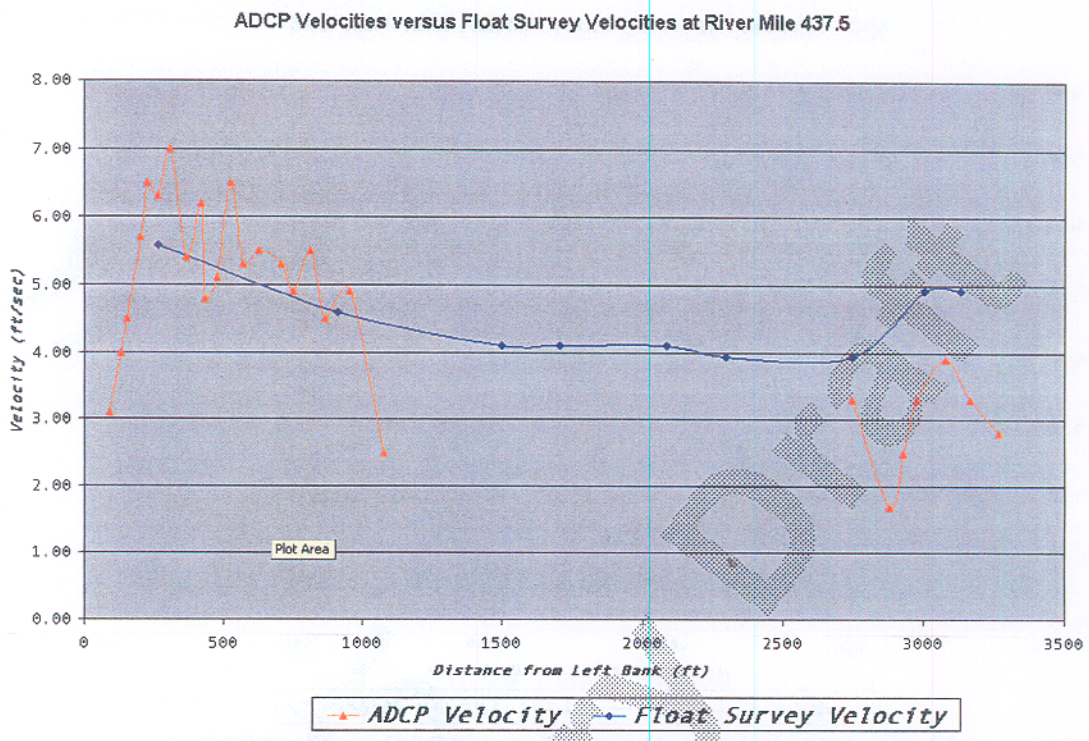

Figure 4-44 Velocity Comparisons, ADCP vs. Float Survey

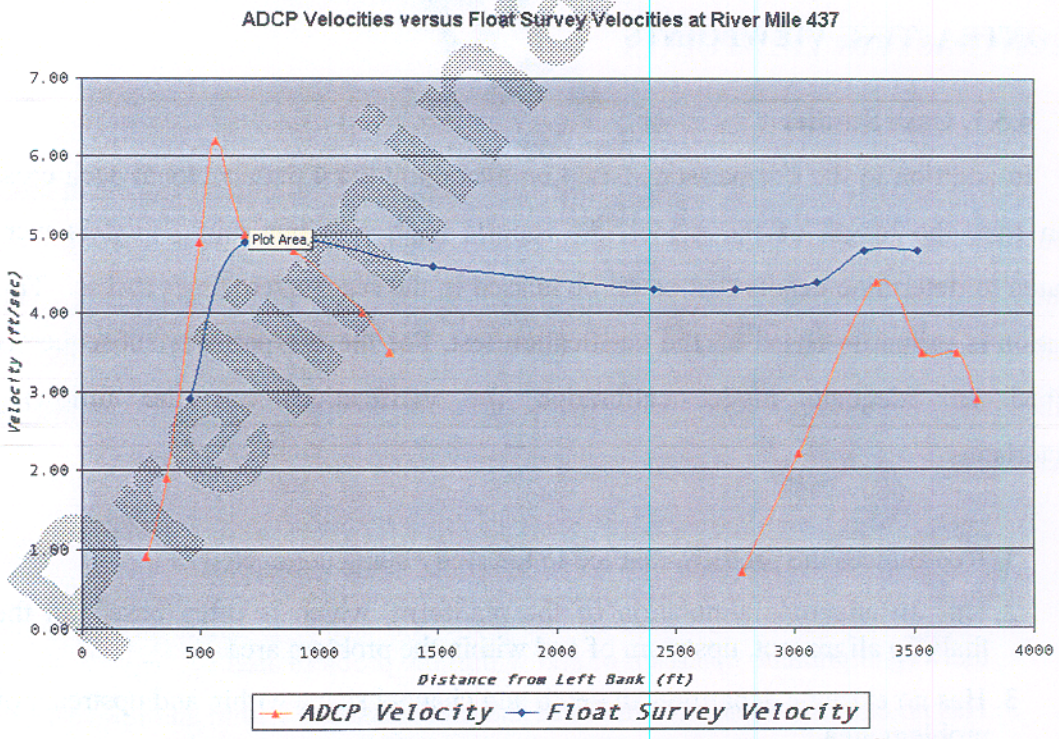

Figure 4.45 Velocity Comparisons, ADCP vs. Float Survey

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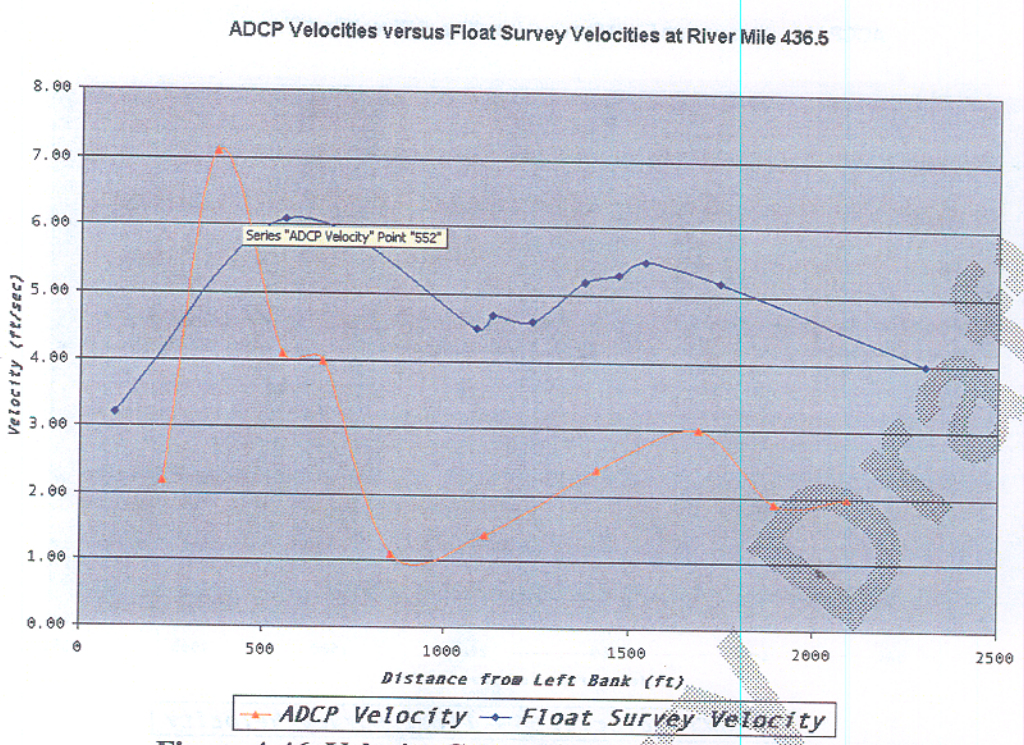

Figure 4-46 Velocity Comparisons, ADCP vs. Float Survey

4.5. CONTRASTING VIEWPOINTS

4.5.1. Case Studies

In addition to the comparisons based on averaging the 4 parameters at each cross section over the length of the model, the reports from previous micro models were evaluated to determine details that could be missed in the reach averaging process. This evaluation is primarily based on the verification test. For the comparisons subsequently described an adequate model calibration (or verification) has the following characteristics:

1. Reproduces the problem that led to the study being conducted
2. Has an adequate simulation of the planform, which is often based on the thalweg alignment, upstream of and within the problem area.
3. Has no extreme departures in depth and channel shape within and upstream of problem area.
4. Reproduces flow splits.

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The evaluation of previous studies considers these four characteristics of an adequate verification as well as other factors. Evaluation of these studies is given in chronological order in the following paragraphs.

4.5.1.1 New Madrid, Mississippi River (1996)

This is a complex reach with a bar in the middle of a mild bend. This report stated that the base tests was the average of five surveys. Considering the differences in the 5 Kate Aubrey surveys in the traditional model presented previously, this appears to be a good idea for the base and the plan conditions. No mention of the 5 survey average was found in later reports. This report also states one of the differences mentioned above between the micro model and most other qualitative movable bed models when it states "An important point to consider is that the model results were reflective of low water conditions, while the comparative prototype survey was reflective of high water conditions". Of the 4 requirements of an adequate verification given above, this verification has large departures in depth just upstream of the problem area. Scour in the model about 1-2 channel widths upstream of the bar reached an elevation of about –70 in the prototype compared to –20 in the model. This much deviation in the bed must adversely affect the flow distribution in the problem area. Some of the structures used in alternative tests were placed in the area having large departures in depth.

4.5.1.2 Sante Fe Chute, Doolan Chute, Mississippi River (1996)

The main channel reach is not complex. The Sante Fe verification was subject to a constraint not present in traditional micro models. In traditional micro models the maximum discharge is limited by when the energy in the model is visually excessive. This typically results in a maximum stage of about +15 to +20 ft LWRP. At Sante Fe chute, the additional constraint on the micro model was that the stage had to overtop the closure dike, which was at +20 LWRP. Although stages are not given in the report it seems likely that the dike would have to be overtopped by at least 10 ft (0.008 ft in model) to provide enough flow in the chute to test chute alternatives. The report gives no information on this topic. This added constraint of stages of about +30 ft LWRP would require more discharge than in traditional micro models. This additional discharge may

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have been the reasons for deviations in the base test where model bed elevations at RM 37.8 reached –70 LWRP whereas bed elevations in the prototype were between –20 and –30 LWRP. Of the 4 requirements of an adequate verification given above, this verification has large departures in depth in the problem area. However planform reproduction in the main channel was acceptable. Model approach length appears low. Unknown flow split in model is another weakness of this calibration.

4.5.1.3 Marquette Chute (1997)

The main channel reach at Marquette Chute is a mild bend and not complex. Both verifications (with and without weirs) were good.

4.5.1.4 Mouth of the White River (1998)

The low radius bend just upstream of the confluence with the White River makes this a complex reach. Problem leading to model study was adequately represented in the model. The micromodel verification test comparison with the prototype was satisfactory upstream of the mouth but at and downstream of the mouth the model bathymetry differed significantly from the prototype. At one mile below the confluence of the White River at RM 598, lowest model bed elevations were –20 to –30 LWRP whereas the prototype bed elevations were –80 LWRP. These differences made it impossible to use the micro model bathymetry in a navigation model at ERDC.

4.5.1.5 Savannah Bay, Pool 13, Mississippi River (1998)

This is a complex reach with a flow split upstream and in the test reach. This report provided a plot showing the differences in bed elevation between the base test and the prototype which would be helpful in all MBM reports. The base test has some large differences from the prototype. Significant differences in the upstream transition reach would make it all but impossible for the flow distribution to be correct in the calibrated reach. Figure __ shows a plot of micromodel and 1996 prototype cross section at RM 538.9 in the main channel only. RM 538.9 is the center of the problem reach requiring dredging in the prototype. Figures _ and _ are plots of the actual cross section shape in model and prototype. The two cross sections are far different as will be the velocity

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distribution. The area behind the islands in the model was significantly deeper than the prototype indicating the amount of flow behind the islands exceeded the actual flow. This was a case where there needed to be some measure of flow split in the model to make certain that the amount of water behind the islands was approximately correct. This model exhibited little similarity to the prototype.

4.5.1.6 Lock and Dam 24 (1998)

This is a complex reach. The critical issue in this study is the similarity of surface currents in model and prototype. None of the data provided demonstrated agreement of model and prototype. Consultant Parker stated of the studies shown to him, this type of study concerned him the most because it looked at the details of the flow.

4.5.1.7 Copeland Bend (1999)

This is not a complex reach because it contains a relatively mild bend and closely spaced structures that are relatively short. The micro model did a good job of replicating the prototype main channel bathymetry in the base test. One concern of this study is the evaluation of dike notching. At the scale of 1:3600, the 50 ft wide notch would be about 0.014 ft wide or about 0.4 cm. These same notches had a maximum head of 10 ft. At a vertical scale of 1:240, the head on the notch was 0.042 ft or 1.3 cm. Add scale effects from these small notch dimensions to what appeared to be porous screen dikes in the model makes it impossible to say whether the flow in the model through the dike was too high or too low, and the magnitude of the error. By not knowing the magnitude of flow through these structures, it would not be possible to use the model to predict if dike notching would have an adverse effect on the navigation channel, which was one of the purposes of the study. Also, this study was to address the stability of the Missouri River bank lines, which is inappropriate for a micro model study.

4.5.1.8 White River (2000)

Two separate models were conducted, Augusta and Clarendon. With the exceptions of the sharp bends, these reaches are not complex because of mild curvature and no dikes. Augusta base test looked fairly good with the exception that point bars

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were generally lower in model than in prototype and the sharpest bend at RM 192-193 exhibited too much scour of the bed and had to be armored in the model. Augusta bends were milder than Clarendon bends. The Clarendon model base test was also fairly good until the bend at RM 96.3 which had a radius / width of about 2. This bend also had too much scour of the bed and had to be armored in the model. In this bend, the micro model channel was degraded across the channel width with little indication of point bar development, as opposed to the prototype which had substantial point bar development. The next bend downstream at RM 95.8 also had to be armored and exhibited the same trend in the model. The models did not indicate the correct trends at these bends.

4.5.1.9 Wolf Island Bar (2000)

This is a very complex reach. Of the 4 requirements of a verification, this model is deficient in two areas. At RM 936.5 just upstream of the problem navigation reach at RM 935-936, model scour reached an elevation of –40 LWRP whereas prototype scour reached an elevation of –80 LWRP. Figure _ shows a cross section plot from model and prototype. Figures _ and _ show the actual cross section shape and dimensions in model and prototype. The velocity distribution into the problem reach can not be correct with this much deviation in cross section. The second problem with the verification is the flow split. The micromodel report presents data showing the flow split is about 60% side channel and 40% main channel. This is a case where obtaining a reasonable flow split around the bar is necessary. The greater scour in the micromodel main channel and the higher bed elevations in the micromodel side channel strongly suggest that too much flow was going down the main channel in the micromodel.

4.5.1.10 SEMO Port (2000)

It is difficult to see what value was added by this study since the problem is one of suspended load and the model moves as bed load. The verification was conducted with and without bendway weirs. The verification was weakest at the mouth of the harbor, particularly for the with weir verification where the region of bed elevations below –30 was much greater than in the prototype. The verification upstream and downstream of the mouth looked reasonable. Of the 4 requirements for a verification, the model did not

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reproduce the problem. It is also difficult for this author to believe the micromodel can simulate eddies such as the eddy at the entrance to the harbor. The use of dye in the micromodel to infer anything about the movement of suspended sediment is not correct.

4.5.1.11 Schenimann Chute (2000)

This reach is complex only because it has many dikes and weirs. The entrance region of the model was much too close to the problem area. The pool crossing sequence in the downstream portion of the main channel in the verification test was out of phase compared to the prototype. At RM 59.8, the thalweg was on the left bank in the prototype and on the right bank in the model. At RM 58.7 the thalweg was on the right bank in the prototype and on the left bank in the micromodel. The 200 ft wide chute in the prototype was 0.5 inch wide in the model. Wall effects in such a narrow channel are far greater in the model than in the prototype.

4.5.1.12 Vicksburg Front (2000)

The Vicksburg Front micromodel was conducted to evaluate proposed channel improvement design alternatives and is shown in Figure 4-47. 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".

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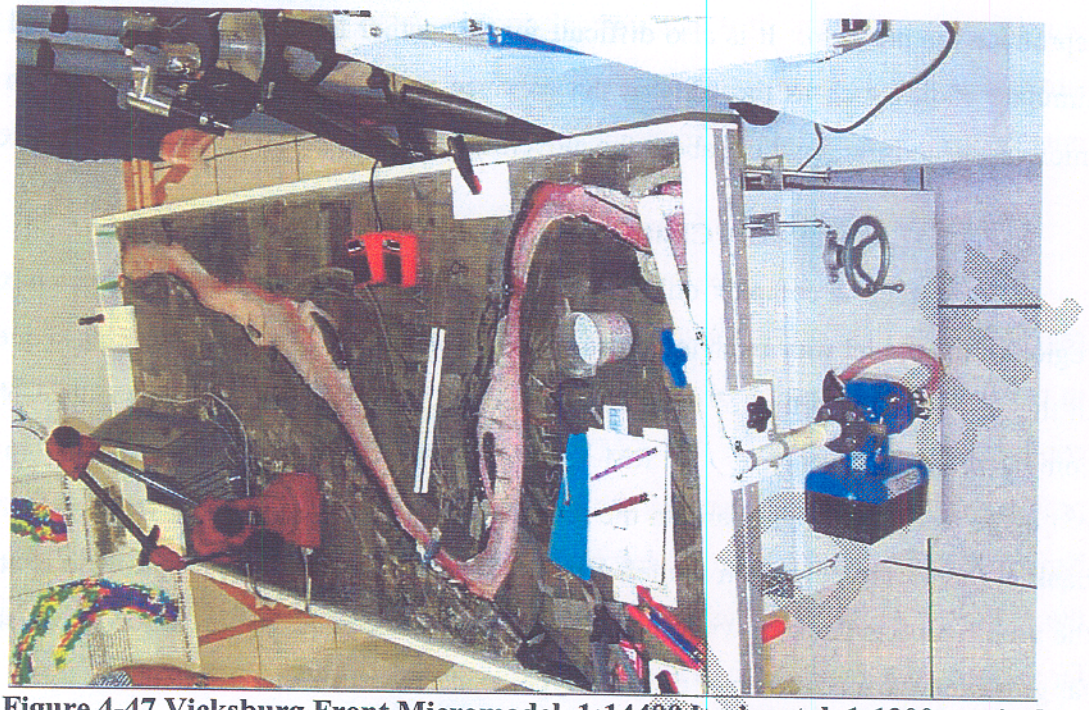

Figure 4-47 Vicksburg Front Micromodel, 1:14400 horizontal, 1:1200 vertical

The Vicksburg micromodel 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 micromodels. 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

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continuos flow simulation. Under these flow conditions, no filling of the side channel was observed."

Figure 4-48 shows pathlines from confetti streaks at high flow in the micromodel 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 micromodel 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 +30 ft to +35 ft LWRP.

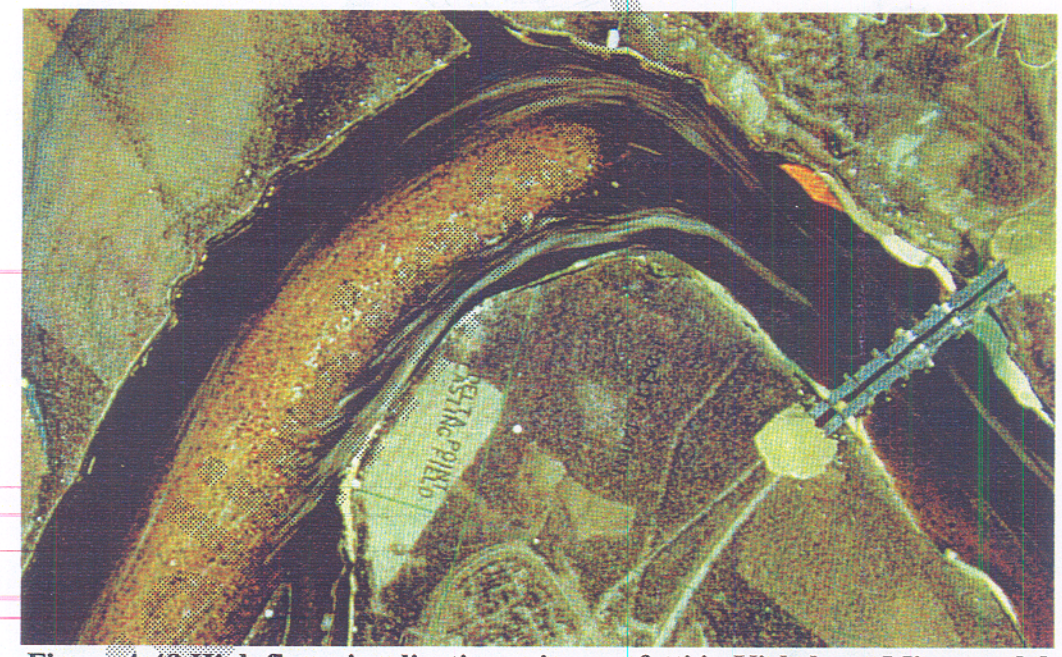

Figure 4-48 High flow visualization using confetti in Vicksburg Micromodel

4.5.1.12.1 Particle Image Velocimetry (PIV) in Vicksburg Micromodel

Subsequent to completion of the Vicksburg micromodel and as part of this evaluation, the model was rerun using PIV to determine surface velocities in the micromodel. The PIV techniques are described in Gaines (2002). Water level data collected during the PIV measurements averaged +19.5 ft LWRP, which is in agreement

with previous micromodel experience. Figures 3-49 and 4-50 show the pathlines and velocity vectors at high flow from the Vicksburg model PIV. Figure 4-51 shows both PIV and confetti pathlines from the micromodel and similar trends are shown. Mississippi River discharge corresponding to +19.5 ft. LWRP is about 600000 cfs and average channel velocity is about 1.5 m/sec.

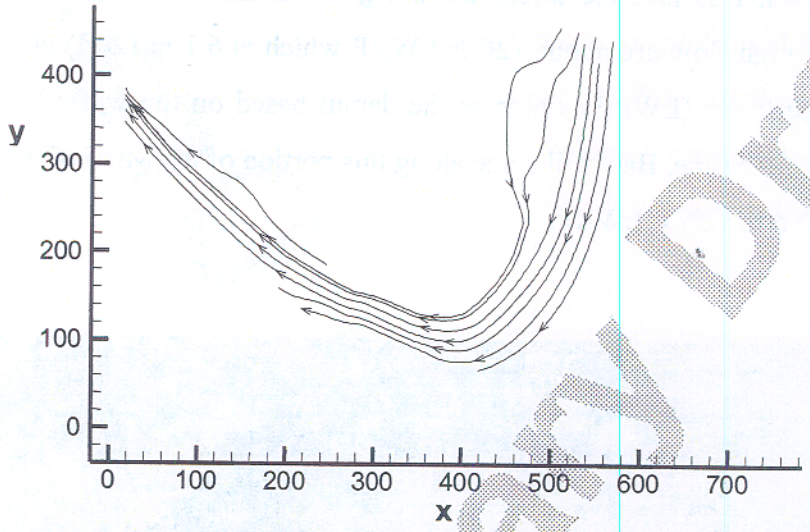

Figure 4-49 Pathlines from Vicksburg micromodel PIV

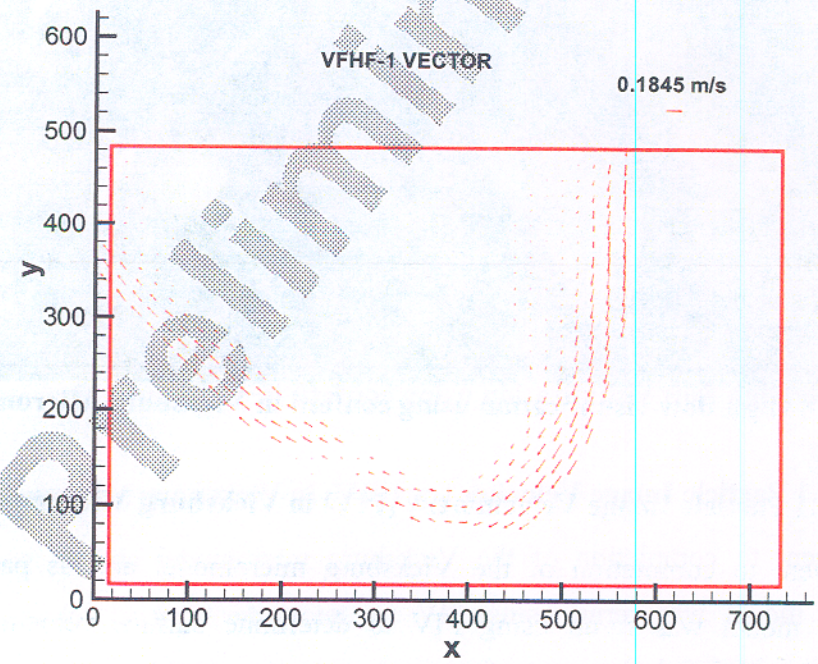

Figure 4-50 Velocity vectors from Vicksburg micromodel PIV

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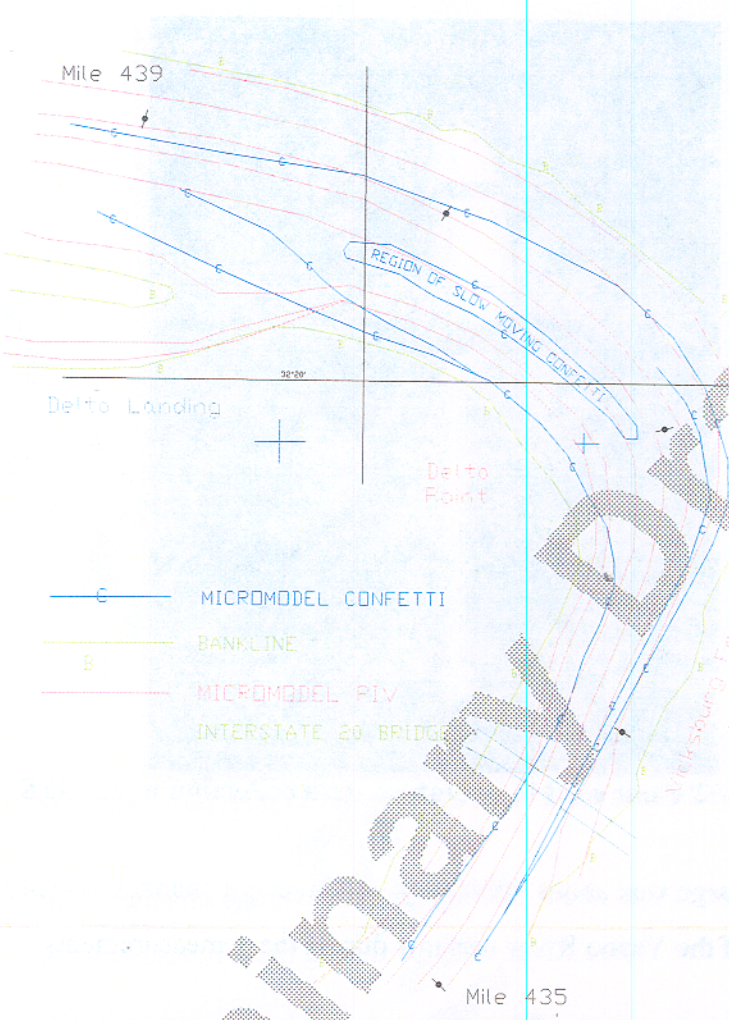

Figure 4-51 Comparison of PIV and Confetti Streaks in Vicksburg Micromodel

4.5.1.12.2 Prototype Surface Velocity with Global Positioning System (GPS)

The prototype surface flow visualization was conducted using floats with recording GPS units placed on the floats (Figure 4-52). The floats were 1 ft. diameter buoys with about 2 ft. long vanes suspended in the water which prevented significant influence of wind. The float shown in Figure 4-52 is the same design as used in the Vicksburg tests but has 3 ft. long vanes. The data was taken during 11-15 May 2000. Stage on the Vicksburg gage during testing was a mid-bank flow of +18.8-ft LWRP on 11 May, +18.2-ft LWRP on 12 May,+17.2-ft LWRP on 13 May, and +16.2-ft LWRP on 15 May. The majority of the measurements were made on 12 and 13 May during which

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Figure 4-52 Float used in prototype data collection using GPS

average discharge was about 500000 cfs and average channel velocity was about 4 ft./sec. Flow out of the Yazoo River was low during these measurements.

4.5.1.12.3 Comparison of Surface Velocity at Cross Sections: GPS vs. PIV

Velocity data were taken from both the GPS field data and the PIV model data and plotted in Figures 4-53 to 4-55 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 4-56-4-58 for the micromodel base test, the 1994 and 1997 prototype used in the micromodel 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:

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1. River Mile 434.5: The micromodel base test cross section at RM 434.5 is significantly higher than the bed in all three prototype surveys (Figure 4-56) 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 4-53) was different in micromodel and prototype GPS but was consistent with the differences in cross section shape with maximum in the micromodel near the left bank and maximum in the prototype about a third of the way from the left bank.

2. River Mile 437.5- The micromodel base test cross section compared well with the 1994 and 1997 prototype surveys used in the verification (Figure 4-57). 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 micromodel. The most significant difference between the 2000 prototype survey and the micromodel or 1994 and 1997 prototype surveys is the height of the middle bar which is about 10 ft lower than in the micromodel. The velocity plot at RM 437.5 (Figure 4-54) shows differences between micromodel 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 micromodel shows about the same ratio of velocity over the middle bar to velocity on the left bank as the prototype GPS velocity. However, micromodel velocity ratio of left bank/right bank velocity was far greater than the prototype.

3. River Mile 439.5. The micromodel base test cross section compared well with the 1994, 1997, and 2000 prototype surveys left of the island (Figure 4-58) except for the shallow area approaching the island. On the right side of the island, the micromodel 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 micromodel 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.

4.5.1.12.4 GPS, PIV, and Confetti Comparison of Surface Velocity

The tracks from the GPS float measurements are shown on Figure 4-59 along with the PIV measurements. The confetti streaks were plotted along with the GPS tracks in Figure 4-60. 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 micromodel. 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

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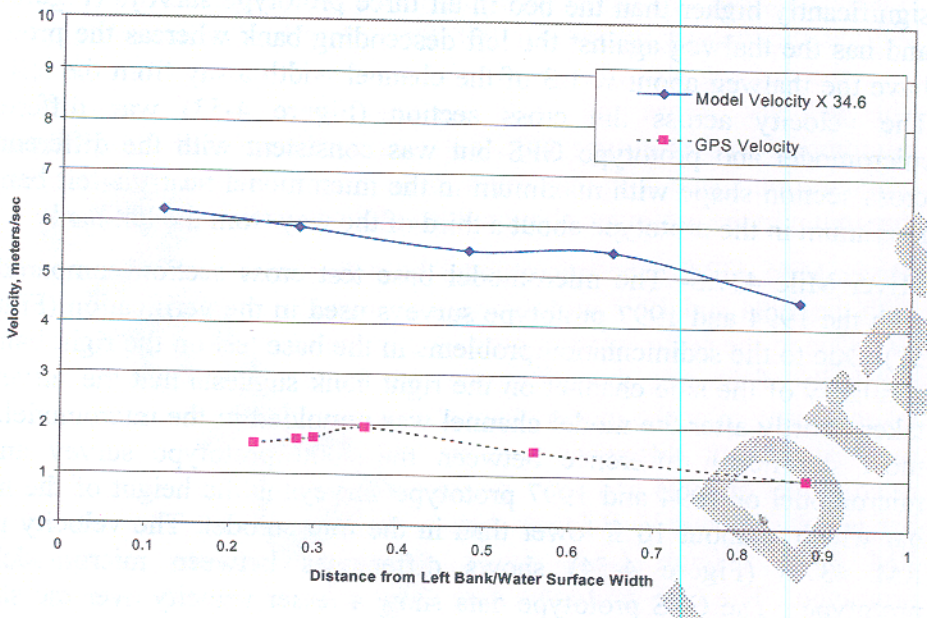

Figure 4-53 GPS Velocity (Field) versus PIV Velocity (Model), RM 434.5

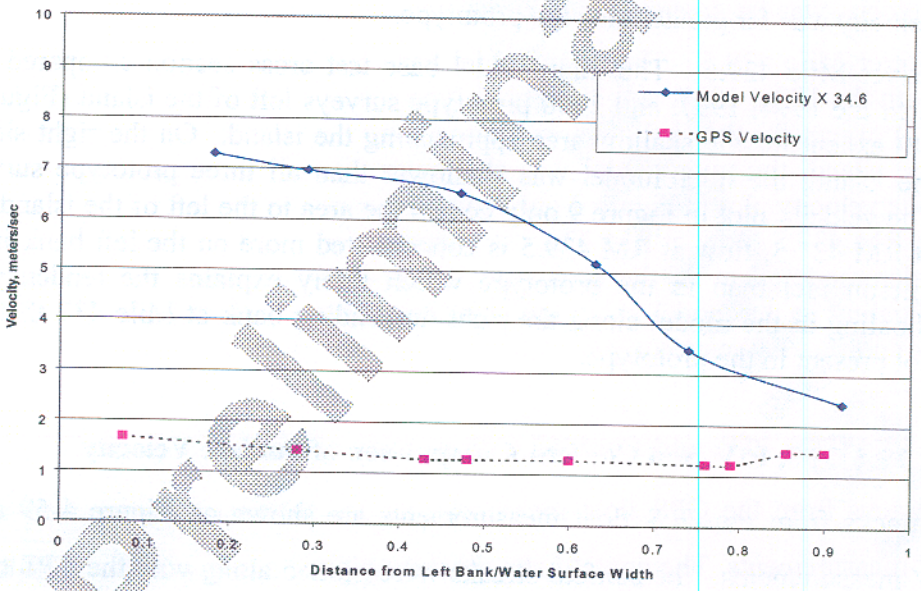

Figure 4-54 GPS Velocity (Field) versus PIV Velocity (Model), River Mile 437.5

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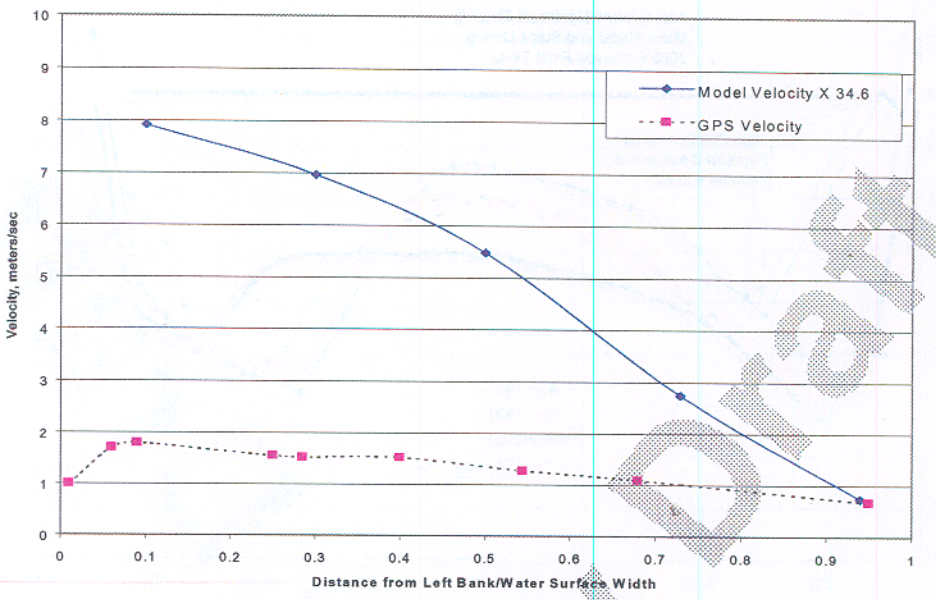

Figure 4-55 GPS Velocity (Field) versus PIV Velocity (Model), River Mile 439.5

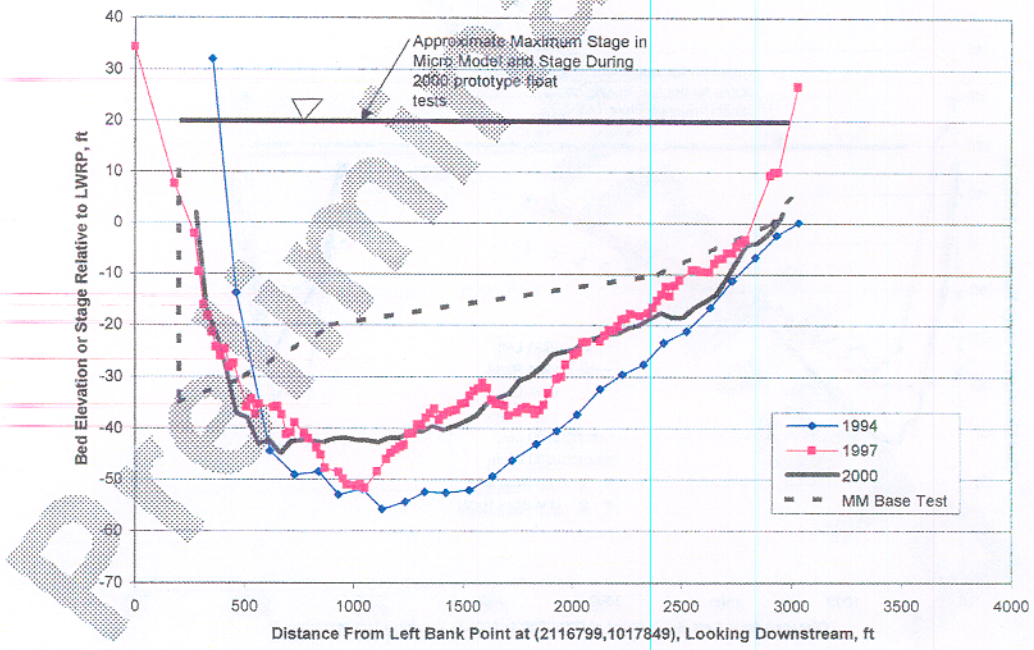

Figure 4-56 Cross Section at River Mile 434.5.

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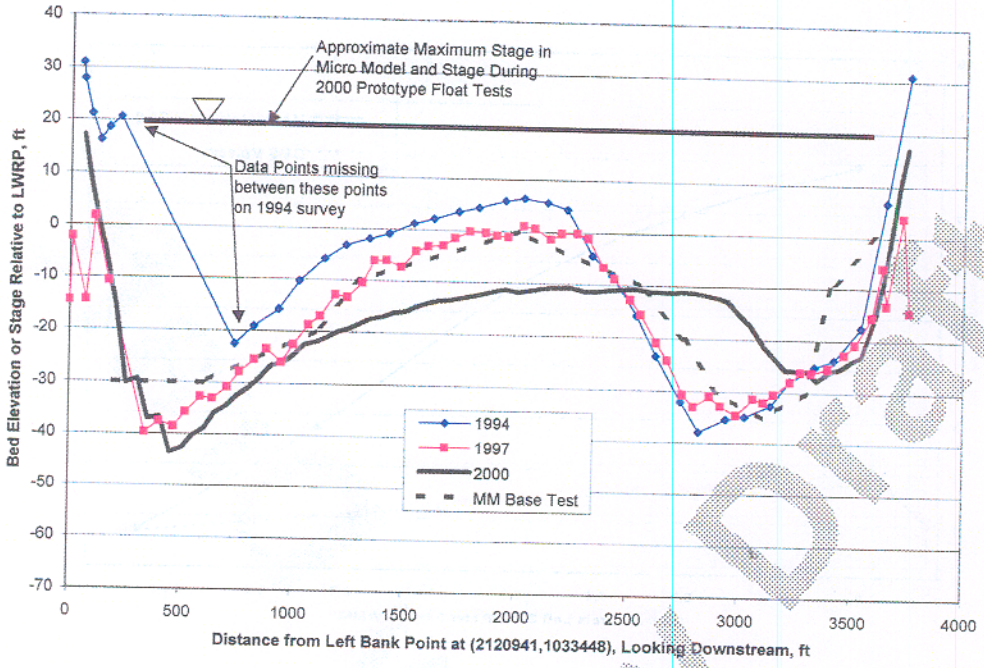

Figure 4-57 Cross Section at River Mile 437.5.

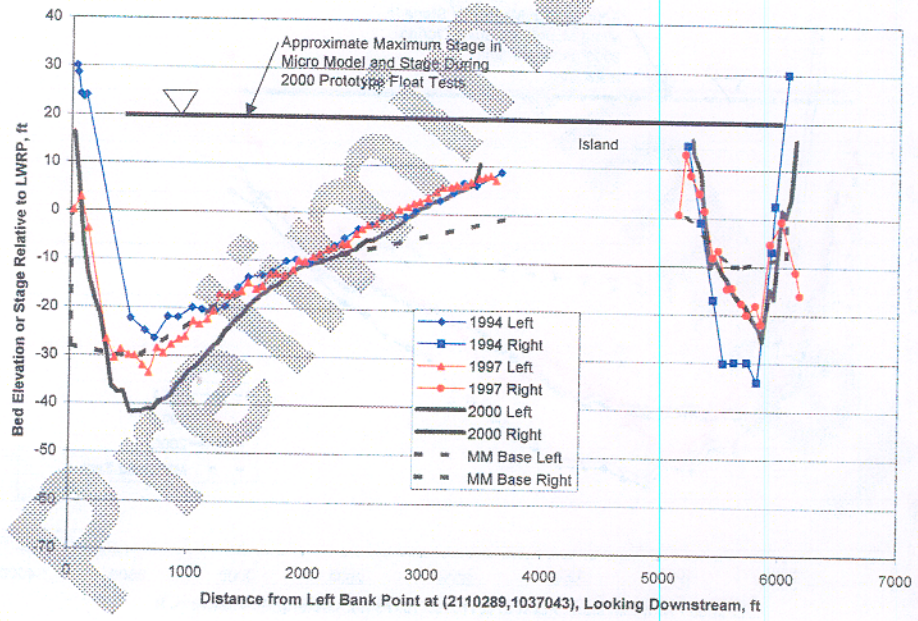

Figure 4-58 Cross Section at River Mile 439.5

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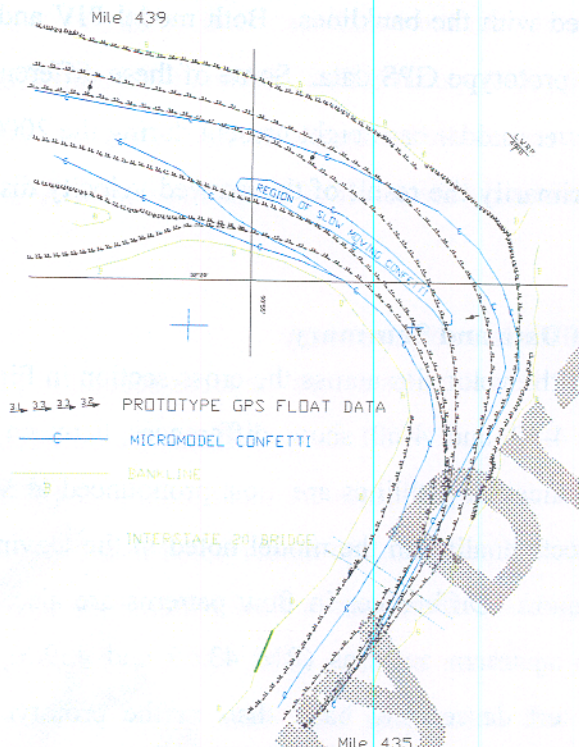

Figure 4-59 Comparison of PIV in Micromodel and GPS in Prototype

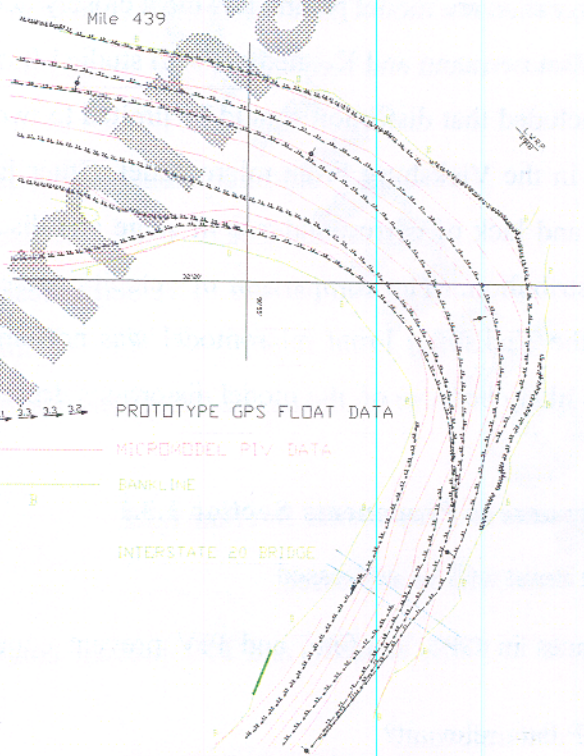

Figure 4-60GPS/confetti

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micromodel 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.

4.5.1.12.5 Analysis of Data and Summary

Comparison of the velocities across the cross-section in Figures 4-53 to 4-56 and pathlines in Figures 4-59 and 4-60 show differences between the micromodel 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 micromodel 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 two or three compared to the value of 12 used in the Vicksburg Front micromodel. 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 herein show that flow distribution in the Vicksburg Front micromodel was not similar to the prototype. The dissimilarity was likely because of the model distortions described above.

4.5.1.12.6 Response to Proponents Section 1.3.1

The following items will be addressed.

1. Do differences in GPS, confetti, and PIV prevent conclusions on MM flow patterns?
2. Is the ADCP data relevant?
3. Are the float velocities too low?

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4. After having prepared the ASCE paper, read the rebuttal, and prepared this response, what are the appropriate conclusions?

4.5.1.12.6.1 Item 1: Do differences in GPS, confetti, and PIV prevent conclusions on MM flow patterns?

"A float will indicate the actual locus of a point moving with the fluid, which is called a path line" (Rouse, Engineering Hydraulics, 1950). Also from Rouse "a streamline is defined as a line which lies in the direction of flow at every point at a given instant." (I have to frequently remind myself of the difference between these two lines). Confetti and GPS floats are both path lines simply having different lengths. PIV is somewhat different because it interpolates the entire flow field to define streamlines. PIV in the Vicksburg MM was based on 200 frames at 30 frames per second and represents the best depiction of the flow field in the MM because it uses about 7 sec of model data whereas the confetti is based on probably a 0.5-1.0 sec camera shutter opening. If flow in the model or river was completely steady (no variation with time) at all points in the reach, confetti, GPS floats, and PIV would give identical flow patterns. We all know that flow in the river is not steady as shown by the model photos provided by MVS and the GPS floats at Vicksburg where path lines can cross. The three different methods show this unsteadiness in different degrees. Short confetti path lines would not show much of the unsteadiness that is present unless one compared several different photos. PIV would show very little of the unsteadiness that is present because of the averaging over 7 sec. Some small differences in PIV would be seen if comparing different 7 sec windows. The GPS floats released at different times and allowed to traverse the reach show much of the unsteadiness that is present in the river or model. If one understands these differences in the three methods, I believe the methods can be used to compare flow patterns in model and prototype. The most appropriate information from the micromodel is the PIV data because it quantifies the velocity and uses a 7 sec averaging window compared to 0.5 – 1.0 sec with confetti. In addition, the confetti pictures in the Vicksburg Front model were difficult to use because only a few path lines could be defined.

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4.5.1.12.6.2 Item 2: Is the ADCP data relevant?

When I first started this comparison, I planned to use float, confetti, GPS, and ADCP to make comparison. My abstract to Estes Park stated I would use ADCP. In preparing the paper, I looked at the stage for the ADCP data and stage for the float and PIV data and found they were significantly different. On 10 October 1999 when ADCP measurements were taken, the Vicksburg District website showed a gage reading at Vicksburg of 4.2 ft which is equal to 4.1 ft LWRP. This low water agrees well with comments by MVS that they could not get across the middle bar when doing the ADCP transects. Based on conversations recently with Charlie Little of the Vicksburg District, the discharge at Vicksburg for a gage reading of 4.2 ft is 235000 cfs and average channel velocity is 2.8 ft/sec. The float data and the micromodel PIV data were taken at about 19.5 ft LWRP which corresponds to a discharge of 537000 cfs. I considered these differences in stage and Q to be too large to use in the comparison. In addition, I could not compare the ADCP collected at low flow to the low flow PIV because Andy Gaines discounted the quality of the low flow PIV.

Another concern of using the ADCP was again heard at the Estes Park conference. MVS is certainly correct in stating that ADCP is widely accepted for measurement of total discharge. I heard no one advocating using ADCP velocities collected during a normal transect mode and comparing to model (physical or numerical) velocities. One or two speakers advocated against such comparisons. It has always struck me as impossible to obtain the average velocity at a point in an unsteady open channel flow when the ADCP meter is only measuring velocity at a point for a matter of seconds or less. Some people take the ADCP and sit at a point for enough time to collect reliable point velocities. One presentation at Estes Park concluded the ADCP had problems near the surface and another presentation concluded there were problems because of interference from the boat.

MVS expressed concern that their ADCP velocities at low flow were greater than the float velocities at medium to high flow. Elimination of the ADCP data based on low stage and Q makes it unnecessary to go into all the factors that could explain this but

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Charlie Little said the Vicksburg gage rating exhibits some loopiness. The ADCP data were taken on a rising stage and the float data were taken on a falling stage.

4.5.1.12.6.3 Item 3: Are the float velocities too low?

In Maynord (2002), the float velocies were checked by determining the average channel velocity based on discharge/area and comparing to surface velocity. That effort was repeated as documented herein. After some confusion between gage reading and LWRP, the stages on the Vicksburg gage and discharge during the GPS float study were as follows:

Date	Gage reading, ft*	Q, cfs**
11 May 2000	20.6	565000
12 May 2000	20	550000
13 May 2000	19	525000
15 May 2000	18	510000

*From Vicksburg District web site
**From rating curve provided by Charlie Little at Vicksburg District, 6 August 2002.

Whether one averages all 4 days or the 12th and 13th when most measurements were made, the flow was about 537,000 cfs during the float survey. The average gage reading was 19.4. At Vicksburg gage which is 0.3 miles downstream of bridge, this corresponds to an LWRP = 19.3 ft.

The year 2000 cross section at RM 439.5 has an area of 126,000 sq ft at +19.3 ft LWRP excluding area right of island which has limited flow because of the dikes. Based on Q/A, average channel velocity = 537,000/126,000 = 4.26 ft/sec. At RM 434.5, area is almost identical at 19.3 ft LWRP at 125,900 sq ft.

Based on conversation with Charlie Little, average channel velocity at the Vicksburg gage at a stage of about 19.4 is about 4.5 ft/sec with a range from 4-5 ft/sec.

At the Estes Park EWRI conference, we heard an interesting paper by USGS on using surface velocity to conduct discharge rating. Our team talked about this same technique using PIV in micromodel to determine flow splits in divided reaches. The ratio of depth averaged velocity/surface velocity is a major variable and typically varies from 0.7 to 1.0 with an average value of 0.85 being typical. Using depth average velocity of

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0.85* GPS surface float velocity with incremental areas gives Q = 494,000 cfs at RM 439.5 which compares reasonably well with gage value of 537,000 cfs from the rating curve.

At first glance these GPS velocities seemed low. After comparing to Q/area, talking to Charlie Little about historical data, and using new USGS technique, the GPS velocities are correct.

4.5.1.12.6.4 Item 4: After having prepared the ASCE paper, read the rebuttal, and prepared this response, what are the appropriate conclusions?

On completion of the ASCE paper I looked equally at (1) path lines through the bend from micromodel and prototype and (2) cross section plots of velocity to make my conclusion that model and prototype flow distributions are different. After looking at the unsteadiness of the path lines through the bend exhibited by the GPS floats that can not be seen (but is certainly present) in the model PIV and confetti, I can see how MVS takes the position that the differences make the conclusion doubtful. While I don't agree with their conclusion, I can see their position.

What I now focus on, and I tried to do at the Estes Park presentation, is the comparison of cross-section plots from PIV and GPS at the two upstream cross sections. These velocities are comparable. The PIV is averaged over 7 sec and the GPS was taken every three sec and velocity magnitude shown in ASCE plots are based on averaging over 60 sec. This velocity comparison shows a significant concentration of velocity on the left bank in the micromodel that is not present in the prototype. More GPS floats would not change this finding. The occurrence of incorrect filling of the right bank side channel in the micromodel only serves to reinforce this conclusion regarding the flow distribution.

4.5.1.12.6.5 Concluding Remarks on Vicksburg Front Flow Visualization

1. If one understands the differences between confetti, PIV, and GPS floats, comparisons can be made.
2. ADCP data are not relevant to this comparison.

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3. Float velocity magnitude compares well with average channel velocity magnitude.
4. Focus of this comparison should be cross section velocity at two upstream cross sections using PIV in model and GPS in prototype.
5. Analysis of model similarity must also consider incorrect filling of side channel in micromodel.
6. I stand by my conclusion in the Estes Park paper that the flow distribution in the Vicksburg Front micromodel is not similar to the prototype.
7. I also stand by my statement at Estes Park that ice photos and ADCP comparisons have not been adequate to show agreement of flow patterns in micromodel and prototype.
8. As I stated at Estes Park and will state in the final micromodel report, the micromodel should not be used for the fourth category of Navigability and flow patterns.

4.5.1.13 Ballard's Island, Illinois River (2001)

Calibration of the main channel looked good in the micro model. This reach is relatively straight and not complex. This study and several others contained the following statement "Clay was placed in the bed of the model to better approximate prototype conditions. This indicates that non-erodible materials may be present at this point in the river." Parker points out "The high distortion, and resulting nearly vertical banks may exaggerate the tendency of the thread of high velocity to collide with the banks, so shifting somewhat the points of bank attack and exaggerating the scour." The combination of the micromodel with a numerical simulation allowed the study to evaluate the potential for velocity changes that could impact navigation at the upstream and downstream entrances to the island.

4.5.1.14 Bolters Bar/ Iowa Island (2001)

Extremely complex reach. The micro model provided a fairly good simulation of bed topography in the main channel. Chute channel bathymetry varied in model and prototype. Dardenne Chute was too shallow. A portion of Bolter Chute between Dardenne and Bolter Islands was also too shallow. After Bolter and Dardenne Chutes combined, the channel continued to be too shallow all the way to the confluence with

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Iowa Chute. The entrance and portion of Iowa Chute between Bolter and Iowa Islands in the micro-model represented prototype conditions very well, but the Chute channel downstream of the confluence tended to shoal more than the prototype. These differences in depth are most likely tied to the micro-model not reproducing the flow splits. Since flow splits is a critical issue in this study, the verification was insufficient.

4.5.1.15 Lower Atchafalaya River (2001)

Complex reach because of junctions and distributaries. Tom Pokrefke of ERDC was asked by the New Orleans District, project sponsor, to provide a review of the micro model. In his unpublished review he stated "The Base Test micro model bathymetry appeared to provide a very reasonable replication of the 1999 Prototype survey. Overall the trends and meandering of the Atchafalaya River were adequately replicated in the micro model." Pokrefke also stated "Generally speaking, the micro model adequately replicated the pool-crossing-pool sequences of the prototype in the area under study." Pokrefke also noted concerning the flow visualizations "This reviewer personally questions the validity or usefulness of such. The reviewer does not feel that such flow visualizations are indicative or able to be related to any prototype condition, nor are they meaningful in any way evaluating the effects of a plan on navigation conditions. In the Morgan City/Berwick Bay Reach the currents upstream, through, and downstream of the three bridges are critical, and as such need to be addressed in another type of study."

4.5.1.16 Lower Peoria Lake (2002)

This is a complex reach with flow entering a wide lake containing a dredged channel. From the base test and Alternatives 1, 2, and 4, the main navigation channel is being filled with sediment. If this reflects the trends in the river, one would expect more dredging than the amount listed in the report. Flow visualization from micromodel confetti and prototype ADCP appear to have no resemblance. With the main channel filling with sediment incorrectly and the flow patterns differing in model and prototype, the model is not reproducing the trends of the prototype.

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4.5.1.17 Kate Aubrey Base and Plan Tests, Traditional and 2X Micromodel

4.5.1.17.1.1 General - Bathymetry maps were compared in micromodel and prototype for base and plan tests. Comparison of the bathymetry in the verification/base tests was based on the 1975 and 1976 prototype data because these years showed the consistent left-right-left-right sequence of thalweg movement observed in the prototype. Prototype data from 1973 was not considered because it represented an anomalous condition on the river due to the high flows. In the plan tests, the dike arrangement as existed in 1998 was placed in the micromodel. Comparison of the bathymetry in the plan tests was based on the 1998 and 2001 prototype data. Data from 1999 and 2000 was limited to low water and were not used in the comparison. The traditional and 2X micromodels will be addressed separately.

4.5.1.17.1.2 1:16000 Micromodel Verification/Base Test - The verification test was evaluated based on the 4 criteria given subsequently for an adequate verification. The 1:16000 micromodel tended to reproduce the shallow crossing at about RM 792.4 which was the problem being addressed in the model. The micromodel reproduced the left-right-left-right thalweg sequence. The micromodel had no large departures in depth within and upstream of the problem area. Flow splits were not an issue in the Kate Aubrey model. Although not an exact reproduction of the prototype trends, the verification of the 1:16000 micromodel is considered adequate based on meeting the four requirements for verification.

4.5.1.17.1.3 1:8000 Micromodel Verification/Base Test - As in the 1:16000 micromodel, the 1:8000 micromodel verification is considered adequate based on meeting the four requirements for verification.

4.5.1.17.1.4 1:16000 Micromodel Plan Test - Both the 1998 and 2001 surveys had a continuous navigation channel through the problem area. The 1998 survey had a middle bar located within the contracted channel at about RM 790.9. The 1998

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survey may have been indicative of the development of the navigation channel and the 2001 survey presents a channel with some additional development time. Both 1998 and 2001 prototype surveys continue to show the left-right-left-right thalweg pattern present in 1975 and 1976, although it was within the contracted channel limits. Since this is an evaluation of the plan test, the first of the 4 criteria for an adequate verification, reproduction of the problem, is not applicable. However, the micromodel showed that shoaling occurred in the contracted reach that was not present in the prototype. The 1:16000 plan micromodel does not replicate the thalweg pattern. At RM 793, the lateral extent of deep water in the micromodel is far greater than the prototype. Had this been an attempt at verification of the micromodel, this outcome would have certainly been rejected as an adequate representation of prototype trends. Based on these differences, the 1:16000 micromodel did not predict prototype trends.

4.5.1.17.1.5 1:8000 Micromodel Plan Test - The 1:8000 micromodel showed shoaling at RM 791.5 that was not present in the prototype. The 1:8000 plan micromodel does not replicate the thalweg pattern. Had this been an attempt at verification of the micromodel, this outcome would have certainly been rejected as an adequate representation of prototype trends. Based on these differences, the 1:8000 micromodel did not predict prototype trends.

4.5.1.17.1.6 Summary - This comparison is important to this evaluation for the following two reasons:

1. This comparison demonstrateed the difficulty of the using reach averaged cross-section parameters to assess model performance. The reach averaged parameters generally showed the plan Kate Aubrey micromodel tests to be in better agreement with the prototype than the verification when evaluating thalweg position, cross section area, and hydraulic depth. When comparing width and width/depth, the verification test was in better agreement with the prototype than the plan tests. The evaluation of a bathymetry map, which has been the subjective method used for many years, shows the plan test to be far weaker than the verification test.
2. Far more importantly, this comparison represented the most extensive evaluation of the micromodel's predictive performance when using detailed

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before and after bathymetry data. Results show that a model can be calibrated to existing conditions but not predict prototype performance. This was exactly what Professor Yalin stated when he said "I regret such a 'model' can not be used for predictive purposes."

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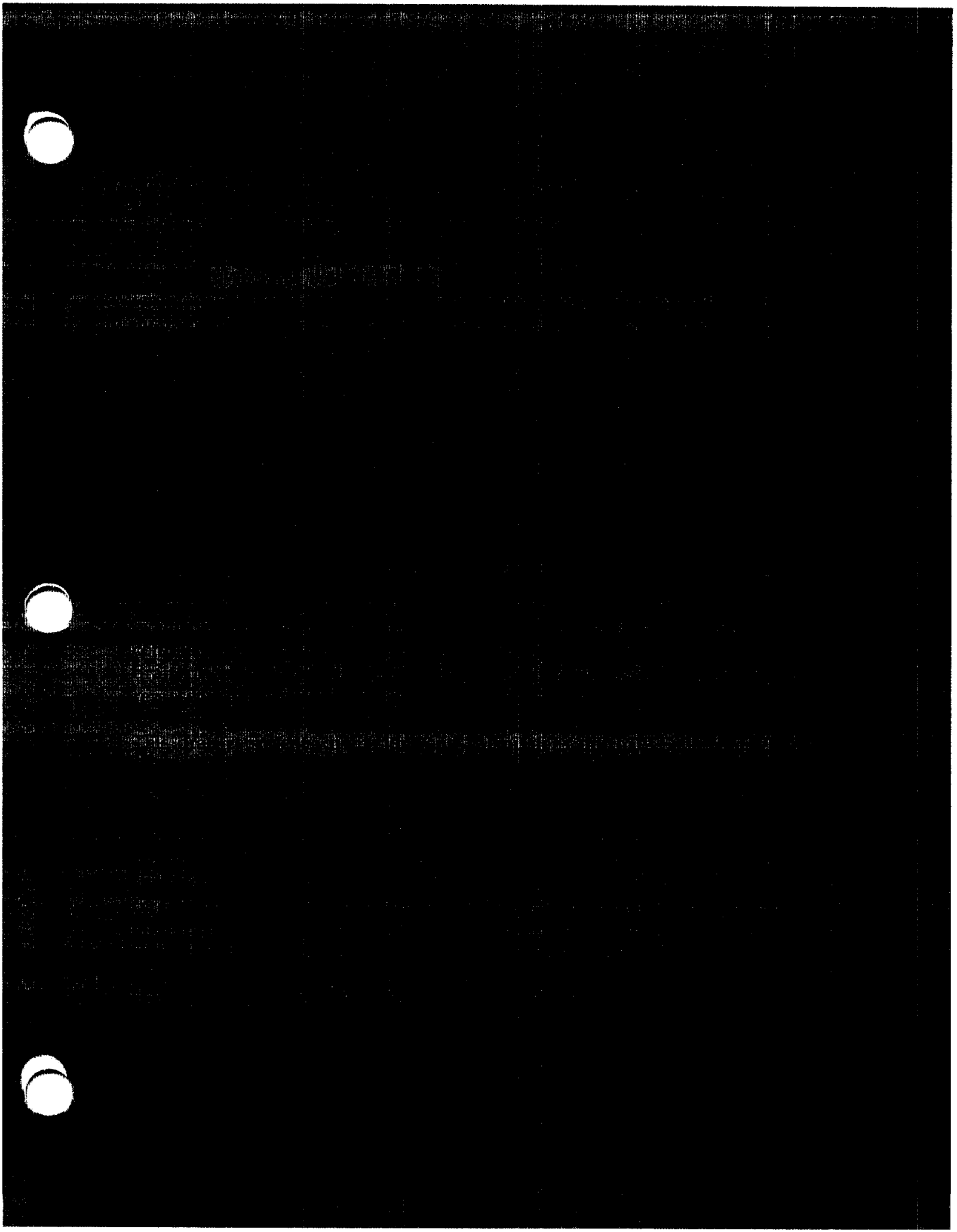

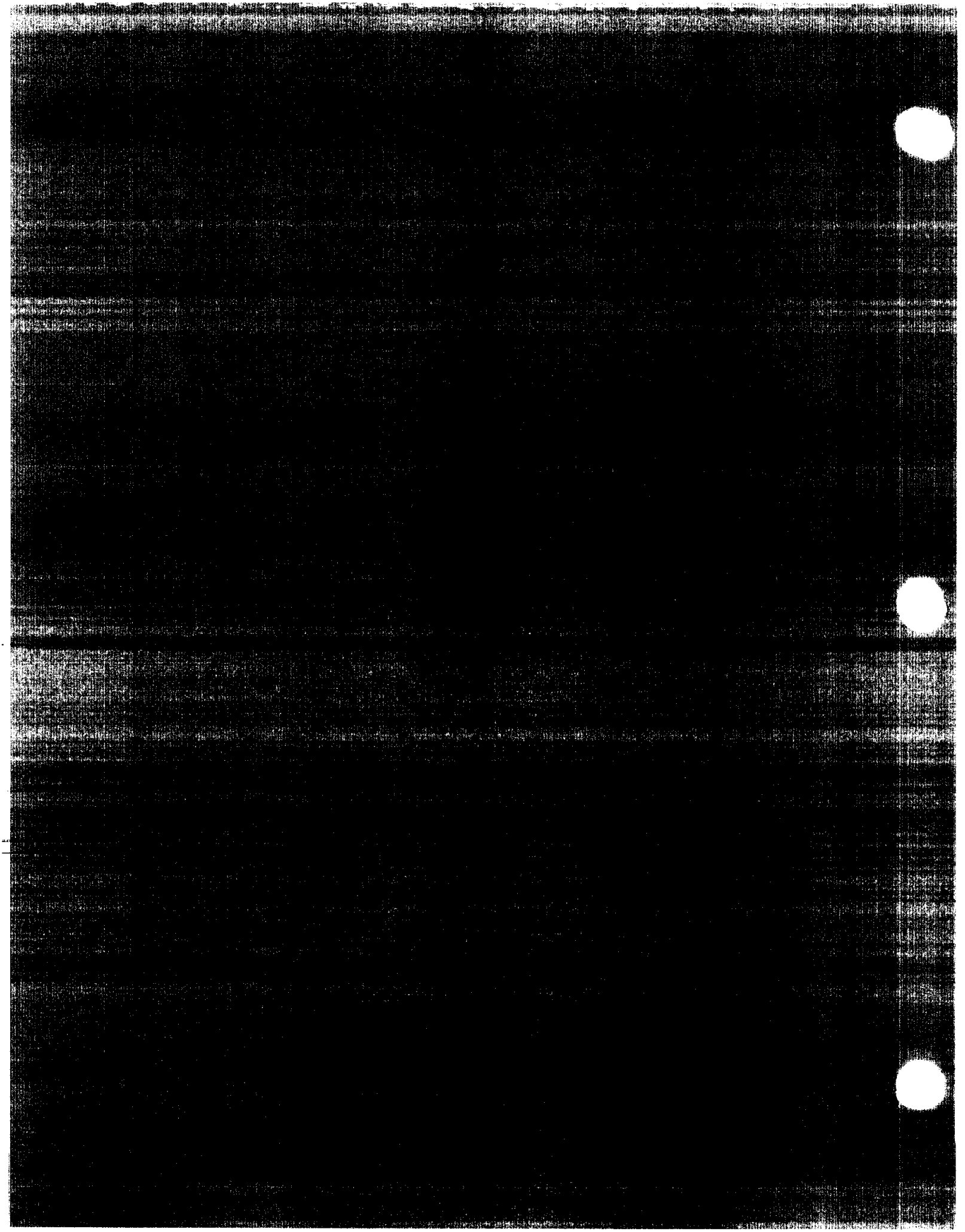

5. CONCLUSIONS

5.1. GENERAL

As with any model, the potential for misuse of the results is possible. Prior use of the large-scale physical models (WES or University) restricted who could conduct model studies because of space, costs, and operational requirements. As a result, model results were produced, processed and analyzed under the direction of persons trained and experienced in physical loose-bed modeling. The advent of micromodels as a viable engineering tool removes much of the restriction to a relatively few individuals/entities because micromodels are relatively small and affordable. Thus, widespread use of these models by inexperienced modelers is a concern. This concern also exists for numerical models. Today's availability of inexpensive computers and modeling software provides a means for almost anyone to open shop as an "expert" hydraulic/sedimentation modeler. Simply having a computer and modeling software does not warrant many claims of modeling competence in government, university and private sector arenas. Likewise, having micromodel equipment does not guarantee that model results are interpreted appropriately.

While the concern about inappropriate model use is not restricted to micromodels, the avenue for model misapplication by individuals having insufficient training in river hydraulics and sedimentation becomes a distinct likelihood. This is particularly true given the meager cost of setting up a micromodel lab (the 3-D laser scanner, the most expensive component of present micromodel equipment, is considered optional).

Future use of micromodels requires a set of safeguards to ensure that only experienced river and hydraulic engineers (emphasis on both aspects) conduct micromodel studies and interpret micromodel results.

5.2. POINTS TO CONSIDER

The evaluation of any topic raises the specter of criticism. The perceived criticism can be taken as an affront to the method, technique, or capability of a particular approach. There may also be a personal connotation on the part of the one who

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performed the work whether in large-scale or small-scale loose-bed physical models or numerical models.

Evaluation of a technology must include an assessment of previous works. Because the very nature of a qualitative model or approach indicates a lack of perfect agreement with the real world, the review often identifies some deficit or deviation between the model result and the observed prototype behavior. Such is the case for both large- and small-scale loose-bed models. Neither of these model approaches has claimed to exactly reproduce prototype conditions. As such, a review of previous large- and small-scale models reveals differences between model results and the prototype -- a fact completely expected.

In this context, defining capabilities and limitations for such models must consider the fact that the models (and modelers) were constrained from the onset. Of those model studies included herein, calibration or verification of the model bathymetry served as the sole assessment factor when determining its suitability for alternative testing. The modeler's judgement regarding whether the model was calibrated/verified incorporated both internal and external constraints.

Internal constraints depend upon the physical characteristics of model components at the scale dimensions. A prime example of an internal constraint is the use of water as the fluid in the model, which limits the model's ability to reproduce viscous forces in the correct proportion. Internal constraints cannot be overcome without changing model scales, sediment material characteristics, fluid characteristics, and possibly operational procedures.

External constraints consist of prototype data availability, of funding limitations, of time restrictions, and on the relative degree of answer sought. The latter, relative degree of answer sought, plays a significant role in this process because some models were conducted simply to confirm a design already developed or to provide a visual demonstration of the expected results to other non-technical personnel. In this later role, the model serves only as a diagnostic tool. External constraints often serve as rigid constraints -- typically, external constraints cannot be avoided or modified without great difficulty.

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Statements regarding capabilities and limitations for qualitative models should be tempered by a consideration of both internal and external constraints. Circumstances may exist where a qualitative model result is desired to confirm a technical opinion or supposition. In this case, the internal constraints of the model are understood. One acknowledges that the model may not fully depict prototype conditions because of scale effects, distortions, and a lack of similitude. But, the result aids in confirming (in conjunction with previous experience of similar problems, measured prototype data, or other model studies) that the proposed work will function as desired.

Absolute limitations, therefore, may only exist for individual applications. Ultimately, the person(s) responsible for developing a problem solution makes the decision whether to use a particular engineering tool or not. The present evaluation attempts to identify the principle internal limitations that exist and to describe the possible ramifications of those limitations. With this knowledge, a potential modeler can: 1) assess whether the micromodel provides the level of detail needed to assess the problem at hand, 2) determine whether alternate methods are necessary in lieu of the micromodel, or 3) determine if model efforts (numerical and/or physical) in addition to the micromodel are warranted.

In a general sense, the present evaluation identifies a need to suggest procedural changes in the application of models (numerical and physical) other than the micromodels as described herein. To the JV team's knowledge, no other model has been subjected to the level of scrutiny currently focused on the micromodels. Other models should be subjected to a similar review in order to determine their areas of applicability and if procedural changes are necessary.

5.3 ETTEMA AND MUSTE (2002) CONCLUSIONS

Investigators at IIHR reported conclusions derived from the study of fixed bed flume experiments (Ettema and Muste, 2002). Those conclusions are repeated below for the reader's convenience.

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1. Thalweg alignment and separation region in the vicinity of a dike in a loose-bed channel are functions of the parameters

$$\frac{u_{*o}}{u_{*c}}, \frac{Re}{\sqrt{f}}, \frac{We}{\sqrt{f}}, \frac{V_o^2}{gLf}, \frac{W}{Y}, \frac{L}{W}, \frac{R}{D} \qquad \text{(Set 3)}$$

Reynolds number, relative roughness, and resistance coefficient (Re, f, and R/D) characterize the approach flow distribution in which the dike is to be placed. Shear velocity ratio (u_{*o}/u_{*c}) characterized the state of bed-sediment mobility in the approach flow. These parameters, together with flow velocity head, aspect ration, and relative dike length (V_{02}/gLf, W/Y, and L/W) describe the flow field around the dike. The Weber number parameter $We/\sqrt{f}$ expresses the influence of surface tension, and is important for only very shallow flows.

2. When approximate constancy of the parameter u^*o/u^*c is the primary similitude criterion used to operate a model for a dike of given W/L, distortion of the other flow parameters in Set 3 may influence thalweg alignment and separation region. The distortions, essentially stem from natural limitations in scaling sediment size, may cause scale effects that increase in influence as length scales (prototype/model) increase.

3. The scale effects became evident as the following deviations (values in model compared to scaled prototype values) in thalweg alignment and separation regions:

   (i) As X_r [the horizontal scale ratio] increases, flow thalweg requires a longer distance, relative to dike length, to return to the channel centerline downstream of a dike. The distance downstream of the dike was almost three times as long for the channel equivalent to a micromodel than for the baseline channel [2.7 feet wide]. Figure 32 of the IIHR report indicates the distortion variation with X_r.

   (ii) As X_r increases, the maximum lateral location of the thalweg, T_c, decreases until an asymptotic value of approximately (W-L)/2.

   (iii) As X_r increases, the downstream flow-separation region contracted from $B_1/L \approx 14$ to $B_1/L \approx 4$ for the channel equivalent of a micromodel.

   (iv) As X_r increases, the width of the flow-separation region decreased asymptotically to the length of the dike (i.e., $B_2/L \rightarrow 1$).

4. The flow parameters in Set 3 directly affect the distribution of pressure and local flow structure around the upstream face of a dike. Through that action, they affect the strength of wake eddies developed by a model dike. In consequence, the dike's wake region contracts in extent. The shedding of the strengthened wake eddies intensifies turbulence generated by the model dike.

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Increased turbulence generation and increased dispersion of turbulence results in a longer flow length, relative to dike length, for flow symmetry to re-establish downstream of a dike. Commensurately, it takes longer for flow thalweg to return to channel centerline.

5. The depth of local scour relative to dike length, d_{Se}/L, for a non-porous dike, increased as X_r increased from the baseline loose-bed channel to the channel comparable to a typical micromodel channel. The value of d_{Se}/L associated with the nominal micro-scale channel was about 3.5 times that for the baseline loose-bed channel.

6. Relative to channel width, the lateral extent of local scour increased as length scales reduced. For the non-porous dike in the baseline loose-bed channel, the local scour extended across two-thirds of the channel width. For the non-porous dike in the nominal micromodel channel, the extent of local scour extended almost the entire width of the channel.

7. Local scour reduces the length of the downstream separation region to $B_1/L=4$, for the baseline loose-bed channel and the channel comparable to a micromodel. A scour hole re-contours the channel bed so as to direct flow more directly behind a model dike. Increasing dike porosity, e, decreased depth of local scour, d_{Se} (Figure 44 of the IIHR report). The same proportionate reductions in d_{Se} occurred for the baseline loose-bed channel and for the channel typical of a micromodel channel. At porosity $e \approx 0.75$ to 0.80, $d_{Se} \approx 0$.

8. Increasing dike porosity, e, decreases the length of the thalweg excursion around a model dike (Figure 43 of the IIHR report). For the channel comparable to a micromodel channel, dike porosity between 0.50 to 0.80 produces a thalweg excursion similar to that for the baseline fixed bed channel. However, a dike with this porosity has no separation region.

5.4. CONCLUSIONS BY THE JV EVALUATION TEAM

5.4.1. Capabilities

1. **Micromodels can be used effectively to demonstrate and communicate complex hydraulic and sedimentation issues (level 1).** Demonstration of hydraulic and sedimentation principles in gross terms requires no specific model design. Simply having a flume with flowing water and sediment serves to illustrate many basic principles. The addition of a model insert that represents a particular prototype reach only enhances the demonstration effect. The visual nature of the micromodel allows scientists that are not familiar with hydraulic or sedimentation phenomena to "see" how water and sediments interact within the channel.

2. **Micromodels provide an opportunity to educate various audiences (level 1).** This follows directly from the demonstration and communication aspects of

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micromodel capabilities. Often, local sponsors and other non-technical individuals have a vested interest in river processes. Use of the micromodel to help these individuals understand the complexities of river hydraulics provides a mechanism to arrive at desired project outcomes.

3. **Micromodels provide a means to qualitatively compare relative bed changes between alternative modification plans.** Past experience with micromodels indicates that after a period of calibration (where the model is adjusted to reproduce observed prototype conditions), various alternatives can be analyzed in a qualitative sense to aid in selection of a recommended plan of modification. The screening of alternatives in this way helps engineers and other scientists assess which alternatives provide the desired channel response. The relative comparisons are not used (and cannot be used) to indicate absolute elevations or dimensions in the prototype. Specification of absolute elevations and/or dimensions requires quantitative analysis beyond the scope of present micromodel methodologies. Qualitative comparisons are consistent with levels 1) and 2).

4. **Micromodels identify general scour and depositional trends.** The qualitative application of micromodels identifies overall behavior of the channel bed in response to various alternatives. The qualitative nature of general scour and depositional trends is consistent with level 2.

5. **Micromodels provide supplemental information for other model results (e.g. numerical or larger physical models).**

6. **Qualitative velocity trends and patterns: Examination of main flow concentrations and general flow direction. Flow pattern determination in response to bathymetric changes imposed to the streambed.**

7. **General navigation studies to bathymetric and flow pattern response.**

8. **Main channel and side channel bathymetric analysis and study. Rearrangement of the bed forms to decrease dredging and to improve or diversify aquatic conditions.**

9. **Qualitative analysis of the three degrees of translation freedom as described by Ettema in "A Framework for Evaluating Micro-Models."**

10. **Flow and sediment response trend studies at multiple entrances (tributaries) and outlets (distributaries).** (Mouth of the White River, Memphis Harbor, Morgan City)

11. **Analysis and resolution of outdraft at lock approaches and bridge crossings.** (LD24, LD25, Mouth of the White River, Morgan City, Vicksburg Front)

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12. **Implementation of Bendway Weirs; flow and bathymetric response.** (LD24, SEMO Port, Mouth of the White River, Morgan City, Vicksburg Front)

13. **Innovative design of environmental river engineering structures, i.e. notched dikes, chevrons, hard points, etc.** (Copeland Bend, Bolters Bar, JB Bridge, Cottonwood)

14. **Channel contraction measures to reduce dredging.** (White River, Clarendon and Augusta; Savanna Bay, Copeland Bend, Bolters Bar, JB Bridge, New Madrid, Morgan City)

15. **Dike and closure structure modification to increase scour or flow within side channels and off channel areas.** (Sante Fe Chute, Marquette Chute, Schenimann Chute, Savanna Bay, Wolf Island, Salt Lake Chute, JB Bridge)

16. **Sedimentation patterns within slack water harbors.** (SEMO Port, Memphis Harbor)

17. **Stream realignment at bridge crossings.** (Big Creek)

18. **Analysis and study of inflow sedimentation of lakes.** (Slagle Creek)

19. **Deposition patterns at water intakes.** (Highbanks)

5.4.2. Limitations

1. **Unknown discharges used in the micromodel** - Prior to starting the JV evaluation, flows were largely unknown in the micromodel. A few exceptions where timed volumetric measurements were made are the cases where model discharge was known. Model discharge was established by a visual assessment of the state of sediment mobility. The shape of the actual hydrograph was also unknown because control of model discharge was accomplished by specifying a valve opening. Implementation of flow meters in routine micromodel operation alleviated these limitations.

2. **Operational sensitivity to position of by-pass line** - Prior to the JV evaluation, a by-pass in the delivery piping provided for adjustment of water delivered from the pump to the micromodel headbay. Micromodels typically used flexible piping to convey water and sediment and any movement of the piping changed the distribution of flow between the by-pass line and the primary line leading to the model headbay. Changes in this distribution produced fluctuations in the amount of water delivered to the model. The primary concern with the by-pass occurred when sediment lodged in the pump

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intake requiring removal of the pump. After the pump intake was opened, replacing all of the flexible piping in the original positions was extremely difficult. Therefore, discharges delivered to the model were altered slightly. Because slight adjustments in any model operational parameter potentially causes significant changes in model bed response, a stable discharge was crucial to achieving model calibration. Implementation of a constant-head assembly in the micromodel procedures alleviated this limitation.

3. **Micromodels do not reproduce prototype stages**. Stages directly impact the amount of energy in the model. Stages that are too low (using a stage of +20 LWRP in model to represent a stage of +30 in prototype) produce different velocity and sediment distributions within the channel cross-section. As a result, the ability of the thalweg to adjust laterally is restricted. Observations in both micromodels and loose-bed flume studies support this. Additional problems arising from incorrect stage pertain to overtopping of training structures. Where stages are too low, structure elevations must be adjusted vertically to achieve the "appropriate" level of overtopping flow. Such adjustments are necessary to obtain a desired lateral velocity distribution in the model channel. These adjustments lead to the possibility for misinterpreting model data when converting to prototype scales.
   Simulation of incorrect stages in the micromodels coupled with vertical scale distortion leads to a velocity distribution associated with a narrow-deep channel (model) as opposed to a wide relatively shallow channel (prototype). Therefore, model shear and velocity distributions do not represent prototype conditions. The narrow and deep channel that exists in the micromodels precludes full development of 2-dimensional and 3-dimensional velocity distributions. Micromodels have an overly restricted thalweg -- the model thalweg cannot adjust laterally within the cross-section with the same degree of flexibility that occurs in the prototype. Narrower channels and increased vertical distortion produces a larger deviation in velocity and shear distributions from prototype conditions. Inadequate representation of stages limits micromodels to levels 1) and 2).

4. **Micromodels do not represent prototype discharges**. Current operation of micromodels using a cyclic hydrograph touts the claim that "model hydrographs mimic the average annual response of the prototype." However, adoption of flow meters into routine model operation revealed that the cyclic hydrograph provides only a limited representation of a true hydrograph cycle. The problem with the cycle lies in the control valve hardware -- the valve provides insufficient resolution and control to obtain the desired hydrograph cycle. Present discharge hydrographs in the model vary on rising and falling limbs due to the valve operating characteristics. Lack of control near minimum and maximum flow settings result in operation of the model at minimum/maximum flows for a disproportionate period of time. Improvements in the valve hardware are essential to provide consistent and

predictable control of model discharges. Such improvements provide the capability to develop design hydrographs that more closely mimic prototype discharge trends.

Current discharge control limits micromodels to levels 1) and 2) because the variable discharge drives development of desired bathymetry. The model hydrograph should provide a representation of prototype discharge characteristics. Achievement of more consistent control of discharge does not translate to the use of micromodels in levels 3) and 4). Other factors play a more significant role in expanding the use of micromodels to these levels.

5. **Micromodels have exaggerated Froude numbers.** Exaggeration of Froude number in loose-bed models results from efforts to obtain similar sediment mobility between the model and the prototype. The exaggeration in Froude number results from velocities that are higher than required for Froude similitude. The higher velocities are required to produce the dynamic similitude prescribed by u_*/u_{*c}. Accordingly, flow parameters influenced by mean stream velocity (V or V^2) are likewise exaggerated. Ettema argues additional points on the effect of exaggerated velocity head ($V^2/2g$).

   A simplified consideration of the energy equation demonstrates the effect of exaggerated velocity head.

$$\frac{P_1}{\gamma} + Z_1 + \frac{V_1^2}{2g} = \frac{P_2}{\gamma} + Z_2 + \frac{V_2^2}{2g} + \text{Losses}$$

where, P is pressure, Z is elevation, V is mean stream velocity, g is the unit weight of water, g is the gravitational constant, the subscript 1 denotes an upstream location, the subscript 2 denotes a downstream condition, Losses represent all energy losses between location 1 and 2. Losses include frictional/roughness losses, form losses, and contraction losses among others. Losses are generally a function of V^2. Therefore, exaggeration of velocity significantly impacts the energy relationship. Contraction losses represent the effects of dikes and related training structures. Exaggerated velocities have a negative impact on flow patterns and flow/velocity distributions, particularly in the vicinity of training structures (Ettema's report and observations from micromodels and UMR flume work). A similar negative impact occurs in channels with pronounced curvature (e.g., sharp bends).

Froude number (and velocity) exaggeration limits micromodel usefulness to levels 1) and 2). Use of micromodels should be restricted to these levels based upon current micromodel approaches. Where required to provide a demonstration tool for levels 3) and 4), micromodels may be used with extreme caution, but only in conjunction with other model results and adequate explanation by experienced personnel. Future developments in the micromodel may enhance model capabilities by reducing velocity and Froude number exaggeration. Recent use of a lighter weight sediment material, Polyester PlastiGrit Type I, tends to reduce the slope required to achieve sediment mobility which in turn reduces the Froude number exaggeration.

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6. **Surface velocity patterns are adversely affected by scale distortions and exaggeration of Froude Number**. Increased distortion of the vertical scale results in model channels having smaller B/y than found in the prototype channel. Circulation in channels with small B/y ratios is stronger as evidenced by observations in the laboratory and in small streams. Davinroy (1994) presents corroborating isovelocity data for prototype and model at a cross-section in the Dogtooth Bend reach of the Mississippi River (Figures 5-1 and 5-2, respectively). Davinroy's figures depicting isovelocity contours indicate a somewhat stronger circulation pattern in the micromodel than found in the prototype. Although there are similarities between the prototype and the model in that both exhibit several higher velocity cells across the channel width, the lateral distribution is different in the micromodel than shown in the prototype (Figures 5-1 and 5-2). The prototype data show the highest thread of velocity located approximately 250 feet from the left bank position while the micromodel data show the highest thread of velocity at a distance of 400 feet, a difference of 150 feet. The difference of 150 feet between these locations may appear minor. However, this represents approximately 10 percent of the total channel width.

7. **Roughness characteristics in the micromodel are not adequately scaled.** The lack of appropriate roughness in micromodels is closely associated with their inability to reproduce prototype stages. Estimates of friction factors and roughness coefficients for micromodel sediments and flow conditions indicate that roughness is too low in micromodel channels. In other words, the model is too smooth.

   Because stages (and depths) are not correctly reproduced in micromodels, surface flow patterns are not correct. Surface flow patterns have greater errors

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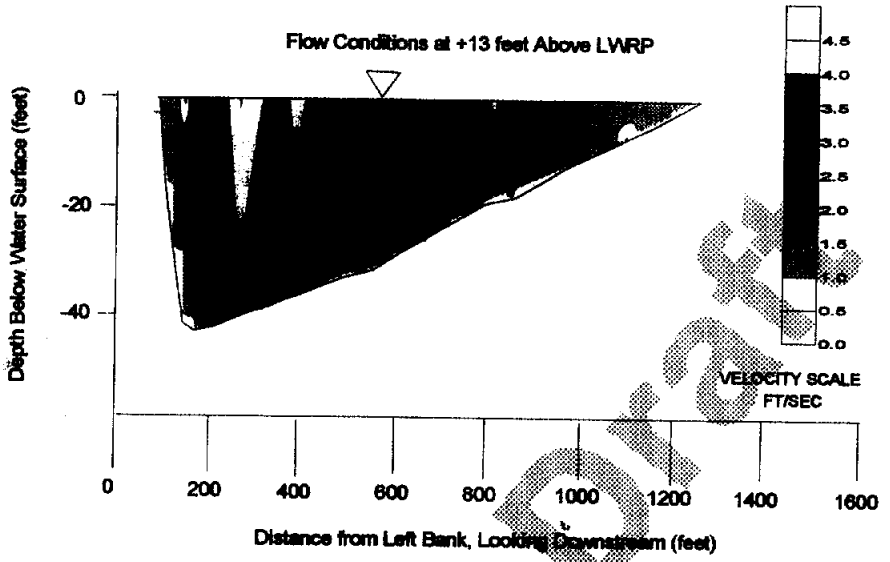

Figure 33. Cross Sectional Velocity Isovels at Mile 34.3, Prototype

Figure 5-1 Cross Section Isovelocities at Mile 34.3, Dogtooth Bend Prototype, Mississippi River (Davinroy, 1994)

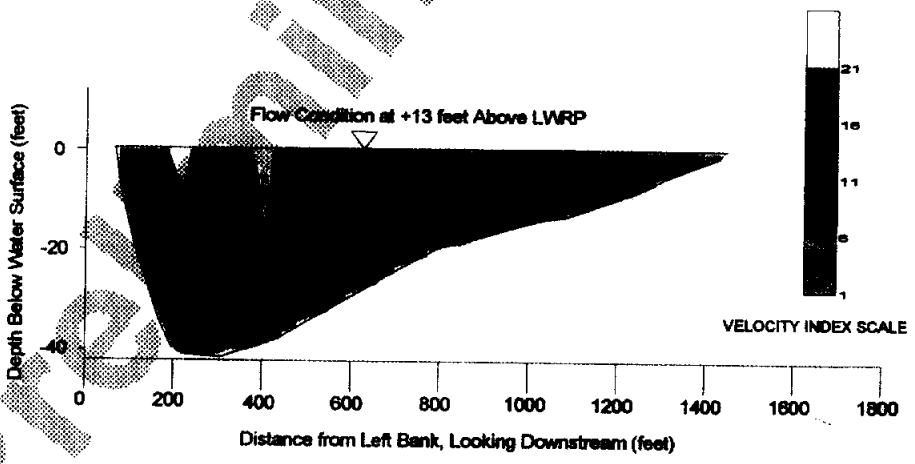

Figure 34. Cross Sectional Velocity Index Isovels at Mile 34.3, Micro Model

Figure 5-2 Cross Section Isovelocities at Mile 34.3, Dog Tooth Bend Micromodel (Davinroy, 1994)

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for prototype reaches containing a high degree of flexibility in thalweg position (not laterally constrained) and/or having high sinuosity.

Based on flume tests by Gaines (2002) using flow depths typical in micromodels, micromodel sediment has an average Darcy f of 0.11 that is equal to a Chezy C of 27 $m^{1/2}$/sec. This value is consistent with values for model C presented in Gujar (1981) who found C = 25-30 $m^{1/2}$/sec for fine and coarse sand, 20-25 $m^{1/2}$/sec for fine bakelite, and 25-35 $m^{1/2}$/sec for coarse bakelite. The micromodel value can be compared to typical Mississippi River values of C = 50 $m^{1/2}$/sec. With a distorted Froude model, achieving the correct friction requires the ratio of C in prototype to model be equal to the square root of the distortion. With a typical distortion of 11 and a prototype C = 50 $m^{1/2}$/sec, model C would have to be 15 $m^{1/2}$/sec. While we know the micromodel is not a Froude model, these values show that the micromodel, having a typical C of about 27 $m^{1/2}$/sec, is too smooth which is generally the case with distorted models.

The model smoothness issue is a possible explanation of why high stages are difficult to run in the micromodel and maximum stage is limited to about +20 LWRP in Mississippi River channels where bankfull is about +30 to +35 LWRP. At higher stages, velocity becomes too great in the model. Similarity of friction is also important in simulating flow in bends. Although the micromodel has an extreme exaggeration of relative roughness, the model is too smooth because of the large vertical scale distortion.

9. **Model Shields Parameter Less than Prototype** - Graf's category of empirical or qualitative loose-bed models has model Shields parameter less than the prototype. Qualitative loose-bed models also use lightweight sediments, vertical scale distortion, and slope increase but only to achieve an acceptable level of sediment transport. Glazik and Schinke (1986) describe loose-bed models experience using a model Shields parameter significantly less than the prototype. As quoted in Glazik and Schinke (1986), results from Liebs (1942) and the assumption of a specific gravity of 2.65 results in a Shields parameter of 0.030 that represents "initial movement of single grains", 0.047 represents "initial, though slow, transformation of the bed", and 0.076 represents "beginning of vivid bed material movement".

Model design and operation in Glazik and Schinke (1986) is based on a model Shields parameter of about 0.061. The prototype in their report, for which a model study case history was presented, had a prototype Shields parameter of 0.51 which shows that using 0.061 in the model is a significant relaxation. The Mississippi River and other major alluvial rivers often have Shields parameter in excess of 1.0. Hecker and White (1989) describe a loose-bed models used on the Arkansas River where the Shields Parameter was less than the prototype. Based on personnel communication with Tom Pokrefke and Charles Nickles who conducted ERDC coal bed loose-bed models, "beginning of vivid bed material movement," or a Shields parameter of 0.076, best described the techniques used at ERDC. Although actual

depths and slopes used on the coal bed models suggest a Shields parameter that is closer to 0.061, either 0.061 or 0.076 show a significant reduction of Shields parameter was used in the ERDC models.

Chitale ((19??) states that movable bed model design is based on "adequate tractive force to ensure satisfactory bed movement". Shen (1990) states that if the rate of sediment movement is not an issue and the only need is to create a movable bed, a Shields parameter need only be greater than the critical value. The use of loose-bed models for bed similarity studies without having equality of Shields parameter is consistent with conclusions by Laursen and Alawi (1989) regarding the effects of velocity on scour. Laursen and Alawi (1989) found that scour was independent of shear/critical shear ratios greater than about three to four.

The few slope measurements taken in the micromodel have shown a slope of about 0.01. At a maximum stage in the micromodel of +20 LWRP, the hydraulic depth is about 35 ft in typical Mississippi River applications. The hydraulic radius is about 83% of the hydraulic depth for a distortion of 11 which is an average distortion value used in micromodels. Using a typical vertical scale of 1:800 results in a model hydraulic radius of 0.036 ft. Using a specific gravity of 1.47 and a model D_{50} of 1.0 mm, results in a typical Shields parameter used in the micromodel of 0.23. This value is compared to prototype values on the Mississippi River that are typically greater than 1.0.

The micromodel Shields parameter is closer to the prototype than in both the model by Glazik and Schenke (1986) and the coal bed models at ERDC. Because of the importance given to the Shields parameter in the rational approaches of Yalin and Einstein and Chien, some might be tempted to conclude this is a favorable feature of the micromodel. However, it happens in the micromodel because of the large vertical scale distortion in conjunction with the large Froude number distortion. The experience of previous qualitative models by Glazik and Schenke (1986) and the ERDC coal bed models is toward a significantly lesser Shields parameter resulting in general bed movement. This approach allows the modeler to minimize vertical scale distortion and Froude number exaggeration.

The primary advantage of smaller Shields parameter in the model than in the prototype, and almost certainly the reason its use has evolved, is that distortions in Froude number and vertical scale can be reduced, which should result in improved reproduction of the flow field and thus improved reproduction of the bed morphology. Another factor concerning the Shields parameter is its effect on the time scale for sediment movement. Small models having large Shields parameters will respond extremely fast. Such rapid response reduces testing time but was intentionally avoided in the ERDC coal bed models.

10. **Slope distortion in the micromodels is too high**. Slopes in the micromodels are highly tilted to achieve a desired state of sediment mobility using the

PlastiGrit Type II sediment material. Exaggeration of model slope tends to restrict thalweg adjustment laterally within the channel. This results from exaggerated velocities and from a prototype channel represented as a narrow and deep cross-section. The latter results primarily from the vertical scale distortion. Distortion of slope produces velocities that are not necessarily reproduced correctly in terms of magnitude and direction. Incorrect reproduction of velocity magnitude and direction leads to incorrect reproduction of flow details. Current slope distortions used in micromodels limit applications to levels 1) and 2).

11. **Micromodels operate on a sediment equilibrium principle.** Use of the equilibrium concept for micromodel operation becomes a limitation only if prototype bathymetry results from a non-equilibrium condition. Where the prototype undergoes constant changes in boundary conditions (bankline migration, rapid scour or deposition trends, etc.), the equilibrium approach may lead to incorrect model results. The potential for incorrect model predictions increases as the rate and magnitude of the non-equilibrium condition in the prototype increases. Micromodel use is restricted to problems where prototype banks do not change appreciably over time and where the prototype exhibits no long-term aggradation-degradation trends.

12. **Sediment materials used in micromodels limit their application to sand- or gravel-bed streams with active bed transport.** The PlastiGrit sediment material behaves in a similar manner to sand. Simulation of bed response with a cohesive bed is beyond the capability of existing physical and numerical models. the mechanics of cohesive material erosion and transport is not understood and no empirical methods exist to simulate channel adjustment.

13. **Tributary and divided channels impose requirements to ensure adequate representation of flow and sediment distributions between the respective channels.**

14. **Adequate documentation of micromodel operational and design parameters facilitates a better understanding of how the model represented the prototype.**

15. **Availability of prototype data limits understanding of some boundary conditions.**

16. **Suspended sediments cannot be modeled using micromodel techniques.** Sediment material characteristics change appreciably when sizes are in the clay and silt range. Suspended sediments at prototype scale typically fall in

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the silt/clay particle sizes with some suspended sediments being as large as sand sizes. However, cohesionless materials in the prototype having a median particle size of even 1.0 mm would require model sediments in the clay sizes if the correct horizontal and vertical model scales are used. At such reduced sizes otherwise cohesionless materials exhibit cohesive characteristics. Therefore, model sediment sizes are distorted in order to maintain cohensionless bed transport. The sediment sizes thus used in models do not provide any mechanism for simulating suspended sediments in the prototype. This is evident from the Shields Regime diagram (Figure 3-5).

17. **Inability to achieve good verification in some previous micro model tests**
18. **Conclusions from consultant on applicability to only laterally constrained reaches**
19. **Differences in Kate Aubrey plan tests**
20. **Lack of repeatibilty of Kate Aubrey traditional micromodel tests**
21. **Poor replication of currents in Vicksburg Front model**
22. **Unknown % flow splits in divided channel reaches**
23. **Unknown flow characteristics through notches/dikes**
24. **Water Surface Profile Analysis (in channel and floodplain)**
25. **Floodplain Sedimentation**
26. **Velocity Magnitudes**
27. **Quantitative & Near Field Scour and Deposition Analysis**

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6. RECOMMENDATIONS

6.1. PROTOCOL FOR MICROMODELS

With insight regarding current applications of the micromodel methodology and potential limitations of the micromodel, the potential modeler must decide on the appropriate course of action: 1) The micromodel provides the necessary outputs for analyzing the problem at hand or 2) Other means must be sought to analyze the problem. If the decision to conduct a micromodel study is made, the necessary procedures are then outlined in order to achieve the desired outcomes.

The following sections describe procedures for calibration of the micromodel that will serve to develop confidence in the model results.

6.1.1. General

In order to achieve confidence in loose-bed model results, certain steps are required. First, model design should follow accepted techniques and use a consistent methodology. Second, analysis of model results should include a quantitative estimate of model and prototype agreement for the calibration condition. Third, documentation of model design and operation parameters and their relationship to the corresponding prototype parameter values is necessary.

Proper interpretation of model results requires that model operation adhere to certain basic procedures. That is not to say that all models involve exactly the same steps to achieve calibration or to perform alternative comparisons. Indeed, there are different constraints placed on each model situation. These constraints depend upon the problem to be solved (e.g. degree of technical complexity and/or human expectations/perceptions), on the availability of prototype data, and on the availability of time/funding. A detailed description of the problem[11] begins the modeling process.

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[11] The description should include sufficient details to provide a general statement defining why prototype conditions are undesirable and to provide specific data (e.g. flow paths, velocities, bathymetry, dredging history, navigation reports, etc.) that define the problem as quantitatively as possible.

6.1.2. Problem Definition. The problem must be defined and study objectives stated. This includes specific qualitative descriptions of the problem or problems so the modeler can determine the applicable model limits and establish a general approach for conducting the model effort. The specific problem location is identified and described regarding one or all of the following:

1. Extent of problem
2. Inadequate Navigation Depth or width
3. Inadequate/Undesirable Channel Alignment (navigation, bridges, etc.)
4. Undesirable flow distribution through main channels and side channels
5. Environmental adaptations of existing structures
6. Environmental enhancement objectives
7. Undesirable Depositional Patterns
8. Bank stability/Recession
9. Excessive Dredging Requirements
10. Evaluating changes in/Effects of existing structures
11. Entrance and Exit conditions that may be relevant to the problem

The problem definition also helps in developing model study objectives, which should be stated prior to beginning model design. Objectives often include: defining the location of training structures, establishing general controlling elevations for the structures, and a projection of prototype channel response to proposed changes. Where existing structures are analyzed to determine their effects, goals include establishing whether modifications are required to produce a desired outcome (e.g. where dikes are notched to provide back channel areas for environmental purposes).

6.1.3. Procedures

Model methodology should include the following steps as part of the calibration process.

1. Verify and describe the way that the model reproduces the problem(s) as observed in the prototype.

2. Verify and describe how the model reproduces the thalweg alignment found in the prototype. Some expression of goodness-of-fit should be provided. This can be accomplished by plotting the morphologic parameter of thalweg location by Range for model and prototype data. Calculation of the MSE and

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differences are also required to describe the level of overall agreement for the model.

3. Check other morphologic parameter values to insure that model values are not too far from prototype values. This step is important because the hydraulic geometry of the channel affects the model's representation of velocity and sediment distributions. Area and depth are principle parameters to be considered and emphasis should be given to keeping model areas and depths within a certain tolerance of prototype values. Present data do not support a rigid criteria to be applied. Future research may help establish a required level of agreement. The required level of agreement should be based upon the effects that result from deviating from an ideal representation of prototype channel characteristics. Until additional research defines a required level of agreement, recommended tolerances are to keep model parameter values within one standard deviation of the prototype reach-averaged parameter values. Where this is not feasible, limited regions may be permitted to deviate by no more than two standard deviations of the prototype reach-average value. As a general guide, model values should not deviate from prototype values by more than approximately 1/3 of the respective prototype values at any location within the model reach.

4. Document the use of techniques to limit scale effects in the model. The use of artificial bank roughness (wire mesh along the banks), the placement of clay along the bank to provide sloped banks or to adjust roughness, and the use of "non-erosive" materials in the model to limit scour depths are techniques currently used in the micromodels. A map of locations digitized from the model where these features are used provides the recommended method for documenting the use of these techniques.

6.1.3.1 Calibration Process.

The intended use of the model also affects the calibration measures to be employed. Where prototype geometry is relatively simple and only general trends in bed response are sought, calibration requires only a one-step process. Where prototype geometry is complex a two-step calibration process becomes necessary to establish the degree of confidence that can be placed on the model results. Where surface flow paths are to be used in high-risk problem solutions, a third step becomes necessary.

6.1.3.2 Basic Calibration.

A single-step calibration process involves achieving agreement between model and prototype bathymetry. The level of agreement between model and prototype bed

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elevations serves to establish the degree of confidence that the modeler places on model results. Morphologic similarity can be established by determining model and prototype values for thalweg position, cross-section area, top width, hydraulic depth, and the width divided by the depth.

6.1.3.3 Complex Prototype Conditions.

A two-step calibration process includes the preceding step but adds a second verification process. The second step involves taking conditions after the base calibration timeframe where changes have been observed in the prototype and then placing those changes in the model. The model response to those changes is compared to the observed prototype changes in order to confirm (or verify) that the model adequately reproduces model conditions. The second step provides an additional level of confidence necessary when dealing with complex flow situations. Typical complex flow situations include a channel with one or more sharp bends, a channel division, a channel confluence, or where hydraulic structures are present (i.e. bridges, locks and dams, or similar structures). The verification step also uses morphologic similarity to assess model and prototype agreement.

Split flow conditions within the model reach require an additional measure to assure the proper distribution of flow between the separate channels. LSPIV techniques provide a semi-quantitative measure of the model flow distribution. Prototype division-of-flow data provide a means to determine or at least bracket prototype flow distribution.

6.1.3.4 Surface Flow Patterns.

The three-step calibration process becomes necessary when surface flow patterns are used to assess model response. Here, the model response includes the relative comparison of various alternatives. Confirmation of surface flow patterns in the model with prototype data provides the third calibration step. The high degree of vertical scale distortion and the large exaggeration in Froude number influence surface flow patterns in the micromodels. This influence results in model flow patterns that may be different than prototype flow conditions[12]. For this reason, use of the surface flow patterns obtained

[12] The word may is used at this point to signify that the influence is largely unknown by looking only at model data.

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from a micromodel requires extreme caution. Confirming the general location and alignment of surface flow patterns in the micromodel with observed prototype flow pattern data provides a means to overcome the unknown influence of vertical scale and Froude number distortion on model surface flow patterns.

The significance of the third step increases when the problem under consideration involves a hazard or risk to human safety. Hydraulic theory and observations by investigators indicates that surface velocity distributions can have deviations of ten percent or more of the channel with in channels with a high degree of scale distortion. Because a deviation of ten percent of the channel width may have a major impact on interpretation of model results, the use of a micromodel as the sole basis for assessing alternatives in a high-risk situation is problematic and should be avoided. Other methods such as features designed external to the micromodel[13], two-dimensional numerical models and/or larger-scale loose-bed physical models should be used in conjunction with micromodel flow visualization results to assess recommended alternatives.

Although not mandatory, it is strongly suggested that surface flow patterns be recorded using both time exposure photography and video footage. While the time exposure photography captures a single image of the seeding particles, a video recording of the seeding can provide a more complete understanding of the flow patterns. The video recording also provides an excellent demonstration tool for explaining the similarities and differences between the model and prototype flow patterns and between various alternatives and the base test.

6.1.4. Similarity

The observed degree of similarity for a particular model study should be documented through the Shields regime diagram, the roughness distortion graphs, the morphologic similarity graphs, and the Froude similarity criterion. Documentation of similarity relationships provides information necessary for correct interpretation of model results.

[13] The hydraulic design of artificial scour protection in the vicinity of a bridge is one example of such a feature.

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Model design should incorporate an assessment of the Shields criterion for both prototype and anticipated model conditions. The degree of Froude number exaggeration should also be calculated. The roughness and slope distortion should also be evaluated. The Shields criterion and the roughness and slope distortion factors provide a mechanism for balancing sediment mobility and boundary roughness effects in the model. Applying the ripple factor, which is a function of the sediment transport, is a useful way to achieve this balance. The current research indicates that increased sediment material particle size (e.g., increased D_{50}) will improve roughness similarity in the micromodel.

6.1.5. Improvements Resulting from Evaluation

Early during the course of conducting the evaluation, severe deficiencies in the micromodel procedure were modified. The two main modifications included the adoption of flow metering and the use of a constant-head system for delivering water and sediment to the model.

Standard micromodel methodology should incorporate the use of flow meters to document model discharges and hydrograph shape.

Standard micromodel methodology should incorporate the use of a constant-head assembly to deliver water and sediment to the model headbay.

6.2. DATA REQUIREMENTS

Previous model study data were insufficient to assess even basic similarity criteria. Data were also insufficient to evaluate scale effects. Because similarity criteria and scale effects are important to understanding and interpreting model results, future model studies should document sufficient information to allow assessment of similarity criteria and scale effects. Data needs are relatively straightforward and should require minimal increases in model time and cost. The benefits derived from collection of these data are two fold: 1) understanding scale effects may permit wider application of the models to solve problems of a more quantitative nature and 2) understanding the distortion of slope, velocity, Froude number, hydraulic radius and sediment transport may produce better overall model similarity than presently exists. The minimum data necessary to achieve these benefits include the following:

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1. (*) Model reference plane (e.g. flume) transverse and longitudinal slopes.

2. (*) Model water surface elevations (in model coordinates) in at least three locations continuously throughout the hydrograph cycle so that model water surface slopes can be documented. If continuous readings are not feasible, model water surface elevations should be obtained at maximum and minim discharges as a minimum. Locations of measurements should also be documented in model coordinates (x,y,z coordinates in inches or mm depending on the method used for surveying the model).

3. (*) Model discharge throughout the hydrograph cycle. As a minimum, the maximum and minimum discharges used for the calibration case should be documented in numeric form. The shape and duration of the hydrograph should be reported (graphic form preferrable).

4. (*) Prototype discharge in at least two locations and at two water surface elevations (one near the minimum stage to be modeled and one near the maximum stage to be modeled). Water surface elevations (e.g. water surface slopes) are also required to document the conditions for when discharge measurements were made.

5. (***)Volumetric sediment transport in the model after calibration (obtained by timed capture of a volume of water and sediment or other means).

6. (*) Gradation of model sediment material. Model sediment gradation can be determined for batches of sediment material or for individual models with minimal cost and time.

7. (*) Gradation of prototype sediment material. Approximate prototype sediment gradations are available for the lower Mississippi River and can be easily obtained for other channels.

8. (*) Model bathymetry in model coordinates (pre-conversion to prototype coordinates).

9. (**) Model morphologic parameter values in model coordinates (pre-conversion to prototype coordinates). Locations of ranges to be used in generating morphologic parameter values can be identified by digitizing left and right bank points on the model with the Microscribe™ or Faro Arm™ and then obtaining the corresponding prototype locations by conversion of the model range coordinates into prototype coordinates with the convert utility.

10. (*) Model morphologic parameter values (at prototype scale) for comparison of calibrated bathymetry to prototype values (see 11).

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11. (*) Prototype morphologic parameter values for each prototype bathymetric survey utilized in the study effort.

(*) Denotes required data
(**) Denotes highly desirable data
(***) Denotes desirable data

Sediment transport measurements in the prototype are also needed to assess similarity in sediment transport. However, the costs associated with measurement of sediment transport (particularly bed load) and the inherent inaccuracies of measuring sediment transport in large alluvial rivers preclude acquisition of this data on a routine basis. Sediment transport in the prototype may be estimated using standard transport relationships (e.g. Yang, 1978). Measurement of prototype sediment transport is desirable to verify/develop coefficients used in the various transport relationships. Prototype sediment transport data should be acquired as budgetary constraints permit.

Use of a standard form or forms to document the information provides a systematic way to acquire and publish the known data listed above. A draft format is under development and will be provided with the final version of the report.

6.3. ADDITIONAL RESEARCH

Loose-bed models described in this report can provide a reliable means for design and analysis of river training structures subject to the limitations described previously. Through application of loose-bed models, the modeler can gain insight into various prototype responses to structure designs. Projected prototype response can also be investigated to determine impacts on channel behavior. Further research on applications of small-scale loose-bed models can enhance methods for applying these models. However, additional data needs to be collected in present and future model studies to facilitate this research.

The present investigation proposed four categories of similarity depending on the level of detail required, on the risk to human life, on the relative solution accuracy and on operational constraints. A Failure Modes and Effects Analysis (FMEA) can help

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identify important criteria needed to define each category. Future investigations should focus on defining the categories used in the FMEA.

A primary goal of the present evaluation included estimation of scale and scale distortion effects in the small-scale models. This goal was not achieved. Data available from the previous model study results were insufficient to assess scale effects. A minimal amount of data collected from on-going and future model studies can provide the requisite inputs for defining scale studies and relaxation of scale ratios. The necessary data are included in the recommended micromodel protocol.

Variability in prototype bathymetric data has a major influence on the attainment of model similarity. Additional investigation of this variability may yield methods for weighting individual Range data (temporally and spatially) in order to define required similarity criteria.

Simulation of prototype discharges should mimic prototype hydrograph tendencies. Where prototype hydrographs are variable, model hydrographs should be developed so that model discharges behave in a similar fashion. The effect of variable hydrographs on bed development are only partly realized in current loose-bed modeling. The effects of simplified sine wave or triangular type hydrographs versus alternate hydrograph shapes (including rapid rise, rapid fall, and constant discharge) warrants additional study.

Limited testing performed on structure porosity as a relaxation technique should be expanded to determine how structure porosity impacts model bathymetry. Structure porosity plays a significant role in reducing the local scour tendencies and deflection of the surface flow patterns and thalweg location in small-scale channels. Optimization of the porosity effect is desirable and warrants further investigation.

Present applications of the loose-bed models provide only a qualitative representation of training structures. Quantitative application of loose-bed models to achieve optimized training structure designs requires the reproduction of details in the model. These details pertain to flow and sediment transport phenomena and to structure lengths and heights. Model sensitivity to changes in structure length and to structure

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height must be investigated before advancements can be achieved in structure design optimization.

Current investigations included a limited number of experiments involving a short contraction structure. Additional experimentation is necessary to define the impacts of channel width on flow and depositional characteristics in the vicinity of short contractions. Further research is also needed to determine the effects of channel width on flow and bathymetric response in the vicinity of long contractions.

Bed material gradation has a major impact on model roughness characteristics. Both roughness coefficients (e.g. Chezy C or Darcy-Weisbach f) and the relative roughness are affected by the D_{50} particle size. Because roughness also impacts selection of vertical scale (through the roughness distortion factor), the distortion of bed material size requires greater relaxation of slope and roughness similarity for the model. The ripple factor (μ_f) provides an indication of the degree of similarity relaxation required for a given slope distortion, roughness ratio, and sediment particle size. The present research developed a technique for approximating the value of μ_f. However, actual values of μ_f are necessary for model and prototype to permit adjustment of roughness (through the vertical scale and sediment particle size) to compensate for the relative influence of suspended sediment transport. Approximating the value of μ_f requires collection of data in prototype and model systems. Additional research should attempt to quantify this correction factor.

Reproduction of scaled water surface elevations in the small-scale model depends on the roughness characteristics of the sediment material and on the slope distortion used in the model. The degree of Froude similarity employed in model design also directly impacts the water surface elevations. Accurate model water surface elevation data are required to assess morphologic similarity in native model units (e.g. at model scale, inches or millimeters). Currently, water surface elevation data are limited. A means for tracking water elevations in the model is required to determine model cross section areas, widths, and depths in the model.

The ability of the small-scale models to predict prototype response was investigated for the Kate-Aubrey reach of the Mississippi River. Additional cases where

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model study results led to construction of the recommended alternative in the prototype should be sought where field data can be collected to compare with predicted model response.

The current evaluation considered the similarity of loose bed physical models. A similar evaluation of numerical sediment transport models was not found in the literature. Comparisons of numerical model results to prototype conditions using the morphologic parameter approach described herein should be accomplished. Comparisons should be performed for the calibrated model conditions and for a predicted model response.

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APPENDIX A

CONSULTANT REPORTS

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The reports contained in this appendix represent opinions of the three panelists consulted early in the JV evaluation effort. Copies of the individual reports are provided for reference only and are arranged in alphabetical order.

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Robert Ettema

Review Report on

EVALUATION OF MICRO-MODELING CAPABILITIES AND EXPANDED APPLICATIONS

Report submitted to
The U.S. Army Corps of Engineers
Waterways Experiment Station
St Louis District
Memphis District

by
Robert Ettema
Iowa Institute of Hydraulic Research
Department of Civil and Environmental Engineering
Iowa City, IA 52245

June 27, 1999

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1. Introduction

This report reviews a draft plan of study developed by the U. S. Army Corps of Engineers to evaluate the capabilities and possible extended application of micro-scale physical models of river reaches. The models, termed micro-models, are used by the Corps' St Louis District to aid in the design of river-control works, especially for relatively large, navigable reaches of the Mississippi River system. Typical micro-modeling scales, in round numbers, are about $1{:}10^4$ horizontal and $1{:}0.5 \times 10^3$ vertical; the horizontal scale typically is selected to coincide with the scale used by the Corps for its standard aerial photographs of rivers. The essential issue the plan of study aims to address is the degree to which micro-models reliably replicate flow and sediment-transport processes in rivers.

In principle, micro-models are not new. For a good century, they have been used to aid understanding of complicated flow and fluid-transport processes, as well as to help confirm the performance of diverse hydraulic structures. It is well-known, for example, that the prominent hydraulic engineer Osborne Reynolds, in the late 1880s and early 1890s, used a micro-scale models at two sets of scales, to obtain insights for locating flow-training works to ensure satisfactory performance of a navigation channel in estuary of the Mersey River, England. The models, an early distorted geometry models, were built at a horizontal scales of $1{:}3.2 \times 10^4$ and $1{:}1.1 \times 10^4$ with corresponding vertical scales of about $1{:}1.0 \times 10^3$ and $1{:}0.40 \times 10^4$; the models were approximately 1 to 2 m long (Freeman 1929). It appears that the models were used primarily to determine whether contraction of the flow near the entrance to the estuary would deepen the navigation channel through a bar at the entrance to the Mersey estuary. Reynolds' protégé, Levison Vernon-Harcourt continued the work using a micro-scale model to investigate much the same concerns for the estuary of the Seine River.

What is new about the micro-scale models, or micro-models, at the Corps' St Louis District is the application of technologies facilitating sophisticated control, operation and data acquisition. Whereas the micro-scale models of the 1880s and 1890s were built small out of necessity (notably because suitable large pumps and laboratories were not readily available), automated smallness has become a virtue for the St Louis micro-models. And indeed, the evident virtues of micro-models are their relatively modest cost, the short duration entailed in getting insights from them, and their portability. For engineering projects subject to tight limits on budget and schedule, and with a need to explain complex flow processes to the general public, these virtues are highly significant and appealing.

A disconcerting aspect of micro-models, however, is the apparent laxity in the explicit consideration of dynamic similitude and its constraints; in simple words, the theoretical considerations attendant to modeling and the processes being modeled seem to be inadequately defined or taken into account. The only explicit similitude consideration is that relating horizontal length. In this respect, the criticism could be leveled that micro-models really are not proper hydraulic models; whereas hydraulic models usually are designed and operated with similitude criteria kept foremost in mind, micro-modeling seems to disregard them or set them aside. This ostensibly weak, or ill-defined, theoretical basis opens micro-models to the charge that they lack rigor and are merely a convenient but risky short cut to getting information of uncertain reliability.

The accuracy and reliability of hydraulic models have been (and continue to be) the subject of much study and discussion by hydraulic engineers. Whenever a new hydraulic-modeling concept or application arises, or when a similitude criterion is relaxed in some novel way, it becomes the subject of scrutiny. The scrutiny inevitably entails consideration of similitude concepts expressing proportionate relationships between key geometric quantities and forces driving or resisting motion in prominent physical processes. Over the years, well-documented sets of similitude criteria and suggested modeling limitations have emerged to help guide hydraulic modeling. For practical engineering purposes, the scrutiny of modeling should be accompanied by an appraisal of the requisite levels of accuracy and reliability of information sought from a model. Guidelines for requisite accuracy in the design of various hydraulic structures have not been well developed over the years.

An historical irony is that the apparent utility of the early micro-models stimulated the subsequent rapid development of larger, more exact models of loose-bed rivers and estuaries.

2. Components of the Proposed Study

The proposed plan of study would comprise three investigative components, which may be summarized as follow:

A. Become familiarized with current micro-modeling practice, then develop a framework for studying model-prototype conformity.
B. Investigate the sensitivity of micro-modeling results to the model bed material used.

C. Investigate the repeatability of micro-model results.

The details of the three components are described in Appendix I. Appendix II (Topics) is an informal list of issues posed by the Corps for investigation during component B of the study.

3. General Impressions

I would like to lead into my evaluation by offering a few general impressions about the proposed plan of study:

1. The proposed study will require a consistent theoretical framework based on similitude and laboratory-effect considerations. As is explained subsequently in this report, micro-modeling capabilities cannot be evaluated effectively without such a framework. Nor, for that matter, can the issues listed in Appendix II be posed or answered appropriately in the absence of such a framework. Quite possibly, such a framework remains to be developed early in the study. Also, I would urge that the word "theoretical" not be thought of as being purely academic; the capabilities and possible extended application of micro-modeling cannot be evaluated in an abstract or ad-hoc manner.

2. An important facet of the proposed study should be an evaluation of the levels of accuracy needed for designing river-training works. The target levels of accuracy and reliability obtainable with micro-models should be consistent with those levels. The early micro-scale models of the Mersey and the Seine estuaries were useful in part because great accuracy was not needed in designing the channel-training structures modeled. It might also be added that the records are unclear as to the actual veracities of the models.

3. A simple truism in modeling is that model results are only as good as the knowledge of the people interpreting them. Usually, the more knowledgeable the modeler, the less exact need be the model; this goes for all hydraulic and computer modeling. Reynolds and Vernon-Harcourt used micro-scale models, but arguably both men also were among the most knowledgeable fluid mechanicians of their day. To be effective, the proposed study also should evaluate the level of expertise needed to design and interpret micro-models.

4. Micro-modeling is motivated in part by the substantial pressures imposed on Corps Districts to get engineering information in a timely and cost-effective manner. There is a risk that those pressures give rise to unrealistic estimates of the capabilities of micro-models. In my opinion, micro-model use is constrained to the single, but very significant, class of river-training applications for which approximate, information is sought regarding the impacts of relatively large-scale hydraulic structures (e.g., wing dams, bendway weirs) placed in relatively wide, essentially two-dimensional flow situations. For other applications, the modeling client must be in a position to stand the risks incurred with uncertain information accuracy.

These impressions are offered in a constructive and uncritical spirit. They underlie my evaluation of the proposed study. I admire the enthusiasm of the micro-modeling group at the St Louis District, and am intrigued by their modeling innovations (e.g., use of very lightweight model bed sediment and automation of model operation and data acquisition). I do believe, though, that advances cannot be made without sound knowledge, and that micro-modeling needs to fit within the broader context of hydraulic modeling practice.

4. Essential Tasks

A sound framework for evaluating the capabilities and expanded applications of micro-models must be based on considerations of modeling similitude and laboratory limitations. Without a clear theoretical basis, study components A, B, and C likely will be inconclusive. I would suggest, therefore, that the study be configured to accomplish the following tasks:

1. Get acquainted with current micro-modeling practice. This task largely has been done, or at least is well underway. The one-day visit to St Louis on May 1, 1999, together with the reports provided, help accomplish this task.
2. Develop an evaluation framework based on the key sets of similitude criteria relevant to water flow and sediment transport in loose-bed channels, and to component processes such as local scour at hydraulic structures (e.g., piers, weirs, and groins). The subsequent portion of this report provides some suggestions in this regard.
3. Conduct tests to determine the consequences of selected important scale effects resulting from relaxation of similitude criteria. This is the hard part.
4. Conduct tests to determine the consequences of selected important laboratory effects. This part too is fairly hard.
5. Compare qualitative trends and quantitative micro-model conformity with field data and/or data from larger models. This part requires close consideration of similitude criteria and laboratory effects.
6. Assess the level of expertise needed for interpreting and implementing insights from micro-models. This task also entails assessing the level of accuracy and reliability of information needed for various river-training activities.
7. From the outcome of tasks 1 through 6, delineate application limits for micro-models.
8. Prepare a comprehensive report.

The tasks essentially entail identifying the variables and consequent non-dimensional parameters associated with flow and sediment transport in loose-bed channels. The key similitude criteria then are straightforwardly evident. Inevitably, all the key similitude criteria cannot be satisfied, and compromises are needed. The likely scale effects, or consequences of relaxing similitude criteria, need to be identified and their impacts determined by means of controlled tests. The consequences of important laboratory effects likewise need to be identified and determined. Fore-armed with knowledge about key similitude criteria, and the impacts of scale and laboratory effects, meaningful comparisons can be made using data obtained from the field and/or other models. The level of background expertise needed to effectively make such comparisons, and to interpret model results, must be assessed in this procedure. The comparisons will delineate the extent of micro-modeling capabilities. A comprehensive report is needed to

document the study's findings. Given the perception that micro-modeling potentially lacks theoretical rigor, it is necessary that likely modeling limitations and uncertainties be understood at the outset of a micro-modeling project.

A concern immediately apparent from the foregoing list of tasks is that the study may be overly ambitious. The study raises many issues are of overall importance for hydraulic modeling and for the processes being modeled. Where possible, use should be made of existing information published in various reports and papers, as numerous studies already have examined many of the issues. In addition, the ensuing sections of this review report are intended to help condense the issues to a select number of key concerns to be considered when evaluating the capabilities of micro-models. The key issues relate directly to similitude, and lead to considerations of scale and laboratory effects. (The point here is that similitude is vital for scaling between model and prototype; if you abandon similitude, you abandon the path back from model to prototype.)

5. Similitude

The similitude principles underlying hydraulic modeling are fairly straightforward and readily understood. Their implementation, though, usually requires a sound understanding of the underlying physical processes, an appreciation of the dominant processes, and recognition of a model's capacity to replicate those processes. It is important, therefore to establish the accepted ranges for distinct regimes of flow and sediment-transport behavior; e.g., fully turbulent flow, supercritical flow, dune-bed flow regime. The forces of interest are attributable to inertia, gravity, boundary drag, pressure, viscosity, and surface tension. Similitude seeks to keep the ratios of these forces in proportion, at least insofar that flow patterns and water-surface profiles are accurately simulated.

The ensuing two sub-sections consider key similitude issues for modeling flow in fixed-bed and loose-bed channels.

5.1 Modeling flow in fixed-bed (or stationary bed) channels

Variables. The essential variables involved may be stated functionally as

$$S_w = f_{S_w}(\rho, \nu, \sigma, S_o, k, B, R, U, g) \qquad (1)$$

in which here S_w, the water-surface slope, is taken to be a dependent variable. The fluid properties specified are fluid density, ρ, kinematic viscosity, ν, and surface tension, σ, (which usually does not play a significant role in for river flow). Channel geometry variables of importance are channel slope, S, channel roughness, k, channel–section hydraulic radius and width, R and B. And, U is section-average velocity, with g being gravity acceleration.

Similitude Considerations. The variables can be combined non-dimensionally to give the following functional relationship and set of similitude criteria:

$$S_w = \Phi_{S_w}\left(S_o, \frac{k}{R}, \frac{B}{R}, \frac{UR}{\nu}, \frac{U^2}{gR}, \frac{\rho RU^2}{\sigma}\right) \quad (2)$$

in which the following well-known parameters (and similitude criteria) for open-channel flow emerge:

$Fr = \frac{U}{\sqrt{gR}}$, Froude number

$Re = \frac{UR}{\nu}$, Reynolds number

$We = \frac{\rho RU^2}{\sigma}$, Weber number

$\frac{k}{R}, \frac{B}{R}$ are relative roughness and aspect ratio, respectively. They are geometric ratios of great importance for replicating flow distribution, flow patterns, and turbulence, as well as bedforms and channel forms in loose-bed channels.

A common use of fixed-bed hydraulic models is to determine water-surface profiles and flow patterns in channels too complicated in bathymetry to readily enable calculation of such profiles or patterns. From Eq. 2, though, it quickly becomes evident that micro-models cannot be used accurately for this application, because they inadequately simulate flow resistance; they do not produce fully turbulent flow, and they are subject to exaggerated surface-tension effects. The ensuing explanation elaborates this limitation.

The Froude-number criterion prescribes similitude for forces attributable to fluid inertia and gravity, and it usually is the prime similitude criterion for modeling fixed-bed open-channel flow. But, by itself, it may be insufficient for prescribing similitude of flow resistance and water-surface profiles. Flow resistance can be described using relationships such as the Darcy-Weisbach or Manning's equations. The Darcy-Weisbach equation, for instance, states

$$U = \sqrt{\frac{8gRS_f}{f}} \quad (3)$$

in which S_f = slope of the energy gradient of the flow, and the dimensionless resistance coefficient, f, can be written in functional form as

$$f = \Phi_f(k/R, Re, B/R, \textit{channel shape}) \quad (4)$$

The Moody diagram shows this functional relationship for prismatic conduits. It indicates zones of laminar flow and fully turbulent or hydraulically rough flow conditions. The criterion

$$\mathrm{Re}\, f^{1/2}\left(\frac{k}{4R}\right) \geq 200 \tag{5}$$

delineates the zone of fully rough flow in a conduit of hydraulic roughness, R. This equation is one means to estimate the minimum model-scale Reynolds number needed to ensure fully turbulent flow in a prismatic conduit. Flows in rivers, canals, and most open channels of civil engineering significance typically are fully rough flows with Re in excess of 10^4. Micro-models with depths of about 1 inch and flow velocities of about 2 inches/sec convey flows with Re of about 10^3; therefore, micro-model flows probably are in the transition regime for which flow profiles and patterns vary with Reynolds number. Here, perhaps, is another historical irony related to Reynolds. His interest in flow resistance and flow stability led to the first formal distinction of laminar and turbulent flow regimes. Yet his involvement in nominally the first hydraulic model of a river-training problem required relaxing the distinction between flow regimes; he did use two models to examine scale effects, however.

The influences of surface tension on free-surface flow behavior require consideration Weber-number (We) similitude. It also may be interpreted as a ratio of water velocity, U, to the celerity of capillary waves, $(2\pi\sigma/\rho\lambda)^{0.5}$, with wave length, λ, taken as a characteristic length. Whereas surface tension exerts negligible influence in most free-surface flows of civil engineering importance (rivers, canals, and drainage systems), it cannot be neglected for very shallow flows such as in hydraulic models. Based on a comparison of propagation speeds of gravity waves and capillary waves, water depths in model channels should not be less than about 20 mm (nominally one inch); with $We \approx 100$. This consideration, together with that for fully turbulent flow, usually sets a lower limit to the vertical-length scale for a model.

The capability to accurately replicate free-surface profiles has not been a critical concern for micro-models, as they have been used primarily to investigate bathymetry changes in loose-bed channels. However, similitude limits concerning flow profiles and patterns limit the extended application of micro-models beyond providing approximate, qualitative insights. A key issue to be investigated in the Corps study is whether micro-models simulate flow profiles and patterns with acceptably close accuracy for the purposes of designing river-training works.

5.2 Modeling flow and sediment transport in loose-bed channels

Before discussing similitude criteria for loose-bed modeling, it must be acknowledged that qualitative insights into the tendency of sediment to erode or accumulate at a site (e.g., in the vicinity of a river-training structure) can be obtained without express attention to similitude criteria. A hasty caveat in this regard is that scale and laboratory effects should not influence qualitative trends. Flow in the model need only be

sufficiently swift to move model bed particles. Also, for example, if a fixed model were designed primarily for determining the flow performance of a hydraulic structure like a water intake, the model might still be operated to obtain a qualitative evaluation as to whether local sediment accumulation or erosion problems might arise. The model's flow velocities (based on Froude-number similitude) may be sufficient to move sediment placed on the model's bed. To increase sediment mobility in the model, model flow velocities might be increased by trial. In such tests, the model sediment serves essentially as a sediment-movement tracer, facilitating delineation of potential regions of sediment accumulation or erosion. The utility of such tentative modeling depends, of course, on the experience of the modeler, and on the reliability of the information sought by the modeler" client.

Loose-bed modeling usually aims at simulating and illuminating any or combinations of the following processes:

1. Flow and, relatedly, bathymetry distribution in a channel;
2. Rates of sediment transport; and,
3. Local patterns of flow and sediment movement in the vicinity of hydraulic structures.

The micro-modeling limitations cited above for simulating flow in fixed-bed channels also prevail for loose-bed channels. But now the similitude criteria are not meaningfully expressed in terms of Froude number, though Reynolds number and Weber number remain directly pertinent. Parameters relating flow and sediment movement now are needed. The following discussion indicates the variables and the similitude criteria typically used for flow and sediment transport.

Variables. The significant variables influencing the fairly simple condition of uniform steady flow of water and transport of bed sediment in a channel with a bed of cohesionless spherical particles may be expressed functionally as

$$A = f_A(\rho, \nu, \sigma, d, \rho_s, B, R, S_o, g) \tag{6}$$

Here, A is a dependent variable. For the purposes of micro-modeling a river reach A might be the overall flow-resistance coefficient, f, thalweg sinuosity, ζ (zeta), or volumetric rate of sediment transport per unit width of channel, q_s. Particle properties specified are particle diameter, d (a substituted for surface roughness), and density, ρ_s. Uniform flow is defined in terms of its hydraulic radius, R, channel slope, S_o, as well as channel roughness, which here is characterized in terms of d.

Similitude Considerations. The variables in Eq. 6 can be combined to form several sets of non-dimensional parameters. A convenient set is

$$\Pi_A = \varphi_A\left(d\left(\frac{g\Delta\rho}{\rho\nu^2}\right)^{1/3}, \frac{\rho RS}{\Delta\rho d}, \frac{\rho_s}{\rho}, \frac{d}{R}, \frac{B}{R}, \frac{\sigma}{\rho g S R^2}\right) \tag{7}$$

Re-arranging the parameters can lead to alternate sets.

The first parameter in Eq. 7 is a dimensionless parameter relating particle diameter and fluid properties ρ and ν. The parameter is independent of local flow conditions, implying that strict similitude in modeling sediment movement requires the use of lightweight model sediment. As water properties ν and ρ cannot be reduced in scale when water is used to model water, and particle-size limits constrain scale reduction of d, ρ_s often is the only variable left to reduce. The last parameter in Eq. 7 relates surface tension to boundary or bed drag.

The second parameter usually expresses the ratio of the average or nominal bed drag to the submerged weight of the average bed-particle size. It is termed alternately (depending whose book you read) the Shields number, particle mobility number, flow intensity, particle Froude number, Fr_*, and a densimetric Froude number. It is useful for characterizing the condition of incipient motion of particles on a bed, and for describing the intensity of bed particle movement.

The density ratio ρ_s/ρ expresses the relative density of particle and water. The parameters d/R and B/R are as defined for fixed-bed flow.

When the volume rate of sediment transport into a reach is an independent variable, it may be expressed non-dimensionally and used to replace one of the other parameters in Eq. 7. For instance the volume rate of sediment transport, q_S, may be expressed non-dimensionally as $\frac{q_S}{\sqrt{g(\Delta\rho/\rho)d^3}}$. This parameter may be the dependent parameter Π_A of concern. Alternately, for example, if altered hydraulic radius, R, is the dependent variable under consideration for a channel-narrowing study, R/B may be the dependent parameter; with d/B and $\frac{q_S}{\sqrt{g(\Delta\rho/\rho)d^3}}$ being adjusted independent parameters in Eq. 7.

The parameters in Eq. 7 constitute a set of similitude criteria for flow resistance and sediment transport in loose-bed channels. The increase in number of similitude criteria increases the difficulty attaining model similitude. Clear identification and understanding of the essential processes of focal concern therefore are important. Practical concerns stemming from the difficulty in replicating the material properties of water and sediment at model scale dictate that some similitude criteria must be relaxed and that models be designed primarily on the basis of similarity of sediment movement. In quite a few situations, selective relaxation of criteria may not unduly compromise modeling results, because replication of extended water surface and bed profiles may not be crucial for simulating local patterns of flow and sediment movement. The differences in particle behavior, occurring over the size range of particles considered in a given situation, prescribe practical limits for loose-bed modeling. It is difficult to get the model sediment sufficiently fine and light without introducing the usually undesired effect of electrostatic forces between particles. For particles less than about 0.1 mm in diameter, particle

behavior becomes increasingly dependent on ionic forces rather than gravity. This concern may set a lower bound on model scale.

The essential similarity of sediment motion usually is assessed in terms of two flow and sediment-transport conditions that entail slightly different particle-motion criteria. One condition is the incipient motion and consequent bedload movement of particles comprising a loose bed. Similitude of boundary shear stress is the basis of a key similitude criterion for this condition, which subsequently is discussed in the context of flow over a planar bed, flow with bedforms, and sediment movement as bedload. Micro-modeling cannot explicitly satisfy the criteria in Eq. 7.

The second condition pertains to the movement, and possible settling, of particles suspended in a fluid, especially for suspended-particle movement in highly turbulent flows. The fall velocity of suspended particles is used to develop a critical similitude criterion for this condition.

As with modeling flow profiles and patterns, the central issue to be investigated is whether micro-models simulate profiles and patterns of water and sediment movement (and, thereby, bathymetry) with acceptably close accuracy for practical engineering purposes. To address this issue, scale and laboratory effects should determined. Also, the requisite levels of accuracy and reliability should be determined for engineering design. Virtually all the concerns listed in Appendix II (Topics) revolve around this central concern.

6. Scale-Effect Tests

Scale effects are the unwanted side effects produced in a model by variables not scaled in accordance with similitude requirements. They quickly arise, because modeling usually does not satisfy more than one criterion for dynamic similitude of flow or fluid transport. Scale effects increase in severity as the ratio of prototype to model size increases or the number of physical processes to be replicated simultaneously increases.

As micro-models primarily are intended to reveal local trends in water and sediment movement, it is important that scale-effect tests be conducted to determine the extents to which relaxation of the parameters in Eqs 2 and 7 alter trends. In other words, the key issues to be investigated concern the extents to which flow patterns are affected by laxity of similitude criteria for Shields number, Reynolds number, Weber number, relative roughness, and flow aspect ratio (or vertical distortion). The proposed study should systematically address these issues by means information already published, conduct of laboratory tests, then comparison with available field data and obeservations.

The similitude criteria in Eqs 2 and 7 form a rational basis for properly posing and addressing many of the issues listed in Appendix II (Topics). The following responses to the issues repeatedly link back to consideration of the parameters in Eqs 2 and 7:

1. This question is not properly posed. Froude number is not really an effective parameter for loose-bed flows.

2. Work with the parameters in Eq. 7.
3. Work with the parameters in Eq. 7 For example, it would be interesting to determine how and when relaxation in similitude of aspect-ratio, B/R, and relative roughness, d/R, influence thalweg sinuosity and flow distribution.
4. The extent of quantitative use of the model depends on the extent to which similitude criteria are taken into account. Throw out the similitude criteria, then you also throw out the quantitative use of model results.
5. The veracity of the flow patterns depends on the limits to which the parameters in Eq. can be relaxed.
6. Several laboratories (notably the Waterways Experiment Station) have the requisite data, but meaningful comparisons can only be made if similitude criteria are taken into account.
7. The techniques entail consideration of similitude criteria, such as in Eqs 2 and 7.
8. This is an overly simplistic approach. May I suggest you see the Technical Note by Ettema et al. (1997) on bridge scour. Factors like relative roughness play a major role in scour depths, for instance.
9. Work with the similitude criteria to conduct sensitivity tests on scale-effects.
10. This is a useful way to compare model and prototype behavior.
11. This is a useful way to compare model behavior at two scales. Similitude criteria need to be used.
12. This is both a laboratory-effect issue and a scale-effect issue. The overall issue seems not well posed, though.
13. This issue reinforces the point that similitude criteria are important. Abandon them, and you abandon reality.
14. This issue is inadequately posed.
15. This issue is inadequately posed.
16. Issues related to water slope and associated water drag on the channel bed should be evaluated in the context of similitude criteria.
17. Work with the parameters in Eq. 7.
18. Work with the parameters in Eq 7.
19. Work with the parameters in Eq. 7.
20. Work with the parameters in Eq. 7.
21. Work with the parameters in Eq. 7.
22. Work with the parameters in Eq. 7.
23. Work with the parameters in Eq. 7.
24. Work with the parameters in Eq. 7

Many of the issues require resolution by means a series of scale models of the same prototype built at different scales. In this regard, a test series of interest would be to examine scour at the end of a spur dike extending into the thalweg of a channel bend. The spur (possibly in conjunction with the existing spur dikes) likely would move the bend thalweg back towards the center of the channel, away from its current position, while maintaining a similar bend radius and deflection angle, if the channel were sinuous-braided morphology. Two questions to be examined might be –

1. How does one accurately quantify the combination of the local scour at the spur nose

and the bend scour for the either existing channel alignment or for the alignment defined by the spurs?

2 At what scales and vertical distortion do models no longer accurately replicate the scour combination?

7. Laboratory-Effect Tests

Laboratory effects arise because limitations in space, model constructability, instrumentation, or model operation impede precise replication or measurement. They also arise from incorrect replication of boundary conditions and prototype materials. As micro-models primarily are intended to reveal trends, it is important that tests be conducted to determine when laboratory effects alter trends.

The following laboratory effects should be considered for investigation:

1. Flow and sediment recirculation. The present design of micro-models may not treat sediment inflow rate (or $\frac{q_S}{\sqrt{g(\Delta\rho/\rho)d^3}}$) as being independent of conditions in the channel reach modeled; e.g., a higher sediment load out from the model seems to result in a higher sediment load entering the model.
2. Water-level regulation in the model. As micro-models are quite short and have exaggerated flow velocities, water-level drawdown at the model tailgate influences flow velocities over a substantial portion of the modeled flow. This concern clouds findings on flow and bathymetry processes in the downstream portion of micro-models.
3. Angle of bed sediment repose. Eq. 7 does not explicitly include angle of static sediment repose. For typical alluvial sediments, angle of repose can be related directly to sediment size. However, this may exaggerate local flow depths, and thereby concentrate flow in parts of a micro-model channel where a local scour hole encroaches excessively across a channel.

8. Concluding Comments

First, let me apologize for the length of this review report. The foregoing sections on similitude and related matters considerably bulked up the report. Those sections, though, helped me structure my thoughts on the proposed plan of study.

Micro-models have their place as a design aid for river engineering. They potentially can yield preliminary, qualitative, and approximate insights into the larger geometric-scale processes associated with flow and fluid-transport processes. Their wise use, though, requires due consideration of similitude criteria and consequent scale and laboratory effects. Additionally, their wise use requires a sound knowledge of the processes being modeled and of the appropriate levels of design accuracy and reliability needed for the river-training works whose performance they are simulating. As with all hydraulic models, the bottom line for micro-models is that the limits of their applicability fundamentally depend on the extents to which they meet similitude considerations and on the level of risk the model user is prepared to assume.

9. References

Ettema, R., Melville, B. W., and Barkdoll, B. (1998), "Scale Effect in Pier-Scour Experiments," American Society of Civil Engineers, Journal of Hydraulic Engineering, Vol. 124, No. 6, pp639-642.

Freeman, J. R. (1929), Hydraulic Laboratory Practice, American Society of Civil Engineers, New York, NY.

Warren Mellema

WARREN J. MELLEMA, P. E.
CONSULTING HYDRAULIC ENGINEER

12333 Shamrock Road Omaha, Nebraska, 68154
Tel (402) 333-7648 Fax (402) 333-1799 e-mail midwest_inter@compuserve.com

Dr. Steve Maynord
Dept. of the Army, WES
3909 Halls Ferry Road
Vicksburg, Ms. 39180-6199

28 May, 1999

Dear Steve:

Enclosed find my comments concerning the Micro-Model and associated topics. I trust that you will find the comments to be of value to you as you proceed on this interesting project.

Please feel free to contact me if you have questions regarding my comments. I have attempted to respond to the basic issues raised, and have proposed several items for your consideration. I am available to assist on the computation procedure of the "Einstein evaluation procedure" discussed in my comments is such assistance is needed, but did not attempt to go into detail in the procedure at this point in time, plus I have more than utilized my allotment of hours for this project under this proposal.

I would appreciate receiving copies of the other consultants reports when they become available if possible. It was a pleasure working with you on this project.

Take Care!

Warren J. Mellema, P.E.
Consulting Hydraulic Engineer

COMMENTS: MICRO-MODEL CAPABILITIES AND APPLICATIONS

1. General Considerations

A. The general approach used in the overall development of the Micro-Model is an attempt to reproduce those channel features that are of most interest and importance to the practicing river engineer. The development and operation of a mobile bed model presents the modular with a practical dilemma,; that of attempting to construct a model that will reproduce those channel features most important to him in sufficient detail in a reasonable time and at a cost without compromising the results. These practical constraints usually force a relaxation of model scales and distortions, as the often conflicting demands of time, scale and cost simply cannot be achieved in a laboratory environment

B. The overall problem of the modeler boils down to one of attempting to be able to conduct tests in a laboratory environment that will reproduce those stream qualities that one deems most important, knowing full well that certain features in the model do not and cannot reflect reality. One can feel comfortable with this philosophy as long as the model results which are known to be out of scale do not interact and unduly influence those channel features that are most important to us, and that changes in model operating characteristics (discharge, velocity, sediment transport, etc.,) reflect reality in the prototype. It is the latter that often determines the fate of the model exercise, for if changes in the model operating characteristics cannot be validated and correlated to the prototype, the results remain questionable and of limited value.

C. The general concept that various size rivers can in fact be considered as models of larger rivers;, that small rivers are in fact models of medium size rivers, etc., and when carried to the extreme, that laboratory models are in fact miniature rivers has considerable merit, and certain channel characteristics seem to follow basic relationships regardless of their size, and is really the basis of basic similitude criteria. The question that confronts us is how far down the size scale can these relationships in fact be carried without compromising the results. Distortion in scales in and of themselves do not compromise the result as long as these distortions do not begin to interact with each other and impact those features of most interest to the modeler. Certain channel features are easily scaled down and mathematically determined, whereas other channel features and characteristics are not easily determined either mathematically or physically. We can easily scale down the horizontal and vertical features, use lightweight material, etc., however, as long as we continue to water as the fluid (which is not scaled), we at some point will approach the limit at which we can have confidence in the results.

2. Similarity Criteria for an Alluvial Stream

A. The issue of determining similarity criteria for and alluvial stream has plagued researchers for years, and remains a constraint even today. The developers of the Micro-Model are certainly to be commended for their attempts to approach this issue using some innovative techniques, using scales and procedures seldom used to date, an a attempt to gain practical insight into the impact of mans activities on one of the largest rivers in the world. The question remains,

however, as to how to interpret the results of a laboratory model using micro dimensions when compared to a river with macro dimensions.

B The selection of scales for an undistorted fixed boundary model involving only the study of flow characteristics is usually a simple, forthright procedure. The major constraints are the area available, the minimum depth of flow required in the model, and sufficient capacity for supplying fluid to the model. Distortions may be introduced with almost equal facility, the vertical scale may differ from the horizontal , or the slope may be distorted. Dynamic similarity is obtained by maintaining a constant Froude Number between the model and prototype. The only factor normally requiring adjustment by judgment or by trial and error is the roughness of the model boundary.

C. The introduction of a mobile boundary in the model immediately complicates the procedure. If the scale reduction is appreciable, it is impossible to reproduce a model scale the physical and dynamic dimensions of the prototype. It becomes necessary to accept the fact that certain scale ratios must be varied in a manner such that the end result is acceptable. The allowable variations may depend largely on the factors to be studied in the model.

D. Distortions in the scales are usually necessary when modeling a natural alluvial stream. Generally if one attempts to model a wide, shallow watercourse and still retain the principles of true geometric similarity, the resulting model either becomes too large for the laboratory, or the depth of flow and the sediment size have to be considerably decreased. This causes the model surface to act as a hydraulically smooth boundary with viscous forces dominating both the water and sediment behavior. This often happens in very small shallow flume studies.

E. If the model is designed to study only the general pattern of bar formations at the confluence of two streams, or even to study the effect of channel changes, generally the variations may be accomplished in the type of material used for the model stream bed, the model discharge, the model slope, and the time scale. The flow velocity in the model must be adequate to transport the model bed material, although not necessarily at the corresponding prototype rate. This is accomplished primarily when selecting the model discharge and slope. The disparity in transport rates is taken into account by varying the time scale. This latter variation is usually a matter of trial and error, reproducing known prototype discharges until the model reproduces the known corresponding prototype channel conditions.

F A model designed to reproduce almost all of the functions of the channel, including transport rates, involves an extremely complicated design. There are computation procedures available where these functions can be approximated, accepting certain functions as controls and varying the other functions to an acceptable degree. It will usually be found that a model designed on the basis of these computations must be re-adjusted by trial and error procedures. It may be found that the vertical dimensions of the channel bed forms or of the scour patterns will be greatly exaggerated, and this may affect the flow characteristics so that the model must be operated at a vertical scale differing from that initially chosen. A discussion of a moveable bed model that was designed and operated in the above manner can be found in the following publication:

3. Micro-Model Operation and Observations

A demonstration of a micro-model for a reach of the Mississippi River was conducted on May 18, 1999 in the St Louis District River Engineering Center. Some general observations of the facility and how it was operated are as follows.

A. Calibration of the model is based almost entirely on its ability to reproduce some fixed river topographic condition, and basic model parameters such as slope, discharge, velocity, sediment load, Froude Number, Reynolds Number, etc., are adjusted as required until the desired bed topography is achieved.

B. The model per se in locked into a predetermined plan form, with no opportunity for three dimensional freedom to meander outside of this boundary.

C. The pre-determined longitudinal scale appears to be closely adhered to, whereas the vertical scale is adjusted as required to reflect a known bed configuration.

D. Virtually no material is moving in suspension, and nearly all moveable material is transported as bed load.

E. The actual size of the plastic beads used a bed material was not readily available, however, if scaled according to the length scale would be approaching boulder size material.

F. There is no attempt to match a given water surface elevation or slope, and the water surface at the lower end of the flume falls freely over a sharp crested weir. This results in a drawdown on the lower portion of the model, impacting the lower portion of the model basin.

G. Several locations were observed where no bed material was present on the bottom of the channel, thus raising the question as to the ultimate depth of scour in these locations .

H. The size and extent of the scour holes around and downstream from control structures or sharp bends in the model channel appeared to be out of proportion, both laterally and longitudinally, compared to other model features.

I. There is apparently no attempt to measure and/or record basic hydraulic data on the individual model runs (velocity, depth, slope, etc.).

J. Although attempts are made to reproduce an annual hydrograph, the rate and magnitude of the rise associated with these variations in discharge appears to be arbitrary, and do not conform to either the assumed vertical scale or the stage discharge relationships of the prototype

K. Calibration procedures used involve adjusting basic parameters as required in order to produce the desired bed configuration

L. Reynolds Number in the model was not readily available, however, flow did not appear to be in the turbulent range as would be found in the prototype

M. Although the model is stated to represent a closed system circulating both sediment and water, the use of a collection tank, a collection area at the downstream end, and an approach area leaves this issue questionable. It is not clear how one knows when equilibrium conditions in fact have been achieved.

N. Observations of previously completed model studies compared to the prototype conditions were impressive, as it appears that through adjustment of model parameters one is able to force the model to reproduce general prototype bed configurations. The degree to which changes noted in the model due to modifications in either structural configurations or channel alignments are directly transferable to the prototype is uncertain.

O. There was no observable dune or ripple movement along the bed of the model, - all sediment movement appeared to be by sliding of hopping along the bed of the model.

4. Model Reliability

A basic question that needs to be addressed in river process models is the degree to which the model results are transferable to the prototype. The closer that all natural phenomena are to reflecting true similitude relationships, the more confidence one can have in the model results. Models that are forced to reproduce a pre-determined set of conditions are at a distinct disadvantage, as there is no reliable means by which one can transfer the often highly distorted relationships that one observes in the model to the prototype. Following are some suggested evaluation procedures that can assist the modeler in determining if in fact his model results have any practical significance to the real world.

A. One method that has considerable merit is to separate the hydraulic radius into its component parts, R' and R", where R' is a measure of the hydraulic roughness resulting from the size of the grains that form the bed, and R" becomes a measure of the roughness resulting from the channel bars and other form roughness, thus R' + R" = R Total (Area/Top Width). The ratio R'/R Total between the model and the prototype should be comparable between the model and prototype if one hopes to achieve the proper roughness relationship between the two. These relationships are important in modeling streams where considerable sediment transport occurs. This subject is discussed in detail in the following publication

Einstein & Barbarossa
"River Channel Roughness"
Transactions, ASCE, Vol 117,1952

B. A second relationship which can be used to indicate similarity between model and prototype is the intensity of shear on the bed of the stream. ψ', and can be determined from the following relationship:

$$\psi'' = \frac{(S_s - S_f)\, d_{35}}{S_f\, R'\, S}$$

Where
- ψ' intensity of shear on the bed
- S_s specific gravity of the bed material
- S_f specific gravity of the fluid
- d_{35} the grain diameter at which 35% by weight is finer
- R' hydraulic radius caused by the bed grains
- S energy slope

Einstein indicates that for the model and prototype to exhibit similar sediment transport characteristics near the bed, the value of ψ'_p / ψ'_m should be unity. Although this is seldom accomplished in distorted small models, the use of a light weight material as the bed material greatly assists in minimizing the distortion between model and prototype. An additional reference that ties these functions together for a number of rivers and models is as follows:

"Moveable Bed Model for Alluvial Channel Studies"
By: Harrison & Mellema
Proceedings, 12 Congress of IAHR, Vol 1, June 1967, p202

C. A third comparison that is very useful is to evaluate and compare the lateral flow distribution across the channel, both for the model and prototype. This can be normalized by comparing the unit discharge across the channel as a percentage of the total unit discharge.

D. If channel meandering within the high banks is a major stream characteristic , the model should attempt to exhibit this also, therefor the model velocity and depths should be able to transition between erosion and deposition phases of flow. An example of this type of analysis can be found in the publication by Harrison & Mellema above.

E. If deposition in the dike fields at various flows is a stream characteristic, the model should be operated at velocities and have material in suspension which will permit this to happen. The deposition phase should be treated equally and with as much importance as the erosion phase.

F. The model should be able to demonstrate equilibrium conditions from a sediment transport standpoint. This translates into a situation where the sediment in should equal the sediment out, and one should be able to demonstrate this by running the model an extended period of time with minimal change in bed formations, elevations, etc.

G. The vertical scale should be large enough to make measurements, both longitudinally and vertically, to ensure that the scour action around river control structures do not dominate the bed forms. Scour hole dimensions tend to be a function of the vertical scale, and can frequently dominate the bed forms in the model

H. A model that is verified should be able to reproduce two or more prototype conditions, with no change in the model scale relationships, (Q, Vel, Length, etc). Ideally, one of these conditions should be with and one without channel control structures

I The model should be long enough to get a steady state profile that produces normal depth throughout the length of the model

J. The discharge rating curve relationship between the model and prototype must be related and in general have the same shape in order to have confidence in the results

5. Issues Concerning Micro-Models

Micro-models of the scale demonstrated raise a host of practical and technical issues. Several of these issues are discussed below, and relate to the "list of topics" distributed at the 18 May meeting in St. Louis. These comments are based on the authors background and experience in dealing with moveable bed models.

A. Observed velocity distributions in the vertical are probably not reliable or even measurable, and thus are probably only representative of grain roughness, and therefore not directly comparable to normal velocity distributions measured in and open channel. This could easily be verified and evaluated in a straight flume test with runs at various Froude Numbers, depths, etc, all the way down to mico-model values.

B. Tests should be run throughout the full range of flows expected in the prototype, with the possible exception of high overbank flows. Running tests at a series of steady state discharges may be more appropriate and easier to evaluate than by running a hydrograph of uncertain scales.

C Scour hole dimensions in a moveable bed model tend to be a function of the vertical scale and underwater angle of repose of the bed material, thus tend to be exaggerated relative to the other model topographic features.

D. Transposing model results from a distorted model that deviates widely from conventional similitude criteria is most difficult, as all model features tend to act independently and do not respond in the same proportion and relationship as found in the prototype.

E. The lateral flow distribution within the model can be forced to reflect the prototype for a given set of conditions, however, subjecting this set of conditions to a higher or lower discharge would not necessarily reflect what would happen in the prototype. This can easily be demonstrated by comparing models of varying distortions.

F. A comparison between model and prototype bathymetry should be conducted at more than one condition (stage & discharge), to have validity. This can best be accomplished by comparing a reach both before and after river control structures have been installed.

G. Scour hole dimensions off the end of dikes or around the outside of bends are probably exaggerated in all distorted models, but even more so in the case of a micro-model. This is partially due to the dis-similar relationship between the relative roughness between the model and prototype bed material and in the construction material used to represent the dikes.

H. The impact of using and exaggerated Froude Number and distortion used in the micro-model can only be accomplished through a systematic series of tests relating the significant similitude criteria to model results.

I. Lateral velocity comparisons between the prototype and micro-model at various longitudinal scales would be a useful and beneficial exercise, and assist in building confidence between the model and prototype.

J. Comparing micro-model results to undistorted model studies represents a valid laboratory comparison to better understand the influence of model distortion on model results.

K. The sediment in sediment out concept in a model represents a valid verification process, and is frequently utilized in model investigations as an indicator of equilibrium conditions.

L. Micro Models should as a minimum reflect bank full conditions found in the prototype, as it is often that these high flows influence and are responsible for the actions found in back chutes, etc., where deposition of sediments is of primary importance.

M. Energy and water surface slopes throughout the model should be stable over time, and parallel to each other and the bed slope.

N. Models that are properly calibrated should be reasonably stable throughout the full range of discharges and stages, and should be tested for low, medium, and high flows. If the model topography changes dramatically or becomes unstable at high discharges, the results are questionable.

O. Highly distorted models have a limited direct relationship to the prototype, particularly when addressing issues such as sediment and time. A logical first step is to attempt to scale the discharge parameters using traditional Froude relationships, and adjusting the time scale until one obtains the desired result. The time scales for water and sediment in a distorted model are not directly comparable, as velocity and transport rates and relationships between the model and prototype do not follow strict similitude criteria. This in turn impacts all subsequent hydraulic and sediment relationships such as slope, model discharge, hydograph shape, (both magnitude and shape), velocity, etc. This does not imply that one cannot run a hydrograph in the model.

however, there is no rational way of determining with the extent of the hydrograph or how to properly interpret the results of such an exercise. Bed configuration changes resulting from changes in the model hydrograph are primarily an indicator of how the model responds to changes in stage and discharge, however, no direct relationship exists on how to transpose what one observes in the model to the prototype when virtually none of the basic parameters are properly scaled according to similitude criteria

P. The sediment grain size in a model should ideally consist of a graded mixture of sizes that will be transportable at model velocities both as bed load and as suspended load. A grain size mixture that is only transported as bed load does not and cannot accurately reflect sediment processes in areas where deposition due to material in suspension is likely to occur (back chutes, etc.). Material that moves primarily as bed load can dramatically influence the overall roughness relationships in the model, and thus influence the shape of the resulting bed formations. This condition is more representative of a mountain stream consisting of boulders with steep slopes and Froude Numbers approaching 1 rather than of a sand bed stream at sub-critical flow conditions.

6. Proposed Scope of Study

Following are comments on the proposed studies designed to more fully understand and identify the capabilities and limitations of the micro-model.

A. Component A of Proposed Study

1. Comparisons between previously conducted model studies and prototype promises to be a worthwhile and rewarding exercise. It is suggested that the selected study reaches cover as wide of array of prototype conditions and model scales as possible in order to determine the relationship between modeling techniques (scales, distortions, etc.) and corresponding results. It would be advantageous if the comparisons not only concentrate of observed topography, but also attempt to compare and relate the flow distribution across the channel at key locations in the model and prototype.

2. It is suggested that comparisons be made of both pre and post construction conditions in the prototype if such basic data is available, which will assist in gaining insight and direction into how well the model actually was able to determine the channel response as a result of the installation of various regulation works. A good record of historical flows since construction will be required to evaluate this data and make meaningful comparisons

3. An analysis of how and where these past studies fits on the Einstein and Barbarossa shear charts (see par 4A & 4B) is suggested - in order to determine how and to what extent the various shear components fit with other rivers and model studies. This analysis is one of the few known methods which addresses this issue in a forthright and technically sound manner, and would assist greatly in building confidence in the modeling process

B. Component B of Proposed Study

1. This series of tests should prove to be very helpful and give insight into the impact of model scale relationships relative to the bed material selected, its impact on channel roughness, and its impact on the channel topographic features.

2. It is suggested that flume tests be conducted that "bracket" the velocity and depths that are capable of moving sediment,- i e.: tests should be run that result in little or no movement, tests at normal or average movement, and tests at high rates of transport. These tests will demonstrate how these factors impact the bed topographic features, and assist in separating the roughness into its component parts. They will also assist in giving insight into the correct set of model conditions (velocities, depths, Froude Number, etc.) to operate and be able to achieve both scour and fill through the river reach as the case may be. It is essential that all pertinate hydraulic data be collected to permit one to calculate basic hydraulic and similitude functions.

3. Tests should be conducted to evaluate the impact of various time scales on the resulting bed forms. This will assist in determining how to properly evaluate and compare tests when using a systematic hydrograph vs tests conducted using only a series of steady state discharges. Since changes in water depth in a distorted model in effect change the vertical scale and resulting distortion, the time and extent of a subjected hydrograph can dramatically influence model results. This is an important question that needs to be systematically addressed in order to gain some measure of confidence in how to interpret model results and translate these data to the prototype.

4. It would be advantageous to conduct the above tests using various grain sizes - in order to possibly arrive at a size and gradation that minimizes the roughness due to the grains in the model. The size of the particles in the micro-model appear grossly out of scale in comparison to other model features, and attempts to minimize this distortion would be desirable. Tests to determine grain roughness can best be evaluated in a straight flume under controlled conditions where all pertinent hydraulic parameters can be observed and monitored. A visual observation of the bed configuration is not necessarily the overriding factor in the selection of the proper bed material in the model.

C. Component C of Proposed Study

1. This component promises to be most enlightening if conducted in a systematic manner. Since more than one "energy level" will be investigated, it is reasonable to not change or adjust any scale relationships between high and low flows. This will be an excellent test of the models reliability to reproduce the prototype at a range of discharges, depths, and velocities.

2. The time scale should be varied to determine if in fact the model has established equilibrium conditions with the sediment movement and bed form development.

3. If possible, the model should be calibrated against a pre-construction condition, then structural changes made in the model, followed by a post construction condition, with no

changes in model slope, Q, etc. A model that is in fact in equilibrium should demonstrate a ability to reproduce prototype conditions at more than one discharge.

4. It is suggested that all pertinent hydraulic and physical parameters be measured and determined in these tests, monitoring such things as scour hole dimensions, slope, velocity distribution, etc.

D. Suggested Study Component D

Although the above three components are necessary and will provide valuable information from which to assess the micro-model, an additional modeling approach is submitted for your consideration. This approach is to conduct a systematic evaluation of the impact of various model scales and distortions only on the "scour" aspect of distorted models using light weight material. As stated previously, it is believed that the dimensions of scour holes and scour in general appears to be out of proportion to other topographic features in the model, and often tends to dominate the bed forms. In order to test and/or demonstrate this concept, it would seem appropriate to devise a straight forward series of tests in a straight flume containing only one transverse dike structure, which in turn would be subjected to a structured and controlled series of tests where the horizontal and vertical scales are systematically changed and subjected to various discharges and Froude Numbers. The primary focus of these tests would be to measure the size, depth and extent of the scour hole that develops from the riverward end of the structure. This kind of systematic test would assist greatly in evaluating the impact of various scales and distortions on the scour aspect of the bed formations, and give important insight into how to interpret and compare model studies conducted at varying distorted model scales. These tests would not necessarily assist in determining how to transpose data to the prototype, but would give valuable insight into the issue of the reliability of the erosion and scour process observed in distorted moveable bed models such as the micro-model. The use of various bed grain sizes and specific gravity of these materials would be a logical extension of these tests if possible.

7. Potential Uses of a Micro-Model

Distorted river models have been used extensively over the years to evaluate a host of river related issues, with varying degrees of success. The true test of a model is its ability to reproduce those dominate river characteristics that the modeler wishes to evaluate, and this of coarse is accomplished by demonstrating its ability to in fact reproduce principle stream characteristics under a variety of discharge conditions. An alluvial channel (a channel whose bed is compose of non-cohesive sediment that has been or can be transported by the flow) by its very definition is one that transports sediment both as suspended load and bed load, and it therefore becomes and essential element of the modeling process. Uses of a model where the entire sediment process consists of bed load is therefore restricted to those cases where the suspended load does not play a role or impact the question at hand. A second constraint is presented where the distortion in scales are so exaggerated that they begin to interact with and influence each other. A third constraint involves a distortion in basic hydraulic factors associated with stage/discharge relationships which are not in accordance with or bear any resemblance to the prototype.

Following are several potential uses of the micro-model, and a brief discussion of the potential uses and adaptability of such a model. These discussions are based upon the authors background, experience, and observations over the years, and are not based on experience in operating models at the scales and distortions used in the micro-model.

A. Navigation Channel Design

Models of this scale can probably be used to demonstrate general locations of scour and fill, however, the extent and level of these deposits and scour holes are probably not to scale and not directly transferable to the prototype. This is particularly true in the scour mode, and /or in locations where the sides and bed of the model are "fixed" and not transportable.

B. Dredging Studies

The micro-model can probably be used to demonstrate the temporary impact of a dredge cut within a channel, however, there is no known way of transferring this to the prototype, since the time scale of the sediment transport along the bed of the model would be indeterminate.

C. Small Rivers - Bed Scour

If scour is the primary issue, a undistorted vertical to longitudinal scale is generally required. Scour tends to response to the vertical scale only, and the underwater angle of repose of the bed material.

D. Outdraft Studies at Locks

This issue appears to be more directly related to surface velocities and structural and channel alignment, and therefore may be an area where a micro-model can be used as an indicator. Vertical to horizontal scale ratios and distortions should be kept to a minimum.

E. Closure Structures.

The impact of closing off major chutes, particularly those where considerable flow passes at normal discharges may have potential to be observed and evaluated in a micro-mode. If, however, the major transport mechanism in the chute consists of suspended sediment, the model must be capable of transporting and depositing suspended sediment at model velocities.

F. Build Islands out of Dredge Spoil

The model could potentially be used to demonstrate the impact of constructing islands out of dredge spoil, however, the stability and ultimate location of these deposits would probably not be directly transferable to the prototype.

G. Side Channel Openings

Scour and deposition in side channels is highly dependent upon the sequence of flows to which they have been subjected - (i.e. High flows may scour them out, low flows may result in low velocities and deposition. The impact of high flows passing through a chute can possibly be demonstrated with such a model, however since the model does not carry any significant material in suspension, it is doubtful if the deposition phase of the process can be demonstrated with any degree of reliability.

9. Summary and Conclusions

A. The Micro-model technique represents a unique and innovative tool to evaluate and demonstrate alluvial channel processes. Its use as a design tool is being evaluated, and the proposed tests will provide valuable assistance in determining the applicability of the model for various river issues.

B. The highly distorted scales make transformation of model data to prototype conditions most difficult and in some cases indeterminate. This issue is being partially addressed in the proposed studies, but still may not fully answer all of the questions regarding this complex issue.

C. Investigations are encouraged to fully document all proposed studies, and gather all pertinent physical and hydraulic data in order to determine and compare model results with other studies and investigations. This is essential in order to gain confidence in model results.

D. Modelers should be careful not to unduly "force" the model to reproduce a set of river conditions. It is recognized that this can be accomplished physically by adjusting such things as slope, scales, etc., however this complicates interpretation of model results when subjected to other flows. It the model is in fact a miniature river, it should have the same degrees of freedom as a river. If these degrees of freedom are constrained or removed , one no longer has a model of a river, but a laboratory flume waiting for a river to match it.

E. The micro-model constructed and applied to date obviously has an ability to demonstrate the impacts of how bed forms are formed in a micro-model environment, and as such appears to be a great tool for demonstration purposes.. Its use as a design aid is still being evaluated, and this entire experience should be a giant step forward in answering some of the issues surrounding its reliability as a design aid.

Gary Parker

REVIEW OF MICRO MODELS OF RIVERS

Review by Gary Parker
St. Anthony Falls Laboratory University of Minnesota
June 30, 1999

Introduction I was asked to serve on a panel of reviewers of micro models of rivers. I read the following reports in this regard:

1. Sedimentation and navigation study of the lower Mississippi River at the White River confluence, miles 603 to 596. Hydraulic micro model investigation. 1998
2. Sedimentation study of the Mississippi River Marquette Chute. Hydraulic micro model investigation. 1997
3. Navigation study at the approach to Lock and Dam 24, Upper Mississippi River. Hydraulic micro model investigation. 1998.
4. Physical sediment modeling of the Mississippi River on a micro scale. M.S. thesis by Robert Davinroy. 1994.

In addition to the above, I visited the Applied River Engineering Center of the Army Corps of Engineers, St. Louis, on May 18, 1999. At that time I had a chance to view several micro models in operation. This report represents my evaluation of their scientific validity and engineering usefulness.

The configuration of the micro model The micro model is built into a standard table with a length and width on the order of meters. The surface of the model is horizontal except where the river is placed. Aerial photography is placed to the correct scale over the flat surface. The desired river geometry is cut into the material that makes this surface. In the models that I inspected no attempt had been made to accurately model overflow across the entire floodplain. Many of the larger point bars were, however, modeled in such a way as to allow for some floodplain effects.

The bed of the river is rendered erodible using a lightweight granular material made of plastic urea. Water and sediment are recirculated using a garden pump and an ingenious scheme to maintain water surface elevation in the pump sump while recirculating the sediment. There was no gate at the downstream and of the model. Discharge, stage and bed elevation could be measured, the last of these with a three-dimensional digitizer.

Various engineering works were tested in the micro models. These include dikes, bendway weirs, navigation locks and chevrons, as well as the effect of removing existing structures.

A key feature of the micro models that I reviewed was extreme distortion between the horizontal and vertical scale, with values ranging from 10:1 to 16:1. In addition, the models appeared to be strongly tilted. This conclusion is based on the following observation. Although river slopes were not quoted for the reaches in question, my understanding is that they are likely in the range 1×10^{-5} to 5×10^{-5}. Even with a distortion of 16:1, this would yield a slope of no higher than 8×10^{-4}, or an elevation drop of 1.6 mm over 2 m. The bed slope in the models that I saw appeared to be substantially higher than this.

Strict modeling criteria A more or less standard technology has been developed in for movable-bed physical models of rivers. It is useful to review this technology to provide a basis for evaluating micro models.

Modeling of steep mountain streams The ideal movable-bed model is undistorted, and obeys precise geometric and Froude similarity. The sediment has the same specific gravity as the natural sediment and reproduces the same relative grain size distribution. The imposition of Froude and geometric similarity ensures that the nondimensional Shields stress in the model is the same as that in the field for any given flow. Since bank and floodplain erosion and deposition cannot usually be accurately modeled at small scale, these are normally fabricated out of nonerodible material such as concrete or polyurethane foam.

Such physical models are routinely built and operated. The kind of stream for which they work best is coarse-bedded (gravel or coarser) steep mountain streams. In order to see how this works, it is useful to introduce a few terms and cite an example.

Let B denote mean bankfull width, Q denote bankfull discharge, H denote mean bankfull depth, S denote mean bed slope and D denote the geometric mean grain size of the material exposed on the surface. In addition, let λ denote the scale ratio (model: prototype). The imposition of Froude and geometric scaling yields the relations

$$(S)_m = (S)_p$$
$$(B)_m = \lambda(B)_p$$
$$(H)_m = \lambda(H)_p$$
$$(D)_m = \lambda(D)_p$$
$$(Q)_m = \lambda^{5/2}(Q)_p$$

where the subscript m denotes model and p denotes prototype. An example scaling with λ = 1:20 is given below.

Table 1

Parameter	Q	B	H	D	S
Prototype	120 m^3/s	25 m	1.5 m	80 mm	0.005
Model	67 l/s	125 cm	7.5 cm	4 mm	0.005

The construction of such a model is quite feasible. Both the model and the prototype have a bankfull Froude number **Fr** of 0.83.

The morphology of such streams is typically created by bedload transport. The overall average dimensionless Shields stress τ^* and shear velocity u_* at bankfull flow are given by the relations

$$\tau^* = \frac{HS}{RD} \qquad u_* = \sqrt{gHS}$$

where g denotes the acceleration of gravity, $R = (\rho_s/\rho - 1)$, ρ_s is sediment density and ρ is water density. The imposition of Froude and geometric similarity ensures that the Shields stress in the model and prototype are the same. This for the most part ensures that there should be reasonably good scaling in sediment transport. In order for this to be true, however, the flow needs to be in the fully rough turbulent regime, according to which

$$\mathbf{Re_*} = \frac{u_* k_s}{\nu} > 70$$

In the above relation $\mathbf{Re_*}$ denotes the roughness Reynolds number, k_s is the roughness height, which can be loosely estimated as equal to 4 D in a gravel bed stream and ν denotes the kinematic viscosity of water. Assuming a water temperature of 20°C in both the model and the prototype, the prototype value of $\mathbf{Re_*}$ is 8.7×10^5 and the model value is 970. This places both flows in the turbulent rough regime.

Modeling of suspended load in steep mountain streams It thus follows that steep coarse-bedded mountain streams can often be modeled with an undistorted Froude model. Although the morphology of such streams is governed by gravel, they often transport copious amounts of sand that find homes in the bed in the interstices of the gravel and in zones of slack water. Precise geometric scaling of the sand is usually not possible. For example, if the sand size is 0.3 mm in the prototype the corresponding size in the model at a scale ratio of 1:20 is 15 microns. Material of this size can be expected to be cohesive, and therefore would not provide a good model of sand transport in a mountain stream. It is possible to find material with this size that is intrinsically noncohesive (e.g. silica flour). When used in a hydraulic model, however, it quickly develops a biofilm and becomes effectively cohesive.

The way out of this dilemma is suggested by mode of transport of sand in a gravel-bed stream, which can be expected to be predominantly suspension. In the case of sediment suspension, the ratio u_*/v_s of shear velocity to sediment fall velocity is a better dimensionless parameter on which to base scaling than the Shields stress. It is thus possible to impose the condition

$$\left(\frac{u_*}{v_s}\right)_m = \left(\frac{u_*}{v_s}\right)_p$$

Using the example of the Table 1, the following can be deduced using a standard relation for fall velocity and the assumption that the specific gravity of both prototype and model sand is 2.65:

Table 2

Parameter	u_*	D	v_s	u_*/v_s
Prototype	27.1 cm/s	0.3 mm	3.90 cm/s	6.95
Model	6.07 cm/s	0.11 mm	0.87 cm/s	6.95

That is, sand transport can be modeled using a value of D of 0.11 mm, a sand size that can be expected to be completely noncohesive.

Models of plains sand bed streams Very different problems are posed by plains sand bed streams. Gravel bed mountain streams and sand bed plains streams tend to occupy different regimes, as shown by the figure below, in which

$$\mathbf{Re}_p = \frac{\sqrt{RgD}\,D}{\nu}$$

denotes a dimensionless particle Reynolds number.

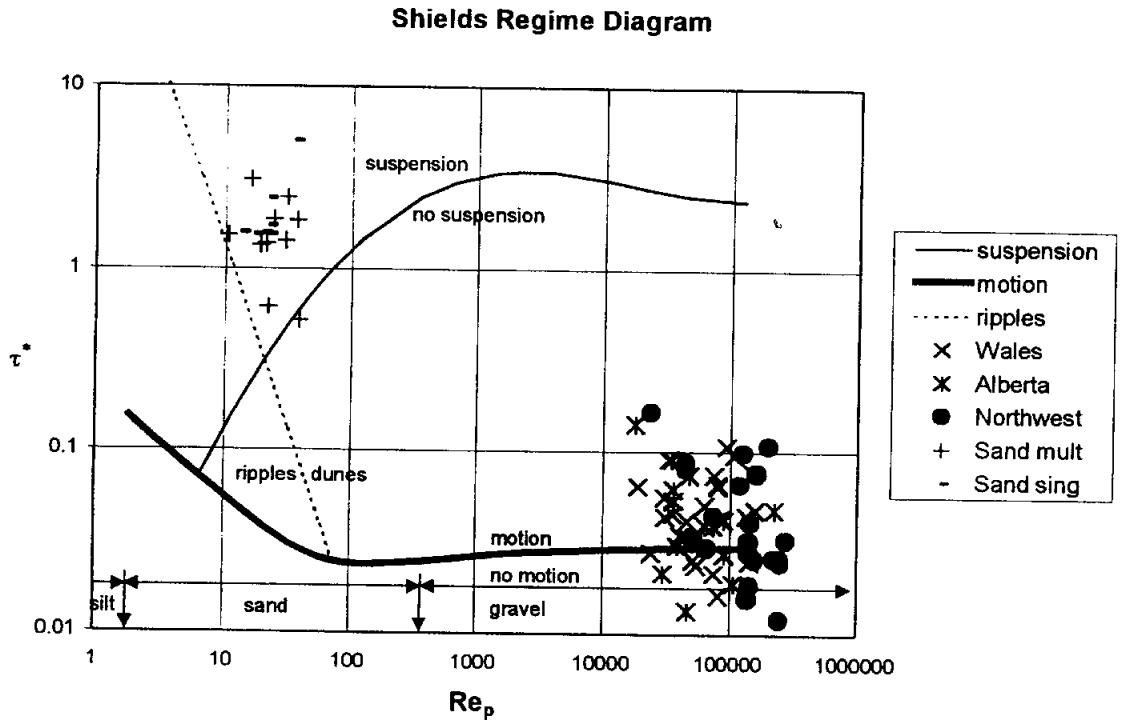

Figure 1

The points labeled Wales, Alberta and (Pacific) Northwest (USA) pertain to gravel bed streams at bankfull conditions; the rest of the points pertain to sand bed streams with D < 0.5 mm at bankfull conditions. Sand bed streams in general have much higher flood Shields stresses, and much lower slopes than gravel bed streams.

Several problems arise in attaining similitude in models of sand bed streams. The three most essential of them concern slope, depth and grain size. Consider the example of the prototype case from Table 3, taken from a physical model study of the Minnesota River.

Table 3

Parameter	Q	B	H	D	S
Prototype	600 m^3/s	90 m	4.0 m	0.4 mm	0.0001
Model	1.1 l/s	45 cm	2.0 cm	2 mμ	0.0001

The model parameters are based on an undistorted Froude model with a scale ratio λ of 1:200, a value that allows a reach with a length of 3000 m to be fitted within a basin with a length of 15 m. With a slope of 0.0001, the elevation drop between the upstream and downstream end of the model is only about 1.5 mm. This makes it almost impossible to accurately evaluate slope in the model. In addition, bankfull depth in the model is only 2.0 cm, a very shallow flow. Finally, the prescribed size for model sediment is 2 mμ, i.e. at the border between silt and clay. These considerations make such a model unacceptable.

The problem is not insoluble if one is willing to make compromises. The first of these is the use of lightweight sediment, such that R is less than 1.65. For example, for coal or crushed walnut shells R is about 0.40, and for the urea particles used in the micro modeling it is 0.23. This is, however, a relatively minor compromise. The more significant one is the use of a distortion factor in the model, such that the vertical scale ratio λ_V differs from the horizontal scale ratio λ_H. A strict imposition of Froude similarity in combination with distorted geometric similarity yields the relations

$$(S)_m = \frac{\lambda_V}{\lambda_H}(S)_p$$

$$(B)_m = \lambda_H (B)_p$$

$$(H)_m = \lambda_V (H)_p$$

$$(Q)_m = \lambda_V^{3/2} \lambda_H (Q)_p$$

Note that grain size scaling is not included in the above relations. Since it can be seen from Figure 1 that sand bed streams at bankfull flow are typically in the range for copious suspension, the fall velocity criterion

$$\left(\frac{u_*}{v_s}\right)_m = \left(\frac{u_*}{v_s}\right)_p$$

can be used to determine grain size in the model.

Consider as an example the case for which λ_H = 1:200 and λ_V = 1:40, so that the distortion is 5:1. In addition, assume that the model sediment is lightweight with a specific gravity of 1.4, so that R = 0.4. The scalings of Table 4 result:

Table 4

Parameter	Q	B	H	D	S
Prototype	600 m^3/s	90 m	4.0 m	0.4 mm	0.0001
Model	11.9 l/s	45 cm	10 cm	0.42 mm	0.0005

It is seen now that both depth and grain size in the model are now in the manageable range. In addition, the elevation drop across the model is now in the range of 7.4 mm, again manageable.

There is a price to be paid for the distortion. That is, although Froude similarity is maintained, the aspect ratio B/H is 22.5 in the prototype and 4.5 in the model. For many purposes the consequences of this discrepancy are not severe. Consider, for example, the thread of high velocity in a meandering stream. This thread must cross the channel from one side to the other as the bend changes sense in the downstream direction, as illustrated in Figure 2.

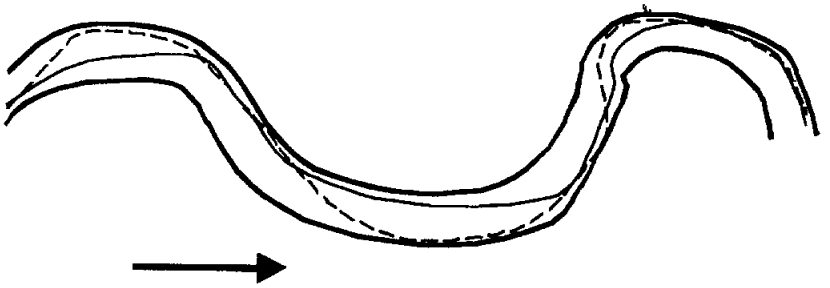

Figure 2

At the same bed slope, the smaller the value of aspect ration B/H the shorter is the transition in the thread of high velocity from a bend with one sense of curvature to a bend with the opposite sense. The distortion would thus entail a loss of accuracy in the flow pattern, and thus a loss of ability to represent flow in bends.

In the case of the thread of high velocity, this loss of accuracy is essentially counteracted by the fact that the slope of the stream is larger in the model than in the prototype. The higher slope at the same Froude number dictates a larger friction coefficient, and thus a tendency to delay the crossover of the thread of high velocity. The relevant scaling parameter is

$$\frac{B}{H}\mathbf{Fr}^{-2}S$$

where **Fr** denotes the Froude number of the flow. It can be easily worked out that this number is the same in the model as in the prototype in a distorted Froude model.

This happy circumstance does not carry over to the details of the flow around smaller hydraulic structures such as weirs, dikes, bridge abutments and bridge piers. For example, the distortion exaggerates the vertical component of velocity, and thus distorts the shape of the scour holes around such structures. Consider the flow around

the spur dike illustrated in Figure 3. The bed is at the angle of repose over only a relatively small fraction of bed area in the prototype; this fraction increases in a distorted model as B/H decreases. The result is a scour hole in model that scales up to have a larger area than that in the prototype.

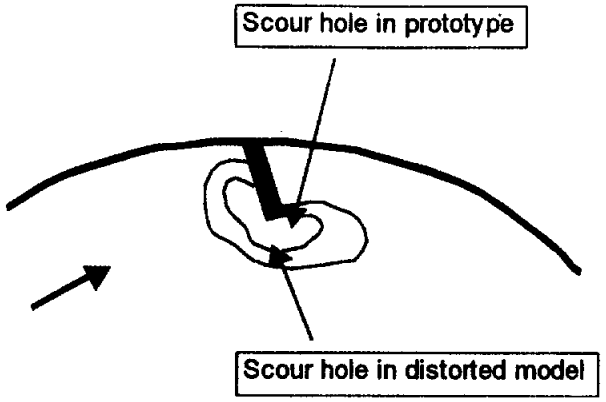

Figure 3

Pessimism should be tempered, however, the observation that the scour hole in a distorted model, exaggerated though it may be, still occurs in essentially the right location.

Tilted models and process models It is common to increase the bed slope of the model in excess of that predicted by strict distorted Froude modeling. The usual reason for this is the use of sand as the bed material in a model of a field sand bed stream. Because the depth-slope product is reduced by a factor λ_V^2/λ_H in the model but sediment size is reduced only modestly or not reduced at all, the Shields stress in the model is often much less than that in the prototype. As a result, the slope is further increased until an active mobile bed is achieved.

This extra adjustment in slope usually requires an adjustment in flow discharge so as to achieve Froude similarity. This in turn renders the dimensionless bed friction coefficient C_f, given by the relation

$$C_f = \mathbf{Fr}^{-2}S$$

larger in the model than in the prototype. The result is a model the similitude relations for which become confused.

There is no easy way around this dilemma. It is useful, however, to consider such a tilted model as a member of the class of process models. In process models precise similitude is not sought. Rather, the model is adjusted so that the processes and patterns of morphology, such as the pattern of scour and fill, are reproduced as faithfully as possible. Because the same physical phenomena are represented in the model as in the prototype, the model is still useful as a diagnostic tool. It must be remembered, however, that even after calibration for a specific flow, further change in flow conditions may change the bed of the process model in a way that differs somewhat from that of the prototype.

Implications for micro models Based on the above comments, the micro model must be thought of as a process model rather than one that satisfies strict similitude. This is for the following reasons.

- In addition to heavy distortion, the bed appears to be significantly tilted as well.
- The bed sediment was selected because it appeared to perform well rather than because of any criterion involving similitude.
- Although I did not obtain precise data, I am fairly sure that the Froude number in the micro models is significantly higher than that prevailing in the corresponding field sites.
- Model calibration was implemented by matching bed morphology rather than through strict similitude

In light of the above considerations, *the results of micro models must be interpreted with care*. I offer the following caveats.

- The fraction of the bed that is above the angle of repose in the micromodel is liable to be considerably higher than that in the field. This is due principally to the extreme distortion. Results based on the model study may lead to, for example, the overuse of riprap to stabilize the bed.
- The way in which sediment accretes on bars may not be accurately represented. This is because fully turbulent flow is not achieved in some of the micromodels, a feature caused not by the distortion but because of the very small scale of the model.
- The high distortion, and resulting nearly vertical banks may exaggerate the tendency of the thread of high velocity to collide with the banks, so shifting somewhat the points of bank attack and exaggerating the scour depth.

These comments are not meant to imply that micro models are useless. It has recently been shown (Smith, 1998) that self-formed meanders can develop up to the point of cutoff in a model not much larger than the micro models I saw. Although the shape of the bends are definably different from field-scale alluvial bends, most of the processes are clearly similar, including point bar formation, deep scour on the outside of banks and features that resemble scroll bars. All this is achieved in a flow that is also barely turbulent. The micro model is thus a useful tool that is waiting to be verified further.

It was encouraging to find that R. Davinroy had devised a means to reduce the exaggerated scour in micro models. This was done by modeling an impermeable structure in the field as a permeable structure in the model. The permeability partly compensates for the exaggeration in scour depth due to the distortion. The physical basis for this empirical conclusion is sound: the permeability acts to suppress vertical velocities by allowing for a cross flow.

Comments for the development of micro models While I was at the Applied River Engineering Center I heard some rather cavalier disparagement of the principles of similitude. In particular, I heard the opinion that as long as the micro model was able to reproduce the field bed morphology the precise criteria of similitude mattered not a whit. I am sure that the statement was an exaggeration for the sake of making a point. It is, however, not particularly helpful. The laws of Newtonian physics apply to micro models until someone can conclusively prove otherwise.

With this in mind, I recommend that the following type of study be pursued to aid the development of (and determine the limitations on) micromodels. A reach of a medium to large sand bed river should be modeled in the conventional way using lightweight bed material and a distortion of no more than 4 or 5. The same reach should be modeled with a micro model in the way that such models are presently implemented. Detailed measurements of bed and water surface slope, flow velocity and sediment transport rate should be taken in addition to measurements of bed topography. The results should be compared with each other and field data. This comparison should be done for a variety of flows. A comprehensive evaluation of the relative merits of standard distorted modeling and micro modeling should be performed. Based on this, guidelines and recommendations for future implementations of micro modeling should be devised.

A point of some concern is the downstream end of the model. In the absence of a means to accurately measure bed slope, it is impossible to determine the effect of adding a tailgate. I believe that a tailgate is necessary to minimize backwater effects. These are (likely) not nearly as large in the model as in the prototype because of the (likely) considerably higher Froude number in the model. It is always good practice, however,to avoid a free overfall at the downstream end of a river model.

While I strongly believe that the physical basis for micro modeling needs to be established further, I am a strong supporter of the concept. Micro models allow for a representation of the relevant river processes at a very low cost. They provide a tool for a comparative evaluation of various river countermeasures. I intend to develop a somewhat similar micro model table in order to introduce the undergraduates at my university to a) meandering, b) braiding, c) alluvial fans, d) scour in bends, e) flow bifurcations and f) bed aggradation and degradation.

Reference

Smith, C. E. 1998 Modeling high sinuosity meanders in a small flume. *Geomorphology*, 25(1-2), 19-30.

Preliminary Draft

APPENDIX B

LOOSE-BED FLUME SURFACE FLOW PATTERN COMPARISONS, UNIVERSITY OF MISSOURI-ROLLA

Preliminary Draft

APPENDIX B

LOOSE-BED FLUME EXPERIMENTS - UNIVERSITY OF MISSOURI-ROLLA

(B-1) Experiments

Flume experiments conducted at the University of Missouri-Rolla (UMR) included the use of three flume widths, 2-inches, 6-inches, and 12-inches. Gaines (2002) provides a detailed description of the experimental equipment and procedures. Gaines (2002) also describes findings pertinent to friction coefficients and sediment transport characteristics for the PlastiGrit sediment material.

The experimental design used the 12-inch flume as a prototype condition for evaluating the effects of vertical distortion in the smaller width flumes. The maximum flume width of 12-inches was the largest width feasible with facilities available at UMR and with available funding.

The experimental design utilized a pseudo (approximate) Froude similarity criterion in specifying scaled discharges between the three flumes. Experimentation intended to provide commensurate sediment mobility within test series, and pseudo Froude scaling provided a starting place for calculating scaled discharges between the three flume sizes for each series. In other words, Froude number was held approximately constant for each series of testing in the 12-inch, 6-inch, and 2-inch flumes.

For experiments involving training structures, Froude numbers ranged from 0.50 to 0.81. The minimum Froude number of 0.5 in the 12-inch flume does not provide conditions necessary to fully mimic the distortion of Froude number found in micromodels. Typical micromodels have Froude numbers in the 0.5- 0.6 range while the value of prototype Froude numbers range between 0.1 to 0.2. However, observations from the UMR experiments provide for a valid assessment of wall boundary effects on surface velocity patterns in the vicinity of a single training structure. Nonetheless, the UMR flume results provide insight into the response of micromodels due to wall influences because a greater exaggeration of Froude number serves to compound the wall effect. Because the range of Froude numbers used in the UMR experiments encompass the Froude numbers typically experienced in micromodels, the wall boundary effects would be similar. The lower Froude number found in actual prototypes have a substantially lower wall effect than indicated in the 12-inch flume at a Froude number of 0.5.

(B-2) General Observations

Large Scale Particle Image Velocimetry (LSPIV), dye traces, video recordings, timed exposure photography, and visual observations provided the basis for observations.

Surface flow patterns obtained during loose-bed flume experimentation at UMR identify several scale effects that result as channel width decreases. Wall boundary layer effects become more pronounced with the smallest width tested (2-inch wide flume). The lack of streaklines within about 0.33 inches from either wall identifies the extent of the boundary layer that develops against the wall. This effect, though present, substantially reduces in the twelve-inch wide flume. The relative size of any boundary

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layer at the wall of the twelve-inch flume compared to the training structure length is several orders of magnitude less than found in the two-inch flume width. Six-inch flume results are similar to those obtained for the two-inch flume (using the twelve-inch flume as the baseline condition), but wall boundary layer effects are less than found in the two-inch wide flume. Overall, streaklines from the six-inch flume experiments were in much closer agreement with the twelve-inch flume results than were the two-inch flume results. Except in the most general terms (e.g., deflection of streaklines near a training structure), there were several cases where the two-inch flume streaklines had no resemblance to the twelve-inch flume streaklines.

Use of porosity failed to reduce the wall boundary layer observed in the two-inch wide flume. As a result, the training structure was only partially effective -- the wall boundary effect negated about one-half of the structure's length relative to the flow. Further investigation using photos of the two-inch wide flume without training structures indicated the presence of the wall boundary layer. The wall boundary layer in the two-inch flume extended about 1/3 of an inch from the wall (2/3 of an inch total or 1/3 of the entire flume width).

Although structure submergence potentially alters the streaklines in the vicinity of the training structure, the wall boundary layer remains a dominant factor in comparing streaklines in the two-inch flume to those observed in the twelve-inch flume. Because at least 1/3 of the width experiences the wall effect in the two-inch flume, velocity distributions have a high probability to incorrectly represent prototype conditions. Relative comparisons made using streaklines from the two-inch channel seem to convey more quantitative information than possible given the likelihood for incorrect representation of prototype conditions. Similar results occur for the six-inch flume width; however, the wall boundary effects are markedly less than exist for the two-inch width. Therefore, some minimum channel width appears reasonable when streaklines become necessary to interpret model results.

Based upon the flume experiments at UMR, the flume studies at IIHR, and observations from actual micromodels, a minimum width of about six-inches should be considered where streaklines are to provide qualitative information toward assessing relative differences between alternatives. Greater widths are highly desirable. In addition to reduced wall boundary layer effects, the greater width generally results in lower vertical distortion and lower Froude number exaggeration. Lower Froude numbers are highly desirable to reduce distortion in velocity patterns. This is especially true for curved channels where additional forces (e.g. centrifugal forces) affect the velocity patterns. Achievement of lower Froude number exaggeration requires the use of a lighter sediment material. Recent introduction of a Type I PlastiGrit (Polyester with Specific Gravity=1.27) provides one means to reduce Froude number distortion by allowing the use of flatter slopes while maintaining active sediment movement.

Experiments at UMR included a single solid training structure and a single porous training structure. The three training structures are illustrated in Figure B-1. All tests utilized structure elevations above the water surface (e.g. no tests included structure submergence). Structure porosity was scaled based upon a head versus discharge relationship as discussed by Gaines (2002) (Figure B-2 and Figure B-3). The scaling resulted in increased porosity with decreasing channel width and training structure length.

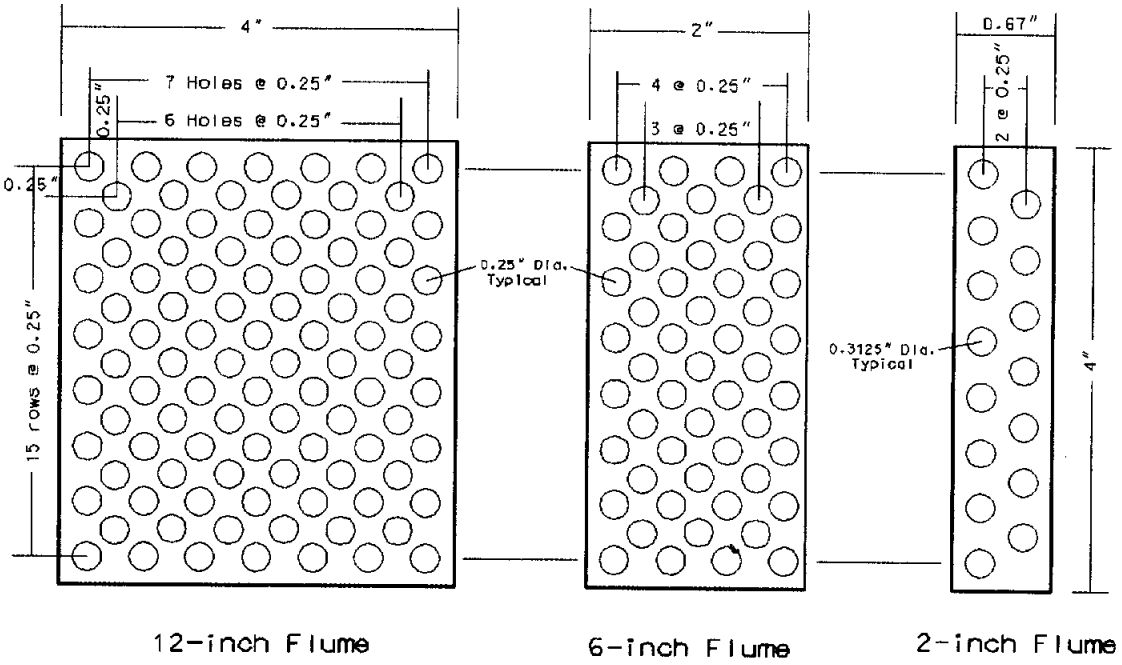


Figure B-1. Porous Training Structures - UMR Loose-Bed Flume Experiments

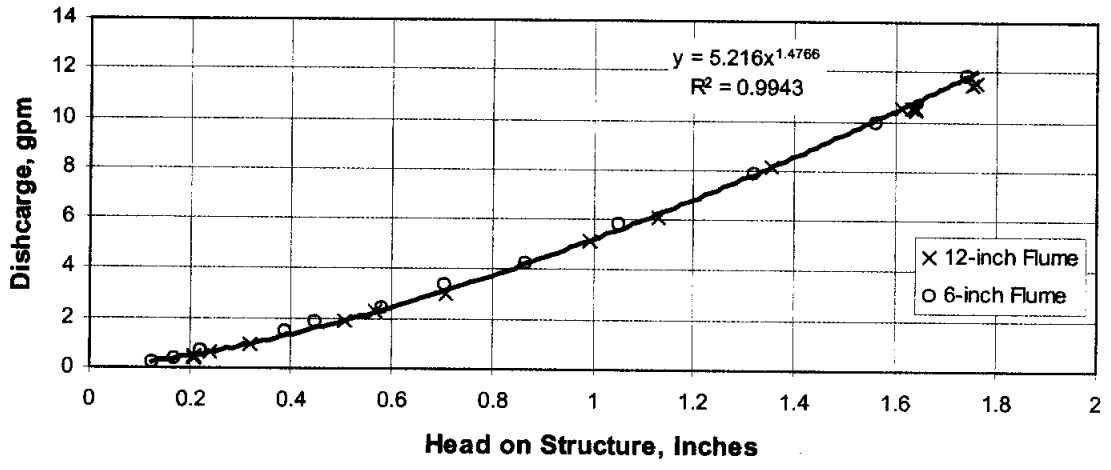


Figure B-2. Head versus Discharge Relationship for Scaling Porosity Between 6-inch and 12-inch Flumes

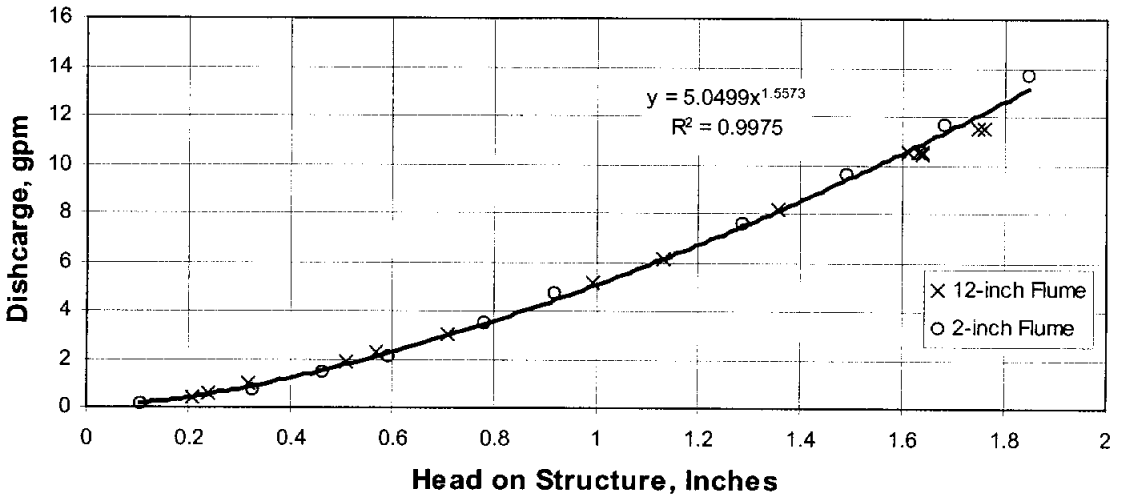


Figure B-3. Head versus Discharge Relationship for Scaling Porosity Between 2-inch and 12-inch Flumes

(B-3) Specific Observations

All experiments conducted with the training structures exhibited an influence of scour pattern at the dike on the resulting surface flow pattern. Following are observations made from the experiments (see also Figures B-6 through B-11, Appendix C, Gaines, 2002).

1. Experiments 1013 - Single solid structure, Froude number approximately 0.7 to 0.78, τ_* approximately 0.26, and mean flow depth approximately 0.65-0.71 inches. Figure B-1 depicts streaklines for these experiments.

   a. Twelve-inch flume: Streaklines approach the dike and do not deflect until approximately 1/4 to 1/2 the length of the dike. Approximately 1/2 of the dike length is impacted by straight (or nearly so) streaklines.

   b. Six-inch flume: Streaklines approach the dike and deflect at a point approximately one dike length upstream of the dike position. A circulation pattern upstream of the dike exists along the entire dike length. No part of the dike is impacted by straight streaklines as found in the twelve-inch flume.

   c. Flow is deflected approximately 1.5 to 2 dike lengths upstream of the dike. The presence of wall boundary layer effects are evident from the lack of streaklines adjacent to the wall -- streaklines appear no closer than 1/2 dike length from the wall.

2. Experiments 1014 - Single solid structure, Froude number approximately 0.6, τ_* approximately 0.2, and mean flow depth approximately 0.425 inches. Figure B-2 depicts streaklines for these experiments.

a. Twelve-inch flume: The flow does not deflect until approximately 1/2 times the dike length. Circulation occurs over 1/3 of the dike length adjacent to the flume wall.

b. Six-inch flume: Streaklines begin to deflect approximately one dike length upstream of the dike position. Circulation occurs over 1/2 to 3/4 of the dike length.

c. Two-inch flume: Wall boundary layer is evident with an approximate thickness of 1/2 of the dike length. Deflection of the streaklines begins approximately 1.5 to 2 dike lengths upstream of the dike position.

3. Experiments 1015 - Single solid structure, Froude number approximately 0.5, τ_* approximately 0.1 to 0.12, and mean flow depth approximately 0.33 inches. Figure B-3 depicts streaklines for these experiments.

a. Twelve-inch flume: Deflection begins about one dike length upstream, but transition is very abrupt. Circulation occurs over one-half the dike length.

b. Six-inch flume: Deflection also begins approximately one dike length upstream of dike position, but transition is less abrupt than for twelve-inch flume.

c. Two-inch flume: Wall boundary layer again about 1/2 dike length in thickness. Deflection of streaklines begins approximately two dike lengths upstream of dike and appears to be smooth (not abrupt as observed in the six-inch and twelve-inch flumes).

4. Experiments 1017 - Single porous structure, Froude number approximately 0.75, τ_* approximately 0.26 to 0.3, and mean flow depth of 0.6 inches. Figure B-4 depicts streaklines for these experiments.

a. Twelve-inch flume (e= 0.3006): Minimal deflection until approximately 1/3 of dike length. Only about 1/2 dike length shows defection by presence of circulation region -- streaklines for inner 1/2 of dike length show only slight deflection as particles "pile up" and go around the dike. No wall boundary layer visible.

b. Six-inch flume (e=0.3252): Circulation region approximately one dike length with streaklines showing deflection over full dike length (approach is about a 45 degree angle).

c. Two-inch flume (e=0.4293): Strong presence of wall boundary layer evident from separation of streaklines from wall by about 1/2 dike length. Deflection

more pronounced (about a 60 degree angle approaching the dike) and begins at 1.5 dike lengths upstream of the dike position.

5. Experiments 1018 - Single porous structure, Froude number approximately 0.6 to 0.7, τ_* approximately 0.2, and mean flow depth approximately 0.45 inches. Figure B-5 depicts streaklines for these experiments.

a. Twelve-inch flume (e= 0.3006): Deflection of streaklines begins approximately 1/3 of dike length upstream of dike position. Circulation occurs over 1/4 of dike length.

b. Six-inch flume (e=0.3252): Deflection of streaklines begins approximately one dike length upstream of dike. Circulation occurs over 3/4 to one dike length.

c. Two-inch flume (e=0.4293): Wall boundary layer is about 1/2 of dike length in thickness. Circulation region extends over the full dike length.

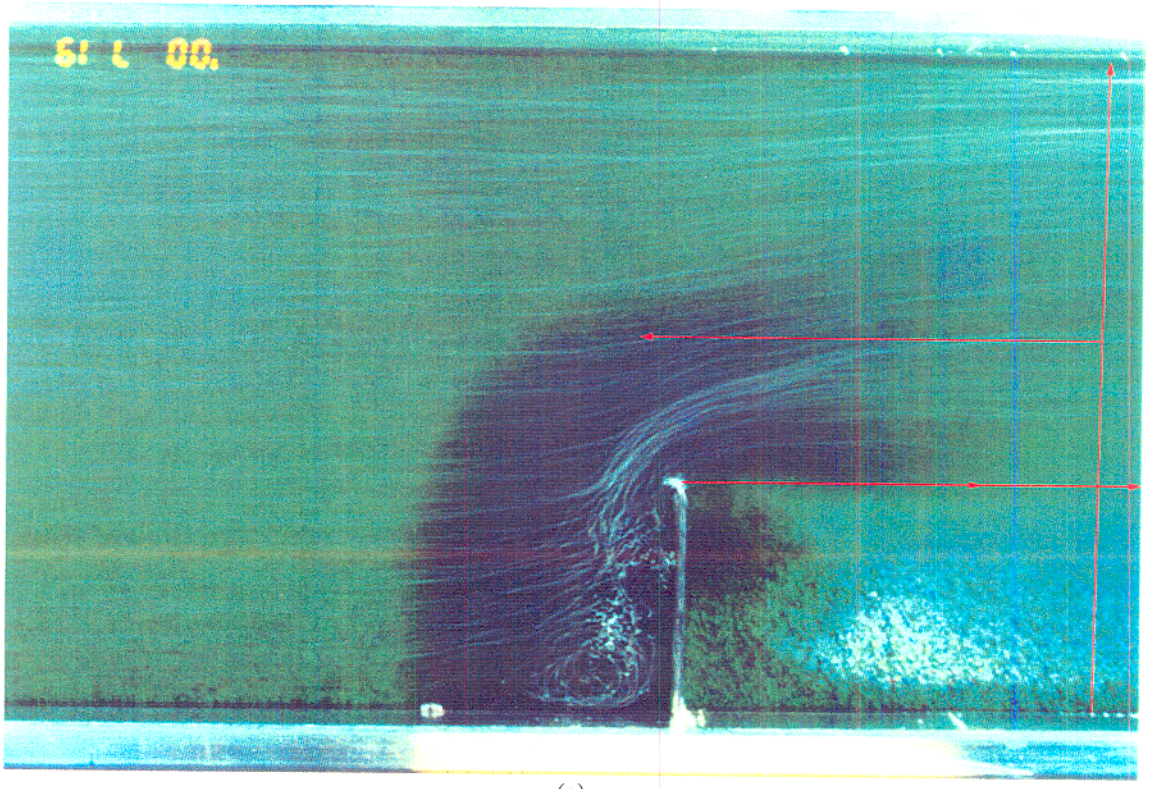
6. Experiments 1019 - Single porous structure, Froude number approximately 0.5, $\tau*$ approximately 0.08 - 0.12, and mean flow depth approximately 0.3 inches. Figure B-6 depicts streaklines for these experiments.

a. Twelve-inch flume (e= 0.3006): Flow diverted entirely to open area opposite of the dike. The dike resulted in deposition upstream and downstream of the dike with minimum flow depths of approximately 1-2 millimeters. This run was repeated three times with the bed leveled at the start of each run. The same discharges, slopes, and operating conditions were used for all three runs. The same result occurred for each of the three repetitions.

b. Six-inch flume (e=0.3252): Flow deflection begins approximately one dike length upstream of dike axis. Circulation region extends over 2/3 of the upstream dike face. Streaklines at inner 1/3 of dike length have minimal deflection until immediately upstream of the dike structure.

c. Two-inch flume (e=0.4293): Wall boundary layer evident from photo and video. Deflection begins approximately 1.5 dike lengths upstream of dike and is more streamlined (less abrupt) than for the six-inch run.

No experiments were conducted with Froude number lower than approximately 0.5 because sediment transport ceased with lower discharges. The preceding experiments used a Type II PlastiGrit (Urea) sediment. Gradation of the sediment was the commercially available 16/20 size (D_{50}=1.16mm). Specific gravity of the Urea plastic is 1.47.



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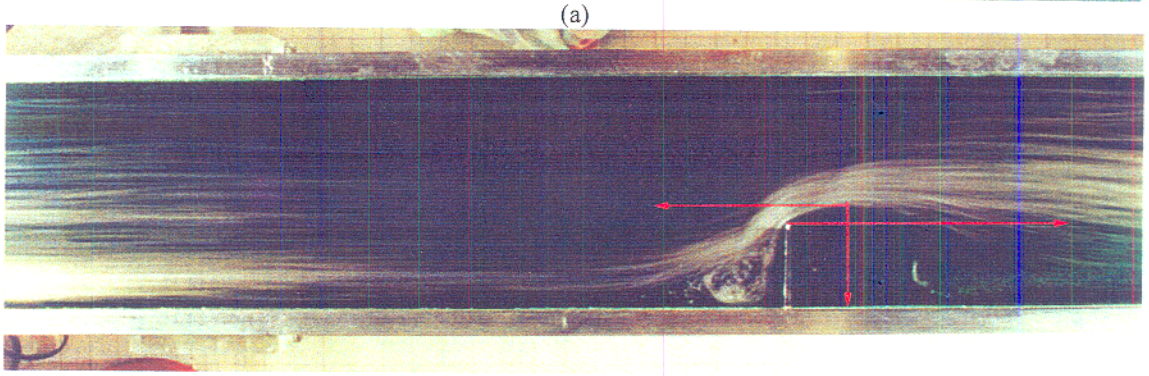

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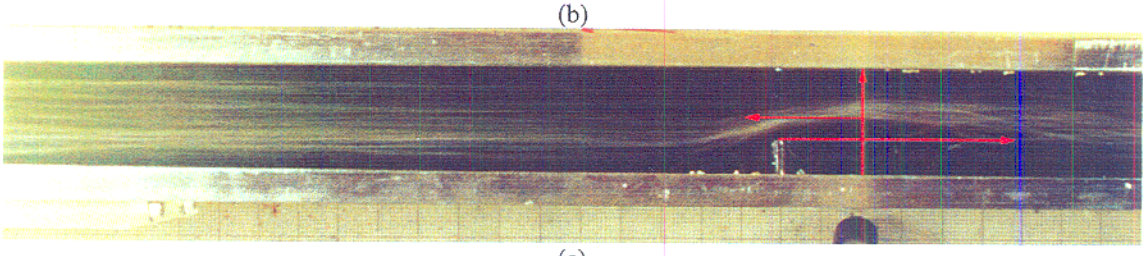

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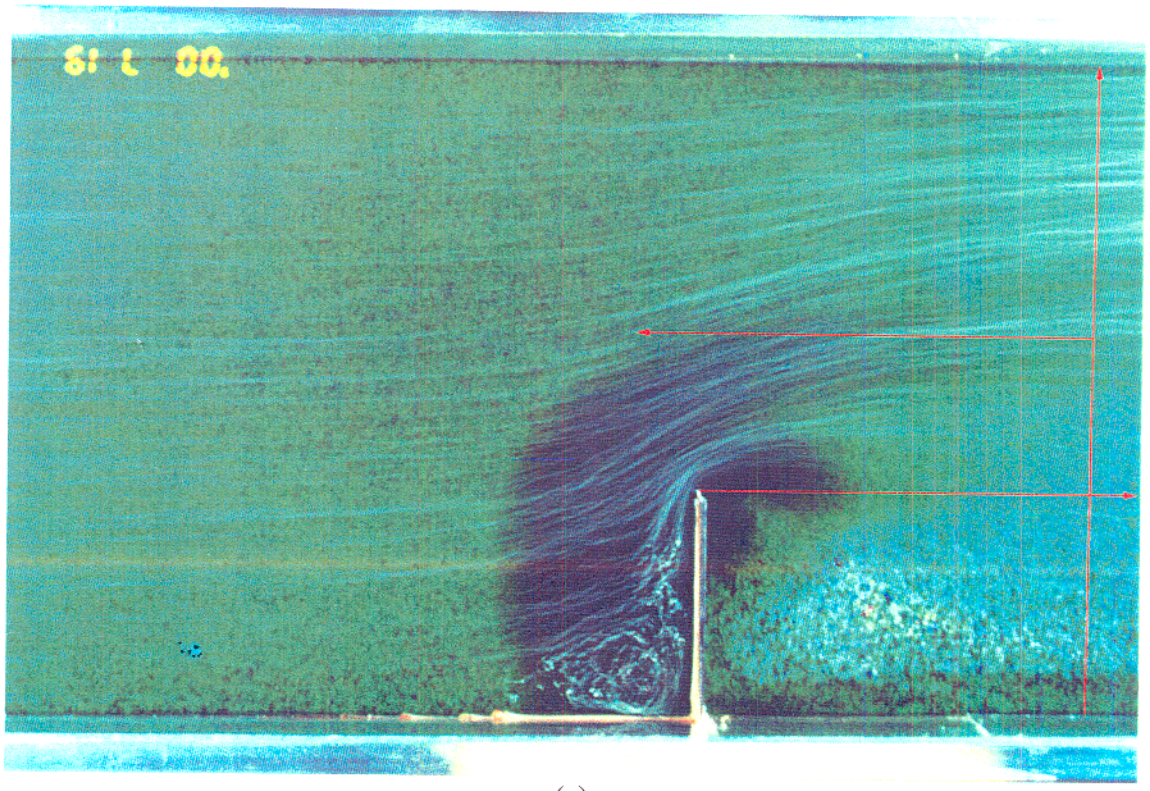
Figure B-1 LSPIV Imagery/Time Lapse Photographs of Run 1013, (a) 12-inch flume, (b) 6-inch flume, and (c) 2-inch flume.



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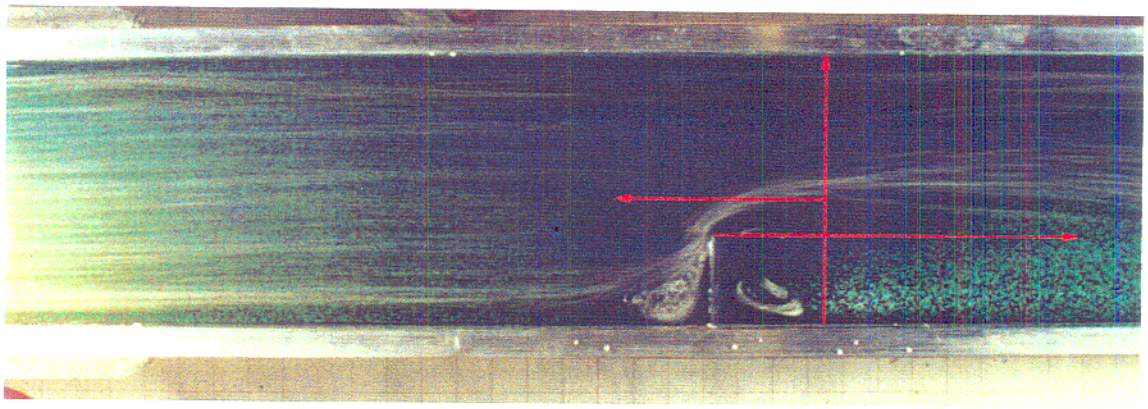

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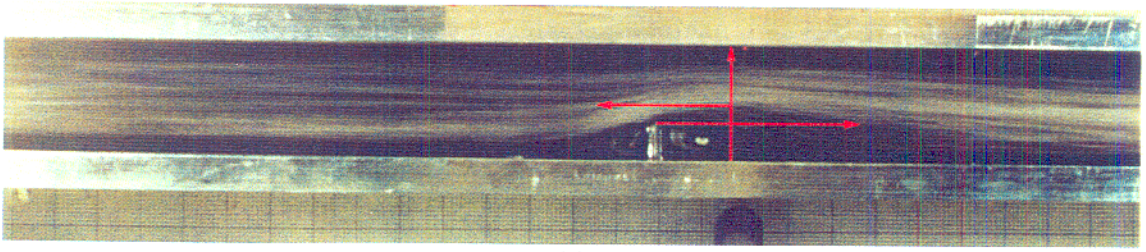

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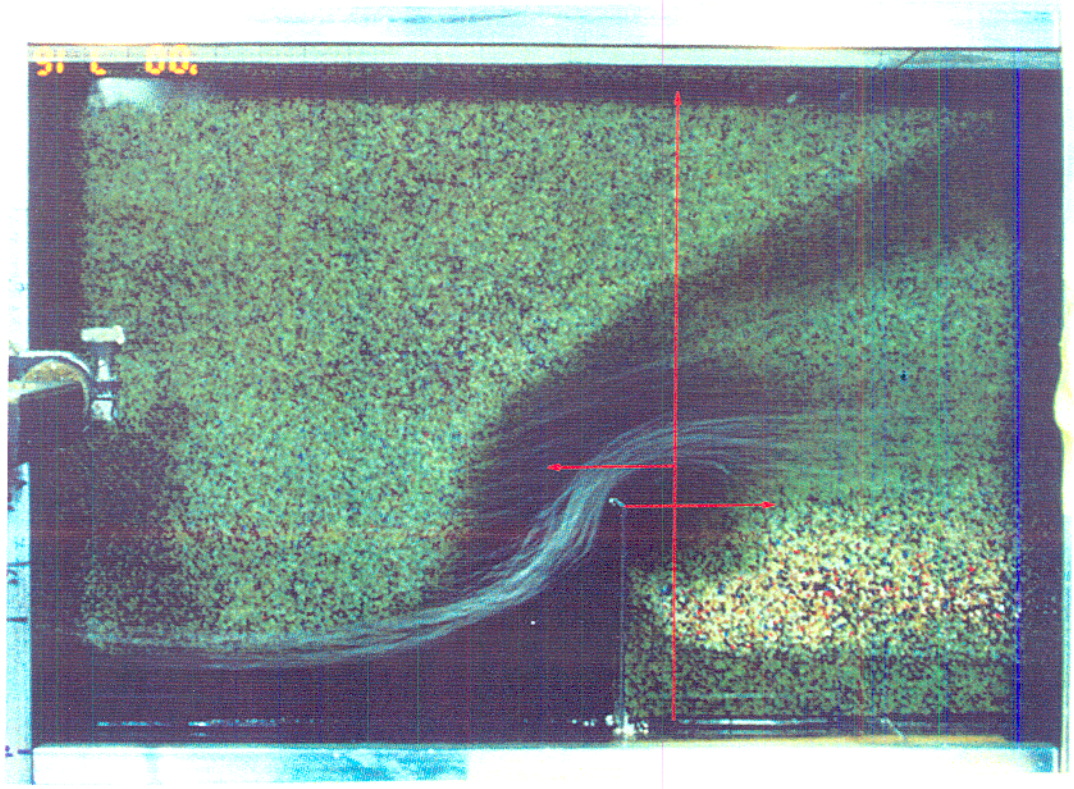
Figure B-2 LSPIV Imagery/Time Lapse Photographs of Run 1014, (a) 12-inch flume, (b) 6-inch flume, and (c) 2-inch flume.



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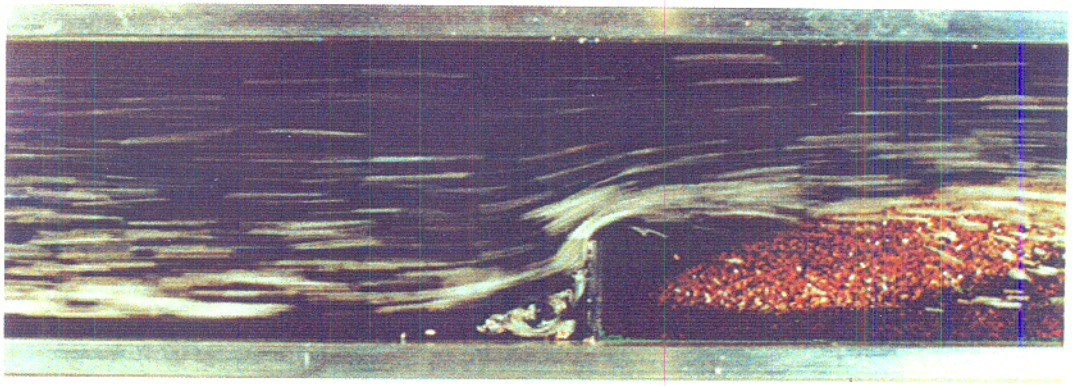

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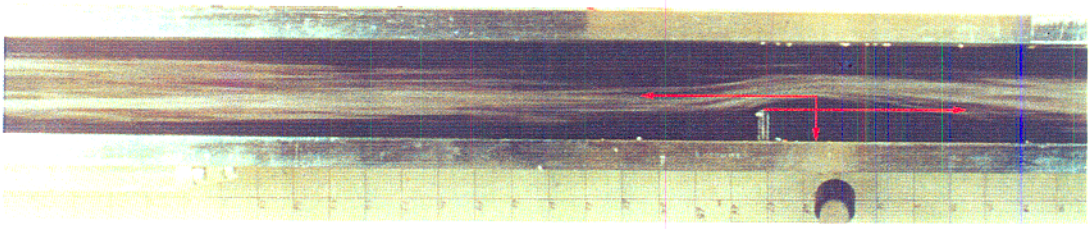
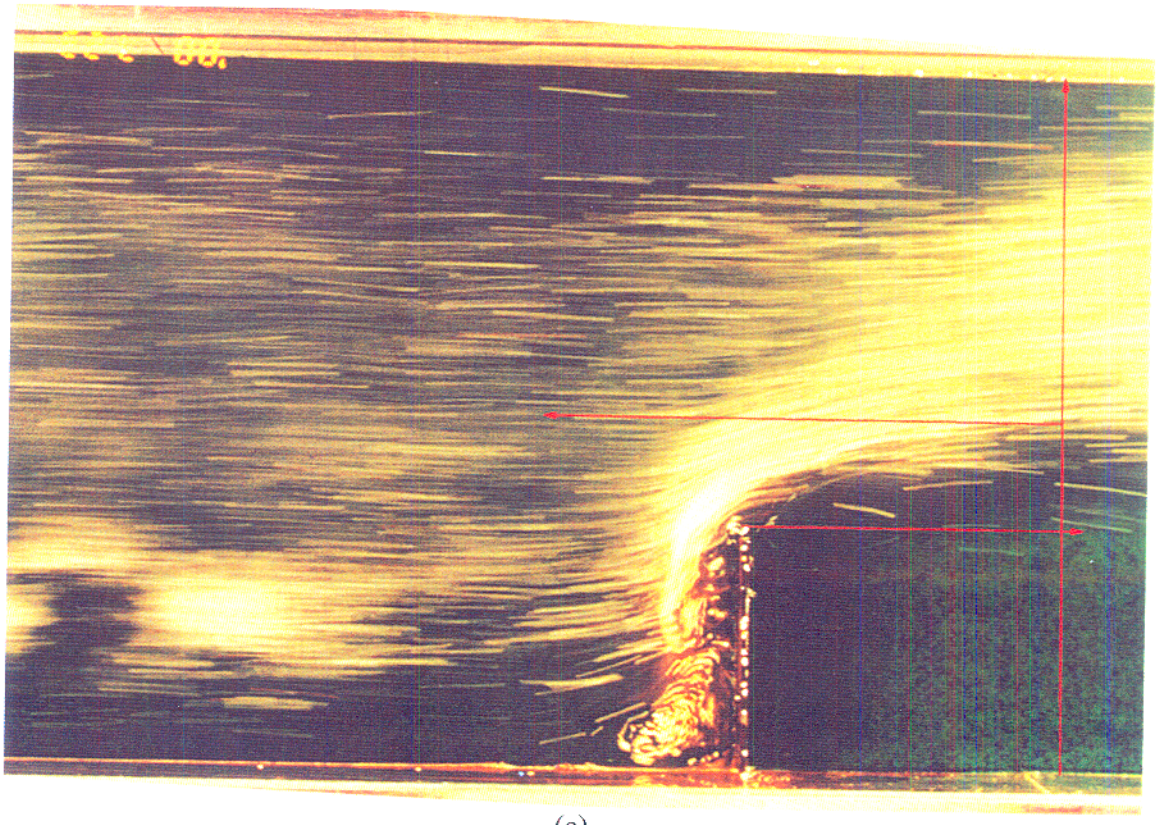


(c)

Figure B-3 LSPIV Imagery/Time Lapse Photographs of Run 1015, (a) 12-inch flume, (b) 6-inch flume, and (c) 2-inch flume.



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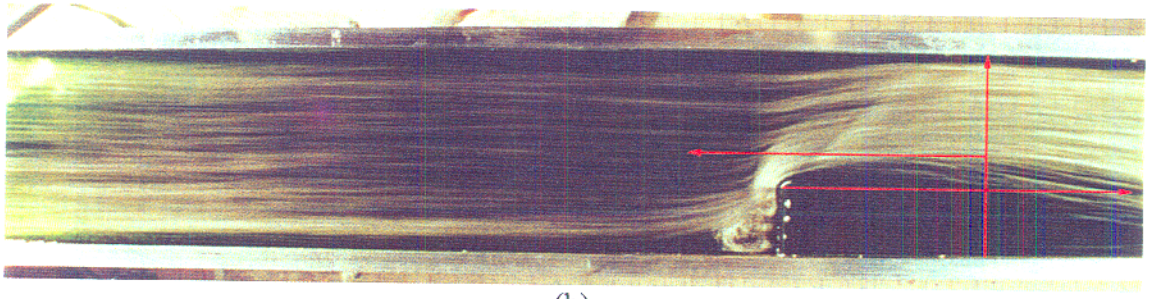

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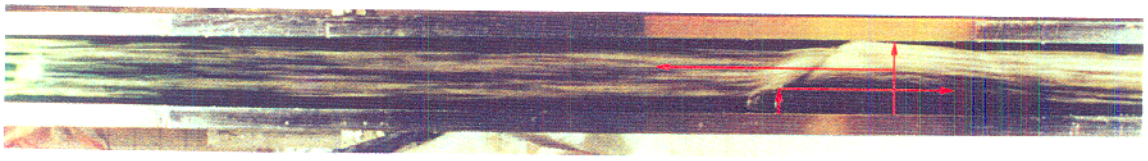

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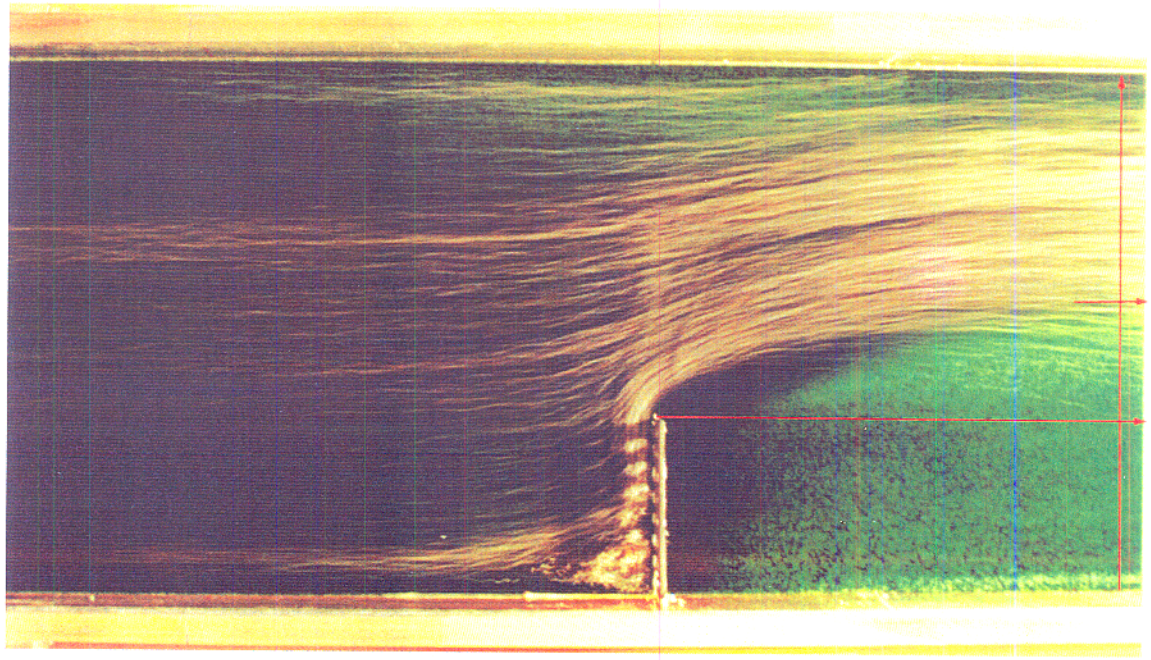
Figure B-4 LSPIV Imagery/Time Lapse Photographs of Run 1017, (a) 12-inch flume, (b) 6-inch flume, and (c) 2-inch flume.



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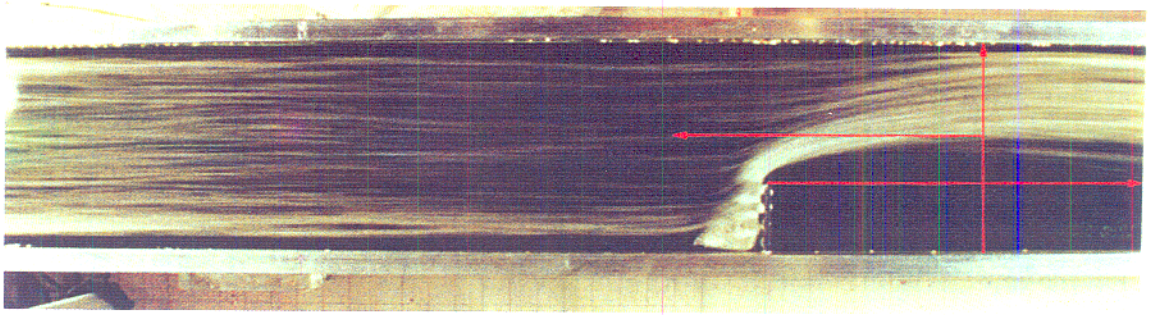

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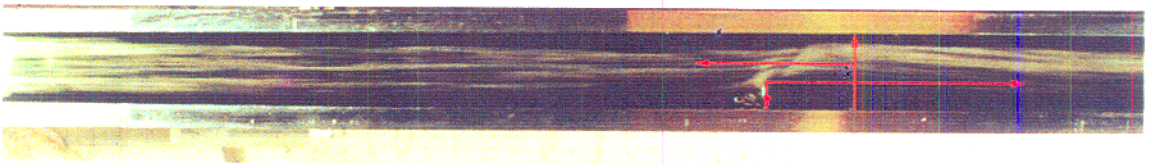
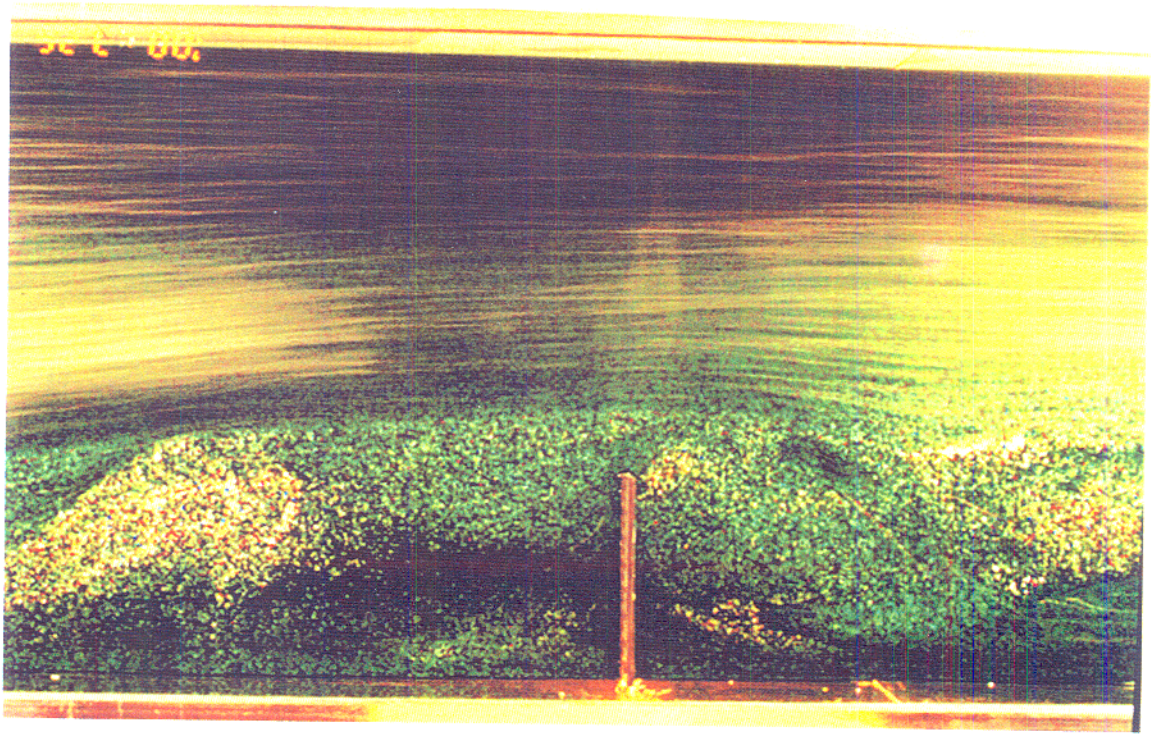


(c)

Figure B-5 LSPIV Imagery/Time Lapse Photographs of Run 1018, (a) 12-inch flume, (b) 6-inch flume, and (c) 2-inch flume.



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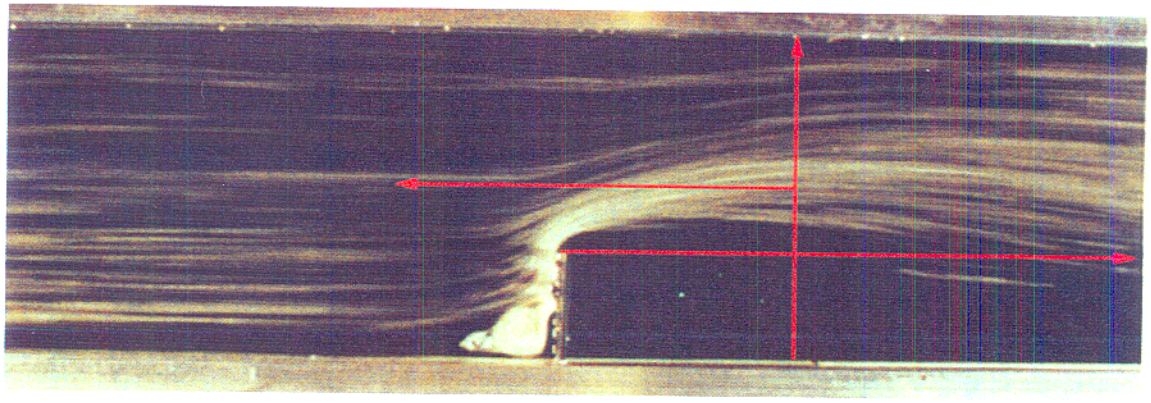

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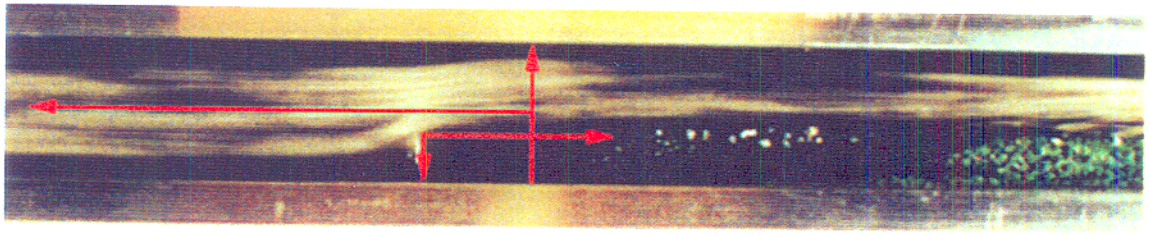

(c)

Figure B-6 LSPIV Imagery/Time Lapse Photographs of Run 1019, (a) 12-inch flume, (b) 6-inch flume, and (c) 2-inch flume.

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APPENDIX C

ANALYSIS OF PREVIOUS MODEL RESULTS USING SCALE RATIOS

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ADAPTED FROM GAINES (2002) CHAPTER 6

6.2 SIMILARITY CONSIDERATIONS

The study of river behavior is an area in which hydraulic modeling procedures have been used very successfully. Use of both fixed-bed and movable-bed river models have been responsible for saving millions of dollars in flood damage to adjacent properties as well as saving countless lives. Moveable-bed similitude is much more difficult to establish than the fixed-bed counterpart because sediment transport equations are much less reliable than the fixed-bed hydraulic equations. Two major complicating factors cause this relaxation in similarity between model and prototype. First, the roughness in a moveable-bed model is dependent on both the flow depth and the boundary configuration which includes boundary surface roughness due to particle size and roughness due to bed forms. Fixed-bed model roughness also depends upon the flow depth, but only the fixed surface roughness of the rigid boundary influences flow resistance. Significant changes in the resistance can occur with changes in flow because discharge affects the type and size of bed forms. In turn, changes in bed form directly impact overall resistance. Second, the time scale of the sediment movement is different from the water movement. The suspended sediment may have a time scale similar to the water being transported. However, other factors such as bed load, formation and movement of the bed forms, and scour or deposition may all occur at different rates. For these reasons, loose-bed river models are used in a qualitative way to predict general trends in the prototype.

The Froude number criteria is a similarity criterion that is often used for loose-bed models. Use of the Froude number criterion has been supported as a predominant factor through extensive experimental evidence. However, some relaxation of this criterion is also supported by various investigators (Zwamborn, 1966. Struiksma, 1980). In order to reduce surface tension effects and to achieve a desired state of sediment mobility, the flow depth is distorted in loose-bed models. Slope is likewise distorted. With an increase in slope to obtain sediment mobility, it is necessary to increase the roughness in order to satisfy the Froude number requirement for velocity and to avoid distorting the

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time scale. If possible, the model is designed to eliminate prediction factors for velocity and time. This places many constraints on the use of small-scale models for the study of river training structures.

Similitude must be based upon techniques other than those that require strict conformance with theoretical criteria. A technique used in loose-bed modeling (e.g. micromodeling) attempts to simulate or reproduce the river-reach bed material movement and bed configuration with a reasonable sediment time scale. In order to attain these goals, distortion not only of the vertical scale, but also of the sediment size, the resistance, the transport ratio, and the Froude number may be required.

Most river models are constructed with one horizontal scale (length and width) and a distorted vertical (depth) scale. However, some river models are built with one distortion factor for depth and another for slope. Using distortion factors for vertical distances introduces an arbitrary multiplier into the prediction equation unless compensating distortions are employed. The magnitude and form (linear, exponential, power or other type relationship) of the prediction factor can be approximated by considering a general sediment transport equation supplemented by the Chezy or Manning roughness relationship.

The Shields curve (Shields, 1936, Buffington, 1999) represents the limiting condition between transport and no transport. The Shields diagram provides a basis for rational moveable-bed model design (Garcia, 2000). This criterion requires two equations to describe sediment similitude. The particle Reynolds number (Re*) and dimensionless shear stress (τ^*) can be calculated from the hydraulic and sediment characteristics of the given flow. Sediment similitude will be assumed satisfied if two conditions are met:

$$(\tau^*)_m = (\tau^*)_p \tag{6-1}$$

and

$$(Re^*)_m = (Re^*)_p. \tag{6-2}$$

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It is assumed that a point on the Shields diagram completely describes the characteristics of a given flow with respect to the sediment transport, to the bed forms, and to the resistance.

The basic similitude equations shown in (6-1) and (6-2) can be rewritten in terms of the prototype to model ratios and the submerged specific gravity (α) as follows:

$$\alpha = \frac{(\gamma_s - \gamma)}{\gamma} \tag{6-3}$$

(considering that $\gamma = \rho g$ and $g_r = 1$ for the models allows the substitution of Δ_r for α_r)

$$\tau_o = \gamma R_h S_f \tag{6-4}$$

$$u_* = \sqrt{\frac{\tau_o}{\rho}} = \sqrt{g R_h S_f} \tag{6-5}$$

$$\tau_* = \frac{\tau_o}{(\gamma_s - \gamma)D} = \frac{\tau_o}{\gamma \alpha D} = \frac{R_h S}{\alpha D} \tag{6-6}$$

$$Re_* = \frac{u_* D}{\upsilon} = \frac{\left(\sqrt{g R_h S_f}\right) D}{\upsilon} \tag{6-7}$$

$$S_r = \frac{y_r}{x_r} = \frac{1}{G} \tag{6-8}$$

where G is the slope distortion ratio. From equations (6-3) through (6-8), dimensionless shear stress similitude becomes

$$\tau_{*_r} = \frac{R_{h_r} y_r}{\Delta_r D_r x_r} = 1 \tag{6-9}$$

and, assuming that υ_r=1, particle Reynolds number similitude becomes

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$$(Re_*)^2 = \frac{R_{h_r} y_r D_r^2}{x_r} = 1 \qquad (6\text{-}10)$$

As with a fixed-bed model, $(R_h)_r$ is not independent in the movable-bed model, but depends on x_r and y_r. The difficulty is that $(R_h)_m$ and $(R_h)_p$ must be determined directly from each of the two channel cross-sections.

Similitude based upon the Froude law and a roughness equation is desired to ensure that water surface slopes and flow depths are properly simulated in the model. The vertical scale is more appropriate for a distorted model. The Froude Law gives

$$v_r = y_r^{1/2} \qquad (6\text{-}11)$$

and if the Chezy formula (Equation 2-88) for roughness is used, then

$$C_m = \beta\, C_p \qquad (6\text{-}12)$$

where C is the Chezy roughness coefficient defined by

$$C = \frac{v}{\sqrt{R_h S_f}} \qquad (6\text{-}13)$$

and β is a roughness distortion factor. Therefore, the roughness ratio (C_r) becomes

$$C_r = \frac{C_p}{C_m} = \frac{1}{\beta} = \frac{v_r}{\sqrt{R_{h_r} S_{f_r}}} = \frac{y_r^{1/2}}{(R_h^{1/2})_r \left(\frac{y_r}{x_r}\right)^{1/2}} = \frac{x_r^{1/2}}{(R_h^{1/2})_r}. \qquad (6\text{-}14)$$

The roughness distortion factor (β) can be adjusted to compensate for distortion of depth and slope. However, different degrees of roughness distortion are required at different sections of the model because the value of the hydraulic radius (which

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influences the velocity) is dependent on the depth to width ratio and the depth to width ratio varies widely throughout the reach length of river models. The effect of slope distortion on hydraulic radius depends on the shape of the cross-section. A hydraulic radius ratio can be approximated by assuming an equivalent rectangular area section as follows: (1) approximate the rectangular width as equal to water surface width and (2) approximate the rectangular depth as equal to the hydraulic depth. Figure 6-1 depicts the equivalent rectangular section concept. Hydraulic depth (H) is used to represent depth in the similitude ratios. The top width (W) is also used in estimating the values of various ratios.

Slope ratios are computed as

$$\left(\frac{y}{L}\right)_m = G\left(\frac{y}{L}\right)_p \quad \text{or} \quad S_r = \frac{1}{G}. \tag{6-15}$$

The slope distortion factor is

$$G = \frac{x_r}{y_r} \tag{6-16}$$

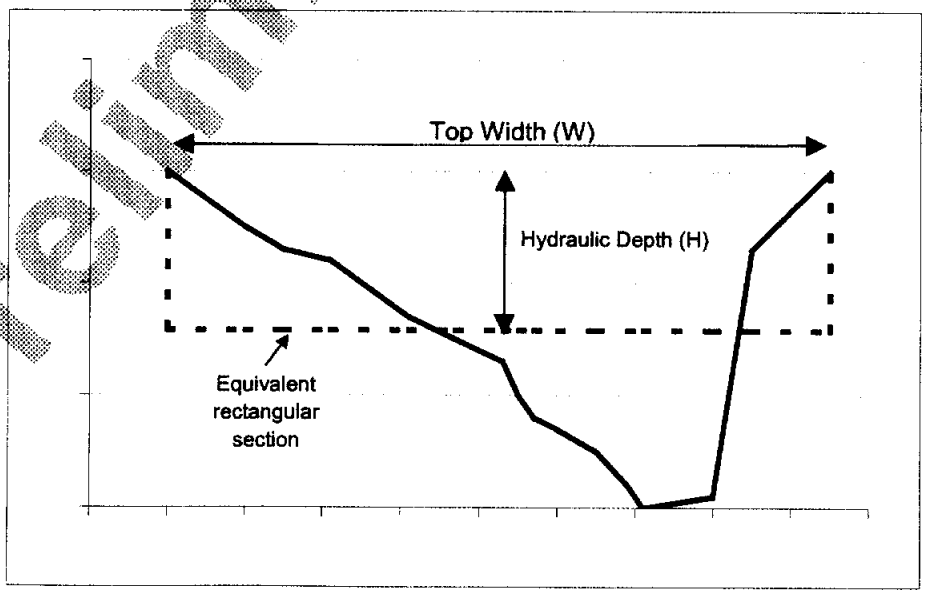

Figure 6-1 Equivalent Rectangular Section

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and the hydraulic radius ratio is

$$R_{h_r} = \frac{(R_h)_p}{(R_h)_m} = \frac{\left(\frac{W \cdot H}{W + 2H}\right)_p}{\left(\frac{W \cdot H}{W + 2H}\right)_m}. \quad (6\text{-}17)$$

Substituting the depth ratio (H_r) and width ratio (W_r)

$$H_r = \frac{H_p}{H_m} = y_r \quad \text{and} \quad W_r = \frac{W_p}{W_m} = x_r \quad (6\text{-}18)$$

into Equation (6-17) produces the hydraulic radius ratio (in terms of prototype values) as

$$R_{h_r} = y_r \left[\frac{1 + 2G\left(\frac{H}{W}\right)_p}{1 + 2\left(\frac{H}{W}\right)_p} \right]. \quad (6\text{-}19)$$

Substituting this hydraulic radius ratio (Equation 6-19) into the Chezy roughness ratio (Equation 6-14) yields

$$C_r = \frac{1}{\beta} = G^{1/2} \left[\frac{1 + 2\left(\frac{H}{W}\right)_p}{1 + 2G\left(\frac{H}{W}\right)_p} \right]^{1/2}. \quad (6\text{-}20)$$

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This system of three similitude equations contains four independent scale ratios, α_r (or Δ_r), D_r, x_r, and y_r. The first two ratios pertain to the sediment material density and size. The last two ratios provide the model size and distortion. As previously discussed, the roughness distortion factor (β) in equation (6-20) is an adjustment to compensate for the depth and slope distortions necessary for sediment mobility in the model.

Duboy's earlier work on bed load transport showed that the dimensionless sediment transport was a function of the dimensionless shear stress (τ^*) as represented in the Shields diagram (Simons and Sentürk, 1992).

$$\varphi(\tau_*) = \frac{q_s}{u_* D} \tag{6-21}$$

where q_s is the volumetric sediment discharge per unit width. Expressing the entire sediment transport equation in terms of ratios gives

$$\left(\frac{q_s}{\sqrt{gR_h S}\, D}\right)_r = \left(\frac{R_h S}{\Delta D}\right)_r \qquad g_r = 1 \text{ and } S_r = \frac{1}{G} \tag{6-22}$$

which results in the following equation for the volumetric sediment transport ratio $(q_s)_r$

$$q_{s_r} = \frac{\left(R_h^{3/2}\right)_r y_r^{3/2}}{\Delta_r x_r^{3/2}} = \frac{\left(R_h^{3/2}\right)_r}{\Delta_r G^{3/2}} = 1. \tag{6-23}$$

The time required for deposition to fill a specified volume is equal to the volume divided by the transport rate

$$T_r = \frac{x_r y_r}{q_{s_r}} \tag{6-24}$$

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If $(q_s)_r = 1$, then this becomes

$$T_r = x_r y_r \tag{6-25}$$

Otherwise, Equation (6-24) represents the sediment time ratio. Substituting the expression for $(q_s)_r$ into Equation (6-24) results in

$$T_r = \frac{x_r^{5/2}\Delta_r}{(R_h)_r^{3/2} y_r^{1/2}} = \frac{x_r^2 \Delta_r G^{1/2}}{(R_h)_r^{3/2}}. \tag{6-26}$$

Vanoni (1978) and Yang (1973) have both shown that the sediment discharge (or total bed material concentration) is dominated by a dimensionless unit stream power variable. Vanoni (1978) relates sediment transport to the dimensionless unit stream power as

$$q_s = \varphi\left(\frac{vS}{\sqrt{gD_{50}}}\right). \tag{6-27}$$

Therefore,

$$q_{s_r} = \left(\frac{v_r S_r}{\sqrt{g_r D_{50_r}}}\right) = \frac{y_r^{1/2}\left(\frac{y_r}{x_r}\right)}{\sqrt{g_r D_{50_r}}} = \frac{y_r^{1/2}}{G g_r^{1/2} D_{50_r}^{1/2}}. \tag{6-28}$$

If $g_r = 1$, then

$$q_{s_r} = \frac{y_r^{3/2}}{x_r \sqrt{D_{50_r}}} = \frac{y_r^{1/2}}{G D_{50_r}^{1/2}} \tag{6-29}$$

where D_{50} reflects the physical size of sediment particles.

Yang (1973) relates sediment transport to the dimensionless unit stream power as

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$$q_s = \varphi\left(\frac{vS}{\omega}\right). \tag{6-30}$$

This modifies the equation for q_{sr} as

$$q_{s_r} = \left(\frac{v_r S_r}{\omega_r}\right) = \frac{y_r^{1/2}\left(\frac{y_r}{x_r}\right)}{\omega_r} = \frac{y_r^{1/2}}{G\omega_r}, \text{ and} \tag{6-31}$$

$$q_{s_r} = \frac{y_r^{3/2}}{x_r \omega_r} = \frac{y_r^{1/2}}{G\omega_r}. \tag{6-32}$$

In Equations (6-30), (6-31) and (6-32), the sediment fall velocity (ω) reflects the interaction between sediment particles and water. The fall velocity is also affected by particle shape and water viscosity and temperature.

The data obtained from the 16 WES large-scale models and from the 14 micromodels (e.g., reach weighted parameters from Appendix A) were used to compute various similitude criteria represented by Equations (6-9), (6-10), (6-14), (6-23), (6-26), (6-29), and (6-32). Graphs of these data were generated in an attempt to identify the degree of similitude achieved as a function of the slope and roughness distortion factors.

Flume data utilized in the current investigation were also used to compute these similitude criteria. Ratio values for flume data were calculated using the widest flume (and lowest Froude number) as the prototype condition. All other flume widths and flow conditions were then used to describe separate model conditions. This allowed the inclusion of both loose-bed flume and previous model data on the same graph. Where flume ratios aided in assessment of data depicted in the graphs, both model and flume results are included. Otherwise, only model ratios are shown.

Deviations from ideal similitude (where parameter ratio values equaled 1.0) were further broken down by sub-categories of hydraulic depth to width ratio (H/W), relative roughness ratio (H/D_{50}), Froude number ratio (Fr_r), or sediment mobility Froude number ($\omega/(g^{1/2} D_{50}^{1/2})$).

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6.2.1 Shields Diagram Approach. The similarity criteria expressed by Equations (6-9) and (6-10) pertain to sediment mobility which is an important aspect of loose-bed model design and operation. Similarity of these criteria requires that each ratio equal unity. A line having a 1:1 slope (the line of perfect agreement) indicates equal amounts of distortion between ordinate and abscissa. Figure 6-2 presents ratio values for the thirty model studies included in this study. In Figure 6-2 large-scale models are represented by the x-symbol while micromodels are depicted by the triangles.

The data in Figure 6-2 plot in distinct groupings by sediment particle size ratio as represented by the lines labeled by the D_{50_r} values. The lines of equal D_{50_r} were drawn by a visual fit through the data points.

The groupings described by particle size ratio (lines of equal D_{50_r}) indicate that the particle Reynolds number ratio decreases with smaller particle size ratio (e.g. when model particle sizes are increased for a given prototype particle size). The τ^* ratio values did not exhibit a dependence on the particle size ratio.

Micromodel data plot slightly below the line of perfect agreement indicating that the use of the PlastiGrit sediment provided an equal degree of distortion in particle Reynolds number and dimensionless shear stress. The large scale coal-bed model data fell approximately one or two log cycles above the line of perfect agreement indicating that model shear stress was too low for the given particle sizes used. This conforms to procedures utilized in selecting sediment material for the coal-bed models (where the models were operated at a very low state of shear stress to prevent development of bed forms and to ensure that sediment moved predominantly as bed material (Maynord, 2001)).

The single large-scale sand-bed model fell approximately one log cycle below the line of perfect agreement which indicates that the model shear stress was too high for the sand used in the model.

Flume data were not included in the analysis of Shields parameter ratios because flume data involved the same sediment material and sizes for both model and prototype conditions. Analysis of the flume data in terms of prototype to model ratios therefore provided no additional information for data shown in Figure 6-2.

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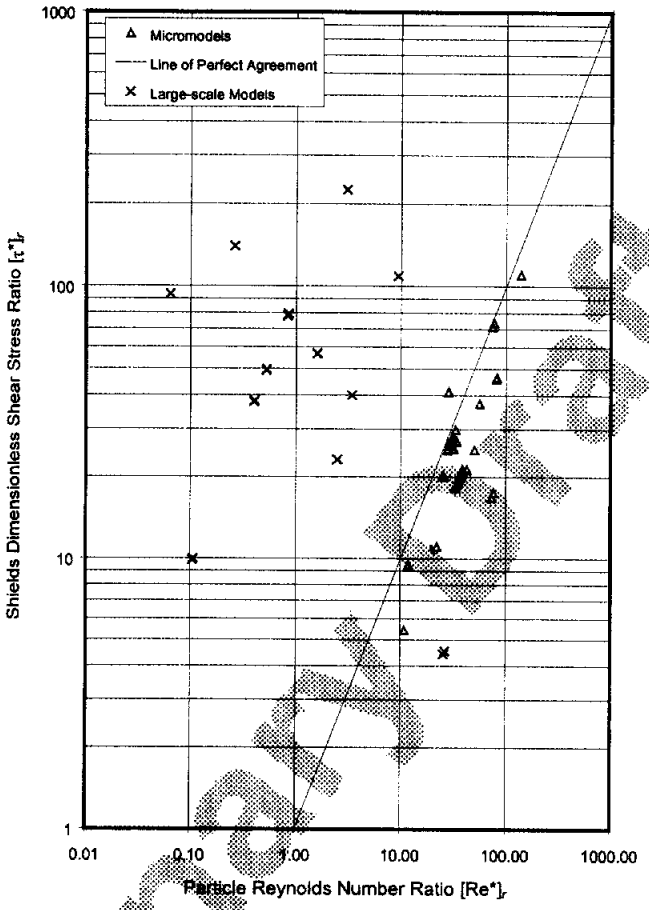

Figure 6-2 Shields Parameter Ratios for Sediment Mobility

7.1.2 Roughness Relationships. Model roughness affects the way that depths and velocities are simulated. Roughness effects on energy dissipation are a function of the flow Reynolds number. The Moody diagram is commonly used to evaluate roughness effects in pipes (Gray, 2000). However, the limited data available for the large- and small-scale models precluded estimation of flow Reynolds number. Therefore, the roughness ratio (Equation 6-14) was plotted against the Reynolds number ratio approximated as a scale ratio ($y_r^{1.5}$) as shown in Figure 6-3. Except for the large-scale sand-bed model, all model roughness ratios fall in two groupings. The large-scale model data plot between $y_r^{1.5}$ values of 300 to 3000 while micromodel data plot between 2000 to

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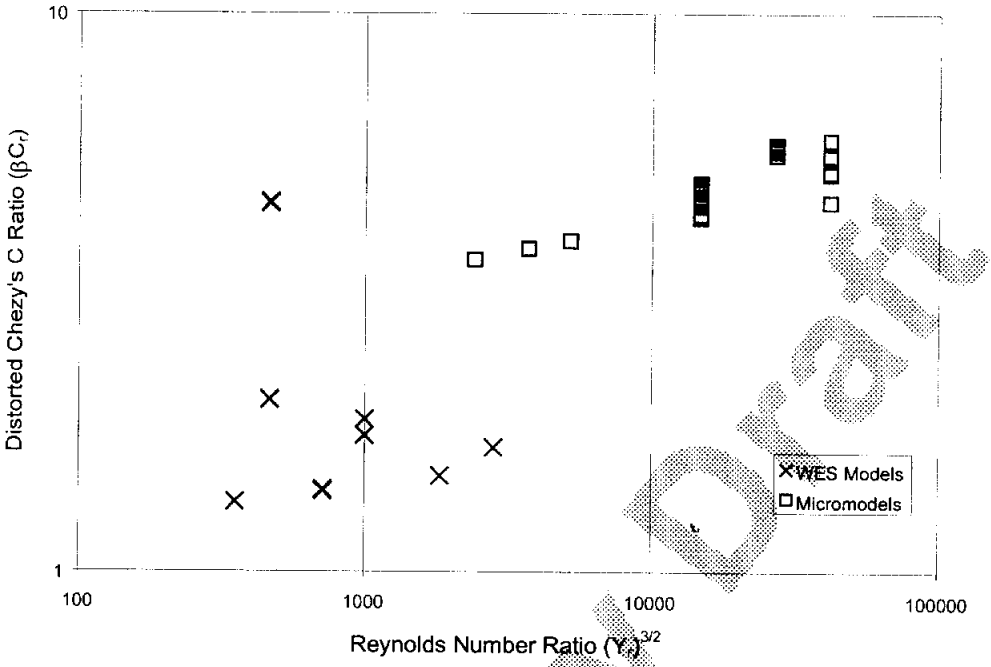

Figure 6-3 Chezy Roughness versus Reynolds Number Relationship

50000, approximately one log cycle greater than found for the large-scale model data. Roughness ratio values for the micromodels were approximately one-half log cycle greater than for the large-scale models. The only sand-bed large-scale model plotted at coordinate 475,4.6 indicating that roughness ratio for this model was in close agreement with the micromodel data.

There appeared to be a power function relationship between the large-scale and the micromodel data shown in Figure 6-3. Evaluation of Chezy roughness for small-scale and large-scale models (described in subsequent paragraphs) further supported that a relationship exists for data shown in Figure 6-3. However, no specific relationship (e.g. a regression fit) could be established using the Reynolds number approximation. Actual Reynolds number ratios derived from prototype and model measurements are required to develop the relationship between model roughness and the flow Reynolds number. Additional research in this area is necessary to establish this relationship.

Comparison of roughness distortion ratios to the slope distortion factor is presented in Figure 6-4. Data for the large-scale models fall on or very close to the line

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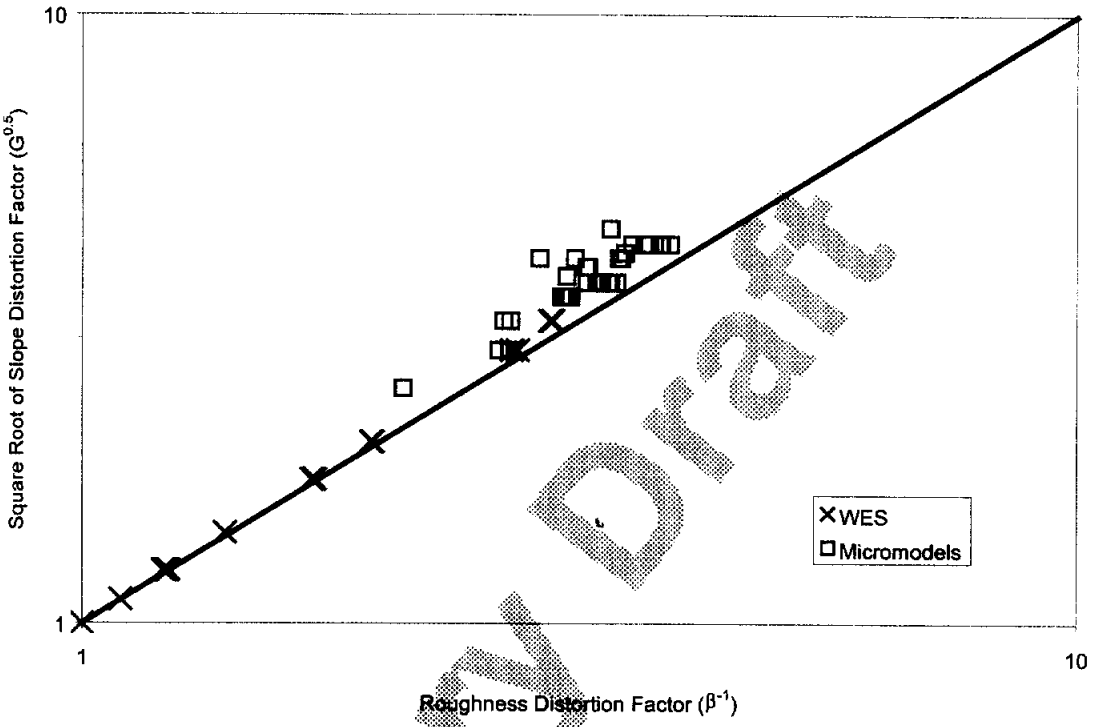

Figure 6-4 Model Slope versus Roughness Distortion Relationship

of perfect agreement (having a slope of 1:1). The line of perfect agreement represents equal amounts of distortion between the roughness ratio and the slope distortion factor (actually $G^{0.5}$). The large-scale model data shown in Figure 6-4 plot closest to 1,1 and are near to the line of perfect agreement. Micromodel data plot to the right of the large-scale models and above the line of perfect agreement, but are also in close proximity to the line.

The position of the data relative to the line indicates that micromodel slope and roughness distortion compensate to maintain a degree of similarity. Because ideal similarity is not achieved, a degree of relaxation in roughness and/or slope similarity is required. The distance between individual model points and the line of perfect agreement expresses a degree of relaxation found in the previous micromodel study results. Points plotting further from the line of perfect agreement have more disproportionate distortion

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between slope and roughness (and a greater degree of relaxation is required) than points located near the line. In other words, a point plotting on the line of perfect agreement would have equal amounts of distortion (e.g., similitude parameters equal to 1).

Development of estimates for the degree of relaxation requires a consideration of sediment transport rates and time scales.

6.2.3 Time Scales. The sediment mobility is a primary consideration for loose-bed model studies, and the Shields approach to similarity of sediment mobility is an expression of the probability that sediment particle movement will occur. However, the rate of sediment movement is not expressed by this approach. The rate of sediment movement and the rate of water movement in the model should also be commensurate with the rate of sediment and water movement in the prototype. Analysis of the relationship between the sediment time ratio expressed in Equation (6-26) and the hydraulic time, expressed as

$$t_r = \frac{x_r}{y_r^{1/2}}, \qquad (6\text{-}33)$$

provides a partial definition of the degree of relaxation in the time scales. Figure 6-5 presents the model and flume data for hydraulic and sediment time ratios. The flume data of Williams (1970) and the UMR flume data coincide in the same grouping in this figure. Ratios of flume data indicate smaller t_r values than found in either large- or small-scale models. Flume data and large-scale model data (excluding the sand-bed large-scale model) appear to have a power function relationship as is demonstrated by the linear tendency of the plot on the log-log scale shown in Figure 6-5. Micromodel ratios fell one t_r log cycle and one to two T_{sr} log cycles above the large-scale model ratios, respectively.

One possible criterion for hydraulic and sediment time was expressed by Zwamborn (1966) as shown in Equation (2-63) [e.g., $T_{sr} \approx 10t_r$] where the hydraulic time

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scale is multiplied by a factor of 10 to obtain an estimated sedimentation time scale. Therefore, model and flume values calculated for t_r were multiplied by 10 and compared

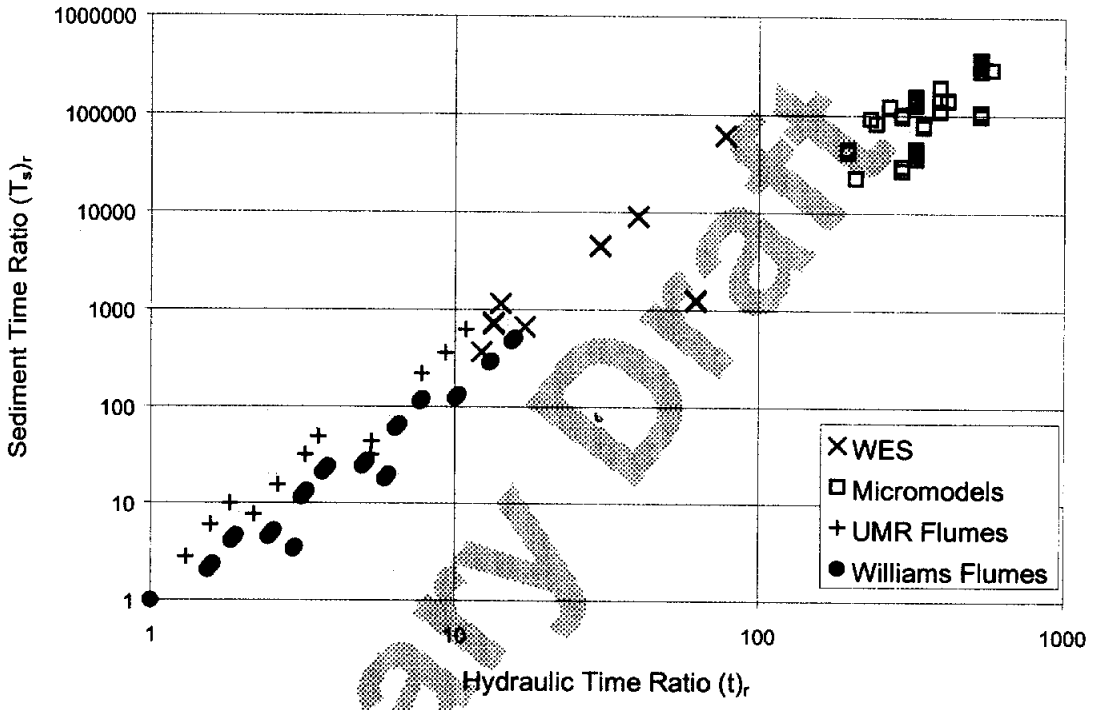

Figure 6-5 Model Sediment versus Hydraulic Time Scale Relationship

to a line of perfect agreement (slope 1:1). A graph of the modified t_r values is shown in Figure 6-6. The general description of each data set remains unchanged relative to the axis values. However, a regression of each set of data shown in Figure 6-6 indicates that the groupings form parallel bands. Lines visually fitted through each of the groupings have slopes greater than the line of perfect agreement depicted in Figure 6-6. The greater slopes indicate that sediment time for the large- and small-scale models is greater than the factor of 10 suggested by Zwamborn (1966). It is unclear why the large- and small-scale models analyzed would require a greater factor than suggested by Zwamborn (1966). One possible explanation for the need for a higher multiplier can be found in the specific gravity of the sediment particles. For instance, the only sand-bed large-scale model data (two points at approximately 610, 1100) plot close (within 0.1 log cycle) to

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the line of perfect agreement in Figure 6-6. The remaining model data represented lighter weight sediments of coal or PlastiGrit and plot approximately one log cycle higher than

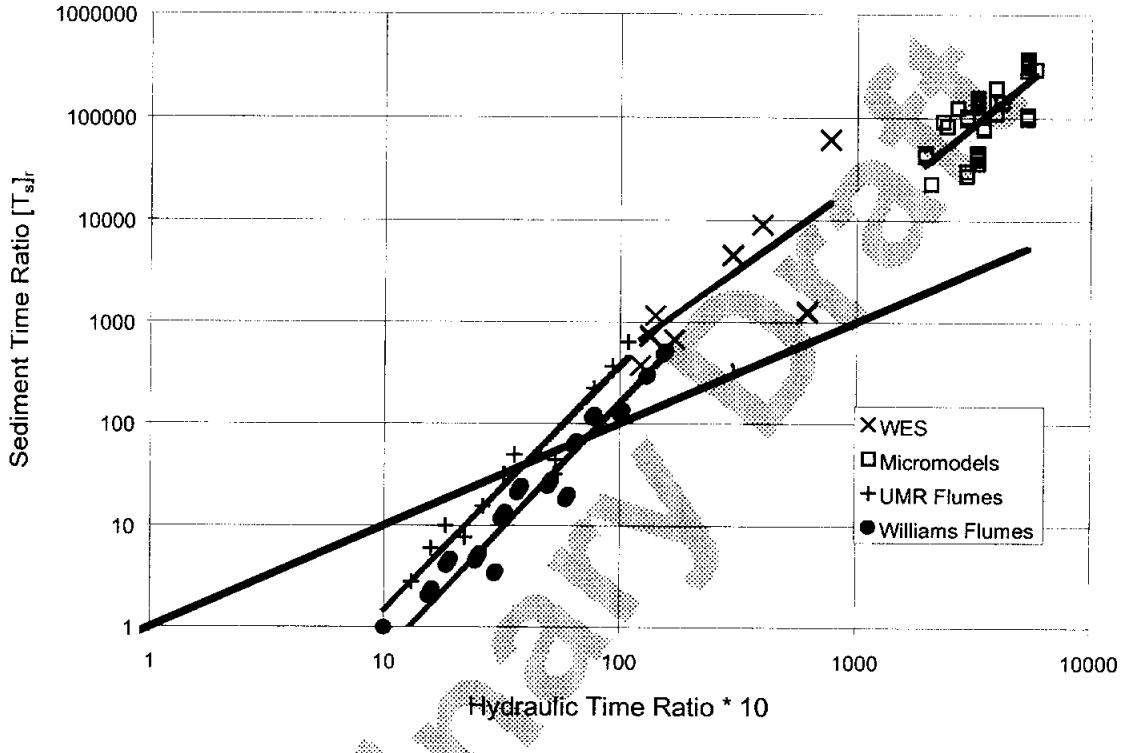

Figure 6-6 Zwamborn's Time Ratio Criterion for Distorted Models

the line of perfect agreement. The flume data also indicate that sand required a lower multiplier than the PlastiGrit sediment material.

Further analysis of the rate of sediment movement was accomplished by analyzing the sediment transport ratio and two unit stream power relationships.

6.2.4 Unit Stream Power. Vanoni's (1978) unit stream power (Equation 6-29) is representative of a combination of the flow velocity, energy slope and the bed sediment material size (Vanoni, 1978). Unit sediment discharge is a direct function of the unit stream power variable. Therefore, ratio values of unit stream power described by Equation (6-29) were graphed against values of unit sediment discharge ratio from Equation (6-23). This graph is shown in Figure 6-7. Williams' (1970) experimental

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flume data and flume results from the present investigation are not included in this figure. Micromodel ratio points plot in a linear fashion above and to the left of the large-scale model data. Excluding the sand-bed model, unit stream power ratio values in the large-scale models plot approximately one-half log cycle to the right of the small-scale model

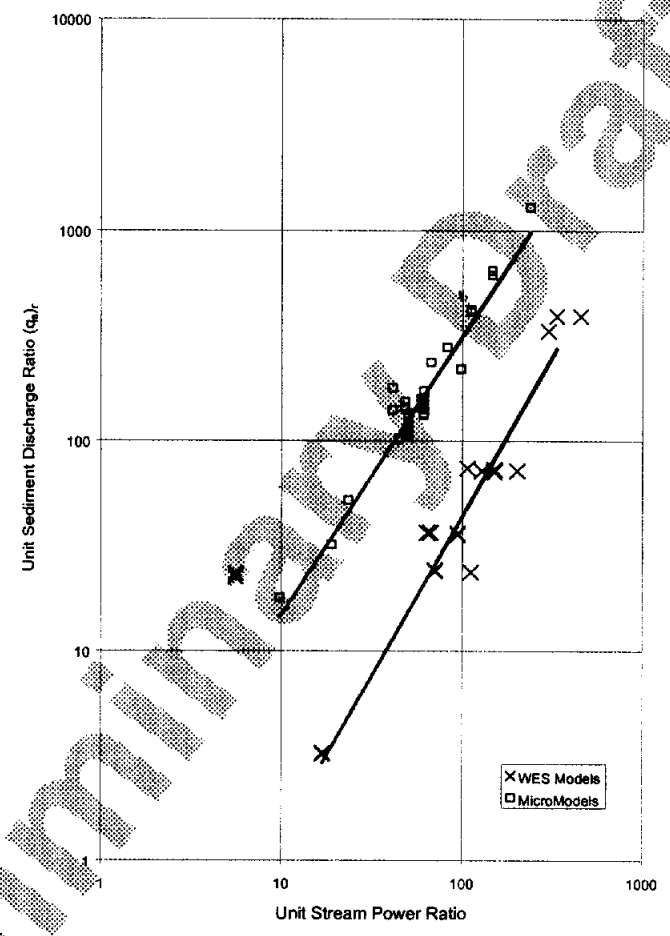

Figure 6-7 Vanoni's Sediment Transport Relationship

data. Large-scale coal-bed model data fell within a single log cycle for the unit stream power ratio. Micromodel data fell within approximately 1.1 log cycles for this ratio. Both large-scale coal-bed model and micromodel data fell within two log cycles for the unit sediment discharge ratio. Large-scale coal-bed model data and micromodel data seemed to exhibit the same trends (e.g. same slope of a linear regression fit of the data).

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However there was an approximate five fold difference in unit sediment discharge ratio values between the large-scale coal-bed models and the micromodels. The rate of sediment movement expressed in terms of the unit sediment transport for the small-scale models is greater than for the large-scale models as expected from analysis of the hydraulic and sediment time ratios.

Yang's (1973) unit stream power ratio (Equation 6-32) includes the bed sediment fall velocity, the flow velocity and the energy slope (Yang, 1973). Values for Yang's unit stream power described by Equation (6-32) were plotted against values of unit sediment discharge ratio from Equation (6-23). Figure 6-8 shows a graph of the data. Micromodel data fall approximately one log cycle (on the unit sediment transport ratio axis) above the large-scale model data. A power function regression fit of each set of data (micromodel and large-scale model) yields almost identical slopes (e.g. 1.22 for the micromodel data and 1.23 for the large-scale model data). Correlation coefficients (R) of 0.93 and 0.91 for the micromodel and large-scale model data, respectively, indicate that the regression represents a good fit of the data (regression based on a power function fit of the calculated values of 27 data points and 29 data points for the small- and large-scale models, respectively).

Analysis of both Vanoni's (1978) and Yang's (1973) unit stream power relationships provided a means to compare the use of sediment particle size (D_{50}) and sediment particle fall velocity (ω) in assessing similarity of sediment mobility. Both methods yielded similar results (e.g. magnitude of ratio values, position of small-scale model data relative to the large-scale model data and regression slopes of the respective data sets). This indicates that either particle size (D_{50}) or fall velocity (ω) can be used in assessing sediment transport similarity. An additional implication of the slope of the regression lines pertains to a distortion factor (or ripple factor, μ_f) that will be discussed in subsequent paragraphs.

Comparison of the unit sediment transport ratio and the dimensionless shear stress ratio provides additional information to assess the rate of sediment movement. Clearly, the sediment transport is a function of the dimensionless shear stress used in the Shields diagram. The relationship of dimensionless shear stress and the unit sediment transport is

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shown in Figure 6-9 for large-scale models and for micromodels using the ratio approach described previously in this section. Micromodel ratio values plotted as a power function parallel to and within one unit sediment transport ratio log cycle of the large-scale model values. Results from this comparison provide results that are commensurate with results from the Vanoni and Yang analysis. Because the relationship between unit sediment

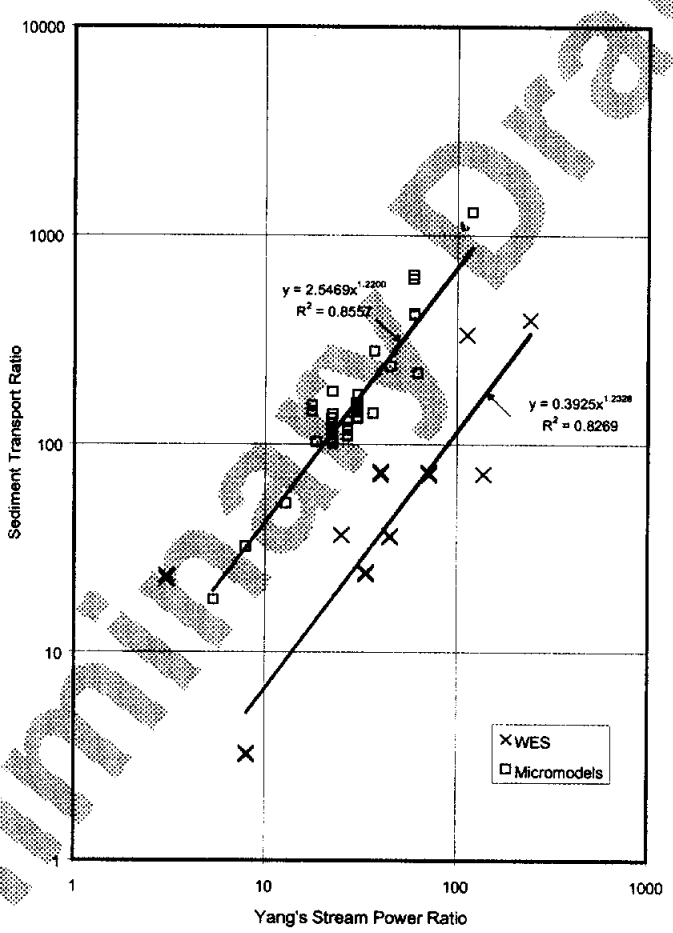

Figure 6-8 Yang's Sediment Transport Relationship

transport ratio and the dimensionless shear stress represents either Vanoni's or Yang's relationships, Figure 6-9 provides a basis for considering Zwamborn's (1966) suggested use of shear velocity divided by the fall velocity (u_*/ω) instead of the dimensionless shear stress (τ^*).

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According to Zwamborn (1966), the ratio of shear velocity to the fall velocity (u_*/ω) provides more realistic model scales than the dimensionless shear stress (τ^*). Zwamborn concluded that the u_*/ω parameter provides good similarity in river morphology when the Froude scaling is utilized and particle Reynolds number ratio is less than 10. Evaluating the impact of using u_*/ω as a replacement for τ^* required examination of a plot of the parameter values. Figure 6-10 is a plot of τ^* and u_*/ω. A line of perfect agreement (slope = 1:1) represents an equal degree of distortion between these parameters. The data for both large- and small-scale models plot below the line of Perfect agreement indicating that use of the u_*/ω parameter results in a relatively large relaxation in similitude for the dimensionless shear stress. Of particular interest is the fact that the

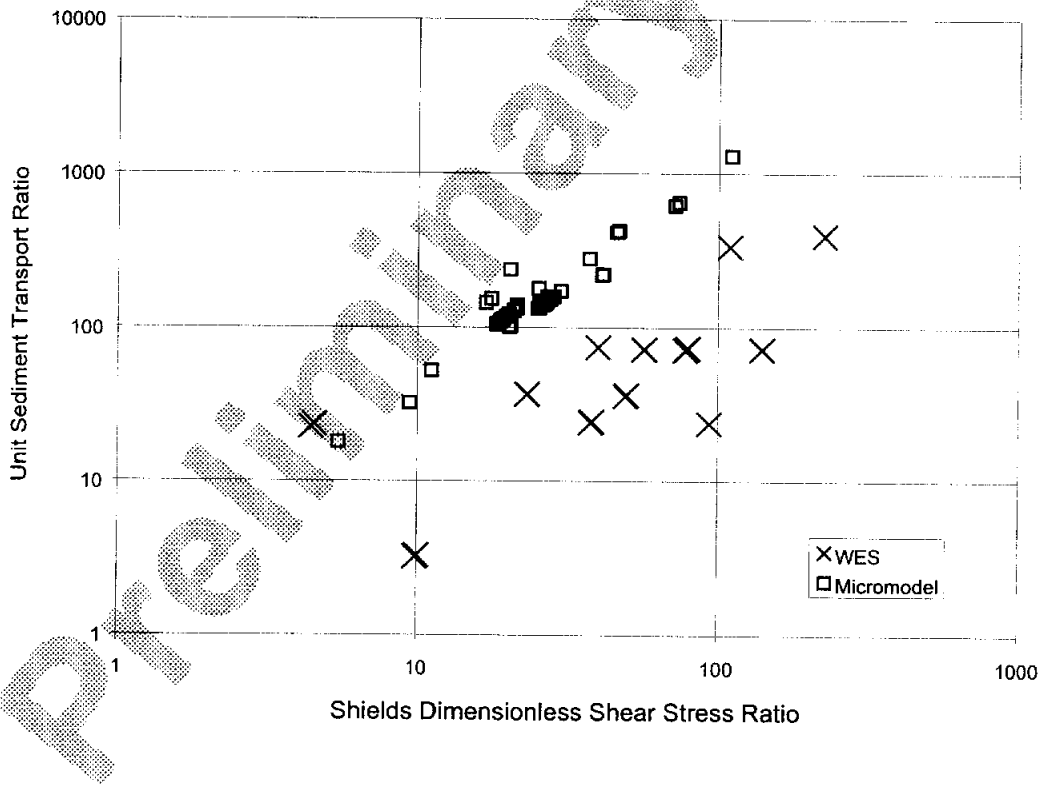

Figure 6-9 Shields Sediment Transport Relationship

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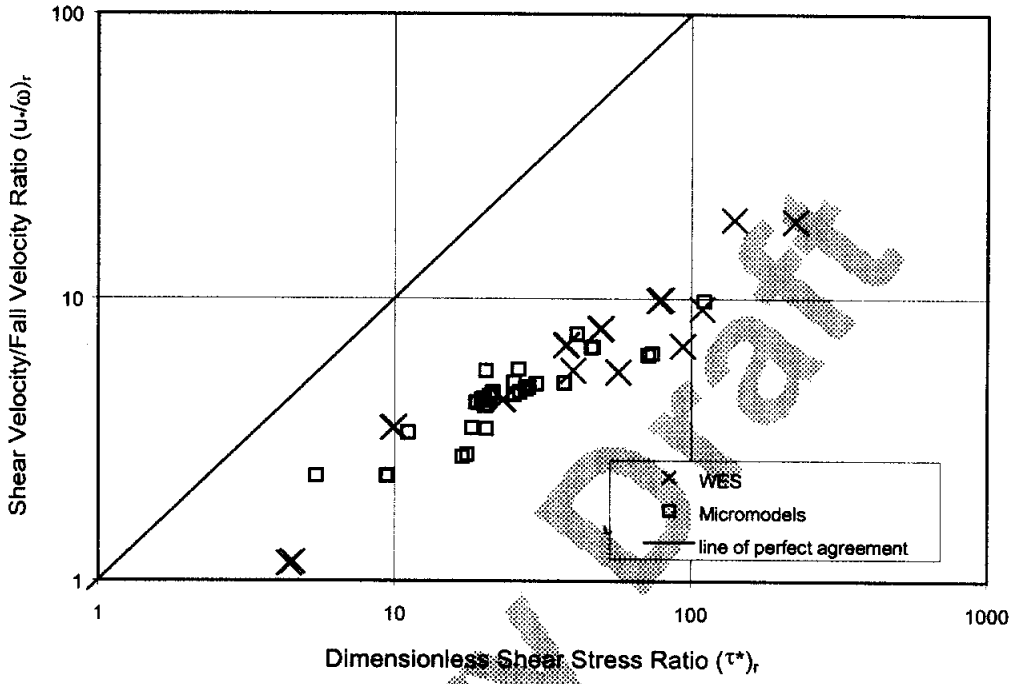

Figure 6-10 Zwamborn's Criterion for Morphological Similarity

small-scale model data exhibit a large amount of overlap with the large-scale model data. Because the micromodels had a relatively high degree of similarity using the Shields regime diagram (Figure 6-2), there is no utility in using the alternate parameter of u_*/ω for micromodel design.

6.2.5 Distortion Ratios. A graph of slope distortion factor (G) versus the roughness distortion factor (β) are shown in Figure 6-11 for fifteen assumed prototype H/W values. The figure H/W values ranged from 0.001 to 0.1. The range of H/W values for actual prototype reaches (0.005 to 0.05) fell within this interval. Prototype H/W values were used in calculating the hydraulic radius ratio (Equation (6-19)). The lines of equal H/W provide an indication of the degree of relaxation in the roughness distortion factor for a given model having scale ratios x_r and y_r.

The graph depicted in Figure 6-11 provides a means for balancing the relationship between slope distortion and the roughness distortion during model design.

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For example, a known prototype value of H/W can be used to assess the slope and roughness distortions calculated for a trial sediment material and slope in the model. Successive trials using different model sediment material gradations and model slopes could be used to achieve a better match between model and prototype for these factors.

Roughness plays in important role in many hydraulic phenomena. Therefore, consideration of the roughness (through relative roughness ratios and the roughness distortion factor) during model design can help achieve better reproduction of water surface slopes and velocity distributions. Because vertical scale is selected during calibration of the micromodels, the roughness distortion factor is not known *a priori*. Figure 6-11 could therefore be used to help establish roughness requirements for a model with a given vertical distortion. Data calculated from the thirty previous model studies are plotted on the figure for reference.

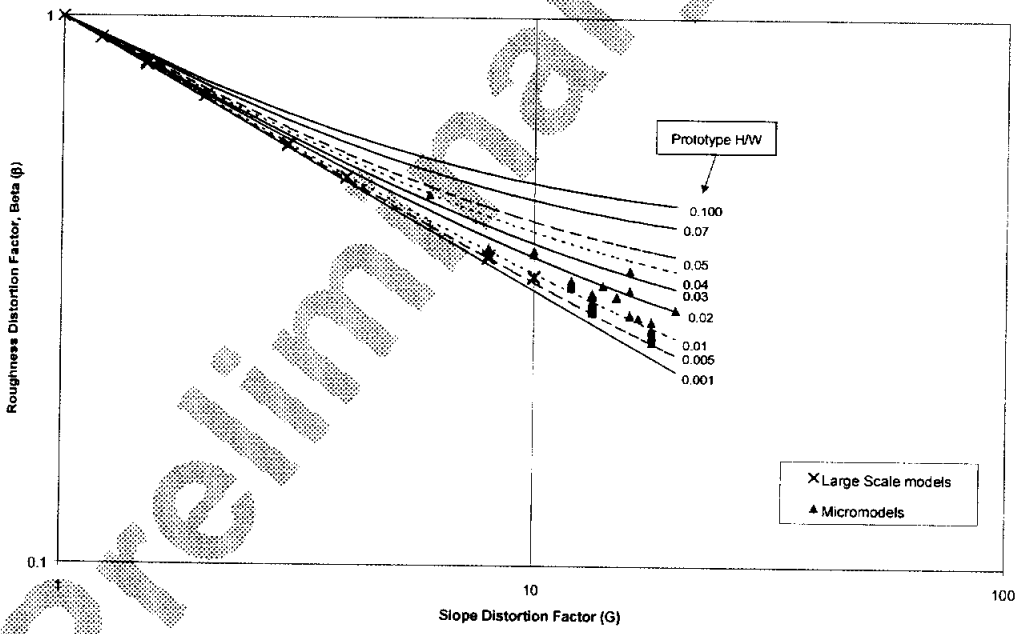

Figure 6-11 Slope versus Roughness Distortion for Prototype Depth to Width Ratios

An additional factor can be introduced to account for distortion of sediment mobility through the Shields dimensionless shear stress. Jansen (1979) describes the use

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of a ripple factor (μ_f) (also mentioned by Zwamborn, 1966, and Struiksma, 1980) to provide correction of the dimensionless shear stress (τ^*) in loose-bed models. Jansen(1979) modifies the shear stress equation by the addition of this factor as:

$$\tau^* = \frac{1}{y''} = \frac{\mu_f R_h S}{\Delta D} \qquad (6-34)$$

and

$$x'' = \frac{q_s}{D_{50}\sqrt{g\Delta}} \qquad (6-35)$$

where y" is listed as a flow parameter and x" is listed as a sediment transport parameter. The correction factor μ_f allows for the fact that only part of the shear stress is used for transport. Because μ_f also acts as a correction factor to adapt the basic formula to transport measurements, different expressions for μ_f have been developed. To date, very few experiments for testing $x''=\varphi(y'')$ and developing an expression for μ_f have been conducted. Jansen states that a logical choice is

$$\mu_f = \left(\frac{C}{C'}\right)^2. \qquad (6-36)$$

where C is the Chezy roughness and C' is the grain roughness component of the overall roughness.

Meyer-Peter and Muller used the D_{90} particle size to estimate C' (Equation 6-37). However, Meyer-Peter and Muller (1948) modified the exponent 2 to 3/2 for experiments using D≥4 mm and no suspended load. Many formulas can be written for $x''=\varphi(y'')$, but it is normally presented in the form $x=ay^b$ regardless of which transport formulas are used for the actual computations. The Meyer-Peter and Muller equations were

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1. Basic Form - $x = 13.3(y^{-1} - 0.0047)^{1.5}$
2. Ripple Factor

$$\mu_f = \left(\frac{C}{C'}\right)^{3/2} = \left(\frac{C}{5.75\sqrt{g}\log 12\frac{y}{D_{90}}}\right)^{\frac{3}{2}} \qquad (6\text{-}37)$$

3. Characteristic grain-size

$$D = \overline{D} = \sum^{i}\left(\frac{D_i}{P_i}\right)\sum^{i} P_i \qquad (6\text{-}38)$$

where D_i is the particle size for size fraction i and P_i is the percentage of each size fraction. The exponent b in the basic form is also the exponent of the ripple factor. The formula for $C' = \phi(D_{90})$ shown in equation (6-37) has been extensively tested and used for rivers with coarse bed material (Meyer-Peter and Muller, 1948, Jansen, 1978, Simons and Sentürk, 1992, Julien, 1995).

An approximation for μ_f can be obtained using Duboy's bed load transport equation and Yang's unit stream power equation. The value of the exponent b is the slope of a regression fit of the data when plotted on logarithmic coordinates with unit stream power as the abscissa and unit sediment transport plotted as the ordinate (e.g. Figure 6-8). Although data are insufficient to estimate the true value of μ_f for the current investigation, a significant finding is that the value of μ_f approximated from calculated slopes in Figure 6-8 are consistent for both the large-scale and small-scale models. The significance lies in the fact that although unit sediment transport rates and stream power are different for the large- and small-scale models, sediment transport characteristics are similar (e.g. the relationship between unit sediment transport and stream power behave in a similar manner).

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For basic similitude, the total roughness ratio (C_r) should be equal to the inverse of the square root of the slope ratio,

$$C_r = \frac{1}{\sqrt{S_r}} \tag{6-39}$$

Based upon previous efforts, with no correction for ripple factor,

$$C_r = \frac{1}{\beta} \tag{6-40}$$

and

$$\frac{1}{\sqrt{S_r}} = \sqrt{G} \tag{6-41}$$

From equation (6-36)

$$[\mu_f]_r = \left(\frac{C_r}{C_r'}\right)^b \tag{6-42}$$

where C'_r represents the grain roughness ratio. With no correction for ripple factor, the assumption was previously made that $C'_r = C_r$. The actual value of C'_r is different than C_r and the correction factor μ_f must be used to correct roughness and slope distortion. The exponent *b* is taken from the Yang's sediment transport relationship in Figure 6-8.

Therefore, the maximum correction needed to make Figure 6-4 equal to the line of perfect agreement (slope = 1:1) can be estimated as follows:

1. Given a fixed value of slope distortion (G), compute μ_{fr} for correcting roughness as μ_{fr}/β or given fixed values of roughness distortion $1/\beta$, compute μ_{fr} for correcting slope distortion as $G^{1/2}/\mu_f$ based on the equation

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$$(\mu_f)_r = \left[\beta\sqrt{G}\right]^{1.22} \qquad (6-43)$$

2. Using Equation (6-43) to calculate the correction factor μ_{fr}, the corrected roughness ratio becomes

$$C_{r_c} = \mu_{f_r}\left(\frac{1}{\beta}\right) \qquad \text{Roughness Correction}$$

or

$$\beta_c = \frac{\beta}{\mu_{f_r}} \qquad \text{Roughness Distortion Corrected}$$

3. Using Equation (6-43) to calculate the correction factor μ_{fr}, the corrected slope ratio is

$$\left(\frac{1}{\sqrt{S_r}}\right)_c = \left(\frac{\sqrt{G}}{\mu_{f_r}}\right) \qquad \text{Slope Correction}$$

or

$$G_c = \left(\frac{\sqrt{G}}{\mu_{f_r}}\right)^2 . \qquad \text{Slope Distortion Corrected}$$

The magnitude of μ_f provides an expression of the degree of relaxation found in the models. The value of μ_f for the micromodels ranged between 1.062 to 1.492 (a degree of relaxation of 6.2 percent to 49.2 percent). The value of μ_f for the large-scale models ranged between 1.000 and 1.086 (a degree of relaxation of 0.0 percent to 8.6 percent). Values of μ_{fr}, β_c, and G_c for all models are shown in Table A-2, Appendix A.

Figures 6-12 and 6-13 show the estimated maximum corrections plotted for roughness and slope, respectively, using the assumed distortion parameter. Actual model corrections would involve adjustments to both distortion parameters simultaneously.

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Future research is necessary to define the correction factor, μ_f. Additional data (e.g., slopes, hydraulic radius, and estimates of roughness) for model and prototype are needed to facilitate any future research.

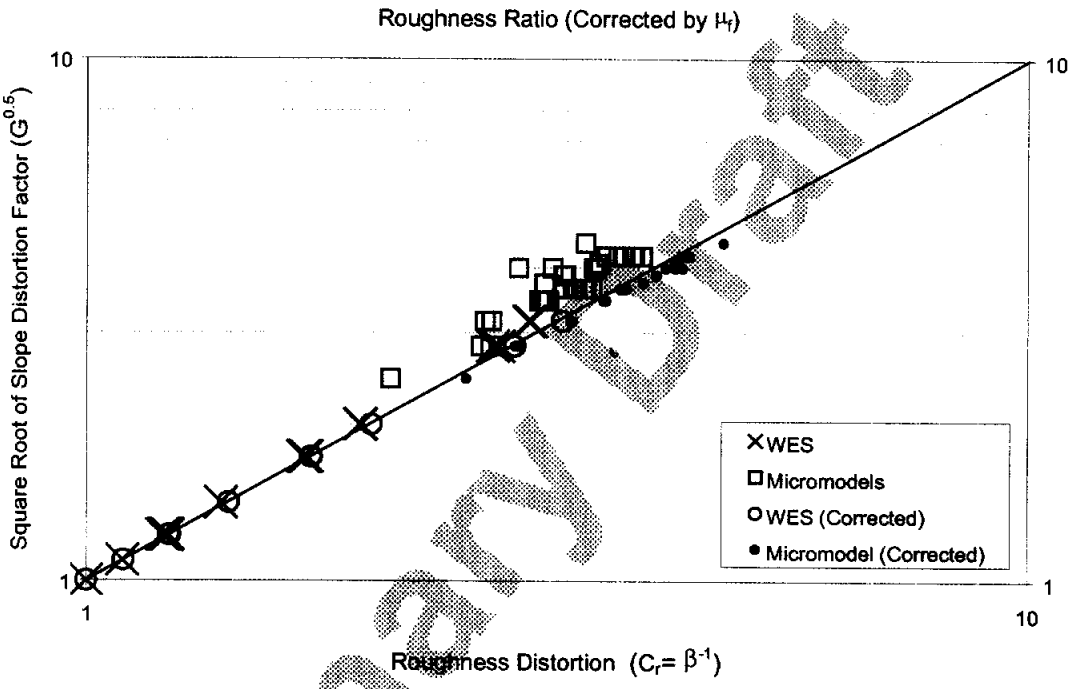

Figure 6-12 Model Roughness Distortion Corrected using Ripple Factor (μ_f)

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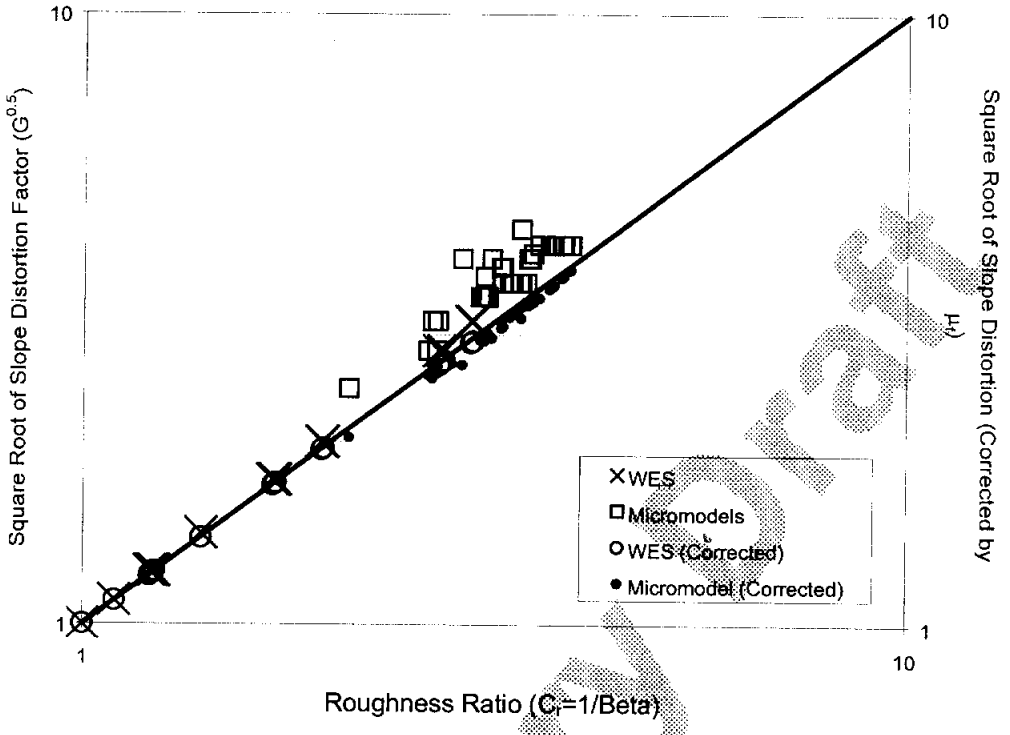

Figure 6-13 Model Slope Distortion Corrected using Ripple Factor (μ_f)

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APPENDIX D

COMPARISON STUDY OF DIKE SYSTEMS - FRANCO (1982)

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APPENDIX D: COMPARISON STUDY OF DIKE SYSTEMS - FRANCO (1982)

The following paragraphs are extracted from the introduction of the Franco (1982) report.

> The MRC Potamology Program included laboratory studies and field investigations to determine the characteristics of Mississippi River channels and factors affecting the performance of various types of training and channel stabilization structures. The first phase of the laboratory study was concerned with studies to determine factors affecting the performance of rock dikes and to develop design principles that would provide more effective structures at lower cost. These studies were conducted in an existing flume that permitted the reproduction of two alternate bends with a troublesome crossing in between which could be considered as typical of some of the problem reaches in the Mississippi River. Studies on rock dikes were suspended before they were completed to permit the study of side channel closure and to determine the effectiveness of dike systems proposed for the improvement of critical and unstable reaches. However, the study was successful in providing information on the performance of dikes and some of the basic principles that should be considered in the layout and design of rock dikes and dike systems.
>
> After the suspension of the dike study and some preliminary studies concerned with side-channel closures, the available facilities were used to obtain general indications as to the effectiveness of dike systems and plans proposed for the improvement of specific troublesome reaches of the Mississippi River. (This phase was later transferred to the MRC Channel Improvement Program.) It was realized at the time the studies were undertaken that the conventional type of movable-bed model study could not be made because of the limited size of the flume and limited time available for model adjustment and testing. The scales of the models and lengths of the reaches that could be reproduced were controlled by the size and shape of the available flume and the need for development of the hydraulic forces required to move the model bed material (fine sand) in simulation of the movement of sediment in the river reach under study. For this reason the horizontal scale ratios (model to prototype) were generally smaller and the distortions of the linear scales were generally much higher than were considered desirable for studies of this time. In spite of the limitations, it was believed that some general indications could be provided as to the performance of the proposed plans and of any modifications that might be required. The studies also provided representatives of the offices concerned an opportunity to observe developments in the model and to satisfy themselves as to the adequacy of any plan or modifications proposed.

The results of each model study were submitted to the District office concerned upon completion of each test without a formal report or a complete analysis and evaluation of the data obtained. The reaches studied in the models had been selected as study reaches in the river and were therefore observed closely in the field. Field data taken in these reaches included periodic surveys of the riverbed covering periods before, during, and after construction. These surveys also included some detailed water-surface elevations based on a number of temporary gages established for the purpose and, in some cases, current direction and velocities based on float observations.

In order to determine the value of these types of studies and some indication of the degree of accuracy possible, a comparison of model indications with developments in the field was authorized. This comparison involved an analysis of model results and procedure used and an analysis and evaluation of all data, comparison of model indications with prototype developments, and conclusions indicated. In order to reduce the time and cost involved, only sketches of selected surveys indicating the more significant developments are included herein. Also, evaluations and conclusions are based on the prototype data available at the time that the original draft was prepared on each reach. Any prototype surveys that were made and became available after that time are not considered. Initially, rough drafts of reports on each reach were prepared and submitted are included herein with some changes based on comments received and editing.

After analyzing each model-prototype case separately, Franco made conclusions about the overall model performance for the MRC potamology program. Final conclusions are extracted from the Franco (1982) report as follows:

The model studies covered herein were designed and conducted to obtain some quick indications as to the effectiveness of the plans proposed for the improvement of some of the more troublesome and complicated reaches of the Mississippi River. The plans tested were proposed by the sponsoring office and in some cases, modified during the course of the study in collaboration with representatives of the offices concerned. In most cases, construction had already been scheduled or was in progress at the time the model studies were undertaken. Because of the construction schedules for the various reaches, time did not permit the use of the conventional type of movable-bed model studies on any of the reaches.

All of the model studies were conducted in an existing facility, which was initially designed for research on dikes, and was limited in size and shape. The model horizontal scales varied from reach to reach as required to reproduce the essential features of the reach. The distortion of the linear scales (horizontal and vertical) varied from 6 to 10.83, which is considerably higher than would normally be used in studies of this type. Even with the high distortion, the hydraulic forces were not sufficient to move the model bed material (sand) in simulation of movement of sediment in the prototype without some exaggeration of the velocity scales.

Distortion of the linear scales produces a difference in the width-depth ratio of the model channel from that of the prototype, and exaggeration of the velocity scale produces some changes in the alignment of currents and in the proportional amount of lateral differential in water level. Because of these and other dissimilarities, the reliability of movable-bed models has to be based on verification of the model. Model verification is an intricate process of adjusting the hydraulic forces, operating technique, rate of introducing bed material, etc., until it has demonstrated its ability to reproduce conditions known to have existed in the prototype during a given period. Except in the case of Island No.63, adjustment of the models was limited by the time available, and in some cases, was omitted almost entirely. An important factor that has to be considered in the adjustment is the rate of introducing bed material in simulation of the sediment movement into the prototype reach from upstream, which varies with stage and discharge. If not properly adjusted, the model channel would aggrade or degrade with respect to the prototype channel and could affect the location, alignment, and depth of the low-water channel, and the amount and type of deposition, particularly in reaches that tend to be unstable. The effects could be cumulative if several runs are made without remolding the model bed to an existing prototype condition, as was the case in most of these studies. The model results could also be affected when reproducing prototype reaches that have gravel bars, remnants of old structures and islands, towheads, and old sandbars that have varying degrees of erodibility, the extent of which is generally not known, and are difficult to simulate in the model.

In the evaluation of the results of movable-bed model studies, the limitation of the model in reproducing prototype conditions as indicated by the verification of the model and the effects of the flow hydrograph on developments as indicated by the base test have to be considered. Use of the results of tests of improvement plans as obtained from the model without considering all of the factors involved and conditions imposed on the model could lead to conclusions not warranted by the results of the study. In comparing model indications, differences between plan tested and that constructed in the river, and the effects of any dredging in the

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prototype not reproduced in the model have to be considered. Also, all model surveys were made after a substantial high-water period and should compare more closely with prototype surveys made after a high-water period than those made in a low-water period.

The comparison of model results with prototype developments indicates that these types of models predicted, and least qualitatively, most of the principal trends that actually occurred in the river with the plans tested. The degree of accuracy of the models varied and depended to a considerable extent on the accuracy of the model adjustment, characteristics of the reach, flow conditions, and similarity between plans tested and actual construction. The greatest differences between model and prototype trends were obtained in the study of the Island 21-Wrights Point reach. In this case, the model indicated some deposition and reduction in flow in the side channel, which did not occur in the prototype with the plan tested. This model was not in good adjustment as indicated by the tendency for the model channel to degrade with some shoaling in the side channel not indicated by the prototype surveys available at that time. The reach was affected by the pile dikes, permeability, and condition and amount of stone fill, which were not adequately defined. The model did indicate the need and effectiveness of the closure dike across the side channel and the tendency for scouring below the dike.

The most accurate prediction of conditions that actually occurred in the river was obtained with the model of the Island No. 63 reach. This model was in good adjustment before tests of plans were undertaken and the flow hydrograph used was more indicative of the flow that actually occurred in the river than the hydrograph used in other studies. As a result, the model reproduced almost quantitatively conditions that developed in the river up to October 1976. In the Keyes Point-Forked Deer reach, the model indicated that none of the plans tested would produce a satisfactory channel. In the prototype, a satisfactory channel had not developed in that reach by the end of the study period, even with additional construction and considerable dredging. In the Carruthersville-Lindwood Bend Reach, the plan proposed and tested had not been completed in the river and a direct comparison between model and prototype could not be made. The model indicated that all of the structures as proposed for that reach would be required to develop a satisfactory channel around the concave side of the bend. The portion of the plan completed in the river did not produce the desired results even with considerable dredging, although some improvements were indicated.

Because of the complex nature of alluvial streams, the effectiveness of plans proposed for improvement of troublesome reaches cannot always be determined by analytical means. Although conventional types of movable-bed model studies would

generally provide better results, the types of studies described herein can be valuable in providing some general indications of the results that can be expected from a particular plan and the need for modifications at less cost than with the conventional type of studies. Franco (1982) states "experience with these studies indicates the need for model adjustment, evaluation of model results based on the accuracy of the adjustment, and the use of a flow hydrograph that would be more representative of flow conditions which can be expected in the reach under study than the hydrograph used in most of the tests."

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APPENDIX E

DOGTOOTH BEND WES MODEL STUDY: CASE STUDY OPINION DAVINROY (2002)

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Dogtooth Bend Case Study: A Typical Process of Modeling, Design, & Construction

The following describes the Dogtooth Bend model study and how the recommended conceptual design from this model was transferred to a final design, was constructed in the river and how the resultant bed configuration compared to the bed forms predicted by the model study.

During the early 1980's numerous collisions and groundings involving tows were occurring in bends on the Mississippi River within the St. Louis District. Two of these accidents resulted in major oil spills into the river. Due to point bar formation, repetitive maintenance dredging was required to artificially maintain adequate widths in these bends during low water conditions. Therefore, between 1984 and 1992, a movable bed model at WES was used by the St. Louis District to address these problems. Figure 1 shows the 1983 prototype bathymetry of the reach that was used for model verification. Figure 2 shows the model Base Test bathymetry used for making relative comparisons between alternative plans. In Figures 1 and 2, elevations above -10 LWRP are not color coded and may appear lightly shaded, light-blue represents elevations between -10 and -20 LWRP, dark blue represents elevations between -20 and -30 LWRP, and white represents elevations below -30 LWRP.

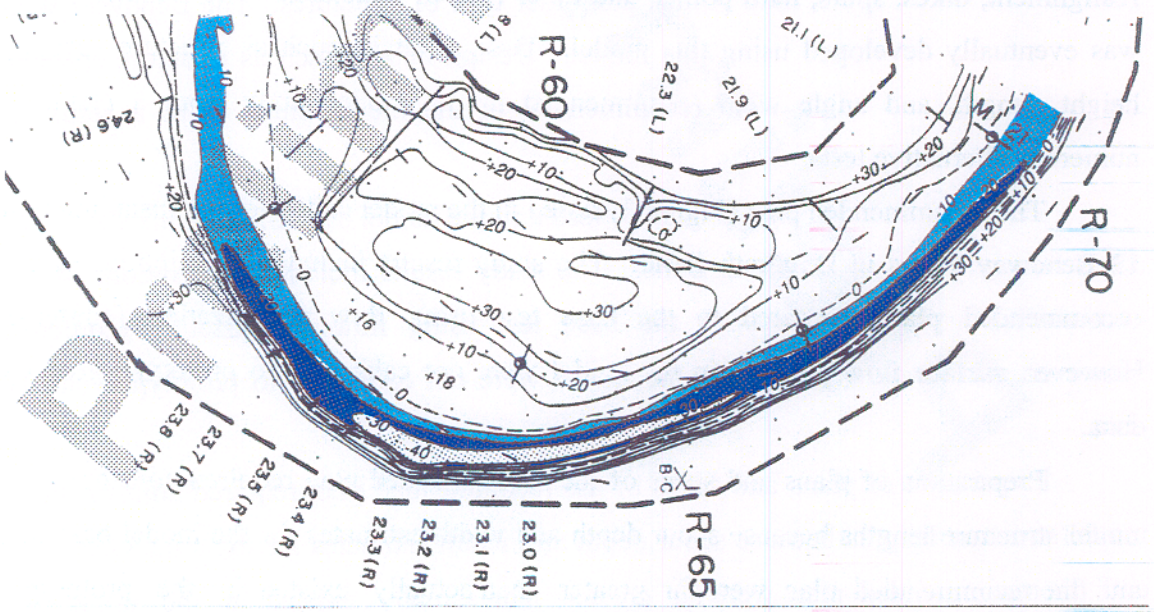

Figure 1 Prototype Bathymetry from 1983 Survey, Dogtooth Bend WES Model

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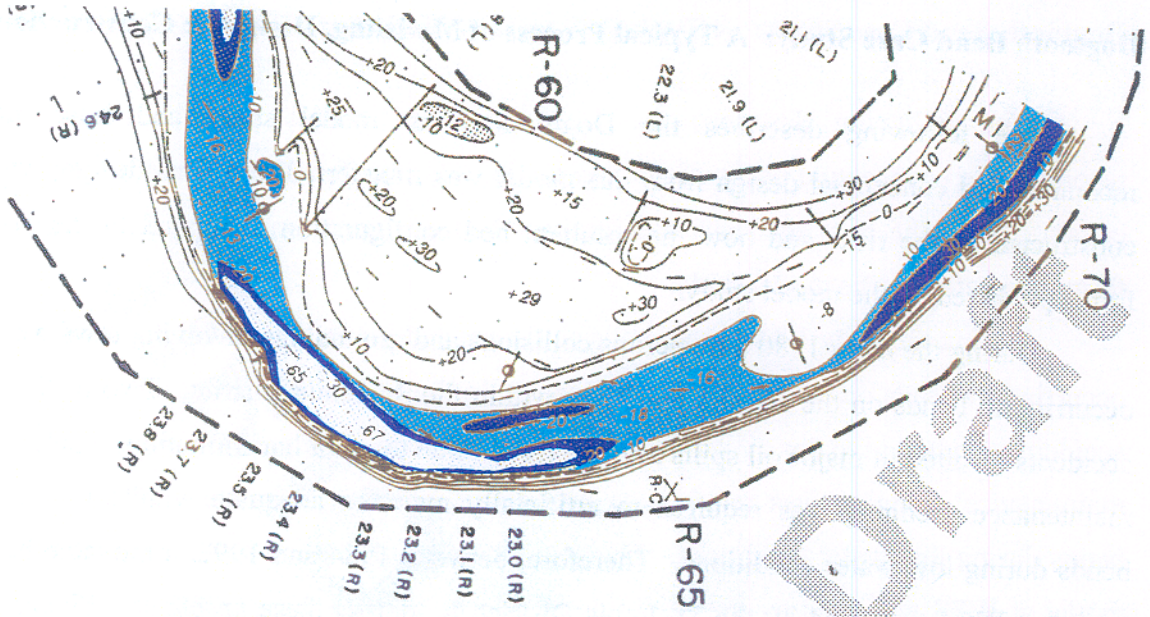

Figure 2 Model Base Test Bathymetry, Dogtooth Bend WES Model

Two particular bends (Prices Bend, Mile 30 and Dogtooth Bend, Mile 22) containing the highest accident rates were modeled as part of the Dogtooth Bend Movable Bed Model Study, Miles 40 to 20 (Technical Report HL-94-10). The model scales were 1:400 horizontal and 1:100 vertical (distortion of 4). The model was used to study a variety of design alternatives to address the bend problems, including channel realignment, dikes, spurs, hard points, and other type of structures. The Bendway Weir was eventually developed using this model. Design details such as structure spacing, height, length, and angle were recommended in the model study from a result of numerous alternative tests.

The recommended plan (Figure 3) tested in the model called for the installation of 13 Bendway Weirs in Dogtooth Bend. The study results included descriptions of the recommended plan compared to the base test using flow visualization (confetti). However, surface flow patterns in the model were not calibrated to prototype velocity data.

Preparation of plans and specs of the recommended plan required adjustment of model structure lengths because scour depth and width estimates for the model base test and the recommended plan were far greater than actually existed in the prototype.

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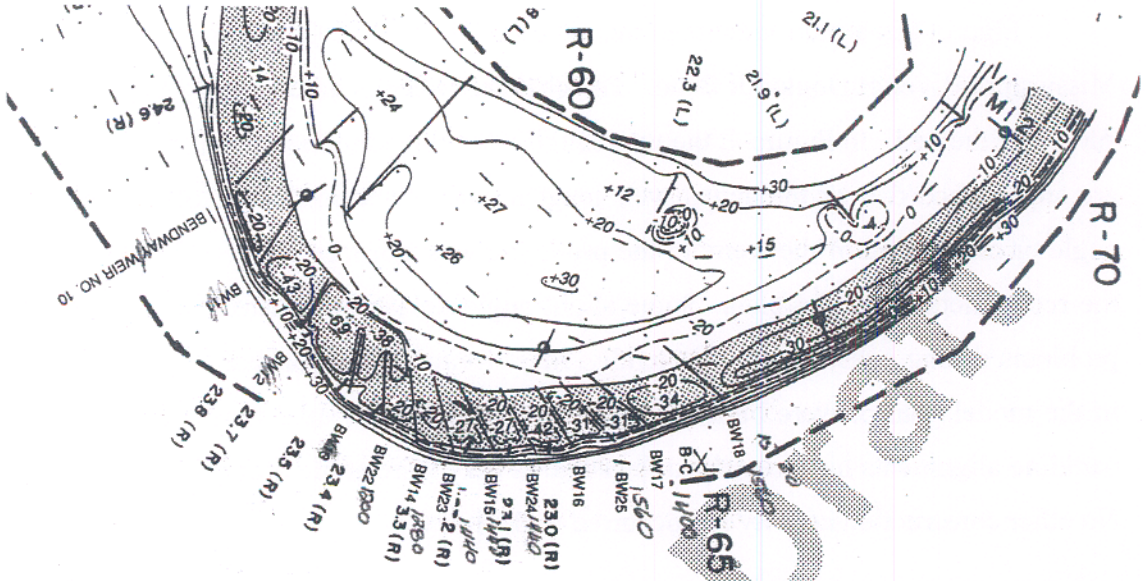

Figure 3 Recommended Bendway Weir Design Configuration and the Resultant Bed Configuration of the Dogtooth Bend WES Model.

Therefore, the lengths of the weirs had to be constructed considerably shorter than those tested in the model.

Table 1 shows weir lengths from the recommended design plan of the model study as compared to the actual constructed design. All weirs were model tested and constructed at –15 feet LWRP.

Table 1 Model Designed and Actual Constructed Bendway Weir Lengths.

Weir Number	Model Length (ft)	Actual Construction Length (ft)	Difference Model to Prototype (ft)
Weir 24.2	1520	650	870
Weir 23.8	1440	617	823
Weir 23.7	1060	525	535
Weir 23.5	1160	935	225
Weir 23.4	1200	880	320
Weir 23.3	1280	894	386
Weir 23.2	1440	962	478
Weir 23.1	1440	780	660
Weir 23.0	1440	735	705
Weir 22.9	1560	700	860
Weir 22.8	1400	700	700
Weir 22.7	1560	610	950
Weir 22.45	1520	610	910

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Figure 4 is a plan view map depicting a year 2000 channel sweep survey of the Mississippi River at Dogtooth Bend. The channel sweep is an extremely high-resolution survey of the bed. In Figure 4, the weir lengths developed in the model study plan (blue) are superimposed over the actual weir lengths constructed in the prototype (red). The angle or orientation of the weirs in the prototype was constructed as close as possible to the recommended model plan. Some slight angle deviations existed due to unforeseen problems during construction. Generally, most weirs were either built at the angle used in the model plan or were built at a slightly different angle of just a few degrees. The bankline alignments have remained the same as they were at the time of the model study. No other construction activity has occurred in the reach.

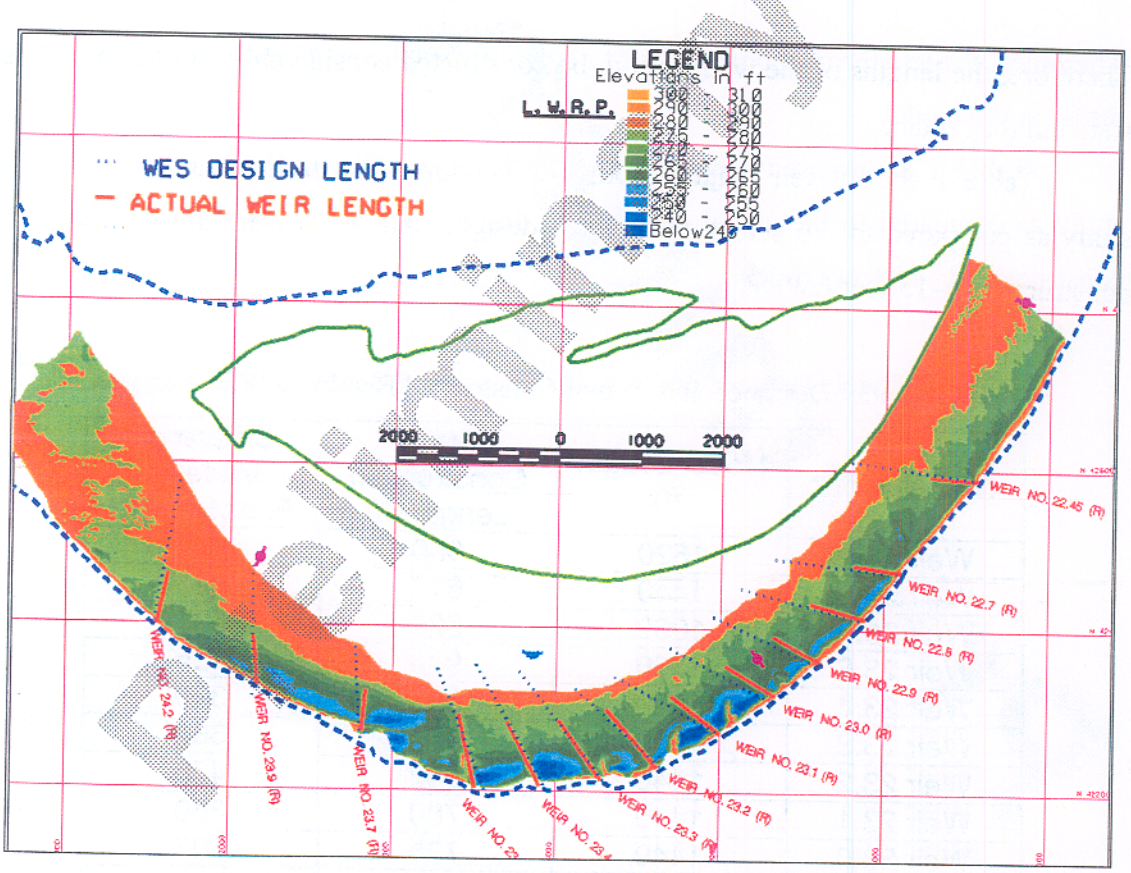

Figure 4 Year 2000 Hydrographic Channel Sweep Survey with the WES Model Recommended Design (Blue) Shown with the Constructed Structures (Red)

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Figure 5 shows the location of cross-section ranges used for the comparison of differences in the bed configuration observed in the prototype and predicted by the model. The ranges were slightly skewed in order to align the sections between weirs and to ensure that the structure profiles were not incorporated in the analysis. Cross-section plots of the model bed (blue) versus the 2000 sweep survey (red) are shown in Figures 6 through 14.

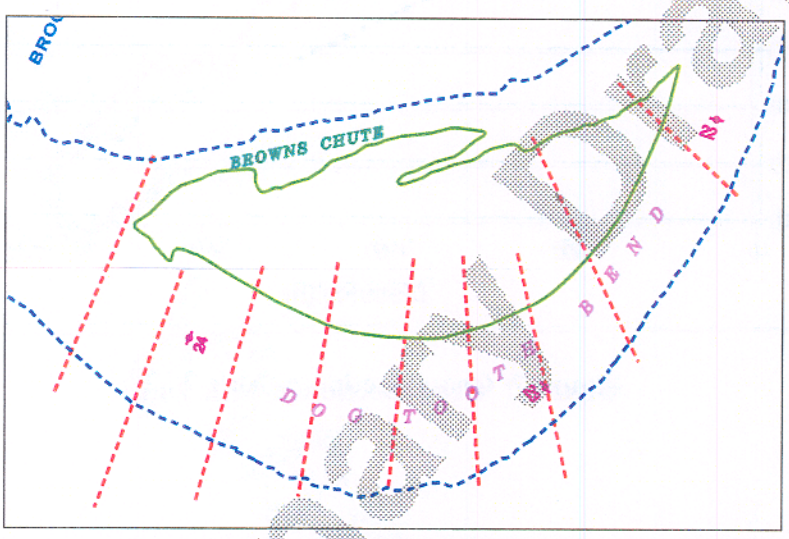

Figure 5 Cross-Section Ranges Established for Model to Prototype Comparison

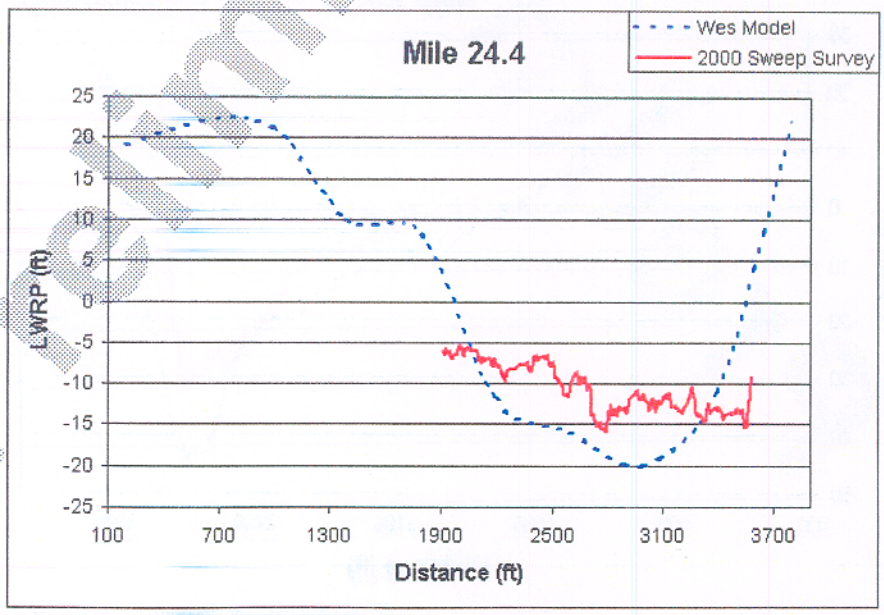

Figure 6 Cross Section at Mile 24.4

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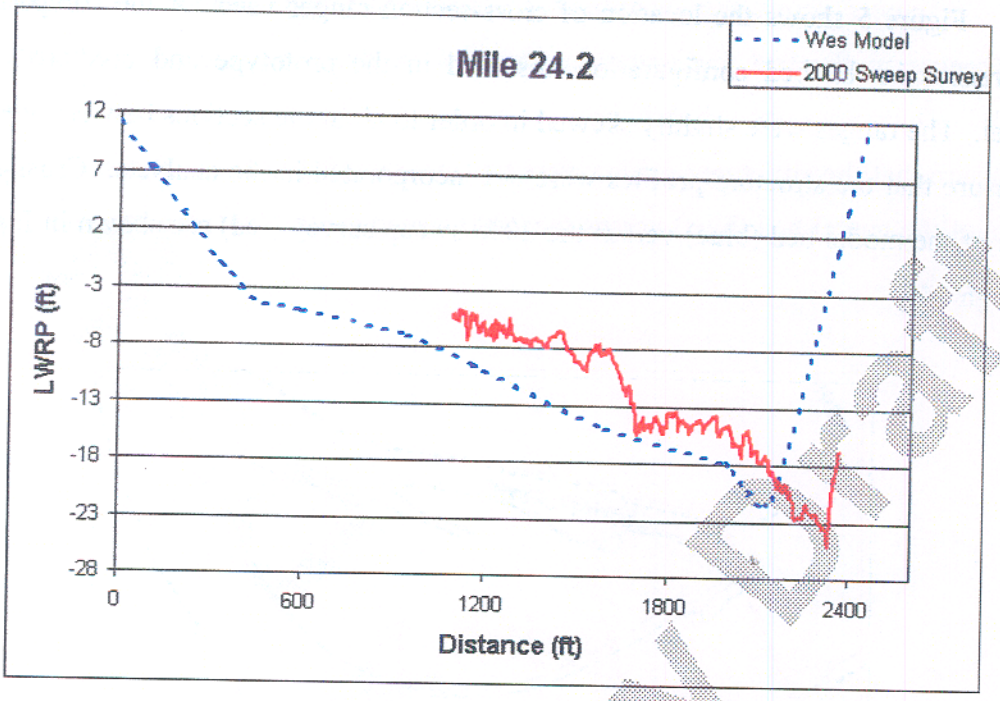

Figure 7 Cross Section at Mile 24.2

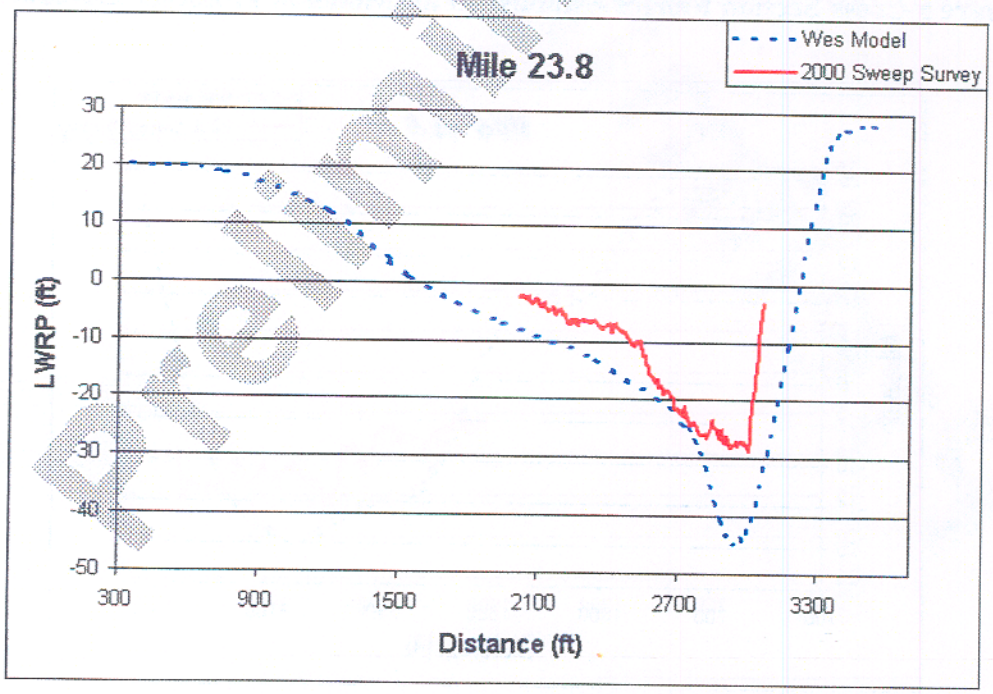

Figure 8 Cross Section at Mile 23.8

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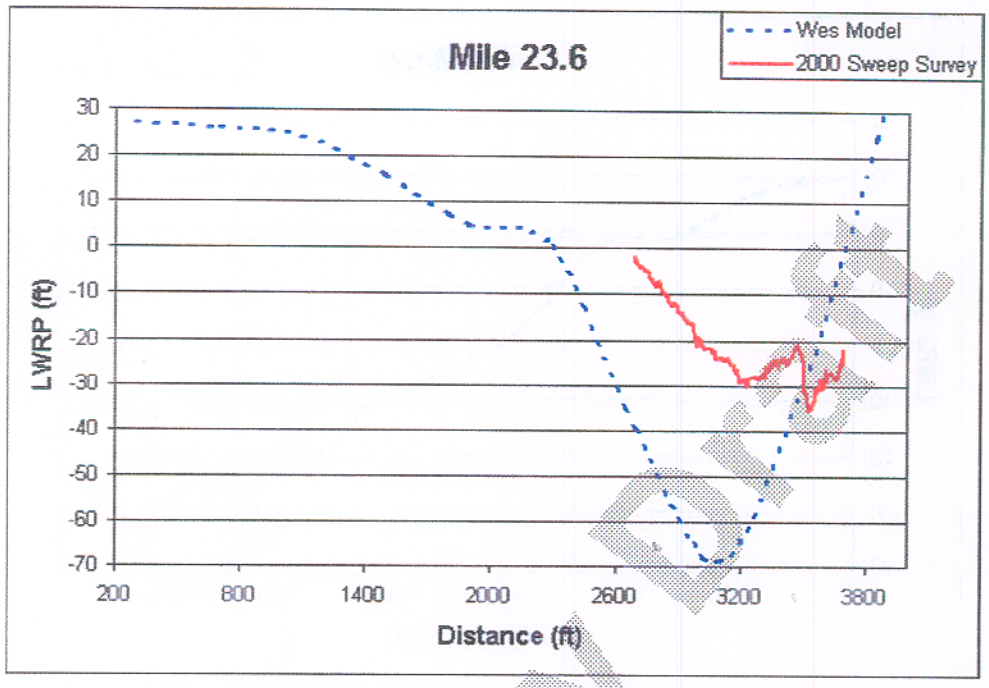

Figure 9 Cross Section at Mile 23.6

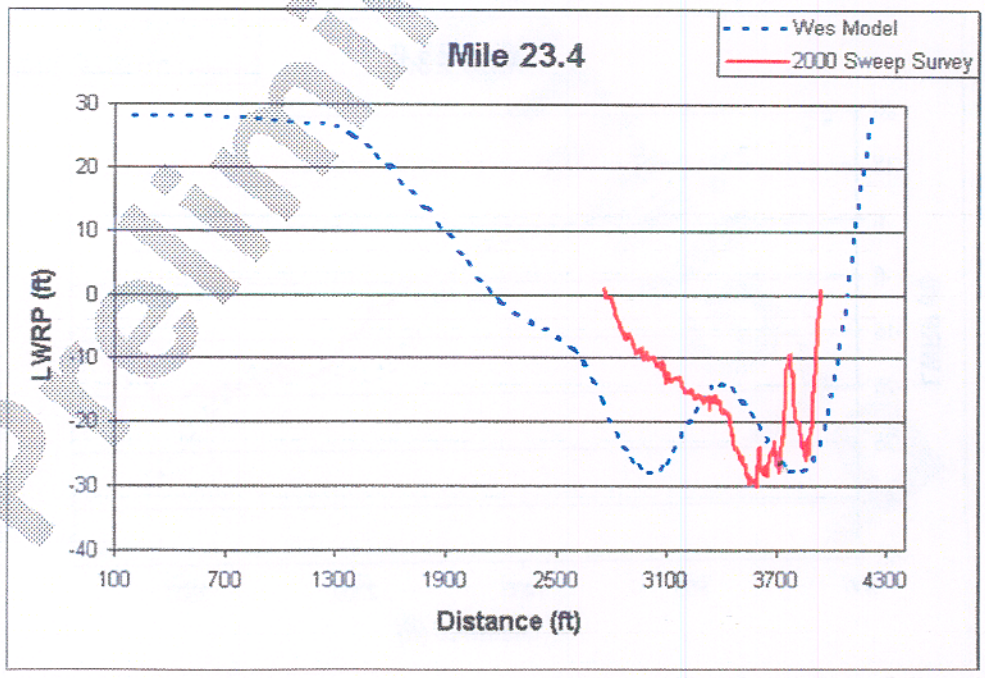

Figure 10 Cross Section at Mile 23.4

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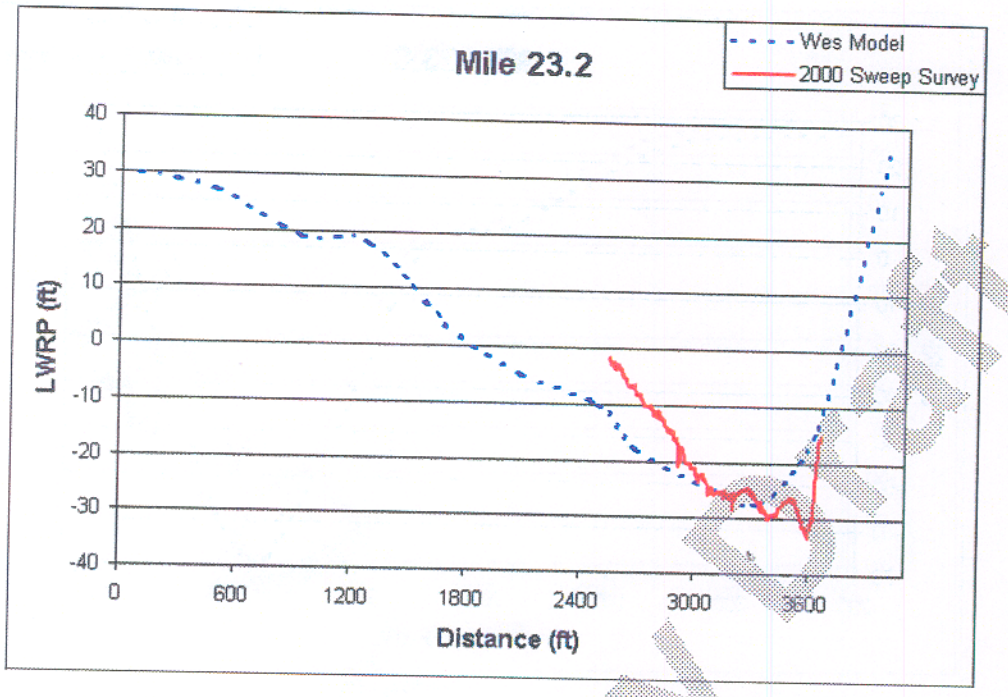

Figure 11 Cross Section at Mile 23.2

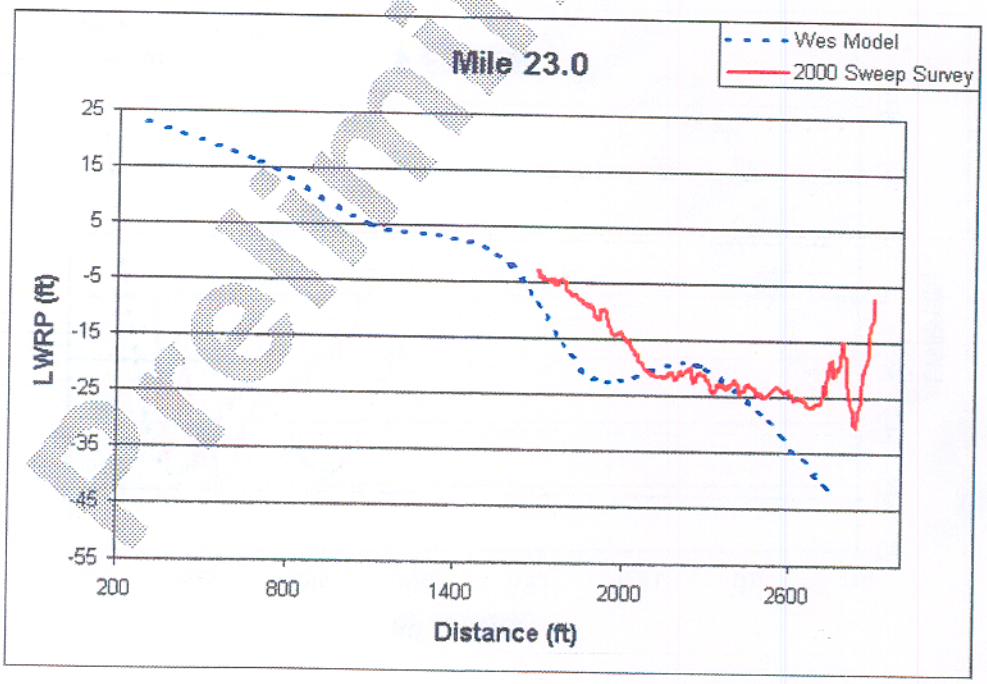

Figure 12 Cross Section at Mile 23.0

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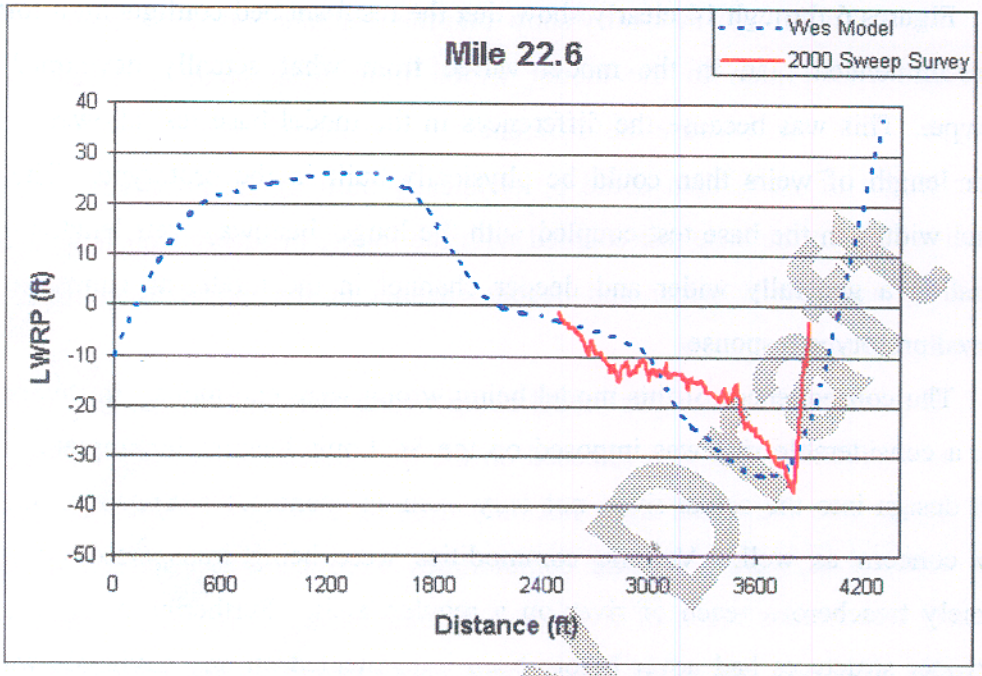

Figure 13 Cross Section at Mile 22.6

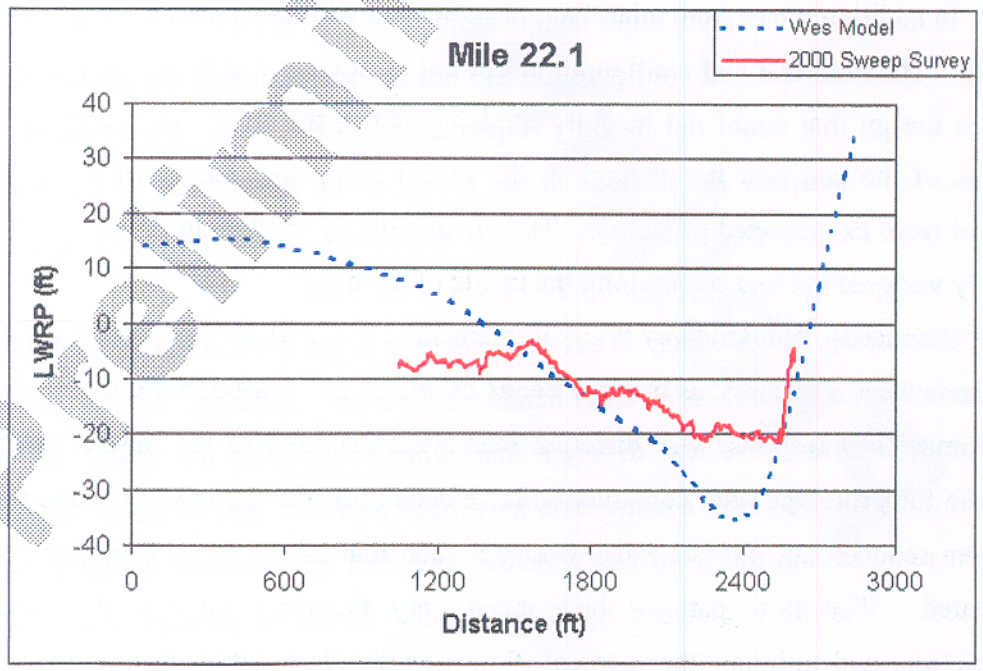

Figure 14 Cross Section at Mile 22.1

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Figures 6 through 14 clearly show that the resultant bed configuration formed by the recommended plan in the model varied from what actually developed in the prototype. This was because the differences in the model base test allowed for much greater length of weirs than could be physically built in the prototype. The greater channel widths in the base test coupled with the longer bendway weir lengths as tested resulted in a generally wider and deeper channel in the model as compared to the observed prototype response.

The consequences of this model being wrong were enormous. In this particular study, a considerable risk was imposed on the St. Louis District for implementing the model design into the actual river, not only from an economic perspective, but from a safety concern as well. Volatile commodities were being transported through this extremely treacherous reach of river on a regular basis. Furthermore, these types of underwater structures had never before been implemented on any navigable waterway. The structures were designed to have tows pass directly over top of the weirs but their effects on current patterns had not been completely established. Although flow visualization of surface floaters was used in the model, no prototype velocity data was collected to calibrate the model to.

In addition, there were other factors associated with the model itself that increased the risk. The base test bed configuration did not accurately match the prototype, which led to a design that could not be fully implemented in the river. Furthermore, several sections of the concrete flume floor in the model along the outside of the bend were exposed from exaggerated bed scour. This inconsistency created an armoring affect that laterally widened the bed scour along the inside of the bend.

Ultimately, the Bendway Weirs implemented in the Mississippi River at Dogtooth Bend have been a success, as in other bends on the river. Although the final design and the ultimate bed response was different than what occurred in the model, the general trends in the prototype after construction have been positive. The extent of the point bar has been reduced and the bend has widened such that maintenance dredging has been eliminated. The flow patterns have been very favorable through the bend after construction and mimics the general flow trends observed with the model flow visualization.

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A key factor for the success of this design was the use of a phased construction approach, with intense prototype monitoring conducted before, during, and after construction. Today, 185 of these structures have been constructed in phases at various bends in the river. Both accidents and dredging have been greatly reduced in these bends. As part of this phased approach, towboat pilots were interviewed as engineers rode through the bend to receive feedback on the navigation effects of the weirs. Adjustments were then made where appropriate.

The end result has been the successful implementation of a newly developed river training structure using a model that did not perform exactly like the prototype. However, were the engineers fooling themselves by using the results of this model? As with all other movable bed models of the past, the answer was no, because the engineers used the model as a general indicator of what could be expected to occur in the prototype and not the absolute indicator. The river engineers knew the limitations that existed in the model and still proceeded with design and construction. Then what were the consequences of the model being wrong? The better question is, what would be the consequences of ignoring the results of the model and not building any structures? The answer to this last question would be millions of dollars worth of additional dredging, more collisions and groundings, and more oil spills resulting in substantial environmental damage, and finally, the possibly of the loss of human life.

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REFERENCES

ASCE, (2000). *Hydraulic Modeling: Concepts and Practice*, Manuals and Reports on Engineering Practice no. 97, American Society of Civil Engineers, New York.

Blench, T., (1955). "Scale Relations Among Sand-Bed Rivers Including Models," Proceedings ASCE, vol. 81, no HY.

Blench, T., (1957). "Regime Behavior of Canals and Rivers," Butterworth, London.

Blench, T., (1964). "River Engineering," Illustrated Notes, Dept. of Civil Engineering, University of Alberta, Edmonton, Canada.

Blench, T., (1969). *Dimensional Analysis and Dynamical Similarity for Hydraulic Engineers*, University Bookstore, Edmonton, Alberta.

Biedenharn, D.S., (1995). *Lower Mississippi River Channel Response Past, Present, and Future*, Doctoral Thesis, Colorado State University, Fort Collins, CO.

Buffington, J.M., (1999). "The Legend of A.F. Shields," Journal of Hydraulic Engineering, ASCE, New York.

Davinroy, R.D., (1994). *Physical Sediment Modeling of the Mississippi River on a Micro Scale*, Masters Thesis, University of Missouri-Rolla, Rolla, Missouri.

Davinroy, R.D., (1999). "River Replication," Civil Engineering, July, ASCE, New York.

Davinroy, R.D., (2001). Personal Communication, St. Louis, MO.

Davinroy, R.D., (2002). Written Opinion on Dogtooth Bend WES Model Study, St. Louis, MO.

Derrick, D., Pokrefke, T.J., Jr., Marden, B.B., Crutchfield, J.P., and Henderson, R.R., (1994). "Design and Development of Bendway Weirs for the Dogtooth Bend Reach, Mississippi River, Hydraulic Model Investigation," Technical Report HL-94-10, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Einstein, H.A., (1950). "Report on the Investigation of the Fundamentals of the Action of River Training Structures," Contract No. DA-04-203-eng-191, US War Department.

Einstein, H.A., (1950). "The Bed Load Function for Sediment Transportation in Open Channel Flows," USDA Technical Bulletin 1026.

Einstein, H.A., and Barbarossa, (1952). "River Channel Roughness," Transactions, ASCE, Vol. 117.

Einstein, H.A., and Chien, N., (1956). "Similarity of Distorted River Models with Movable Beds," Transactions, ASCE, Vol. 121, New York.

Ettema, R., (2002). "Scale-Effect Trends on Flow Thalweg and Flow Separation at Dikes in Flat-bed Channels," Draft IIHR Technical Report No. XXX, University of Iowa, Iowa City, IA.

Ettema, R., (2000). "A Framework for Evaluating Micro-Models," *IIHR Limited Distribution Report* 295, Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, IA.

Foster, J.E., (1975). "Physical Modeling Techniques used in River Models," Proceedings of the 2nd annual Symposium on Model Technology, ASCE, New York.

Franco, J.J., (1978). "Guidelines for the Design, Adjustment, and Operation of Models for the Study of River Sedimentation Problems," Instruction Report H-78-1, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Franco, J.J., (1982). "Model-Prototype Comparisons Study of Dike Systems, Mississippi River," Technical Report HL-82-10, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Freeman, J.R., (Editor), (1929). *Hydraulic Laboratory Practice*, ASME, New York.

Gaines, R.A., (2002). *Micro-Scale Moveable Bed Physical Sediment Models*, Dissertation, University of Missouri-Rolla, Rolla, MO.

Gaines, R.A., (1999). "Micromodel Procedures," Report to UMR Graduate Committee, Unpublished.

Gaines, R.A. and Maynord, S.T., (2001). "Microscale Loose-Bed Hydraulic Models," Journal of Hydraulic Engineering, Vol. 127, No.5 , ASCE, New York.

Gaines, R.A., Gordon, D., and Maynord, S.T., (2022). "Comparison Studies to Determine Model to Prototype Agreement," Technical Report In Progress, US Army Corps of Engineers, Memphis, TN.

García, M., (2000). "Discussion: The Legend of A.F. Shields," Journal of Hydraulic Engineering, ASCE, New York, pp 718-720.

Garde, R.J. and Ranga Raju, K.G., (1974). *Mechanics of Sediment Transportation and Alluvial Stream Problems*, John Wiley and Sons, New York.

Gasser, M.M., Ahmed, A.F., and Gaweesh, M.T.K., (1989). "Calibration of Beni-Mazar Movable Bed Model," Journal of Hydraulics, ASCE, New York.

Gehrig, W. and Jurisch, R., (1981). "Model Investigation with Movable Bed to Simulate the Bed Level Downstream of a Barrage," Proceedings 19th Congress of the IAHR, New Delhi, India.

Gehrig, W., (1967). "Über die Frage der naturähnlichen Nachbildung der Feststoffbewegung in Modellen," Dissertation, Mitt.H.29, Franzius Inst. TH Hannover.

Gehrig, W., (Edited by H. Kobus), (1980). "Hydraulic Modeling," German Association for Water Resources and Land Improvement, Bulletin 7, issued in co-operation with IAHR, pp 323.

Gessler, D., Gessler, J., and Watson, C.C., (1998). "Prediction of Discontinuity in Stage-Discharge Rating Curves," ASCE, Journal of Hydraulic Engineering, March, New York.

Gessler, J., (1971). "Modeling of Fluvial Processes," River Mechanics Volume II, H.W. Shen, Fort Collins, Colorado.

Glazik, G., (1969). "Practical Performance of River Scale Model Tests with Movable Bed," XIII th Congress of the IAHR, Kyoto, Proceedings Vol. 5-1, (Seminars), pg. 211.

Glazik, G., (1978). "Morphological Processes in Hydraulic River Models with Movable Bed and Practical Performance of Scale Model Tests," Advances in Sediment Transport, Polish Academy of Sciences, Conference Jablonna, Wydawnictwo "Ossolineum," Wroclaw.

Glazik, G., (1984), "Influence of River Model Distortion on Hydraulic Similarity of Structures Arranged at the Channel," Proceedings, Symposium on Scale Effects in Modeling Hydraulic Structures, IAHR, Esslingen.

Graf, W.H., (1984). *Hydraulics of Sediment Transport*, Water Resources Publications, Littleton, Colorado.

Gray, D.D., (1999). *A First Course in Fluid Mechanics for Civil Engineers*, Water Resources Publications, Colorado.

Gujar, V.G., (1981). " Determination of Scales for Mobile Bed Models with Special Reference to River Models," Irrigation and Power, Vol. 38, No. 2.

Jaeggi, M.N.R., (1986). "Non Distorted Models for Research on River Morphology," Proceedings of Symposium '86, IAHR, Toronto, Canada.

Jain, S.C., (1981). "Quantification of Movable-Bed Model Verification," Proceedings 19th Congress of the IAHR, New Delhi, India.

Jansen, P.Ph., (1979). *Principles of River Engineering*, Pitman Publications, Ltd., London.

Johnson, P.A. and Brown, E.R., (2001). "Incorporating Uncertainty in the Design of Stream Channel Modifications," Journal of the American Water Resources Association, No. 01121, pp. 1225-1236.

Jonte, M., (1949). "Note sur l'étude des coupures des boucles de l'Isére en amont de Grenoble,", (Proposed cutoffs of the Meanders in the Isére River Upstream of Grenoble), La Houille Blanche, Vol. 4, spec. no. A, p376.

Kobus, H., (1980). "Hydraulic Modeling," German Association for Water Research and Land Development, Bulletin No. 7.

Kobus, H., (Editor), (1984). "Symposium of Scale Effects in Modeling Hydraulic Structures," IAHR, Stuttgart, Germany.

Leopold, L.B., Wolman, M.G., and Miller, J.P. (1964). *Fluvial Processes in Geomorphology*, Freeman, San Francisco, CA 522 pp.

Preliminary Draft

Lopez, F. and Garcia, M., (2001). "Risk of Sediment Erosion and Suspension in Turbulent Flows," Journal of Hydraulic Engineering, Vol. 127, No. 3, March, 2001, New York, pp. 231-235.

Melville, B.W. and Coleman, S.E. (2000). *Bridge Scour*, Water Resources Publications, LLC, Highlands Ranch, Colorado.

Parker, G., (1998). "River Meanders in a Tray," Nature, Vol. 395.

Parker, G., Wilcock, Peter R., (1993). "Sediment Feed and Recirculation Flumes: Fundamental Difference," ASCE, Journal of Hydraulic Engineering, Vol. 119, No. 11.

Reynolds, O., (1888). "On Certain Laws Relating to the Regime of Rivers and Estuaries, and on the Possibility of Experiments on a Small Scale," Report of the British Association, Water Resource Center Archives, University of California, Berkley.

Rosgen, D., (1996). *Applied River Morphology*, Wildland Hydrology, Colorado.

Rouse, H., (1934). "Evaluation of Boundary Roughness," Second Hydraulics Conference, Bulletin 27, University of Iowa Studies in Engineering, 1934.

Rouse, H., (1938). *Fluid Mechanics for Hydraulic Engineers*, Dover Publications, Inc., New York.

Rouse, H., (1939). "Experiments on the Mechanics of Sediment Suspension," Proceedings 5th International Congress of Applied Mechanics.

Rouse, H., (1946). *Elementary Mechanics of Fluids*, John Wiley & Sons, Inc., New York.

Shen, H.W., (Editor), (1971). *River Mechanics Volume I*, H. W. Shen Publisher, Fort Collins, Colorado.

Shen, H.W., (Editor), (1971). *River Mechanics Volume II*, H. W. Shen Publisher, Fort Collins, Colorado.

Shen, H.W., (1986). "Movable Bed River Models," Proceedings of Symposium '86, IAHR, Toronto, Canada.

Shen, H.W., (editor), (1990). *Movable Bed Physical Models*, NATO, Kluwer Academic Publishers, Boston.

Stevens, J.C., (Editor), (1942). *ASCE Manual 25: Hydraulic Models*, American Society of Civil Engineers.

Struiksma, N., (1980). "Recent Developments in Design of River Scale Models with Mobile Bed," IAHR Symposium, Belgrad and Delft Hydraulics Laboratory, Publication No. 236.

Struiksma, N., (1983). "Bakelite as Bed Material in River Scale Models with Moveable Bed," TOW Rivers, Report S 276/R 1119.

Struiksma, N., (1983). "Results of Movable Bed Experiments in the DHL Curved Flume," Delft Hydraulics Laboratory, TOW Rivers, Report R 657-XVII.

Preliminary Draft

Struiksma, N., (1986). "Scale Effects in the Reproduction of the Overall Bed Topography in River Models," Proceedings Symposium on Scale Effects in Modeling Sediment Transport Phenomena, IAHR, Toronto, Canada.

Suga, K., and Baba, Y., (1971). "Effects of Distorted Models of Curved Channels," Annual Conference, Japan Society of Civil Eng.

Suga, K., (1973). "Some Notes on Hydraulic Model Tests of River Channels," Proceedings of the IAHR Symposium on River Mechanics, Bangkok, Thailand.

USBR, (1980). *Hydraulic Laboratory Techniques*, Water Resources Technical Publication, Denver, Colorado.

Vollmers, H.J., (1989). "The State of Art of Physical Modeling of Sediment Transport," Sediment Transport Modeling: Proceedings of the International Symposium, Hydraulics Division, ASCE, New York.

WES, (1949). "Report of First Conference with Hydraulics Consultants on Effects of Model Distortion on Hydraulic Elements," Unpublished Report, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

WES, (1950a). "Report of Second Conference with Hydraulics Consultants on Effects of Model Distortion on Hydraulic Elements," Unpublished Report, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

WES, (1950b). "Report of Third Conference with Hydraulics Consultants on Effects of Model Distortion on Hydraulic Elements," Unpublished Report, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

WES, (1957). "Triangular-Flume Study of Distortion Effects," Research Report No. 2-1, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

Williams, G.P., (1970). "Flume Width and Water Depth Effects in Sediment-Transport Experiments," Sediment Transport in Alluvial Channels, Geological Survey Professional Paper 562-H, US Geological Survey, Washington, D.C.

Yalin, M.S., (1965). "Similarity in Sediment Transport by Currents," Hydraulic Research Station, Paper No. 6, Wallingford.

Yalin, M.S., (1971). *Theory of Hydraulic Models*, MacMillan Press LTD, London.

Yalin, M.S., (1986). "Some Aspects of Physical Modeling on Flows with a Free Surface," Proceedings of Symposium '86, IAHR, Toronto, Canada.

Yalin, M.S., (1992). *River Mechanics*, Pergamon Press, New York.

Yang, C.T., (1996). *Sediment Transport Theory and Practice*, McGraw-Hill Companies, Inc., New York, NY.

Zwamborn, J.A., (1966). " Reproducibility in Hydraulic Models of Prototype River Morphology," La Houille Blanche, No. 3.

Zwamborn, J.A., (1967). "Solution of River Problems with Movable-bed Hydraulic Models," CSIR Report, MEG 597, Pretoria, South Africa.

Preliminary Draft

MICROMODEL STUDY REPORTS

Boeckmann, J. D., Davinroy, R. D., Gordon, D. C. and Rhoads, A. M., (2000). Sedimentation and Navigation Study of the Lower White River Near Augusta and Clarendon, Arkansas, Technical Report M12, U.S. Army Corps of Engineers St. Louis District, Hydrologic and Hydraulics Branch, Applied River Engineering Center St. Louis, MO.

Davinroy, R. D., (1995). Sedimentation Study of the Mississippi River New Madrid Reach, Miles 891 to 883, Hydraulic Micro Model Investigation, St. Louis District Corps of Engineers, Potamolgy Section, Hydrologic and Hydraulic Engineering Branch, St. Louis, MO.

Davinroy, R. D., Gordon, D. C. and Hetrick, R. D., (1998). Navigation Study at the Approach to Lock and Dam 24, Upper Mississippi River, Hydraulic Micro Model Investigation, Technical Report M2, U.S. Army Corps of Engineers St. Louis District, Hydrologic and Hydraulics Branch, Applied River Engineering Center St. Louis, MO.

Davinroy, R. D., Gordon, D. C., and Hetrick, R. D., (1998). Navigation Study at the Approach to Lock and Dam 24, Upper Mississippi River, Hydraulic Micro Model Investigation, Technical Report M2, U.S. Army Corps of Engineers St. Louis District, Hydrologic and Hydraulics Branch, Applied River Engineering Center St. Louis, MO.

Davinroy, R. D., Gordon, D. C., and Hetrick, R. D., (1996). Sedimentation Study of the Mississippi River Sante Fe Chute, Doolan Chute Hydraulic Micro Model Investigation, Technical Report M1, U.S. Army Corps of Engineers St. Louis District, Hydrologic and Hydraulics Branch, Applied River Engineering Center St. Louis, MO.

Davinroy, R. D., Gordon, D. C. and Riiff, E. H., (1998). Sedimentation and Navigation Study of the Lower Mississippi River at the White River Confluence, Miles 603 to 596, Hydraulic Micro Model Investigation, Technical Report M7, U.S. Army Corps of Engineers St. Louis District, Hydrologic and Hydraulics Branch, Applied River Engineering Center St. Louis, MO.

Davinroy, R. D., Gordon, D. C. and Riiff, E. H., (2000). Sedimentation Study at Memphis Harbor Lower Mississippi River, River Miles 742 to 735, Hydraulic Micro Model Study, Technical Report M8, U.S. Army Corps of Engineers St. Louis District, Hydrologic and Hydraulics Branch, Applied River Engineering Center St. Louis, MO.

Davinroy, R. D., Gordon, D. C., Rhoads, A. M. and Riiff, E. H., (2000). Environmental and Navigation Improvement Study of Wolf Island Mississippi River, Miles 936.5

Preliminary Draft

to 929, Technical Report M9, U.S. Army Corps of Engineers St. Louis District, Hydrologic and Hydraulics Branch, Applied River Engineering Center St. Louis, MO.

Davinroy, R. D., Gordon, D. C., and Hetrick, R. D., (1997). Sedimentation Study of the Mississippi river Marquette Chute Hydraulic Micro Model Investigation, Technical Report M3, U.S. Army Corps of Engineers St. Louis District, Hydrologic and Hydraulics Branch, Applied River Engineering Center St. Louis, MO.

Kirkeeng, T. A., Davinroy, R. D., Gordon, D. C. and Mathes, C. J., (1998). Navigation Improvement Study of the Upper Mississippi River Near Savanna Bay, Pool 13, Sedimentation and Hydrodynamic Investigation, Technical Report M6, U.S. Army Corps of Engineers Rock Island District, Operations Division, Rock Island, IL.

Kirkeeng, T.A. and Landwehr, K.J., (2001). Navigation Study Ballard's Island, Illinois River, River Miles 247.2 To 248.8, Marseilles Pool, Hydraulic Micro Model and Numerical Model Investigation, Technical Report M18, U.S. Army Corps of Engineers Rock Island District, Hydraulics Branch – Hydrologic Engineering Section, Rock Island, IL.

Preliminary Draft

BIBLIOGRAPHY

Allen, J., (1942). "An Investigation of the Stability of Bed Materials in a Stream of Water," Journal Inst. C.E., March.

Allen, J., (1947). *Scale Models in Hydraulic Engineering*, Longmans, Green and Co., New York.

ASCE, (1975). *Sedimentation Engineering*, Manuals and Reports on Engineering Practice no. 54, American Society of Civil Engineers, New York.

ASCE, (2000). *Hydraulic Modeling: Concepts and Practice*, Manuals and Reports on Engineering Practice no. 97, American Society of Civil Engineers, New York.

Avery, P., (1982). "Problems of Sedimentation Modeling with Particular Reference to River Intake Models," Conference Proceedings, International Conference on Hydraulic Modeling of Civil Engineering Structures, Coventry, England.

Barr, D.I.H, (1968). "Discriminating Formulation of n Term Non-dimensional Functional Equations from, (n+1) Term Dimensionally Homogeneous Equations, with Particular Reference to Incompressible Viscous Flow," Proceedings, Institute Civil Engineers, Vol. 39.

Barr, D.I.H., (1969). "Basic Procedures for the New Approach to Similitude," Water Power Spray.

Barr, D.I.H., and Herbertson, J.G., (1968). "A Similitude Framework for Regime Theory," Proceedings, ICE, Vol. 41.

Barr, D.I.H., and Herbertson, J.G., (1968), "Similitude Theory Applied to Correlation of Flume Sediment Transport Data," Water Resources Research, Vol. 4, No. 2.

Barr, D.I.H., and Smith, A.A., (1967). "Application of Similitude Theory to Correlation of Uniform Flow Data," The Institution of Civil Engineers, London.

Blench, T., (1955). "Scale Relations Among Sand-Bed Rivers Including Models," Proceedings ASCE, vol. 81, no HY.

Blench, T., (1957). "Regime Behavior of Canals and Rivers," Butterworth, London.

Blench, T., (1964). "River Engineering," Illustrated Notes, Dept. of Civil Engineering, University of Alberta, Edmonton, Canada.

Blench, T., (1969). *Dimensional Analysis and Dynamical Similarity for Hydraulic Engineers*, University Bookstore, Edmonton, Alberta.

Biedenharn, D.S., (1995). *Lower Mississippi River Channel Response Past, Present, and Future*, Doctoral Thesis, Colorado State University, Fort Collins, CO.

Bogardi, J., (1974). *Sediment Transport in Alluvial Streams*, Akadémiai Kiadó, Budapest, Hungary.

Buchanan, T.J. and Somers, W.P., (1969). "Discharge Measurements at Gaging Stations," Techniques of Water Resources Investigations, US Geological Survey, *Book 3*, Chapter A8.

Buffington, J.M., (1999). "The Legend of A.F. Shields," Journal of Hydraulic Engineering, ASCE, New York.

Central Board of Irrigation and Power, (undated), Manual on River Behaviour, Control and Training, Publication No. 6.

Chauvin, J.L., (1962), "Similitude des modèles de cours d'eau à fond mobile, (Similitude in movable-bed river models)," Bulletin du centre de Recherches et d'Essais de Chatou, No. 1, T.P. 240.

Chow, V.T., (1959). *Open Channel Hydraulics*, McGraw-Hill Inc., New York.

Cunge, J.A., Holly, F.M., and Verwey, A., (1980). *Practical Aspects of Computational River Hydraulics*, Pitman Advanced Publishing Program, Boston, MA.

Davinroy, R.D., (1994). *Physical Sediment Modeling of the Mississippi River on a Micro Scale*, Masters Thesis, University of Missouri-Rolla, Rolla, Missouri.

Davinroy, R.D., (1999). "River Replication," Civil Engineering, July, ASCE, New York.

Davinroy, R.D., (2001). Personal Communication, St. Louis, MO.

Derrick, D., Pokrefke, T.J., Jr., Marden, B.B., Crutchfield, J.P., and Henderson, R.R., (1994). "Design and Development of Bendway Weirs for the Dogtooth Bend Reach, Mississippi River, Hydraulic Model Investigation," Technical Report HL-94-10, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

De Vriend, H.J., (1981). "Steady Flow in Shallow Channel Bends," Comm. On Hydr. 81-3, Dept. of Civil Engineering, Delft Univ. of Technology, Delft, The Netherlands.

Digital Origins, (1996). *Users Manual to PhotoDV*, Digital Origin, Incorporated, Mountain View, CA.

Duncan, M. and Smart, G., (2001). "Flow Resistance: An Overview of Formulae for Alluvial Channel Flow Estimation," Internet, Accessed July 2001, http:\\www.niwa.cri.nz/pgsf/RiverMechanics/images/resistance%20summary.pdf.

Durst, F. and Tropea, C., (1982). " Flows Over Two-Dimensional Backward-Facing Steps," IUTAM Symposium Proceedings, Marseille, France.

Einstein, H.A., (1950). "Report on the Investigation of the Fundamentals of the Action of River Training Structures," Contract No. DA-04-203-eng-191, US War Department.

Einstein, H.A., (1950). "The Bed Load Function for Sediment Transportation in Open Channel Flows," USDA Technical Bulletin 1026.

Einstein, H.A., and Barbarossa, (1952). "River Channel Roughness," Transactions, ASCE, Vol. 117.

Einstein, H.A., and Chien, N., (1956). "Similarity of Distorted River Models with Movable Beds," Transactions, ASCE, Vol. 121, New York.

Engels, H., (1912). Versuche über den Riebungswiderstand zwischen Wasser und Bettsohle, Zeitschrift f. Bauwesen.

Engelund, F., (1981). "Similarity Laws of Alluvial Streams," Technical University Denmark, Prog. Rep. 55, p. 21.

Ettema, R., (2002). "Scale-Effect Trends on Flow Thalweg and Flow Separation at Dikes in Flat-bed Channels," Draft IIHR Technical Report No. XXX, University of Iowa, Iowa City, IA.

Ettema, R., (2000). "A Framework for Evaluating Micro-Models," *IIHR Limited Distribution Report* 295, Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, IA.

Ettema, R., Fujita, I., Muste, M., and Kruger, A., (1997). "Particle-image Velocimetry for Whole-field Measurement of Ice Velocities," Cold Regions Science and Technology 26, Elsevier.

Falvey, H.T., (1999). "Misuse of Term 'Model'," Comment to the Editor, Civil Engineering, December, ASCE, New York, p. 6.

Fisher-Rosemount, (1999). "Quick Theory, Flow and Density Theory of Operation for Micro Motion Coriolis Mass Flowmeters," Fisher-Rosemount, Boulder, CO.

Foster, J.E., (1975). "Physical Modeling Techniques used in River Models," Proceedings of the 2nd annual Symposium on Model Technology, ASCE, New York.

Franco, J.J., (1978). "Guidelines for the Design, Adjustment, and Operation of Models for the Study of River Sedimentation Problems," Instruction Report H-78-1, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi.

Franco, John J., (1963). "Hydraulic Models for Study of River Sedimentation Problems", Paper 58, Sediment in Streams, Publication 970, U.S. Department of Agriculture, 2nd FISC, Jackson, Ms.

Freeman, J.R., (Editor), (1929). *Hydraulic Laboratory Practice*, ASME, New York.

French, R.H., (1985). *Open Channel Hydraulics*, McGraw-Hill Book Company, New York.

Gaines, R.A. and Max, D.W., (2002). "What is Micromodeling," Proceedings, Memphis Area Engineering and Science Conference, Christian Brothers University, Memphis, TN.

Gaines, R.A., (2002). *Micro-Scale Moveable Bed Physical Sediment Models*, Dissertation, University of Missouri-Rolla, Rolla, MO.

Gaines, R.A., (1999). "Micromodel Procedures," Report to UMR Graduate Committee, Unpublished.

Gaines, R.A. and Maynord, S.T., (2001). "Microscale Loose-Bed Hydraulic Models," Journal of Hydraulic Engineering, Vol. 127, No.5 , ASCE, New York.

Preliminary Draft

Gaines, R.A., Gordon, D., and Maynord, S.T., (in preparation). "Comparison Studies to Determine Model to Prototype Agreement," Technical Report In Progress, US Army Corps of Engineers, Memphis, TN.

García, M., (2000). "Discussion: The Legend of A.F. Shields," Journal of Hydraulic Engineering, ASCE, New York, pp 718-720.

Garde, R.J. and Ranga Raju, K.G., (1974). *Mechanics of Sediment Transportation and Alluvial Stream Problems*, John Wiley and Sons, New York.

Gasser, M.M., Ahmed, A.F., and Gaweesh, M.T.K., (1989). "Calibration of Beni-Mazar Movable Bed Model," Journal of Hydraulics, ASCE, New York.

Gehrig, W. and Jurisch, R., (1981). "Model Investigation with Movable Bed to Simulate the Bed Level Downstream of a Barrage," Proceedings 19th Congress of the IAHR, New Delhi, India.

Gehrig, W., (1967). "Über die Frage der naturähnlichen Nachbildung der Feststoffbewegung in Modellen," Dissertation, Mitt.H.29, Franzius Inst. TH Hannover.

Gehrig, W., (Edited by H. Kobus), (1980). "Hydraulic Modeling," German Association for Water Resources and Land Improvement, Bulletin 7, issued in co-operation with IAHR, pp 323.

Gessler, D., Gessler, J., and Watson, C.C., (1998). "Prediction of Discontinuity in Stage-Discharge Rating Curves," ASCE, Journal of Hydraulic Engineering, March, New York.

Gessler, J., (1971). "Modeling of Fluvial Processes," River Mechanics Volume II, H.W. Shen, Fort Collins, Colorado.

Glazik, G., (1969). "Practical Performance of River Scale Model Tests with Movable Bed," XIII th Congress of the IAHR, Kyoto, Proceedings Vol. 5-1, (Seminars), pg. 211.

Glazik, G., (1978). "Morphological Processes in Hydraulic River Models with Movable Bed and Practical Performance of Scale Model Tests," Advances in Sediment Transport, Polish Academy of Sciences, Conference Jablonna, Wydawnictwo "Ossolineum," Wroclaw.

Glazik, G., (1984). "Influence of River Model Distortion on Hydraulic Similarity of Structures Arranged at the Channel," Proceedings, Symposium on Scale Effects in Modeling Hydraulic Structures, IAHR, Esslingen.

Graf, W.H., (1984). *Hydraulics of Sediment Transport*, Water Resources Publications, Littleton, Colorado.

Gray, D.D., (1999). *A First Course in Fluid Mechanics for Civil Engineers*, Water Resources Publications, Colorado.

Gujar, V.G., (1981). " Determination of Scales for Mobile Bed Models with Special Reference to River Models," Irrigation and Power, Vol. 38, No. 2.

Preliminary Draft

Haan, C. T., (1977). *Statistical Methods in Hydrology*, The Iowa State University Press, Ames, IA.

Hecker, G.E., Larsen, J., and White, D.K., (1989). "Calibration of a Movable Bed River Model," Sediment Transport Modeling: Proceedings of the International Symposium, Hydraulics Division, ASCE, New York.

Henderson, F.M., (1966). *Open Channel Flow*, MacMillan Publishing Co. Inc., New York.

Herbertson, J.G., (1968). Data Correlations for Sediment Transport in Flumes, Reprints of Bulletin of the IASH, XIII, No. 2.

Herbertson, J.G., (1969). "Scaling Procedures for Mobile Bed Hydraulic Models in Terms of Similitude Theory," Journal of Hydraulic Research, IAHR, Vol. 7, No.3.

Hwang, N.H.C., (1981). *Fundamentals of Hydraulic Engineering Systems*, Prentice-Hall, Inc., New Jersey.

IAHR, (1937). Report on First Meeting, Berlin.

Ivicsics, L. (1975). *Hydraulic Models*, Water Resources Publications, Fort Collins, CO.

Jaeggi, M.N.R., (1986). "Non Distorted Models for Research on River Morphology," Proceedings of Symposium '86, IAHR, Toronto, Canada.

Jain, S.C., (1981). "Quantification of Movable-Bed Model Verification," Proceedings 19th Congress of the IAHR, New Delhi, India.

Jana, W.S., (1982). *Introduction to Fluid Mechanics*, Brooks/Cole Engineering Division, Wadsworth Inc., Belmont, California.

Jansen, P.Ph., (1979). *Principles of River Engineering*, Pitman Publications, Ltd., London.

Jasek, M., Muste, M., Ettema, R, and Kruger, A., (1999). "PIV and Numerical Estimation of Yukon River Discharge During an Ice Jam Near Dawson," Proceedings 10th Workshop on River Ice, Winnipeg, MB, Canada, pp. 223 - 235.

Johnson, P.A. and Brown, E.R., (2001). "Incorporating Uncertainty in the Design of Stream Channel Modifications," Journal of the American Water Resources Association, No. 01121, pp. 1225-1236.

Jonte, M., (1949). "Note sur l'étude des coupures des boucles de l'Isére en amont de Grenoble,", (Proposed cutoffs of the Meanders in the Isére River Upstream of Grenoble), La Houille Blanche, Vol. 4, spec. no. A, p376.

Julien, P.Y., (1995). *Erosion and Sedimentation*, Cambridge University Press, New York.

Kline, S.J., (1965). *Similitude Approximation Theory*, McGraw-Hill Book Company, New York.

Knauss, (1980). "Hydraulic Modeling," IAHR, Bulletin No. 7.

Knight, D.W. and Macdonald, J.A., (1979). " Hydraulic Resistance of Artificial Strip Roughness," Journal of the Hydraulics Division, Vol. 106, No. HY6, ASCE, pp. 675-690.

Preliminary Draft

Kobus, H., (1980). "Hydraulic Modeling," German Association for Water Research and Land Development, Bulletin No. 7.

Kobus, H., (Editor), (1984). "Symposium of Scale Effects in Modeling Hydraulic Structures," IAHR, Stuttgart, Germany.

Kramer, H., (1934). "Sand Mixtures and Sand Movement in Fluvial Models," Proceedings ASCE, Vol. 60, p. 443, April.

Krey, H., (1925). Grenzen der Übertragbarkeit der Versuchsergebnisse und Modellähnlichkeit bei praktischen Flussbauversuchen, Zeitschr. f. angewandte Math, u. Mechanik.

Krey, H., (undated). Widerstand von Sandkörnern und Kugeln bei der Bewegung im Wasser als Grundlage der Schwemmstoffbewegung in unseren Flüssen, Mitteilung VWS H. 1.

Kuelegan, G.H., (1938). *Laws of Turbulent Flow in Open Channels*, National Bureau of Standards Journal, Res. 21.

Leopold, L.B., Wolman, M.G., and Miller, J.P. (1964). *Fluvial Processes in Geomorphology*, Freeman, San Francisco, CA 522 pp.

Liebs, W., (1942). Die Nachbildung von Flüssen mit beweglicher Sohle im Modell, Mittielngen der Preußischen Versuchsanstalt für Wasser-, Erd- und Schiffbau, Berlin, Heft 43.

Lopez, F. and Garcia, M., (2001). "Risk of Sediment Erosion and Suspension in Turbulent Flows," Journal of Hydraulic Engineering, Vol. 127, No. 3, March, 2001, New York, pp. 231-235.

Maddock, T., (1968). Discussion on "Similitude Theory Applied to Correlation of Flume Sediment Transport Data," by Barr, D.I.H., and Herbertson, J.G., Water Resources Research, Vol. 4, No. 2.

Martins, R., (editor), (1989). *Recent Advances in Physical Modeling*, NATO, Series E: Applied Sciences, Vol. 165, Kluwer Academic Publishers, Boston.

Max, D.W., Gordon, D., Gaines, R.A., (2002). "Operation and Calibration Procedures for Micromodels," Proceedings, 2002 Hydraulic Measurements and Experimental Methods Conference, ASCE, Colorado.

Maynord, S.T. (2000). Unpublished Correspondence, Waterways Experiment Station, US Army Corps of Engineers, Vicksburg, MS.

Maynord, S.T. (2001). Personal Communication, Vicksburg, MS.

Melville, B.W. and Coleman, S.E. (2000). *Bridge Scour*, Water Resources Publications, LLC, Highlands Ranch, Colorado.

Micro Motion, (1999). *Elite® Sensor Instruction Manual*, Micro Motion. Incorporated, Boulder, CO.

Micro Motion, (1999). *ProLink® Users Manual*, Micro Motion Incorporated, Boulder, CO.

Draft

Morgan, H.L., (1999). *Through Shifting Currents*, US Army Corps of Engineers, Memphis District, Memphis, TN.

Mueller, D.S., (1989). "Physical Modeling of Major Cutoffs," Journal of Hydraulics, ASCE, New York.

Murphy, G., (1950). *Similitude in Engineering*, The Ronald Press Company, New York.

Muste, M. and Ettema, R, (2000). "Studies to Determine Scale Effects in Micro-Models of Flow Fields at Dikes and Bendway Weirs," Unpublished Report, IIHR, University of Iowa, Iowa City, IA.

Muste, M., Xiong, Z., Bradley, A., and Kruger, A. (2000). "Large-Scale Particle Image Velocimetry – a Reliable Tool for Physical Modeling," *Proceedings* of ASCE 2000 Joint Conference on Water Resources Engineering and Water Resources Planning & Management, Minneapolis, MN.

Muste, M., Xiong, Z., Kruger, A., and Fujita, I. (1999). "Error Estimation in PIV Applied to Large-Scale Flows," *Proceedings* 3rd PIV Conference, Santa Barbara, CA, pp. 619-624.

Nickles, C.R., (2000). Unpublished Report, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Onishi, Y., Hroncich, M.J., and Sayre, W.W., (1975). " Undistorted Movable-Bed Model Study for a River and Power Plant Intake System," Proceedings of the 2nd annual Symposium on Model Technology, ASCE, New York.

Parker, G., (1998). "River Meanders in a Tray," Nature, Vol. 395.

Parker, G., Wilcock, Peter R., (1993). "Sediment Feed and Recirculation Flumes: Fundamental Difference," ASCE, Journal of Hydraulic Engineering, Vol. 119, No. 11.

PhotoDV (1999). *Users Manual*, Digital Origin, Mountain View, CA.

Pokrefke, T., (1975). "Physical River Model Results and Prototype Response," Journal of the Hydraulics Division, ASCE, New York.

Prahlad, N. V., Godbole, M. L., (1981). " Scaling Techniques to Overcome Model Limitations," Proceedings 19th Congress of the IAHR, New Delhi, India.

Prasuhn, A. L., (1987). *Fundamentals of Hydraulic Engineering*, Holt, Rinehart and Winston, New York.

Przedwojski, B., (1986). "Model Distortion Influence on Flow Characteristics in River Bends," Proceedings of Symposium '86, IAHR, Toronto, Canada.

Raudkivi, A.J., (1990). *Loose Boundary Hydraulics*, Pergamon Press, Oxford, England.

Reynolds, O., (1888). "On Certain Laws Relating to the Regime of Rivers and Estuaries, and on the Possibility of Experiments on a Small Scale," Report of the British Association, Water Resource Center Archives, University of California, Berkley.

Rosgen, D., (1996). *Applied River Morphology*, Wildland Hydrology, Colorado.

Rouse, H., (1934). "Evaluation of Boundary Roughness," Second Hydraulics Conference, Bulletin 27, University of Iowa Studies in Engineering, 1934.

Rouse, H., (1938). *Fluid Mechanics for Hydraulic Engineers*, Dover Publications, Inc., New York.

Rouse, H., (1939). "Experiments on the Mechanics of Sediment Suspension," Proceedings 5th International Congress of Applied Mechanics.

Rouse, H., (1946). *Elementary Mechanics of Fluids*, John Wiley & Sons, Inc., New York.

Rozoskii, I.L., (1961). "Flow of Water in Bends of Open Channels," Israel Program for Scientific Translations, Jerusalem.

Sall, J., and Lehman, A., (1996). *JMP Start Statistics: A Guide to Statistical and Data Analysis Using JMP and JMP IN Software*, SAS Institute, Duxbury Press, New York.

SAS, (1996) *JMP Start Statistics*, International Thomson Publishing Company, New York, NY.

Schlichting, H., (1951). *Boundary-Layer Theory*, McGraw-Hill Book Company, New York.

Schuum, S.A. and Khan, H.R. (1972). "Experimental Study of Channel Patterns," Geological Society of America Bulletin, V. 83, pp1755-1770.

Schwarze, H., " Hydraulic Model of a Combined Tidal and Inland River System with an Extremely High Distortion," Proceedings XX Congress of the IAHR, Moscow, USSR.

Shen, H.W., (Editor), (1971). *River Mechanics Volume I*, H. W. Shen Publisher, Fort Collins, Colorado.

Shen, H.W., (Editor), (1971). *River Mechanics Volume II*, H. W. Shen Publisher, Fort Collins, Colorado.

Shen, H.W., (1986). "Movable Bed River Models," Proceedings of Symposium '86, IAHR, Toronto, Canada.

Shen, H.W., (editor), (1990). *Movable Bed Physical Models*, NATO, Kluwer Academic Publishers, Boston.

Shields, I.A., (1936). "Anwendung der Aenlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung," Mitteilungen der Preussischen Versuchsanstalt fur Wasserbau und Schiffbau, Berlin, Germany, translated to English by W.P, Ott and U.C. van Uchelen, California institute of Technology, Pasadena, California.

Simons, D.B. and Sentürk, F., (1992). *Sediment Transport Technology Water and Sediment Dynamics*, Water Resources Publications, Littleton, CO.

Snamenskaya, N.S., (1969). "Morphological Principle of Modeling River-Bed Process," Proceedings 13th Congress of the IAHR, Kyoto, Japan.

Training Draft

Stevens, J.C., (Editor), (1942). *ASCE Manual 25: Hydraulic Models*, American Society of Civil Engineers.

Struiksma, N., (1980). "Recent Developments in Design of River Scale Models with Mobile Bed," IAHR Symposium, Belgrad and Delft Hydraulics Laboratory, Publication No. 236.

Struiksma, N., (1983). "Bakelite as Bed Material in River Scale Models with Moveable Bed," TOW Rivers, Report S 276/R 1119.

Struiksma, N., (1983). "Results of Movable Bed Experiments in the DHL Curved Flume," Delft Hydraulics Laboratory, TOW Rivers, Report R 657-XVII.

Struiksma, N., (1986). "Scale Effects in the Reproduction of the Overall Bed Topography in River Models," Proceedings Symposium on Scale Effects in Modeling Sediment Transport Phenomena, IAHR, Toronto, Canada.

Suga, K., and Baba, Y., (1971). "Effects of Distorted Models of Curved Channels," Annual Conference, Japan Society of Civil Eng.

Suga, K., (1973). "Some Notes on Hydraulic Model Tests of River Channels," Proceedings of the IAHR Symposium on River Mechanics, Bangkok, Thailand.

Sturm, T.W., (2001). *Open Channel Hydraulics*, McGraw-Hill Companies, Inc., New York, HY.

Sveum, D.J., Mellema, W.J., (1972). "Navigation Model Tests for Straight Reach of Missouri River," Journal of Waterways, Harbors and Coastal Engineering Division, ASCE, Vol. 98, No WW2.

Szilágyi, Gy., (1953). "Mozgó medrü folyók modellkísérlete, (Model Experiments on Movable-bed Rivers)," MTA Müszaki, Tud. Osztály Közleményei, No. 3-4.

US Army Corps of Engineers, (1969). "Missouri River Design Study," MRD Hydraulic Laboratory Series Report No. 1, Mead Hydraulic Laboratory, Mead, Nebraska.

US Army Corps of Engineers, (1990). "Waterborne Commerce of the United States: Calendar Year 1988," Part 2, Introduction, Office of the Chief of Engineers, Washington, DC.

USBR, (1980). *Hydraulic Laboratory Techniques*, Water Resources Technical Publication, Denver, Colorado.

Vanoni, V.A., and Brooks, N.H., (1957). "Laboratory Studies of the Roughness and Suspended Lad of Alluvial Streams," M.R.D. Sediment Series No. 11.

Vennard, JK, and Street, RL, (1982). *Elementary Fluid Mechanics*, Sixth Edition, John Wiley and Sons, New York.

Vining, G. Geoffrey, (1998). *Statistical Methods for Engineers*, Duxbury Press, New York.

Vogel, H.D., (1933). "Practical River Laboratory Hydraulics," Proceedings, ASCE, Vol. 59, p. 1413.

Preliminary Draft

Vollmers, H.J., (1989). "The State of Art of Physical Modeling of Sediment Transport," Sediment Transport Modeling: Proceedings of the International Symposium, Hydraulics Division, ASCE, New York.

Vries, M. de, (1973). "Application of Physical and Mathematical Models for River Problems," Delft Hydraulics Laboratory, Publication No. 112.

Wang, S.Y., (Editor), (1989). Sediment Transport Modeling: Proceedings of the International Symposium, Hydraulics Division, ASCE, New York.

Watt, A.D., (1973). "A Small Scale Hydraulic Model in Marine Transportation Studies," Proceedings of the IAHR Symposium on River Mechanics, Bangkok, Thailand.

WES, (1935). Paper 17, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

WES, (1949). "Report of First Conference with Hydraulics Consultants on Effects of Model Distortion on Hydraulic Elements," Unpublished Report, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

WES, (1950a). "Report of Second Conference with Hydraulics Consultants on Effects of Model Distortion on Hydraulic Elements," Unpublished Report, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

WES, (1950b). "Report of Third Conference with Hydraulics Consultants on Effects of Model Distortion on Hydraulic Elements," Unpublished Report, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

WES, (1957). "Triangular-Flume Study of Distortion Effects," Research Report No. 2-1, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

WES, Unpublished Report, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.

White, F.M., (1974). *Viscous Fluid Flow*, McGraw-Hill Book Company, New York.

White, W.R., (1968). "Design Criteria for Mobile-bed River Models, (with Particular Reference to the River Jaff Model)," Hydraulics Research Station, Wallingford, INT. 71, pp. 23 and figures.

Williams, G.P., (1970). "Flume Width and Water Depth Effects in Sediment-Transport Experiments," Sediment Transport in Alluvial Channels, Geological Survey Professional Paper 562-H, US Geological Survey, Washington, D.C.

Willis, J.C., (1969). Comments on "Similitude Theory Applied to Correlation of Flume Sediment Transport Data," by Barr, D.I.H., and Herbertson, J.G., Water Resources Research, Vol. 5, No. 5.

Yalin, M.S., (1965). "Similarity in Sediment Transport by Currents," Hydraulic Research Station, Paper No. 6, Wallingford.

Yalin, M.S., (1971). *Theory of Hydraulic Models*, MacMillan Press LTD, London.

Yalin, M.S., (1986). "Some Aspects of Physical Modeling on Flows with a Free Surface," Proceedings of Symposium '86, IAHR, Toronto, Canada.

Yalin, M.S., (1992). *River Mechanics*, Pergamon Press, New York.

Yang, C.T., (1996). *Sediment Transport Theory and Practice*, McGraw-Hill Companies, Inc., New York, NY.

Zwamborn, J.A., (1966). " Reproducibility in Hydraulic Models of Prototype River Morphology," La Houille Blanche, No. 3.

Zwamborn, J.A., (1967). "Solution of River Problems with Movable-bed Hydraulic Models," CSIR Report, MEG 597, Pretoria, South Africa.

Preliminary Draft