MICROMODEL EVALUATION REPORT

Prepared For:

The US Army Corps of Engineers, Mississippi Valley Division
The US Army Corps of Engineers, Memphis District
The US Army Corps of Engineers, St. Louis District
The US Army Engineer Research and Development Center

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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. 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.

These early designs 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 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. 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 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
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

Due to the complex, dynamic phenomena of sediment transport, there have never been any reliable equations or formulas available to the river engineer to predict the general three-dimensional bed response of the river. The river is a physical land feature that is ever changing in dimensional shape. Both the movement of water and sediment is constant. 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 helped to sometimes fill the void created by the lack of available scientific design procedures. The river engineer would use the model to observe the general bed response and in some 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 simply provided additional 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 in the preceding paragraphs. Rock dikes, revetments, and/or other types of structures would be conceptually formulated and then presented to and discussed with the various interests groups. If the proposed plans were accepted, the river engineer would then proceed with final design and implementation using a phased construction approach. A phased construction approach involved building the proposed structures incrementally in the prototype, over time, to allow observation of the actual response for the river. The intent was to let the river respond gradually after the first construction phase, monitor the response, and then proceed into the next phase making adjustments to the design as necessary to achieve the desired river improvement. The ultimate goal was the completion of the intended measure of improvement. Rational evaluations could then be made for each phase of the design, as 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. Rock structures have been extended, re-angled, degraded, and in some cases removed as a result of the phased approach.

In summary, past and present river engineering design 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, physical 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 a phased-construction procedure.

1.2. Development of the Micromodel

Historically, the Corps of Engineers has employed relatively large-scale movable-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 some of the most troublesome 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 used 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 sizes 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.

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 began to use the 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 Mississippi Valley Division and provided complete transfer of the technology.

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 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

A strong desire for expanded use of the micromodel technology throughout the Corps of Engineers exists because of the relatively meager cost and minimum space requirements for conducting these type studies. However, a number of issues about the small-scale models exist. Therefore, in 1998 a joint venture team was chartered by MVD 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.

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

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

[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.

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

1.4. Consultants

Early in the JV study, three consultants provided an independent, cursory assessment of the proposed research and the micromodel methodology. Two of these consultants, Robert Ettema from the Iowa Institute of Hydraulic Research, University of Iowa and Gary Parker from the St. Anthony Falls Laboratory, University of Minnesota were from an academic background. The third consultant, Warren Mellema, had previous practical experience from the Corps of Engineers Mead Hydraulics Laboratory, Missouri River Division. Each of the three consultants had previous experience with movable-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 for one afternoon. 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 single-day observations and outlined suggestions relative to the joint venture (JV) evaluation proposal. Copies of the individual reports provided by the consultants are included in Appendix A.

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 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 effects. The fixed-boundary flume studies are described more completely in Ettema and Muste (2002).

1.5. Report Goals

This report intends to provide a potential micromodel user with enough information to make a cursory assessment regarding whether to pursue its use for their particular situation. This report can only provide a brief discussion of issues, as they are understood as of this writing. More detailed and up-to-date information should be sought before making a final decision to use (or not use) a micromodel for any particular application. In general, this report does not intend to justify or endorse micromodel use nor does it intend to denounce micromodel use.

As stated in Section 1.3, a strong desire to expand use of the micromodel technology exists within the Corps of Engineers. However, the micromodel is in the early stages of development, and the current state of knowledge about how various aspects of the micromodel (i.e. small scales and high degree of distortion) affect reproduction of the physical processes observed in the prototype is limited. Because current knowledge of these affects is limited, then the micromodel, as it is known today, has limitations. This means that some areas of micromodel use may be considered suspect or even off limits for the present. This does not mean that such limitations exist indefinitely, but that the state of knowledge today does not make those areas completely acceptable. It also does not mean that one cannot use a micromodel in those areas; however, a modeler must employ an extra degree of caution and use extreme vigilance when doing so.

1.6. Key Considerations

The first consideration pertains to individual interpretations of past model study results and of model limitations/capabilities. Throughout the course of evaluating the micromodel, the various investigators arrived at their own, individual conclusions regarding micromodel capabilities and limitations. These conclusions depended largely on the individual's background, experience with movable-bed models, and their experience relative to design of river training structures (such as in the Mississippi River). The sometimes disparate opinions bring to mind the question: Is the micromodel useful? For example, a noted sediment transport and hydraulics mechanician, Yalin (1971), states his opinion that a model can be scientifically valid only if measured quantities in the model are related to their counterparts in the prototype by scale ratios that satisfy the criteria of similarity. The current micromodel approach does not follow similitude principles. Upon seeing the micromodel, Yalin stated, "Just because water runs downhill does not mean that you have a [scientific] model." Does this imply that micromodels are not scientific models or that they cannot be used effectively in the study of river training structures? Gaines advocates that based upon results from several micromodel studies where recommended alternatives were constructed in the prototype the micromodel can indeed prove useful (see Sections 4.1-4.4). Ultimately, the reader must make the decision of micromodel utility based upon information provided below and through further inquiry regarding micromodel use.

Second, because of the empirical nature of most movable-bed models, including micromodels, modelers rely heavily on judgment when designing, operating, and interpreting models. As stated in the preceding paragraph, evaluation of the micromodel involves numerous viewpoints or opinions regarding the use and interpretation thereof. Indeed, appropriate engineering judgment does play a vital role in all movable-bed modeling, particularly in assessing the state of model calibration. However, strict reliance on judgment to evaluate the micromodel's capabilities and limitations could easily lead to differing or even contrasting outcomes. In order to help alleviate some of the confusion that may result from individual interpretations, it becomes necessary to establish some basic definitions and perspectives. There are three principle considerations in this regard.

Third, there are two facets of movable-bed modeling. Each of these facets must be considered during the course of an evaluation. The facets include (1) the process by which a model is designed, operated, and interpreted relative to the prototype problem under consideration and (2) the technical correctness in which a model reproduces the physical processes and laws found at prototype scale. These two facets are important because evaluation of a new technology, such as the micromodel, must rely to some degree on an assessment of previously completed micromodel studies to gain insight into its capabilities and limitations.

A critique of the state of model calibration provides insight into how well a particular model reproduced physical characteristics found in the prototype and some generalizations of those findings may be possible. Although the technical purist would like to focus entirely on the technical merits/deficiencies that exist in the micromodel when critiquing previous model studies, such is not possible because factors influencing the process that produced those results must also be considered. As evident in a comparison of previous movable-bed model studies (Franco, 1982, and USACE, Unpublished), calibration deficiencies are not the exclusive domain of the micromodel. Whether such calibration deficiencies resulted from a technical inconsistency between model and prototype (i.e. due to scale effects) or were the result of constraints placed upon the modeling process (i.e. degree of answer sought or schedule or budget limitations) is unknown. On the other hand, the model practitioner may place primary focus on the process, even to the exclusion of technical considerations. This too is not practicable because physical processes that occur in the prototype must be reproduced in the model.

Exclusive use of bathymetry to establish the relationship between model and prototype behavior is not sufficient to guarantee correct model response when analyzing proposed changes to the system. The physical laws are defined by similitude between model and prototype for various physical parameters. Disregarding similitude in the micromodel would eventually lead to lessened confidence in micromodel results overall. The empirical micromodel process, including the application of engineering judgment, cannot totally disregard the need to obey physical laws. On balance, both the technical/scientific aspects and the design, operation, and interpretation processes of the movable-bed model impact its usefulness for the study of river engineering problems. In the end, the questions that must be answered are (1) To what extent does the model replicate the trends, locations, and magnitudes of response that are important to the prototype reach being simulated? and (2) How well does the calibrated model predict changes to the system when comparing alternatives?

Fourth, the terms calibration, verification and validation must be defined for use in subsequent discussions. Based on ASCE (2000), "Model calibration is the tuning of the model to reproduce a single known event...Tuning the model to reproduce the prototype behavior in this event does not ensure that the model will reproduce different or future events. However, if the model cannot reproduce a known event, little confidence can be maintained that the model will reproduce future events." Gordon and Gaines define micromodel calibration to include adjustment of the model to ensure that the model reproduces general bathymetric trends observed in the prototype which are defined by one or more prototype surveys. Because the micromodel operates with a sediment re-circulation procedure without a preformed bed at the beginning os simulations, no specific time period is simulated during micromodel calibration.

From ASCE (2000), "Verification, ensures that the model behaves properly;...that there are no mathematical errors or other inconsistencies...consists of ensuring that the model obeys known physical laws..." ASCE (2000) also defines the term validation that "consists of ensuring that the model reproduces the relevant physical processes that affect the performance of the structure or device being tested." Maynord(Unpublished) defines validation as the comparison of the calibrated model to a different set of prototype conditions for the purpose of showing predictive capability of the model.

And Fifth, the terms qualitative and quantitative must be defined for subsequent discussions. The distinction between these terms and the context in which they are each used greatly influences one's opinion of the micromodel, or any movable-bed model for that matter. The definition of quantitative implies that something can be expressed as a quantity, is susceptible of measurement or pertains to a number or quantity. Conversely, a definition of qualitative pertains to ideas, views, or interpretations of information, often in a generic sense. A quantitative study can be thought of as being based on testing a theory composed of variables, measured with numbers, and analyzed with statistical procedures, in order to determine whether the predictive generalizations of theory agree with observed study results. Alternatively, a qualitative study can be thought of as a process of understanding a problem that is based on building a complex, holistic picture of the problem and solution, which is formed from analysts views and interpretations of available information without the use of exact measurements, numerical values, or statistical procedures.

In reality, there is a gray area between quantitative and qualitative. For example, some qualitative results can be used in a quantitative manner if measurements and numbers are assigned to the results. In this case, results can be referred to as semi-quantitative. In the end, the use of quantitative versus qualitative in describing movable-bed model results remains a subjective determination.

Herein, Maynord differentiates between the terms qualitative and quantitative by giving the following example:

> "An example of qualitative use of a movable-bed model is when the model is used to show that dike alternative A increased channel depths in crossing X and dike alternative B, which contained higher dikes, further increased channel depths in crossing X. No numbers are given to alternative features or results in a qualitative model. Quantitative use means that numbers are assigned to alternative features in, or results from, the model. There are two levels of quantitative use that should be considered. The first and lowest level of quantitative use is where alternative features in the model such as dike elevations, lengths, angles, and number are stated as being the characteristics of a proposed plan. This is a quantitative use of the model even if the alternative is evaluated on a qualitative basis. The second, higher level of quantitative usage is where results from the model are given numbers. An example of the second, higher level of quantitative use is taking the width of the channel where navigable depths exist as being representative of the prototype. Another example of this higher level of quantitative usage is employing bathymetry of the model to specify the bed contours in another model."

In contrast, Gaines and Gordon utilize quantitative to describe detailed model results when specific features of the prototype (i.e. detailed flow and scour patterns at the end of dikes/structures, or specific amounts of depth changes) are of primary interest while qualitative is used to describe model results in terms of general trends and patterns. Because model structure lengths and elevations are indicative only (final elevations, lengths and alignments in the prototype construction plans are set based upon experience with similar types of structures and on prevailing prototype conditions at the time of construction), Gaines and Gordon do not consider the use of number of structures, elevation of structures or lengths of structures in the model to be a quantitative use of micromodel study results because model results are used to provide a relative comparison between various alternatives (i.e. alternative A yields this response while alternative B yields that response). These results are then applied with engineering judgment to arrive at final designs for the prototype.

2. MOVABLE-BED RIVER MODELS

2.1. General

Movable-bed physical models provide a tool for the study and analysis of complex river engineering problems. The term "movable-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 movable-bed models were small tabletop sized models. These early models were used in the study of estuary and coastal sediment problems. As the movable-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 tabletop models, which are known as micromodels.

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 dimensionless 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.

Physical models, particularly movable-bed models, rarely replicate all flow processes. 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 characteristics often depends more on a modeler's experience and intuition rather 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). The similarity criteria of importance are a defined by the problem under investigation.

2.2. Similitude

Ettema (2001) presents the dimensionless parameters associated with water and sediment movement in channels, prototype or movable-bed model, with a bed of cohesionless particles as:

$$\Pi_A = f_A\left\{D\left(\frac{g(\rho_s-\rho)}{\rho v^2}\right)^{1/3}, \frac{\rho Ri}{D(\rho_s-\rho)}, \frac{\rho_s}{\rho}, \frac{D}{R}, \frac{B}{R}, \frac{\sigma}{\rho giR^2}\right\} \quad (1)$$

Where the dependent variable A in Π_A might be flow resistance, thalweg sinuosity, sediment transport, or some other variable in alluvial channels, D = particle size, g = gravity, ρ_s = particle density, ρ = water density, ν = kinematic viscosity of water, R = hydraulic radius, i = slope, B = channel width, and σ = surface tension. Scale distortions arise when the dimensionless parameters on the right side of the equation are not the same in model and prototype. However, some of the dimensionless ratios, under certain conditions, do not cause significant effects when model and prototype values differ. For example, in a large enough model, the last parameter on the right side of Equation 1 will not be the same in model and prototype but the effects of differences in surface tension in model and prototype will be negligible. It remains to be determined if the surface tension term can be neglected in a micromodel. The first term on the right hand side is a particle density term which shows that if a lightweight bed 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 movable-bed model criteria. The third term ρ_s/ρ is often ignored because density effects are addressed in the first and second terms of the right side of the equation. The fourth term on the right hand side, D/R, is the relative roughness which is rarely equal in model and prototype of sand bed streams and is often assumed to have negligible effects on model results. However, Ettema, Melville, and Barkdoll (1998) have shown significant scale effects of D/R on bridge pier scour. The fifth term on the right side, B/R, is the aspect ratio that is another term that can rarely be maintained the same in movable-bed models and prototype of sand bed rivers.

Three techniques have been used in movable-bed models 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, can not be scaled down due to particle cohesion problems and will be roughly the same in model and prototype when dealing with 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 i. Adjustment of these three parameters have led to three techniques often used jointly in movable-bed models as follows:

1) Lightweight sediment- 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. ASCE (2000) describes some of the various sediment types used in movable-bed models.

2) Vertical scale distortion- Vertical scale distortion is the second technique used to achieve correct sediment movement. Vertical scale distortion results in attempting to model a prototype channel with a model that has an aspect ratio (width/depth) that is less than the prototype. Freeman (1929) described early movable bed model studies by Reynolds and Vernon Harcourt having vertical scale distortions up to 60. More recently, however, the practice has been to use lower distortions than employed by Reynolds and Vernon Harcourt. Jaeggi (1986) concludes that morphological processes are highly dependent on the aspect ratio 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 adequate results. Suga (1973) reports that distortions used in his lab's movable-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 (prototype) 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 than two or three. ASCE (2000) suggests a limit of six. While these previous studies consider distortion to be a necessary evil and have recommended limitations, application of regime theory to movable-bed models requires distortion.

3) Exaggerated 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 that of the prototype that then raises concerns about the ability of the model to reproduce flow patterns. Einstein and Chien (1955) allow some exaggeration of model Froude number but do not recommend a limit. In an example presented by Gujar (1981), a Froude number exaggeration of $F_m / F_p = 2.5$ was classified as large whereas 1.67 was classified as acceptable. 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 movable-bed models of the Elbe estuary which had a vertical scale distortion of 8. 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.

2.3. Types of Movable-bed Models

Graf (1971) categorizes movable-bed models as rational models that are semi-quantitative or empirical models that are qualitative. The Graf categories generally correspond to the degree to which the Equation (1) parameters are equal in model and prototype.

2.3.1. Rational Movable-bed Models

Graf (1971) credits Einstein and Chien (1955) with development of the rational method of movable-bed models. Yalin (1965) and de Vries and van der Zwaard (1975) also developed methods that fall under Graf's category of a rational movable-bed model. The rational method is simply a more rigorous adherence to the similarity criteria in Equation (1) and generally requires large models to apply the method. Rational models are characterized by low vertical scale distortion, low Froude number exaggeration, and equality of Shields parameter in model and prototype.

2.3.2. Empirical Movable-bed Models

Graf's second category, empirical movable-bed models, places less reliance on similarity requirements and greater relaxation of the Equation (1) parameters. 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." Although less rigorous than rational movable-bed model, most empirical models attempt to limit vertical scale distortion and Froude number exaggeration. Empirical movable-bed models have a Shields parameter that is generally less than the prototype that is required in order to limit model size, vertical scale distortion, and Froude number exaggeration. Most recent empirical movable-bed models used at the Engineering Research and Development Center (ERDC, formerly Waterways Experiment Station or WES) employed coal as the model bed material and had model Shields parameter of less than 0.1 whereas the prototypes being studied had Shields parameters in excess of 1. Earlier empirical movable-bed models at ERDC utilized sand for the bed material. Glazik and Schinke (1986) describe movable-bed model experience using a model Shields parameter significantly less than the prototype. Due to the importance of the equality of the Shields parameter in the model and prototype, empirical models are generally limited to assessing bathymetric response.

2.3.3. Other Movable-bed Models

Some movable-bed models do not fit into the two categories delineated by Graf (1971). Freeman (1929) discusses early studies by Reynolds and Vernon-Harcourt which were similar to the empirical model but used Froude scale velocities in models with huge (greater than 20 times) vertical scale distortions. Vernon-Harcourt conducted a study of the Mersey estuary in England in a model with a vertical distortion of 60. Vernon-Harcourt discusses a calibration procedure that includes validation that is a 3-step process that differs from the 2-step process used in the micromodel and many movable-bed models. In the 2-step calibration, the model is adjusted until it can reproduce a certain prototype condition and then it is declared calibrated and ready for prediction. Vernon-Harcourt calibrated his model until it reproduced a known prototype condition as in other movable-bed models. He then tested the model against a different set of prototype boundary conditions (validation) to see if it could reproduce these known changes. If satisfactory in the validation, Vernon-Harcourt then declared the model ready for prediction.

2.4. Uses of Movable-bed Models

The categorization of movable-bed model usage can be dealt with in a variety of ways. One option is to categorize based on structure type such as bendway weirs versus traditional dikes. Another option is to categorize based on problem type such as minimization of maintenance dredging in the main navigation channel versus rehabilitation of side channels for environmental enhancement. Ettema (2001) differentiates movable-bed models based on degree of freedom of lateral movement with movable-bed models of a long constriction having a greater chance of success than those in which lateral movement of the thalweg is relatively unrestricted. Gordon (Unpublished) advocates the use of intended model application to categorize micromodels (as subsequently described in Section 3.3). Maynord (Unpublished) suggests that the movable-bed models can be categorized based on the needed output from the model. Maynord states that some of the various categorization methods can be sub-categorizations of the following four areas:

A. Demonstration, education, and communication – Demonstration, education, and communication includes demonstration of river engineering concepts including the general effects of structures placed in the river.

B. Qualitative Bathymetry Analysis- In qualitative bathymetry analysis, the model only needs to be good enough to compare alternatives and show the correct trends in the model. Stated otherwise, a qualitative river engineering model is primarily used as a screening tool.

C. Quantitative Bathymetry Analysis- Examples of quantitative river engineering movable-bed studies are: (1) determining dike or weir locations, lengths, heights, angles, and number; (2) estimating quantities for dredging; and (3) providing bed topography for another model, either physical or numerical.

D. Flow Patterns- navigability- This use of the movable-bed model involves studies such as navigation through and approaching a lock, bridge, or river confluence and requires the most rigor of all the categories. It includes flow details such as use of velocity measurements or confetti streaks to screen alternatives or to make conclusions about safe navigation.

Categorization of movable-bed model usage based on output needs as suggested by Maynord (Unpublished) may provide a convenient method to consider the increasing requirements for maintaining similitude between model and prototype. However, even here, individual modelers may have differing interpretations of which category fits their particular application. Consider, for example, the case of a river confluence. The problem at the confluence is that high velocities in the main channel make navigation into the tributary channel difficult. Therefore, modeler No. 1 places this model in Maynord's category D because it pertains to a problem involving safe navigation at a river confluence. Modeler No. 1 places chief significance on whether the model can predict prototype response and bases his/her decisions on transfer of model results to the prototype. However, modeler No. 2 places the model in Maynord's category B because it is only used to screen various alternatives in a relative manner. In the latter case, the model results from alternative screenings supplement the modeler's/engineer's experience and understanding of the river and its response to like training structures. In the view of modeler No. 2, primary decision-making rests on the engineer's knowledge of the prototype more than on the model findings—the model is simply a tool to make relative comparisons between several possible alternatives. Although experience and technical expertise is critical to either modeler, the modeler's/engineer's experience with and knowledge of the prototype plays a pivotal role in the case of modeler No. 2.

2.5. Experience of the User

Robert Ettema put forth a simple truism about movable-bed modeling in his initial evaluation of the micromodel (see Appendix A). In his report, He states, "...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 (1890s)." Ettema goes on to state that, "Micromodels have their place as a design aid for river engineering." He also adds that, "As with all hydraulic models, the bottom line for micromodels is that the limits of their applicability fundamentally depend upon the extent to which they meet similitude considerations and on the level of risk the model user is prepared to assume." Strict adherence to similitude requires that all governing parameters (describing geometric, kinematic, and dynamic processes) provide consistent relationships between model and prototype. The level of risk Ettema refers to has the connotation that the model may or may not give correct indications for prototype response depending on the degree to which the model satisfies similitude requirements. Therefore, the modeler must have a fundamental understanding of river engineering which includes basic hydraulic, morphologic and sedimentation concepts and an understanding of reach dynamics in the prototype. In addition, the modeler must grasp how approximations in the model, through relaxation of strict similitude, may influence the model's ability to replicate prototype processes.

As described in Section 1.1, most river engineering depends upon the engineer's intuition, experience, judgment, and their familiarity with the prototype. The most commonplace design of river training structures involves no use of a model. For this approach, there are no equations or specific guidelines to follow. The design process usually consists of a team of river engineers using only their experience and intuition along with a limited amount of data to come up with a completed design; there are no proven methods to define the design process. This design approach involves a substantial risk, particularly when the reach under study is highly variable. In this regard, Gordon raises the question, "with the lack of proven methods available to the engineer, what tools are a available to aid the river engineer in developing designs and specifications for construction? In some cases, movable-bed models have helped to guide the selection of alternatives. Even when a movable-bed model is used, a phased construction approach is typically utilized to reduce the risks associated with traditional design techniques by allowing for adjustments in the design to better-fit observed prototype response.

Models afford the engineer with an opportunity to gain additional information not readily available from the prototype. Thus, models can help reduce the risk associated with the design of river training structures by permitting the engineer to screen proposed designs in the protection of a laboratory setting without the potential for failure in the natural river environment. The success of models to reduce the risk is directly related to their ability to replicate prototype processes. Potentially, the model can give the designer or design team additional insight or confidence over that resulting from intuition alone. However, a false confidence can result if the limitations of the model are not clearly understood.

Physical models rarely replicate all flow processes. This is particularly true of movable-bed models, including micromodels. Because the micromodel technique does not utilize any similitude criteria, Gary Parker (see Appendix A) suggested that they are process models rather than models that satisfy similitude. In light of micromodels being process models, Parker suggested that the results of micromodels must be interpreted with care. The care is required because even after calibration of the bed for a specific flow, further changes in flow conditions may change the bed of the process model in a way that differs somewhat from that of the prototype.

Confidence in the micromodel derives primarily from the calibration process. The effort invested in obtaining an understanding of prototype reach dynamics through data collection, review and analysis during the calibration process and used in micromodel adjustment to achieve replication of bathymetric patterns provides a good foundation for assessing a potential design scenario. Likewise, the modeler obtains a sense of what the model can and cannot do during the calibration process. Artificial means used to achieve model calibration, such as the addition of roughness elements or non-erodible materials, influence potential model response to design alternatives. Whether these artificial means are physically based (actually occur in the prototype as in the case of clay or rock outcrops) or are simply a means to overcome model distortions or model scale effects can have a significant impact on the model's ability to project prototype response. An essential aspect of the model effort then is the ability to recognize the quality and validity of data derived from the model.

The risk associated with any modeling effort (micromodel, large-scale model, or numerical model) depends upon the reach of river under study, the modeler's experience, the modeler's understanding of river dynamics, and the amount of data available. In the end, the river engineer must determine whether available data provides sufficient information for developing the prototype design. If data are insufficient and cannot be obtained, the design involves a greater degree of risk than where data are adequate to define the problem at hand. Although extensive data exist for some reaches, they do not fully describe prototype conditions. Therefore, the phased construction approach allows for changes in design to accommodate prototype response that may be different than originally anticipated.

2.6. Suggested Criteria for Assessing Bathymetry Calibration

The primary question regarding whether a movable-bed model bathymetry reproduces prototype bathymetric trends pertains to the quality of calibration. Maynord (Unpublished) emphasizes that adequate calibration exists when a model has the following characteristics relative to the prototype[3]:

1) Model reproduces the problem that led to the study being conducted

[3] The four characteristics iterated here are commonly used in critiquing movable-bed model bathymetry relative to the prototype.

2) Model has an adequate simulation of the planform, which is often based on the thalweg alignment.

3) Model has no extreme departures in depth near the problem area.

4) Model reproduces flow splits, where important.

Davinroy and Gordon (Unpublished) state that adequate micromodel calibration exists when the following characteristics occur:

1) The model bathymetric trends, resulting from surveys collected on the model, are similar to observations of actual hydrographic surveys of the river under study. This includes bathymetric trends observed in main channels, side channels, and distributaries, if included in the study reach.

2) The model bedload, input and output, is in relative equilibrium with continuous movement of sediment observed and no aggradational or degradational trends occurring within the model study reach.

The preceding characteristics by Maynord (Unpublished) and Davinroy and Gordon (Unpublished) are both applicable to micromodels. However, assessment of each of these characteristics is subjective and depends on an individual's (often visual) interpretation of each characteristic relative to the prototype. Reiterating previous discussions, individual interpretation can lead to quite different conclusions regarding the state of calibration and great care must be exercised in stating calibration attributes. It is also essential to balance an interpretation of results between meeting technological/scientific requirements and dealing with process constraints as pertains to the intended study purpose.

3. MICROMODEL

3.1. Basic Methodology

Davinroy (1994) developed an empirical modeling procedure to study sedimentation problems primarily in the Mississippi and Missouri Rivers. Davinroy's procedure utilized 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). Models resulting from this technique (called "micromodeling" 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). Study results are described in eighteen published and several unpublished 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 paragraphs.

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 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; 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.

The micromodel technique does not utilize established similarity criteria during the design or operation of a model. Instead, micromodeling seeks a form of morphologic similarity (Gaines, 2002, Davinroy, 1994, Glazik, 1978, Hecker, 1989, and Snamenskaya, 1969) where overall bed configuration determines the degree of agreement between model and prototype. The morphologic variables commonly considered in micromodel calibration are thalweg location and general bed-elevation trends. Further explanation of the micromodel technique is provided in Appendix B.

3.2. Micromodel Contrasted with Other Movable-bed Models

Of the two Graf (1971) categories, the micromodel is closest to the empirical movable-bed model category. While similarity laws are not followed closely in empirical movable-bed models, there are definite differences between the micromodel and most previous empirical models as follow:

1) Size- The micromodel is one to two orders of magnitude smaller than most empirical models. Model widths in the micromodel are as low as 1.5 inches compared to 4.5 ft and 11 ft in two models cited in Glazik and Schenke (1986). Model depths as low as 0.4 inches are an order of magnitude less than the minimum of 4 inches recommended in Gujar (1981). No requirements for minimum Reynolds number are used in the micromodel. The small model depths result in extreme distortion of relative roughness.

2) Vertical scale distortion- With a few exceptions, distortion ratios used in the micromodel are about twice that in most empirical models. Micromodels commonly use distortions of 8-15 compared to empirical models cited in Section 2.2 having vertical distortions less than 5. The ERDC models had distortions up to 10.

3) Vertical scale and vertical datum determined as part of the calibration rather than in model design- In converting model bed elevations to the prototype after a calibration test, various vertical scales and vertical datum are tried in the micromodel until the model bed configuration most closely matches the prototype. Jonte (1949), Glazik (1978) and Gasser (1989) also suggest changing vertical distortion as part of model calibration. Gujar (1981) describes the process of determining vertical scale during model design as opposed to determining vertical scale as part of the calibration process.

4) 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. Other movable bed models, including the former ERDC movable-bed models, included stages and discharges at the bankfull condition. Some of the ERDC models were operated at stages and discharges exceeding the bankfull condition.

5) Calibration of micromodel based on equilibrium bed- Previous movable-bed models conduct calibration by starting with a known bed configuration, running representations of the subsequent stage and discharge hydrographs, and comparing the ending bed topography in model and prototype (Franco, 1978). 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 prototype trends of primary interest are reproduced.

6) The small size of the micromodel and the relatively heavy (heavy for plastic) bed material (SG=1.48) results in steep slopes in the micromodel. Water-surface slopes of the few micromodels where slopes have been measured are about 1 percent. Steep slopes result in significant exaggeration of the Froude number. Froude numbers in the two micromodel studies where known, are 4 and 6 times the prototype Froude number compared to movable-bed models discussed under Section 2.2, "Exaggerated model slope" where the Froude number exaggeration was generally 2.2 or less.

7) Model sediment, when scaled to prototype dimensions using a typical vertical scale, is 0.6-1.2 m in diameter compared to 0.1 m in the Glazik and Schenke (1986) model and 0.4 m in the movable-bed models discussed in Franco (1978).

8) No similarity of friction in the micromodel that results in no correspondence of stage in micromodel and prototype. Most empirical models relate stage to a corresponding stage in the prototype. Even with the large exaggeration of the relative roughness, the large distortion in the micromodel results in the model being too smooth which is typical of highly distorted models. This smoothness is likely the reason the micromodel cannot be used to simulate high stages. Zwamborn (1967) discusses requirements for similarity of friction in movable-bed models.

9) Micromodel uses porous dikes to solve exaggerated scour problems around dikes that occur in other distorted models.

10) The micromodel can evaluate an enormous number of conditions in a short period of time due to short duration hydrographs, no bed molding, and automated bathymetry measurement.

The most significant differences in the micromodel and previous movable-bed models are large vertical scale distortion, large Froude number/slope distortion, no correspondence of stages, and the enormous number of conditions that can be evaluated in a short period of time. These differences place the micromodel in a category by itself as shown in Table 3-1 (Maynord, Unpublished). Note in Table 3-1 the distinction that Maynord makes under "similarity criteria" where deviations are allowed or they exist. Maynord does not define the terms small, significant or extreme as used in Table 3-1.

Table 3-1 Three types of movable-bed models (Maynord, Unpublished).

Model Type	Similarity Criteria
Rational	Small deviations allowed
Empirical	Significant deviations exist
Micromodel	Extreme deviations exist

Rational models are designed and operated with similarity considerations and only small deviations are allowed. Empirical models often do not follow similarity criteria, but the manner in which they are operated results in the existence of significant but limited deviations from similarity criteria. In like manner, the operation of micromodels results in extreme departures from similarity criteria.

3.3. Applications

Past micromodel applications generally related to the placement and modification of river training structures for the purpose of resolving bathymetry related issues such as dredging, improving aquatic diversity, thalweg position, and far-field flow patterns. Unfortunately, at the conclusion of the present evaluation effort, the JV team had differing opinions regarding whether the micromodel is applicable in each of these areas. Despite the different opinions amongst the JV team, Gordon asserts that, "micromodels have been used to aid in the design of river training structures that have successfully solved problems relative to each of these categories." The following subsections describe what the model is currently being used for. This does not imply that these applications should or should not be addressed with a micromodel.

3.3.1. Demonstration and Education

The micromodel has been used extensively for the purpose of demonstrating basic river mechanics to teachers, students, biologists, landowners, and tow pilots. A physical model is extremely useful for capturing the attention of an audience and for providing a means for the engineer to simplify, explain and demonstrate complex sediment transport phenomena. The process of gathering background data and applying it during the calibration procedure of the model also aids in the modelers education of reach specific dynamics.

3.3.2. Reducing Dredging Requirements

The Corps of Engineers is responsible for maintaining minimal water depths along numerous navigable waterways. Channel training structures are regularly used to direct and control the river to allow the natural forces of moving water to maintain these depths. However, numerous trouble spots exist where depths must be maintained artificially by dredging. These temporary fixes cost the taxpayer millions of dollars and negatively effect the surrounding aquatic environment. The large-scale movable-bed models have traditionally been used to study remedial solutions to these shoaling areas. The micromodel has also been used to study these type of problems.

3.3.3. Environmental Rehabilitation of Side Channels

Biologists continue to stress the aquatic benefits that secondary channels provide. Numerous projects are directed at improving this habitat by deepening the side channels and providing connectivity to the main channel. The micromodel has been used by engineers and biological resource agencies to study many of these areas. Together, engineers and biologists use the micromodel to study the bathymetric effects of modifying closure structures and adding innovative river engineering structures to the side channels. While the biologists are concerned with creating the best habitat possible, the engineer needs to understand the potential effects on the main channel. By using the model as both an engineering and planning tool, the project teams have developed various designs that are currently waiting for construction funding.

3.3.4. Thalweg Realignment

The micromodel has also been used to study various means of shifting the alignment of a river's thalweg to achieve a variety of design objectives. Repositioning a thalweg can alleviate a chronic dredging problem, reduce bank attack, generate additional aquatic habitat, or shift flow patterns to assist navigation. Furthermore, thousands of bridges over small streams are misaligned with the channel thalweg. This may result in debris jams at the bridge piers as well as significant erosion to the stream banks and bridge abutments. The micromodel has been used to help address problems where stream alignment through a bridge opening has threatened the bridge's integrity. Generally, micromodel studies of smaller tributary streams involve a lower degree of vertical scale, slope, and Froude number distortions than used for studies of the Mississippi River.

3.3.5. Bathymetric and Flow Pattern Evaluation for Navigation Improvement

One of the more controversial uses of the micromodel has been to assess bathymetric patterns and far field flow patterns where a hazard to commercial navigation exists. The controversy stems from use of surface flow patterns in the micromodel for assessing improvement alternatives, particularly in the vicinity of navigation structures such as locks and dams. The issue pertains to the large Froude number distortion used in the micromodel, which produces distorted velocities and velocity distributions in the models. Where surface flow patterns are an integral part of the study objective, such distortions no doubt have an adverse affect on the ability of the model to replicate prototype behavior.

3.3.6. Suspended Sediments

Sediment materials used in micromodels limit their application to sand- or gravel-bed streams that transport sediments predominately as bedload. The PlastiGrit sediment material used in the micromodel behaves in a similar manner to sand. Simulation of bed response with a cohesive bed is beyond the capability of existing movable-bed physical models and available numerical models. The mechanics of cohesive material erosion and transport are not well understood and no empirical methods exist to simulate channel adjustment when cohesive bed and bank materials occur.

3.4. Micromodel Case Studies

Even though theory seems to preclude model dimensions that are less than prototype dimensions (to achieve direct or nearly direct similitude), there have been a number of cases where movable bed model studies lead to a successful solution of river engineering problems. Because movable-bed models typically depart from ideal similitude (i.e. where model to prototype ratios equal unity) in unknown ways, all that can be done to assess the model's ability to replicate prototype behavior must be based upon case studies. A complete assessment of case studies would involve looking at the model's replication of base conditions found in the prototype as well as the model's ability to predict prototype response to a changed condition. Unfortunately, most case studies only afford the opportunity to compare results of the model calibration bathymetry with the prototype because few cases exist where model recommendations have been implemented in the prototype. Thus, the ability of the micromodel to predict prototype response cannot be assessed with any degree of confidence.

The following sub-sections provide a brief description of specific micromodel case studies. In each case, the modeler determined that each model had been sufficiently calibrated to the level necessary for proceeding with alternative testing. The degree of calibration achieved prior to alternative tests was incorporated into the modeler's interpretation of model results. Although the degree of model calibration varied between the various studies, the models permitted relative comparisons between alternatives to determine their effectiveness (Pokrefke, Personal Communication and Gordon, Personal Communication). Where possible, micromodel case studies that have information allowing assessment of their predictive capability are included.

Section 4.2 of this report contains a comparison of calibrated model bathymetry and prototype surveys.

3.4.1. Big Creek (Unpublished)

Gordon (Unpublished) describes Big Creek is a typical meandering, gravel-bed stream located in central Missouri. In 1995, county highway commissioners requested the St. Louis District to help in assessing rapid bank migration on Big Creek that threatened the County Highway 729 bridge abutment. According to Gordon, the St. Louis District utilized a micromodel of the reach to aid in the analysis of possible alternative solutions. The Big Creek micromodel had a horizontal scale of 1:600 and a distortion ratio of 5. Model calibration was achieved from limited field surveys, aerial photography, and field reconnaissance.

Gordon (unpublished) states that following completion of the micromodel study, the recommended structure was constructed in 1997. After the first high water event following construction, the streambed began to develop as projected in the micromodel. Field reconnaissance in the years following (up through 2002) indicated that the stream has developed the thalweg pattern predicted in the micromodel. A depositional area has been established at the threatened bridge abutment and vegetation is naturally stabilizing the bankline.

3.4.2. Mouth of the White River (Gordon and Davinroy, 1998)

Gordon and Davinroy (1998) describe a micromodel study of the Mississippi River at the confluence of the White River. Tows attempting to enter or exit the White River experienced difficulty due to high currents in the Mississippi River. Gordon and Davinroy state the purpose of the micromodel study was to assess general sediment transport and flow response trends of the Mississippi River in this area in order to examine methods for reducing/redistributing Mississippi River velocities by use of bendway weirs. Gordon (Unpublished) states that assessment of alternatives included a qualitative examination of changes to sedimentation patterns, flow patterns and navigation within the main channel of the Mississippi River.

Gordon (Unpublished) states that the model was considered calibrated after it was concluded that model bathymetric patterns were similar to those of the prototype. The recommended alternative described by Gordon and Davinroy (1998) included seven bendway weirs. According to Gordon (Unpublished), the bendway weirs in the model moved the higher velocities and depths toward the center of the Mississippi River channel and away from the confluence and produced a wider navigation channel. Because model channel bathymetry did not replicate exact prototype bathymetry, actual bendway weir designs varied from the model alternative. Final construction plans utilized the recommended alternative to establish the number and general alignment of the bendway weirs, but weir lengths in the prototype were somewhat shorter. The bendway weirs were also built to a slightly lower elevation than recommended by the micromodel study.

Construction of the bendway weirs began in 2001 with completion in January 2002. Gordon (Unpublished) reports that tow pilots who regularly operated in the reach noted significant improvements in general flow patterns immediately following construction. According to Gordon, post-construction hydrographic surveys and ADCP data indicate that prototype response is similar to that predicted by the micromodel.

3.4.3. New Madrid Bar Reach (Davinroy, 1996)

In the early 1990's, the New Madrid Bar reach experienced regular shoaling in the navigation channel between river miles 888 and 887. Davinroy (1996) describes a micromodel used to investigate possible solutions to the shoaling problem in the New Madrid Bar reach. The New Madrid reach was complex in that a middle bar produced a split flow condition. The New Madrid micromodel was one of the earliest micromodel studies and Davinroy states that the model base test condition utilized an average of five surveys. Maynord (Unpublished) points out that no other micromodel study reports record the averaging of multiple surveys to establish an "average sediment response in the micromodel" making this study somewhat unique.

The New Madrid Bar micromodel study recommended construction of a longitudinal dike connecting two stone dikes, Kentucky Point Dikes No. 1 and 2, along the left descending bank and opposite the mid-channel bar (Davinroy, 1996). Construction of the longitudinal dike occurred in 1998 with one modification—an environmental notch was left between the downstream end of the longitudinal dike and Kentucky Point Dike No. 2. Max (2003) reports that dredging in the problem reach has been substantially reduced following construction of the longitudinal dike and that prototype hydrographic surveys are similar to the recommended micromodel alternative.

3.4.4. Lock and Dam 24 (Davinroy et al., 1998)

Davinroy et al. (1998) describe a dangerous outdraft problem at the upstream approach to Lock and Dam 24 on the Mississippi River. Davinroy et al also describe a micromodel study used to develop alternative solutions to rectify the outdraft problem.

In the late 1960's and early 1970's a stone dike was constructed and extended upstream of the lock and perpendicular to the right descending bank in an attempt to alleviate outdraft conditions. According to Davinroy, et al., the dike was only partially successful. The purpose of the micromodel study was to study additional remedial measures, investigate flow mechanics that cause the outdraft problem, and to communicate with various interests regarding planned improvements. In all, thirty alternative plans were tested in the micromodel. A component of the micromodel studies included the use of Acoustic Doppler Current Profiler (ADCP) velocity data to assess prototype surface currents.

Gordon (Unpublished) reports that the recommended plan derived from the micromodel was constructed in two phases. In 1998, the existing stone dike upstream of the lock was extended. In 2002, the four bendway weirs were constructed. The bendway weirs were not constructed as modeled because prototype depths along the Missouri bank were less than indicated in the model. Gordon (Unpublished) indicates that initial results from lock personnel and tow pilots were positive, and tow pilots have described noticeable improvements in the lock approach. Gordon also states that a comparison of pre- and post-construction ADCP surface flow patterns indicate dissipation of the outdraft problem.

3.4.5. Sante Fe Chute (Gordon et al, 1998)

Gordon et al (1998) describe a reach of the Mississippi River where various interest groups desired to improve riverine habitat for fisheries. A micromodel of the Sante Fe Chute reach allowed a team of experts from the US Fish and Wildlife Service, the Illinois Department of Natural Resources, the Missouri Department of Natural Resources, and the St. Louis District to develop and test strategies for developing aquatic diversity in the Chute. Gordon (Unpublished) states that the micromodel also enabled engineers to ensure that proposed alternatives had no adverse effect on the navigation channel.

After micromodel calibration, Gordon (Unpublished) states that the various interest groups were able to test alternatives in the micromodel. The recommended alternative consisted of constructing alternating dikes within the chute channel to achieve the desired aquatic diversity. However, Gordon states that funding constraints prevented construction of the dikes to elevations derived from the recommended plan. Gordon goes on to say that recent field monitoring indicated that the chute channel has partly developed even with the structures at a lower elevation. In 2003, funding enabled the dikes to be raised to the elevation recommended by the micromodel.

3.4.6. Morgan City/Berwick Bay (Gordon and Davinroy, 2001 and Gordon et al, 2001)

Gordon and Davinroy (2001) describe a micromodel study conducted in the Atchafalaya River at Morgan City, LA to an effort to reduce dredging requirements. The Atchafalaya River at Morgan City, LA is part of the Gulf Intracostal Waterway System (GIW), which has a 12-foot by 125-feet wide navigation channel. A number of GIW channels converge in this reach. Gordon and Davinroy state that micromodel study goals were to qualitatively assess sediment transport and flow response trends of the Atchafalaya River and to evaluate design alternatives that would reduce deposition and associated dredging in the reach. Gordon and Davinroy used confetti streaks in the micromodel to compare general surface current patterns of the various alternatives. Gordon and Davinroy evaluated the effectiveness of each design by comparing the resultant bed configuration and flow patterns to the model base test condition.

Gordon (Unpublished) states that the complexity of the reach requires extreme caution when studying alternatives that significantly modifies the flow patterns. Gordon indicates that the recommended design from the micromodel study is currently being analyzed in a three-dimensional numerical flow model and will also be analyzed in a computer navigation simulator to study these effects prior to field implementation.

3.4.7. Marquette Chute (Davinroy et al, 1997)

Davinroy et al (1997) state that the purpose of this micromodel study was to address sediment transport response and interaction between the main channel and side channel of the Mississippi River. The intended goal of the study was to develop increased aquatic diversity in the side channel without adversely affecting the navigation channel. The report states that this study included two base test conditions: one for conditions prior to construction of a series of bendway weirs in 1995 and one for conditions following their construction. Davinroy et al report that both calibration tests were similar to prototype conditions. Maynord (Unpublished) also notes in an interpretation of report plates that both verifications were good. The Davinoy, et al. report does not describe a procedure whereby the second calibration, with bendway weirs, was achieved by adding the additional structures to the first calibration condition.

3.4.8. Savannah Bay (Kirkeeng et al, 1998)

Kirkeeng et al (1998) state that the micromodel study was performed to address the effects of various design alternatives to alleviate maintenance dredging between Miles 540 and 538. The study goals also included consideration of the effects that alternatives might have had within the side channel. The report provides a fairly detailed description of various attributes of the calibrated model bathymetry and states that at the start of the study reach, Mile 540 to 539, both the prototype and model displayed similar channel crossings although the model channel was slightly shallower. The report also states that the principal shoaling area, Mile 539 to 538.5, along the right bank was replicated in the model but that the model also had a tendency to shoal in the navigation channel in this area while the prototype maintained fairly deep.

3.4.9. Copeland Bend (Davinroy et al, 1999)

The stated study purpose was to evaluate design alternatives focused on environmental enhancement by creation of shallow water habitat within Copeland Bend. The study alternative measures used to create the shallow water habitat included environmental notches in dikes. Overall, the reach was not complex because it contained a relatively mild bend and closely spaced, relatively short training structures. The report indicates that the micromodel did a good job of replicating the prototype main channel bathymetry in the base test.

3.4.10. White River (Boeckmann et al, 2000)

This report actually records two separate micromodel studies, the first of the Augusta Reach and the second of the Clarendon Reach. Boeckmann et al state that the study was performed to investigate methods for reducing the amount of maintenance dredging in select reaches of the White River navigation channel. The report describes the calibrated model bathymetry as approximately 15 feet shallower than prototype depths near Mile 196 and 5 feet shallower than the prototype depths between Miles 195 and 194 for the Augusta micromodel-- These areas were stated as locations that required maintenance dredging. The report also states that bend scour in the Augusta model was excessive and required the addition of armor to limit scour depths. The report indicated that crossing locations and depths for the Augusta model were similar to prototype surveys. According to the report, the calibrated Clarendon model exhibited fairly good agreement with prototype surveys except at the bend at Mile 96 where scour was excessive. As with the Augusta model, the report states that armor material was added to the Clarendon micromodel to limit excessive bend scour.

3.4.11. Wolf Island Bar (Davinroy, et al, 2000)

The report states that the micromodel study was performed to examine the effects of various alternatives to maintain existing flow conveyance and to improve the navigation channel crossing between Miles 936 and 935. This reach of the Mississippi River is very complex because of the split flow condition that exists at Wolf Island and the large capacity of the secondary channel. Davinroy et al report that the calibrated micromodel exhibited similar bed response to prototype surveys, but further identified specific trends where model bathymetry differed from prototype bathymetry by as much as 20 to 30 feet. Davinroy et al do not record any information regarding flow distribution between the main and chute channels for the model.

3.4.12. SEMO Port (Davinroy, et al, 2000)

The micromodel study report on SEMO Port explains that since the construction of this slack water harbor in 1988 periodic maintenance dredging has been required. The deposition patterns in the port were typical of slack water areas where sediment tends to accumulate near the interface with the moving river channel. According to the report, the calibrated micromodel showed deposition patterns and flow eddies consistent to those observed in the prototype.

The recommended design obtained from the study consisted of a small dike on the bankline just upstream of the port entrance. Gordon (Unpublished) states that the dike was built to approximately half the recommended design height in 2000. He adds that a reduction in the amount and frequency of dredging has been noticed since construction.

3.4.13. Schenimann Chute (Gordon and Davinroy, 2000)

The Schenimann Chute micromodel was used solely to study bathymetric impacts within the side channel. Two major problems caused the calibration of the model to be below the usual standards used for micromodels. Scale constraints caused the entrance of the chute to be extremely close to the entrance conditions in the micromodel channel. According to Gordon (Unpublished), poor construction of the micromodel insert caused errors in the bathymetric measurements of the model bed. Although these were major issues, it was decided to use the model to investigate structural designs within the side channel because it was felt that the bathymetric trends were sufficient for studying environmental issues.

The recommended design consisted of a set of alternating dikes or hard points to create bathymetric diversity. Notches in the closing structures and dredging were also recommended. The model study did not investigate the design's effects on the bathymetry in the main channel.

3.4.14. Vicksburg Front (Davinroy, et al, 2000)

The micromodel report describes the navigation difficulties at Delta Point due to a sharp bend, a large middle bar, and two bridge crossings near the Vicksburg city front. A micromodel was used to examine the bathymetry and flow patterns in this reach of river.

From the model, it was recommended that four new dikes should be built and two existing dikes should be raised upstream of the bend. Gordon (Unpublished) states that a staged construction approach was utilized with two of the four recommended dikes being built in 2001. He also states that hydrographic surveys following the initial construction showed that a portion of the problematic bar at Delta Point had begun to recede and that the navigation channel had begun to widen. The remainder of the recommended plan is scheduled for construction in 2004.

3.4.15. Ballard's Island (Kirkeeng and Landwehr, 2001)

The report states that the micromodel was performed to analyze the flow and sediment transport characteristics around Ballard's Island. This study utilized a hybrid modeling approach consisting of both a fixed-boundary numerical model and a micromodel. The report describes the calibrated micromodel by stating that the model achieved a similar bed response as indicated by the prototype surveys. However, the report also states that the micromodel had some difficulty in reproducing prototype trends at the entrance to Ballard's Bar, River Mile 248.2 which was within the calibrated reach. At RM 248.2 the model exhibited excessive scour depth at the island boundary which was not present in the prototype. For this reason, the model bed was armored to limit scour depths.

3.4.16. Bolters Bar/Iowa Island (Gordon, et al, 2001)

The reach of river known as Bolters Bar had required dredging at least once a year since the construction of Lock and Dam 26 in the 1930's. A micromodel showed that a set of standard dikes or wingdams would have reduced dredging and met the needs of the tow industry. However, according to the report, resource agencies and recreational boaters would have resisted the construction of these structures in this reach of river where side channels and boat harbors are abundant. The report states that the development of a unique solution was required in this reach in order to meet the objectives of the numerous groups and agencies involved.

From the micromodel study it was recommended that four chevrons and one longitudinal dike should be constructed which were completed in the spring of 2002. Gordon (Unpublished) reports that during the following fall low-water season, the reach did not require its yearly dredging for the first time. Gordon states that hydrographic survey data revealed an increase in depth in the navigation channel and an improved alignment for navigation and that depths increased to at least 15 feet in some of the areas where it was once difficult to artificially maintain 9 feet of water.

3.4.17. Lower Peoria Lake (Kirkeeng, 2002)

Kirkeeng states, "The purpose of the study was to evaluate various combinations of island construction / channel dredging alternatives for the purpose of restoring the Lake Peoria ecosystem." The model study was part of larger feasibility study to restore Lower Peoria Lake, located along the Illinois River. The focus was on addressing sedimentation, which has the major factor in reducing lake depth and is widely believed to be the greatest ecological threat to the Illinois River. He states, that since 1903, the volume of the Lake below elevation 440 feet has decreased by over 60%.

The model was used to study and evaluate sedimentation trends and general flow impacts that could be expected to occur from various island configurations in the Lake. The report adds that although the bathymetry and flow patterns in the model differed slightly from those in the prototype, impacts of the islands on the Lake bathymetry were evaluated in a generic sense.

3.5. A Special Case Study, Kate-Aubrey Reach

3.5.1. Background

Franco (1978) and Gaines (2002) present the history of the Kate-Aubrey reach of the Mississippi River. This reach of the Mississippi River has experienced continual navigation problems since the 1960's. The primary problems in the Kate-Aubrey reach included a poor and inconsistent channel alignment and shoaling in the channel, which required significant dredging to maintain navigable depths. Gaines (2002) presents an analysis of three movable-bed models of the reach. The three models consisted of an ERDC (formerly WES) coal-bed model and two micromodels. Although ERDC sand-bed model studies in the late 1960's and later coal-bed model studies in the 1980's aided in developing improvement plans for the reach, dredging was still required to maintain navigation depths following construction of plans in the prototype.

In 1999 two micromodel studies (one having twice the horizontal scale as the other) were conducted as part of this evaluation in order to investigate scale effects that occur with the micromodel (Gaines, 2002). The two micromodels were calibrated to a mid-1970's timeframe and then subjected to an observed future condition in the prototype (i.e. 1998). Calibration of the two Kate-Aubrey micromodels was assessed by specific criteria established by the JV team (Gaines, 2002 and USACE, In Progress). This criteria considered thalweg location as a primary determinant but also considered model depths and cross-sectional areas relative to the prototype. Flow splits were not a consideration in the Kate-Aubrey models. Ultimately, the JV team agreed that the micromodels had achieved calibration. To evaluate the predictive capability of the Kate-Aubrey micromodels, the models were then adjusted by the addition and modification of training structures in order to reflect future prototype conditions. Operation of both micromodels to simulate the 1998 prototype condition failed to adequately reproduce observed prototype trends.

Comparisons between the ERDC coal-bed model and its prototype reach and the two Kate-Aubrey micromodels and their prototype reach (the ERDC model and the two micromodels were of slightly different reaches) were made using five morphologic parameters--thalweg position, hydraulic depth, channel width, the width to depth ratio, and the cross-sectional area (Gaines, et al, In Progress).

3.5.2. Published Micromodel Study Reports

Table 3-2 shows a list of published micromodel study reports to date. Inclusion of micromodel investigations in Table 3-2 does not constitute an endorsement by the JV team as to the applicability of micromodels to achieve stated study objectives.

Table 3-2 USACE Micromodel Investigations.

Investigation Name (River/Stream)	Horizontal Scale*	Distortion (Horz.:Vert.)
Mouth of White River (Mississippi)	1:12000	10:1
Clarendon, AR (White)	1:4200	14:1
Augusta, AR (White)	1:3600	20:1
Vicksburg Front (Mississippi)	1:14400	12:1
Wolf Island (Mississippi)	1:7200	12:1
Memphis Front (Mississippi)	1:4800	8:1
Sante Fe Chute (Mississippi)	1:7200	6:1
Lock & Dam 24 (Mississippi)	1:9600	16:1
SEMO Port (Mississippi)	1:3600	6:1
Bolters Bar (Mississippi)	1:9600	16:1
Savanna Bay (Mississippi)	1:4800	8:1
Marquette Chute (Mississippi)	1:9600	12.3:1
Copeland Bend (Missouri)	1:3600	15:1
Ballard's Island (Illinois River)	1:3600	15:1
Schenimann Chute (Mississippi)	1:4800	8:1
Morgan City/Berwick Bay (Atchafalaya)	1:7200	6:1
New Madrid (Mississippi)	1:20000	17:1

- Herein scale is model/prototype ratio

4. MODEL/PROTOTYPE COMPARISONS

4.1. General

Maynord (Unpublished) raises the primary question of whether the micromodel can predict prototype response in a calibrated model. Unfortunately, few cases exist where prototype response to changes implemented as a direct result of micromodel recommendations have been measured. Therefore, the ability of the micromodel to be adequately calibrated, i.e. replicate existing conditions, is the only information available in almost all studies.

In order to investigate the ability of model studies to replicate prototype conditions and to obtain some indication of the degree of accuracy possible during model calibration, a comparison of model and prototype bathymetry was made by USACE (In Progress). USACE provide comparison data for thirty model studies, sixteen model studies conducted at ERDC and fourteen micromodel studies.

Maynord (Unpublished) critiqued previous micromodel studies based on a comparison of calibrated model bathymetry and flow visualization, where applicable, to prototype data. Maynord's critique considered only technical merits of the calibration accuracy and did not consider procedural aspects of the model. Davinroy (Unpublished) critiqued the predicted to observed prototype response for two ERDC model studies.

In evaluating the results of movable-bed model studies, the evaluator must consider both model results and the procedure used to achieve those results (Franco, 1982). In comparing model results to prototype conditions, Franco (1982) states that, "Use of the results of tests of improvement plans 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." Franco adds that comparing model indications with developments in the river requires that the differences in flow conditions, differences between plans tested and that constructed in the river, and the effects of any dredging in the prototype not reproduced in the model receive due consideration.

The use of comparisons to establish a measure of required model prototype agreement and the predictive ability of a model must, therefore, reflect both technical as well as procedural aspects of the model. The procedural aspects include the accuracy of model adjustment, characteristics of the reach, flow conditions, and (for predictive analysis) the similarity between model plans and actual prototype construction. Davinroy (Unpublished) stated that although the procedure utilized for the micromodel is different than used by the ERDC models, the micromodel procedure had its origins in the larger, ERDC movable-bed models. Therefore, the interpretation of micromodel results reflects institutional knowledge gained from the ERDC models, which were widely accepted for providing useful results within the river engineering community. For this reason, the ERDC model study results provide insight into the level of accuracy required of the models for the types of studies conducted of river training structures.

As stated in Section 2, movable-bed models fail to replicate all flow characteristics, primarily because of scale and Froude number distortions and associated relaxations in similarity criteria in empirically based models. Consequently, model bathymetry always deviates from prototype conditions in some regard. The magnitude, extent and causes of these deviations vary from one model to another and depend upon the characteristics of the prototype reach. In order to properly interpret model results, it is necessary to have an understanding of 1) how well the model reproduces the prototype relative to the problem being investigated and 2) the deviations observed in the model.

Although a model's capability to replicate prototype bathymetry cannot be established based upon technical considerations only, there is merit in conducting a strict comparison using only the bathymetry (i.e. bed contours, cross-sectional areas, and cross-sectional depths) to obtain an indication of the micromodel's ability to replicate the prototype. Although such a comparison does not consider procedures used, its value comes from providing an approximate quantification of model calibration accuracy. A crucial issue in the following comparisons is that the original modeler(s) determined each model to be calibrated to the level required for investigating the problem that existed in the prototype. In each case, the modeler(s) used the model for analyzing various alternative designs. These analyses were based upon accepted model practices of the facility conducting the model study. The following assessment intends only to investigate the degree of calibration achieved by the models relative to a specific set of criteria applied for a single water surface elevation. The morphologic variables used to define model to prototype agreement comprise only a small subset of the information considered by the original modeler, and the following ranking of the degree of calibration does not intend to counter the original modeler's interpretation.

4.2. Calibrated Model Bathymetry Comparisons by Gaines

Since past movable-bed model experience within the Corps of Engineers originates with the ERDC models, the ability of those models to reproduce their respective prototypes provides a useful reference point when considering micromodel capabilities. The utility of including the former ERDC models lies in having a reference point that serves to define what has been acceptable in terms of model results/outputs. The following sections contain an application of Maynord's (Unpublished) criteria for assessing the quality of model bathymetry calibration (Section 2.6) to the model comparison data shown in USACE (In Progress). However, the subjective nature of even a cursory assessment requires some clarification to provide an idea of the rating criteria used. For the comparisons that follow:

1. Very Good indicates that the model achieved successful calibration for the criteria under consideration.

2. Good indicates that the model achieved a degree of calibration, but fell more than a specified percentage (typically 10%) above/below the prototype for the criteria under consideration.

3. Fair indicates that the model may have been calibrated over portions of the model, but fell more that a specified percentage (typically greater than 20%) above/below the prototype for the criteria under consideration.

4. Marginal indicates that the model failed to reproduce prototype trends over the problem area and departed from prototype values greater than the percentage specified for the Fair rating.

For consistency, Gaines applied these ratings to all model study bathymetry data available during this study. The subjective method used approximate percentages as the basis of applying the ratings as opposed to a more rigorous use of numerical percentage values. Assessments were based on plots of morphologic variables through the problem reach investigated within each model and did not utilize any reach averaging of the values. Biases introduced by one individual's subjective interpretation are likely, yet all models were rated on the same basis. Individuals questioning the following interpretation should review USACE (In Progress) for further clarification and to review available model data. Ratings are based on data for morphologic variables calculated for a water surface elevation corresponding to 0.0 LWRP, as applicable. Other ratings may result for analysis of model and prototype agreement at different water surface elevations.

Reiterating, it is imperative for the reader to recognize that the ratings presented in subsequent sections reflect an assessment of a **CALIBRATED** model bathymetry. The ratings do not critique the model study results as a whole. In each case, the original modeler judged that the model had been calibrated to the level necessary for conducting the particular study at hand. The significance of the ratings is that lower ratings imply that a greater level of experience is required of the modeler in interpreting results while a higher rating would require a lesser level of experience to interpret model results.

The ratings presented herein cannot replace the original modeler's assessment because those modelers considered many factors not included below. Therefore, the following ratings are only provided to facilitate a better understanding of past model calibrated bathymetry and prototype survey agreement. A better understanding in this area helps to establish a level of acceptable model performance as pertains to studies of river training structures.

4.2.1. Baleshed-Ajax Bar – ERDC

Simulation of Planform: Thalweg location was very good.
Departures in depth, width and area near problem area:
- Cross-section Area was fair—greater than 20% too low
- Top Width was good.
- Hydraulic depth was fair—greater than 20% too low.
- Width to Depth ratio was fair—greater than 20% too high and trends not reproduced well.

Reproduce Flow Splits: Unknown around mid-bar
Reproduce Problem: Good

4.2.2. Blountstown – ERDC

Simulation of Planform: Thalweg location was very good.

Departures in depth, width and area near problem area:
Cross-section Area was Fair—some areas greater than 100% too high
Top Width was good—trends reproduced.
Hydraulic depth was fair—some areas greater than 100% too high.
Width to Depth ratio was good.
Reproduce Flow Splits: NA
Reproduce Problem: Good

4.2.3. Buck Island – ERDC

Simulation of Planform: Thalweg location was good—trends did not match 1979 survey.
Departures in depth, width and area near problem area:
Cross-section Area was Fair—trends were out of phase
Top Width was good—trends reproduced within 10% of prototype.
Hydraulic depth was good within center portion of model.
Width to Depth ratio was good.
Reproduce Flow Splits: NA
Reproduce Problem: Good

4.2.4. Chipola-Cutoff – ERDC

Simulation of Planform: Thalweg location was good over half of model but marginal for the other half
Departures in depth, width and area near problem area:
Cross-section Area was good—generally within 10% of prototype
Top Width was good—trends generally reproduced within 10% of prototype except at Ranges 19 and 40.
Hydraulic depth was good—within 10% of prototype in center portion of model.
Width to Depth ratio was good.
Reproduce Flow Splits: Unknown
Reproduce Problem: Good

4.2.5. Devil's Island – ERDC

Simulation of Planform: Thalweg location was good but missed trend in problem area by more than 10%
Departures in depth, width and area near problem area:
Cross-section Area was good—generally within 10% of prototype
Top Width was fair—greater that 20% higher in lower ½ of model
Hydraulic depth was good—within 10% of prototype
Width to Depth ratio was fair—greater than 20% higher in lower ½ of model
Reproduce Flow Splits: NA
Reproduce Problem: Fair

4.2.6. Dogtooth Bend Reach– ERDC

Simulation of Planform: Thalweg location was very good
Departures in depth, width and area near problem area:
- Cross-section Area was fair—trends were out of phase and greater than 20% too low in upper 1/3 of model
- Top Width was good—within 10% of prototype except at R 21
- Hydraulic depth was fair—greater than 20% too low in upper 1/3 of model
- Width to Depth ratio was fair—greater than 20% higher in lower ½ of model

Reproduce Flow Splits: NA
Reproduce Problem: Fair

4.2.7. Kate-Aubrey – ERDC

Simulation of Planform: Thalweg location was fair—greater than 20% off prototype
Departures in depth, width and area near problem area:
- Cross-section Area was fair—greater than 20% below 1976 prototype
- Top Width was fair R 22-25 in problem area, good otherwise
- Hydraulic depth was very good
- Width to Depth ratio was fair in problem area, R22-25, good otherwise

Reproduce Flow Splits: NA
Reproduce Problem: Fair

4.2.8. Lake Dardanelle – ERDC

Simulation of Planform: Thalweg location was very good
Departures in depth, width and area near problem area:
- Cross-section Area was fair—trends out of phase and greater than 20% above/below prototype, some values more than 300% low at locations
- Top Width was fair—trends out of phase and greater that 200% lower at locations
- Hydraulic depth was good—generally within 10% of prototype
- Width to Depth ratio was fair—trends incorrect in upper 1/3 of model and greater than 100% too low at locations

Reproduce Flow Splits: NA
Reproduce Problem: Fair

4.2.9. Lock and Dam No. 2 – ERDC

Simulation of Planform: Thalweg location was very good
Departures in depth, width and area near problem area:
- Cross-section Area was good—within 10% of prototype except R13-18 where greater than 50% above
- Top Width was good—within 10% of prototype
- Hydraulic depth was very good
- Width to Depth ratio was good—generally within 10% of prototype except R42-44 where greater than 100% higher

Reproduce Flow Splits: NA
Reproduce Problem: Very Good

4.2.10. Lock and Dam No. 4 – ERDC

Simulation of Planform: Thalweg location was very good except fair R 71-75
Departures in depth, width and area near problem area:
- Cross-section Area was fair—wrong trends indicated for 1981 survey
- Top Width was very good
- Hydraulic depth was fair—wrong trends indicated for 1981 survey
- Width to Depth ratio was good—trends reproduced but magnitude greater than 20% too low R70-73

Reproduce Flow Splits: NA
Reproduce Problem: Good

4.2.11. Loosahatchie-Memphis – ERDC

Simulation of Planform: Thalweg location was poor in problem area in vicinity of R30
Departures in depth, width and area near problem area:
- Cross-section Area was good—within 10% of prototype except R34-35 where greater than 20% too low relative to 1990 survey
- Top Width was good—within 10% of prototype except R22 where greater than 100% too high
- Hydraulic depth was good in problem area, but fair elsewhere relative to 1990 survey
- Width to Depth ratio was good—generally within 10% of prototype except R21 and R22 where greater than 100% higher

Reproduce Flow Splits: NA
Reproduce Problem: Good

4.2.12. New Madrid – ERDC

Simulation of Planform: Thalweg location was good—within 10% of prototype
Departures in depth, width and area near problem area:
- Cross-section Area was good—within 10% of prototype except trends incorrect R20-22 in problem reach
- Top Width was marginal—greater than 50% too high/low in problem area and 1978 trends not reproduced
- Hydraulic depth was fair—greater than 20% too low/high
- Width to Depth ratio was fair—greater than 20% too low/high relative to 1978 prototype.

Reproduce Flow Splits: Unknown
Reproduce Problem: Fair

4.2.13. Redeye Crossing – ERDC

Simulation of Planform: Thalweg location was good—generally within 10% of prototype

Departures in depth, width and area near problem area:

- Cross-section Area was fair—Incorrect trends and greater than 20% too low
- Top Width was very fair—incorrect trend and greater than 50% too low
- Hydraulic depth was fair—incorrect trend
- Width to Depth ratio was fair—incorrect trend

Reproduce Flow Splits: NA

Reproduce Problem: Fair

4.2.14. Smithland – ERDC

Simulation of Planform: Thalweg location was very good

Departures in depth, width and area near problem area:

- Cross-section Area was good—within 10% of prototype except R35-39 where greater than 50% above
- Top Width was very good
- Hydraulic depth was good—within 10% of prototype except R35-39 where greater than 50% above
- Width to Depth ratio was good—generally within 10% of prototype except R35-39 where greater than 50% lower

Reproduce Flow Splits: Unknown

Reproduce Problem: Very Good

4.2.15. West Access – ERDC

Simulation of Planform: Thalweg location was good—generally within 10% of prototype

Departures in depth, width and area near problem area:

- Cross-section Area was fair—Incorrect trends
- Top Width was good—greater than 10% too low
- Hydraulic depth was fair—incorrect trend
- Width to Depth ratio was fair—incorrect trend

Reproduce Flow Splits: Unknown

Reproduce Problem: Fair

4.2.16. Bass Location, Willamette – ERDC

Simulation of Planform: Thalweg location was good—generally within 10% of prototype except R12-14

Departures in depth, width and area near problem area:

- Cross-section Area was good—generally within 10% of prototype
- Top Width was good—generally within 10% of prototype
- Hydraulic depth was good—generally within 10% except R13-15

Width to Depth ratio was very good
Reproduce Flow Splits: NA
Reproduce Problem: Good

4.2.17. Augusta Reach – Micromodel

Simulation of Planform: Thalweg location was good—generally within 10% of prototype
Departures in depth, width and area near problem area:
Cross-section Area was good—within 10% of prototype
Top Width was good—less than 10% too high
Hydraulic depth was good—generally within 10% of prototype
Width to Depth ratio was good—within 10% of prototype
Reproduce Flow Splits: NA
Reproduce Problem: Good

4.2.18. Copeland Bend – Micromodel

Simulation of Planform: Thalweg location was good—generally within 10% of prototype
Departures in depth, width and area near problem area:
Cross-section Area was fair—greater than 20% too high
Top Width was fair—greater than 20% too high
Hydraulic depth was good—generally within 10% of prototype
Width to Depth ratio was good—within 10% of prototype
Reproduce Flow Splits: NA
Reproduce Problem: Good

4.2.19. Clarendon Reach – Micromodel

Simulation of Planform: Thalweg location was good—generally within 10% of prototype
Departures in depth, width and area near problem area:
Cross-section Area was fair—greater than 20% too high
Top Width was good—within 10% of prototype
Hydraulic depth was good—generally within 10% of prototype
Width to Depth ratio was good—within 10% of prototype
Reproduce Flow Splits: NA
Reproduce Problem: Good

4.2.20. Lock and Dam No. 24 – Micromodel

Simulation of Planform: Thalweg location was good—generally within 10% of prototype
Departures in depth, width and area near problem area:
Cross-section Area was good—within 10% of prototype

Top Width was very good
Hydraulic depth was fair—incorrect trends in 1/3 of model, R 1-25, where greater than 20% too high
Width to Depth ratio was fair—incorrect trend R41-45 and greater than 20% too low R 1-21
Reproduce Flow Splits: Unknown
Reproduce Problem: Good

4.2.21. Memphis Harbor – Micromodel

Simulation of Planform: Thalweg location was fair—incorrect trends
Departures in depth, width and area near problem area:
Cross-section Area was fair—incorrect trends and greater than 20% too low R 26-R35
Top Width was very good
Hydraulic depth was fair—incorrect trends and greater than 20% too low R25-35
Width to Depth ratio was fair—greater than 20% too high R 25-35
Reproduce Flow Splits: NA
Reproduce Problem: Fair

4.2.22. Morgan City – Micromodel

Simulation of Planform: Thalweg location was good—generally within 10% of prototype
Departures in depth, width and area near problem area:
Cross-section Area was good—within 10% of prototype except R 1-3
Top Width was good—within 10% of prototype except R 47-59
Hydraulic depth was good—generally within 10% of prototype except R 6-9 where greater than 50% too high and R 51-55 where approximately 30% too low
Width to Depth ratio was good—within 10% of prototype except R 47-59.
Reproduce Flow Splits: NA
Reproduce Problem: Good

4.2.23. New Madrid Bar – Micromodel

Simulation of Planform: Thalweg location was fair in problem, R 9-11, good otherwise
Departures in depth, width and area near problem area:
Cross-section Area was marginal—greater than 200% too low (model less than ½ prototype area) upstream of problem area at R 3-10, and fair otherwise
Top Width was fair—generally too low by as much as 50%
Hydraulic depth in model was ½ prototype depths upstream of problem reach R5-R8, good otherwise
Width to Depth ratio was fair in problem area
Reproduce Flow Splits: Unknown

Reproduce Problem: Fair

4.2.24. Salt Lake Chute – Micromodel

Simulation of Planform: Thalweg location was fair—trends not reproduced well
Departures in depth, width and area near problem area:
- Cross-section Area was fair—greater than 20% too high
- Top Width was good—generally within 10% of prototype
- Hydraulic depth was fair—trends not reproduced well and magnitude greater than 20% too high
- Width to Depth ratio was fair—greater than 20% too low

Reproduce Flow Splits: Unknown
Reproduce Problem: Fair

4.2.25. Vicksburg Front – Micromodel

Simulation of Planform: Thalweg location was good R 22-43, marginal otherwise
Departures in depth, width and area near problem area:
- Cross-section Area was fair—incorrect trends and magnitudes greater than 20% too high/low
- Top Width was good—within 10% of prototype except R 27 and R 54
- Hydraulic depth was good except R43-46 where poor
- Width to Depth ratio was good except R 44 where fair and R 54 where marginal

Reproduce Flow Splits: NA
Reproduce Problem: Fair

4.2.26. Mouth of White River – Micromodel

Simulation of Planform: Thalweg location was fair—greater than 20% off of prototype
Departures in depth, width and area near problem area:
- Cross-section Area was marginal—greater than 50% too low and incorrect trends
- Top Width was fair—incorrect trends
- Hydraulic depth was marginal—model depths less than ½ prototype depths R9-R25
- Width to Depth ratio was fair—incorrect trends and magnitudes greater than 20% too high

Reproduce Flow Splits: Unknown
Reproduce Problem: Fair

4.2.27. Wolf Island – Micromodel

Simulation of Planform: Thalweg location was very good
Departures in depth, width and area near problem area:
- Cross-section Area was fair—greater than 20% too high and incorrect trends
- Top Width was good—within 10% of prototype

Hydraulic depth was marginal—model depths were ½ prototype depths R5 to R14 and were as much as 2 times prototype depths R24 to R46, also shows incorrect trends

Width to Depth ratio was good—within 10% of prototype except R 15 and 16

Reproduce Flow Splits: Unknown

Reproduce Problem: Fair

4.2.28. Kate Aubrey 1:16,000 – Micromodel

Simulation of Planform: Thalweg location was good—generally within 10% of prototype

Departures in depth, width and area near problem area:

Cross-section Area was good—within 10% of prototype except R 26-30 where fair

Top Width was good—within 10% of prototype except R 56-59 where poor

Hydraulic depth was good—generally within 10% of prototype except R 26-30 where greater than 50% too high

Width to Depth ratio was good—within 10% of prototype

Reproduce Flow Splits: NA

Reproduce Problem: Good

4.2.29. Kate Aubrey 1:8,000 – Micromodel

Simulation of Planform: Thalweg location was fair—generally within 10% of prototype

Departures in depth, width and area near problem area:

Cross-section Area was good—within 10% of prototype except R 33-34 where greater than 50% too high

Top Width was good—within 10% of prototype

Hydraulic depth was good—generally within 10% of prototype

Width to Depth ratio was good—within 10% of prototype

Reproduce Flow Splits: NA

Reproduce Problem: Good

4.3. Predictive Model Bathymetry Comparisons

Several case studies exist where predicted prototype response in the model could be compared to observed prototype response. These cases include situations where 1) the model was calibrated to a previous prototype condition then a future prototype condition was simulated in the model, and 2) the plans recommended as a result of model results were constructed in the prototype and sufficient time has passed to observe prototype response. Each of these scenarios provides data for determining a measurement of a model's predictive ability.

Those models having sufficient data for comparing a future prototype response relative to a model calibration follow. Because the Kate-Aubrey model results described below were for alternative conditions (NOT A CALIBRATED MODEL SURVEY), an additional rating of poor is used where the model failed to reproduce observed prototype behavior.

4.3.1. Kate Aubrey 1:16,000 - Micromodel

Simulation of Planform: Thalweg location was generally greater than 20% difference from prototype

Departures in depth, width and area near problem area:

- Cross-section Area was greater than 20% of prototype and incorrect trends
- Top Width exhibited incorrect trends
- Hydraulic depth was greater than 20% too low and trends not reproduced well
- Width to Depth ratio exhibited incorrect trends

Reproduce Flow Splits: NA

Reproduce Prototype Response: Poor

4.3.2. Kate Aubrey 1:8000 – Micromodel

Simulation of Planform: Thalweg location was greater than 20% of prototype

Departures in depth, width and area near problem area:

- Cross-section Area showed incorrect trends
- Top Width showed incorrect trends
- Hydraulic depth was greater than 20% too low over most of model and trends out of phase
- Width to Depth ratio showed incorrect trends

Reproduce Flow Splits: NA

Reproduce Prototype Response: Poor

4.3.3. New Madrid Bar – Micromodel

The New Madrid Bar micromodel study (Davinroy, 1996) recommended construction of a longitudinal dike connecting two stone dikes, Kentucky Point Dikes No. 1 and 2, along the left descending bank and opposite the mid-channel bar at New Madrid, MO. Construction of the longitudinal dike recommended from micromodel results occurred in 1998 with one modification—an environmental notch was left between the downstream end of the longitudinal dike and Kentucky Point Dike No. 2. Max (2003) reports that dredging in the problem reach has been substantially reduced following construction of the longitudinal (trail) dike. This observation agrees with projected micromodel study findings that the channel would deepen with the addition of the longitudinal dike.

4.3.4. Mouth of White River – Micromodel

The recommended plan developed using micromodel study results for the Mouth of White River reach included construction of seven bendway weirs. Construction of the bendway weirs began in 2001 with completion in January 2002. Post construction data include ADCP measurements on January 31, February 13, March 4, April 24, and May 30 of 2002, and March 12 and 18 of 2003, and hydrographic surveys on February 26 and June 5 of 2002.

Despite the fact that micromodel calibration may have been only fair, Gaines (Unpublished), Gordon (Unpublished) and Smith and Max (Personal Communication) state that prototype response projected from the micromodel has been favorable to observed prototype behavior following construction. The behavior entails dispersion of the higher velocity currents across a wider portion of the navigable channel as compared to the concentration of higher velocity currents against the right descending bank, and the channel cross-section shows a widening of the deeper water area through the bend. Gordon (Unpublished) reports that tow pilots who regularly operated in the reach noted significant improvements in general flow patterns immediately following construction. Post-construction ADCP data and hydrographic surveys indicate that prototype response includes a shift of higher velocities toward the left descending bank and a reshaping of the cross-section to redistribute velocities, respectively, which is similar to that predicted by the micromodel. Smith and Max state that the prototype has developed the characteristics envisioned from interpreting model results. Model results were consistent with results expected from the use of bendway weirs.

4.3.5. Dogtooth Bend – ERDC

Between 1984 and 1992, a movable-bed model study of the Dogtooth Bend Reach of the Mississippi River was used to study ways to reduce repetitive dredging during low water conditions. As a result of numerous tests described in the report, the bendway weir concept was developed and analyzed. Study results recommended the spacing, height, length and angle of the bendway weirs for the recommended plan. As noted previously, the calibration of the Dogtooth Bend model was fair based on morphologic values calculated at an elevation of 0.0 LWRP. However, evaluation of bathymetric data (from report plates) for elevations at –10.0 LWRP, -20.0 LWRP and –30 LWRP reveals a lesser state of calibration at the lower elevations. The significance of the greater model to prototype differences at the lower elevations includes the relatively greater effect on bendway weir dimensions (model recommendations included construction of bendway weirs to an elevation of –15.0 LWRP (Davinroy, 1994)).

Davinroy (Unpublished) describes prototype data obtained following construction of the bendway weirs recommended by the model study. Although the lengths of constructed bendway weirs varied considerably from those used in the model, Davinroy reports that prototype trends have been favorable and agree with overall model study findings. Davinroy states, "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."

4.4. Comparison of Flow Patterns in Calibrated Micromodel

Several previous micromodel studies presented aerial photographs of ice floes and ADCP velocity measurements in the prototype to show correct surface flow patterns in the micromodel. In cases, ice photos are inconclusive or do not support agreement between model and prototype surface flow patterns. Two studies are available to compare flow patterns in micromodel and prototype.

4.4.1. Lower Peoria Lake Micromodel

The goal of this study was to determine the impact of island construction on flow and sediment transport characteristics in the upper portion of Lower Peoria Lake (Kirkeeng, 2002). This is a complex reach with flow entering a wide lake containing a dredged channel. Prototype ADCP near surface velocities presented in the micromodel report show that only small velocities exist outside the dredged navigation channel as shown in the report plates. Flow visualization from the calibrated micromodel with surface confetti show significant velocities over a much greater width, particularly on the left side (looking downstream) of the dredged navigation channel. Significant velocities in the micromodel were delineated using the length of the confetti streaks from the model flow visualization. While the report acknowledges this deviation, many of the tested island alternatives are in the region where velocities are elevated in the micromodel.

4.4.2. Vicksburg Front Micromodel

Davinroy, Gordon, Rhoads, and Abbott (2000) conducted a micromodel study of the Mississippi River in the vicinity of Vicksburg, Mississippi to examine navigation improvements thru a particular troublesome reach. The study compared ADCP data collected in the river with confetti streaks photometrically captured in the micromodel. The study concluded that surface velocity patterns in the micromodel agreed with patterns observed from the ADCP data.

Maynord (2002) presents a comparison of surface currents in the Vicksburg Front micromodel and the prototype. Confetti streaks and Large Scale Particle Image Velocimetry (LSPIV) were used to determine surface velocities in the Vicksburg Front micromodel. Recording Global Positioning System (GPS) units were placed on surface floats in the bend of the river at Vicksburg, MS. The GPS floats were placed at various locations across the channel at the upstream end of the bend and retrieved at the lower end of the bend. The average stage in the river during the four-day measurement period and the stage in the micromodel were almost identical. Maynord converted velocities in the micromodel to prototype scale using the square root of the vertical scale ratio, which is the ratio applicable to distorted models. The plot of the data by Maynord (2002) shows the exaggeration of velocity typical of movable-bed models. Maynord indicates that in the Vicksburg Front Micromodel study the exaggeration is large, on the order of four times the Froude scale velocities. Maynord states that the plot also shows that velocities in the micromodel are concentrated on the left descending bankline when compared to the prototype data. Maynord argues that the concentration of flow on the left bank in the micromodel is consistent with the incorrect sediment deposition observed in the micromodel bathymetry along the right bank at river mile 437.5 that did not occur in the prototype.

Davinroy (Unpublished) produced a rebuttal indicating that the GPS float paths in the prototype used for Maynord's study did not properly capture flow trends observed with ADCP data. Davinroy stated that the float coverage was poor, with a large zone having no coverage over the majority of the main navigation channel. In Davinroy's opinion, the number of floats used was small and inconsistent with the amount of streak lines obtained from confetti seeded onto the model. Davinroy also presented data from previous ERDC model studies that exhibited the tendency for individual floating particles to follow seemingly random paths as they progressed through the reach, sometimes actually crossing in direction. Davinroy pointed out that several of the GPS floats crossed in the prototype at Vicksburg, some crossing by more than 900 feet, and argued that the true direction of flow through the reach was not fully captured.

As a result, Davinroy argues that GPS float paths in the prototype are inconsistent with streak lines obtained from confetti seeded onto the model surface. The argument is partially valid in that a dense seeding of particles provides for interaction between the particles which somewhat limits their lateral (across the general flow direction) dislocation while individual GPS floats are free to follow the main thread of flow in which they are located. However, in the case of the Vicksburg Front study, Maynord suggests that Davinroy's use of ADCP for developing surface flow patterns has three major flaws. First, the ADCP data were for a depth of five or more feet beneath the free surface of the water which based on a logarithmic velocity profile represents conditions different than at the surface. Second, the ADCP data were not representative of time-averaged velocities as were data from the confetti streaks, LSPIV, and GPS measurements. Third, and most importantly, the ADCP data were obtained at a stage approximately 14 feet lower than when prototype GPS float or micromodel confetti and LSPIV data were obtained.

Davinroy (Unpublished) countered that data collected in the past using an electromagnetic current meter on the Mississippi River has shown that the differences in velocity direction between the free surface and depths of five feet are negligible and very similar in appearance. Second, Davinroy states that the confetti streaks were not time-averaged velocities but time-exposed velocities. Third, Davinroy asserts that the micromodel confetti streaks were not correlated to a stage but instead to a high-flow condition in the model. Water stages in the micromodel are not modeled to prototype conditions, instead, the average sediment response at high and low flows are modeled. Davinroy describes the intended purpose of flow visualization to provide a visual representation of the general surface current patterns at these two energy conditions only. Fourth, and most important, Davinroy claims that ADCP data showed that the GPS floats used in the prototype did not show the same general trends observed with the GPS float surveys.

Regardless of differences between the various techniques for estimating surface velocity patterns, Maynord's (2002) presentation of surface velocities at three cross-sections displays disagreement between micromodel and prototype velocities particularly in the sharp bend just downstream of the Yazoo Diversion Canal confluence, which is consistent with scale effects anticipated in a distorted model at a sharp bend. This coupled with observed deviations between model and prototype morphologic variables for the calibrated model indicate that the model to prototype agreement of surface patterns was poor.

4.5. Analysis of Comparisons

Several of the previous calibrated model comparisons show only a fair agreement with prototype conditions when subjected to the rating system previously described. Of the sixteen ERDC models shown in Section 4.2, two rated Very Good, seven rated Good, and seven rated Fair, while the thirteen micromodels had seven that were rated Good and six that were rated Fair. In all, just under half of the models were rated Fair (ERDC models had 44% rated fair and micromodels had 46% rated fair). Add to this the mixed results obtained from the predictive case studies in Section 4.3, and one may conclude that the models have difficulty in replicating prototype conditions. Does this imply that either of these types of models was not useful in developing prototype solutions? Past experience tends to prove otherwise.

From a technical perspective, the failure to achieve even a Fair calibration in the models implies that empirically based movable-bed models have difficulty in producing an accurate replication of the prototype. This is highly dependent on characteristics of the reach under consideration. Whether the empirical approach involves some consideration of similitude as in the large-scale ERDC models or whether the empirical approach disregards any consideration of similitude as with the micromodels, replication of prototype hydrologic, hydraulic, and sedimentation behavior is extremely complex and difficult.

Some of the differences between these models and the prototype can be attributed to variability and uncertainty in the prototype data. However, the relaxations of similarity criteria must also play a role. Because the degree of relaxation in similitude found in the micromodel is as much as an order of magnitude greater than for the larger-scale models, scale effects plays a larger role in whether the model can achieve satisfactory agreement between the calibrated model and the prototype.

Ettema and Maynord (2002) note that in hydraulic models, the usual causes of scale effects are: 1) large, flow-altering length scales, 2) distortion of vertical scale relative to the horizontal scale, 3) inflation of bed sediment size, and 4) amplification of channel slope. All of these scale effect causes are present in the micromodel. Because all four of these causes plus an unknown stage relationship between micromodel and prototype exists and there are unknown interactions, Maynord (Unpublished) states that it is not possible to state which specific causes are responsible for the differences in model and prototype as shown previously. At the small dimensions of flow in the micromodel, Reynolds and Weber numbers are sufficiently different than at full scale as to influence flow behavior and distribution (Ettema, 2001). Maynord further suggests that the large exaggerations of Froude number and vertical scale distortion are likely causes of poor agreement of lateral velocity distribution and thus bathymetry in the model. Ettema (2001) and Ettema and Muste (2002) conclude that micromodels can be useful in situations where the thalweg is constrained to only vertical movement such as in a long constriction. In cases where the thalweg can move laterally, Ettema and Muste assert that model utility diminishes quickly.

In opposition to the opinions that suggest model results are of limited value given the relative number of models rated only as Fair, the limited data available for the predictive cases shown in Section 4.3 suggest that positive results can be obtained from such models. This is despite the fact that the level of model calibration varied amongst the studies evaluated, and in some cases, the model predictive results differed from observed prototype behavior when comparing cross-sectional parameters. Here, the value derives from the additional information afforded to the modeler/engineer who then, through his/her knowledge of hydraulic and sedimentation principles, engineering judgment, and understanding of prototype response to various training structures, develops plans to be implemented in the river.

5. AREAS REQUIRING ADDITIONAL CONSIDERATION

5.1. General

Similitude relationships provide a means to provide consistent relationships between the model and prototype. Current micromodel methodology dispenses with any regard for similitude, other than a similarity in channel bathymetry. Indeed, micromodel design and operation considers no similitude criteria. Nevertheless, Parker (1999) emphasized that the laws of Newtonian physics apply to micromodels just as they do to the prototype and similitude considerations cannot be ignored. Micromodels must also be considered in light of their ability to reproduce the physical phenomena that drive the bed response.

The micromodel has a large number of distortions and relaxations of similitude. Determining the effects of these individual relaxations represents an arduous task. Determining the interactions of the various distortions and relaxations would be extraordinarily difficult. Nonetheless, there is merit in listing areas that need additional investigation. Anyone considering use of the micromodel should be aware of these unknown effects and consider them in light of their particular problem.

The following sub-sections provide a brief outline of the key areas pertaining to micromodels that require additional research.

5.2. Use of Bed Configuration for Navigation Studies

Movable-bed modeling was developed and utilized extensively for analyzing the riverbed with the purpose of achieving improved navigation depths and alignments. Models have been utilized to design the placement, length and height of river training structures to solve frequent dredging problems. Based on inconclusive results of the micromodel's ability to predict prototype bathymetric behavior and on the micromodel's disregard for similitude, the effective use of micromodels in designing structures for these types of problems is debatable. For this reason, a three-step calibration process should be investigated to add confidence in the model's ability to predict changes in the river. Because placement, length, and height of river training structures depend upon replication of prototype behavior, the degree to which similitude requirements must be met should also be investigated further. Relative structure placement between design alternatives (e.g. higher, lower, or at a different alignment) in the micromodels would likely require a lower degree of similitude than would be required for specifying exact elevations, lengths and skew of any proposed structures.

5.3. Use of Surface Current Patterns for Navigation Studies

Time exposure or time-elapsed photography has been used as a secondary benefit in some model studies to capture and examine general surface flow trends induced by the channel boundaries. Because factors other than the channel bathymetry influence surface flow trends and because the micromodel does not consider similitude, correlation of flow paths obtained from the micromodel may not accurately portray prototype behavior. The need for similitude between model and prototype when evaluating general or specific surface flow trends should be evaluated.

5.4. Model Operation

The following items pertain to operation and design of the micromodel.

5.4.1. Effects of Replication/Lack of Replication of Prototype Stage

Stages directly impact the amount of energy in the model. Stages that are too low in the model (indicating that model water level and flow depth is lower than in the prototype for an analogous discharge) produce different velocity and sediment distributions within the channel cross-section. Having disparate stages between the model and prototype also potentially effects how structure elevations are determined in the model. The effects of inadequate replication of prototype stages by the micromodel require further investigation.

5.4.2. Effects of using Scaled Discharges versus not using Scaled Discharges

Current operation of micromodels does not make a correlation between model discharge and prototype discharge. Because most hydraulic parameters are dependent upon discharge, deviation from scaled prototype discharges in the micromodel potentially impacts the model's ability to replicate prototype behavior. Therefore, the effects on model performance resulting from departure from scaled prototype discharge require investigation.

5.4.3. Effects of Hydrograph Shape

Current micromodel operation utilizes either a constant discharge or a variable discharge based upon either a sinusoidal or a triangular shaped valve opening sequence. The variable discharge hydrographs produced by the sinusoidal or triangular shaped valve opening sequence do not replicate prototype hydrograph behavior except in a rudimentary fashion. The degree to which model hydrograph shape reproduces prototype hydrograph shape may have a pronounced effect on development of model bathymetry. However, additional research is required to determine the effect of hydrograph shape on model replication of prototype conditions.

5.4.4. Effects of Structure Porosity

The micromodel currently uses porous wire-mesh to represent various training structures. The adaptation of the porous wire-mesh for this purpose originated from attempts to overcome the problem of exaggerated scour around solid thin-walled sheet metal structures. The use of porous structures in the micromodel eliminated much of the exaggerated scour problems. The porosity of the mesh structures is thought to reduce turbulent effects in the vicinity of the training structures thereby reducing the bed shear stresses that drive local scour. How this effects overall model results is not fully understood. Therefore, additional research is necessary to determine the relationship between structure porosity, overall flow and sediment distribution, and development of model bathymetry.

5.4.5. Effects of Froude Number Exaggeration

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. Accordingly, flow parameters influenced by velocity are likewise exaggerated. Velocity distributions and sediment distributions vertically and laterally across the channel are also affected by Froude number exaggeration. Froude number exaggeration also affects the location of the thalweg and of the flow direction through a reach. The impacts of having an exaggerated Froude number on the ability of the micromodel to replicate prototype behavior requires more detailed and complete investigation.

5.4.6. Effects of Lateral Constriction on Thalweg ability to adjust and on Replication of Prototype Flow Patterns

Experiments conducted by the Iowa Institute of Hydraulic Research and at the University of Missouri-Rolla indicate that reduced model channel width restricts the ability of the thalweg to adjust laterally in the vicinity of training structures. Restriction of thalweg position within the channel induced by lateral constrictions and associated repression of secondary current development potentially impacts the capability of the micromodel to reproduce prototype thalweg tendencies. Lateral constrictions coupled with Froude number exaggeration and other distortions also have an impact on the surface flow patterns. Flume experimentation suggested that flow patterns are adversely impacted by lateral constrictions in channels widths on the order of two inches as compared to channels having a larger width of one to two feet. Additional research is needed to determine the influence of lateral constrictions on thalweg positional freedom and on reproduction of prototype surface flow patterns.

5.4.7. Effects of Bed Material (Gradation, Size and Weight)

Sediments used in micromodels have transport characteristics visually similar to sand. Movement of the micromodel bed material exhibits cohesionless bed-load transport with some particles transported throughout the depth of flow. However, suspended sediment transport is not replicated in micromodels. This occurs primarily because silt and clay sizes and their behavior cannot be replicated at micromodel scales. The average diameter of sediment material used in micromodels represents prototype dimensions of 2 to 4 feet when appropriately converted using the horizontal and vertical scales. Currently, procedures do not accommodate attempts to match prototype gradation curves in the micromodel. Specific gravity of the Urea PlastiGrit employed as bed material in micromodels is 1.47. The lightweight sediment material (relative to sand) provides a means to achieve a higher degree of mobility under micromodel flow conditions. The relaxation in sediment density provides only a minor compromise. This is not true of the roughness characteristics and vertical scale distortions, which are both influenced by the selection of micromodel sediment materials. The influence of bed material size, gradation, and weight on the ability of micromodels to replicate prototype behavior has not been adequately defined. Additional investigations are necessary to define the relationship between micromodel sediment gradation, size and weight and the their ability to reproduce prototype characteristics.

5.4.8. Effects of Scale and Scale Distortion

Scale effects result when ideal scale ratios are relaxed to achieve a particular model result. The significance of a particular scale effect depends upon the magnitude of the effect and how the parameter in question relates to overall model objectives. Scale also involves the physical size of dimensions at model scale. Large horizontal scales reduce linear scales in the model. If these reductions are of sufficient magnitude then model characteristics become distorted (sediment particle size for instance). Beyond a point, the distortions dominate the behavior instead of normal (at prototype scale) physical laws. Use of different horizontal and vertical scales further complicates this issue. The use of different geometric scales in the micromodel produces a linear distortion of linear parameters but non-linear distortions occur in parameters involving power or exponential relationships. Additional investigation is necessary to establish how scale effects and distortion effects impact reproduction of prototype behavior in the micromodel.

5.4.9. Effects of Replication/Lack of Replication of Shields Parameter (Sediment Mobility)

The micromodel produces Shields parameter values lower than found in the prototype. However, the use of loose-bed models for bed similarity studies without having equality of Shields parameter is consistent with most (but not all) model applications. Achieving similarity of sediment movement in the micromodel by a visual assessment results in model Shields parameter values that are only slightly lower than prototype values. At first glance, this appears a favorable attribute of the micromodels. However, this happy coincidence is partly the result of the large vertical scale distortion and Froude number exaggeration. Additional research is necessary to determine how sediment mobility and these distortions interrelate in model operation and to establish the way that they combine to influence model replication of prototype behavior.

5.4.10. Effects of Model Roughness Characteristics being/not being Scaled to Prototype Roughness Characteristics

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. Gaines (2002) found an average Chezy C of 27 $m^{0.5}$/sec in flume tests using flow depths typical of that found in micromodels. This value is consistent with values found by other investigators. This value compares to a C of 50 $m^{0.5}$/sec for the Mississippi River indicating that the model is too smooth. The model smoothness issue is a possible explanation of why high stages are difficult to run in the micromodel. Similitude in friction characteristics is also important in simulating flow in bends. The effects of departure from friction similitude require additional investigation to determine their impacts on the ability of the micromodel to replicate prototype behavior.

5.4.11. Effects of Prototype Variability on Determining Model Parameters and in Interpretation of Model Results

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. While it was 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, 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. Additionally, prototype variability makes the absolute definition of similitude criteria difficult, at best. Additional research is necessary to determine the effects of prototype variability on micromodel operation and design.

5.5. Use of Micromodel in Assessing Dredge Disposal

Sediment material characteristics change appreciably when sizes are in the clay and silt range. Suspended sediments at prototype scale typically fall in the silt/clay particle sizes with some suspended sediment materials being as large as sand sizes. Because silt and clay particle sizes in the prototype scale to sizes that would exhibit cohesive properties at micromodel scale, the micromodel technique cannot be utilized for analyzing suspended sediment transport problems. In the case of dredging disposal, a high concentration of sand sized material is discharged into the water column. Micromodel analysis of the depositional patterns downstream of dredge disposal sites and their persistence over time would therefore seem plausible. However, the short hydrograph cycle times and equilibrium sediment transport approach used in micromodels tend to obscure the true response of temporal depositional features such as dredge disposal plumes. Additional research is needed to determine the applicability of using the micromodel technique to study dredge disposal depositional patterns.

5.6. Use of Micromodel as a Screening Tool

The micromodel has been used to screen alternatives. Screening involves the use of a model to predict the effects of a plan. In screening alternatives, model outcomes are used to make relative comparisons between different alternatives and a base test condition (as opposed to predicting actual prototype response). The relative comparison of alternatives does not negate the requirement to have the model replicate prototype behavior. Results of available validation tests, namely the Kate-Aubrey predictive alternative results, indicate that use of the micromodel as a screening tool is debatable.

6. CONCLUSIONS

6.1. General

Much of the support for micromodel use stems from previous model study results. As with the former ERDC models discussed herein, much of the claimed successes for previous micromodel studies derive from the overall river engineering process. This process involves the experience and intuition of a team of designers. These successes were not predicated on the technical merits of the micromodel methodology alone, but also included the incorporation of indications obtained from the micromodel along with available prototype data and the modeler's experience with prototype response to achieve a prototype design.

In retrospect, the evaluation effort included topics that were too broad. Principle questions such as "How good is good enough?" and "What are the limitations for micromodel use?" were beyond the scope (time and funding) of the effort. Additionally, previous development and refinement of the large-scale model techniques employed by the Corps of Engineers and others since the 1930's continued up until the decline of their use in the 1990's, a period of some 60 years. Thus, the research and development of the micromodel technique likely will continue for an extended period, perhaps several decades.

An evaluation spanning three or so years could only reveal a limited amount of information regarding micromodel capabilities and limitations. Within the analysis completed during this three-year period, no definitive conclusions were possible within the JV team primarily because the technical aspects or the mechanics of the micromodel technique could not be separated from the overall river engineering process. Therefore, many of the controversial issues that persisted at the beginning of the evaluation effort could not be resolved to a consensus viewpoint amongst the JV team. In the end, the JV team could not present a joint conclusion, but identified areas that require further research in order to determine their impact on the ability of micromodels to adequately replicate the necessary prototype characteristics. Those areas are outlined in preceding sections of this document.

6.2. Individual Conclusions

Although the original objective of the joint venture evaluation effort envisioned concensus opinions regarding micromodel limitations and capabilities, such was not possible. Through the course of investigating numerous aspects of movable-bed modeling, and more specifically micromodels, each investigator developed their own, individual views of how the micromodel can be used. The following sub-sections contain individual conclusions by each investigator. Conclusions by Ettema and Ettema and Muste who were contracted to complete flume studies for the evaluation are also included. The conclusions are presented in an upstream to downstream order relative to the Mississippi River.

6.2.1. Ettema and Ettema and Muste, IIHR

Ettema (2001) and Ettema and Muste (2002) conclude that micromodels can be useful in situations where the thalweg is constrained to only vertical movement such as in a long constriction. In cases where the thalweg can move laterally, Ettema and Muste assert that model utility diminishes quickly.

6.2.2. David Gordon, MVS

Based upon a separate comparison of large movable-bed, micromodel, and prototype data, Davinroy, Gordon, and Strauser recommend the following applications for micro modeling:

1. Quantitative bathymetric analysis for qualitative trends. Micromodels may be used in a quantifiable manner, whereas numerical numbers from design alternatives such as width, height, location of thalweg, dikes, etc. may extracted from an observed model response. However, only a qualitative prediction of depths is possible with the model. This is based upon the following:

   a. Several different types of studies have shown that the calibrated and predictive capabilities of the micromodels have been exceptional, including the Mouth of the White River Navigation Study (Gordon, Strauser, Chasteen, Davinroy, Smith, Ellis) 2003 unpublished, Bolters Bar Dredging Alleviation Study (Gordon, Davinroy, Strauser) 2003 unpublished, Sante Fe Chute Environmental Enhancement Study (Davinroy, Gordon) 2002 unpublished, and Lock and Dam 24 Outdraft Study, (Davinroy, Gordon, Strauser, Morgan) 2003 unpublished, Big Creek Bridge Abutment Erosion Study, (Gordon, Davinroy) 2001 unpublished, New Madrid Dredging Reduction Study (Davinroy, Max) 2000 unpublished, Vicksburg Front Navigation Alignment Study, (Davinroy) 2003 unpublished. These successful studies prove that the micromodel can be used for all the applications discussed in Section 3.3, which include Demonstration and Education, Reduction of Dredging, Environmental Restoration of Side Channels, Thalweg Realignment, and Bathymetric and Flow Pattern Evaluation for Navigation Improvement.

   b. Numerical and observational comparisons of large movable bed model studies and micromodel studies completed in this research effort have shown that both models rated similar in their ability to display trends as compared to the prototype. These comparisons also showed that there was no correlation between model distortion and size and the ability to replicate trends in the prototype. If bigger was better, then the large models would have provided results on a magnitude far greater than micromodels, and the research clearly showed that this was not the case.

2. Qualitative surface flow trend analysis. Micromodels may be used to examine general surface flow patterns between model alternatives and the base test. This may be used to study far-field current patterns for general navigation problems or at approaches to bridges, locks, etc. This is based upon the following:

   a. Excellent replication of surface flow patterns as compared to the prototype within the model calibration and within the predicted patterns after construction. For example: Vicksburg Front Model (Davinroy, Gordon, Rhoads, and Abbott) 2000, Morgan City (Gordon, Davinroy, Riiff, Rhoads) 2001, Lock and Dam 24 (Davinroy, Gordon, Hetrick) 1998, and the Mouth of the White River (Gordon, Chasteen, Smith, Strauser, Davinroy) unpublished.

b. Poor results of calibrated and predicted surface flow patterns noted in ERDC's Mouth of the White River Fixed Bed Model (Chasteen, Gutshall, Brooks, Gordon, Smith, Strauser) unpublished. Observations revealed that a large model at ERDC with low distortion failed to provide adequate calibration or comparison of model to prototype velocity conditions. The calibrated and predicted flow patterns of the distorted micromodel were exceptional while those of the undistorted fixed bed model were extremely poor. ERDC modelers recommended that the design not be constructed due to their erroneous model results. After construction, it was shown that the flow patterns produced in the river matched those predicted by the micromodel. The conclusion is that the key to good flow visualization is not the size or distortion of the model but the proper development of entrance conditions and the amount of knowledge the modeler possesses concerning prototype conditions.

c. Past observation of distorted models, both movable and fixed, used at ERDC which used surface confetti for general flow trend analysis, including Dogtooth Bend Model, St. Louis Harbor Model, Mississippi Basin Model, Boston Bar Model, Greenville Bridge Model, Arkansas River Model, Grand Tower Model, and the Port of Anchorage Small-Scale Flow Table Model indicate that at ERDC it has been and is still an acceptable practice to employ distorted models for observing general flow patterns.

Opponents have stressed that the micromodel can only be used as a screening tool as a precursor to a more quantitative analysis. However, this would propose that all river engineering designs must be subjected to a much more rigorous analysis then they currently are subjected to. Most designs are constructed without any kind of screening or analysis beyond the original design conception. Unfortunately, the river engineer has very few tools at his/her disposal to optimize their designs. Beyond experience and intuition, the micromodel may currently be the only practical tool. For example, the Morgan City micromodel was used to study a design submitted by ERDC. The model demonstrated that the design would not efficiently reduce dredging or improve flow patterns along this reach of the Atchafalaya River. The micromodel was used to optimize a design of bendway weirs that would significantly reduce dredging and improve the general flow patterns through the reach. Although some may view the model as only a screening tool, it must also be considered a design optimization tool. Until a better method is developed, the micromodel is the only available tool to aid the river engineer.

Physical movable bed models have been used by the Corps of Engineers for decades to study and develop design solutions to some of the most challenging problems along the nation's navigable waterways. The large-scale models used predominately in Vicksburg provided exceptional results, albeit with a high cost and lengthy time. Due to increased funding constraints, the micromodel is now being used to study some of the same issues that the larger models were used for.

Davinroy and Strauser gained invaluable modeling experience by spending an inordinate amount of time working with these large-scale models in Vicksburg. They were able to gain an intricate perspective of the techniques used to operate and collect data from the large models. Davinroy (1994) essentially developed the micromodel using the same basic guidelines used to operate the larger models.

Many of the criticisms of micromodeling revolve around the issues that the large modelers claimed to have resolved. Many of these issues were not resolved, but were instead concealed within their "factors" and covered up within the model results. By understanding both modeling methods, Davinroy realized that some of the techniques utilized by the large-scale modelers resulted in or created these "factors" to make the model only appear to behave correctly. A review of the model study reports revealed that most of these techniques were not discussed so therefore one would never know to what degree the "factors" were applied to each model. Due to the lack of documentation it may never be known if some of these "factors" had dire consequences on the study results.

The micromodel utilizes the same basic operational and calibration techniques utilized with the large models but dispenses with the "factors" used in the large-scale models. These factors with comparisons and contrasts to the micromodel were clarified and submitted in a draft to this report but were removed as a request from ERDC. For example, the large models used a non-linear, exponentially shifting discharge scale, which only created the illusion that the stage in the model was directly comparable to the prototype. A direct correspondence between stage and discharge within a distorted movable bed model is impossible to achieve. Because of this fact, the micromodel is based upon an energy response and not a stage or discharge response. Although the micromodel does not achieve top of bank stages, the large model also would not have achieved top of bank stages if not for the baseless "changing discharge scale relationship."

The WES technique of utilizing an adjustable rail system to survey and record the model's bathymetry was claimed as a method to develop multiple slopes and varying energy within a model. This idea not only is contradictory to a model being in equilibrium, but also is physically impossible to achieve in a movable bed model. Rather, the rail system was simply a method to manipulate how the depths in the models are recorded and displayed on paper. The micromodel uses a single sloped plane to reference all the model depths.

Another WES routine utilized an actual one-year hydrograph during calibration runs. The routine required that a beginning bed condition be molded into the model with the hydrograph being used to simulate the conditions to achieve the ending bed condition. This technique was not practical because time is not scalable with distorted movable bed models. Although it has been claimed that this method was needed to validate the models, any relationship to time used in physical movable bed modeling is misleading and groundless. The micromodel uses a standard hydrograph that simply traverses between low to high flow conditions without any association to a time scale. The unnecessary relationship to time may have caused equilibrium problems in the riverbed of the large models. It has been noted that in many of the large models, the rate of sediment out of the model did not match the rate at which it was delivered into the model. This suggests that many of the models were not in equilibrium. A longer time period may have allowed the model to equalize itself. Careful observation and the sediment recirculation system exclusive to the micromodel assure that the model is always in equilibrium.

Another major criticism of micromodeling revolves around what is viewed as large distortion and small scale. However, some of the pioneers in the field of hydraulics have used models with small scales and much higher distortion ratios with excellent results. Just recently, ERDC utilized two small scale, distorted fixed bed models in an effort to study flow patterns in an estuary at the Port of Anchorage, Alaska. One model had a horizontal scale of 1 inch = 1,300 feet and a vertical scale of 1 inch = 40 feet for a 1:32.5 distortion ratio. In addition to the large distortion, the model used coarsely terraced bathymetry. The other model, with the actual molded bathymetry, had a horizontal scale of 1 inch = 1,250 feet and a vertical scale of 1 inch = 83 feet for a 1:15 distortion ratio. About this flow table, they stated, "The precision flow table can examine complex steady flow problems rapidly and at low cost" and "is useful for understanding complicated flow problems." Their reasoning for using and accepting these small scale models were:

> "Geometric distortion is justified and accepted for flow models without waves so long as vertical velocities and accelerations are small compared to horizontal flow velocities. Scaling relationships for geometrically distorted physical models are well established and widely accepted (e.g. Hughes 1993)"
>
> *"Because distorted models have steeper slopes that decrease the magnitude of the vertical turbulence components generated by the slope, it should be expected that the prototype might experience stronger vertical turbulence than demonstrated in the model. Once again, whether or not these scale effects degrade the model results will depend on the goals of the modeling and the relevance of the turbulent flow processes to the specific regions of interest within the study area."*

The modelers claimed that the models provided excellent results and concluded the following about the types of studies that could be conducted using the small scale and large vertical distortion:

a. *"Visualizing flow patterns in large estuaries, inlets, or where flow separation and 3-D flow structures are thought to occur."*
b. *"Obtaining velocity measurements near structures and in turbulent regions associated with flow separation at solid boundaries."*
c. *"Quantifying flow conditions in idealized cases for use in validating numerical modeling techniques."*
d. *"Quickly examining project impacts due to structure modification, addition, removal, or relocation."*
e. *"Observing the extent of flow three-dimensionally in order to determine the correct numerical modeling approach."*

The modelers concluded that both models responded almost identically although the distortions were significantly different. The conclusions state that although the physics require these models to be geometrically distorted, the results, which must be interpreted carefully, are exceptional. It also concluded that flow conditions could be quantified. Flow conditions in the micromodel are only used for qualitative analysis of surface patterns. Although this is another area that the model is criticized for, Hughes disputes these statements with the results from his flow table.

The proponents and opponents of micromodeling are mainly divided between the practical side of modeling and the theoretical side. The proponents acknowledge that the theoretical issues could possibly affect modeling results. However, it has yet to be proven that these issues have significantly affected the outcome of any micromodel study. While the critics site the physics as their main concern with micromodeling, they fail to acknowledge the 100% success rate the model has achieved. Numerous model studies have resulted in the construction of the recommended design, which formed the bed forms that the micromodel predicted. Although they have been made aware of these successes, their preconceived ideas about the theoretical side appear to have caused them to disregard achievements. The focus has been on the theory without any regard to the practical applications. The successful application of many designs proves that the technology works and is extremely valuable. The model has accurately predicted the resulting bed formations and flow patterns of 100% of the designs that were conceived with the use the model. Although the model has been highly scrutinized, the detractors willingly fail to recognize these successes in order dissuade its use. These actions are considered to be remarkably irresponsible for those who are considered experts and who are required to evaluate all aspects of the technology.

Although the micromodeling technique has been proven with numerous completed structures, opponents still claim that the micromodel is unsuitable for use in the design of river training structures. Whether this statement is true or not, there are no alternative models, tools, or guidance available to the engineer for designing these types of structures. The overall knowledge of sediment transport is very limited and no equations or numerical models exist that can accurately predict sediment transport rates or the resultant bathymetry of a riverbed. Therefore, the river engineer lacks sufficient guidance for the design of river training structures. Traditionally, the only tools available in the past were experience, intuition, and the large, ERDC movable bed models. The only additional proven tool available today is the micromodel. The multiple successful projects built as a result of the micromodel substantiate the proponent's claim that this modeling technique is an extremely valuable tool for the river engineer.

6.2.3. Roger Gaines, MVM

In the past, river engineering involved development of suitable training features by a trial and error process within the river itself. As river engineers gained experience from previous successes and failures, they developed a knowledge base that aided them in analyzing other problems. Even so, there was a need to develop a tool where designs could be studied without the risks and costs associated with trying different structures in the field. In the latter 1800's movable-bed models were introduced as tools for studying estuaries and coastal problems. Because of the relatively large expense of constructing training structures at prototype scale, the use of movable-bed models provided an economical means for river engineers to test alternative designs.

The original tendency of movable-bed modelers was to build relatively large (compared to the first movable-bed models by Reynolds and Vernon Harcourt) models. The justification for using larger models was essentially to provide conditions as close to prototype scale as possible. Adoption of movable-bed models for use by the Corps of Engineers began at the Waterways Experiment Station (now ERDC) in the early 1900's. Many of the early ERDC movable-bed models were used to study complex navigation problems on the Mississippi River. Over the decades following their first use of movable-bed models, ERDC continually improved and developed their empirical modeling approach. This continued until the mid-1990s when budget's tightened, essentially making it unfeasible to use the large-scale ERDC movable-bed models.

At this point, MVS began to develop a small movable-bed model (the micromodel) costing only a small percentage of the ERDC models. The micromodel technique was based upon a different methodology. However, the concepts used for interpreting ERDC model results were applied to the micromodels. Because the micromodel technique did not consider similitude in their design or operation, ERDC and others questioned their validity. After several rounds of discussions, it was decided that the micromodel should be evaluated to determine its limitations and capabilities.

The reality of river engineering problems is that the technical aspects of any available analysis tool cannot be completely separated from the process in which the tool is utilized. Scale effects as discussed herein result in discrepancies between model and prototype. However, operational constraints, particularly prototype data availability and funding issues, also impact the degree of agreement between model and prototype. Empirical models such as the ERDC movable-bed models cannot replicate all prototype processes. Even with extensive and complex adjustment of model inputs and operation, model calibration is at best fair in about one-half of the models considered in this evaluation. Micromodels, where similitude is not considered as part of the design, have a less rigorous calibration procedure than the ERDC models. But, the micromodel still involves a complex adjustment process during model calibration, and previous comparisons show about one-half of the micromodels to have had a fair calibration.

While there are distinct differences between ERDC model procedures and micromodel procedures, the point being made is that technical merits/deficiencies cannot be used as the sole basis for developing guidelines or criteria for model usage. Ultimately, the modeler's/engineer's experience becomes the deciding factor in transfer of model results to a design that will be implemented in the prototype. Often, model results are used in a generic sense where only gross, overall trends are used to screen between alternatives. If model results fail to follow reasonable expectations, then those results are treated accordingly—they are discounted because of model limitations. On occasion, model study efforts must be (and in the case of the Westover Reach of the Mississippi River have been) terminated when the model fails to reproduce the necessary prototype trends.

Based on experience with the micromodel, an analysis of previous model study results, on observed prototype response to river training structures, and on flume studies, the following are conclusions regarding micromodel use.

1. Micromodels are clearly process models. What this means is that micromodels represent only the general aspects of the prototype that are associated with producing the overall bed configuration. The primary focus of the micromodel technique is to reproduce prototype bathymetric behavior. Flow velocities, velocity distributions, and localized bed behavior are not guaranteed because the focal process is sediment movement. Distortions introduced into the micromodel to achieve the requisite sediment movement adversely effect reproduction of prototype flow characteristics.

2. Micromodel calibration is a critical aspect in their effective use. Adequate calibration must be achieved before any alternatives are evaluated. The degree of calibration should be assessed by both a visual assessment of the model bathymetry and a quantitative comparison of model and prototype morphologic parameters such as cross-section area, flow depth, the width to depth ratio, and the thalweg location throughout the reach being investigated. In the future micromodel calibration should also include descriptions of the degree of similarity achieved for slope, Froude number, and the Shields parameter.

3. Micromodel calibration should include techniques for assuring the correct apportionment of discharge between multiple channels when a model involves a division of flow. Such techniques may involve estimates of discharge in the respective channels or an evaluation of conveyance in each channel relative to the corresponding prototype values of discharge and conveyance.

4. Engineering judgment and experience with the prototype being studied play a pivotal role in conducting and interpreting micromodel studies. Past experience with both ERDC models and the micromodel clearly identifies the need for experience when adapting model results to "real-world" construction plans. Where model calibration is weak, the significance of experience increases.

5. Micromodels provide an excellent tool for demonstrating and communicating complex sediment transport processes to engineers, biologists, resource agencies, local sponsors and the general public.

6. Micromodels provide an excellent tool for educating engineers, biologists, and other study participants in a river's potential response to changes introduced by construction of various river training structures. As such, the micromodel can be used to help generate ideas for alternative structure designs.

7. Micromodels provide a means to screen alternatives through the use of relative comparisons between alternatives using a base test bathymetry and bathymetry from the various alternatives. This includes an assessment based upon the general number, location, and dimensions of alternative structures. This does not imply that micromodel results can be transferred directly to the prototype. Only gross trends in the model bathymetry can be compared by considering general increases or decreases in bed elevations or in thalweg position. Final prototype designs and construction

plans must be based upon engineering judgment and upon the modeler's experience with similar structures at prototype scale.

8. Micromodels have a pronounced boundary effect that is a direct result of scale distortions and Froude number exaggeration. Based upon flume studies and observations in the micromodel, the boundary effect extends approximately one-third of an inch from the channel walls. This wall effect remains consistent regardless of the overall channel width. Micromodels having narrower channels experience a greater influence from this effect because the boundary affects a greater percentage of the flow width.

9. Micromodels provide a means to screen alternatives based on surface flow patterns defined by confetti streaks in relatively straight reaches. Where localized features such as rock outcrops or hydraulic structures exist, flow visualization should not be used in screening alternatives because localized velocity distributions are adversely influenced by model distortions and the associated boundary effects, this is particularly the case for models having distortions greater than about 5 (based upon the Big Creek and Nonconnah Creek micromodels which had distortions of 5 and 3, respectively). Flow visualization in bends of small radius by confetti streaks should not be used or should be used with extreme caution because distortion effects are more pronounced in bends.

10. Micromodels do not provide a means to evaluate quantitative bed response (i.e. specific elevation changes) to a proposed feature.

11. Vertical scale distortion should be reduced as much as practicable in the micromodel. Reduction of vertical scale distortion and slope distortion generally corresponds to a reduction in Froude number exaggeration. A reduction in Froude number exaggeration allows for a greater flexibility in thalweg adjustment within the channel. While this does not require a wider channel, a minimum channel width of six inches is recommended for prototype channels having widths on the order of 2500 feet. Channels narrower than six-inches exhibited an overly constrained thalweg which is mainly a result of wall boundary effects. Preliminary observations from a limited number of experiments in a straight flume and a micromodel channel having channel widths of six inches or greater indicate that secondary current behavior and bed form development can be replicated in the micromodel (Gaines, unpublished) where the Froude number exaggeration is less than 2. While more definitive results are needed, the indications are that the lateral thalweg movement associated with secondary current development can occur in micro-scale channels without the constraint of Ettema's and Muste's (2002) long constriction. These preliminary results await confirmation in the near future.

In summary, micromodel results 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 far less cost than with larger models. Experience with these studies indicates the need for adequate model adjustment, evaluation of model results based upon the accuracy of the adjustment, consideration of scale and distortion effects, and the shape and magnitude of stage and discharge hydrographs used in the model. Model bed elevations and flow depths do not necessarily have to match prototype values, but relative differences between the bed elevations and flow depths between pools and crossings should mimic similar differences that exist in the prototype.

Future goals of the micromodel technique should include 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 current hydrograph used in most micromodel studies and an assurance that stage hydrographs in the model adequately represent prototype stages. An evaluation of model Froude number, Shields number, and slope similitude should be performed and documented for future micromodel studies.

6.2.4. Stephen Maynord, ERDC

"Because all evaluators agree the micromodel is useful for demonstration, education, and communication, the primary question that should be asked and answered in this report is as follows:

"Does the MM give predictions of the prototype adequate to compare alternatives?"

Stated otherwise, "Can the micromodel be used as a screening tool?" The primary question is answered by this author using comparison of available micromodel and prototype data.

Much of this report focuses on side issues other than this primary question. One of these side issues is the effort to show that the micromodel is somehow equal to the ERDC coal bed models. Some seem to believe that if this can be done, this greatly diminishes any responsibility to answer the primary question. This is not a valid approach because:

a. The micromodel needs to be evaluated on its predictions of the prototype based on model-prototype comparisons with data. Anecdotal information presented throughout this report can only be given marginal weight in an evaluation.
b. The evaluation team was not tasked to evaluate ERDC coal bed models and the comparison methods used in this report are not adequate to compare models. The percentages shown give potential users a false sense of accuracy and should not be used to compare models. The plots of model-prototype parameters along the length of the model presented in the appendix would likely be useful in the calibration process.

Another side issue in this report is the focus on the "process" rather than focusing on the primary question based on comparison of model and prototype. Clearly the process is important in educating the modeler. The "process" cannot make up for a model that gives wrong answers.

A third side issue in the MVS conclusions is the comparison to the flow table used by Steve Hughes. The flow table by Hughes has a fixed bed, equal Froude number, reproduces stages, and large distortion. The micromodel has movable bed, model Froude number of 4 to 6 times the prototype, no correspondence of stages in model and prototype, and large distortion.

Even if these models were equivalent, this does not address the primary question."The micromodel, because of its small size and totally empirical design/operation, is different from previous movable bed models and does not fit into either of Graf's categories of empirical or rational models. In addition to its size being as small as 4 cm channel width, the large vertical scale distortion, large Froude number exaggeration, and no correspondence of stage in model and prototype, place the micromodel in a category by itself.

In some studies, the micromodel has been calibrated to match the bathymetric trends of the prototype. In other studies the calibration was poor and the micromodel did not match the bathymetric trends of the prototype. The Vicksburg Front and Peoria Lake comparison of surface velocity in calibrated model and prototype showed no agreement. No previous studies have shown validation of the micromodel to demonstrate the model can predict bathymetry. The two Kate Aubrey micromodel validations did not agree with the observed prototype response. Extreme relaxations of similitude are a primary cause of the model and prototype differences. Recommended applications of the micromodel follow.

1. Demonstration, education, and communication- The micromodel is useful in demonstration, education, and communication and is effective in generating ideas for problem solution and demonstrating river engineering concepts.

2. Qualitative bathymetry analysis- Qualitative bathymetry analysis is use of the micromodel as a screening tool to compare alternatives based on analysis of bathymetry. No numbers should be assigned to alternative features or results from the model in this category. This category is the primary question to be answered in this evaluation. Can the micromodel, which operates with extreme deviations in similarity criteria and can frequently achieve only a poor calibration, still be used to predict and compare alternative plans, even in a qualitative sense? This evaluator has seen no evidence supporting use as a screening tool. Future application of the micromodel in this area requires that the user demonstrate that the model can be validated, i.e. shown to predict changes to the prototype. At some point in the future, several successful validations of the micromodel in each specific study type (for example long constrictions or single dikes or bendway weirs or traditional dikes) would allow use of the existing calibration only model adjustment process for this study type.

3. Quantitative bathymetry analysis- Quantitative bathymetry analysis is use of the micromodel in which numerical values are used to characterize alternative features or in which numbers are assigned to bathymetric results from the model. The following reasons prevent this category from being a capability of the micromodel in either of the two levels of quantitative use described in a previous paragraph.

a. The absence of studies showing predictive capability
b. The poor prediction of bathymetry in Kate Aubrey models
c. Poor replication of currents in Vicksburg Front model
d. Poor or inadequate calibration in about ½ of the micromodel studies
e. Extreme deviations in similarity criteria
f. Lack of correspondence of stage

4. Flow patterns to assess navigation This is use of the micromodel in which confetti pathlines or PIV flow visualization are used to compare alternatives for navigation improvement. The reasons given in item c) prevent this from being a capability of the micromodel.

5. Environmental Studies- The above recommendations are based on the application of the micromodel to a navigable river or to a non-navigable river in the vicinity of a hydraulic structure. While environmental concerns are equal in importance to navigation concerns, the required accuracy of environmental studies may be less than navigation studies. If the required accuracy is less, the existing two-step calibration procedure should be adequate for qualitative bathymetry studies of environmental concerns that do not impact a navigation channel.

In summary, no evidence has been found that the micromodel can be used for anything beyond demonstration, education of both the modeler and the public, and communication between diverse interests. No evidence exists that the model results are adequate to predict the effects of alternatives that is the requirement for use as a screening tool. Contrary evidence exists showing that the model cannot predict in the two Kate Aubrey studies that were critical components of the evaluation.

APPENDIX A

CONSULTANT REPORTS

The reports contained in this appendix represent opinions of the three panelists consulted early in the Joint Venture evaluation effort. The individual reports contain thoughts and observations of each respective panelist after review of several published micromodel reports and a one-day on-site visit to the St. Louis District micromodel facility. Copies of the individual reports are provided for reference only and are arranged in alphabetical order.

Robert Ettema
University of Iowa
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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
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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:

$$S_w = \Phi_{S_w}\left(S_o, \frac{k}{R}, \frac{B}{R}, \frac{UR}{\nu}, \frac{U^2}{gR}, \frac{\rho RU^2}{\sigma}\right) \tag{2}$$

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

$$U = \sqrt{\frac{8gRS_f}{f}} \tag{3}$$

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

$$f = \Phi_f(k/R, Re, B/R, \text{channel shape}) \tag{4}$$

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

$$A = f_A(\rho, \nu, \sigma, d, \rho_s, B, R, S_o, g) \quad (6)$$

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

$$\Pi_A = \varphi_A\left(d\left(\frac{g\Delta\rho}{\rho\nu^2}\right)^{1/3}, \frac{\rho RS}{\Delta\rho d}, \frac{\rho_s}{\rho}, \frac{d}{R}, \frac{B}{R}, \frac{\sigma}{\rho g S R^2} \right) \quad (7)$$

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

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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 an 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.

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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 **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 **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.

Shields Regime Diagram

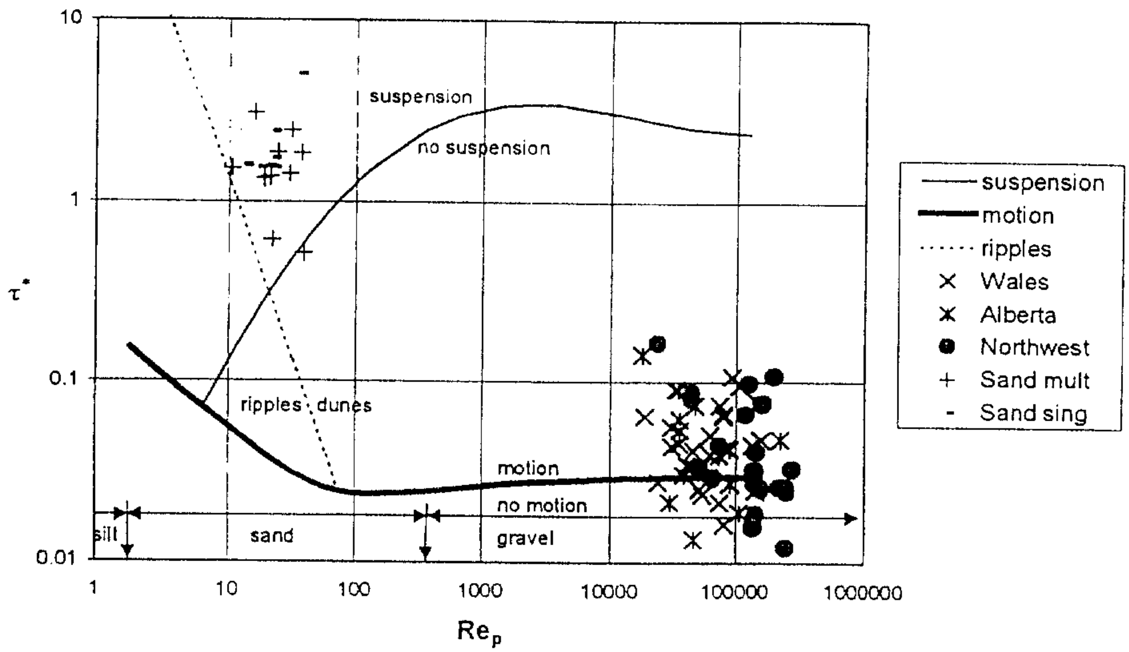

Figure 1

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.

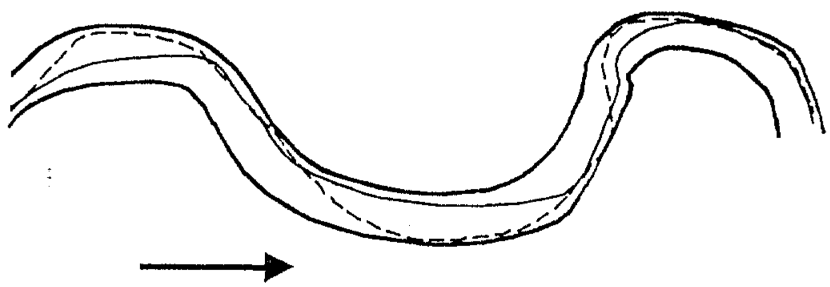

Figure 2

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.

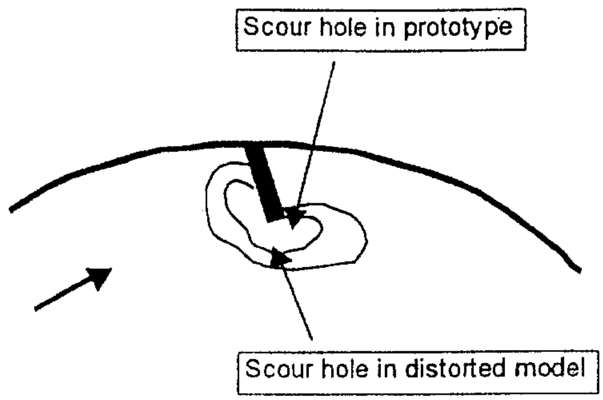

Figure 3

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.

APPENDIX B

MICROMODEL OPERATION AND CALIBRATION PROCEDURES

B-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 micromodel must be properly constructed, setup, calibrated and operated. A fundamental premise of micromodeling 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 limitations, either vertical or horizontal, which may affect the characteristic of the reach being studied.

The micromodel 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.

B-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 3 to 10 miles (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 72 inches long by 36 inches 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 1.5 inches to 15 inches.

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.

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 3-inch 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 3 to 12 inches 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.

B-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 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.

B-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.

B-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 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 2.5 gallons/min. to 3 gallons/min. to establish a high flow limit on the hydrographic cycle. The discharge is then changed to a flow of around 0.75 gallons/min. to 1 gallon/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 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 equaled or 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 +15.0 feet to +20.0 feet 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 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.

B-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 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.

B-7 Simulation of River Training Structures in the Micromodel.

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.

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. 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.

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.

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.

B-8 Recent Developments

In order to achieve a higher degree of sediment mobility with less slope distortion and less exaggeration of the Froude number, a sediment material lighter than the PlastiGrit Type II Urea is being used in some micromodels. The lighter model sediment is PlastiGrit Type I, Polyester, that has a specific gravity of 1.27 (versus 1.48 for the Urea Type II). Initial results from the PlastiGrit Type I are favorable. One advantage of the Type I material is that bed forms (i.e. dunes) can be reproduced in the micromodel when channels are wider than approximately six-inches. At present it is unknown how bed form development impacts overall micromodel results.

APPENDIX C

QUALITY CONTROL AND QUALITY ASSURANCE

APPENDIX C QUALITY CONTROL AND QUALITY ASSURANCE

This appendix contains comments received on previous drafts of the Micromodel Evaluation Report. Responses to comments are included within the original text. Comments are ordered chronologically beginning with the most recent submittals.

Written comments contained within this appendix include submissions by:

Dave Gordon, MVS
Steve Maynord, ERDC
Tom Pokrefke, ERDC
Rob Davinroy, MVS
Charles Nickles, ERDC

Additional Quality Control/Quality Assurance information on the evaluation effort and previous report drafts is available in separate volumes.

Comments to Evaluation Report dated 30 July 2003, Dave Gordon

For the record I would like to reiterate that my previous comments submitted on July 17, 2003 should be included in this report. I will not repeat these comments but please refer to them as needed.

Page 7, Section 1.6. I continue to despise the Yalin statement! Noted.

Page 20, Section 3.2, Item #2: The micro model has used distortions as low as 5 and as high as 20. The WES models used distortion as high as 10. Noted. Add "The WES....".

Page 21, Table 3-1: I continue to dislike this table. Noted.

Page 23: Last P - Change An to A Text modified.

Page 33, Section 4.2: Much Better!! Noted.

Page 41, Section 4.2.25. Remove "Poor Otherwise" Noted.

Page 43, Sections 4.3.1 & 2: Remove references to "poor" Noted. However neither of the Kate-Aubrey model results in these sections reproduced prototype behavior well. Because these model study results reflect a "predictive alternative," they could not be ranked based upon the same rating system used for ranking CALIBRATED model surveys as in 4.2. Added a sentence to clarify the additional rating.

Page 53, Section 6.1: What happened to the 2nd and 3rd paragraphs from the July 15 version? I liked those statements. Removed based on other comments.

Comments on 30 July Draft of Micromodel Evaluation by Steve Maynord, 31 July 03

General- The improvement in this draft is the delineation of each person's conclusions but it is troubling that I had less than 24 hours to review and comment on my first view of MVS and MVM conclusions. The report is seriously deficient on data and facts to back up statements. The main problem is that the main text still contains issues I do not agree with that I stated in my previous review. Chapters 1 and 2 are satisfactory. Chapter 3 needs to have all anecdotal model-prototype information removed and placed in the chapter on Model-prototype comparisons. Chapter 4 contains a large amount of information that I don't agree with. It needs to be broken into a Model-prototype Chapter by Gaines and Gordon and then a new chapter 5 needs to be inserted that presents the model-prototype data I submitted previously. I have included that text below and figures will be sent as well. Specific comments are as follows:

1. Add the following to the beginning of my conclusions: Done.

"Because all evaluators agree the micromodel is useful for demonstration, education, and communication, the primary question that should be asked and answered in this report is as follows:

"Does the MM give predictions of the prototype adequate to compare alternatives?"

Stated otherwise, "Can the micromodel be used as a screening tool?" The primary question is answered by this author using comparison of available micromodel and prototype data.

Much of this report focuses on side issues other than this primary question. One of these side issues is the effort to show that the micromodel is somehow equal to the ERDC coal bed models. Some seem to believe that if this can be done, this greatly diminishes any responsibility to answer the primary question. This is not a valid approach because:

a. The micromodel needs to be evaluated on its predictions of the prototype based on model-prototype comparisons with data. Anecdotal information presented throughout this report can only be given marginal weight in an evaluation.
b. The evaluation team was not tasked to evaluate ERDC coal bed models and the comparison methods used in this report are not adequate to compare models. The percentages shown give potential users a false sense of accuracy and should not be used to compare models. The plots of model-prototype parameters along the length of the model presented in the appendix would likely be useful in the calibration process.

Another side issue in this report is the focus on the "process" rather than focusing on the primary question based on comparison of model and prototype. Clearly the process is important in educating the modeler. The "process" cannot make up for a model that gives wrong answers.

A third side issue in the MVS conclusions is the comparison to the flow table used by Steve Hughes. The flow table by Hughes has a fixed bed, equal Froude number, reproduces stages, and large distortion. The micromodel has movable bed, model Froude number of 4 to 6 times the prototype, no correspondence of stages in model and prototype, and large distortion. Even if these models were equivalent, this does not address the primary question."

End of addition to my conclusions.

2. The majority of my input of model-prototype comparisons is still not included in the report whereas a great deal of anecdotal information in support of the micromodel can be found in Chapter 3. I do not agree with most of chapter 4 which places it under the Gaines and Gordon umbrella. Probably the easiest and fairest way to handle this is to label Chapter 4 as Model-Prototype Comparisons by Gordon and Gaines and add the following in a new chapter as "Model-Prototype Comparisons by Maynord". The following is the same information I provided in my original submission. (The following contains figures and data that are noticeably absent in the report.) Although in a different form, all of the info provided is included in current text. There is much in the report that Gaines and Gordon do not agree with, but in an effort to put together a team report where the team members do not all agree everyone cannot be accommodated.

Following insertion will be provided (without figures) in Appendix C. At the fall 2002 meeting in Memphis, it was agreed that this report would include no figures. Any figures that have been included in previous versions will be included in the supporting documentation.

"Chapter 5. Model-Prototype Comparisons by Maynord (new chapter)

5.1 Comparisons of Bathymetry in Calibrated Micromodel

Although the primary question is whether the micromodel can predict prototype response in a calibrated model, the ability of the micromodel to be adequately calibrated, i.e. replicate existing conditions, is the only information available in almost all studies. If a micromodel cannot be adequately calibrated, it should be limited to demonstration, education, and communication. The published reports from previous micromodel studies were evaluated to determine the ability of the micromodel to replicate existing conditions, i.e., the quality of the calibration. Previous micromodel studies are described in the following paragraphs that do not meet one or more of the 4 characteristics of an adequate calibration given by Maynord previously. Cross sections were compared within the problem reach that generally demonstrate the largest deviation of model and prototype.

1) New Madrid, Mississippi River- The study (Davinroy, 1996) was conducted to develop a structural solution to repetitive maintenance dredging in the main navigation channel. Of the 4 requirements of an adequate calibration given above, this

calibration has large departures in depth within the problem area. Figure 2 shows the channel schematic and the location of cross section AA about 1 channel width upstream of New Madrid Bar. Section AA is the location of some of the structures used in alternative tests. As shown in Figure 3, scour in the prototype reached an elevation of about 21 m below the Low Water Reference Plane (LWRP) in the prototype compared to 6 m below the LWRP in the calibrated model. LWRP is the stage in the Mississippi River that is exceeded about 97% of the time. Bankfull stage is about 9 m above LWRP.

2) Sante Fe Chute, Doolan Chute, Mississippi River- The main channel reach is shown in Figure 4 and contains numerous dikes. The study (Davinroy, Gordon, and Hetrick, 1996) was conducted to establish environmental diversity in the side channel while maintaining project depths in the Mississippi River. The calibrated micromodel bed elevations at River Miles 35.8 and 37.7 reached 21 m below the LWRP whereas bed elevations in the prototype were between 7 and 9 m below the LWRP (Figure 5). Of the 4 requirements of an adequate calibration given above, this calibration has large departures in depth in the problem area. The unknown flow split in model is another weakness of this calibration.
3) Mouth of the White River- The primary objective of this study (Gordon, Davinroy, and Riiff, 1998) was to evaluate design alternatives that would provide improved conditions for navigation near the mouth of the White River (Figure 6). The micromodel calibration 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. Figure 7 shows the hydraulic depth (area/top width) at the LWRP along the reach. Differences in hydraulic depth are up to 10 m at Range 19.
4) Savannah Bay, Pool 13, Mississippi River- The study (Kirkeeng et al, 1998) was conducted to address the effects of various design alternatives to alleviate maintenance dredging between river miles 538 and 540 (Figure 8). This is a complex reach with flow splits upstream and in the problem reach. Figure 9 shows a plot of calibrated micromodel and 1996 prototype cross-section at River Mile 538.9 in the main channel only. The model scoured about 9 m deeper than the prototype in the center of the problem dredging reach. 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.
5) Wolf Island- The objective of this study (Davinroy et al, 2000) was to evaluate various alternatives to maintain existing flow conveyance and address improvement in the channel crossing between miles 935 and 936 (Figure 10). At RM 936.5 just upstream of the problem navigation reach at RM 935-936, model scour in the calibration run reached an elevation of 12 m below the LWRP, whereas the prototype scour reached an elevation of 24 m below the LWRP (Figure 11). The study goal was to maintain existing flow conveyance yet no measures of flow split were made in the model.
6) Schenimann Chute- This study (Gordon and Davinroy, 2000) was conducted to create environmental diversity in Schenimann Chute, while maintaining project depths in the main navigation channel. The Mississippi River at Schenimann Chute is located at river miles 57-63 and has numerous dikes throughout the reach and bendway weirs

along the lower end of the modeled reach. The pool crossing sequence, in the downstream portion of the main channel in the calibration test, was out of phase compared to the prototype, as shown by the prototype and micromodel thalweg location in Figure 12. The micromodel exhibited a well-defined sequence of pools and crossings where maximum depths in the pools below the LWRP were typically 12 to 15 m. The prototype exhibited a weak sequence of pools and crossings where maximum depths in the pools below the LWRP were typically 6 to 9 m. At River Miles 59 and 60, the thalweg was on opposite banks in the micromodel and prototype.

5.2 Comparisons of Flow Patterns in Calibrated Micromodel

Several previous micromodel studies have presented ice flow photographs and ADCP velocity measurements in the prototype to show correct flow patterns in the micromodel. The ice photos and ADCP comparisons do not support or are inconclusive when compared to confetti streaks in the micromodel. Two studies are available to compare flow patterns in micromodel and prototype.

1) Lower Peoria Lake- The goal of this study was to determine the impact of island construction on flow and sediment transport characteristics in the upper portion of Lower Peoria Lake (Kirkeeng, personal communication, 2002, provided draft report). This is a complex reach with flow entering a wide lake containing a dredged channel. Prototype Acoustic Doppler Current Profiler (ADCP) near surface velocities presented in the micromodel report show that only small velocities exist outside the dredged navigation channel as shown in Figure 13 schematic. Flow visualization from the calibrated micromodel with surface confetti show significant velocities over a much greater width (Figure 13), particularly on the left side (looking downstream) of the dredged navigation channel. Significant velocities in the micromodel were delineated using the length of the confetti streaks from the model flow visualization. While the report acknowledges this deviation, many of the tested island alternatives are in the region where velocities are elevated in the micromodel.
2) Vicksburg Front- Maynord (2002) presents results of a comparison of surface currents in the Vicksburg Front micromodel and the prototype. Confetti streaks and Particle Image Velocimetry (PIV) were used to determine surface velocities in the Vicksburg Front micromodel. Recording Global Positioning System (GPS) units were placed on surface floats in the bend of the river at Vicksburg, MS. The GPS floats were placed at various locations across the channel at the upstream end of the bend and retrieved at the lower end of the bend. The average stage in the river during the 4 day measurement period and the stage in the micromodel were almost identical. Figure 14 shows a schematic of the Vicksburg bend and the location of a cross section at river mile 439.5 where velocities were compared from the GPS prototype and the PIV micromodel. Figure 15 shows the cross section velocity plot from micromodel and prototype. Velocities in the micromodel were converted to prototype using the square root of the vertical scale ratio which is the ratio applicable to distorted models. The plot shows the exaggeration of velocity typical of MBM. In this case the exaggeration is large, on the order of 4 times the Froude scale velocities. The plot also shows velocities

in the micromodel are concentrated on the left descending bankline when compared to the prototype data. The concentration of flow on the left bank in the micromodel is consistent with the incorrect sediment deposition in the micromodel along the right bank at river mile 437.5 that does not occur in the prototype.

5.3 Comparisons of Micromodel Prediction of Bathymetry (validation)

As stated previously, the primary question to be answered is "Does the micromodel give adequate predictions when compared to the prototype?" The Kate Aubrey reach of the Mississippi River has experienced shoaling problems that required repeated dredging. Two micromodels of the Kate Aubrey reach were constructed as part of the USACE micromodel evaluation to validate or test predictive capability. These models were a major component of the micromodel evaluation. The two micromodels were a traditional size micromodel having a 1:16,000 horizontal scale and 1:900 vertical scale and a larger (2X) micromodel having a 1:8,000 horizontal scale and 1:600 vertical scale. Both micromodels were calibrated to the 1975 and 1976 bathymetry. The predicted micromodel bathymetry was compared to the 1998 bathymetry (Figure 16) and was not similar to the prototype in both the 1:8,000 (Figure 17) and 1:16,000 (Figure 18) micromodels. The problem area is centered at about mile 791-792. The Kate Aubrey comparisons leads one to conclude that a micromodel can be calibrated yet not be validated and thus used for prediction of alternative effects (or used as a screening tool). Kate Aubrey remains the only comparison of micromodel prediction where before and after measurement of prototype bathymetry exist.

5.4 Analysis of Comparisons

Why are the previous calibrations and the only available validation unsatisfactory? Some of the differences can be attributed to variability and uncertainty in the prototype data but the extreme relaxations in similarity criteria must be a primary factor. Ettema and Maynord (2002) note that in hydraulic models, the usual causes of scale effects are: 1) large, flow-altering length scales, 2) distortion of vertical scale relative to horizontal scale, 3) inflation of bed sediment size, and 4) amplification of channel slope. All of these scale effect causes are present in the micromodel as discussed previously. In addition to these four, the micromodel has no correspondence of stage in model and prototype. Since all four causes plus the stage issue are present in the micromodel and there are unknown interactions, it is not possible to state which specific causes are responsible for the differences in model and prototype shown previously. At the small dimensions of flow in the micromodel, Reynolds and Weber numbers are sufficiently different than at full scale as to influence flow behavior and distribution (Ettema 2001). Large exaggerations of Froude number and vertical scale distortion are likely causes of poor agreement of lateral velocity distribution and thus bathymetry in the model. Ettema (2001) and Ettema and Muste (2002) conclude that micromodels can be useful in situations where the thalweg is constrained to only vertical movement such as in a long constriction. In cases where the thalweg can move laterally, model utility diminishes quickly."

End of new chapter on model-prototype comparison by Maynord.

3. Remove anecdotal conclusions in Chapter 3 that are not substantiated with data. These can be placed in the MVS or MVM conclusions or in model-prototype comparisons by Gordon and Gaines but their placement in the main body of the report implies that I agree with them. I do not because no one presented any data in support of the conclusions. Information presented is taken from reports. The original modeler's opinions are relevant. That's why they are included.
4. In chapter 5, I reiterate my comment to include "Use as a Screening Tool" as an area of additional consideration. If I am not able to make additions to this chapter, it needs to be eliminated or given under MVS and/or MVM authorship. Added.
5. In Chapter 4 on Model-Prototype Comparison by Gaines and Gordon, it would help if you state the ranges used to define the problem area so that someone can come back with the data plots in the appendix and better understand your analysis. Ranges are included where specific departures are noted. The comparison report includes descriptions of each model study, including the locations of the problem.

Steve Maynord

Comments By Rob Davinroy July 28, 2003

a. Throughout report.......Micro model and micro modeling are two words, not one.

1. Page 19. Would like to add a paragraph after item 4): Changed as suggested.

Davinroy and Gordon (unpublished) states that adequate calibration exists when the following characteristics occur:

1) The Model bathymetric trends, resulting from surveys collected on the model, are similar to observations of actual hydrographic surveys of the river under study. This includes bathymetric trends observed in main channels, side channels, and distributaries, if included in the study reach.

2) The model bedload, input and output, is in relative equilibrium, with continuous movement of sediment observed and no aggradational or degredational trends occurring within the model study reach.

Page 21. Section 3.2. We have already commented on this section extensively, and either this section should be dropped or our re-written version included. Our write-up on the comparison between micro models and WES model operations should be included. The section is poorly written because it is not contrasting Micro Models with other movable bed models....item 4 for example is not a contrast, doesn't explain what the other models use, changing discharge scales, etc......items 8, 9, and 10 have no contrast, etc..Objection noted. Suggested write-up will be included in supplemental QA/QC materials for reference.

Item 2....drop the superlative "large"...Is twice the distortion "large"? What about ten times the distortion?...50 times the distortion?...define large versus not so large or small....Noted.

Last paragraph and table.....drop superlative "large" again....see above Noted.

In the table, the superlatives small, significant, and extreme should be dropped....unless you can explain what they mean. Noted. These are by Maynord.

Page 23, first paragraph, drop superlative "extreme" Noted.

Page 24, 3.3.5. drop last sentence, this is an opinion, not fact Noted. Distortions do adversely affect a model's ability to replicate prototype behavior—its been studied and proven. The degree of the effect may be subject to opinion.

Page 25..Paragraph 3.4....first sentence...drop "lengthy" and say "there have been a number of successful problems solved with movable bed model studies Dropped lengthy and modified text.

Next paragraph……Davinroy (unpublished) countered that data collected in the past from the electromagnetic current meter on the Mississippi River has shown that the differences in velocity direction between the free surface and depths of five feet are negligible and very similar in appearance. Second, the confetti streaks were not time-averaged velocities but time-exposed velocities. Third, the micro model confetti streaks were not correlated to a stage but instead a high flow condition in the model. Water stages in the micro model are not modeled, instead, the average sediment response at high and low flows are modeled. The flow visualization is intended to visualize the general surface current patterns at these two energy conditions only. Fourth, and most important, the ADCP data showed that the GPS floats used in the prototype did not show the same general trends observed with the GPS float surveys.

Page 48…third paragraph, drop first sentence…this has not been proven, in fact, the comparison data suggest otherwise…….Section 5.4.2 –Items in this section are the same as in previous summary report—these are areas that require further investigation and should be noted here.

COMMENTS on MICRO-MODEL EVALUATION REPORT RE-WRITE
by Thomas J. Pokrefke, Jr., PE

As requested, I have reviewed the micro-model evaluation report provided to me by Andy Gaines on 7/15/03. These are strictly my personal comments and in no way are they intended to be an official ERDC-CHL response to the report. My comments are provided referenced to the specific chapter, although I have a few general comments initially. I also have a few strictly editorial comments/corrections that I will stick at the bottom of this.

General Comments

Andy and whomever else combined the versions 1 and 2 and Steve Maynord's input deserves an "at-a-boy" for ending up with a document that is well organized and easy to follow. It covers micro-models with enough detail to give the reader a pretty good understanding on what goes on relative to micro-models. More importantly, I got the distinct impression as I read through the report that some of the *emotion* from previous documents was not present and attempts were made to present information with a fairly neutral approach.

Chapter 1, Introduction

I basically have no problem with this chapter, which is very similar to what was presented in Chapter 2 of the Andy's previous version of the report.. I wondered why at the end of section 1.3. the Components of the JV study were not presented in the re-write version. This is not a showstopper, but it was somewhat helpful in understanding what the JV was trying to do.

Noted—others objected to inclusion o fthe components, therefore it was removed.

Chapter 2, Movable-Bed Models

Looked good to me. Portions of this chapter were also in the original version.

Chapter 3, Micromodel

The beginning of this chapter was also in the original version. In section 3.3.6., third sentence, it states that simulation of the response when the bed is cohesive cannot be studied with "... all existing movable bed and numerical models." I believe that this statement is not true for numerical models. In fact, numerical models **are** the only models presently available which are capable of addressing cohesive sediments. Also in the same sentence, I suggest that the word "physical" be added between "existing" and "movable."

did a poor job in verifying 44% of the studies and on micro-model a poor job was done on verifying 46% of the studies (I would say that the micro-modelers would be as shocked as I was with that statement). Since this is one person's opinion, it probably really should not even be included in the report. I went back to the WES Technical Reports for the Buck Island studied (rated "fair"), the Dogtooth Bend study (rated "poor"), and the Smithland study (rated "good") to get a feel for how well, in my opinion, the models at the end of verification reproduced the problems being studied with each of these model studies. I will admit that I have some prejudices here, since I was involved in the verification of the Buck Island and Dogtooth Bend studies, but I just wanted to back off, compare the ending prototype survey with the verification survey, and give my conclusion. The Buck Island study reproduced a problem created by the breaching and failure of two dikes during the 1973 Flood. The largest departure from the prototype bed configuration was in the vicinity of the breached dike within the channels to the right and left of the breached dike. I would rate the verification as "good" since the largest variation was around a dike with little to nothing known about the remnants of the breached area. As with any study, ERDC (WES) never focused on reproducing exact elevations throughout the reach under study. We looked for reproduction of channel planform trends and relative elevations in the pools and crossings. My review of the Dogtooth Bend report resulted in my evaluation that this was a "good" representation of the problems in the reach. The navigation channel narrowed in Price's Landing Bend and Dogtooth Bend, which was the problem being studied, and the crossing coming into Dogtooth Bend was slightly shallower than the prototype, but not by much. On the Smithland study the adjustment survey was no closer to the prototype than the other two studies. In fact the non-navigable channel to the right of Cumberland Island was shallower than the prototype, while the navigation channel to the right of Towhead Island was deeper, wider, and extended farther downstream than the prototype. Even with those differences this is a "good" verification. The Smithland report stated that the verification "was considered adequate to provide general indications of the tendencies that can be expected with the proposed structures." It continues to befuddle me why we want to knock the coal-bed movable-bed models. I would dare say the if a micro-modeler goes back to their study report and revisits the information there, that they could make as strong of an "argument" as I for their models which were rated "poor" or even "fair" in this report.

Text has been modified to reflect that the ratings were for the degree of calibration ONLY and not the model in its entirety. What this shows is that experience and engineering judgement are the MAJOR factors in either modeling effort.

I recommend that the ERDC models be deleted from section 4.2., and if they are not, that the evaluation of the ERDC and micro-models be revisited to show the studies in the light that I believe they were viewed in at the time of verification. I would hate to think that I spent almost 50% (the report says 44%) of my career doing poor work. Again, that is not the message we want to send out to the world.

Of the 13 micro-models presented, 6 of them were classified as being "poor" at reproducing the problem that was being studied. Of those 6, two of them, Memphis

(1) Small scale – section 5.4.8.
(2) Large vertical scale distortion – section 5.4.8.
(3) Low stages run in micromodel – sections 5.4.1. and 5.4.2.
(4) The small size of the micromodel and the relatively heavy bed material results in steep slopes – sections 5.4.5. and 5.4.7.
(5) Model sediment – section 5.4.7.
(6) No similarity of friction – section 5.4.10
(7) Micromodel used porous dikes – section 5.4.4.

Therefore, what the report presents is that micro-models have several differences (10 are listed) from "most previous empirical models" (section 3.2.), and then later it states that there are 14 "key areas pertaining to micromodels the require additional research." It turns out that 7 of those differences are among the 14 additional research items.

In section 5.5., delete the first three sentences. It has nothing to do with micro-models; therefore, it appears to have no value here.

These are areas that anyone considering a movable-bed model should investigate.

Chapter 6, Conclusions

This chapter basically leaves the reader hanging. Conclusions in a report are usually the most read portion of a report; therefore, if the results of this investigation are that research was done but no clear-cut conclusions were reached, present the reader with the concluding viewpoints and supporting information. The first paragraph in the conclusion talks about the engineering process, but that is not what someone wants to hear about when trying to decide if they want to do a micro-model study. The second, third, and fifth paragraphs in the conclusion essentially state that there are a wide range of opinions on the usefulness of micro-models and that the team could agree on virtually nothing. The fourth paragraph presents micro-models as a new technology and says give them a chance. None of this was presented in this light in the report itself. The end of the fifth paragraph and the sixth paragraph are warnings to potential micro-model users. That is my point above, warn the reader and tell him/her why you are giving the warning.

Going through the report I picked up the following that could or should be addressed in the conclusion chapter. The conclusion chapter should not bring out conclusions or positions that were not presented in the body of the report.

(1) A summary history of river engineering and the use of some type of model (Chapter 1).
(2) The need for and development of the micro-model technology (section 1.2.).
(3) The Joint Venture team and consultants and their taskings (sections 1.3. through 1.6.).
(4) Movable-bed models including Maynord's categories (sections 2.1. through 2.3. and section 2.4.).

(8) In section 4.2.5., in the "Top Width" line, the word "that" should be "than."
Correction made.
(9) In the Closing Remarks chapter, last paragraph, last sentence, the "too" should be "tool." Correction made.

If anyone has any questions relative to what I have presented as my comments, they can feel free to contact me and we can discuss it. Again I would like to say that these are my personal comments and opinions and not those of the ERDC-CHL or anyone else in CHL. I believe that Andy had started folding the various opinions from the team members together, but it also appears that differing opinions of specific issues have yet to be definitively addressed in the report. Instead, one team member addresses different issues, but another team member will address the next issue. The best thing that this report can do for the Corps of Engineers is to openly and honestly present the viewpoints and stop right there.

Thomas J. Pokrefke, Jr., PE
Hydraulic Engineer
Coastal and Hydraulics Laboratory
ERDC-WES

Andy this is an exceptionally good report, you are to be commended.

I have read To Po's comments and he covers most of the technical concerns that I have (except for 2), so I will not repeat them.

Concern 1: I have a hard time with statements like "the model results agreed with the prototype response." Call it my Franco training, but making conclusions without some type of data for the reader to agree or disagree with is not good. When I see this, I question what the writer is hiding. I realize that this would increase the size of the report, but without "proof " the report is just words on paper. Whether figures, tables or whatever some type of support for your conclusions needs to be included. Brevity in this case is detrimental to the message you are trying to convey.

Concern 2: You have delved into this matter of micro models more than anyone else and since the JV team was tasked with documenting the "micro model capabilities and limitations", therefore I think you should include a table or the like listing typical river engineering problems (such navigation channel maintenance, side channel development, lock approach currents, and etc.) along with your recommendation of the micro model applicability. You could also include Dave's and Steve's opinions. The conclusion as presented do not address the tasked goal, only that the JV member differ in opinion.

General Comments: I would like to say I concur with Tom that detailed large scale model evaluations is not needed in this report. The detailed large scale model evaluation is important to define the question "How good is good enough?", but does not add much to the task of defining micro model capabilities and limitations, since our effort was directed to micro model to prototype comparisons. Also, Tom being aware of the problem to be resolved with each of the studies he commented on showed that his evaluation of the verification was different than Steve's who was looking at the results without considering what the model was supposed to solve.

I think it should be stressed in this report that the results from a micro model are only as good as the knowledge and experience of the modeler. Which is true for large scale physical models and numerical models.

Andy it has been a pleasure working on this with you and I hope we can team-up on other efforts. Tell Wayne Hi for me.

Charles R. Nickles
Coastal & Hydraulics Laboratory
US Army Engineer Research & Development Center

19 July 2003

Subject: Review and Comment of July 2003 Micromodel (MM) Evaluation Report by Stephen T. Maynord

General Comments:

1. It is important to acknowledge that Andy Gaines has been asked to put together a report under impossible constraints. Although I hate to emphasize one of these constraints, I must state what I stated at the Memphis meeting last fall. My conclusions must be shown and they are not areas of consideration or future study. Further, they must be placed in the conclusions section or the report is not acceptable.
2. All JV members agree that the MM can be used for Demonstration, Education, and Communication (DEC). The main issue that potential MM users need to know is whether the MM can be used as a screening tool to compare alternatives. I prefer to address this issue by asking what I believe to be the primary question, **"Does the MM give predictions adequate to compare alternatives?"** I believe the present report focuses on far less important issues and should be refocused on this primary question.
3. The report attempts to justify poor performance in the MM by poor performance in the ERDC coal bed models. This is the continuing effort to show that the MM is somehow equal to the ERDC coal bed models. Some seem to believe that if this can be done, this greatly diminishes any responsibility to answer the primary question. This is not a valid approach because:
    a. The MM needs to be sold on its successful predictions. Noted
    b. The evaluation team was not tasked to evaluate ERDC coal bed models and the comparison methods used are not adequate to compare models. Disagree, comparisons serve as the basis for establishing "acceptable" practice in the past.
    c. The techniques used to compare width, depth, etc are based on reach averages which tend to hide differences in the problem area. Reaches having large deviations where parameters are too large and then too small cancel each other out. The percentages shown give potential users a false sense of accuracy. The reach averaged values should not be used for anything. The plots of model-prototype parameters along the length of the model we presented in the appendix would likely be useful in the calibration process. Ratings as applied to width, depth, etc. are based on looking at the entire reach (plots by range in the comparison report), not on the reach averaged values developed for previous versions.

    Remove all attempts to equate coal bed and MM and focus on the primary question by showing successes and failures of the MM. Any critique of ERDC coal bed models needs to be approved by Tom Pokrefke. Coordinated ratings with Tom.
4. The report focuses on the process of design, operation, and interpretation for the purpose of emphasizing the value of the knowledge gained during the process. I have no doubt that the modeler learns a great deal in this process and I consider this to be an element of DEC. This is education of the modeler. This process cannot overcome a model that gives wrong answers. Agreed. The constantly repeated focus on the process is a distraction

that the report would have been quite explicit if it had been successful at placing the bendway weirs in the calibrated model w/o weirs and running the model w/o the second calibration. Remove Marquette unless a previously published document shows this to be a true validation using the 3-step calibration. Kate Aubrey remains the only validation attempt I have seen in this evaluation. It showed lack of prediction in the MM. Kate Aubrey was a critical element of this evaluation. The results of this lack of prediction should be highlighted in this report. New Madrid has been discussed off and on for some time. Mouth of White River has only recently

8. As written, the report does not show my findings on the MM in the conclusions. As a minimum, it must have a conclusions section with my conclusions with my name, and no other input from anyone in my section. If that does not happen, the report is not acceptable. I would like my conclusions section to read as follows:

"The micromodel, because of its small size and totally empirical design/operation, is different from previous movable bed models and does not fit into either of Graf's categories of empirical or rational models. In addition to its size being as small as 4 cm channel width, the large vertical scale distortion, large Froude number exaggeration, and no correspondence of stage in model and prototype, place the micromodel in a category by itself.

In some studies, the micromodel has been calibrated to match the bathymetric trends of the prototype. In other studies the calibration was poor and the micromodel did not match the bathymetric trends of the prototype. The Vicksburg Front and Peoria Lake comparison of surface velocity in calibrated model and prototype showed no agreement. No previous studies have shown validation of the micromodel to demonstrate the model can predict bathymetry. The two Kate Aubrey micromodel validations did not agree with the observed prototype response. Extreme relaxations of similitude are a primary cause of the model and prototype differences. Recommended applications of the micromodel follow.

a) Demonstration, education, and communication- The micromodel is useful in demonstration, education, and communication and is effective in generating ideas for problem solution and demonstrating river engineering concepts.
b) Qualitative bathymetry analysis-
   Qualitative bathymetry analysis is use of the micromodel as a screening tool to compare alternatives based on analysis of bathymetry. No numbers should be assigned to alternative features or results from the model in this category. This category is the primary question to be answered in this evaluation. Can the micromodel, which operates with extreme deviations in similarity criteria and can frequently achieve only a poor calibration, still be used to predict and compare alternative plans, even in a qualitative sense? This evaluator has seen no evidence supporting use as a screening tool. Future application of the micromodel in this area requires that the user demonstrate that the model can be validated, i.e. shown to predict changes to the prototype. At some point in the future, several successful validations of the micromodel in each specific study type (for example long constrictions or single dikes or bendway weirs or traditional dikes) would allow use of the existing calibration only model adjustment process for this study type.
c) Quantitative bathymetry analysis- Quantitative bathymetry analysis is use of the micromodel in which numerical values are used to characterize alternative features or

14. Section 3.3.6- The suspended sediments issue should relate to whether a stream is predominately bedload which is delineated by some value of U*/w (1?) and not whether it is active bed transport. Wording changed.
15. Section 3.4, Case studies need to be combined with model-prototype comparisons. Sentence "Because MBM typically depart from ideal similarity ….." brings to mind a discussion we had on the definition of similarity and similarity criteria. We should probably define these two terms in section 1.6. When the terms similitude or similarity criteria are used, reference is to the dimensionless parameters shown in Eq 1 that are used to define the dynamic, kinematic, and geometric relationships between model and prototype. Use is consistent throughout report. Any use of similarity or similar does not imply a reference to the dimensionless parameters of Eq. 1.Nothing added to 1.6.
16. Section 4.1- What is the 3rd pp talking about? It appears to me that the last pp of 4.5 describes use of the MM for DEC. This is talking about making a comparison of model to prototype based solely upon technical merit—do values in the model equal prototype values (i.e. depth in model equals/does not equal prototype depth). Just looking at the bathymetry does not consider other aspects of the model effort. There are occasions when model calibration is less than desired, but constraints placed upon the modeler dictates that the level achieved is sufficient—it's a judgement call based on time, funding, available prototype data, and the scale effects present in the model.
17. Chapter 5- Note in the text that many of the issues are the same ones found in MM contrasted with other empirical MBM. Add to this section another area of consideration- "Use as a Screening Tool" with text as follows: The micromodel has been used to screen alternatives. Screening requires the model to predict the effects of a plan. Results of available validation tests show that use of the micromodel as a screening tool is debatable. The screening issue is wrapped up in uses of the micromodel in section 4 and the categories of section 3.
18. Conclusions:Conclusions have been re-written based on the following and comments received from others.
    a. 2nd pp- remove last 3 sentences because they do not add to report.
    b. 3rd pp- no amount of data would have resulted in a consensus. This pp should be removed because it does not add anything.
    c. I find no conclusions that would help a potential user and little in the remainder of this section to be of great value to the report. Some of the items in the next to last pp are new that should have been presented in the body of the text. I provided conclusions as part of my input that were placed in closing remarks that also contains some conclusions by others. My conclusions section is shown above and should be placed in the conclusions section with my name on them. Have Dave and Andy write their conclusions and put their name on their conclusions. Be specific. Address the issue of using the MM as a screening tool. Avoid statements like the MM provides "additional" information , "useful" information, or "positive results". Don't spend a great deal of time trying to discredit my arguments. State what you believe and why as I have tried to do in my conclusions.
    d. It appears from statements made in the report that some of the JV members believe the following "Even with a poor calibration, the MM gives predictions of

Edits to Evaluation Report dated 15 July 2003, Dave Gordon

Page 10, Section 1.5., 2nd P, "Because current ......vigilence when doing so." I feel the wording here is negative, such as limitations, suspect, off limits, extreme caution, and vigilence. Noted. This is taken directly from Tom Pokrefke's comments on earlier drafts. Based on conversations, this was inserted at DG suggestion.

Page 10, Section 1.6., (Yalin's Statement.) I didn't like this quote before and I like it even less now. I don't know why it keeps popping up everywhere. I don't feel it serves a purpose anywhere in this report. Noted. This simply states Yalin's opinion of what he saw after view the micromodel and discussing micromodel procedures with Rob Davinroy.

Page 11, 2nd P, Last sentence, #1: "...reach being simulated compared with other MBMs." It is very important that the micro models are evaluated in respect to the past performance of other MBMs. The bottom line is how the micromodel (or any model) compares to the prototype—not how one model compares to another.

Page 14, #1: Describe the micro model sediment. See appendix B

Page 15, #2: Discuss other models that used much higher distortions (20 to 30) to give the reader a sense that much greater distortions have been acceptable in the past. Noted. Sentence added to refer to Reynolds and Vernon Harcourt's model distortions.

Page 17, Categories A-D: I don't agree with these. I prefer those in Section 3.3.
The paragraph following A – D is very confusing and doesn't help the reader understand how to use the categories. I would like to eliminate these categories. Noted.

Page 18, 2nd P: Confusing paragraph. What are process models? Shouldn't all models be interpreted with care? See rewrite and Parker's report in App. A.

Page 19, Section 2.6: I agree, and would assume that you do as well, with these 4 requirements. Then why are Maynord's ideas, thoughts, and conclusions being separated out from ours more frequently? Additional references added for clarify the souce. Everything that we have provided is in some unpublished format that was written to be in this report. Why are Maynord's ideas any different? I feel that his ideas are commanding more respect on this team than the rest. Comment noted.

Page 19, last paragraph, 2nd sentence: Explain that these assessments are subjective for most MBMs to let the reader know that this type of critique during calibration is not unique to micro modeling. It was adapted straight from the WES modeling technique. Text modified to clarify this issue.

2) *Vertical Scale Distortion.* Both models rely upon distortion of the vertical scale. In the micro models, the distortion has ranged between 5 and 20. In the WES models, distortions have ranged between 2 and 10.

3) *Determination of the Vertical Scale and Datum.* In the micro model, the vertical scale is adjusted during the calibration phase of the model study. The vertical scale is determined by mathematically applying a single scale factor to all model bed elevations. A parallel datum is then shifted which increases or decreases vertical scale and distortion. Varying scale factors are applied to the model bed configuration to determine which factor results in a bed configuration that most resembles the prototype. This is a trial and error procedure that is used in the calibration process to study bed forms and to adjust the heights of existing river training structures. Once the model is determined to be calibrated, the resulting vertical scale is then used for the duration of the model study. The vertical scale applies constant throughout all lengths of the model as well as the established datum. In the WES Models, an initial vertical scale and datum is established during the molding of the model bed. However, during verification, localized datum changes are made at numerous locations along the model, whereby the datum is either increased or decreased in elevation. The end result is a model that contains a non-parallel datum which varies throughout the length of the model.

4) *Correspondence of Discharge and Stage to the Prototype.* The discharge and stage in the micro model, as described earlier, does not correspond directly to the prototype. However, it would be possible to develop a non-linear relationship as in the WES model methodology for a graphical prototype comparison. However, since the primary purpose of the model is to incur a representative sediment response of the model bed, the non-linear graphical relationship is not deemed necessary. In the WES models, a graphical non-linear, exponential relationship was prepared for model operational guidance and prototype comparison purposes. However, this non-linear discharge scale reduced flows in the WES models at the higher points in the hydrograph. This would have effectively created disproportionate stages without the use of a varying tailbay located at the end of the model to manipulate the stages to higher elevations. This effect combined with localized datum adjustments with rails created stages that only superficially corresponded to the prototype. Both models employed a standard design hydrograph used during the base test and all design alternative testing. Although, these hydrographs did not correlate directly with the prototype, simulation of a low flow to high flow energy response was necessary in both models for the proper movement of the model bed. Typically, stages in the micro model approach 2/3 bankfull. These lower stages in the micro model reduce the energy of the model associated with the distortion effects. Without the use of the variable tailbay, much lower distorted stages would result in the WES models as compared to the prototype. Additionally, the use of a linear discharge scale in the WES models would produce exaggerated mobile bed energy.

9) *Similarity of Friction.* The micro model and the WES models include no provision for providing similarity in prototype friction (or roughness). This should be explained further for both the micro model and WES model.

10) *Composition of Model Dikes.* In the micro model, dikes, weirs, and other rock structures were initially represented by thin-walled sheet metal. From flume experiments conducted in 1998, porous thin-walled steel mesh structures were eventually used to minimize scour to simulate more realistic depositional patterns around structures. These porous structures solve the problem of exaggerated scour around dikes that occur in most distorted models (Figure 2-15). One of the most important aspects of the micro model is the ability to make qualitative predictions on the effects of training structures on the bathymetry or sediment response of a river or stream. The present methodology of achieving this response involves the use of porous structures in the model in the form of steel mesh. The porosity of these mesh structures is critical for reducing turbulent effects and provides a corresponding reduction in shear stress at the model bed.

In the WES models, solid, non-porous structures in the form of concrete, pea-gravel, or thin sheet metal were predominantly used. No information has been found on the study of these type structures on the model bed response.

11) *Time Scales and Sequencing.* In the micro model, durations in the hydrograph are usually on the order of 5 to 15 minutes. Hydrographs are usually run in succession until bed stability is observed. Thus, one particular model test may employ 4 or 5 successive hydrographs equaling 1 hour in total duration based upon whether the model bed response has completely or fully developed. In the WES model, durations of individual hydrographs were as long as 40 hours and were sometimes run multiple times without re-molding the bed. Equilibrium of sediment transport (the amount of sediment placed in the upper end of the model should be equal to the amount of sediment discharged out of the lower end of the model) is a key factor in both modeling methodologies. In either method, the time in the model was not used for the purpose of predicting the bed response time in the prototype.

12) *Relative Depth of Model Bed Within Flume.* In the micro model, the bed is allowed to move freely in the vertical direction because of adequate vertical flume dimensions relative to model scale. In the WES Models, the bed was restricted in its vertical movement because of the minimal vertical dimensions provided by the flume. The unrestricted depth was based upon space considerations and the cost of constructing a deeper concrete flume. Many times the modelers would have to contend with scour patterns that extended onto the concrete floor of the flume. This would sometimes cause other problems to the model study in the downstream direction.

13) *Erosion Resistant Materials.* In the both the micro models and the WES models, various materials have been used to represent erosion resistant material in the

Page 32, 3rd P, last sentence: Davinroy critiqued two ERDC studies. Change text.

Page 33, Section 4.2: As you probably guessed, I do not like this rating system. (I would also imagine that Tom and Steve won't like it either.) The rating system is slanted toward the negative. Most rating systems would have 5 categories with "Fair" being in the middle. The way this is worded immediately gives most models a negative connotation. I realize it is only your input (as stated) but I think that since this is such a large portion of the report, that the entire team needed to participate in this exercise. At this point it is too late to revise. I would like to have this section removed completely. There's no way we can allow ratings of poor for any model study to be published. This text will be taken out of context for years to come. It would be a huge mistake that will haunt us forever. I think I understand what you are trying to conclude from these ratings on Page 45, Section 4.5. However, there has to be a better way to explain that the calibration of movable bed models may appear poor to an outsider, but to any movable bed modeler that is best that you can do with any model considering the complexities of what we are trying to model. Any text where we call the calibration of any model poor, has to be removed. Some of the models that you classify as fair or poor, I know for a fact that we had an excellent calibration. Comment noted. The original rating system inappropriately gave the connotation that the models performed poorly. The intended message was that there are various states of calibration in the models, yet the models provided information that aided the engineer in developing plans for the prototype. Rating system has been revised and text added to clarify this.

Page 44, Section 4.4.2. We don't need to get into this. There is too much disagreement to even discuss this particular model study and furthermore I don't feel that our opinions or data were presented fairly in this report. Especially the conclusions made in the last paragraph. If you insist on keeping it in the report, it will need to be changed to reflect our opinions more accurately. (Which may end up getting rather lengthy.) Noted. See also R. Davinroy's insertion and modification.

Page 45, 5th P: The data from the Comparison Report do not support the conclusions made in this paragraph. The comparison report and Gaines dissertation support these conclusions.

Page 45, Last P: The scale effects are not only present in micromodels but also in most other MBMs. Changed.

Page 46, 1st P: Whose says that there is a poor agreement of lateral velocity distribution and thus bathymetry? Andy and Steve have interpreted the data in this way but we have not. We are not in agreement with this statement so it needs to be removed. We also do not agree with the last sentence. If Ettema's opinion on this subject is to be included, then we should have our disagreement with his opinion stated as well. Noted.

not just a few. I also didn't know that the future goals of micro modeling included the use of a real flow hydrograph. Conclusions have been completely revised.

Page 54, 1st P: What are that numeric tools that river engineers have available to us for designing the placement of river training structures.

I strongly disagree with the last sentence. I feel the model can be used for these purposes but only with caution. In fact we have used the model successfully to design and construct at LD24 and the mouth of the White. Noted. Conclusions completely revised.

Page 54 & 55, Items 1 through 5: I strongly disagree with these statements. Rob, Claude and myself are very disturbed that these are being included. These cannot remain in our joint team report. Noted. Conclusions completely revised.

Page 55: Do not use the word "poor" Noted.

Page 56: Remove the references to Gordon. I thought these were facts. Conclusions have been completely revised.

Subject: Revision of Micromodel Contrasted with Previous Empirical MBM

MM contrasted with previous empirical MBM

Of the two Graf (1971) categories, the micromodel is closest to the empirical MBM category. While similarity laws are not followed closely in empirical MBMs, there are definite differences between the micromodel and most previous empirical models as follow:

1) Small size- The micromodel is one to two orders of magnitude smaller than most empirical models. Model widths in the micromodel are as low as 4 cm compared to 4.5 ft and 11 ft in two models cited in Glazik and Schenke (1986). Model depths as low as 1 cm are an order of magnitude less than the minimum of 10 cm recommended in Gujar (1981). No requirements for minimum Reynolds number are used in the micro-model. 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 empirical models. Micromodels commonly use distortions of 8-15 compared to empirical models cited in the previous section on "Vertical scale distortion".
3) Vertical scale and vertical datum determined as part of the calibration rather than in model design. In converting model bed elevations to the prototype after a calibration test, various vertical scales and vertical datum are tried in the micromodel until the model bed configuration most closely matches the prototype. Gujar (1981) describes the process of determining vertical scale in design.
4) ~~No correspondence of stage in micromodel and prototype- Most empirical models relate stage to a corresponding stage in the prototype.~~ This item is combined with item 9.
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.
6) Calibration of micromodel based on equilibrium bed- Previous MBMs conduct calibration by starting with a known bed configuration, running representations of the subsequent stage and discharge hydrographs, and comparing the ending bed topography in model and prototype (Franco, 1978). 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=1.48) results in steep slopes in the micromodel. Water-surface slopes of the few micromodels that have been measured are about 1 percent. Steep slopes result in significant exaggeration of the Froude number. Froude numbers in the two micromodel studies where known, are 4 and 6 times the prototype Froude number compared to MBM discussed under "Increased model slope" where the Froude number exaggeration was generally 2.2 or less.

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