B-1

JOINT VENTURE TEAM/GAINES

DRAFT 1

1.1. BASIC ENGINEERING ANALYSIS

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

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

Three principle freedoms are apparent from observation of most streams: adjustment in channel depth, adjustment in alignment, and adjustment in cross-section shape. The successful prosecution of a physical sediment model entails reproducing these natural adjustment tendencies. However, owing to the high degree of complexity and mostly unknown processes associated with lateral channel adjustment, such models typically employ a rigid (or nearly so) planform whereby meander migration and bank progression are restricted. Thus, the thalweg is constrained to the confines of the channel banks which limits channel response by one degree of freedom. Where river training structures exist, a further reduction in thalweg positional freedom occurs, and in the extreme case, the channel behaves as a constricted reach with limited potential for adjustment of thalweg position. Distortion of various model parameters (i.e., vertical scale, slope, and roughness) may result in further constricting effects.

The consequences of constricting the thalweg's ability to shift in response to water and sediment may pose problems in achieving successful model results. Because thalweg alignment is often a key component of physical sediment model studies, a reduced ability of the thalweg to move may create difficulties in model calibration and in

applying model results to the prototype. This is especially true for the small-scale models described by Davinroy (1994, 1999) and Gaines and Maynord (2001) where the primary objective is to estimate the position and number of flow-training structures necessary to constrain the channel thalweg alignment and its concomitant depth.

1.1.1. Important Variables. The important engineering variables for most river training essentially relate to thalweg behavior. Table 2-1 provides a recapitulation of factors that influence model and prototype similarity. Consider then the possibilities for thalweg behavior as depicted in Figures 2-2, 2-3 and 2-4 (Ettema, 2000). In Figure 2-2 Ettema depicts an unrestrained case where thalweg position is free to adjust vertically, laterally, and downstream within the channel banks. Principle variables that characterize this case are channel width (W), slope (S_o), sediment size (D), thalweg depth (Y_o), lateral thalweg position within the channel width (T_o), and sinuosity (ζ_o). Figure 2-3 depicts a long constriction that results from multiple training structures. Thalweg position for this case is considered fixed by the constriction. Principle variables characterizing the long contraction are channel width, slope, sediment size, thalweg depth, Y_1, lateral thalweg position, T_1, and sinuosity, ζ_1. Figure 2-4 illustrates a short constriction resulting from a single training structure. Thalweg position for this case is considered partially fixed with freedom to move vertically and to a small degree laterally (freedom to adjust only in the approach to and exit from the cross-section containing the dike). Principle variables of interest for the short contraction are channel width, slope, sediment size, thalweg depth, Y_2, lateral thalweg position, T_2, and sinuosity, ζ_2. The contracted width, W', may also be of interest for the contracted cases (as in Figures 2-3 and 2-4) as Ettema presents the ratio of contracted width to the uncontracted width, termed the contraction coefficient (C_C), as a diagnostic parameter for general flow field similarity.

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

Table 2-1 Factors Influencing Model-to-Prototype Similarity Requirements

Factors influencing NATURAL REACHES

Factors influencing MODIFIED REACHES

GEOMORPHIC/HYDROLOGIC			
Stream	Width:	-variability	
		-bankfull width	
		- low flow width	
	Channel:	-cross-section shape	
		-slope	
		-depth	
	Thalweg:	-straight	
		-sinuous	ζ
		-divided channel	
	Bathymetry	Alignment Geometry	
		- radius of curvature	r_c
		- central angle of bend	α
Hydraulic	Discharge:	-magnitude	Q
		-variability	
		-duration	t
	Flow Velocity:	- mean velocity	V, u, v
		- lateral distribution	
		- secondary currents	
	Turbulence:	- magnitude	
		- flow field	Re
		- boundary	Re·
		- intensity	
	Flow Depth:	- main channel depth	y, h, H
		- lateral distribution	
	Fluid:	- Temperature	T
		- density	r
		- viscosity	n
		- surface tension	σ
	Roughness:	- bed	f_b
		- banks	f_w
		- total	f

SEDIMENT		
Bed Material	median size	D_{50}
	grainsize distribution	
	density	ρ_s
	cohesiveness	
	non-erodible	
Particle	Incipient mobility	θ_c
	State of mobility	θ, τ_*
	Bed-forms:	
	- type	
	- magnitude	
	- wavelength	λ
	Sorting/Armoring	
	Fall Velocity	ω
Transport	Equilibrium State	
	-Equilibrium	
	- Dis-Equilibrium	
	Rate	Q_s
	Form of Transport:	
	- bed load	
	- suspended load	
	Lateral Distribution	

TRAINING STRUCTURE		
Type	Abutment	
	Dike/wingdam	
	Bendway weir	
	Lateral dike	
	Chevron	
	Revetment	
	Vane	
	Closure	
Character	Length	L
	Height/elevation	
	Number	N
	Location	
	- straight reach	
	- bendway	
	-side channel	
	Spacing	l
	Alignment	α
Detailed Features	Notches	
	Porosity	e

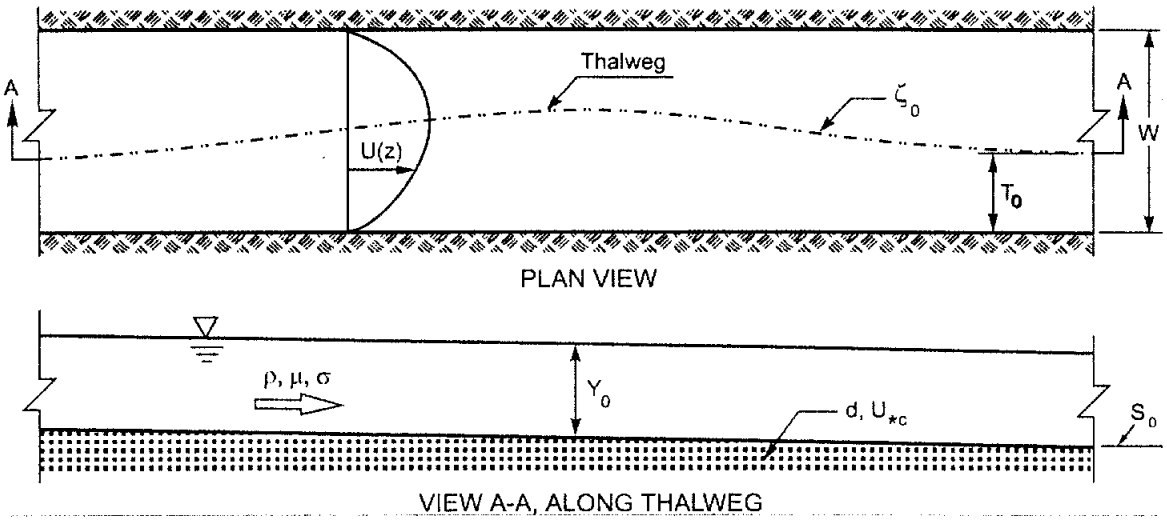

Figure 2-2 Flow, Sediment and Thalweg Alignment Along a Channel of Fixed Width (after Ettema, 2000).

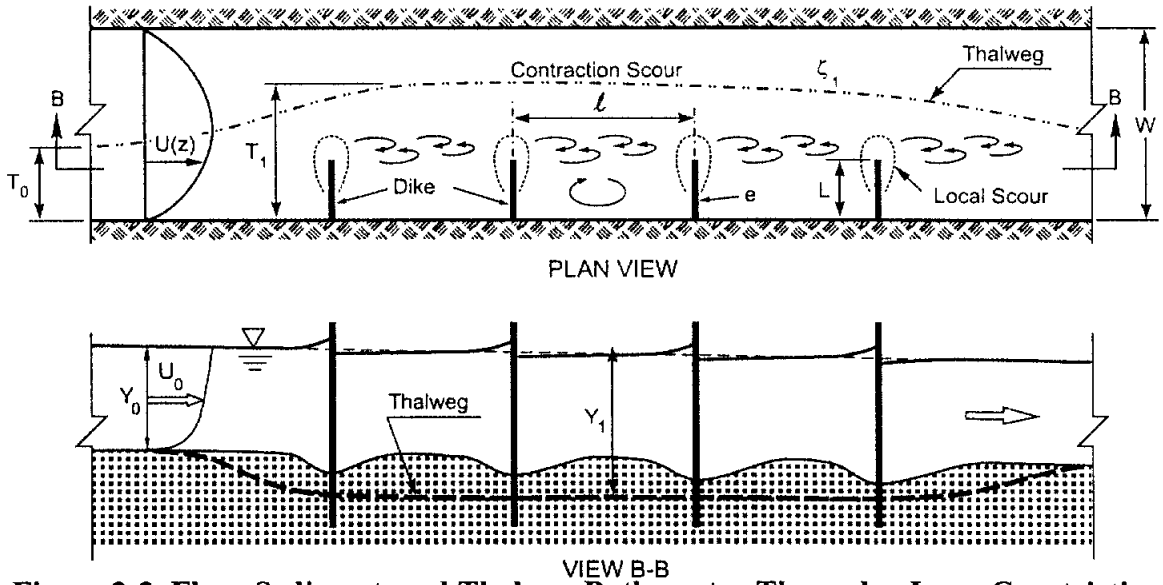

Figure 2-3 Flow, Sediment, and Thalweg Bathymetry Through a Long Constriction in a Channel of Fixed Width (after Ettema, 2000).

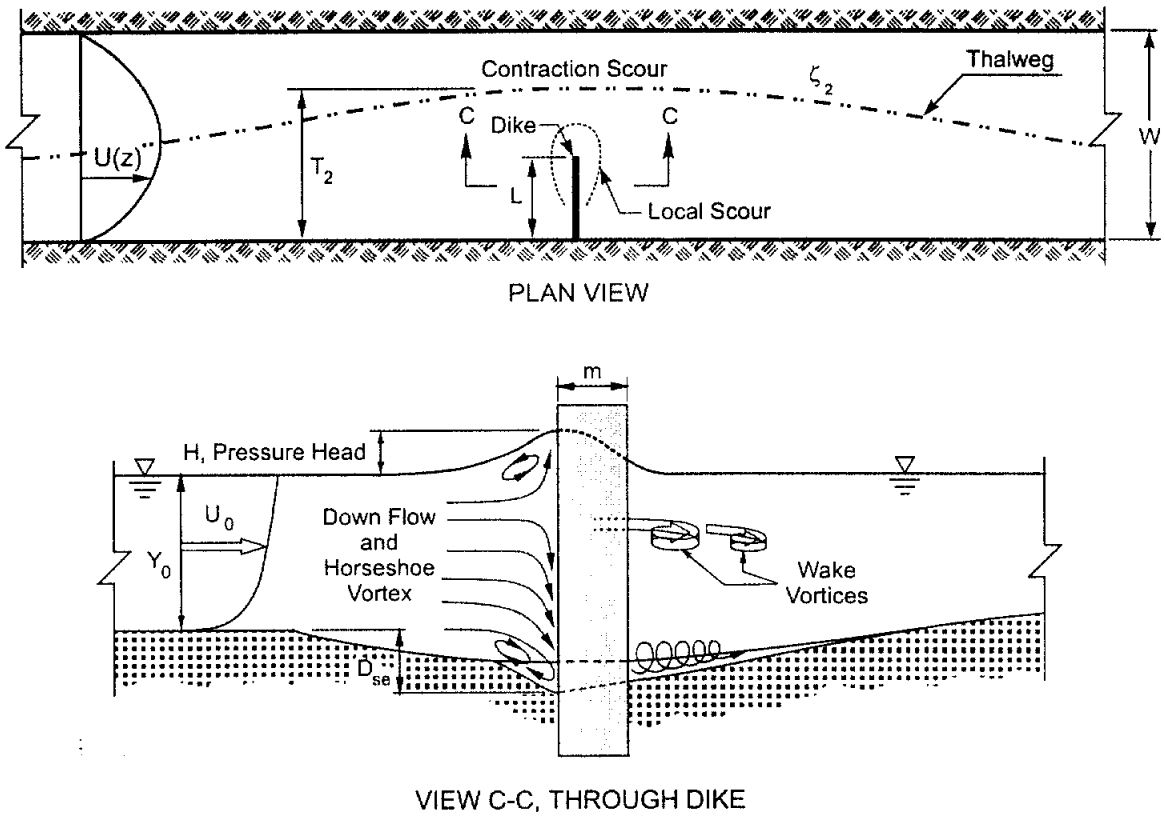

Figure 2-4 Flow, Sediment, and Thalweg Bathymetry Through a Short Constriction in a Channel of Fixed Width (after Ettema, 2000).

for micromodels, as shown in Figure 2-2, are

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

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

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

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

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

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

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

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

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

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

1.1.2. Consequences of Distortions. Ettema (2000) further describes scale effects that result from the relaxation of four common characteristic parameters: increased length scale, vertical distortion, inflated bed sediment size, and exaggerated slope. Ettema provides calculated examples exemplifying the effect of reduced lengths (with no

distortion in the vertical dimension, e.g. $x_r=y_r$) on Reynolds and Weber numbers (viscous and surface tension effects, respectively). Ettema asserts that reduced lengths alter local flow patterns and pressure gradients around simulated hydraulic structures, along the river bed, and along the river banks.

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

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

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

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

Kahn (1970) and Schuum and Kahn (1972) present a relationship between sinuosity and slope that indicates than when slope is increased, sinuosity increases up to a maximum then decreases. Therefore, distortion of slope in a model will likely affect the model's ability to faithfully reproduce sinuosity. Increased slope in the model will likely increase momentum effects through altered velocities. The increased momentum of the flow may offer mitigating effects in the tendency for increased sinuosity according to the Kahn (1970) and Schuum and Kahn (1972) data.

Gaines (2002) sumarizes non-dimensional parameters and relationships that define sets of similarity conditions. These parameters and relationships describe flow and sediment motion in physical sediment models. Establishing a procedure whereby the possible relaxation in similitude criteria are systematically considered in a quantitative manner requires consideration of the inherent variability in prototype conditions. Indeed, similarity relationships mean little if the parameter being "simulated" is not understood in its full context. For example, there is a well known phenomena in rivers whereby a looped rating curve occurs; the so called hysterisis effect. Because all flow field and sediment transport similarity parameters (and processes) depend on discharge, similarity must be viewed as variable; it too is a variable function that changes with time and location (Glazik, 1984, Gujar, 1981, and Gessler, 1977). As a result, similarity can be considered a risk problem. In this context varying levels of similarity relaxation are possible, with each level based upon the acceptable deviations allowable for the particular problem being modeled.

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

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

5. Local scour scale.

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

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

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

Near-field similarity implies an increased attention to dimensionless parameters that describe both hydraulic and sedimentation phenomena. At this level, more attention

is afforded the requirements of similarity as outlined by Zwamborn (1966), wherein three predominant similarity criteria are expressed. Here too, the permissible deviations in similarity are quantitatively undetermined. There are only subtle differences between model approaches at the far-field and near-field levels and some overlap is probable.

Local-field similarity introduces additional similitude requirements. The Einstein and Chien (1956) method for model design may be indicative of the types of similarity required at this level. At this level, requirements may dictate that the two-dimensional flow fields have greater similarity to the prototype than exists at the far- or near-field levels. A possible example for this level is where the model objective is to estimate the anticipated quantities of sediment extracted through a water intake. For this case, the width of the two-dimensional flow field has a major influence on the lateral distribution of velocity and of sediment -- the lateral distribution of velocity and particularly sediment impacts the quantity of sediment available for extraction. Permissible deviations in similarity are not determined for this level.

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

Determining the degree of relaxation permissible in the various similarity conditions at each of these levels is highly desirable. However, establishing criteria for each level becomes increasingly complex as more constraints are imposed on the modeling process.

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

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

There are a number of methods available for qualitatively, semi-quantitatively, or quantitatively assessing the causes and effects of uncertainty. These methods include fault tree analysis, decision trees, and failure models and effects analysis (FMEA) (Johnson and Brown, 2001). All four methods are based on analyses of previous failures. A potential failure is affiliated with a failure cause, a failure mode, and a failure effect. The first three methods require knowledge of probabilities of occurrence for all events that contribute to a failure as well as conditional probabilities for dependent variables associated with the failure. FMEA is a qualitative procedure that has recently been applied to the design of stream channel modifications (Johnson and Brown, 2001). This technique could also be adapted for incorporating uncertainty in the decision-making process for the design of river training structures and other navigation structures. This approach considers risk in terms of the likelihood of a component failure, the consequence of failure, and the level of difficulty required to detect failure.

Formulation of the FMEA begins by identifying the important river system and the proposed project components. Next, the range of possible failure modes is defined. Basic sources of failure modes include documented case studies, laboratory experimentation, field experiences, and expert opinion. Once the failure modes are identified for each component of a hydraulic structure/river system, their effects on the system and other system components, consequences, likelihood of occurrence, methods of detection, and compensating provisions (e.g. possible corrective actions) are listed. A design team assigns numeric ratings (e.g. 1 through 10) for each criterion with the largest values associated with the most severe consequence level and the highest likelihood of

occurrence. A risk priority number (RPN) is then computed as the product of the occurrence, consequence, and detectability ratings for a given failure mode.

Once RPN values are calculated, they can be related to the use of large or small-scale physical models. Various uses of the micromodel can be evaluated from the standpoint of consequences if the model does not having the degree of similitude needed or the level of detail required.

Limits for model application and the allowable deviations in similarity parameters are dependent upon the variability in prototype conditions. The level of expected accuracy (and similarity) from a model must be tempered with knowledge about prototype variability, for this variability defines the basis for the similarity relationship between model and prototype. Therefore, the RPN must reflect variability in the prototype.

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

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

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

Reduced budgets often limit or exclude the use of large-scale physical models. Therefore, focus must turn to the use of the small-scale models, or micromodels. Because physical loose-bed modeling does not follow strict similitude, the degree of confidence placed on the model depends upon the entire modeling process -- how the model is designed, constructed, and operated to achieve morphologic similarity with the prototype. A systematic approach to model design and operation provides significant benefits toward improving confidence in and acceptance of the micromodel.

1.2. PROTOCOL FOR DEVELOPING AND USING MICROMODELS

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

Proper interpretation of model results requires that model operation adhere to certain basic procedures. That is not to say that all models involve exactly the same steps to achieve calibration or to perform alternative comparisons. Indeed, there are different constraints placed on each model situation. These constraints depend upon the problem to be solved (e.g. degree of technical complexity and/or human expectations/perceptions), on the availability of prototype data, and on the availability of time/funding. A detailed description of the problem[1] begins the modeling process.

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

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

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

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

1.2.2. Failure Models and Effects Analysis. Assessment of model performance requirements (e.g. level of flexibility in similarity relationships) begins by conducting a FMEA. The FMEA begins by outlining river system and project components associated with the problem to be investigated. A design team consisting of navigation industry representatives, local sponsors, river/hydraulic engineers, biologists, project managers, and other design engineers, as appropriate, then establishes solution requirements using the components outlined for the FMEA. The design team may consist of a minimum of two members where the problem is relatively simple or as many members as necessary when the problem involves more complex problems.

The design team then assigns RPN ratings to each category.

Table 1-1 FMEA Example for Micromodel of Kate-Aubrey Reach

Components (1)	Failure Mode (2)	Effects on Other Components (3)	Effects on Whole System (4)	Detection Methods (5)	Compensating Provisions (6)
Dredging	Deposition	Minimal	Loss of Navigation Depth	Cross-section surveys	Redredge
Dike construction					
Extend existing LB dikes					
Extend existing RB dikes					
Bendway weirs					

Table 1-2 Prototype Consequences (Johnson and Brown, 2001)

		Outcomes of Failure			
Consequence Category	**Loss of Life**	**Economic Impact**	**Aquatic Habitat Impact**	**Public Scrutiny**	**Rating**
Low	None	▪ Minimal replacement cost relative to project budget ▪ Susceptibility to failure of other measures is not increased ▪ No or minor impacts to public and/or private property	No or minor short-term negative impacts in localized areas	Low	1
Marginal	None	▪ Moderate replacement cost relative to project budget ▪ Replacement of supporting or integrated enhancement measures required ▪ slight to moderate public and/or private property damage (e.g., minor roadway embankments compromised)	Moderate short-term negative impacts in localized areas	Moderate	4
High	None	▪ Moderate to high replacement cost relative to project budget ▪ Replacement of a significant portion of the project ▪ Failure of minor infrastructure, moderate to high public or private property damage	Not used to identify high impact levels	High	7
Crtitical	Possible	▪ High replacement cost relative to project budget ▪ Replacement of a significant portion of the project ▪ Failure of hydraulic or engineering infrastructure; loss of service provided by	Not used to identify critical impact levels	High	10

infrastructure and/or public utilities; high public or private property damage	

Table 1-3 Occurrence Likelihood (Johnson and Brown, 2001)

Occurrence Likelihood	Rating
Impossible or has never occurred previously	2
Remotely possible, similar events may have occurred previously	4
Possible; has previously occurred rarely	6
Probable; has previously occurred occasionally	8
Reasonably probable; has previously occurred frequently	10

Table 1-4 Detection Rating (Johnson and Brown, 2001)

Detection Methods	Rating
Simple visual from field inspection	1
Simple analysis from photo record, bank pin surveys	4
Cross-section or longitudinal surveys; sediment sampling	7
Pressure transducers or other in-situ installations required	10

Table 1-5 Variability in Prototype Parameters

Category	Variability	Rating
Bathymetry	▪ Low - minimal differences observed between successive cross-section surveys; thalweg position consistent (within 10% of channel width) between surveys	2
	▪ Medium - moderate differences observed between successive cross-section surveys; thalweg position changes less than 25% of channel width between surveys	4
	▪ High - Large differences observed between successive cross-section surveys; thalweg position changes more than 50% of channel width between surveys	8
Discharge	▪ Low - Discharge is nearly constant throughout the year	2
	▪ Medium - Discharge varies by less than a factor of four (lowest to highest); rate of change in discharge is less than 20% per day	4
	▪ High - Discharge varies widely, greater than a factor of four (lowest to highest; rate of change in	8

	discharge is greater than 20% per day	
Stage	▪ Low - Stage is nearly constant throughout the year	2
	▪ Medium - Stage varies by less than a factor of four (lowest to highest); rate of change in stage is less than five feet per day	4
	▪ High - Stage varies widely, greater than a factor of four (lowest to highest; rate of change in stage is greater than five feet per day	8

Table 1-6 Modeling Consequences

		Outcomes of Failure			
Consequence Category	**Loss of Life**	**Economic Impact**	**Aquatic Habitat Impact**	**Public Scrutiny**	**Rating**
Low	▪				
Marginal	▪				
High	▪				
Crtitical	▪				

1.2.3. Model Design.

1.2.3.1 Model layout. Appropriate Computer Aided Drafting and Design (CADD) and digital photography files are compiled once the problem location and extent are established. These files are used for layout of the model. The physical dimensions of the micromodel flume establish maximum model dimensions. The maximum dimensions of the flume are typically 76 inches long by 35.5 inches wide. The model horizontal

scale is determined by trial until the required reach fits within the flume. Consideration is also given to the minimum channel width acceptable for evaluating the particular problem under consideration. The minimum main-channel width typically used in the micro-models is about 1.5 inches. Side channels are often smaller than this minimum. However, most problems exist in the main channels and measurement of the bathymetric changes in the side channels is of lesser importance. The minimum (1.5 inches) is imposed primarily because of difficulty in measurement of changes in bathymetry that occur during alternative comparisons.

1.2.3.2 Model insert. The model template, or insert, is constructed using marked up aerial photography and CADD drawing files. The modeler establishes the channel bank lines along the channel. These lines are typically located at the vegetation line or where sufficient information exists at the true top bank location. Bank lines are modified to permit adjustment of the model's banks if bank realignment is to be considered during analysis of the stated problem(s). The modified bank may consist of either of a removable section in the insert or just a setback bank line. Setback bank lines are adjusted to the correct bank lines using modeling clay during the calibration phase of the model. The clay is modified during alternative analysis to appropriately reflect proposed changes. A reference grid is established using a coordinate system such as Universal Transverse Mercator (UTM). The UTM grid is added to the CADD file describing the model limits.

The insert is manufactured from three scaled plots of the prototype reach being modeled. These plots have bank lines and other model features such as islands, grid lines, headgates, and tailgates clearly marked. The manufacturer cuts the insert material to the specified bank lines. Insert material consists of two pieces of acrylic sheeting and a layer of high-density foam. The acrylic sheeting has two of the scaled plots laminated to their top surface. The high-density foam is laminated between the two acrylic sheets. The resulting insert has the lowest acrylic layer over the entire model extent. The foam layer and upper acrylic layers are cut to provide an open trough, or channel, in the desired location. The model channel has vertical banks, which are painted black. Black bank

surfaces help prevent extraneous data from being included in surveys from 3-D laser scanning.

1.2.3.3 Model setup. The insert is secured within the flume using silicon caulking and woodworker's clamps. Clamps are used to prevent movement of the insert during model operations.

1.2.3.4 Initial model slope. Flume tilt is initially adjusted to a slope of 0.01 feet per foot. Sediment added to the insert has a depth of approximately one-half the insert depth. A tailgate at the model exit limits bed elevations. The modeler establishes the tailgate elevation near the insert's mid-depth. The modeler adjusts flume tilt, volume of sediment, and tailgate elevation during initial calibration of the model. Structures placed in the model reflect baseline prototype conditions.

1.2.3.5 Final model slope.

1.2.3.6 Model roughness characteristics.

1.2.4. Model Operation.

1.2.4.1 Initial model calibration – constant flow operation. Model calibration begins by introducing a constant high discharge (approximately at the +15 to +20 LWRP level) to the insert. The constant discharge begins to form the bed bathymetry given the channel alignment, the amount of sediment and the flume tilt. Once bed bathymetry stabilizes, the effective slope is adjusted until the water surface is parallel to a reference plane established from three coordinate points on the insert surface. The effective slope is adjusted by changing the tilt of the flume, adding sediment to or removing sediment from the model, adjusting the tailgate assembly, or a combination of all four. **The fundamental principle of micro-modeling methodology relies on the fact that the bed slope will adjust to an equilibrium condition given a specified channel alignment, sediment size, sediment size distribution, and flow. The premise**

is that the channel will arrive at the same slope regardless of the flume tilt or volume of sediment in the flume. During adjustments to sediment volume and/or flume tilt, measures are added to provide the necessary flow distribution entering the model. Guide vanes, roughness, non-erodible material, and baffles are added as necessary to establish the correct inlet flow distribution. The constant discharge is varied higher and lower to determine appropriate limits for hydrograph cycles. Lower limits result when the flow produces the correct sediment movement in the model for lower flow conditions. Upper limits result when the flow produces the correct sediment movement in the model for higher flow conditions. Correct sediment movement depends largely on the modeler's judgement. Repetitive surveys of the model bed bathymetry measure the state of model calibration. Initial estimates of model vertical scale are made during beginning calibration efforts. Vertical scale determines the spread of the model data when converted to prototype coordinates. As such, a larger vertical scale (e.g. 1 inch = 50 feet versus 1 inch = 25 feet) increases the spread of the converted elevation coordinates. A shift factor determines the vertical offset between model reference plane (which is determined from three coordinate points on the model insert surface) and the model channel elevations. The shift reflects the relative difference between the established reference plane and the model's equivalent Low Water Reference Plane (LWRP). Adjusting the shift translates all model elevation data up or down during the conversion to prototype coordinates. The shift is measured in inches. The amount of adjustment that occurs in prototype coordinates depends on the selected vertical scale. Continual refinements to the shift and vertical scale continue until the model calibration data approximates the prototype data. The actual measure of how well the model data reproduces the prototype data depends on the modeler's interpretation, but is generally evaluated on how the converted model data reproduce prototype survey conditions both in general elevation and location. The effects of shift and vertical selection are best explained through example.

EXAMPLE:

_____ Model Reference Surface
_____ Model Equivalent LWRP location
Maximum model survey elevation: -1.5 inch (relative to reference plane)
Minimum model survey elevation: -2.5 inch (relative to reference plane)

The vertical distance between the model reference plane and the equivalent LWRP is estimated to be 1 inch and the vertical scale is estimated to be 1 inch = 100 feet. This translates into an adjustment of 100 feet in the vertical when the model survey data is converted to prototype coordinates. Using the shift of 1 inch and a vertical scale of 1 inch = 50 feet translates into an adjustment of 50 feet in the vertical when converting to prototype coordinates. Changing the shift to 0.5-inch results in an adjustment of 50 feet with the 1 inch = 100 feet vertical scale and only 25 feet using the 1 inch = 50 feet vertical scale. Likewise, adjusting model survey data with the 1 inch = 100 feet vertical scale would produce a spread of 100 feet vertically in prototype coordinates while the 1 inch = 50 feet vertical scale would only produce a spread of 50 feet.

1.2.4.2 Initial model calibration - unsteady flow operation. Unsteady operation involves operating a control valve in either a triangular or sinusoidal mode. The triangular mode operates the valve to provide a stepped valve opening sequence that results in a linear opening/closing rate between the minimum and maximum settings. The sinusoidal mode operates the valve to provide a stepped valve opening sequence that results in a sine curve opening/closing sequence. Flow does not directly influence how the valve is operated; e.g. a model hydrograph is not truly a flow hydrograph it is a valve opening sequence. In other words, valve opening establishes the flow rate. Recent utilization of flow meters provides a display of flow through the hydrograph cycle; however, valve stepping governs cycle operations at present. Cyclic model operation provides a mechanism for simulating the effects of the hydrograph cycle in the prototype. Use of the triangle cycle option provides a near sine wave response in flow to the model. The sine cycle option provides a pseudo sine wave response in flow (produces a sine shaped curve with extended peak flow periods). Refinement of the maximum and minimum limits of flow occurs during model calibration. Finalization of the shift and vertical scale generally occurs during unsteady flow operations. After final shift and vertical scales are determined, water surface elevations are checked with constant discharges. The water surface elevations are checked at low and high flow limits to determine the prototype stage conditions being modeled. Current procedures typically

limit maximum model flows to produce a +15 or +20 LWRP in the prototype. Typical minimum model flows tend toward 0 LWRP or slightly lower. The upper flow bound results because operation of the models over larger limits causes non-uniform distortion of the energy grade line in the model. The higher flows produce much higher energy in the micro-model and tend to cause excessive sediment movement. Entrance and exit conditions are modified slightly if necessary to improve the model's ability to reproduce the prototype surveys. Addition of non-erodible materials to the model is considered when model conditions can not reproduce very unusual prototype conditions. Follow-up field reconnaissance lends support to use of such non-erodible materials. The non-homogeneous nature of depositional features within channels results in many unusual scour and depositional trends in the prototype. Prototype structures are reset to the appropriate elevations using the finalized shift and vertical scale.

1.2.4.3 Final model calibration. The model is operated for several hydrographs to verify that the bed forms are in equilibrium. The definition of equilibrium generally refers to a state where the bed sediments move in a uniform manner throughout the cycle of operation. No sediment waves appear in the model at equilibrium. Evaluation of the equilibrium condition depends on the modeler to some degree. Structure elevations and positions are checked and verified. The modeler surveys the model bathymetry and converts the model data to prototype coordinates. Plots of the model bathymetry over the model reach are compared to prototype surveys. General trends (e.g. deeper areas, thalweg location, shallower areas, and crossing locations) are compared to the prototype surveys.

Operation of the model through several iterations of the above cycle, flow hydrograph through comparison of surveys, provides a reasonable assurance that model results are repetitive and that the model is indeed at a point of equilibrium. Consistency between repetitive model surveys and their comparison to prototype surveys govern when model baseline conditions have been attained. Development of the baseline conditions is paramount to successfully completing the remainder of model study efforts.

1.2.5. Flow Visualization. Flow visualization in the model attempts to identify velocity streamlines of surface flow conditions. Where prototype data are available, flow visualization provides a positive reassurance that flow conditions in the micro-model resemble prototype flow conditions. Prototype data consist of aerial photography containing ice-flows or possible float data obtained through surface velocity and path measurements. Often, this data is lacking or is difficult to obtain, particularly in warmer climatic regions. Flow visualization utilizes timed photography to record the paths of "floaters" or surface confetti. Floaters actually float on the surface of the model and closely track the flow path. Surface velocities in the model are not estimated from the timed photography at present. Flow visualization provides a means to compare model surface flow paths to the prototype flow paths and serves as a mechanism for comparing flow paths resulting from alternative designs back to the baseline model. Timed photography utilizes a constant flow rate for each series of photographs. Photography obtained at various flow rates provides a method for verifying and comparing model flow conditions at different points in the hydrograph cycle.

1.2.6. Alternatives. Alternative analysis begins after establishment of model baseline, or calibrated, conditions. 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. The model is operated through several repetitive hydrograph cycles with the proposed structures in place. The actual number of hydrograph cycles depends on the relative magnitude of the changes induced by the alternative structures. Slight changes resulting from minor structural elements may require less time for the model to restabilize the bed. More drastic changes due to more extensive structural elements may require increased operation times before the model restabilizes the bed. Bed restabilization occurs when the model bathymetry obtains a new equilibrium condition. The new equilibrium condition results when bed material transport remains relatively consistent over several hydrograph cycles and when no sediment waves are observed in the model. Again, modeler judgement determines when the model attains the desired equilibrium. A survey of model bathymetry is taken

of the resulting equilibrium condition. Conversion of the model bathymetry to prototype coordinates facilitates comparison of each alternative condition to the baseline model condition.

Each alternative condition is prepared and operated as outlined above. Surveys for each alternative are in-turn compared to the baseline model condition. Consultation with technical customers continues throughout the evaluation of alternative designs. Each successive alternative design incorporates information gained from previous alternatives. Often add-on alternatives result from discussions with the client. These additional alternatives attempt to balance projected prototype response with desired engineering and environmental desires.

1.2.7. Report. A comprehensive report documents micromodel study efforts and findings. Each report follows a specified structure and format. Each report documents the pertinent background of the study reach and clearly identifies the problems and objectives for the study. Individuals supplying information, data, or basic knowledge about the reach are acknowledged. Micro-model extent, horizontal and vertical scales and a distortion ratio are documented. The final vertical scale and selected horizontal scale determine the distortion ratio (which is the ratio of the horizontal scale to the vertical scale). The type of sediment material used in the model is also documented. Alternative designs are described in sufficient detail for proceeding to the next level of design. The next design level involves proposing structural modifications recommended by the micro-model study to a review panel for discussion and approval. Design then proceeds by developing a plan of implementation. Construction may be phased over several construction seasons, depending on the magnitude of changes proposed and potential prototype response.

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

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

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

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

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

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

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

1.1.2. Consequences of Distortions. Ettema (2000) further describes scale effects that result from the relaxation of four common characteristic parameters: increased length scale, vertical distortion, inflated bed sediment size, and exaggerated slope. Ettema provides calculated examples exemplifying the effect of reduced lengths (with no distortion in the vertical dimension, e.g. x_r=y_r) on Reynolds and Weber numbers (viscous

and surface tension effects, respectively). Ettema asserts that reduced lengths alter local flow patterns and pressure gradients around simulated hydraulic structures, along the river bed, and along the river banks.

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

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

As an example, consider the influence of flow width, B, on a channel having a trapezoidal cross-section (Figure 1). If the width-depth ratio, B/y, of the channel is very

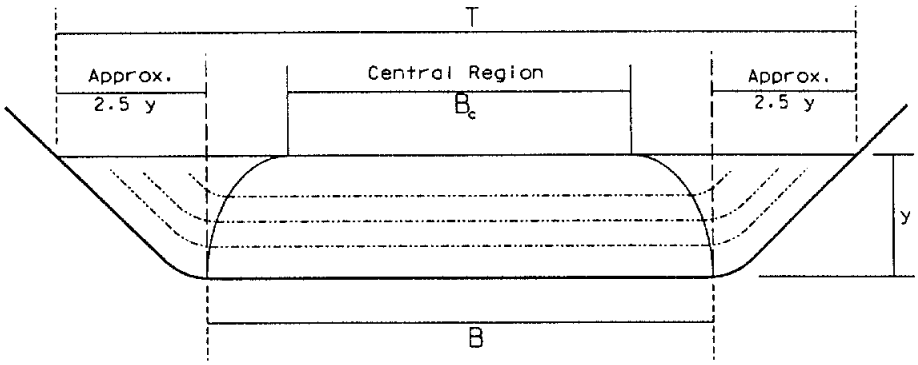

Figure 1. Regions within a Wide Channel

large, then the functional relationship A in the central region of such a flow can be regarded as independent of B/y. Thus, if only the flow properties in the central region are of interest, the requirement that

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

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

Vertical distortion results from selecting different scales for B and y. Large rivers typically have large width to depth ratios (three digits). As such, they behave as wide channels making it possible to consider them in basic two-dimensional terms. For wide channels, the central region depicted in Figure 1 exists. Where B/y is small, B/y < 5 to 10 (Chow, 1959), the wide channel assumption fails, and the channel behaves in a more three-dimensional manner. Circulation in channels with small B/y ratios is stronger as evidenced by observations in the laboratory and in small streams. Yalin (1992) discusses the long-standing debate regarding the relevance of cross-circulation. In this light, Yalin states the following conclusion: "it is not whether but when the cross-circulation is relevant (or prominent) - what is right for small B/y may turn out not to be so when B/y is large." The unknown factor in this case is when does cross-circulation (in the micromodel channels) become relevant. The answer to this lies in comparison of model results to prototype data. Without the confirmation of model velocity patterns (surface flow patterns), interpretation of model results seems speculative and the transfer of model results to the prototype is suspect.

Determining just how far the scales can be relaxed is an all important part of understanding loose-bed model design and operation. Continuing the B/y example leads to the discovery that under given circumstances the central region exists for B>5y (Kuelegan, 1938). Chow (1959) recommends a more restrictive condition where the ratio of B/y is greater than 5 to 10, B > 5y - 10y. Either case permits a degree of flexibility in

selecting scales. However, certain bounds are implied. In loose-bed modeling, the modeler often fixes the degree of relaxation by selection of the vertical scale. In previous model approaches, vertical scale is selected during the initial model design. However, selection of vertical scale in the micromodeling approach occurs during the calibration phase.

A priori selection of model vertical scale yields the advantage of assessing similarity criteria during model design. Accordingly, the Froude criterion provides an estimate of model discharges. Channel bathymetry serves to define gross sediment transport similitude, but similarity in sediment particle mobility is of secondary importance in the sixteen large-scale models considered. Local adjustment of model slope occurs by adjusting reference elevations (the model "rail" used to survey the model). A disadvantage of selecting vertical scale prior to operating the model results from the lack of

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

Slope distortion also occurs as a result of other distortions. Basing approximate similarity on sediment transport, which is a fundamental procedure for most physical sediment modeling, implies a similarity of u_{*c}/u_{*o}. Because u_* is a function of slope, a distortion in slope is essentially the same as vertical distortion with similar scale effects.

Kahn (1970) and Schuum and Kahn (1972) present a relationship between sinuosity and slope that indicates than when slope is increased, sinuosity increases up to a maximum then decreases. Therefore, distortion of slope in a model will likely affect the model's ability to faithfully reproduce sinuosity. Increased slope in the model tends to increase momentum effects through altered velocities. The increased momentum of the flow may offer mitigating effects in the tendency for increased sinuosity according to the Kahn (1970) and Schuum and Kahn (1972) data.

Gaines (2002) summarizes several non-dimensional parameters and relationships that define sets of similarity conditions. These parameters and relationships describe flow and sediment motion in physical sediment models. Establishing a procedure whereby the possible relaxations in similitude criteria are systematically considered in a quantitative manner requires consideration of the inherent variability in prototype conditions. Indeed, similarity relationships mean little if the parameter being "simulated" is not understood in its full context. For example, there is a well known phenomena in rivers whereby a looped rating curve occurs; the so called hysterisis effect. Because all flow field and sediment transport similarity parameters (and processes) depend upon discharge, similarity must be viewed as variable; it too is a variable function that changes with time and location (Glazik, 1984, Gujar, 1981, and Gessler, 1977). As a result, similarity can be considered a risk problem. In this context varying levels of similarity relaxation are possible, with each level based upon the acceptable deviations allowable for the particular problem being modeled.

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

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