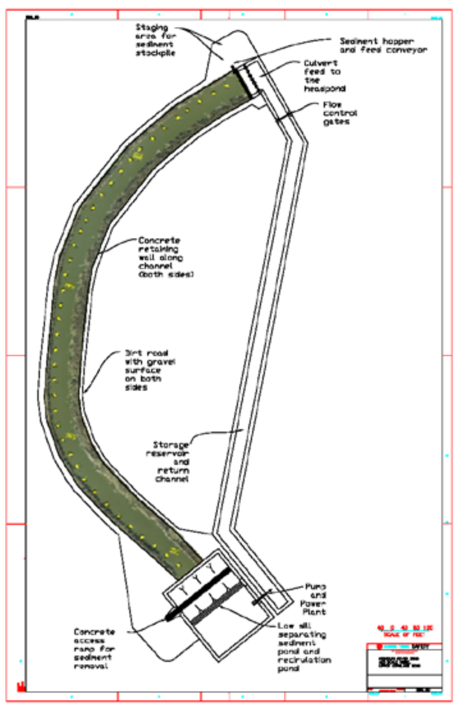
RECLAMATION
Managing Water in the West

Hydraulic Laboratory Report HL-2010-05

Physical Hydraulic Model Proposal for US Army Corps of Engineers Missouri River Bend Model



U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

August 2011

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
15-10-2010	Technical	From Sep 10, 2009 To Oct 15, 2010

4. TITLE AND SUBTITLE Physical Hydraulic Model Proposal for US Army Corps of Engineers Missouri River Bend Model	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Mefford, Brent Gill, Tom	**5d. PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Bureau of Reclamation Hydraulic Investigations and Laboratory Services Group 86-68460 Denver Federal Center PO Box 25007, Denver CO 80225	**8. PERFORMING ORGANIZATION REPORT NUMBER** HL-2010-05
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) US Army Corps of Engineers Omaha District 1616 Capital Avenue Omaha NE 68102	**10. SPONSOR/MONITOR'S ACRONYM(S)** USACE **11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Available from National Technical Information Service, Operations Division, 5285 Port Royal Road, Springfield, Virginia, 22161 http://www.ntis.gov

13. SUPPLEMENTARY NOTES

14. ABSTRACT
A feasibility study has been completed for a scale physical hydraulic model study to examine potential means of creating shallow water habitat along selected stream bends along the Missouri River in the reach between Sioux City, IA and Rullo, NE. As part of the feasibility study, model design and operating concepts have been developed along with a pre-appraisal-level cost estimate. An appropriate scale identified for the model study would dictate an outdoor location to meet space requirements and would require a surrogate sediment material (coal) to achieve sediment scaling criteria.

15. SUBJECT TERMS
Shallow water habitat, scale physical hydraulic model, moveable bed model navigation channel, sediment scaling

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Robert F. Einhellig
a. EPORT	**b. ABSTRACT**	**a. THIS PAGE**			**19b. TELEPHONE NUMBER** *(Include area code)*
UL	UL	UL	SAR	86	303-445-2142

Hydraulic Laboratory Report HL-2010-05

Physical Hydraulic Model Proposal for US Army Corps of Engineers Missouri River Bend Model

Prepared: Brent Mefford, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services Group, 86-68460

Tom Gill

Prepared: Tom Gill, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services Group, 86-68460

Robert F. Einhellig

Technical Approval: Robert F. Einhellig, P.E.
Manager, Hydraulic Investigations and Laboratory Services Group, 86-68460

Tony L. Wahl

Peer Review: Tony Wahl, P.E.
Hydraulic Engineer, Hydraulic Investigations and Laboratory Services Group, 86-68460

11/22/2010
Date

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Hydraulic Investigations and Laboratory Services Group
Denver, Colorado

August 2011

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Acknowledgments

Acknowledge contributors to the work who are not authors of the report.

Hydraulic Laboratory Reports

The Hydraulic Laboratory Report series is produced by the Bureau of Reclamation's Hydraulic Investigations and Laboratory Services Group (Mail Code 86-68460), PO Box 25007, Denver, Colorado 80225-0007. At the time of publication, this report was also made available online at **http://www.usbr.gov/pmts/hydraulics_lab/pubs/HL-2010-05**.

Disclaimer

The information provided in this report is believed to be appropriate and accurate for the specific purposes described herein, but users bear all responsibility for exercising sound engineering judgment in its application, especially to situations different from those studied. References to commercial products do not imply endorsement by the Bureau of Reclamation and may not be used for advertising or promotional purposes.

Cover Photo: provide credit for cover photo (optional)

Provide any desired statement regarding source of funding

CONTENTS

TABLES

FIGURES

APPENDICES

Background

In mid 2009, the US Army Corps of Engineers Omaha District (COE) asked the Hydraulic Investigations and Laboratory Services Group of the US Bureau of Reclamation (Reclamation) to consider whether they had the capabilities and resources to conduct a large scale physical hydraulic model study of one or more selected reaches of the Missouri River. From preliminary information supplied, Reclamation engineers determined that physical space and flow rate requirements for the desired model scale would exceed in-house capabilities of the hydraulics laboratory facility in Denver, Colorado. Reclamation agreed to perform a preliminary feasibility study to examine potential for performing the model study at an external location. Sites to be considered would include irrigation district facilities and possibly laboratory facilities of other entities. This proposal documents the findings from Reclamation's feasibility study.

Introduction

COE is currently working to increase the acreage of shallow water habitat along reaches of the Missouri River while concurrently maintaining navigational channel requirements. The COE Omaha District is undertaking a shallow water habitat enhancement effort along the Missouri between Sioux City, IA (river mile 734), and Rulo NE (river mile 498). COE objectives for the proposed physical hydraulic model study include evaluation of alternative conditions to maximize shallow water habitat (SWH), and to serve as a visual aid/display tool to demonstrate proposed modifications to stakeholders prior to in-stream construction work.

A "kick-off" meeting for this feasibility study was held September 10, 2009 at Reclamation's Technical Service Center in Denver. [A list of meeting attendees is included in Appendix A of this document.] The kickoff meeting was opened with a presentation by COE of a broad overview of previous COE activities involving in-channel modifications to enhance navigation capability. More recently, developing and sustaining SWH along the river has been added as a project objective.

A Biological Opinion calls for the establishment of 20 to 30 acres of shallow water habitat per river mile from Sioux City to the convergence with the Mississippi, and the COE channel modifications are seeking to meet that objective. A physical model would be utilized to examine creation of the needed additional SWH by widening the river top width an additional 300 to 400 feet at selected locations. A desired function of the model would be to evaluate different SWH restoration schemes, including the performance of various types of flow control and sediment control structures. The physical model would be an additional tool used in collaboration with numerical models and field investigations to guide best practices for SWH restoration along the river.

Model Study Objectives:

Model study objectives as identified by COE are summarized as follows:

- Model existing channel conditions.
- Model alternative channel conditions.
- Evaluate SWH creation for various alternatives.
- Evaluate impacts on authorized project purposes (navigation, flood control, bank stabilization, etc.)
- Sediment transport for existing and alternative conditions.
- Use model in conjunction with prototype data and 2D model.
- Display tool for non-Corps agencies, partners, etc.

Of these, the primary objectives / issues are:

1) Evaluate project impact on sediment transport through the bend

2) Provide a visual aid for a display tool

COE-Provided Model Parameters:

- The initially identified segment of the Missouri to potentially be modeled is known as the Lower Little Sioux Bend approximately 2.3 river miles in length.
- The suggest range of flows to be modeled varies from a 90% August exceedance flow of 28,000 ft^3/s to as high as 80,000 ft^3/s. [The 10 year event is approximately 92,000 ft^3/s.]
- Average Channel Width = 600 feet
- SWH to be created by channel width widening = 400 feet. maximum widening
- SWH habitat areas of interest will be 0-5 ft flow depth
- Rock structures will be used to maintain the navigation channel depth and location along the outside of the bend and induce sediment deposition to create SWH in dike field

- Alternative stretches of the river subsequently identified by COE to possibly be modeled in lieu of the Lower Little Sioux Bend are “upper” and “lower” bends of the Copeland reach.
- The Copeland upper site is located at RM 568.8-565.2 (3.6 RM)
- The Copeland lower site is located at RM 565-562.5 (2.5 RM)

Preliminary Model Scaling Considerations:

COE has expressed a desire for the scale to be kept as large as feasible to maintain the maximum visual sense of similitude possible for use of the model as a visual display tool. Issues in achieving realistic similitude in sediment transport rapidly become insurmountable problems as model size is diminished. At the same time, the scope of prototype conditions being simulated causes the model to rapidly approach limits of space and discharge availability as scale is increased. Using these general guidelines, model geometric scales of 1:12, 1:14 and 1:15 were considered in the physical modeling feasibility analysis.

Hydraulic Analysis:

Hydraulic modeling parameters were examined with the objectives of correlating sediment transport initiation, sediment transport rate, and channel bed-forms to the degree possible between prototype and model. For a general overview, the upper Copeland bend – posing the largest space requirements of the river reaches under consideration for the model study – was used for prototype parameters. The following channel length, width and major hydraulic limits were assumed for all scales investigated. The model channel slopes were selected based on sediment transport modeling and are discussed under that topic.

Table 1 - Model Scaling Summary

	Prototype	Model Scale		
		1:12	1:14	1:15
Width, ft	1200	100	85.71	80
Length, ft	21,000	1750	1500	1400
Max Q, ft^3/s	80,000	160.38	109.09	91.8
Max depth, ft	37	3.08	2.64	2.47
Min depth, ft	2	0.17	0.14	0.13
Slope	0.00022	0.00052	0.00054	0.00056

For the purposes of the model, SWH was assumed to pertain largely to flow depths from 2 ft to 5 ft. The primary limiting condition on depth is flow turbulence as indicated by Reynolds Number (*Re*). Generally the scale of river models are selected to provide flow *Re* larger than 5000. This is a general rule of thumb that accounts for the fact that the demarcation between viscous and turbulent flow is often uncertain and flow conditions in a river can vary widely. Locally, some flow conditions with Reynolds Numbers as low as 2000 may be acceptable. Using a 2 ft depth as a lower bound was chosen as the likely limit of physical modeling for the range of model scales investigated. Figures 1 (1:12 scale), 2 (1:14 scale) and 3 (1:15 scale) give model *Re* as a function of prototype and model flow velocity and flow depth. The areas shown in brown correspond to flow conditions (depth and velocity) with *Re* greater than 5000. The flow conditions corresponding to areas shown in light purple indicate *Re* in the model would be between 5000 and 2000. These flow conditions will likely provide reasonable similarity between model and prototype; however, these flow conditions should be limited in scope. Flow conditions yielding *Re* shown in green would not be expected to provide good similarity of flow conditions.

Sediment Modeling:

The proposed model would consist of moveable bed material overlying stabilized boundaries. Stable boundaries would be located to enable deposition and/or reasonable amounts of scour to occur at locations of interest. Designing the model to provide good similarity of sediment movement is required. Sediment transport in the prototype occurs as both suspended load and bed load. Suspended load is very fine grain material that can remain in suspension for long periods. Suspended load would be very difficult to accurately model in a physical model of the size studied. There was no attempt to include modeling of suspended load in this investigation and all references to sediment modeling herein refer to modeling of bed load. The Missouri River at Copeland Bend carries large amounts of bed load with a D_{30}, D_{50} and D_{94} of about 0.3 mm, 0.4 mm and 2.0 mm, respectively. The bed load is assumed to be largely non-cohesive sand. Modeling bed load transport is based on providing similarity between prototype and model for several key parameters, including particle fall velocity, dimensionless shear and channel roughness (surface roughness and bed form). At the Reclamation Hydraulics Laboratory, sediment modeling has developed as a practice combining theory, judgment and field verification. A method for modeling sediment originally developed by Dodge (1983) using work by Taylor and Vanoni (1975), Einstein (1954), Gessler (1971) and others is used at the Bureau of Reclamation (BOR) Hydraulics lab. A full discussion of sediment modeling is not presented herein. A recent publication by Gill and Pugh (2009) is attached as a reference, [Appendix B], describing in greater detail the aspects of this method of sediment modeling.

Sediment modeling often requires distortion of model parameters to be introduced to improve model-prototype similarity. Imparting distortion to a model implies one or more dimensions may have more than one scale relationship applied to them. This is often the case in sediment models because particle behavior can change as a function of grain size. The fall velocity of sediment particles greater than about 1 mm will follow a relationship proportional to approximately the square root of the grain diameter. Material smaller than about 0.2 mm will settle approximately proportional to the grain diameter squared. Strict Froude scaling of fall velocity only applies when both prototype and model material lie fully above 1 mm or below 0.2 mm. Scaling of non-cohesive material is also limited to model particle sizes greater than about 0.1 mm. Smaller size material can take on cohesive properties that alter sediment transport behavior. Achieving acceptable similarity of particle fall velocity and particle transport behavior often requires distortion of model particle density and size. Selection of model particle density is generally governed by available materials. Coal, some plastics and natural fiber materials with specific gravity values greater than one can be used. Coal was selected for this project because of its density is approximately one half that of granitic sand and it is available in large quantities.

Sediment modeling also requires similarity of intensity of transport and intensity of shear. The work of Taylor suggests similarity is possible when the prototype/model ratio of the difference between Shields parameter (dimensionless shear) and the critical shields parameter is equal. Figures 4, 5 and 6 give plots of dimensionless shear for each model scale investigated. Prototype data points shown represent values of the Shields parameter for a range of hydraulic radius values from 1.5 to 30. Model data points are the result of adjusting model particle size, sediment density and model slope to obtain model values of the Shields parameter that lie on a curve parallel to the critical Shields curve in common with prototype data. This method is referred to herein as the Shields parameter offset method. Model data is calculated using prototype hydraulic radius values scaled by Froude law. A single value of model slope and particle density is applied to each scale. Gessler (1971) using the relationship for friction factor, $f=(8gdS/V^2)$, shows the slope ratio (prototype/model) is equal to the ratio of friction factors. In this study, model slope distortion was determined using an iterative approach. A trial model slope was selected for evaluation of grain size using the Shields parameter and particle fall velocity. These values were then used to calculate model friction factor and the prototype /model friction factor ratio. Therefore, the present study assumed no significant bed forms in the friction factor calculations. This assumption should be refined with further analysis to include bed form resistance. Model slopes are presented in Table 1 for the three scales investigated. Achieving similarity of channel friction between prototype and model was determined to require distortion of the model slope by a factor of about 2.4.

Similarity may not be possible for all grain sizes and therefore judgment must be used to determine where deviating from similarity is acceptable. For example, good similarity of fall velocity for large particles may not be required if the particles are not likely to be suspended or settling times are small in both prototype and model. Table 2 presents the grain size distributions determined for each model scale based on similarity of particle fall velocity and sediment transport using the Shields parameter offset method. Grain size distribution for each model scale is shown graphically in figures 7,8 and 9.

Table 2 – Comparison of Prototype and Model Sediment Size Gradation

		Model Scale		
Bed Material	Prototype	1:12	1:14	1:15
dia., mm	Sand	Coal	Coal	Coal
D_{10}	0.23	0.23	0.21	0.2
D_{30}	0.32	0.4	0.37	0.35
D_{50}	0.43	0.49	0.46	0.44
D_{65}	0.49	0.53	0.5	0.49
D_{85}	0.82	0.98	0.87	0.85

Figures 4-6 also show predicted bed form based on Chabert and Chauvin (1963) as published in Simon and Sentürk (1976). Similarity of bed form type between prototype and model is likely where both prototype and model conditions fall in similar bed form zones. A different approach proposed by A. Mercer and published in Shen (1971) using V^*/w, (V^*=shear velocity, w= particle fall velocity) and wd/v, (d=particle grain size, v =fluid viscosity) is given in figure 10. Both methods were found to give similar results for ripple and dune bed forms.

Following selection of the model slope, grain size distribution and sediment material, a check of sediment modeling can be made using dimensional analysis as proposed by H. Einstein (1954). Einstein showed that similarity of sediment transport intensity can be described by the relationship of the following dimensionless ratios being equal to 1.

$$qB_r*(\rho_s-\rho_f)^{-3/2}{}_r*D^{-3/2}{}_r=1 \qquad \text{Equation 1.}$$

where; qB_r=ratio of bed load transport per unit width, $(\rho_s-\rho_f)^{-3/2}{}_r$ =density ratio and $D^{-3/2}{}_r$=grain size ratio (subscript r refers to the ratio of prototype to model, s denotes sediment and f denotes fluid).

The unit bed load transport is calculated based on the Meyer-Peter and Mueller transport equation for non-cohesive material. Einstein further proposed that similarity of shear intensity can be described by the following relation of dimensionless ratios;

$$(\rho_{s-}\rho_f)_r * D_r * S^{-1}_{r*} \eta^{-1}_{r} = 1 \qquad \text{Equation 2.}$$

where; S = energy slope and η = ratio of hydraulic radius due to grain roughness to that of the total section.

The hydraulic radius of the total section defined as η requires similarity of hydraulic radius with respect to channel irregularities including bed forms. Numerous researchers have published lab data, field data and predictive algorithms describing the part of hydraulic radius attributed to bed forms, Engelund(1966), Sentürk(1977), White(1981), Yang (2008). A review of this research indicates considerable uncertainty remains in predicting bed form resistance independent of field data. Prediction of the resistance of ripples appears to contain less uncertainty than that of dunes. This may be due to lower variability in the length to height ratio of the bed form. In the present study, the hydraulic radius attributed to the bed for ripple bed forms was determined based on Sentürk (1976). Applying Sentürk's method as well as other methods for dune bed forms was found to provide widely varying results. Therefore in the study, estimates of bed resistance for dune bed forms were based on field data from the Missouri River near Omaha, NE presented by Einstein and Barbarossa (1952). This is a topic that is likely worth additional investigation and discussion prior to final model design.

Tables 3 to 5 give the predicted distortion of sediment modeling parameters for each model scale. Values presented for intensity of transport and shear were calculated based on Einstein's dimensional analysis approach following grain size selection using fall velocity and the Shields parameter offset method. Perfect similarity would be indicated by a value of 1 in each case.

Table 3- Predicted Model Distortion of Sediment Scaling Properties, 1:12 Scale

Grain dia., mm % passing	Grain Fall Vel. ft/s	Shields Parameter Offset (Sp-Spcr)p/(Sp-Spcr)m	Intensity of Transport	Intensity of Shear riffle bed*	dune bed *
10	0.85	1.08	1.35	0.90	1.90
30	1.04	1.04	1.38	0.89	1.87
50	1.08	0.98	1.27	0.94	1.99
65	1.04	0.95	1.10	1.02	2.17
84	1.39	1.01	1.27	0.94	1.99
95	1.73	1.10	1.38	0.89	1.87
				* Rb based on Senturk using 2.5 ft/s channel velocity	* Rb taken from Missouri River Data presented by Einstein

Table 4- Model Distortion of Sediment Scaling Properties, 1:14 Scale

Grain dia., mm % passing	Grain Fall Vel. ft/s	Shields Parameter Offset (Sp-Spcr)p/(Sp-Spcr)m	Intensity of Transport	Intensity of Shear riffle bed*	dune bed *
10	0.56	0.93	1.09	1.17	3.03
30	0.94	1.06	1.43	0.98	2.52
50	0.98	0.99	1.30	1.04	2.69
65	0.97	0.98	1.16	1.12	2.90
84	1.22	0.93	1.17	1.12	2.88
95	1.57	0.89	1.17	1.12	2.88
				* Rb based on Senturk using 2.5 ft/s channel velocity	* Rb taken from Missouri River Data presented by Einstein

Table 5- Model Distortion of Sediment Scaling Properties, 1:14 Scale

Grain dia., mm % passing	Grain Fall Vel. ft/s	Shields Parameter Offset $(Sp-Sp_{cr})_p/(Sp-Sp_{cr})_m$	Intensity of Transport	Intensity of Shear riffle bed*	Intensity of Shear dune bed *
10	0.66	1.06	1.34	1.06	2.99
30	0.91	1.07	1.46	1.00	2.82
50	1.01	1.05	1.41	1.03	2.88
65	0.92	0.97	1.14	1.17	3.29
84	1.27	0.99	1.27	1.10	3.09
95	1.63	0.96	1.27	1.10	3.09
				* R_b based on Senturk using 2.5 ft/s channel velocity	* R_b taken from Missouri River Data presented by Einstein

Sediment load and sediment transport time must also be distorted to achieve similarity. For an undistorted model, bed load per unit width can be shown to scale by $L^{3/2}$, where L is the length scale. Imposing distortion of sediment density and grain size also requires distortion of sediment load. Scaling of bed load was evaluated for each model scale using the Meyer-Peter Mueller bed load equation, Gessler (1971). Load scale ratios were calculated using

$$Bl_{p/m} = \{(\frac{\tau - \tau_c}{(\gamma_s - \gamma)k})^{3/2}\}_{p/m}\{(\gamma_s - \gamma)^{3/2}\}_{p/m}\{k^{3/2}\}_{p/m} \qquad \text{Equation 3.}$$

where *Bl* = bed load scale for bed load per unit time and width and *k* =grain size. The subscript *p/m* indicates the ratio of prototype to model.

The sediment time scales presented for the three model scales were derived based on Einstein(1954) and Gessler(1971). The time scale related to modeling total sediment load was shown by Einstein using dimensional analysis to be

$$T_r = L_r d_r \left(\rho_s - \rho_f\right)_r / Bl_r \qquad \text{Equation 4.}$$

where *L*= length, *d*=depth and *T*=time

Substituting the Meyer-Peter Mueller equation for bed load, Gessler presents the time scale ratio for cohesionless material as

$$T_r = l^2{}_r \left[\left(\frac{\tau - \tau_c}{(\gamma_s - \gamma)k}\right)^{-3/2}\right]_r \left(\gamma_s - \gamma\right)^{-1/2}{}_r\, k^{-3/2}{}_r \qquad \text{Equation 5.}$$

Table 6 presents model scales for sedimentation processes. The scale values varied by about 10 percent over the range of hydraulic radius and grain size investigated. An average of the values is reported. Bed load measurements provided by COE for the Missouri River near Nebraska City are shown in Table 7 with the corresponding rates computed for each of the geometric model scales. Computations are based on an assumed river width of 700 ft. Model sediment requirements were determined by extracting a typical flow hydrograph using the USGS Nebraska City gauging station. Probability of high flow occurrence and duration are given in figures 11 and 12. This data was used to select a typical hydrograph for evaluating sediment load and length of model tests for each geometric scale. The hydrograph was scaled to model and then model load rates applied. Figure 13 gives the selected prototype hydrograph and sediment load. Figures 14 to 16 give scaled hydrograph and sediment load values for 1:12, 1:14 and 1:15 scale models, respectively.

Table 6 - Model Distortion of Sediment Scaling Properties, 1:14 Scale

	Geometric Model Scale		
Sedimentation Scale	1:12	1:14	1:15
Bed load per unit width	13.1	16.2	17.6
Time (sediment transport)	73.3	82.3	86.2

Table 7 - Prototype Bed Load Rates in Model Scale

Prototype		Geometric Model Scale		
River Discharge	Bed Load	1:12	1:14	1:15
ft^3/s	tons/hr/ft	Model Bed Load, tons/hr/ft		
20000	1.69	0.15	0.12	0.11
40000	4.85	0.42	0.35	0.33
50000	6.81	0.59	0.49	0.46
60000	8.98	0.78	0.64	0.61
80000	13.90	1.21	0.99	0.94

		Velocity, ft/s					
		prototype	1.09	1.46	2.19	4.38	6.56
		model	0.32	0.42	0.63	1.26	1.89
Depth, ft	prototype	model	Re #				
	2.00	0.17	3759	5012	7518	15035	22553
	2.50	0.21	4698	6265	9397	18794	28191
	3.30	0.28	6202	8269	12404	24808	37212
	5.00	0.42	9397	12529	18794	37588	56382
	10.00	0.83	18794	25059	37588	75176	112764
	15.00	1.25	28191	37588	56382	112764	169146
	17.50	1.46	32889	43853	65779	131558	197337
	20.00	1.67	37588	50117	75176	150352	225527
	30.00	2.50	56382	75176	112764	225527	338291

Viscosity Effects
Possible Viscosity Effect
No Viscosity Effect

Figure 1 - Model Reynolds Numbers 1:12 Scale

		Velocity, ft/s					
		prototype	1.09	1.46	2.19	4.38	6.56
		model	0.29	0.39	0.58	1.17	1.75
Depth, ft	prototype	model	Re #				
	2.00	0.14	2983	3977	5966	11931	17897
	2.50	0.18	3729	4971	7457	14914	22371
	3.30	0.24	4922	6562	9843	19687	29530
	5.00	0.36	7457	9943	14914	29828	44742
	10.00	0.71	14914	19886	29828	59657	89485
	15.00	1.07	22371	29828	44742	89485	134227
	17.50	1.25	26100	34800	52199	104399	156598
	20.00	1.43	29828	39771	59657	119313	178970
	30.00	2.14	44742	59657	89485	178970	268454

Viscosity Effects
Possible Viscosity Effect
No Viscosity Effect

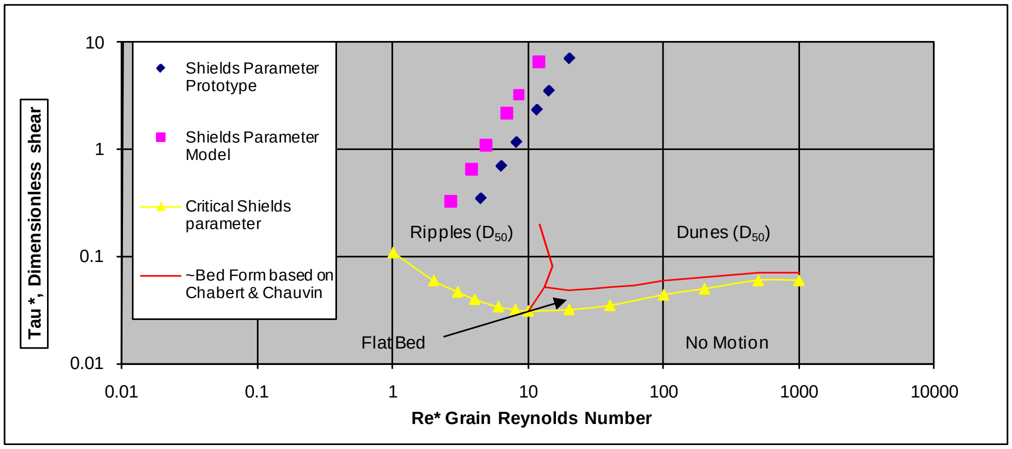
Figure 2 - Model Reynolds Numbers 1:14 Scale

		Velocity, ft/s					
		prototype	1.09	1.46	2.19	4.38	6.56
		model	0.28	0.38	0.56	1.13	1.69
Depth, ft	prototype	model	Re #				
	2.00	0.13	2690	3586	5379	10758	16137
	2.50	0.17	3362	4483	6724	13448	20172
	3.30	0.22	4438	5917	8876	17751	26627
	5.00	0.33	6724	8965	13448	26896	40344
	10.00	0.67	13448	17930	26896	53791	80687
	15.00	1.00	20172	26896	40344	80687	121031
	17.50	1.17	23534	31378	47068	94135	141203
	20.00	1.33	26896	35861	53791	107583	161374
	30.00	2.00	40344	53791	80687	161374	242061

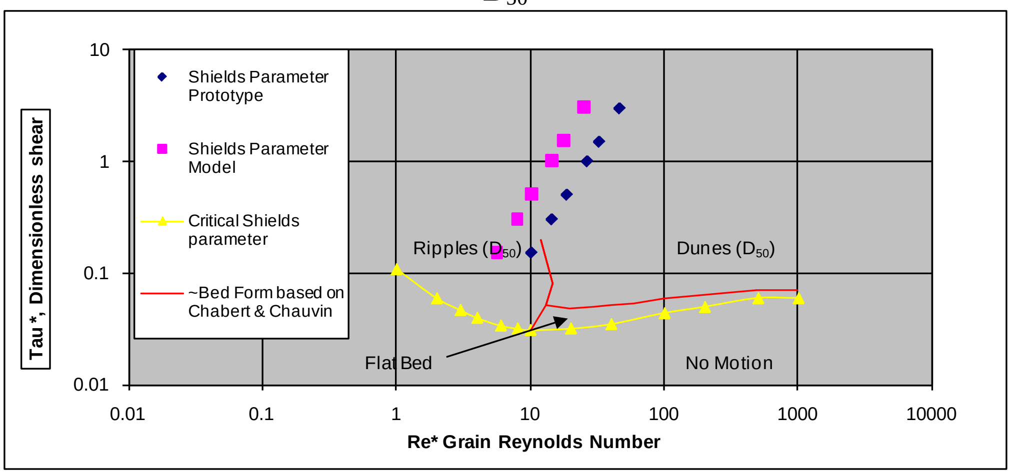
Viscosity Effects
Possible Viscosity Effect
No Viscosity Effect

Figure 3 - Model Reynolds Numbers 1:15 Scale

D_{10}



D_{50}



D_{85}

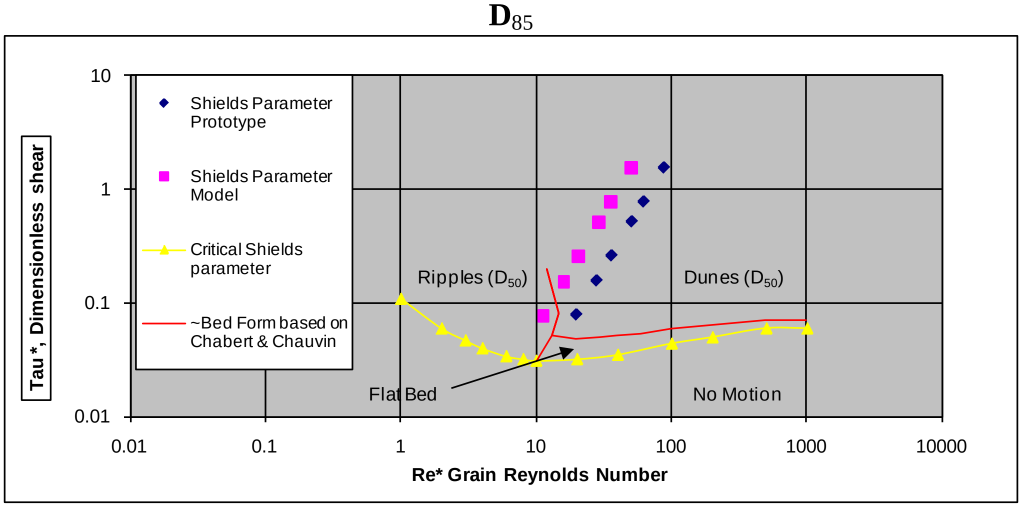
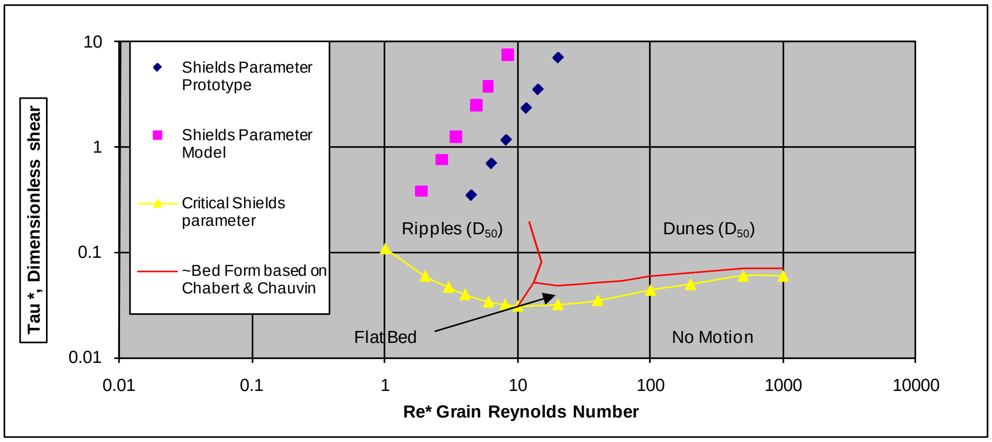


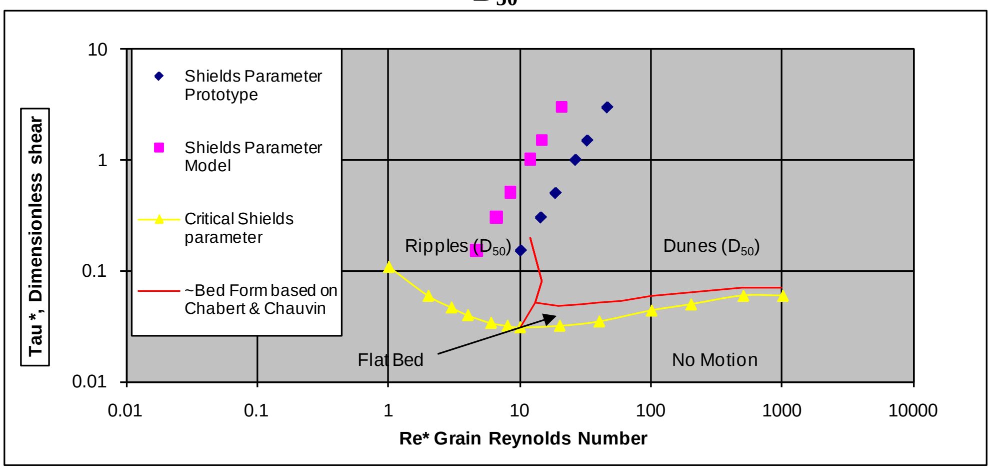
Figure 4 – Grain Reynolds Number vs. Dimensionless Shear, 1:12 Model Scale

Plot showing prototype and model values of Shields parameter over a range of hydraulic radius values from 1.5 to 30.

D_{10}



D_{50}



D_{85}

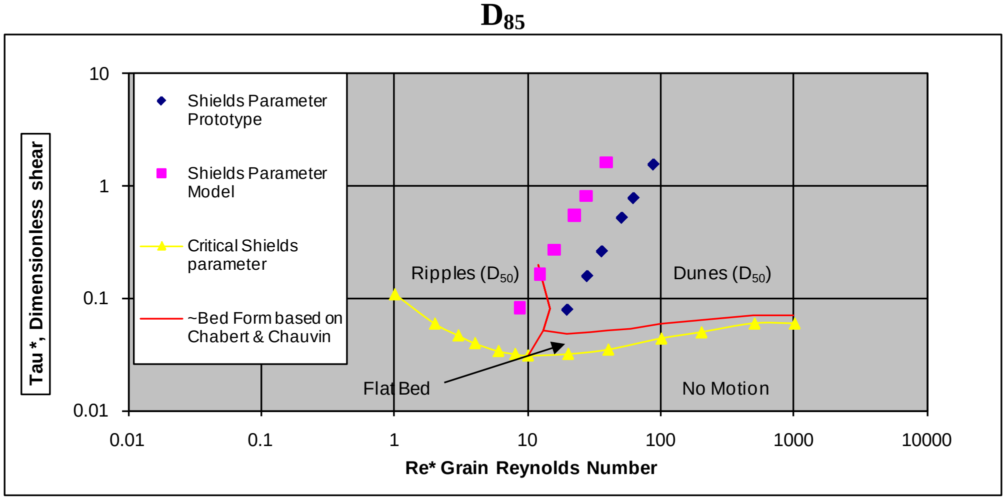
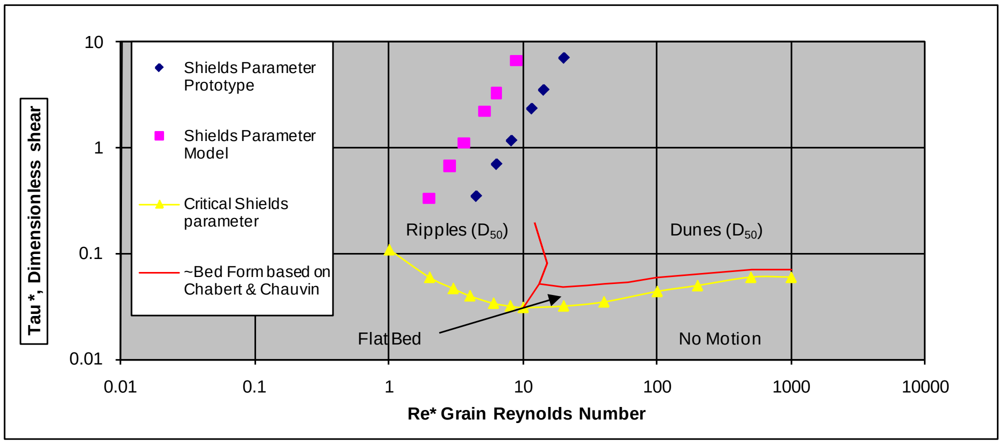


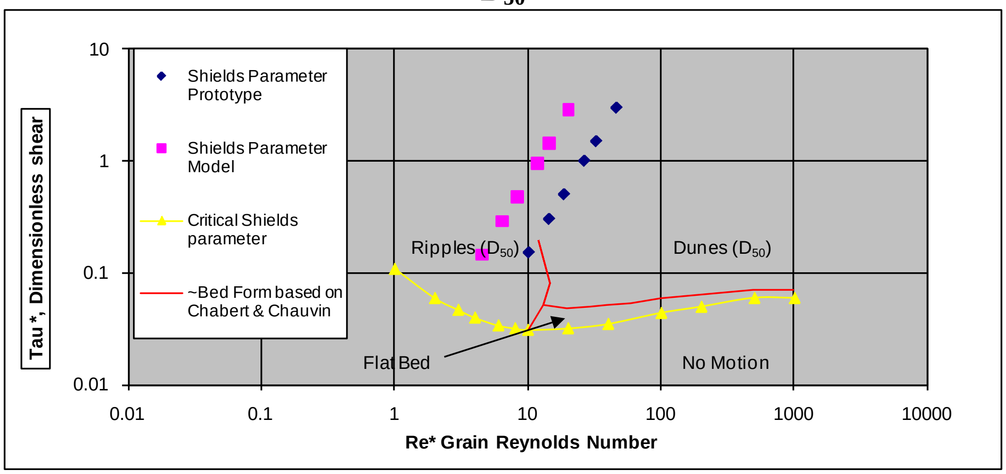
Figure 5 - Grain Reynolds Number vs. Dimensionless Shear, 1:14 Model Scale

Plot showing prototype and model values of Shields parameter over a range of hydraulic radius values from 1.5 to 30.

D_{10}



D_{50}



D_{85}

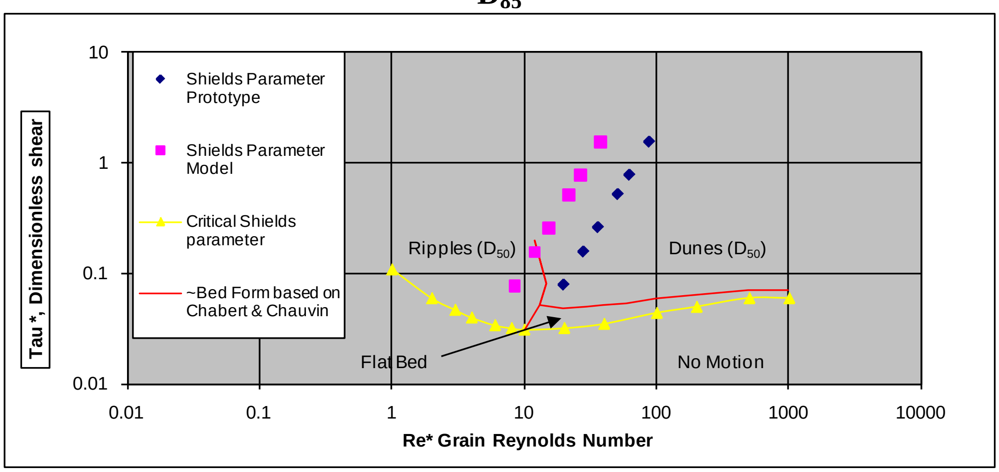


Figure 6 - Grain Reynolds Number vs. Dimensionless Shear, 1:15 Model Scale

Plots showing prototype and model values of Shields parameter for a range of hydraulic radius values from 1.5 to 30.

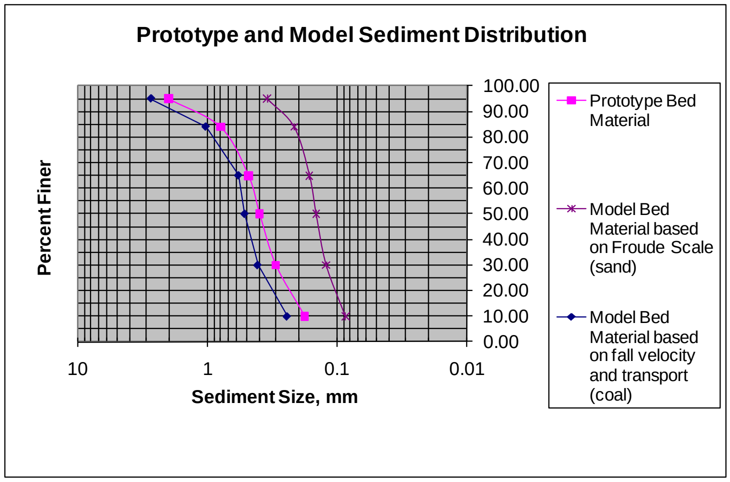


Figure 7 - Grain size distribution for 1:12 scale model

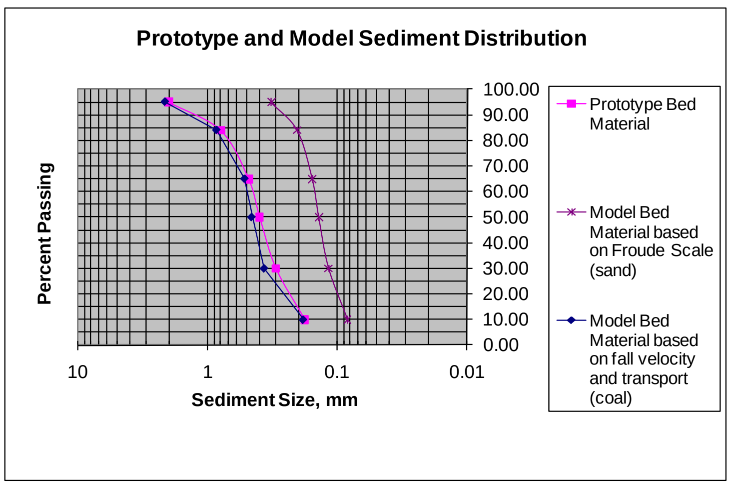


Figure 8 - Grain size distribution for 1:14 scale model

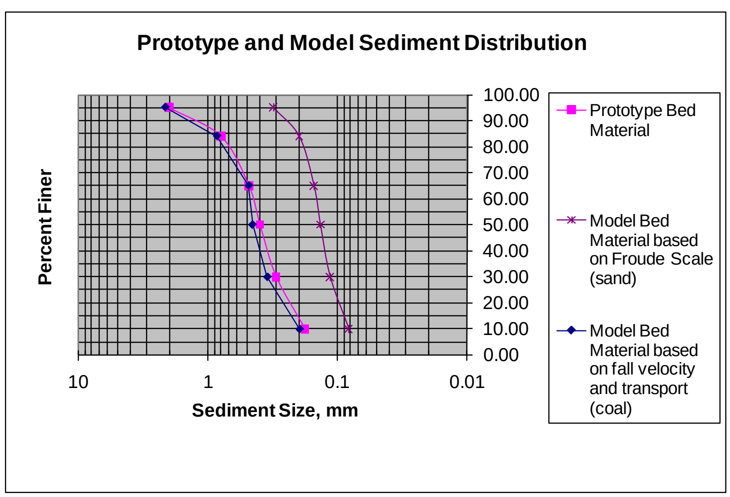


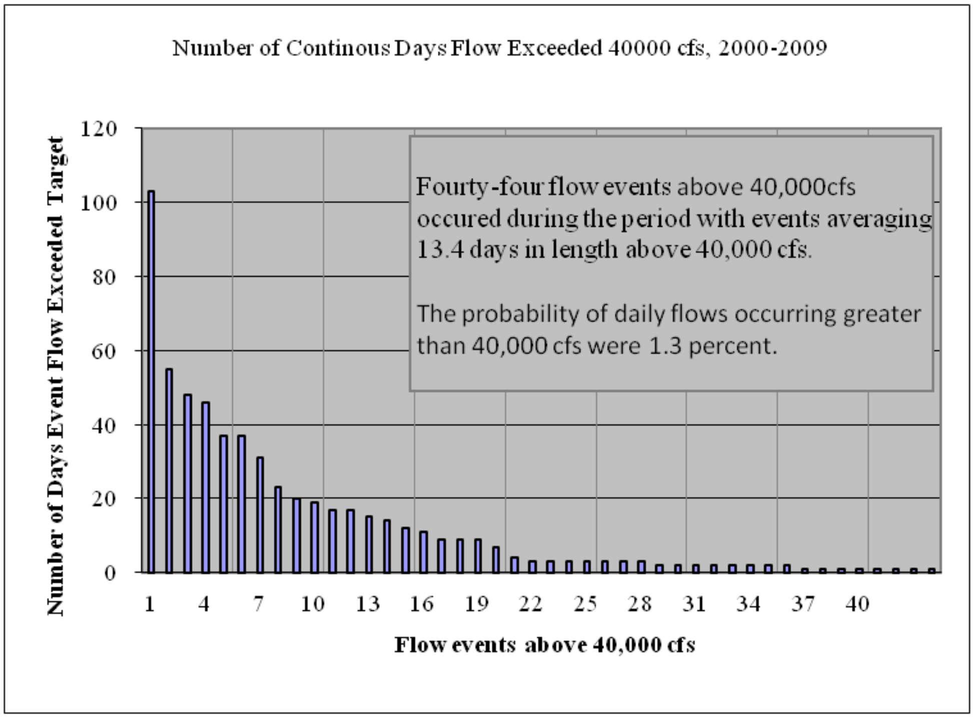
Figure 9 - Grain size distribution for 1:15 scale model

Prototype			1:12 Scale Model			
Hyd Rad, R (proto)	1.5	3	5	10	15	30
	Ripple	Ripple	Dune	Dune	Dune	Dune
Model						
Hyd Rad, R (model)	0.13	0.25	0.42	0.83	1.25	2.50
	Ripple	Ripple	Ripple	Ripple	Dune	Dune

Prototype			1:14 Scale Model			
Hyd Rad, R (proto)	1.5	3	5	10	15	30
	Ripple	Ripple	Dune	Dune	Dune	Dune
Model						
Hyd Rad, R (model)	0.11	0.21	0.36	0.71	1.07	2.14
	Ripple	Ripple	Ripple	Ripple	Dune	Dune

Prototype			1:15 Scale Model			
Hyd Rad, R (proto)	1.5	3	5	10	15	30
	Ripple	Ripple	Dune	Dune	Dune	Dune
Model						
Hyd Rad, R (model)	0.10	0.20	0.33	0.67	1.00	2.00
	Ripple	Ripple	Ripple	Ripple	Dune	Dune

Figure 10 - Prediction of Prototype and Model Bed Form Types for a Given Hydraulic Radius Based on A. Mercer and Presented by Shen et.al (1971).



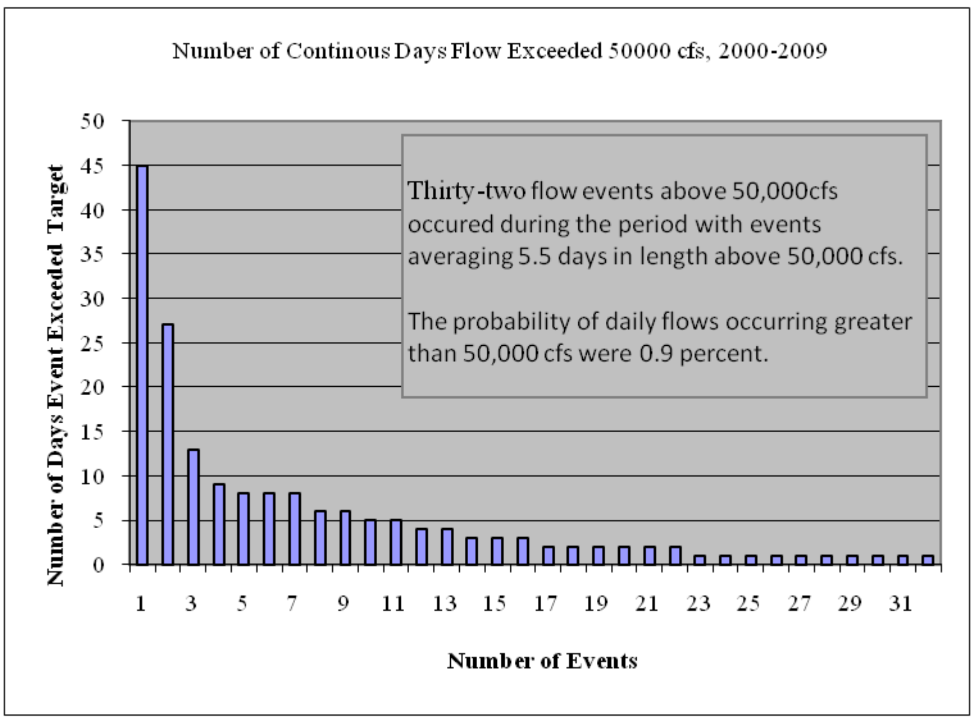
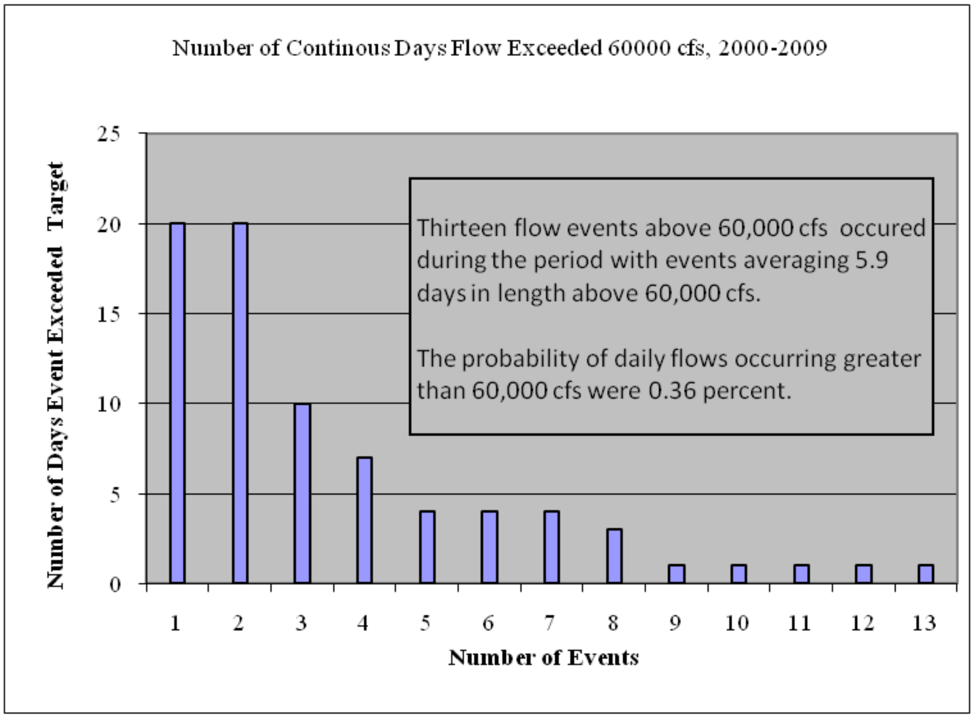


Figure 11 - Probability of Flow Occurrence and Duration for the Missouri River at Nebraska City, 2000 - 2009



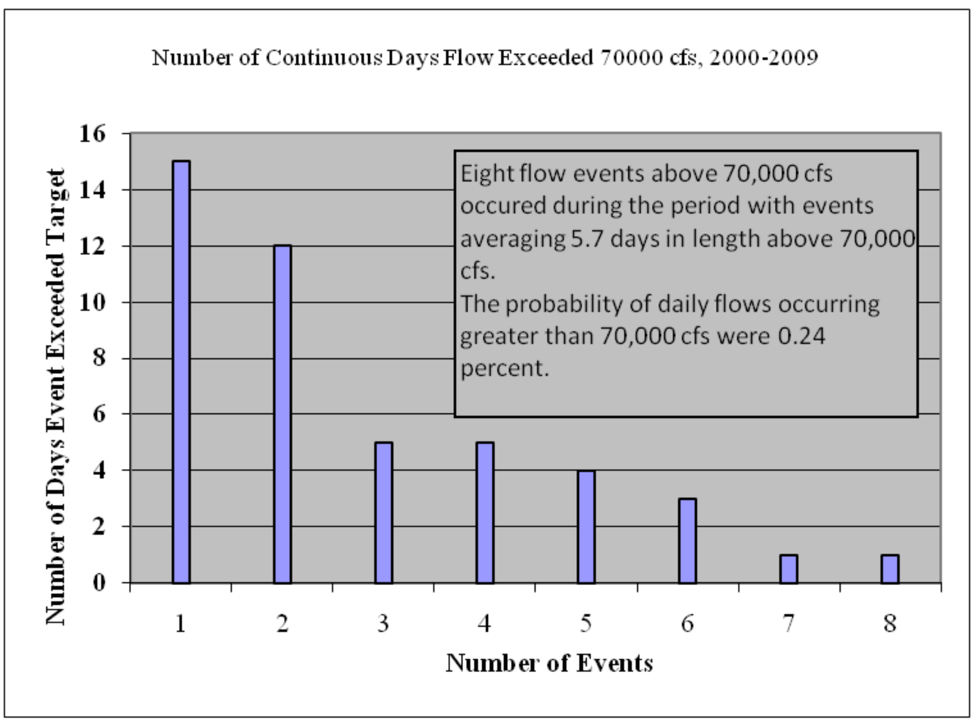


Figure 12 - (continued) – Probability of flow occurrence and duration for the Missouri River at Nebraska City, 2000 - 2009

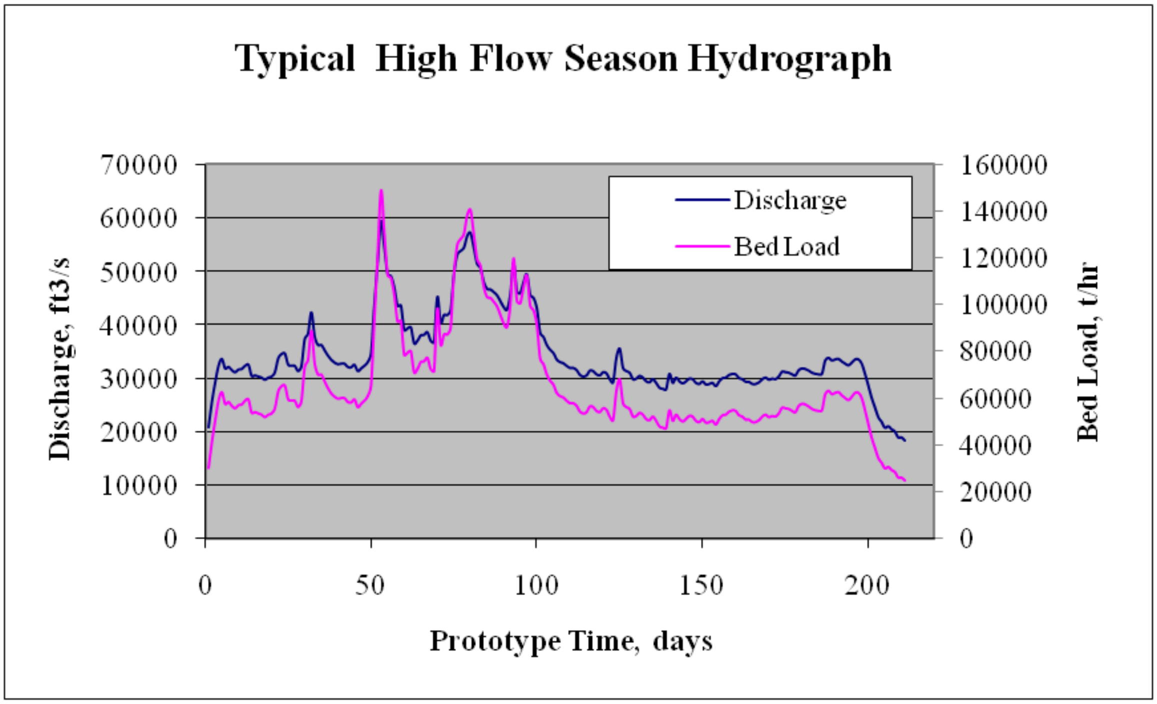


Figure 13 - Missouri River Flow and Bed Load Measurements from Nebraska City, Nebraska.

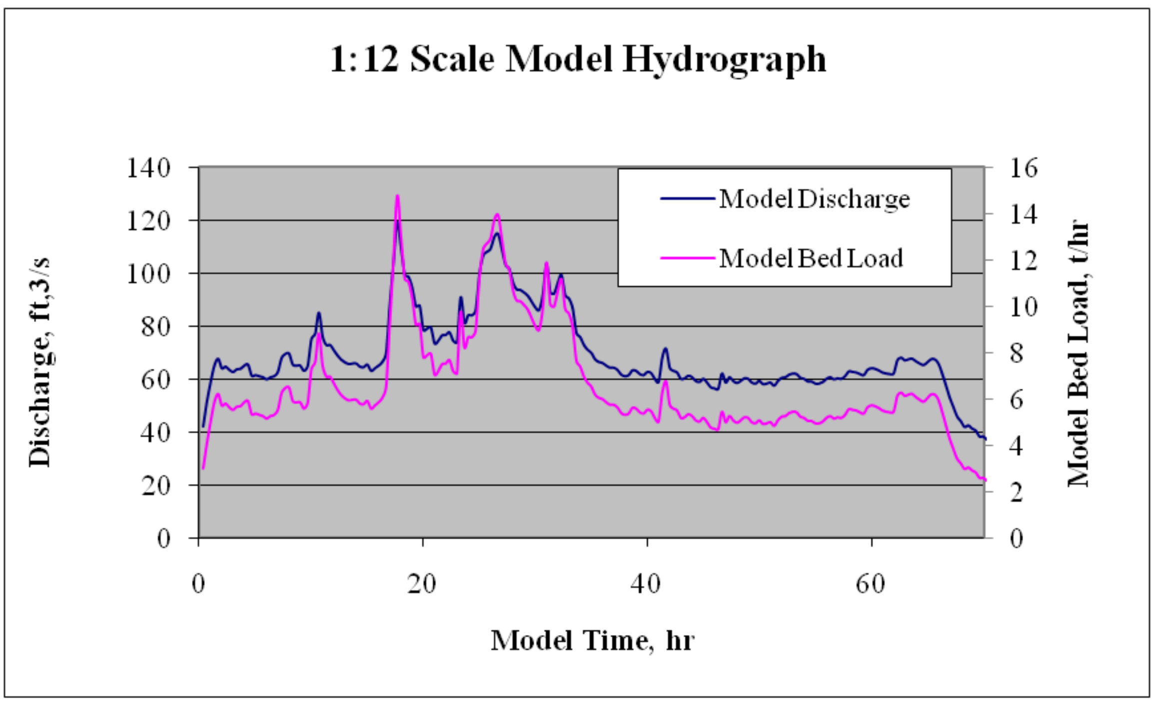


Figure 14 - Missouri River Flow and Bed Load Values Given in Figure 12 Scaled to a 1:12 Model.

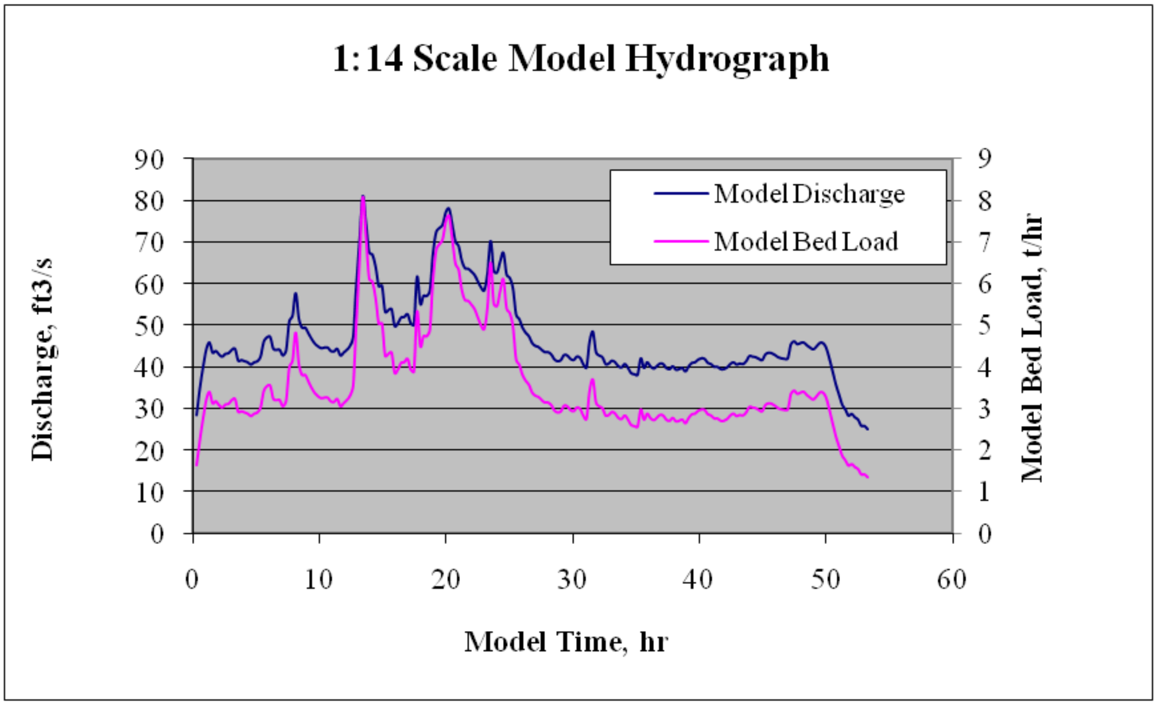


Figure 15 - Missouri River Flow and Bed Load Values Given in Figure 12 scaled to a 1:14 Model.

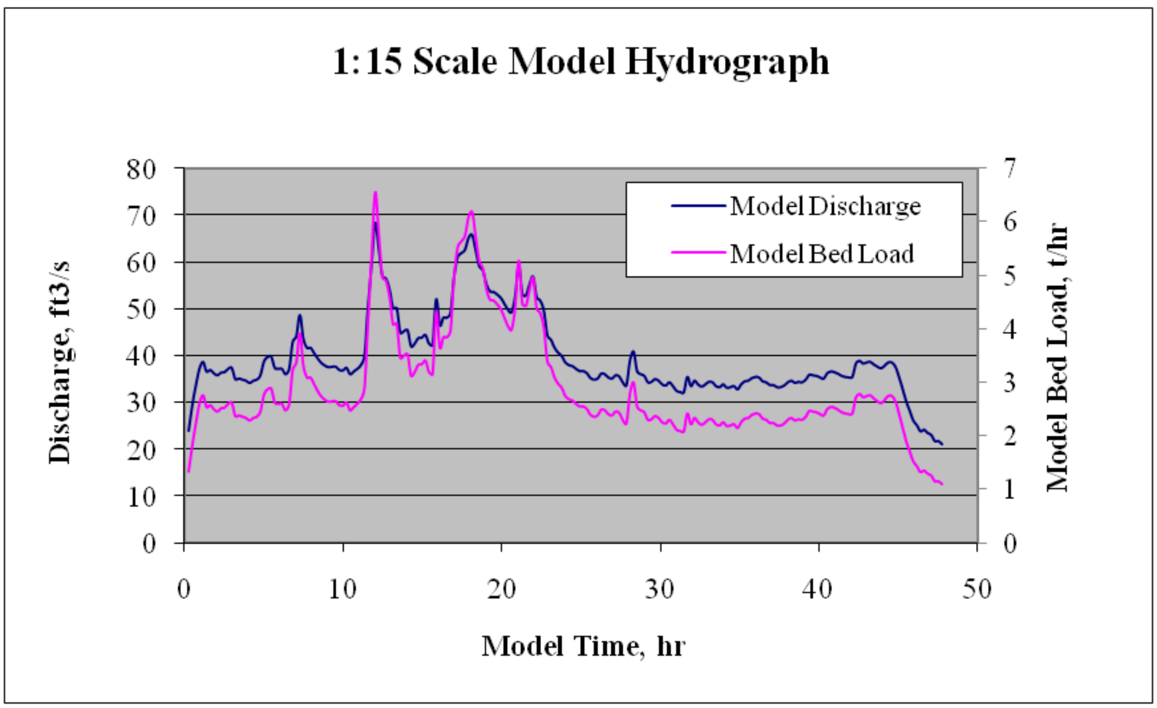


Figure 16 - Missouri River Flow and Bed Load Values Given in Figure 12 scaled to a 1:15 Model.

Site Considerations:

To minimize operational costs of the model, sites were initially sought that could provide gravity-driven flow through the model. A preliminary investigation into sites offering gravity flow resulted in three possible sites for the model which are described following this section for benefit of the reader, although these sites are not recommended. The need to introduce large amounts of coal as sediment and then restrict its exit from the model area along with operational flexibility requirements made all gravity flow sites problematic. Therefore, it was concluded that the design of a recirculation system was likely the best approach. Pumped recirculation greatly expands the number of potential model sites and operational flexibility. Key desirable factors now become a site with reasonably flat land in proximity to a suitable water source that could be used for initial filling of the model basin and periodic replenishment of water lost through evaporation and seepage. A preliminary design and pre-appraisal level cost estimate of a 1:15 scale recirculation model was developed. A schematic of a model facility is shown in figure 17. Designs and costs were only developed for a 1:15 scale model as it represents the lowest cost option.

Recirculation Model Option:

The model layout shown in figure 17 is similar to smaller hydraulic models built by Reclamation's Hydraulics Laboratory. The model shown consists of a test channel with headpond upstream, a tailwater pond serving as a combination settling pond and pump sump downstream and a combination return channel and storage reservoir connecting headpond and tailwater pond. The preliminary design of the model channel has concrete walls forming the channel borders. The headpond, tailwater pond and return channel would be earthen excavation with earthen embankments. All water conveyance structures are lined with a flexible membrane with soil cover to limit seepage losses. A gravel flow diffuser is used between the headpond and the test channel to still the flow. Sediment is fed into the model downstream of the flow diffuser using conventional conveyor/hopper systems used in sand processing. Tailwater elevation is controlled at the downstream end of the channel using a slatted baffle system combined with a small undershot gate for automated fine stage control. The return channel has sufficient volume to hold all model water prior to and following a test. A regulating gate structure providing flow measurement and flow control is shown separating the headpond and return channel. Water is pumped from the tailwater sump into the return channel using a low-head-high-volume axial flow pump with either electric or diesel power. For the present level of design we assumed sediment would be removed from and returned to the stock pile area by front loader following a test. A concrete access pad is shown in the tailwater settling basin for this purpose. The channel topography could be formed by several methods. For the cost estimate we assumed it was formed using local soils treated with a high quality soil binder to add stability. Although we believe this would work well for a model of this size, limited testing of this procedure would be required prior to model construction. We estimate a recirculation model of the Upper Copeland Bend would require a site size of between 25 and 40 acres.

Data collection on a large model is challenging. In this report we discuss the major instrumentation needed for the model study. We have many other ideas for access and measurement that are not sufficiently developed to include at this point in the study. The model would contain automation of the flow control gates located in the return channel and the tailwater control system. Water surface elevation would be measured using small span acoustic water level sensors similar to devices used in our lab. A number of these water level sensors would be spaced permanently along the model at set intervals and in the head and tailwater ponds. Others would be used in temporary locations for specific tests. Data from all water surface, flow measurement and sediment feed instrumentation would be collected using a computer based data acquisition system. It is our understanding that much of the site specific data requirements would be in the SWH zones and therefore located in areas relatively near the banks. Portable suspended work platforms should allow work access to these areas during model operation. It may also be possible that an instrumentation platform could be designed that would span the width of the model. This idea was briefly investigated for the 1:15 scale model and requires further study. In addition to work platforms, a number of cable lines would be stretched across the channel to allow use of instrumentation designed for remote measurements like boat mounted shallow water Acoustic Doppler Current Profilers and Acoustic Doppler Velocity meters. Following a model run, the topography of the model can be measured using either ground based LIDAR or near-field photogrammetry. Both methods have been used in our laboratory and give excellent results for large models.

Physical Modeling Project Cost Estimate:

A pre-appraisal level cost estimate has been developed for a 1:15 scale recirculating model. This cost estimate is presented on pages 22-25 of this report. As much detail as possible for a pre-appraisal design was included in the estimate. Recent cost estimates for similar work that has been produced by Reclamation's estimating group were utilized as guidelines in generation of the pre-appraisal level estimates provided in this document. The pre-appraisal values shown in this report have not been reviewed by the Reclamation estimating staff.

A location for the recirculation model was not specified for the cost estimate. We did assume the model would be located within roughly 50 miles of a mid-sized city. The initial construction cost of the model is estimated to be about $3.5 million dollars. The annual operating cost including staff and materials during testing is estimated to be $1 million. The total project cost is estimated at $7.5 million, assuming one year of construction followed by four years of testing. Additional years of testing could be added as needed.

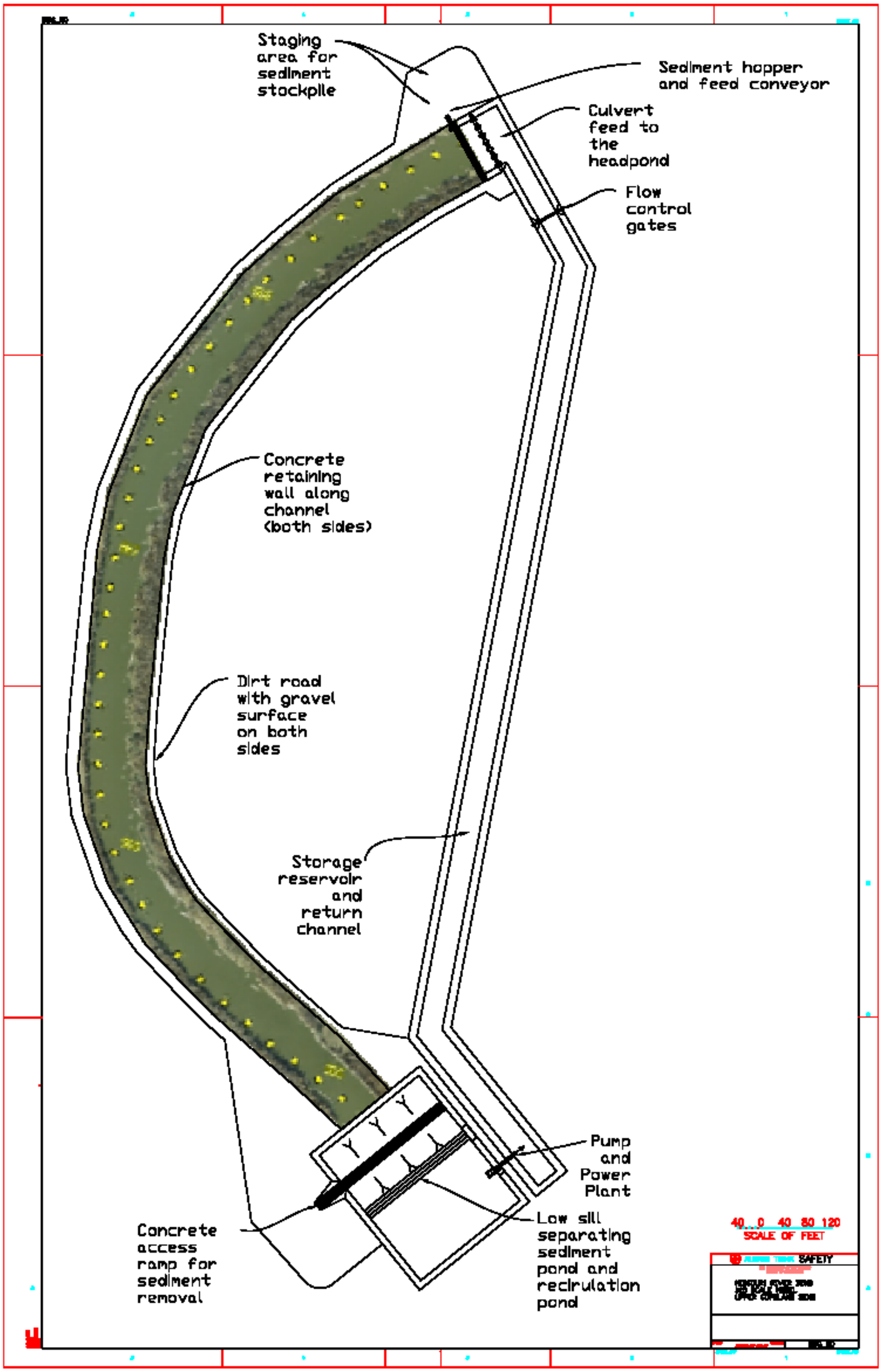


Figure 17 - Plan View of 1:15 Scale Recirculation Model of Upper Copeland Bend on the Missouri River.

Cost estimate sheets for 1:15 scale recirculation model.

CODE: D-8450

ESTIMATE WORKSHEET

SHEET 1 OF 4

FEATURE:	PROJECT:
Pre-Appraisal Level Cost Estimate Pumped Flow Option Test Facility	Missouri River Hydraulic Model
	REGION:
WOID:	FILE:

PLAN ACCT.	PAY ITEM	DESCRIPTION		CODE	QUANTITY	UNIT	UNIT PRICE	AMOUNT
	1	Excavate and stockpile test channel material			10,400	yd^3	$8.00	$83,200
		(Excavated channel 2.5' deep x 80' wide x 1400' long)						
	2	F&I Concrete walls along channel						
		(0.67' wide x 3' high with footer or large interlocking block construction)			700	yd^3	$800.00	$560,000
		(full length of channel with a low wall across ends)						
	3	F&I Liner			12,500	yd^2	$4.00	$50,000
		(Firestone BEPD Rubber "Pondguard" or 40mil PVC)						
	4	Head pond excavation						
		(80' wide x 30' long x 4' deep)			360	yd^3	$8.00	$2,900
	5	F&I Head pond liner			380	yd^2	$4.50	$1,700
		(Firestone BEPD Rubber "Pondguard" or 40mil PVC)						
	6	F&I Head pond flow diffuser						
		(80' long gravel baffle 4.5 ft high x 0.5' thick)			360	ft^2	$15.00	$5,400
		(steel frame with wire face and gravel fill)						
	7	Tailwater pond excavation			7,200	yd^3	$8.00	$57,600
		(Assumes tailwater pool holds all water when						
		model is shut down)						
	8	F&I Tailwater pond liner			4,000	yd^2	$4.50	$18,000
	-	(Firestone BEPD Rubber "Pondguard" or 40mil PVC)	-	-	-	-		
	9	Axial Flow Pump			1	ea	$165,000.00	$165,000
		(100 ft^3/s at 10ft lift)						
		MWI HAC336 Hydraflo with diesel power plant						
	10	F&I Pump sump			11	yd^3	$800.00	$8,800
		(concrete sump 5'x10'x5')						
	11	Land (5 year lease)			25	ac	$2,000.00	$50,000
		2200 ft x 500 ft plot						
	12	F&I gravel surfacing			500.00	yd^3	$100.00	$50,000
	13	Flow meter	(acoustic)		1.00	ea	$5,000.00	$5,000
					Subtotal			$1,077,600

QUANTITIES		PRICES	
BY BWM	CHECKED BY BWM	CHECKED	
DATE PREPARED February 24, 2009	APPROVED DATE	PRICE LEVEL Pre-Appraisal	

CODE: D-8460

ESTIMATE WORKSHEET

SHEET 2 OF 4

FEATURE:	PROJECT:
Pre-Appraisal Level Cost Estimate Pumped Flow Option Test Facility	Missouri River Hydraulic Model
	REGION:
WOID:	FILE:

PLAN ACCT	PAY ITEM		DESCRIPTION	CODE	QUANTITY	UNIT	UNIT PRICE	AMOUNT
	14	F&I Return Channel						
		(trapezoid 2:1 ss, 26 ft bottom width, 5 ft deep)						
			Compacted Fill (2' berms)		2,900	yd^3	$12.00	$35,000
			Excavation (3')		4,400	yd^3	$8.00	$35,000
			Liner		6,000	yd^2	$4.50	$27,000
	15	F&I Tailwater control structure			80	ft	$30.00	$2,400
	15	Crushed Coal			1,000	ton	$90.00	$90,000
		(2 millimeter minus material)						
		(coal @$15/ton, crushing@$20/ton, $50/ton transportation)						
	16	F&I Coal conveyor and feed hopper			1	ea	$125,000	$125,000
		(used or multiyear lease)						
	17	Water control structure (return channel)			1	ls	$75,000	$75,000
	18	Compacted backfill			4,000	yd^3	$12.00	$48,000
		(site dependent construction quantity, estimate based on channel invert area)						
	19	F&I Concrete drive (flat work with wire)			60	yd^3	$450	$27,000
	20	Power to site			1	ls	$25,000	$25,000
		(assumes power is nearby, two poles and line)						
	21	Instrumentation						
			Acoustic water level sensors		20	ea	$350	$7,000
			Acoustic Doppler velocity meter		2	ea	$8,000	$16,000
			Shallow water Acoustic Doppler Profiler		1	ea	$7,000	$7,000
	22	Near-field photogrammetry camera			1	ea	$5,000	$5,000
	-	(bed contouring)	-	-	-	-		
	23	Construction/office trailer			1	ls	$15,000	$15,000
	-	(12'x 35')* varies with location lease or purchase	-					
	24	Portable pump and power plant (wash down water supply)			1	ls	$8,000	$8,000
	25	Misc. (lights, fencing, fuel, heavy equipment rental, other)			1	ls	$150,000	$150,000
					Subtotal			$697,400

	QUANTITIES	PRICES	
BY	BWM	CHECKED BY BWM	CHECKED
DATE PREPARED February 24, 2009		APPROVED DATE	PRICE LEVEL Pre-Appraisal

CODE: D-8480

ESTIMATE WORKSHEET

SHEET 3 OF 4

FEATURE:

Pre-Appraisal Level Cost Estimate

Pumped Flow Option

Test Setup and Testing per Year

WOID:

PROJECT:

Missouri River Hydraulic Model

REGION:

FILE:

PLAN ACCT.	PAY ITEM	DESCRIPTION	CODE	QUANTITY	UNIT	UNIT PRICE	AMOUNT
	1	Water /yr		10	acft	$2,500	$25,000
		(Compacted road base material with binder)					
	2	Form river channel shape		6,000	yd^3	$25	$150,000
		(Compacted road base material with binder)					
		(Atlas soilLok@100 gal/ac)		2,000	gl	$13	$26,000
		(shipping)			ls	$2,000	$2,000
	3	Staff					
		(2 engineers @ 6 months/ yr)		2	yr	$130,000	$260,000
		(2 technicians @ 6 months/ yr)		2	yr	$70,500	$211,500
		(2 craftsman @ 6 months/ yr)		2	yr	$66,000	$132,000
	4	PerDiem					
		(6 people, 6 months/yr)			ls	$95,800	$95,800
	-	- -	-	-	-		
							$902,300

QUANTITIES		PRICES	
BY BWM	CHECKED	BY BWM	CHECKED
DATE PREPARED February 24, 2009	APPROVED	DATE	PRICE LEVEL Pre-Apprasial

CODE: D-8460

ESTIMATE WORKSHEET

SHEET 4 OF 4

FEATURE:	PROJECT:
Pre-Appraisal Level Cost Estimate Pumped Flow Option Cost Summary	Missouri River Hydraulic Model
	REGION:
WOID:	FILE:

PLANT ACCT.	PAY ITEM	DESCRIPTION		QUANTITY	UNIT	UNIT PRICE	AMOUNT
	1	Model design		1	ea		$80,000
	2	Initial model construction		1	ea		$1,775,000
		(sheets 1 & 2)					
		sub total items 1&2					$1,855,000
		Design and Construction contingency	25%				$463,750
		Model cost					**$2,318,750**
	3	Annual cost of testing 6 month period			ls		$902,300
		(labor and misc items)					
		Testing phase contingency	25%				$225,575
		sub total - annual cost of operation					**$1,127,875**
	4	Project closeout			ls		$250,000
		(land restoration and labor)					
		Total Project Cost for 5 Year Project (1 year design & construct and 4 years of testing)					**$7,080,250**
		(additional years of testing could be added)					

QUANTITIES		PRICES	
BY BWM	CHECKED	BY BWM	CHECKED
DATE PREPARED February 24, 2009	APPROVED	DATE	PRICE LEVEL Pre-Appraisal

Preliminary Gravity Flow Site Investigation:

Prior to initiating formal work on this study, Reclamation staff had attempted to identify potential sites for this model study while making site visits associated with other work. Aspects considered for these prospective site investigations included:

- Available flow rates in excess of 100 ft^3/s that could be maintained for a period of up to multiple days
- Locations where model flows could be returned to the system (typically irrigation delivery system) such that a minimal amount of model flow would represent consumptive use
- Availability of significant land area adjacent to a water source (typically a canal) that is currently in low-valued use, with particular interest where a potential model site could be constructed on government-owned land
- Head availability in order to minimize or eliminate need for pumping associated with model operation
- A site and canal layout that would allow model operation would have minimal or no impact on other aspects of a water delivery system.
- An operational water supply that would be relatively unaffected by weather events

This limited and unfunded preliminary investigation included soliciting input from field contacts in various localities where Reclamation's Hydraulic Laboratory staff are involved in on-site projects. Three sites were identified that met multiple criteria from the list above.

Bard Irrigation District, CA:

The Bard ID headworks at the point at which their delivery system is fed by the All American Canal often conveys flows in excess of 100 ft^3/s – particularly during the high demand period of the summer. This site is located in extreme southeastern California, just north of Yuma AZ. Near the outflow from the All American, there is a sizable tract of currently unused land owned by Reclamation. Flow from a model at this site could readily be returned to the Bard Canal.

An estimated 15 feet of head differential between the All American and flow in the Bard Canal would likely be sufficient to meet objectives of no pumping requirements. Capturing this head would require significant modification of the Bard turnout on the All American, and in the worst case might require construction of a new independent turnout.

Since there is no dry-up season for the All American, if more than a modification of the existing turnout is required, logistics would become considerably more complex.

Delivering flow from the turnout to the potential model site would involve conveying flow across a maintained gravel road. Outflow from the model would need to be returned to the Bard Canal a short distance below the All American turnout. If water is taken via the existing turnout, it may be necessary to construct a pipeline for the full length of the model to conserve as much of the energy head as possible for driving flow through the model and any necessary settling ponds.

Precipitation events are rare in this part of the country. Shutdown of water deliveries due to a rain storm is only occasionally seen in the fall and winter “monsoon” season, and is almost unheard of during the high demand summer season. A key drawback to this site is the travel distance from Reclamation’s Denver Laboratory base and from the COE Omaha District office.

Colorado River Indian Tribes (CRIT) Irrigation District, AZ:

The CRIT system diverts water from the Colorado River near Parker AZ. Approximately nine canal miles from the head of the main CRIT delivery canal, there is approximately a 6 foot drop adjacent to a tract of undeveloped land. Reclamation’s staff has previously examined this site as a potential location for a gravity-in gravity-out re-regulation reservoir. For that study, this site – located in the upper half of the main canal path – was determined to be too far up the delivery system to function effectively to limit system spills. A re-regulation reservoir would ideally be located down gradient from 65 to 75% of the delivery area.

The chief “pluses” offered by this site are the 6 foot head availability and a flow rate that typically exceeds 200 ft^3/s. As noted there is adjacent undeveloped land that could be considered for locating a model, but this property like all land within the district is tribally owned (not federal property).

Twin Loups Irrigation District (TLID), NE:

TLID is located in north central Nebraska with district offices near the small town of Scotia. District water sources include water impounded in Calamus Reservoir by Virginia Smith dam on the Calamus River, and diversions from the North Loup River. Davis Creek Reservoir is a reregulation storage facility in the TLID main canal located approximately 30 canal miles below Virginia Smith Dam.

At the flow is delivered from the TLID Main Canal to Davis Creek Reservoir, there is a drop in water surface elevation in excess of twenty feet. At this location, there would be ample Reclamation-owned land above the reservoir high water line for construction of a physical hydraulic model of the proposed scale for this project along with settling ponds and other facilities that would be associated with the study

Flow rate availability would also be excellent. Given the nature of the water transfer operations and the reservoir storage capacity, during the irrigation season TLID could provide desired flow rates up to a 200 ft^3/s range during model runs – rain or shine – with limited impact on TLID staff time and no impact on delivery to irrigators or water delivery system operating efficiency.

Both TLID management and Reclamation's Nebraska-Kansas Area Office have expressed willingness to participate in facilitating use of this site, should it be selected. It is within reasonable proximity to Reclamation's Denver Office (~ 6.5 hours driving time) and fairly close to the COE Omaha District Office (~3.5 hours driving time). One aspect not offered by this site is favorable topography. This area of Nebraska is rolling hill country consisting of fine grained loess soils. It would be desirable to limit the impacts of the uneven topography by fitting the curvature of the river reach to be modeled (or of the mirror image of the actual river reach) to the existing lay of the land to the extent possible.

Other Sites Considered:

Two additional sites that have been suggested for consideration are the Colorado State University (CSU) Engineering Research Center (ERC) located about one hour's drive north of Denver below the Horsetooth Reservoir Soldier Canyon Dam, and the Agricultural Research Service's (ARS) Hydraulic Engineering Research Unit (HERU) located immediately below the dam forming Lake Carl Blackwell, just west from Stillwater, Oklahoma. COE representatives at the "kick-off" meeting also noted that favorable sites may exist adjacent to some of the numerous COE water projects.

The CSU ERC has approximately 200 ft of head available when Horsetooth reservoir is full. The pipe delivery system is capable of delivering flows up to 200 ft^3/s for some of the ERC outdoor flumes. Horsetooth water used at the ERC facility comes from an annual allotment resulting from CSU's ownership of Colorado-Big Thompson (CBT) project units. Thus the annual volume of water available for use on outdoor facilities at this site is limited by the number of CBT units owned. Outflow from the ERC outdoor flumes runs into College Lake, which is just south of the ERC. CSU uses water from College Lake to irrigate lawns on campus, but as model test outflow rates exceed campus irrigation needs, College Lake will fill and spill.

An informal contact was made with Dr. Greg Hanson, ARS-HERU Research Leader. Dr. Hanson indicated that space availability would be a difficulty for the extended time this model is projected to remain operational.

Space Availability Assessments:

An estimated footprint of each of the three potential bends to be modeled has been created in AutoCad. These footprints were then overlaid onto aerial photo maps of potential model sites to enable a basic visual assessment of adequacy of available space.

The figures below show overlays of a 1:12 scale model and of a 1:15 footprint of the Lower Little Sioux bend at the Bard ID site discussed above.

Figure 18 - 1:12 Lower Little Sioux Bend Overlay at Bard Irrigation District Site

Figure 19 - 1:15 Lower Little Sioux Bend Overlay at Bard Irrigation District Site

(Mirror image model)

Land currently not in use near the Bard Main Canal headworks that was considered as a potential model site is triangular in shape, bounded on the north side by Mehring Road, to the southeast by the Bard Main, and to the southwest by a lateral canal. At a 1:12 scale, the 2.3 mile Lower Little Sioux bend model would exceed available space. A mirror image 1:15 scale model of the Lower Little Sioux bend appears to just fit within available space. Since both the upper and lower Copeland bends are longer than the Lower Little Sioux bend, this exercise was not repeated for model footprints from the Copeland bends.

Figure 20 - 1:12 Lower Little Sioux Bend Mirror Image Overlay at Colorado State University Engineering Research Center Site

The CSU ERC facility includes laboratory facilities for hydraulic engineering, materials engineering, and wind engineering in a complex just south of Laporte Avenue. Outdoor facilities are distributed along a draw extending from the ERC laboratory buildings to College Lake. Based on the aerial photo overlay above it may be possible to locate a 1:12 (or smaller) mirror image scale model of the Lower Little Sioux Bend along this draw at the CSU facility without impacting existing outdoor hydraulic facilities. As noted above, a key factor would be water supply unless the model is run with pumped recirculation.

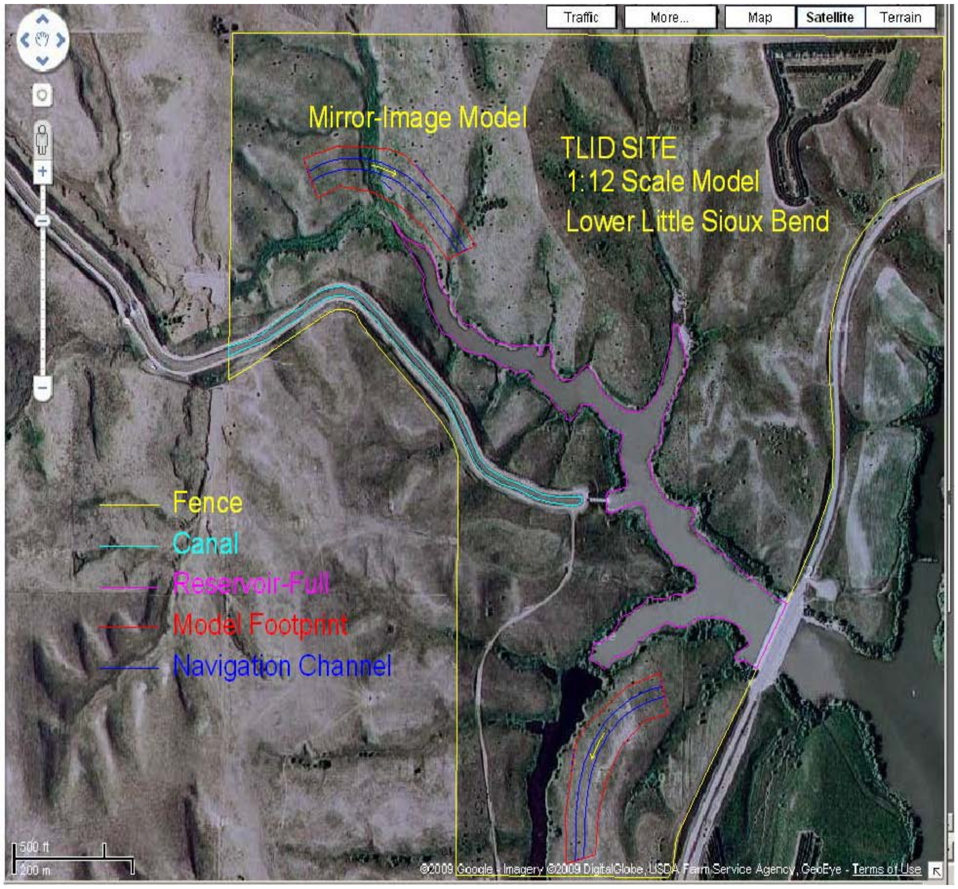


Figure 21 - Overlays of 1:12 scale model (regular and mirror image) at Twin Loups Irrigation District's Davis Creek Reservoir inlet

At the Twin Loups ID site, 1:12 scale model footprints of the Lower Little Sioux Bend may be fitted to the site with additional room available (regular and mirror image versions are shown in Figure 20 in an attempt to best utilize existing topography). This site offers ample space, attractive head availability, and highly agreeable flow availability conditions, but it is challenging terrain.

Post-Review Summary:

A draft version of this report was reviewed on behalf of USACE by Steven A. Hughes and by Thomas J. Pokrefke. Their reviews may be found in Appendices C and D of this document respectively. Discussions presented by each of the reviewers point to areas where more in-depth investigations would be appropriate if the project is advanced beyond the feasibility level study documented by this report.

A suggestion of note presented by Hughes is to consider incorporating a small scale model study in conjunction with the large scale model to serve as a cost-effective demonstration and education tool in addition to serving as a tool for refining the initial design and subsequent modifications of the large scale model. Both reviewers pointed out the need to recognize and plan for operational issues posed by locating a model study in an outdoor setting. The Pokrefke review is fairly detailed and concludes with a list of fifteen recommendations. Reclamation has prepared discussions in association with the Pokrefke list of suggestions. The Pokrefke suggestions with associated Reclamation discussions appear at the end of this section.

Both reviewers express an extensive degree of concurrence with the underlying concepts and the modeling approach proposed by Reclamation. The reviews do call attention to areas of apparent inconsistencies in projected modeling parameters presented by Reclamation, along with areas where the reviewers' respective experiences and philosophies might provide insights beyond the resources Reclamation has drawn on to produce this report. Given the feasibility-level project scope and associated budget limitations, Reclamation feels that the appropriate action at this juncture is to recognize that areas exist where more detailed investigations are needed if the project goes forward. Discussions included in the reviews provide direction for initiating further efforts.

As this report is being completed, the most recent communications with the Omaha District COE staff indicate that the estimated model study costs are being weighed against an alternative of a prototype scale study at an in-river site. Thus it is uncertain whether or when any activities might be initiated following this feasibility study.

Pokrefke Review Suggestion List – from the Pokrefke Review, Appendix D – and associated Reclamation discussions (italicized)

1) The amount of river widening for the SWH needs to be resolved. Reclamation states 300 to 400 ft, which is significantly different than the 600 ft stated by the Omaha District.
   This comment may be attributed to differing inferences taken from the referenced document, "Missouri River Physical Model Outline January 2009". The 400 ft value for width expansion is taken from the second bullet of section 3 of this outline. Given the differing interpretations of the information in this document, Reclamation concurs with the reviewer's statement of need for resolution.

2) Rather than considering potential model scales of 1:12, 1:14, and 1:15, it is suggested that scales of 1:12, 1:15, and 1:18 (or 1:20) be considered.

The model scales were determined based on the limitations of correctly modeling shallow water habitat using a non-distorted geometric scale. The differences between the scales are small, yet are intended to reflect model cost/performance tradeoffs which can be significant for such a large model.

3) A coal gradation that does not produce ripples but rather coal waves is recommended. Such a gradation will also reduce the possibility of the coal acting cohesive and armoring the model bed.
As with the above item, if the project moves beyond presently completed work, the coal gradation and ripple vs. wave sediment movement issues raised in the review should be examined in greater detail. Based on discussion presented and references cited in the review Reclamation agrees that this is an area where more detailed investigation is needed.

4) Reclamation should select one gradation and use that regardless of the scale model to be constructed. Small variations in gradations, such as those presented in the proposal, will be difficult to obtain, especially for the large volumes of coal that will be required to conduct the model study.
Reclamation agrees that "idealized" gradations presented in this feasibility report are barely differentiable for the selected model scales from a practical perspective. Further, the appropriate gradation for use based on practical reality may largely be a function of the product ranges resulting from available crushing alternatives, along with the fractions that remain after washing out fines.

5) During model operation re-handling of coal material should be minimized to reduce "grinding" the coal and creating unacceptable fine-grain fractions that may impact the study.

   Minimizing the creation of additional fines as part of coal re-handling processes is definitely a key consideration in development of the design for a sediment handling system. When considered alongside recommendation #15 (storing model coal sediments under water during non-operational periods), a slurry system for handling the coal sediment may be desirable.

6) It is recommended that a coal gradation coarser than those presented in the proposal be considered. One suggestion would be a coal gradation with D_{85} of about 1.6 mm, D_{65} of 0.9 mm, D_{50} of 0.8 mm, D_{30} of 0.8 mm, and D_{10} of 0.4 mm. This gradation or

one similar to it will eliminate the likelihood of the model sediment moving in ripples and staying non-cohesive provided the fines (grains smaller than 0.1 or 0.2 mm) are washed out during processing. Reclamation may want to consider conducting some flume tests for various gradations to determine the sediment movement and bed forms and the influence of the fines on movement.

This recommendation is essentially the same topic raised in recommendation #3. Reclamation agrees that this is a topic that should be revisited at the outset of any further work on this project.

7) Recommend that the computed sediment loads be checked to ensure that the quantities shown in Figures 14 through 16 are correct.

   Notation of inconsistencies in Reclamation's presentation of sediment load scaling is well taken. This topic should also be revisited at the outset of any further activities on this project.

8) Consider operating the model using stepped stage/discharge hydrographs to make the model operation easier and to enhance testing repeatability.
   Reclamation appreciates and agrees with the practicality of a stepped hydrograph approach for model runs. To the extent that COE is also agreeable, Reclamation would concur with this suggestion.

9) Recommend that the transition from the return channel into the headpond is sufficiently sized to allow the flow to "turn" to maintain a proper flow distribution

   into the model.

   In addition to the recommendation that channel size should be scrutinized for adequacy, features such as turning vanes may be desirable for ensuring that flow entering the model from a return channel has desired distribution across the model and correct approach flow direction.

10) Recommend that all project stakeholders be informed that a semi-fixed bed model study is being conducted and such a model has the capability of determining areas of shoaling but does not have the capability of producing scour.

    The model design concept presented by Reclamation in a general manner may have been envisioned by the reviewer under a more constrained perspective than Reclamation had envisioned. The hardened base described in the report would be set at an elevation yet to be determined below the initial river bed to allow for a *limited range of scour to be represented in the model. Reclamation fully appreciates concerns raised that the model be able to simulate impacts of scour as well as of deposition. A more detailed consideration of appropriate horizons between hardened boundaries and movable sediments is beyond the scope of and the budget provided for this feasibility-level investigation. [The last paragraph on page 3 of this report has been edited to better clarify the proposed model design concept – particularly the intended capability for scour to be able to occur in the model.]*

11) Consideration should be given to conducting a phased testing procedure to document specific changes for the various plans. A phased testing procedure will also allow collecting detailed data around structures and channels to determine the potential for scour in those areas. If appropriate, the potential scour areas can be modified in the semifixed-bed model prior to continuation of testing.

    The suggested phased testing procedure would represent a highly appropriate means for locating suitable hardened boundary locations and for making boundary modifications as necessary.

12) During the phased testing "fixed-bed" tests can be conducted to evaluate the model operation and determine if local velocities have increased sufficiently after Phase 1 to potentially create local scour issues. That information can then be used to modify the plan.

    Reclamation concurs with this suggestion that follows closely with recommendation #11.

13) To address navigation issues the collection of current direction and velocity data for at least 3 flow conditions during the various phases of the testing procedure is recommended.

    Limited discussion of data to be collected or of proposed data collection methods has been included in this feasibility level investigation. Reclamation concurs that the current direction and velocity data collection recommended in the Review would need to be included in a model study.

14) The issue of model water temperature should be addressed to ensure repeatability of the model testing program over time and through various weather seasons.

See next item

15) The model design should include consideration of maintaining the coal model material under water during non-operational periods.

Recommendations 14 & 15 reflect the expertise that has been developed at WES in coal-sediment model studies as well as in outdoor model studies. Reclamation is highly appreciative of these shared perspectives and is fully agreeable to including repetition of tests at differing water temperatures and to underwater storage for coal sediment during non-test periods.

References

Taylor B.D. and Vanoni, V.A., "Temperature Effects in Alluvial Streams", W.M. Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology, Calif. Discussed in "*Sedimentation Engineering, ASCE Manuals and Reports on Engineering Practice", Vanoni (editor),* No. 54*"*, ASCE, New York NY, 1975.

Dodge, R.A. *Model Similitude – Extended for Active Sediment Transport PAP-450*. USBR Water Resources Research Laboratory. Denver CO. 1983.

Simons and Sentürk, "*Sediment Transport Technology*", Water Resource Publications, Fort Collins, Colorado, 1977.

Mercer A.G., published by Shen, H.W. (Editor), "*River Mechanics – Analysis of Alluvial Bed Forms*", Chapter 10, Colorado State University, Fort Collins, Colorado, LCC:70-168730

Yang, S. and Tan S., "*Flow Resistance over Mobile Bed in Open-Channel Flow*", Journal of Hydraulic Engineering, July 2008

Einstein, H.A. and Chien, N., "*Similarity of Distorted River Models with Moveable Beds*", Transactions of American Society of civil Engineers, December, 1954.

Gessler J., published by Shen, H.W. (Editor), "*River Mechanics – Modeling of Fluvial Processes*", Chapter 21, Colorado State University, Fort Collins, Colorado, LCC:70-168730

White, P.J., Paris, E., and Bettes, R., "The Frictional Characteristics of Alluvial Streams: A New Approach", Proc. Inst. Civil Engrg., London, Part 2, 69(3).

Appendix A

September 10, 2009 “Kick-Off” Meeting Attendees List:

Tony Wahl	USBR Hydraulics Lab	twahl@usbr.gov	303 445 2155
Bob Einhellig	USBR Hydraulics Lab	reinhellig@usbr.gov	303 445 2142
Brent Mefford	USBR Hydraulics Lab	bmefford@usbr.gov	303 445 2149
Tom Gill	USBR Hydraulics Lab	tgill@usbr.gov	303 445 2201
Ronnie Heath	USACE-ERD-CHL	ronald.e.heath@usace.army.mil	
Steven Hughes	USACE-ERD-CHL	steven.a.hughes@usace.army.mil	
John Remus	USACE Omaha	john.i.remus@usace.army.mil	402 995 2349
Teresa Reinig	USACE Omaha	teresa.a.reinig@usace.army.mil	402 995 2721
Dan Pridal	USACE Omaha	daniel.b.pridal@usace.army.mil	402 995 2336
Tom Pokrefke	USACE Omaha Contractor	tjplwp@cablelynx.com	601 638-6080

Appendix B

Sediment Transport Similitude for Scaled Physical Hydraulic Modeling

Thomas W. Gill[1] and Clifford A. Pugh[2]

[1]Hydraulic Investigations and Laboratory Services Group, US Bureau of Reclamation, PO Box 25007, Denver Colorado,80225; PH 303 445 2201; FAX 303 445 6324; email: tgill@usbr.gov

[2]Consultant, Retired -US Bureau of Reclamation, 10133 W. Powers Ave., Littleton CO, 80127; PH 303 979 6269; email: cliffordapugh@aol.com

Abstract

Studies of the hydraulics of sediment transport – a field with extensive associated complexities – have yielded a diverse set of empirically-derived predictive methodologies. Researchers at the Bureau of Reclamation's Hydraulic Investigations and Laboratory Services Group have identified an approach for design of movable bed physical scale models based on a relationship between dimensionless bed shear (Shields parameter) and dimensionless unit sediment transport (Taylor's function). Using a method that includes selection of model particle size and density based on terminal velocity (fall velocity) for particles in both scale model and prototype; model design parameters may be identified to produce model-prototype similitude for aspects of sediment transport including incipient motion and approximate transport capacity. This paper further expands the methods described in ASCE's Manual 110, Appendix C (Pugh, 2008) on "Sediment Transport Scaling for Physical Models." When the model is not large enough to compensate for the scale effects, the sediment density and or slope of the model may need to be adjusted to match the model and prototype Taylor's Function curve for constant dimensionless transport rate.

Introduction

A 1:24 scale (M:P, model : prototype) physical hydraulic model study was conducted in 2004 at Reclamation's Hydraulics Laboratory in Denver CO that examined alternatives for limiting sediment intake at a planned diversion on the Rio Grande River near Albuquerque, NM. This paper follows methodologies used to identify appropriate parameters for model design.

Scale Physical Hydraulic Modeling & General Hydraulic Similitude

Scale model studies of hydraulic systems have proven a cost-effective means of investigating performance of a proposed structure or of proposed system modifications, provided requirements for hydraulic similitude are met. Idealistically, this requires matching the ratio of appropriate pairs of forces in both scaled model and prototype that play significant roles in the physical processes being examined. Often of interest is the ratio of inertial forces to viscous forces (a dimensionless ratio known as the Reynolds Number) as well as the ratio of inertial forces to gravity forces (also dimensionless, known as the Froude Number) in both model and prototype. The stream Reynolds Number (Re) for wide, shallow channels is the product of fluid velocity (V) and flow depth (y) divided by the fluid's kinematic viscosity (ν). The Froude Number (Fr) is the fluid velocity (V) divided by the square root of the product of the gravitational constant (g) and the flow depth (y).

$$\mathrm{Re} = \frac{Vy}{\nu} \qquad\qquad Fr = \frac{V}{\sqrt{gy}}$$

In practical applications, meeting both criteria would require scaling of not only physical dimensions, but scaling of fluid properties (i.e. viscosity, fluid density) – which can almost never be achieved due to the fact that fluids with suitably scaled properties almost never exist. In most physical model studies of water conveyance and control systems, water is both the model and prototype fluid for economic reasons. If turbulent flow conditions exist in both model and prototype for the aspect(s) of a system being examined, viscous force effects are significantly diminished and observations from model performance will relate to prototype performance within a useful degree of accuracy. Hence physical open channel flow hydraulic models are commonly designed to adhere to Froude number scaling and to maintain turbulent flow conditions for the modeled aspects of interest in order to avoid having viscous forces (commonly referred to as "Reynolds effects") impact model performance. A stream Reynolds number of 2000 represents the minimal range for turbulent flow conditions.

Additional Sediment Modeling Considerations

For sediment movement, the hydraulic scale of interest is at the bed sediment particle diameter. Particle movement is a function of shear force – or the drag force – exerted by fluid moving past bed particles that exceeds forces holding the particles in place. Bed shear (τ_o) is calculated as the product of fluid density (ρ) (or more correctly density of the fluid and suspended particle mixture) and the square of the shear velocity (u_*). Shear velocity is calculated as the square root of product of the gravitational constant (g), the channel's hydraulic radius (R) and slope (S). For wide shallow channels like the modeled stream reach of the illustrative example, hydraulic radius is approximated by the depth of flow (y). The magnitude of drag force exerted depends on degree of turbulence present and thus is a function of the Reynolds Number. The form of the Reynolds

Number used for consideration at the bed particle scale is known as the "Grain" Reynolds Number, (Re_*), defined as the product of the shear velocity (u_*) and grain size (d_s) divided by the fluid kinematic viscosity (ν) or $Re_* = u_* d_s / \nu$. Hence:

$$\tau_o = \rho\sqrt{gyS} \qquad\qquad \mathrm{Re}_* = \frac{u_* d_s}{\upsilon}$$

Generally, it is not feasible to simply reduce particle size according to geometric model scale. As particle size is reduced, cohesiveness properties may change dramatically, completely altering the sediment transport mechanics between model and prototype. Using a model particle size in excess of the scaled value may necessitate using a lower density bed material in the model, increasing the model slope, or a combination of density and slope adjustments to produce transport mechanics with a useful degree of similarity between model and prototype.

An approach that has been employed for moveable bed scale model studies at Reclamation's Hydraulics Lab is based on an apparent relationship between dimensionless bed shear known as Shields' Parameter (τ_*), and dimensionless unit sediment transport (q_{*s}). Shields' Parameter is defined as the bed shear (τ_o) divided by the product of buoyant specific weight (γ_s - γ) and particle size (d_s). Dimensionless unit sediment transport, known as Taylor's function, is defined as the unit sediment ($q*_s$) divided by the product of shear velocity (u*) and grain sediment size (d_s)

$$\tau_* = \frac{\tau_o}{(\gamma_s - \gamma)d_s} \qquad\qquad q*_s = \frac{q_s}{u * d_s}$$

The threshold condition for either mobilization or deposition of a given particle is commonly referred to as the condition of incipient motion. Using data from laboratory flume studies, Shields was able to show that for a given grain Reynolds number there is a unique dimensionless shear value at which the state of incipient motion exists. Dimensionless shear values representing the incipient motion state are plotted against grain Reynolds number to produce a curve for the condition of incipient motion. Dimensionless shear values that lie on this curve are known as "critical" Shields parameter values. (Vanoni, 1975)

In studies with low sediment discharge rates by Taylor (as discussed in Vanoni, 1975), the amounts of sediment being transported from the flume were measured and results analyzed in terms of dimensionless unit sediment transport. Taylor determined Shields' parameter values and Taylor function values for each data point. He found that when Shields' values for data points of constant Taylor's function value were plotted against grain Reynolds number, curves approximately parallel to the critical Shields parameter were produced. (Vanoni, 1975).

When plotted on the Shields' diagram, Taylor's data appears below the critical Shield's parameter suggesting that the critical Shields' curve represents a constant Taylor's function value of some small value of dimensionless unit sediment transport. Figure 1 is the Shields' diagram showing the apparent parallels Taylor found for Shields' parameter values associated with constant Taylor's function values, and the critical Shield's parameter curve.

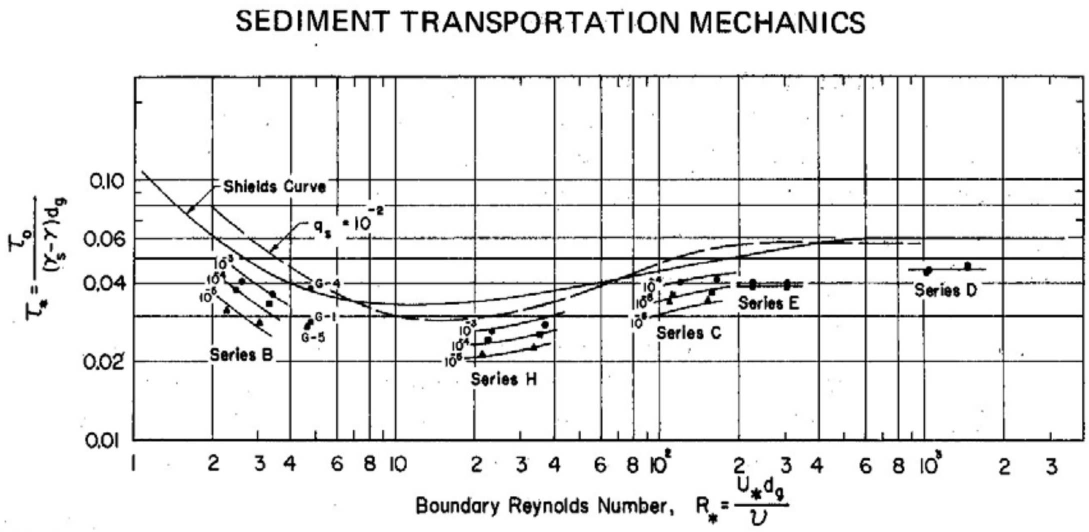


Figure 1. Plot showing the "critical" Shields values along with Shield's values for constant-value segments of Taylor's function data (from Vanoni 1975)

In keeping with theory relating similitude and dimensionless parameters it follows that when Taylor's function values for scale model and prototype are equivalent, similitude would exist in sediment transport. Pugh and Dodge (1991) proposed that the parallel relationship Taylor had shown between Shields' parameter values associated with constant Taylor's function values for small rates of sediment discharge and the critical Shields' values might hold for higher sediment discharge rates. If so, the target Shields' value for the model and the corresponding prototype Shields' value would lie on the same curve paralleling the critical Shields' values curve. By equating the differentials between actual Shields values and critical Shields' values at the respective grain Reynolds numbers for both model and prototype, similitude in sediment transport rates could be achieved.

For cases where prototype grain Reynolds' number is greater than 100, but where geometrically scaled particle size produce grain Reynolds numbers below 100, Pugh and Dodge reported success achieving target differentials between model dimensionless shear and critical Shield's values by increasing model particle size. A guideline used was to attempt to equate model and prototype particle fall velocity (ϖ_o). Fall velocity is terminal velocity of a particle of given shape, density and size falling through a fluid of given properties. Fall velocities are commonly approximated using empirically derived relationships based on laboratory observations. An empirical relationship for fall velocity developed at the Reclamation Hydraulics Laboratory (Dodge, 1983) based on settling chamber data for sand particles in clear water is:

For d_s >0.3 mm, $\omega_o = 11 * \frac{d_s^{0.5}}{100}$ For d_s < 0.3 mm,

$$\omega_o = 80 * \frac{d_s^2}{100}$$

The parallel relationship between grain shear for constant value Taylor's functions and critical Shields' values provides a design guideline for similitude in sediment transport capacity. Actual transport rates are a function of both transport capacity and sediment availability. A scaled sediment load relationship may be derived by applying an empirical bed load transport equation to both model and prototype over a range of discharges. A mathematical relationship can then be identified between corresponding predicted loads. A formulation of the Meyer-Peter & Mueller (M-P&M) equation as presented in Vanoni, (1975) was utilized for this purpose in the illustrative model study. M-P&M was developed for sand grain sediments and can be applied to sediments of varying density. The derived relationship was utilized to compare measured sediment feeding rate in the model with prototype bed load field data.

Design of the Illustrative Physical Model

Selection of Scale

Selecting an appropriate scale was a function of space availability, including as many of the prototype channel features as possible, and maintaining a large enough scale to limit the effect of viscous forces. The available model box was approximately 8.86 m wide and 20.5 m long. A 1:24 scale factor was identified as near the upper limit for scale that would enable construction of the entire diversion structure and bank-full model of the upstream channel within the 8.86 m box width. Even at this scale, the Reynolds number in the diversion bays assuming 1.84 m^3/s diversion per bay and 0.984 m depth (prototype) is approximately 1600. This falls below a minimum value of 2000 for turbulent flow conditions. Thus model flows in the diversion bays are subject to some degree of Reynolds' effects. Due to higher velocities, flows through gate openings on the diversion structure should be in the turbulent range and be less impacted by Reynolds effects.

Examination of Sediment Transport Similarity

For this study model adjustments were identified following an iterative sediment transport model scaling methodology described by Pugh (Pugh 2008). The initial step was to look at Shields' values for particles of prototype density and of geometrically scaled size with equivalent channel slope in both model and prototype. Analysis of field samples of prototype sediments indicated a prototype grain size of 51mm. A geometrically scaled model grain size would be 0.021 mm. Corresponding Shields values calculated for these model and prototype grain sizes were determined for flow depths of 0.248 m, 0.328 m, 0.656 m, 0.984 m, 1.640 m, and 2.297 m. Formulas were entered into spreadsheet cells to calculate dimensionless shear and grain Reynolds number for model and prototype at each of the selected flow depths. These Shields values are shown in Figure 2.

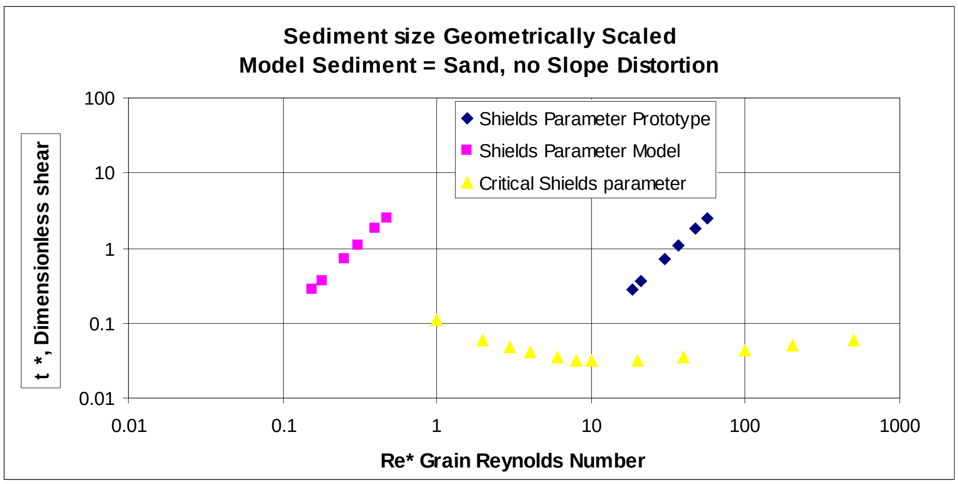


Figure 2. Shields diagram showing dimensionless shear for prototype

And geometrically scaled grain model grain sizes

It is readily apparent from Figure 2 that corresponding model and prototype dimensionless shear values come nowhere near lying on curves parallel to the critical dimensionless shear. For the next adjustment, model grain size is increased to equate fall velocity between model and prototype. For the 1:24 scale model, a resulting model grain size of 0.142 mm was derived. Figure 3 shows the model and prototype Shields values for fall velocity adjusted model particle size.

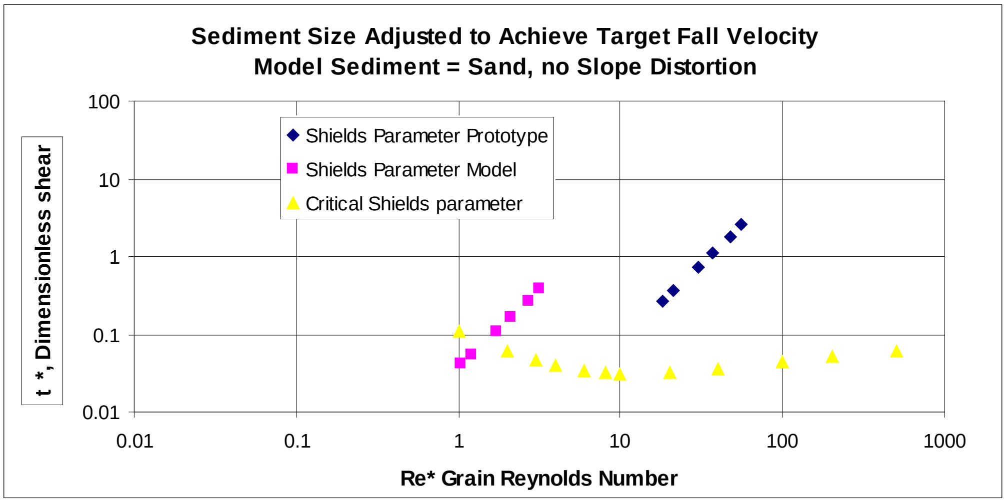


Figure 3. Shields diagram showing dimensionless shear for prototype and model grain size adjusted for fall velocity

As seen in figure 3, the model particle adjustment to equate model and prototype fall velocities resulted in a shift of model dimensionless shear values for the selected stream depths, but does not bring these values near enough to lying on parallel curves with corresponding prototype dimensionless shear values. For the next adjustment, model sediment of reduced density was utilized. An available stock of crushed coal was found to have a grain size of 0.88 mm and a specific gravity of 1.27. Figure 4 shows the dimensionless shear values, assuming the available crushed coal stock is used as the model sediment, in comparison with prototype dimensionless shear for corresponding stream depths.

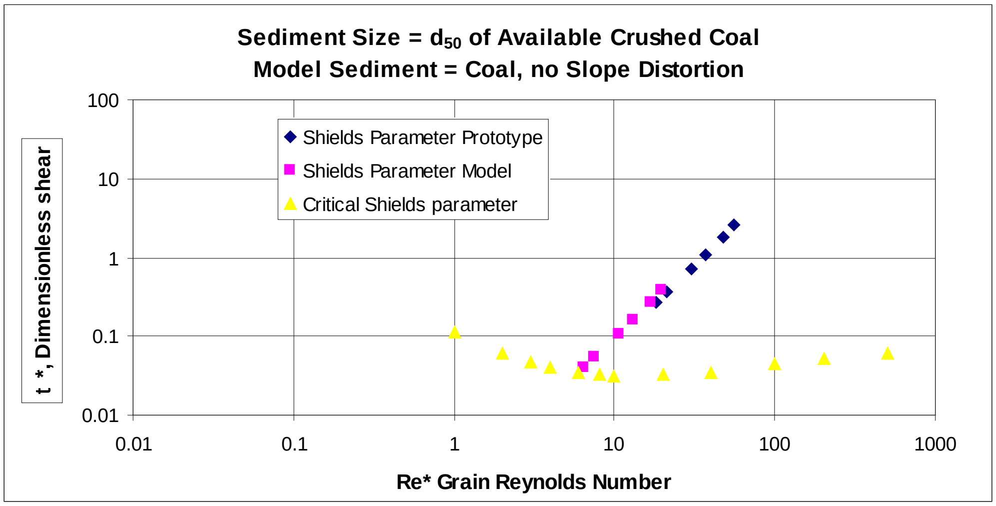


Figure 4. Dimensionless shear for crushed coal as model sediment in comparison with prototype dimensionless shear and critical dimensionless shear values.

Figure 4 shows that consideration of crushed coal as the model sediment produced a significant shift in model dimensionless shear values, but corresponding model and prototype are still below the prototype curves parallel to the critical dimensionless shear plot. The remaining parameter that could be adjusted for the iterative design method would involve exaggerating the model slope. Different slope distortions were examined until the relationship plotted in Figure 5 was identified.

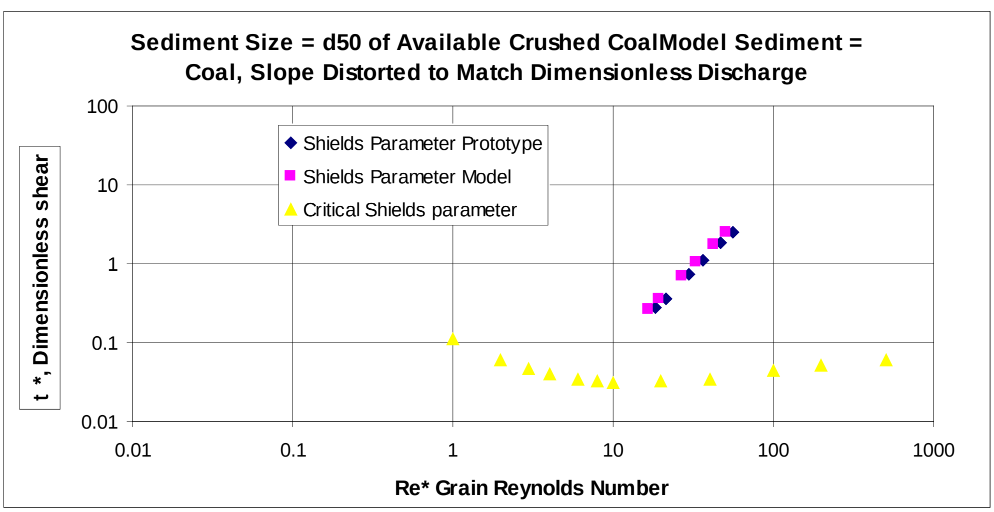


Figure 5. Dimensionless shear using crushed coal as the model sediment with a 6.5:1 slope exaggeration (model: prototype)

From the appearance of Figure 5, the combination of a 6.5:1 slope exaggeration coupled with use of lighter weight model sediment (the available crushed coal) as the model sediment appears to have created appropriate adjustments to enable the model and prototype to have sediment transport similitude. At this point, model parameters of 1:24 (M: P) geometric scale, available crushed coal for model sediment, and 6.5:1 (M:P) bed slope exaggeration were settled upon for model testing.

Sediment Discharge Scaling Methodology for Model Operation

An approximation of the relationship between the sediment discharge rates of model and prototype for the selected model parameters was needed to determine an approximate rate for feeding sediment into the model. This rate was determined by applying the Meyer-Peter and Muller (M-P&M) bed load transport equation to each case for corresponding Froude-scaled stream discharges. The Meyer-Peter and Mueller equation was developed from studies of sand-sized bed particles with particles of varying densities and provides unit sediment discharge (g_s) in metric tons/meter/second. The formulation of this equation presented by Vanoni (Vanoni, 1975) as follows:

$$\left(\frac{k_r}{k'_r}\right)^{\frac{3}{2}} r_b S = 0.047(\gamma_s - \gamma)d_m + 0.25\left(\frac{\gamma}{g}\right)^{\frac{1}{3}}\left(\frac{\gamma_s - \gamma}{\gamma_s}\right)^{\frac{2}{3}} g_s^{\frac{2}{3}}$$

Where: k_r = roughness coeff. (= 1/n where n = Manning's roughness coeff.)

$k'_r = 26/d_{90}^{1/6}$ (d_{90} in meters)

γ = specific weight of water (metric tons/cubic meter)

γ_s = specific weight of sediment (metric tons/cubic meter)

r_b = hydraulic radius (~ depth for wide channel)

S = channel slope

d_m = effective sediment diameter (= $\Sigma_i\, p_i d_{si}$ where p_i = % by wt. of size d_{si})

g = gravitational constant

g_s = bed load (metric tons/meter/second)

This equation was manipulated to calculate unit bed load (g_s) for both model and prototype, then multiplied by respective channel widths, as a basis for scaling transport rate, given differing model/prototype sediment densities as well as model slope distortions. A numerical approximation of the relationship between M-P&M predicted transport for prototype and model was obtained as linear fit of calculated values. This relationship is shown in Figure 8. The relationship shown in Figure 8 was subsequently used as basis for sediment feed rates in the 2004 illustrative model study.

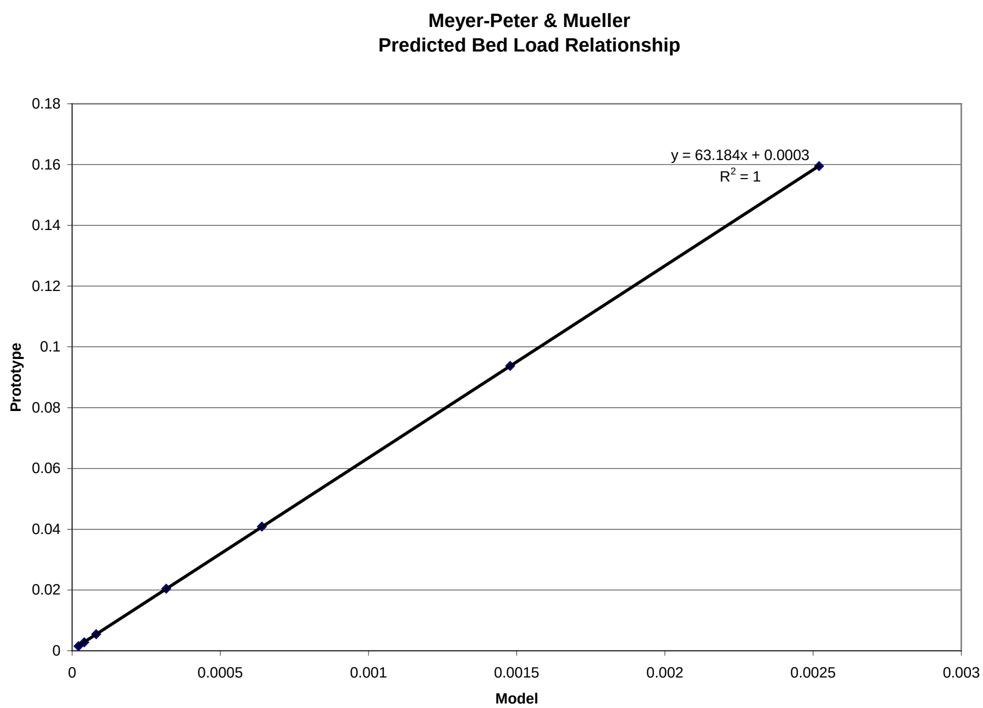


Figure 8. Plot of the M-PM model/prototype bed sediment transport comparison

(in metric tons/second) for the identified model parameters at selected flow depth.

Summary

Franco (1978) described alluvial channel engineering as ". . . a matter of experience and general judgment . . ." Despite the widespread availability of vastly enhanced computational tools since this statement was made, sediment transport engineering tools can offer limited precision at best. When attempting to account for the impacts of scaling, the degree of imprecision is magnified for physical scale modeling of sediment transport. Numerous assumptions have been a part of development of the iterative model parameter identification tool described in this paper. For multiple physical scale model sediment transport studies conducted at Reclamation's Hydraulic Laboratory, it has enabled researchers to examine prototype transport process with a useful degree of similitude. The results of applying these adjustments to sediment management at the proposed Rio Grande Diversion in the example model study in this paper have produced reasonable results and allowed evaluation of changes to the proposed diversion structure to exclude sediment from the intake. All of the model distortions available were used in this study, making it a good illustration of how to use the procedures described in ASCE's Sedimentation Engineering Manual-No.110.

References

Dodge, R.A. *Model Similitude – Extended for Active Sediment Transport PAP-450*. USBR Water Resources Research Laboratory. Denver CO. 1983.

Franco, J.J. *Guidelines for the Design, Adjustment and Operation of Models for the Study of River Sedimentation Problems*. Hydraulics Laboratory. Department of the Army. Waterways Experiment Station. USACE. Vicksburg MS. 1978.

Garcia, Marcelo H., (editor) "*Sedimentation Engineering, Processes, Measurements, Modeling, and Practice, ASCE Manuals and Reports on Engineering Practice – No. 110",*

Pugh, Clifford A., "*Appendix C, Sediment Transport Scaling for Physical Models",* ASCE, Reston, VA, 2008.

Gill, T. Physical Model Study: City of Albuquerque Drinking Water Project, Sediment Management at the Proposed Rio Grande Diversion, US Bureau of Reclamation Hydraulic Laboratory Report HL-2004-01. Denver CO. Nov, 2004

Pugh, C.A. "Sediment Transport Scaling for Physical Models". Appendix C. *Sedimentation Engineering: Processes, Measurements, Modeling, and Practice. No. 110.* ASCE. New York N.Y. 2008

Pugh, C.A. & Dodge. R.A. "*Design of Sediment Models*". Proceedings of the Fifth Federal Interagency Sedimentation Conference, Las Vegas NV. FERC. Washington D.C. 1991.

Vanoni, V.A.(editor), "*Sedimentation Engineering, ASCE Manuals and Reports on Engineering Practice*. No. 54*"*, ASCE, New York NY, 1975.

Appendix C

ERDC/CHL - Hughes 1 *Draft* Physical Hydraulic Model Proposal for COE River Bend Model By U.S. Bureau of Reclamation

Commenter

Steven Hughes, Coastal and Hydraulics Laboratory, ERDC
Phone: 601-634-2026
Email: Steven.A.Hughes@usace.army.mil

General Comments

It is evident from the proposal that the Hydraulic Investigations and Laboratory Services Group of the U.S. Bureau of Reclamation bring extensive physical modeling experience to the project. Furthermore, the staff is highly qualified to design, construct, and operate the proposed physical model; and they will be able to interpret physical models results in the context of the model shortcomings.

The proposed physical model is primarily intended to investigate alternatives for creating and maintaining shallow water habitat (SWH) in the Missouri River. Stabilization of habitat would involve the use of various control structures to direct river flow during normal and flood conditions.

The model study objectives listed in the proposal are quite ambitious with multiple variations that will result in numerous model test configurations to be considered. Narrowing the test matrix to an achievable number of tests will be a challenge, and most likely the test matrix will evolve as more is learned about the model response in the early stages of testing.

An important aspect related to creation of SWH in the Missouri River is the sustainability of the SWH over time. Evaluation of SWH longevity depends on erosion and deposition of sediment being carried by the river. Thus, the decision was made to incorporate a movable bed in the physical ERDC/CHL - model. This introduces another level of difficulty and considerable expense to the modeling effort.

Physical Model Scaling

Hydrodynamics

Flow in the proposed model will be scaled according to the Froude model scale for geometrically undistorted physical models. Froude scaling of the flow is correct and appropriate for flows with a free surface. As noted in the Reclamation proposal, the main concern is at locations where the flow Reynolds number is less than the threshold for turbulent flow. This scale effect was carefully analyzed for the three proposed model length scales, and it was shown that potential Reynolds scale effects were limited to locations with shallow depth and low flow velocities. Was any consideration given to a geometrically distorted model to give more depth in the model? Perhaps this would make the sediment scaling more difficult. Also, there is a scale effect associated with large-scale eddies that could be problematic in the areas of the SWH.

Geometry

The proposed model uses the same length scale for vertical and horizontal dimensions in the channel cross section. This means the model cross section is geometrically undistorted. However, the downstream slope of the channel is approximately 2-1/2 times steeper in the physical model than in nature. This slope distortion was introduced after an iterative evaluation of bottom friction in the model, and the slope distortion is intended to pro-vide similarity of flow resistance in the model. Thus, measured model velocities should be reasonably correct when scaled to prototype using the Froude similarity relationship.

Sediment Transport

The proposal contains a very thorough analysis of similitude requirements for sediment transport. The methodology is a combination of theory, empirical adjustments, and past experience that attempts to achieve similarity between prototype and model for both initiation of sediment transport and sediment transport rate. The reviewer admits to being unqualified to critique much of the sediment transport similarity proposed by Reclamation. Only bedload sediment transport was considered because it is not practical to achieve similarity of both bedload and suspended sediment transport in a reduced-scale model. This compromise is valid, particularly in the SWH regions where flow velocities are reduced and bedload should be the dominant mode of transport. The time scale for sediment transport was also distorted from the Froude time scale according to an established sediment transport equation. Coal was selected to represent sediment in the model for several good reasons. Coal is lighter than sand, it can be rendered to the necessary grain size, it is inexpensive, and it is available in large quantities. Using coal as the model sediment is probably the only practical choice for this model.

Scaling Summary

The Reclamation staff has done a thorough analysis of the similitude requirements for the proposed physical model, and they are clearly experts in this arena. The fact that the staff has conducted similar movable-bed studies greatly contributed to the rational description of scaling proposed for the physical model.

Model Validation

The proposal does not specifically detail what model validation testing is planned. Validation would likely involve replication of the flow hydrody-namics of an existing river bend with comparison to field measurements. Validation of the sediment transport aspects of the existing river bend would be more difficult, but there appears to be bulk sediment transport estimates available for comparison.

Ideally, it would be good to have some type of physical model verification for the SWH; but clearly this is not feasible because of the huge field effort that would be required to gather necessary data. Perhaps a post-construction evaluation of a SWH could be performed in the future to compare how well the model predicted the behavior of an actual SWH that was constructed based on model tests.

Physical Model Configuration

Rejection of Gravity-Flow Model Option
The original thought was to locate the physical model at a site where the necessary flow volume was available as gravity-driven flow from existing infrastructure. Three sites were examined with the final conclusion that none of the sites had a distinct advantage over construction of a recirculating model. This reviewer agrees with the Reclamation conclusions. The decision to recommend a recirculating flow model provides more options for locating the model to best suit the involved parties.

Model Construction

The proposed construction methodology builds on past successful models, and the details of how to accomplish the model construction should be well understood by Reclamation staff. In other words, there should not be too many unanticipated problems with model construction; and the construction cost estimate is expected to be reasonably accurate for this very preliminary stage of planning.

It is proposed that the bathymetry/topography for each channel configuration selected for testing will be sculpted using local soils. A hardening agent would be used to stabilize the soil against erosion. So (as I under-stand it) the physical model would resemble a fixed-bed model with a veneer of movable sediment (coal) placed over the fixated soil bathymetry. Model sediment will be fed into the upstream portion of the model and collected at the downstream end. Consequently, erosion in the model will occur until the underlying soil bathymetry is exposed, at which time no further erosion can occur. The proposal implies that some experimentation with the soil hardening agent will be necessary, which seems like a good idea.

Reconfiguring the model to a different bathymetry is facilitated by the proposed construction method, although it certainly is not a trivial under-taking. Careful thought will be needed to minimize to the extent possible large-scale modifications to the model bathymetry. However, tweaking of smaller areas of the SWH bathymetry can be accomplished with relative ease.

The scale of the physical model means it will be constructed outdoors and exposed to the elements. Depending on where the model is sited, consideration must be given to how the model bathymetry reacts to temperature extremes and possibly freeze/dry cycles. Considerable effort may be needed to repair damage after each winter season. The concrete portions of the flow recirculation system are more resistant to the effects of weather. Finally, daily weather conditions may affect the testing schedule (e.g., heavy rain and strong wind).

The flow recirculation and control system is based on previous successful modeling efforts, and there are few uncertainties associated with being able to design, construct, calibrate, and operate the system with required precision. The flow control system will be automated, and this helps pro-duce consistent, repeatable test conditions, particularly when the model simulates time-varying discharge hydrographs.

Measurements

The proposal includes descriptions of the important model measurements. Generally, we are interested in the model response to a given forcing con-dition at the upstream boundary. Model hydrodynamic forcing consists of the discharge hydrograph at a given still water elevation at the upstream boundary. Model hydrodynamic response consists of water elevations and flow velocity at selected locations throughout the modeled region. The other major model response is the change in bathymetry as a result of the flow conditions and the influx of sediment at the upstream boundary.

The proposal included provisions for acquiring the measurements necessary to document model forcing and response. The described instrumentation is reliable, and the Reclamation staff has experience with all of the instrumentation. Flow visualization techniques will be used to demonstrate flow patterns in the model.

Results from the large-scale physical model may be needed to help calibrate/develop/improve numerical models of river bends and associated SWH. If this is the case, it will be necessary to examine the validation needs of the numerical model and allow for acquiring measurements to fulfill those needs.

Physical Model Cost

The cost estimate included in the proposal was examined, but no effort was made to validate the cost of individual items. The estimate was developed with considerable detail and thought, particularly in the construction of the model. Given Reclamation's prior experience with similar models, the construction estimate most likely includes all necessary components, and the total construction cost is thought to be fairly accurate for this stage of project development. The 25-percent contingency is certainly appropri-ate for construction of a movable-bed model of this size and capability.

Little detail was given on the annual operating cost of $1M for 6 months of operation. This figure is certainly in the right ballpark, and I would not be surprised to see a higher number once a testing plan is developed.

Suggestion for a Preliminary Smaller-Scale Physical Model

One of the stated primary objectives is to use the large-scale physical model as a "display tool" to educate non-Corps partners, etc. Whereas this is certainly an option with the large-scale model, demonstrations would need to coincide with model testing because running movable-bed models outside of planned experiments will result in unwanted model sediment movement. Similar demonstrations using a small-scale fixed-bed model might be nearly as instructive for non-technical audiences.

It is recommended that the U.S. Bureau of Reclamation include in their proposal the design and construction of a smaller-scale model of the pro-posed large-scale physical model. This preliminary model would be constructed at the start of the project with the dual purpose of educating non-Corps partners, and more importantly, as a working design tool for optimizing the large-scale model. The preliminary model does not have to be very big, and it could be conveniently located at the Denver experimental facility if space exists.

The preliminary model would have a fixed bed, but it could be designed in some way to accommodate easily changing the bathymetry from the exist-ing condition to various proposed conditions. First, this allows visitors and partners to realize the utility of the large-scale model; and second, it gives model engineers a tool for selecting the most promising (and sustainable) SWH configurations for testing at large scale in the movable-bed model. Lightweight tracer will give at least a qualitative sense of where erosion and deposition might be expected for each potential SWH configuration.

Constructing and operating this smaller-scale preliminary model will help identify problems early in the project, and it should optimize the large-scale testing program where costs are significantly higher. The number of bathymetry configurations (and control structure variations) that can be tested at large scale is limited by both cost and time. However, the smaller-scale model can be used as an effective screening tool with ample opportunity to demonstrate the best scenarios for SWH creation to vested interests. It may be possible to acquire useful hydrodynamic measurements using the preliminary model, but this will depend on the scale of the model and the confidence the model engineers have in their mitigation of scale effects. At a minimum, engineers might be able to gain insight into measurement needs and locations for the large-scale model.

Summary

The staff of the Hydraulic Investigations and Laboratory Services Group of the U.S. Bureau of Reclamation has presented a well-considered proposal for a large-scale movable-bed physical model that can be used to help de-sign viable shallow-water habitat in the Missouri River. The experience and knowledge gained in previous physical modeling projects is reflected in the proposal, and the engineers have tackled the difficult problem of scaling sediment transport with good scientific rigor combined with practical compromise.

The preference for a recirculating model makes good sense, and it provides greater flexibility with respect to siting the model. The proposed model layout, flow control system, and construction procedures are based on experience from past models; and there is good expectation that the model can be constructed and commissioned without any show-stopping problems.

The projected cost of model construction is realistic, but yearly operational cost is more difficult to estimate until a testing program is developed.

Construction of a preliminary small-scale version of the large-scale physical model is recommended as both a model design tool and a as visual display tool for demonstrating to partners the utility of the large-scale model

Appendix D

Computational Hydraulics and Transport LLC

300 Front Street
PO Box 569
Edwards, Mississippi
Phone: 601-852-2555
cht@canufly.net

April 26, 2010

SUBJECT: Review of US Bureau of Reclamation's "*Draft* Physical Hydraulic Model

Proposal For COE River Bend Model"

The contract between Computational Hydraulics and Transport LLC (CHT) and the U.S,Army Corps of Engineers, Omaha District (contract # W912P8-06-D-0110) stipulates that CHT is to provide the Omaha District with an evaluation of the subject report. The purpose of this document is to provide that evaluation report including comments,conclusions, and recommendations of Mr. Tom Pokrefke, CHT partner.

The evaluation presented herein is based on documents provided by the U.S, Army Corps of Engineers, Omaha District (Omaha District), the US Bureau of Reclamation (Reclamation), and information presented during the September 10, 2009 meeting at the Reclamation's Technical Services Center at the Denver Federal Center. Furthermore, as the evaluation progressed various references were reviewed to provide additional information. Those references are annotated in the document and a list of references is provided at the end of the evaluation.

<u>General Comments</u>

Before any detailed comments are made, I would like to state that the Reclamation did an excellent and thorough effort presenting the necessary data and information in their proposal. Relative to selection of scales, model bed material, etc., I found the order of presentation very logical and easy to understand, which is very difficult for such a complex and interwoven model study. I have been involved with physical, movable-bed models since 1968 and coal bed models for about 40 years; however, the "largest" scale coal bed I have been involved on was a 1:72-scale undistorted coal bed model. Therefore, the Reclamation's effort to propose a 1:12-scale, or even a 1:14- or 1:15-scale model is a large step in advancing the science of movable coal bed modeling.

It was disconcerting to realize after the detailed discussions/explanations relative to the coal movable-bed model material that the Reclamation was actually considering a semifixed-bed model and not a typical movable-bed model using coal as the bed material. The issue of the semifixed-bed model approach will be addressed at the end of the specific comment section as it was presented in the proposal.

In my review one of the first things I did was number the pages to aid the reader in locating the proposal detail on which I am addressing. I will provide a paragraph number for that particular page as an aid to the reader. Also, any figures that I have included in my review are referred to as numbered "plates" to reduce confusion with the Reclamation proposal.

<u>Specific Comments</u>

On page 1, paragraph 4 – it states that the "creation of the needed additional SWH by widening the river top width an additional 300 to 400 feet at selected locations." I thought that the Omaha District was looking at an additional 600 feet, not 300 to 400 feet.The 600 foot maximum top width increase was presented in the "Missouri River Physical Model Outline" presented at the September 10th meeting. Hopefully this difference does not significantly impact the cost of the model construction, but an additional 200 feet over what was stated in the proposal would be more than 13 feet (at the 1:15-scale) over probably nearly the entire length of the model . The Reclamation should address this discrepancy. It should be noted that on page 2 under "COE-Provided Model Parameters:" the 400 foot maximum widening was repeated.

On page 2, paragraph on "Preliminary Model Scaling Considerations" – it states "Issues in achieving realistic similitude in sediment transport rapidly approach becoming insurmountable problems as model size is diminished." I agree with this statement for "realistic similitude" but I wonder if it is just as true as model size in increased. More will be presented on that issue later in this review relative to model sediment sizing.

On page 2, same paragraph – I question the effort on considering both 1:14 and 1:15 scale models in that the differences between those two scales is relatively insignificant. I think that considering scales of 1:12, 1:15, and 1:18 (or perhaps even 1:20) may have been more helpful. I say this when you consider that 2.0 feet (prototype) of SWH depth at these scales would result in a model water depth of 2.0-, 1.6-, and 1.3-inches, respectively. Even at 1:20 the model water depth would be 1.2-inches. I present this issue for possible consideration as the Reclamation goes forward with more detailed model design.

On page 3, Table 1 – I suggest that this table be moved to the next page after the reference to Table 1. I was confused reviewing Table 1 relative to the model slope since the information presented in that line was based on the "distortion of the model slope by a factor of about 2.4" which is not discussed until page 4, paragraph 2. In consideration of Table 1 however, I found that the proposed distorted model slope is very reasonable and close to the slopes used at the Waterways Experiment Station (WES) on coal-bed models. Franco (1978) showed on his Table B2 for much smaller scale coal-bed model than being proposed by the Reclamation, total model bed slope of about 2.5 ft/mile. It should be noted that the slopes presented on Table B2 were developed through an iterative model adjustment process based on years of experience constructing, adjusting, verifying, and operating coal-bed models. Table 1 shows a model bed slope equal to 2.75 ft/mile for the 1:12 scale model and 3.0 ft/mile for the 1:15 scale model. It is my opinion that the WES and proposed Reclamation slopes have a high degree of agreement and are reasonable values.

On page 3, paragraph 1 – analysis and conclusions developed relative to Reynolds Numbers are very reasonable. Since the occurrence of areas of 2 ft (prototype) depth is probably fairly limited, that value to use as a basis is reasonable. Additionally, as discussed later in the proposal, since the model will be operated using some type of stage/discharge hydrograph, the likelihood for laminar flow to set up and be maintained for an extended period of time is low.

On page 3, paragraph 2 – I agree completely with the statement that modeling suspended sediment load would be very difficult to reproduce in a model of the scale being considered.

Starting on page 3, paragraph 2 and going through page 8, relative to sediment modeling, I have concern with the coal gradations under consideration by Reclamation. My concern is based on my years of experience dealing with coal-bed models and the practicality of working with the gradations presented in Table 2 on page 5. On WES coal-bed models, even though they were constructed at a much smaller scale than the proposed. Reclamation models (see Table B3 in Franco, 1978), the coal gradation was much larger than the gradations presented in Table 2. The WES models used a washed, crushed coal with a specific gravity of about 1.3 and a mean diameter (D_{50}) between 2 and 4 mm. The only exception I found to this was a WES model study conducted in the late 1930's which used coal with a D_{50} of 0.8 mm (see WES, 1938)..

WES normally purchased "natural carbon crushed coal" with a nominal gradation of 1-inch to 1/16-inches. Upon receipt, WES crushed, washed, and sieved the coal prior to installation in a model. The purpose of the washing was to remove as much of the finegrained coal particles as possible. The desired gradation for model-ready coal was a D_{100} of about 9.6 mm (3/8-inch), a D_{50} of about 3.0 mm, and a D_5 of 1.0 mm. Plates 1 and 2 are examples of two sieve analyses for washed coal used in WES models in the past. It should be noted on Plate 2 that with a top screen with 3/8-inch openings and a No. 16 bottom screen approximately 20 percent of the sample was smaller than the No. 16 sieve. During various coal-bed model studies over the years it was observed that these finer grains (we called it coal dust) would segregate from the coarser grains, would act almost as a cohesive layer, and would product a fine-grain “armor” area in the model. This would have to be manually removed from that portion of the model and replaced with suitable coal to allow coal movement to occur. Gessler (1971) observed that“cohesionless prototype bed material cannot be scaled down below about 0.1 or 0.2 mm, otherwise the material will develop cohesion.” This is probably exactly the phenomenon we experience during some of our coal bed modeling.

Franco (1978) stated, “Coal, when properly sized, can be moved without ripples. Coal beds having large quantities of small grain sizes will tend to form ripples....” Even when WES coal-bed models had sufficient fine-grain to create an armor layer, ripples did not form and the bed material movement in the models was always coal waves or dunes.

Concerning coal-bed movement, Franco (1978) stated, “Larger grain sizes will tend to form sand waves or dunes that move progressively downstream with normal velocities. Besides its effect on bed form, larger grain sizes require greater tractive force and velocity to be moved and thereby affect the velocity scale and slope of movable-bed models.”

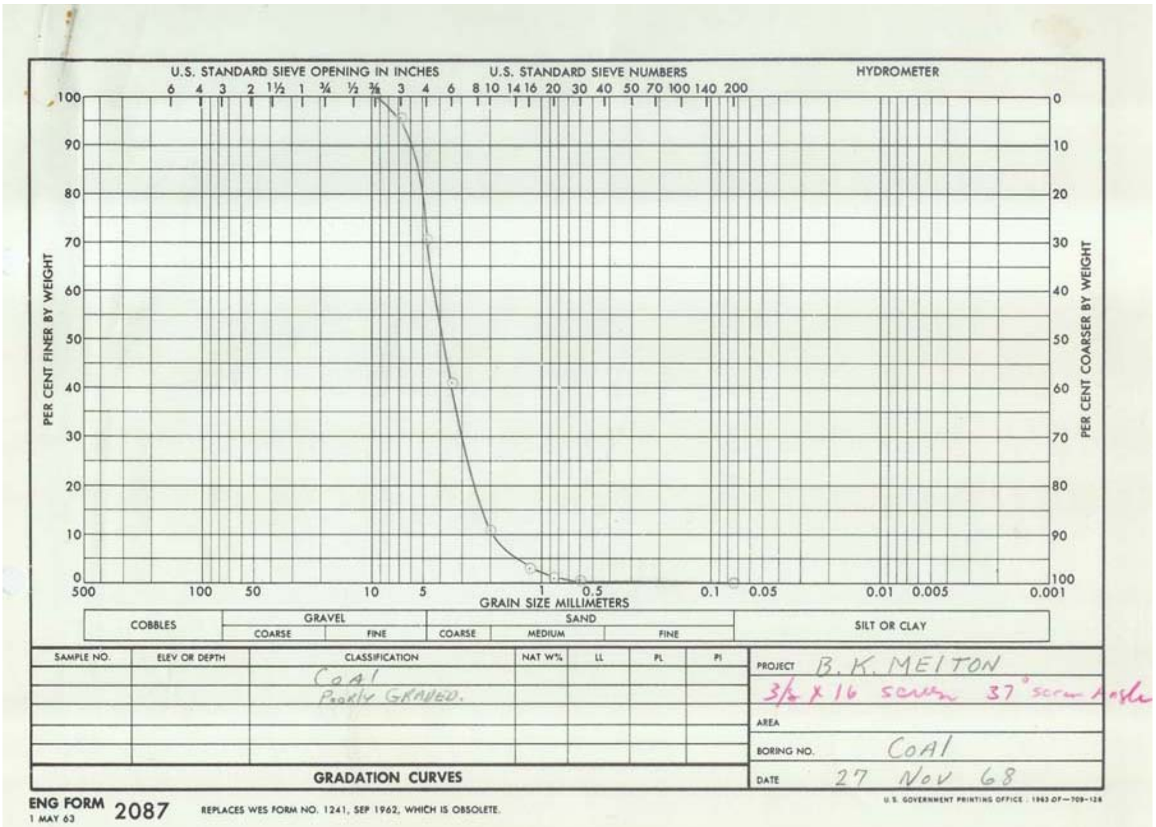


Plate 1. Coal gradation curve for WES model with D_{50} of about 4.0 mm.

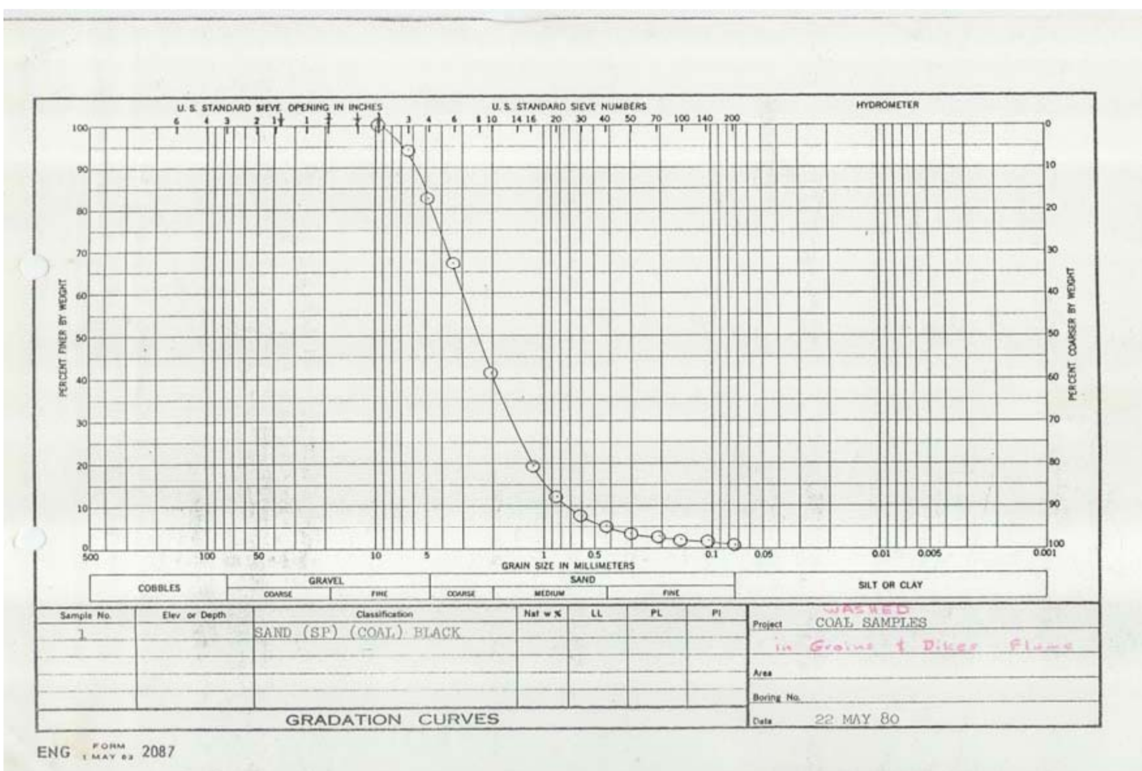


Plate 2. Coal gradation curve for WES model with D_{50} of about 2.5 mm.

The Reclamation presented their approach to determining the necessary sediment gradation for the three model scales in a very thorough and understandable manner. Plus Appendix B to the proposal provided excellent and detailed explanation of the approach taken for the proposal. Based on the information provided in Table 2 on page 5, I plotted the coal gradation curves for the 1:12 and 1:15 scale models on Plate 3. It can be seen from that plate that there is very little difference in the size gradation between the two model scales. It is my opinion that the gradations are in fact so close that practically speaking, it would be very difficult to crush, wash, and sieve large quantities of coal to represent these two gradations.

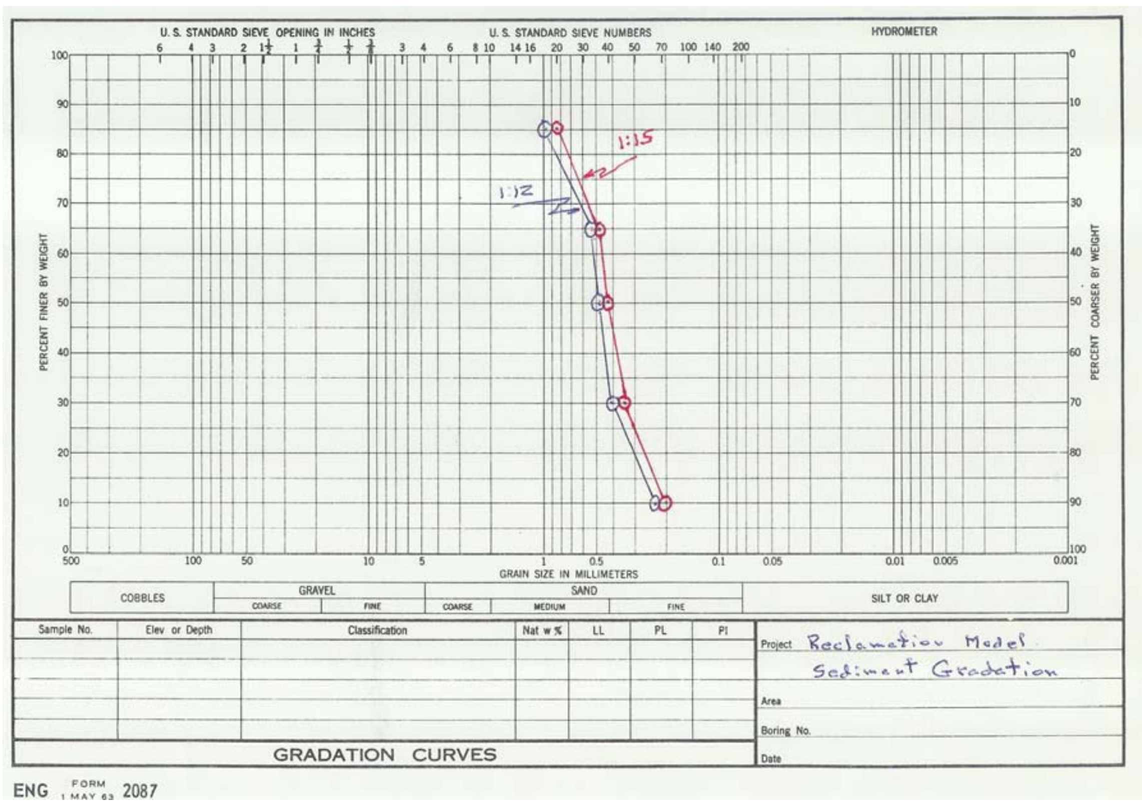


Plate 3. Reclamation model sediment gradation for 1:12 and 1:15 scale model.

On pages 5, Table 2 and Figure 10 on page 14, the proposal presents the projected bed form (ripples or dunes) based on the model sediment sizing. ASCE (2000) states that using sediment diameters “less than 0.7 mm may produce ripples for flows near or slightly above the flow associated with incipient bed motion.” Simons and Richardson (1971) presented a figure showing that for lower stream powers ripple bed forms are present when the mean fall diameter is less than 0.7 mm. Fenwick (1969) stated, “use of too-fine-grained movable-bed material, which can cause such excessive bed riffling as to obscure the determination of true bed elevations.” As shown on Plate 3 above, for both the 1:12 and 1:15 scale

model, about 75 percent of the coal bed material is finer than 0.7mm. Therefore, ripples are highly likely to occur and may do so for the vast majority of the flows reproduced. It is my opinion that the Reclamation would have better results even in the SWH areas of the model if the coal bed material moves in waves and not ripples since ripples would probably occupy a significant portion of the water depth there whereas coal waves would be distributed over the length of the SWH area and not impact the bed roughness as much as ripples.. Concerning cohesive attributes of the model sediment proposed by the Reclamation, Gessler (1971) in the discussion of model bed material becoming cohesive for sizes smaller than 0.1 or 0.2 mm; stated that "If only a relatively small fraction such as 10 or 20% of the bed material in the model falls below this limit, one can simply eliminate the grains below 0.1 or 0.2 mm." Since the D_{10} for the Reclamation proposal falls within this range, as was done at WES, the modelers will have to ensure that these finer fractions are removed if the gradation as proposed is used.
On page 8, Table 6 – a sediment transport time scale is presented. Based on Figure 13 on page 17, the testing hydrograph is 210 days (prototype) long. Therefore, using the Table 6 time scales the model testing hydrographs should be about 69, 61, and 58 hours long for the 1:12, 1:14, and 1:15 scale models, respectively. The model hydrograph lengths for the 1:14 and 1:15 scale models (see Figures 15 and 16) do not agree with the Table 6 data.

On page 8, Table 7 – I tried to understand exactly what was being presented for the "Model Bed Load." It appears that the model bed load rates presented do no include the specific gravity of coat or the sediment time scale presented in Table 6. For example, for a prototype discharge of 80,000 cfs on the 1:12 scale model, Table 7 presents a model bed load of 1.21 tons/hr/ft. At the top of page 8 the Reclamation states the computations were based on an assumed prototype width of 700 ft, which would equate to 58.3 ft at a scale of 1:12. Therefore, the model bed load at the 80,000 cfs (prototype) discharge would be 1.21 times 58.3 which equals 70.6 tons/hr. Assuming using a coal with a specific gravity of 1.3 would mean that the coal weighs 81.1 lb/ft^3 which means that for the 80,000 cfs discharge the modelers are going to have to input over 1,700 ft^3 of coal per hour. To me it was a very eye-opening realization on the volumes of coal that will have to be available and handled during the model testing.

On page 8, Table 7 and Figures 14 through 16 on pages 17 and 18 – I attempted to analyze the bed sediment hydrograph on the figures based on the information on Table 7. On Figure 14 I used the 40,000 cfs event around the prototype time of 40 hours and the 60,000 cfs event at about prototype time 51 hours. I again assumed that the computations were based on the 700 ft river width (58.3 ft model). From Table 7 with the 1:12 scale model for the 40,000 cfs event I used 0.42 tons/hr/ft and for the 60,000 cfs event I used 0.78 tons/hr/ft. Based on this information I computed 24.5 and 45.5 tons/hr for the 40,000 and 60,000 cfs discharges, respectively. However, Figure 14 indicates bed sediment volumes of about 10 and 18 tons/hr for the same two flows, respectively. I computed the same two flows using the 1:15 scale model data on Table 7 with a model channel width of 46.7 ft. Here I used 0.33 and 0.61 tons/hr/ft for the 40,000 and 60,000 cfs flows, respectively. I computed bed sediment loads of 15.4 and 28.5 tons/hr for the two flows, respectively; however, Figure 16 showed bed sediment loads less than 10 tons/hr.

On pages 17 and 18, Figures 14 through 16 – the Reclamation may want to consider operating the model using a stepped-hydrograph for stages and discharges. Franco (1978) gives an excellent explanation and examples for blocking stage and discharge hydrographs for movable-bed model studies. This will allow the Reclamation to operate the model much easier than using a continuously varying hydrograph and make reproduction of hydrographs from one plan to another repeatable and possibly subject to less confusion.

On page 19, paragraph 2 – it appears that the sizing of the headpond and space between the diffuser and upstream model limit is adequate; however, the Reclamation needs to ensure that this portion of the model is of sufficient size for the water from the return channel to change direction by 90 degrees. Depending of the model scale selected, the maximum discharge that has to make that turn could approach 100 cfs and the energy contained in the flow entering the headpond. Based on some of my computations, the Reclamation needs to ensure that the conventional conveyor/hopper system is capable of handling more than 1,000 ft^3/hr. One area of concern should also be the rehandling of the coal over the period of the study. This is especially true when machinery, such as frontend loader, dump trucks, conveyor belts, hoppers, etc. are used. At WES we found that over a period of time rehandling of our coal produced the fine-grain coal material that armored the model bed at times.

On page 19, paragraph 2 – the Reclamation presents the proposed method for reproducing the prototype topography in the model. From this explanation it appears that the Reclamation is not proposing a movable-bed model using crushed coal for the bed material, but is proposing conducting the study using a semifixed-bed model. Relative to semifixed-bed models, Franco (1972) states the following:

> "These types of models are used when channel development and modifications are involved in the design of the project and time would not permit a movable-bed study. During the course of the study involving use of training and channel contraction works, a study is made of currents and the bed is modified by hand, based on the indications developed. …. Plastic material is also used to indicate the movement of sediment and shoaling tendencies."

As proposed by the Reclamation, the model will show areas of deposition, but will not provide any indication of scour on the existing channel topography that may result from construction of new river training structures or modification to existing river training structures. This would also be true of the SWH areas created in the model for the various plans to be investigated. At this point, I had to reevaluate the modeling proposal since conducting a semifixed-bed model study has certain ramifications to be presented.

Since the Reclamation made a thorough and comprehensive effort relative to use of coal for the movable-bed material, in the case of a semifixed-bed model study, the coal would actually be used to trace areas where sediment moves through a particular area or accumulates and shoals in another area. Considering the study to be conducted and the desired information that the Omaha District has stated is needed from the model study, I tried to look at the model study in phases.

Phase 1. During the verification/adjustment/base conditions relative to the existingnavigation channel and point bar (where the SWH will be constructed), the coal will have to essentially move down the main channel without significantly accumulating in any area or “sweeping” the channel completely “clean.” In my opinion, this will require that the roughness in the model will have to be artificially adjusted and that having the coal material move in waves, rather than with ripples, would be essential to produce meaningful model results. Operation of the model in essentially a “fixed-bed mode” is what Steve Hughes suggested in the September 10th meeting. Taking this approach first in the adjustment/verification phase will help establish operational logistics and help the Reclamation observe potential problems and/or anomalies associated with the model and resolve those issues during the adjustment/verification phase. Once the “fixed-bed mode” tests are completed, sediment can be introduced into the model and tracer testing can be conducted to complete this phase.

Phase 2. Once the verification/adjustment/base tests are completed, the SWH areas should be excavated, but no structures associated with the plan installed in the model. This is another time that the model could be operated in the “fixed-bed mode” to make some observations and possible adjustments. Then a test should be run to verify that the point bar area will in fact accumulate tracer coal material. It seems reasonable to assume that shoaling should occur on the point bar, although some of the existing prototype river training structures may have to be in place to verify shoaling on the point bar. This test would be an interim test between the base test and SWH tests to ensure that the model reproduces expected river engineering phenomenon. This test will also aid in evaluating the existing navigation channel for impacts.

Phase 3. Following the Phase 2 test, the SWH area plans can be constructed in the model and testing conducted to provide the information that the Omaha District needs from the study. This will be based on what happens with the coal tracer material in the SWH area and navigation channel. If the coal accumulates in the SWH areas, which is part of the point bar and an area typically associated with shoaling, then the plan would have to be modified to focus on reducing the shoaling tendencies in the SWH areas. Until the point is reached that shoaling in the SWH areas in minimized, the impacts to the navigation channel cannot be meaningfully evaluated. With all this being said, I must remind the reader that **none** of this testing on a semifixed-bed model will evaluate the potential for scour within the SWH areas. Perhaps, as Franco (1972) stated, around dikes or structures associated with the SWH plan the Reclamation can obtain meter or point velocities and use these velocities to determine the potential of scour. Then the model topography can be modified based on measured velocities and discussions between the Reclamation and Omaha District.

At this point the issue of navigation needs to be addressed. Using the phased operation discussed above, the semifixed-bed model can be used to evaluate navigation issues resulting from installation of the SWH areas. On navigation models at WES one critical type of data always taken are current directions and velocities (CD&V's). The purpose of the CD&V's is to determine how the currents at navigation depth (9 ft for the Missouri River) are directed and their magnitudes across the channel and moving downstream.

ASCE (2000) discussed CD&V's entitled "flow velocities" on a riverine model and numerous WES reports of navigation model studies also have examples of this type of data. Plate 4 is an example of CD&V's from a WES model. The Reclamation should consider taking CD&V's for at least a low flow, medium flow, and the maximum navigable flow for this reach of the Missouri River. That data should be taken at a minimum for the semifixed-bed model phases 1 and 3, but during all three phases would be ideal. These data will provide information for the existing conditions (Phase 1) and with the SWH areas in place (Phases 2 and 3). Differences in the CD&V's between the various phases can be attributed to the SWH project and the Omaha District can determine if these differences are significant enough to modify the SWH design or to make adjustments in the navigation channel training structures. Whether testing a remote-controlled tow with loaded barges and a pusher is needed should be based on an analysis of the data from the various phases. On WES navigation model studies remote-controlled tow tests are usually conducted with base conditions and when final improvement plans are developed on the model.

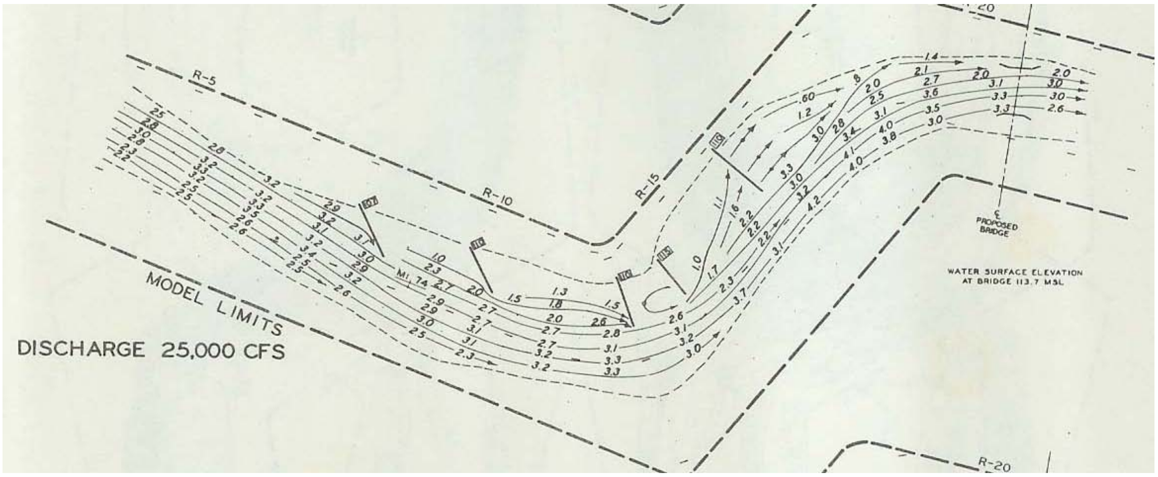


Plate 4. Example of Current Directions and Velocity data from WES model. Flow is left to right.

On page 19, paragraph 3 (which carries over to the top of page 20) – there is a discussion of water-surface measurements. I assume that the Reclamation is considering monitoring water-surface elevations using piezometers located along the model with gage wells connected with pipes into various locations along the main navigation channel and to the SWH.

On page 20, partial paragraph at the top of the page – the Reclamation mentions the possibly of having an “instrumentation platform” spanning the model width. By my measurements (from Figure17) I figured that the platform would have to be about 150-ft long. At WES we had several platforms spanning river models but never one that long. Also, it is unclear what is meant by “instrumentation” and if the plans are to use this platform to make elevation measurements, significant sagging of the platform may occur.

One other issue that should be addressed relative to the modeling effort is water temperature. Franco (1978) stated in his discussion on using coal as the movable-bed material, “Coal beds having large quantities of small grain sizes will tend to form ripples, particularly when water temperature is lowered to less than about 60$_{o}$F.” There is a discussion in Fenwick (1969) in the dynamics of sediment transport relative to water temperature on the Missouri River at Omaha. I am sure that this is a phenomenon that the Omaha District personnel are aware of and deal with often. The issue is brought up at this point strictly for consideration by the Reclamation and to ensure repeatability in the model results. If the model water temperature is allowed to vary significantly over the testing periods, the model results may be influenced, to the detriment of the study, by those variations.

On final issue relative to the Recirculation Model Option presented on page 19 is pointed out in Franco (1978). Franco stated, “It is generally not practical to use coal in models constructed outdoors because of the effects of the weather.” In the case of the Reclamation proposal, this “warning” can be minimized since a semifixed-bed model study is being considered. Additionally, if the model design includes an option of flooding the navigation channel and SWH areas during non-operational times and keeping the coal tracer material underwater at those times, the effects of the weather should be minimized. With all of that being said, the Reclamation may also want to consider the impacts of freeze/thaw of the model topography which is to be constructed "using local soils treated with a high quality soil binder to add stability." That binder may be capable of handling the freeze/thaw issue.

On page 20 relative to the Cost Estimation – I reviewed the estimated costs associated with the model study and the Estimate Worksheets on pages 23 through 25. In my opinion the Reclamation did a thorough job covering virtually all of the aspects of the study. I do not feel comfortable addressing the rates presented since I have been out of actually modeling design and construction for several years since I retired from WES and really do not have a "handle" on what costs and/or rates would be in the Reclamation's modeling area. I will leave the cost estimate details to the ERDC-CHL personnel if they deem it necessary to address. With all of this being said, I will say that after listening to the discussions on the modeling effort in the September 10th meeting, I estimated (strictly a "seat-of-the-pants" guess) that with the size of the model being considered and the extent of the modeling required to address the SWH issues that the model study would cost at least $5-million and would last 5 years. I was close on the time frame, but 50% off on the estimated cost.

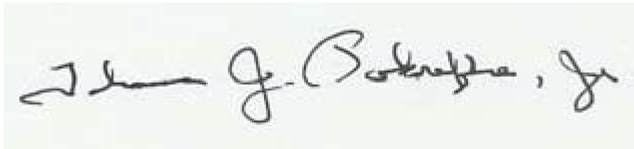
Recommendations

The following recommendations are provided for consideration by the Reclamation and Omaha District as further details are worked out for the Physical Hydraulic Model Study for the COE River Bend Model:

16) The issue relative to river widening for the SWH needs to be resolved. The difference in the Reclamation proposal of 300 to 400 ft is significantly different than the 600 ft stated by the Omaha District.
17) Rather than considering potential model scales of 1:12;, 1:14, and 1:15, it is suggested that scales of 1:12, 1:15, and 1:18 (or 1:20) be considered.
18) A coal gradation that does not produce ripples but rather coal waves is recommended. Such a gradation will also reduce the possibility of the coal acting cohesive and armoring the model bed.
19) The Reclamation should select one gradation and use that regardless of the scale model to be constructed. Small variations in gradations, such as those presented in the proposal, will be difficult to obtain, especially for the large volumes of coal that will be required to conduct the model study.
20) During model operation re-handling of coal material should be minimized to reduce "grinding" the coal and creating unacceptable fine-grain fractions that may impact the study.

21) It is recommended that a coal gradation coarser than those presented in the proposal be considered. One suggestion would be a coal gradation with D_{85} of about 1.6 mm,D_{65} of 0.9 mm, D_{50} of 0.8 mm, D_{30} of 0.8 mm, and D_{10} of 0.4 mm. This gradation or one similar to it will eliminate the likelihood of the model sediment moving in ripples and staying non-cohesive provided the fines (grains smaller than 0.1 or 0.2 mm) are washed out during processing. The Reclamation may want to consider conducting some flume tests for various gradations to determine the sediment movement and bed forms and the influence of the fines on movement.
22) Recommend that the computed sediment loads be checked to ensure that the quantities shown in Figures 14 through 16 are correct.
23) Consider operating the model using stepped stage/discharge hydrographs to make the model operation easier and to enhance testing repeatability.
24) Recommend that the transition from the return channel into the headpond is sufficiently sized to allow the flow to "turn" to maintain a proper flow distribution into the model.
25) Recommend that all project stakeholders be informed that a semifixed-bed model study is being conducted and such a model has the capability of determining areas of shoaling but does not have the capability of producing scour.
26) Consideration should be given to conducting a phased testing procedure to document specific changes for the various plans. A phased testing procedure will also allow collecting detailed data around structures and channels to determine the potential for scour in those areas. If appropriate, the potential scour areas can be modified in the semifixed-bed model prior to continuation of testing.
27) During the phased testing "fixed-bed" tests can be conducted to evaluate the model operation and determine if after Phase 1 local velocities have increased sufficiently to potentially create local scour issues. That information can then be used to modify the plan.
28) To address navigation issues the collection of current direction and velocity data for at least 3 flow conditions during the various phases of the testing procedure is recommended.
29) The issue of model water temperature should be addressed to ensure repeatability of the model testing program over time and through various weather seasons.
30) The model design should include consideration of maintaining the coal model material under water during non-operational periods.

The comments/suggestions/recommendations provided herein should in no way be considered as a criticism of the Reclamation or their proposal. The model study being proposed truly extends far past the "norm" for sedimentation modeling, and the effort put forward by the Reclamation staff is noteworthy. My sole purpose is to provide some hopefully meaningful points to enhance this modeling effort.



Thomas J. Pokrefke, Jr. Partner

<u>References</u>

American Society of Civil Engineers (ASCE), *Hydraulic Modeling Concepts and Practice*, ASCE Manuals and Reports on Engineering Practice No. 97, American Society of Civil Engineers, Reston, VA, 2000.

Fenwick, G. B., (Editor), *State of Knowledge of Channel Stabilization in Major Alluvial Rivers,* Chapter V, *"Fluvial Hydraulic Models,"* Technical Report No. 7, Committee on Channel Stabilization, Corps of Engineers, U.S. Army, October 1969.

Franco, John J., *Notes on Model Techniques for Investigation of Channel Stability Problems*, Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, November 1972.

Franco, John J., *Guidelines for the Design, Adjustment and Operation of Models for the Study of River Sedimentation Problems*, Instruction Report H-78-1, Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, August 1978.

Gessler, J., published by Shen, H.W. (Editor), *River Mechanics*, Chapter 21, "*Modeling of Fluvial Processes,"* Colorado State University, Fort Collins, CO, 1971.

Simons, D.B. and Richardson, E.V., published by Shen, H.W. (Editor), *River Mechanics,* Chapter 9, *"Flow in Alluvial Sand Channels"*, Colorado State University, Fort Collins, CO, 1971.

WES, *Model Study of Plans for Channel Improvement at Dogtooth Bend, Mississippi River,* Technical Memorandum No. 109-1, U.S. Waterways Experiment Station, Vicksburg, MS, April 2, 1938