9. Analysis

a. Analysis tools for dam removal

v. Hydrodynamic, sediment transport and physical modeling

1.0 Rationale

Sediment erosion from the reservoir and subsequent deposition downstream are frequently the main concerns associated with a dam removal due to the possible effects on infrastructure, navigation, water quality, fisheries, habitat, etc. (ASCE 1997). More specifically, reservoir erosion could lead to bank failure, high suspended sediment loading, and release of contaminants. Downstream, excessive sediment loading could raise bed elevations leading to flooding, increase lateral channel mobility leading to bank erosion, and, if the sediment is fine, negatively affect spawning gravels (ASCE 1997). In some systems, however, controlled release of sediments can restore the downstream ecosystem by adding complexity in the form of larger particles, wood, and nutrients (ASCE 1997).

The three main ways to manage reservoir sediment when removing a dam are river erosion, mechanical removal, and stabilization (ASCE 1997; Randle 2003). River erosion entails allowing some or all of reservoir sediment to be eroded from the reservoir by the river, and is typically the least expensive but possibly most detrimental alternative (Randle 2003). Mechanical removal, or dredging, involves removing some or all of the reservoir sediment prior to exposure of sediment to river flows and is an expensive but possibly necessary alternative if sediments are contaminated, dominated by fines, in large quantity, or there is sensitive habitat or infrastructure downstream (Randle 2003). Stabilization is used in similar situations, but the stabilization alternative seeks to prevent sediment releases to downstream by engineering a channel through or around the sediment and protecting against erosion (Randle 2003).

The best alternative or combination of alternatives for a given dam removal is a function of a number of factors such as: sediment quality, sediment quantity, ability of sediment to mobilize, water quality, predictability of erosion and deposition, riparian infrastructure and landowners, downstream confinement, presence of threatened and endangered species, and cost (SOS workshop). Preferred sediment outcomes in the reservoir and downstream can be optimized using the range of options within each sediment management alternative and combinations of sediment management alternatives. For example, within the river erosion alternative, there is a range of options based upon the choice of the timing (low flow or during a runoff event), amount (complete dam removal or removal in stages) and type (fine or contaminated sediment can be removed through dredging prior to sediment release) of sediment available for erosion.

Hydraulic, sediment transport, and/or physical models have been used to evaluate alternatives and/or predict dam removal outcomes for several slated (e.g. Mantilija Dam) and executed (e.g. Chiloquin Dam, Savage Rapids Dam, Marmot Dam) dam removals. Several sets of researchers and professionals have adapted existent hydraulic and sediment transport models (e.g. HEC-6 or HEC-6T (Goodell and Bradley 2005; Mussetter and Trabant 2005; Thomas 2005)), and two groups have developed new models explicitly for dam removal: DREAM-1, DREAM-2 (Cui et al. 2006a; Cui et al. 2006b) and The Dam Remover: MARK1 (Cantelli et al. 2007). With physical models, one is able to iteratively simulate 3D processes present in rivers in a controlled, accessible setting.

2.0 Hydrodynamic and sediment transport models:

2.1 General Data Requirements

Geometry of channel and floodplain, *particle size distributions (fine vs. coarse, cohesion), *sediment layer thickness, elevation to bedrock in reservoir (base level), roughness, boundary conditions (discharge, upstream sediment supply, downstream bed elevation, downstream water depth)

Some of the above requirements can be estimated or approximated without great loss of comparability with reality. The accuracy of the two starred elements, particle size distribution and sediment layer thickness, is essential for a reasonable approximation of outcomes (Cui and Wilcox 2008).

2.2 Modeling Procedure

1) Conceptual model

   Prior to choosing a hydraulic or sediment transport model, it is a good idea to build a conceptual model. Conceptual models can be used to determine the essential components that need to be modeled (e.g. rapidly varying flow at the downstream face of the sediment wedge), gain a qualitative understanding of the process, and provide a check on the numerical results (Randle and Bountry 2005). The conceptual model should describe what will happen to the sediment in the reservoir and the upstream sediment load after the dam is removed (Randle and Bountry 2005).

2) Initial parameters for numerical model

   The first build of a model will likely consist of simplified field data (e.g. three dimensional data converted into one dimensional data), and a "best guess" at model specific parameters, such as the hiding factor in Parker's (1990) sediment transport formula (Thomas and Chang 2008). For one dimensional models, such as DREAM-1 and DREAM-2, it is especially important to average data over the appropriate spatial scale, multiple channel widths or a reach, so that features such as pool-riffle sequences and alternating bars, for which the generation mechanisms cannot be simulated in a 1D model, are not being simulated (Cui and Wilcox 2008). Another consideration for models, such as HEC-6, which are only capable of modeling steady flow is having a sufficiently small time step, and therefore short cross section spacing, to be able to model the rapidly varying flow and steepness of the downstream face of the sediment wedge (Goodell and Bradley 2005).

3) Parameter adjustment

   a. Calibration of numerical model

   Once the model is complete, it needs to be tested so that any estimated parameters can be adjusted to fit the system. If there is sufficient field data (at least two physical snapshots in time with the hydrology and any other perturbations in between them), model results can be compared to real world results, and parameters can be adjusted to make the model results more comparable.

   b. "Zero-process," "warm-up period," base run, or priming

Another frequent precursor to long-term, large-scale simulations is a “zero-process” (Cui et al. 2006b), “warm-up period” (Randle and Bountry 2005), base test (Thomas and Chang 2008), or priming (Bountry and Randle 2001). When performing long-term modeling, the model must be able to reproduce background conditions which can be assumed to be at quasi-equilibrium: aggradation and degradation occur within limited bounds as would be expected without major perturbations (Cui et al. 2006b; Cui and Wilcox 2008; Cui et al. 2008). For simulating a dam removal, this can consists of running the model with the appropriate predicted/future hydrology but the dam in place, and adjusting estimated parameters until the channel is in quasi-equilibrium (Cui and Wilcox 2008). Subsequent model runs with the dam removal and future/predicted hydrology should begin with the resulting quasi-equilibrium model, and be compared to the quasi-equilibrium model result (Cui and Wilcox 2008).

By using and comparing to a state of model quasi-equilibrium or performing a calibration with real world data, results associated with modeling the field data can be separated from results related to the dam removal.

4) Validation of numerical model

   Ideally, there is sufficient field data to compare model results to real world results for validation as well as calibration. Validation consists of comparing model results to real world results that have not been used to adjust model parameters. Validation establishes the soundness of applying the model to conditions outside of those used to create the model.

5) Plan run/test: Evaluation of dam removal

   Once the model has been created and adjusted, the dam removal and predicted hydrology can be applied and the results can be evaluated relative to the conceptual model and base run.

6) Sensitivity analysis

   To assess the influence of different model parameters on model results, and therefore the influence of uncertainty in model parameters, the model should be run with boundary and/or initial conditions changed by 25 % (Thomas and Chang 2008).

<u>2.3 Model considerations:</u>

It has been recommended that for models to accurately represent the important processes associated with dam removal, models must be able to handle:

1) Subcritical, supercritical, and transient flows

2) Multiple size classes/layering;

3) Changes in channel width for the reservoir; and

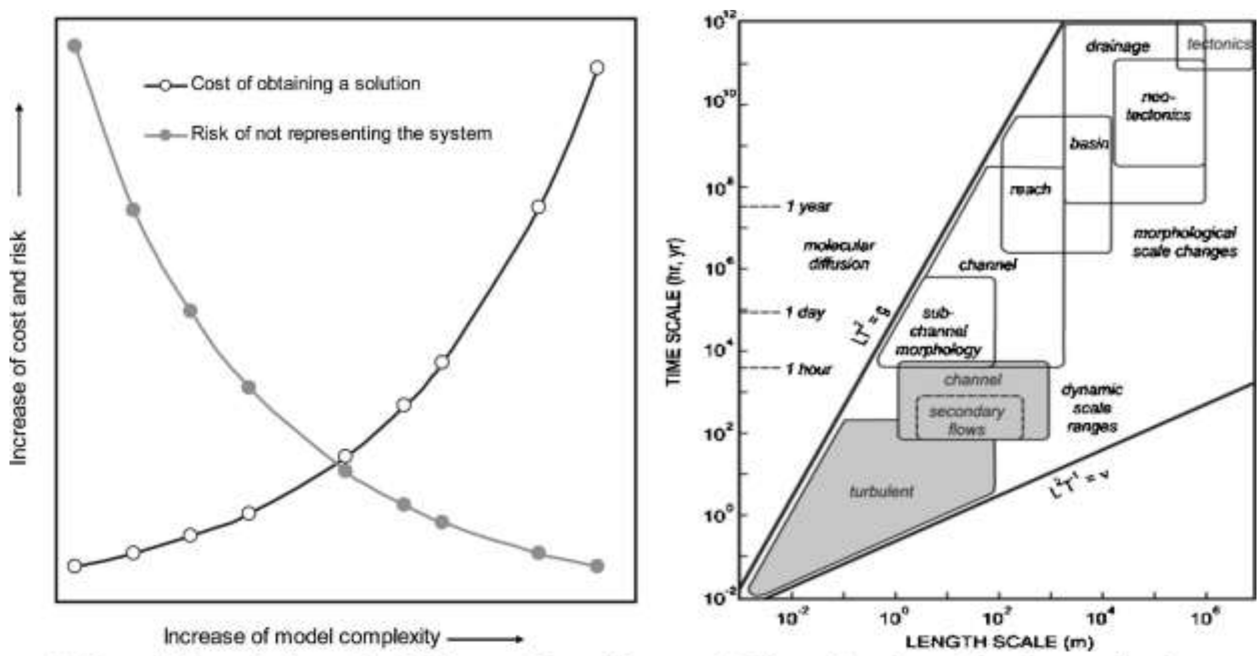
4) Gravel abrasion (Cui et al. 2006b)

Alternatively, models without some of the above capabilities (e.g. limited to single layer or single channel width), may be used with manual adjustments during model runs (Mussetter and Trabant 2005; Randle and Bountry 2005).

<u>2.4 1D vs. 2D vs. 3D:</u>

One of the main deciding factors for model choice, including dimension, is whether the model is capable of simulating all necessary processes and complexity for the given problem (Papanicolaou et al. 2008). Model dimension choice requires balancing cost, risk and complexity as well as considering the spatial and temporal scales of interest (see figures from (Papanicolaou et al. 2008). Another consideration included in cost is whether it is possible to collect the data required for the desired model complexity (Papanicolaou et al. 2008).

One dimensional hydraulic and sediment transport models have been the dominant models used for dam removals because of the large spatial scales and long time frames typically of interest for dam removals. Two and three dimensional models, due to their longer processing times, are currently being put to use in coordination with one dimensional models for short time frames in limited locations requiring more detail (Spasojevic and Holly 2008). In areas such as bends, piers, and hydraulic structures, multi-dimensional models are typically required (Papanicolaou et al. 2008). If a rapid removal can be assumed or there is a legacy thalweg, one straight channel can be reasonably expected to form in the reservoir and using a one dimensional model is acceptable (Cui and Wilcox 2008). However, both 1D and 2D models tend to over predict pool deposition due to the use of average or depth averaged velocities (Randle and Bountry 2005).



a) The model complexity trade-off diagram (adapted by Overton and Meadows 1976).

b) Illustration of spatial and temporal scales (adapted by Church 2006)

From (Papanicolaou et al. 2008)

2.5 Examples:

Model (Applications)	**Model Capabilities**	**Data input**	**Data output**	**Relevant questions**
CONCEPTS (Langendoen et al. 2005)	1D, erodible boundary, non-cohesive/ cohesive, unsteady	upstream discharge and sediment, bed particle size distribution, *structure properties*, water temperature, cross section spacing, cross section geometry (as streambed, stream bank, and floodplain): elevation of bed rock, porosity of streambed, hiding factors, number of soil layers, depth below bed surface, bed composition, cohesive bed parameters, roughness (Manning's n or use Karim's friction factor relation), bank top elevation of the soil layer, bank material properties, bank critical shear stress, bank material composition, bank groundwater table,	discharge, flow depth, stage, velocity, flow area, flow top width, wetted perimeter, hydraulic radius, conveyance, sediment yield, cum. sediment yield, friction slope, energy head, Froude number, bed shear stress, sediment discharge, thalweg elevation, change in bed elevation, cum. change in bed elevation, lateral erosion, cum. lateral erosion, in-bank top and bottom width of cross section, factor of safety, bank height, particle size distribution, characteristic particle sizes, apparent cohesion, pore-water force, matric suction force, weight of failure block, weight of water on the bank, horizontal component of confining force, groundwater elevation, location of bank top	sediment transport, bank erosion
DREAM-1 **DREAM-2** (Cui et al. 2006a; Cui et al. 2005; Cui et al. 2006b; Cui et al. 2008)	1D, erodible/ movable boundary, non-cohesive, steady/quasi-steady	cross section geometry (rectangles with widths equal to the bankfull channel width) and spacing, channel profile, thickness of fine **(and coarse)** sediment deposits in the reservoir and downstream reaches, **surface and subsurface particle-size distributions**, upstream sediment load and discharge, **volumetric abrasion coefficients for coarse sediment,** and	Sediment thickness in the reservoir and downstream, sediment flux rates, **surface and subsurface particle size distributions**	sediment transport, **particle size distribution**

		the downstream boundary condition (downstream water surface elevation or fixed bed elevation), *angle of repose*		
FLUVIAL-12 (Chang 2005; Chang 2008)	2D, erodible/ movable boundary, non-cohesive, steady/ unsteady	Cross section geometry and spacing (in Hec-2 format), roughness (Manning's n), sediment layer thickness, bed particle size distribution, discharge, slope, *water temperature*, *angle of repose*	Gradation of sediment load, transverse distribution of depth averaged velocity, initial bed composition, water surface profile through time and space, channel width, water surface elevations, discharge, velocity, energy gradient, median sediment size, bed-material discharge, cross-sectional profiles, sediment delivery	sediment transport, flood rise
GSTAR 1D (Now SRH-1D) (Greimann and Huang 2006)	1D, erodible/ movable boundary, non-cohesive/ cohesive, steady/ unsteady	cross section geometry and spacing, angle of repose (above and below water), roughness (Manning's n), discharge, upstream sediment load, downstream boundary condition (water surface elevations, discharge, rating curve, or weir), *ineffective flow areas*, *water temperature*	cross section geometry, sediment load, water surface elevation, discharge, grain size distribution, bed shear stress, channel top width, hydraulic radius, friction slope, sediment volume deposited, sediment mass balance, sediment concentration, bed thickness, sediment load	sediment transport, flood rise, particle size distribution
HEC-6/ HEC-6T (Goodell and Bradley 2005; Mussetter and Trabant 2005; Thomas 2005)	1D, movable boundary, non-cohesive, steady flow	cross section geometry and spacing, roughness (Manning's n), bed layer thickness, bed particle size distribution, upstream sediment load, sediment properties, discharge, temperature, downstream water surface elevation	bed elevation changes, water surface elevations, volume of sediment entering and exiting model, transport potential, load, bed gradation per grain size,	sediment transport, flood rise
HEC-RAS (Bountry and	1D, mobile boundary, non-	cross section geometry and spacing, roughness (Manning's n), discharge,	Water surface elevations, velocities, contraction or expansion loss, critical	flood rise, sediment

Randle 2001; Randle and Daraio 2003; Roberts et al. 2007)	cohesive/ cohesive, steady/quasi-unsteady/ unsteady flow, water quality	upstream/downstream flow boundary conditions (e.g. water surface elevation, rating curve, critical depth, normal depth), bed particle size distribution, sediment control volume (erodible limits, minimum elevation/maximum depth), sediment boundary conditions (e.g. rating curve, sediment load series, equilibrium load), *ineffective flow areas*, *structures*, *water temperature*	depth, energy grade elevation, cross section area, Froude number, hydraulic depth, total stream power, cross sectional flow, shear stress, top wetted width, wetted perimeter, bed elevation change, sediment weight, sediment volume, sediment flux	transport, water quality
The Dam Remover: MARK1 (Cantelli et al. 2004; Cantelli et al. 2007; Wong et al. 2004)	1D, mobile boundary, non-cohesive, steady	reservoir cross section geometry (as trapezoid)- slope of channel banks, initial channel bed width, maximum channel bed width; cross section spacing, delta slope, front slope, upstream bed profile intersection, downstream bed profile intersection, critical Shields stress, fraction of bed shear stress acting on channel banks, submerged specific gravity of sediment, flood discharge, median grain size, geometric standard deviation, bed porosity	reservoir bed elevations, reservoir channel bed width, reservoir water depth, reservoir total sediment transport	sediment transport

Data about models largely from manuals or the model interface (with the exception of DREAM-1 and DREAM-2); Data input components in italics are optional or have default values in the model

2.6 Additional Information

Randle and Bountry (2005) provide a comprehensive discussion of components and issues with numerical modeling of dam removals. Cui and Wilcox (2008) discuss the history of dam removal modeling, and the essential components of dam removal models. Papanicolaou et al. (2008) provide an overview of many hydrodynamic and sediment transport 1D, 2D, and 3D models.

3.0 Physical models

Flume experiments have been shown to provide powerful and accurate information regarding the sediment dynamics of rivers associated with dam removal (Cui et al. 2008, Cantelli et al. 2004). Such experiments inform both conceptual and numerical models, leading to potentially more informed decision making with the availability of better predictions and descriptions of adverse impacts. In addition, flume experiments offer a number of important opportunities, including the ability to focus on one variable at a time, to study variables through a wide range, and to make detailed and thorough measurements, making flume experiments an efficient way to test hypotheses and make accurate observations of complex physical and biological processes.

There are two types of physical models: rigid boundary, which can be used to examine hydrodynamics, and erodible boundary, which can be used to examine hydrodynamics and sediment transport. With the downscaling of geometry typically employed to create physical models, scaling of kinematics (time and velocity) and dynamics (force) is also required to make processes observed in the physical model and prototype, or river being modeled, comparable (Ettema et al. 2000; Pugh 2008).

3.1 Definitions:

Dynamic similarity: the ratios of hydraulic forces (driven by gravity, viscosity, pressure, surface tension, and elasticity) between the model and prototype are the same (Pugh 2008).

Froude-number similitude: similitude for fluid inertia and gravity forces (needs to be satisfied at geometrically similar locations for flows with a free surface) (Ettema et al. 2000)

Geometric distortion: unequal vertical and lateral scales between the model and prototype (typically smaller vertical scale than horizontal scale in order to achieve sufficient dynamic similitude) (Ettema et al. 2000).

Geometric similarity: the ratio of horizontal and vertical dimensions between the model and prototype are the same (Pugh 2008).

Kinematic similarity: the ratio of velocities and accelerations between the model and prototype are the same (automatically occurs if dynamic similitude is satisfied) (Ettema et al. 2000; Pugh 2008).

Reynolds number similitude: similitude for fluid inertia and viscous forces (applies to modeling flow around or in a hydraulic structure or channel resistance) (Ettema et al. 2000).

Scale ratio: prototype value/ model value

Similitude: indicator of the relationship between the model and prototype (Graf 1971).

Tilting: unequal vertical and downstream horizontal scales between the model and prototype (Julien 2002)

3.2 Modeling Procedure (Modified from Chapter 12 of Ettema et al. 2000)

1) Choose similitude criteria by identify relevant processes and forces; information desired
    a. A rigid-bed model is one in which the Shields parameter of the bed material, τ_*, is less than 0.03. Typically, rigid-bed model scales are based on either:
        i. Exact geometric similitude using Froude-number similitude (resistance to flow is neglected and flow is 3D with non-negligible vertical acceleration); or
        ii. Distorted/tilted geometry using Froude-number and Manning-Strickler similitude (resistance to flow is important and gravitation acceleration dominates lateral or vertical) (Julien 2002).
    b. A mobile-bed model is typically used when the Shields parameter of the bed material, τ_*, is greater than 0.06. Four similitude criteria need to be met for mobile-bed models (Julien 2002):
        i. Froude number
        ii. Resistance (Manning-Strickler)
        iii. Dimensionless grain diameter (d_*)
        iv. Bed-material entrainment (Shields parameter)

2) Determine physical extent of model
   Considerations:
    a. Minimum upstream and downstream extents to capture flow effects at points of interest. Downstream must extend far enough to capture tailwater effects.
    b. Maximum model size is typically a function of facility size (floor space) and the maximum discharge that can be produced.
    c. Viscosity and surface tension of water provide the upper limits for the geometric scale.
3) Gather required data
    a. Bathymetry
    b. Hydrology
    c. Sediment properties
    d. Proposed removal plans
4) Determine model scales
    a. Facility limitations: maximum discharge, maximum head, floor area, ceiling height (consider if will need scour or deposition capability as well)
    b. Construction considerations: achieve required accuracy and precision (small model discrepancies can lead to large differences at prototype scale)
    c. Instrumentation limitations: size and sensitivity – access, measuring volume surrounding an instrument such as a velocity meter
    d. Scale effects (discrepancies between model and prototype behavior due to reduced scale of model)

i. introduction of additional forces and processes (e.g. ionic forces for particles smaller than 0.1 mm)

ii. cavitation & friction (small orifice holes), surface tension (Froude-scaled models with depth less than 25 mm)

iii. Limitations

1. USBR for spillways of large dams: length scale ratios X_r 30-100; min depth 75 mm
2. Canal structures X_r = 3-20
3. River model horizontal scales X_r = 100 to 1000, vertical scale ratio for distorted Y_r = 20 to 100
4. vertical distortion may require roughness elements – blocks, stones, or metal strips (may alter lateral currents, large eddies, large-scale mixing)- metal mesh laid flat on bottom
5. For loosed-bed modeling, a limit of 6 for vertical distortion (Ettema et al 2000)

5) Model creation

a. Accuracy and precision need to be sufficient to recreate prototype features that influence the process of interest

b. Horizontal and vertical control for the model needs to be accessible and exterior to the model.

c. The inlet reservoir should have a baffle system and tailwater reservoir.

Examples

1. Baffle materials: rock, perforated plywood sheets, fiberglass insulating panels, furnace filter panels, arrays of short conduit sections, stacked pipes, metal vanes
2. Water level control in tailbox: flap gates

d. Elevated walkways are helpful for measurements

e. The materials used to make the model should be chosen based upon visibility, roughness, durability, resistance to deformation due to water absorption, and strength.

Examples:

1. Lumber (sugar pine, redwood) and plywood (epoxy-coated, marine-grade)
2. Concrete
3. Metal – aluminum, brass or stainless steel (prevent corrosion)
4. Fiberglass or urethane coatings
5. Clear acrylic plastic (Lucite or Plexiglas)- visibility, ease of machining
6. High-density closed-cell urethane foam (resistance to water damage, easy workability)
7. Plywood contours, wire mesh, thin coat of mortar
8. Sediment- constrained by particle size (relative magnitude of weight and interparticle electrostatic force) and specific gravity; beware of interparticle electrostatic forces, bed ripples

Sediment considerations

i. Model sediment must be denser that model fluid

ii. Model sediment should not float (surface tension forces when sediment only slightly heavier than fluid and when sediment is fine)
iii. No breakdown or decay of sediment during transport
iv. Sediment should not discolor the water
v. Angle of repose
vi. Simulate size gradation if modeling bed armoring
vii. < 0.7 mm diameter may result in ripples for flows ~ incipient motion

Table 1: Properties of Typical Model Sediment (from Ettema, 2000 and Julien 2002)

Material	Specific Gravity	Size (mm)	Comment (Julien 2002)
Polystyrene	1.035-1.05	0.5-3	Floats, difficult to wet, durable
Gilsonite (an asphalt)	1.036	variable	
Nylon (polyamidic resins)	1.16	0.1-5	
Lucite	1.185	variable	
PVC	1.14-1.25	1.5-4	Hydrophobic
Perspex	1.18-1.19	0.3-1	Dusty
Acrylonitrile butadiene styrene	1.22	2-3	Adds detergent against air-bubble adherence
Crushed brown coal	1.20-1.27	variable	
Crushed apricot pits	1.32	0.3	
Ground walnut shells	1.33	0.15-0.41	Possible inhomogenity in specific gravity and sorting
Styravene	1.40	variable	
Bakelite	1.40-1.50	0.3-4	Porous, tends to rot, changes diameter, floats
Pumice	1.4-1.7		
Loire sand	1.5	0.63-2.25	Dusty
Lytag (fly-ash)	1.7	1-3	Porous
Quartz sand	2.65	0.1-1.0	

6) Instrumentation (ASCE 1993)
   a. Discharge:
      i. Open channel: weirs and flumes
      ii. Closed conduit: venture meters, orifices, and flow nozzles
      iii. Specialized devices: rotameters (less accurate), ultrasonic and electromagnetic flow meters
      iv. Calibration: volumetric and weight tanks
   b. Velocity:
      i. Classic: pitot tubes, current meters, propeller meters)
      ii. Other: electromagnetic current meters, hot-wire and hot-film anemometers (turbulence), laser-Doppler velocimeters (LDV)-(needs clear water), acoustic-Doppler velocimeters (ADV), particle-image velocimetry (PIV), particle-tracking velocimetry (PTV)

c. Pressure:
    i. Flush-mounted piezometer taps (monitor using manometer tubes or bourdon-tube pressure gauges)
    ii. Transducers (automated and dynamic)-deflection or strain of an internal diaphragm, changes in output of a piezoresistive crystal
d. Water level
    i. Point gauge over water surface, hook gauge mounted in a stilling well, capacitance-type wave probe, ultrasonic devices
e. Bathymetry
    i. Laser-line bottom-relief scanners, mechanical (amphibious) bed profile follower (van Gent et al. 2008)
f. Other (e.g. time, temperature, displacement, force, stress and strain, vibration)

7) Model operation
    a. Initial adjustments: instrument calibration
    b. Calibration: adjusting model parameters in order to reproduce a known event (Ettema et al. 2000)
        i. Check the stage-discharge relationship at structures being use to control flow (Ettema et al. 2000)
        ii. Determine sediment transport time scale by adjusting model discharge or slope such that sediment in the model moves in accordance with the calibration event (Ettema et al. 2000)
    c. Verification: ensuring that model behavior follows physical laws (conservation of mass, momentum, and energy) without mathematical errors or inconsistencies (Ettema et al. 2000)
    d. Validation: ensuring that the processes of interest are being reproduced (Ettema et al. 2000)

3.6 Examples

Marmot Dam

A physical model of the Sandy River was built at the National Center for Earth Surface Dynamics (NCED) at St. Anthony Falls Laboratory. The goal of the model was to analyze the effects on reservoir sediment erosion of notch placement and breach discharge for the earthen coffer dam put in place to allow the removal of Marmot Dam (Grant et al. 2008). The model was geometrically distorted with scales of 1:150 in the horizontal and 1:70 in the vertical (Grant et al. 2008). Froude and Shields number similitude were used to scale the model, flow rates, grain size distribution, and time (Grant et al. 2008). The model was created using concrete and wood: model scale templates of each cross section were placed and then concrete was used to fill in the form (Grant et al. 2008). The model was sealed and painted prior to the introduction of water (from the Mississippi River) and sediment (coarse and fine sand) using mechanical volumetric sediment feeders (Grant et al. 2008). The model cofferdam was made of erodible modeling clay (Grant et al. 2008).

Eight runs with different notch locations (river right, center, and left) and model discharges (70.8 m^3/s and 155.7 m^3/s) were performed (Grant et al. 2008). Model elevations were determined for each run using eight sheet lasers spaced 120 prototype feet apart (Grant et al. 2008). A high resolution digital camera (Nikon D70) was used to take laser topographic images of the dam and upstream river section (Grant et al. 2008).

3.7 Equations

Froude number: $\frac{V}{\sqrt{gh}}$ Shields parameter: $\tau_* = \frac{hS}{(G-1)d_s}$

Froude number similitude criterion: $Fr_r = \frac{Fr_p}{Fr_m} = \frac{V_r}{\sqrt{h_r}} = 1$

where V = water velocity, g = gravity acceleration, h = channel depth (Julien 2002)

Manning-Strickler similitude criteria for a distorted model

$$\left(\frac{z_r}{d_{sr}}\right)^{1/6}\left(\frac{z_r^{1/2}S_r^{1/2}}{V_r}\right) = 1$$

Table 10.1. *Scale ratios for hydraulic models*

	Rigid-bed (Froude)			Mobile-bed			
	Scale	Exact	Tilted	Complete General	$(d_{*r} = \tau_{*r} = 1)$ $m = 1/6$	$d_{*r} \neq 1$	Incomplete $Fr_r \neq 1$
Geometric							
Depth	h_r	L_r	z_r	z_r	z_r	z_r	z_r
Width	W_r	L_r	y_r	y_r	y_r	y_r	y_r
Length	x_r	L_r	x_r	$z_r\left(\frac{1+4m}{1+m}\right)$	$z_r^{1.43}$	$z_r^{1+2m}d_{sr}^{-2m}$	$z_r^{3}d_{sr}^{2}$
Particle diameter	d_{sr}	L_r	$z_r^{4}x_r^{-1}$	$z_r\left(\frac{2m-1}{2+2m}\right)$	$z_r^{-0.286}$	d_{sr}	d_{sr}
X-section area	$W_r h_r$	L_r^2	$z_r y_r$	$y_r z_r$	$y_r z_r$	$y_r z_r$	$z_r y_r$
Volume	$X_r W_r h_r$	L_r^3	$x_r y_r z_r$	$y_r z_r\left(\frac{2+5m}{1+m}\right)$	$y_r z_r^{2.43}$	$y_r z_r^{2+2m}d_{sr}^{-2m}$	$y_r z_r^{3}d_{sr}^{2}$
Kinematic							
Time (flow)	t_r	$L_r^{1/2}$	$x_r z_r^{-1/2}$	$z_r\left(\frac{1+7m}{2+2m}\right)$	$z_r^{0.918}$	$z_r^{0.5+2m}d_{sr}^{-2m}$	$z_r^{2-m}d_{sr}^{3+m}$
Time (bed)	t_{br}	—	—	$z_r\left(\frac{2+5m}{1+m}\right)$	$z_r^{2.438}$	$z_r^{1.5+3m}d_{sr}^{-1-3m}$	$z_r^{3}d_{sr}^{2}$
Velocity	V_r	$L_r^{1/2}$	$z_r^{1/2}$	$z_r^{1/2}$	$z_r^{1/2}$	$z_r^{1/2}$	$z_r^{m}d_{sr}^{-1-m}$
Shear velocity	u_{*r}	$L_r^{1/2}$	$z_r x_r^{-1/2}$	$z_r\left(\frac{1-2m}{2+2m}\right)$	$z_r^{0.286}$	$z_r^{0.5-m}d_{sr}^{m}$	d_{sr}^{-1}
Settling velocity	ω_r	—	—	$z_r\left(\frac{1-2m}{2+2m}\right)$	$z_r^{0.286}$	—	d_{sr}^{-1}
Discharge	Q_r	$L_r^{1/2}$	$y_r z_r^{3/2}$	$y_r z_r^{3/2}$	$y_r z_r^{1.5}$	$y_r z_r^{1.5}$	$y_r z_r^{1+m}d_{sr}^{-1-m}$
Unit bedload discharge	q_{br}	—	—	1	1	$d_{sr}^{1+m}z_r^{0.5-m}$	1
Dynamic							
Mass	M_r	L_r^3	$x_r y_r z_r$	$y_r z_r\left(\frac{2+5m}{1+m}\right)$	$y_r z_r^{2.43}$	$y_r z_r^{2+2m}d_{sr}^{-2m}$	$y_r z_r^{3}d_{sr}^{2}$
Pressure	p_r	L_r	z_r	z_r	z_r	z_r	z_r
Shear stress	τ_r	L_r	$z_r^{2}x_r^{-1}$	$z_r\left(\frac{1-2m}{1+m}\right)$	$z_r^{0.57}$	$z_r^{1-2m}d_{sr}^{2m}$	d_{sr}^{-2}
Force	F_r	L_r^3	$x_r y_r z_r$	$y_r z_r\left(\frac{2+5m}{1+m}\right)$	$y_r z_r^{2.43}$	$y_r z_r^{2+2m}d_{sr}^{-2m}$	$y_r z_r^{3}d_{sr}^{2}$
Dimensionless							
Slope	S_r	1	$z_r x_r^{-1}$	$z_r\left(\frac{-3m}{1+m}\right)$	$z_r^{-0.43}$	$d_{sr}^{2m}z_r^{-2m}$	$z_r^{-1}d_{sr}^{-2}$
Darcy–Weisbach	f_r	1	$z_r x_r^{-1}$	$z_r\left(\frac{-3m}{1+m}\right)$	$z_r^{-0.43}$	$d_{sr}^{2m}z_r^{-2m}$	$z_r^{-2m}d_{sr}^{2m}$
Froude	Fr_r	1	1	1	1	1	$z_r^{m-0.5}d_{sr}^{-1-m}$
Reynolds	Re_r	$L_r^{3/2}$	$z_r^{3/2}$	$z_r^{3/2}$	$z_r^{1.5}$	$z_r^{3/2}$	$z_r^{1+1m}d_{sr}^{-1-m}$
Shields	τ_{*r}	—	—	1	1	1	1
Grain Reynolds	Re_{*r}	$L_r^{3/2}$	$z_r^{5}x_r^{-3.5}$	1	1	$d_{sr}^{1+m}z_r^{0.5-m}$	1
Dimensionless diameter	d_{*r}	—	—	1	1	$d_{sr}^{\frac{2+2m}{3}}z_r^{\frac{1-2m}{3}}$	1
Sediment density	$(G-1)_r$	—	—	$z_r\left(\frac{3-6m}{2+2m}\right)$	$z_r^{0.857}$	$z_r^{1-2m}d_{sr}^{2m-1}$	d_{sr}^{-3}

From Julien (2002)

3.8 Additional Information

Julien has several examples with detailed calculations for parameters based upon similitude for various types of models in his chapter on physical river models (2002). Ettema et al. go into more depth, including models with ice or debris, discuss more of the theoretical basis of similitude, and the consequences of distortion, tilting, and relaxed similitude (2000).

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