United States Society on Dams

Modeling Sediment Movement in Reservoirs

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Prepared by the USSD Committee on Hydraulics of Dams, Subcommittee on Reservoir Sedimentation

U.S. Society on Dams

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COLLABORATE: Build networks and relationships to strengthen the community of practice.

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FOREWORD

Because dams alter the natural balance of water and sediment, all reservoirs will experience, to a greater or lesser extent, sedimentation. The conventional concept of managing reservoir sedimentation by allocating "dead storage" for a predetermined useful reservoir life of 50 to 100 years is no longer considered state of the art. Effective management of reservoir systems can benefit from models which predict future behavior and response to perturbation or management actions. This report focuses on mathematical models of reservoir hydrodynamics and sedimentation (as opposed to physical models) including model inputs such as bathymetry, hydrology and sediment properties and boundary conditions. Several widely available models are presented, although the reader is directed to appropriate references for specific model details. The report describes application of mathematical models to reservoir sedimentation, including the issues of selecting an appropriate transport function, sediment delivery to reservoirs, deposition patterns, and modeling specific reservoir sediment management strategies.

This report was prepared by the USSD Committee on Hydraulics of Dams, Subcommittee on Reservoir Sedimentation. The lead authors were Martin J. Teal, WEST Consultants, Inc.; Jennifer Bountry, U.S. Bureau of Reclamation; and Daniel Pridal, U.S. Army Corps of Engineers. Our thanks go to the publications review committee consisting of Jerry W. Webb (U.S. Army Corps of Engineers), Samuel L. Hui (Bechtel Global Corporation), and Timothy J. Randle (U.S. Bureau of Reclamation) for providing valuable review comments. Our appreciation extends to James E. Lindell (MWH), former Chair of the Hydraulics Committee, for his help in taking this project to fruition.

Martin J. Teal
Chair, Subcommittee on Reservoir Sedimentation
USSD Committee on Hydraulics of Dams

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1.0 INTRODUCTION

1.1 Problem Statement

Because dams alter the natural balance of water and sediment, all reservoirs will experience, to a greater or lesser extent, sedimentation. The conventional concept of managing reservoir sedimentation by allocating "dead storage" for a predetermined useful reservoir life of 50 to 100 years is no longer considered state of the art. In the planning and design of new reservoirs, engineers should incorporate the concept of sustainable use and operation (e.g., Palmieri et al., 2003; Reclamation, 2006; Annandale, 2013). For existing reservoirs, engineers should take appropriate remedial measures to prolong their useful functions within economic, social, political, and environmental constraints. Being able to foresee and mitigate sedimentation issues during the design phase, or resolve these issues for existing projects, requires the ability to predict sediment movement.

1.2 Purpose and Scope

Effective management of a reservoir system requires a model which can predict future behavior and response to perturbation (Morris and Fan, 1998). All models are born as “thought experiments” and, depending on the situation, they may grow in complexity to include conceptual frameworks, desktop calculations, numerical simulations, and physical scale modeling. Real-world or "prototype" hydrologic systems are complex, and their behavior is analyzed with models which are greatly simplified and do not reproduce system behavior exactly. In engineering analysis this uncertainty is offset by applying informal or formal safety factors, to convert approximate modeling results into acceptable design parameters.

The purpose of this report is to inform readers of the existing mathematical methods available to predict sediment movement in and around reservoirs. There is a vast amount of material available on the subject; this paper attempts to distill accepted and applied (rather than theoretical) methods for the practitioner and provide reference sources for further information. Although beyond the scope of this document, in complex reservoir systems or for certain management questions it may also be useful to incorporate conceptual and physical models. Typical analyses for which reservoir sedimentation models may be useful include:

- estimating more accurately the live storage of the reservoir for use in reservoir water yield analysis relative to water supply and hydropower production studies, throughout the life of the project,
- locating and designing sluicing outlets at the dam for discharge of fine sediment via density current
- evaluating if and how to use reservoir drawdown, or other sediment management strategies, as a means to reduce sediment accumulation in reservoirs

2.0 MATHEMATICAL MODELS OF SEDIMENT TRANSPORT

2.1 Introduction

A model is defined as a representation of a system or phenomenon in which simplifications have been made in scale and/or time compared to the prototype. In engineered systems, models and their associated simplifications of reality are often created to be able to understand and reproduce to some extent complex physical processes that occur in nature. For example, when studying reservoir systems, being able to predict water movement (hydraulics or hydrodynamics) and sediment movement that will occur in response to a storm or dam operation is useful. The two models most commonly employed for this type of analyses are physical models (usually constructed at a reduced scale in a hydraulics laboratory) and mathematical models (the focus of this paper). Historically, physical models were often employed in reservoir studies along with simple numerical computations. Given the recent advances in computing power, mathematical models are now common either as stand-alone analysis tools or used in conjunction with physical models.

2.2 Hydrodynamics

Correctly modeling the movement of water, or hydrodynamics, within a reservoir is necessary before one can try to estimate sediment processes. A number of considerations, given in the sections below, are necessary for hydrodynamic modeling even before considering adding sediment to the simulations.

2.2.1 Model Complexity

The hydrodynamics of reservoirs can be represented by a suite of modeling techniques ranging from qualitative with simplified assumptions to complex approaches that address multiple interactions among variables. The type of mathematical model chosen for each particular application should reflect the physical characteristics of the reservoir and complexity of the question (Reclamation, 2006). One- and two-dimensional models are widely used for engineering applications. One-dimensional models are appropriate for narrow reservoirs, where the flow is highly channelized and closely follows the thalweg, and where transverse mixing is well accomplished. One-dimensional models are well suited to applications requiring long time simulations or multiple alternative analyses. On the other hand, when the reservoir pool is wide and without a single clear flow direction, multi-dimensional models must be used. Commonly used codes that simulate both hydrodynamics and sediment are covered in the “Commonly Available Models” section of this paper.

2.2.2 Geometry/bathymetry

Development of a topographic or bathymetric surface to represent the reservoir bottom and post-construction sedimentation is one of the most important input data components to any reservoir model application. The geometry data defines the topography and bathymetry of the reach to be simulated; i.e., the channel bed, banks, and floodplain. Reservoir pool geometry has a major influence on hydraulic behavior and the pattern of sediment deposition in reservoirs (Morris and Fan, 1998). Topographic data also allow comparison of reservoir conditions over time, such as changes in sedimentation patterns and storage volume. The topographic and bathymetric surface includes the area below the normal reservoir pool along with the above water area that can become inundated during high flows. Sand, gravel, and cobble sized sediments tend to deposit as deltas in the upstream end of the reservoir and these deposits extend well upstream of the normal reservoir pool. Therefore, the topographic channel surface should also include the upstream riverine component. Together, the topographic and bathymetric data sources should provide an accurate representation of the spatial variations in terrain. Although the terrain representation should accurately describe the reservoir width and depth variations, the level of detail or precision should correspond to the purpose of the investigation. The data can also be used to generate reservoir surface area and storage capacity tables or curves (also called area-capacity tables or curves) at varying reservoir pool elevations. This can be particularly useful when comparing reservoir surveys over time to determine the rate and magnitude of loss in storage capacity due to sedimentation within the reservoir pool (Figure 1). Computer programs from U.S. Bureau of Reclamation (Reclamation), the U.S. Army Corps of Engineers (USACE), and others are available.

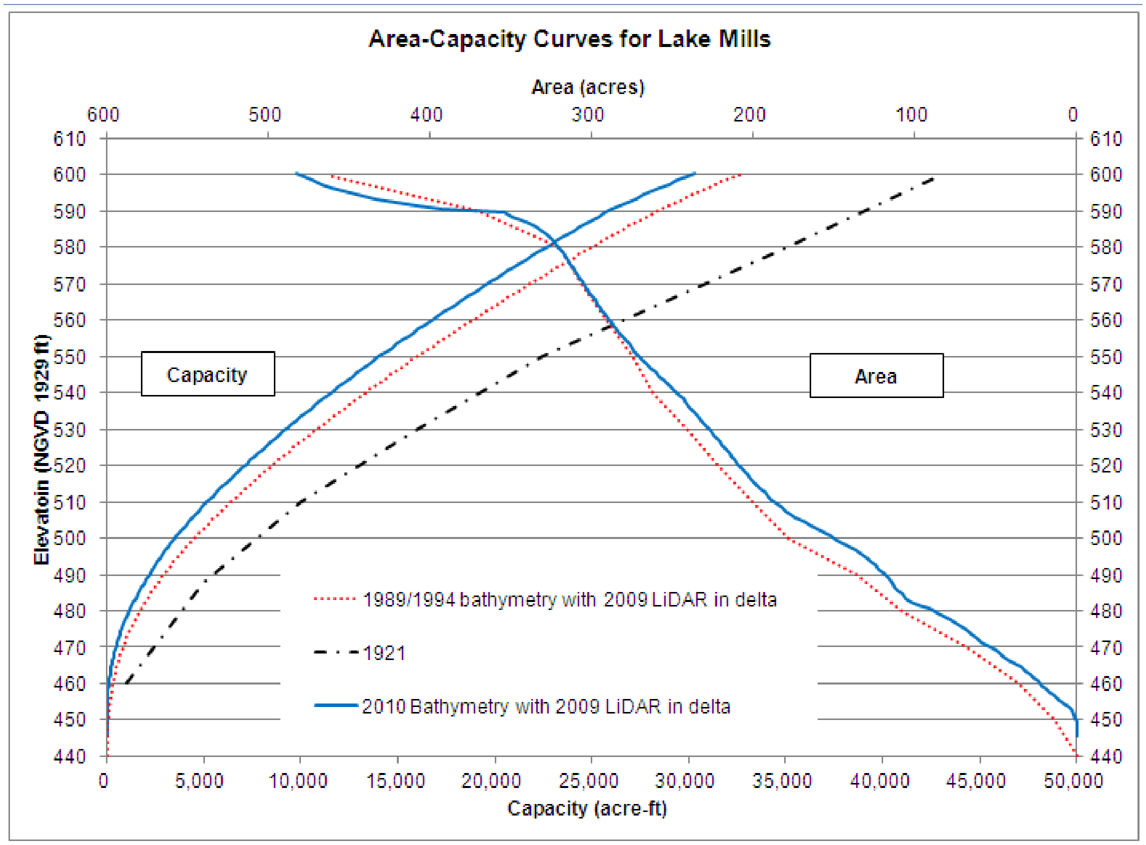

Figure 1. Example area-capacity curve for Lake Mills Reservoir on the Elwha River, Washington State generated with a GIS-based approach.

Reservoir area-capacity can also be developed using a geographic information system (GIS) program. A GIS-based method utilizes a detailed topographic surface generated from the survey data to determine the areas and volumes between specified elevation increments (e.g., Carlson et al., 2010). The GIS method accounts for irregularities in the surface topography and bathymetry, allowing the user to determine the precision of results based on the precision of the topographic and bathymetric information.

The decision on which instrumentation and data collection technique to use is typically based on how complex the reservoir bathymetry is anticipated to be, range of depths within the reservoir, logistical considerations for accessing the site and launching boats and equipment, vegetation and infrastructure obstacles, dam operations, and the level of accuracy required to answer project management questions. The reservoir bathymetry is typically collected by a boat equipped with depth sounder and surveying equipment that can provide a horizontal position and depth for each sounding (Figure 2 and Figure 3; see Chapter 9 in Reclamation, 2006). The depth data are then subtracted from the water surface elevations to generate reservoir bottom elevations (bathymetry) as shown in Figure 2. In many cases, it is appropriate to utilize a single water surface elevation for generating the reservoir bottom data assuming the reservoir stage does not fluctuate throughout the survey. Bathymetric reservoir data are often collected by mapping the lake bottom in grid format with both longitudinal and lateral lines at close parallel spacing. Additional detail may be acquired in areas of interest such as near dam outlets, along the historical river channel path, at major topographic breaks, and where there is anticipated sedimentation. Depth sounders can range from single-beams, which collect a single point at each data collection location, to multi-beam scanners that provide nearly continuous data along the reservoir bottom. The simplest survey equipment could include a small boat or canoe, fish finder, a handheld GPS instrument, and field book for recording data by hand. Deeper and more complex reservoirs typically include higher accuracy survey equipment and depth sounders, along with calibration equipment for speed of sound, water temperature, etc.

The portion beyond the boundaries of the normal reservoir pool can be represented by data collected with traditional ground survey techniques, but is more commonly represented by remote-data collection techniques. These techniques include data methods such as photogrammetry and LiDAR. Recent research has also explored tools such as satellite-based topography, photogrammetry from unmanned aircraft systems (http://rmgsc.cr.usgs.gov/uas/), and even manually operated balloons with cameras that can produce digital elevation models. Shallow reservoir areas and riverine sections above the reservoir pool or in tributaries may require unique survey techniques such as rafts mounted with depth sounding equipment and GPS or robotic total station equipment (Figure 3). Manipulation of the pool elevation to allow for increased coverage for either boat or remote sensing surveys can also help with these areas.

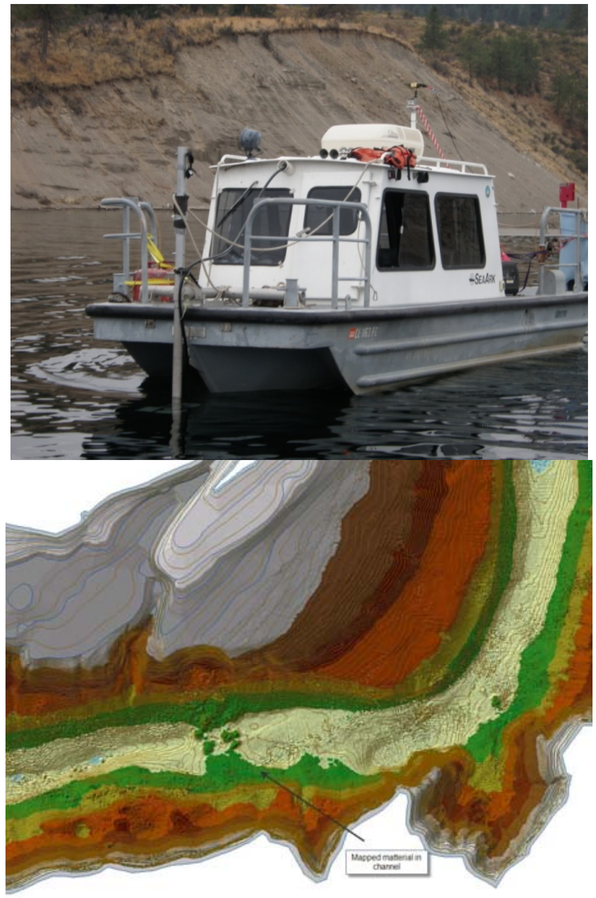

Figure 2. Survey vessel (top) and terrain product (bottom) from recent Lake Roosevelt survey (Ferrari, 2012).

Reservoir surveys should be conducted by personnel with adequate field safety training which may include, but is not limited to, wilderness first aid, motorboat operator training, and whitewater rescue. Specific considerations should be included for dam operations which may require additional personnel and safety protocols during the survey near spillways, outlets, gates, and other structures. Weather conditions, particularly wind and lightning, can also present sudden environmental hazards. Reservoirs with whitecap conditions are dangerous for small boats and should be avoided because they can capsize or swamp the boats and because depth measurements become too erratic. Reservoirs with shallow bedrock, tree stumps, floating or submerged logs should be surveyed at very slow speeds. Areas with woody debris and shallow, turbid, or fast water conditions should also be surveyed with extreme caution. Care must also be taken to develop a survey plan with local emergency responders and reservoir operators, particularly in areas with public recreational use that may be concurrent with the survey.

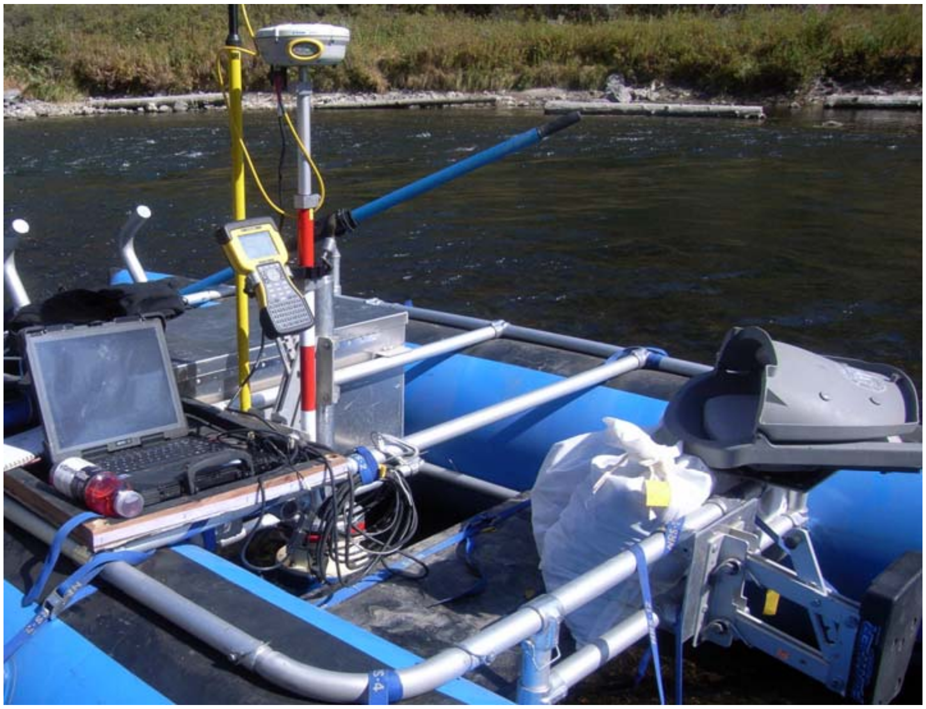

Figure 3. Example bathymetric equipment setup with RTK GPS, ADCP, and laptop on river cataraft for shallow reservoir areas or riverine segments. Photography courtesy of Sedimentation & River Hydraulics Group, Reclamation, Denver, Colorado.

Once the data has been collected from the different sources, it is combined to generate a spatially- referenced topographic and bathymetric surface in the form of contours, a TIN (triangular irregular network), or digital terrain model. To generate a surface, typically a reservoir polygon is developed to encompass the bathymetric data and a boundary polygon is used to define the extent of the surface. Depending on the density of data collected and spatial variation in topography and bathymetry, additional post-processing of the data and interpolation in data gap areas and at transition areas between survey data sources may be required. Interpolation may be done using standard triangulation techniques, or with more sophisticated techniques, such as kriging. The uncertainty of the final topography and bathymetry surfaces should be estimated and documented. Assembly of the combined terrain model should also consider the selected hydrodynamic model needs.

Roughness associated with the surfaces defined by the geometry/ bathymetry plays an important role in determining flow depths and velocities; friction factors must be given in the form of numerical values associated with particular regions of the bed, or in the form of relationships that allow their representation as a function of other parameters such as hydraulic and/or sediment properties. For one-dimensional models, local energy loss coefficients must also be given, such as those due to channel bends, natural or manmade obstacles to the flow, bridge piers and abutments, etc. These may be prescribed based on field measurements and observations, or they may be calculated (e.g., Arcement and Schneider, 1989), which commonly requires an iterative procedure.

2.2.3 Hydrology

Knowledge of the size and time distribution of streamflow is essential to many aspects of water management and environmental planning (Viessman et al., 1977). Engineers and scientists often characterize stream discharge at given locations in terms of annual hydrographs, storm hydrographs, and instantaneous peak discharges. Investigators will also evaluate the longitudinal variability of stream discharge and available sediment loads with changing drainage area, local geology, and incoming tributaries. Further, changes over time must be considered that affect discharge hydrographs, land use and associated runoff or sediment loads, or features that divert or increase discharge along the river (Thorne et al., 1997).

Reservoir hydraulic and sedimentation models require a set of hydrologic input data to represent the incoming river discharge from the upstream watershed, i.e., inflow hydrographs. When available, historical stream gage data is the most common source used to develop the inflow hydrographs. This information is often available from Federal and state agencies such as the U.S. Geological Survey or other local government sources. If stream gage data are not available, then new field measurements can sometimes be made and historical flows can be estimated by correlations with data from other nearby stream gages. For ungaged locations, precipitation-runoff models are another potential way to develop inflow hydrographs.

The type of flow hydrograph needed depends on the objectives of the sedimentation analysis. An incoming (upstream) flow hydrograph from a historical or hypothetical storm event is generally sufficient for single event sedimentation analysis. However, modeling of longer-term behavior of the reservoir system, including examination of sediment accumulation and management techniques, will require representative long-term discharge hydrographs. Reservoir storage routing computations require not only an input (upstream) hydrograph but also the release flows (downstream output hydrograph).

Long-term discharge hydrographs provide context for the seasonal variation in flow magnitude, which can be useful for analyzing reservoir sediment management options and timing. For example, some streams are perennial (flow continuously) with highest sediment transport occurring during a winter rainy season or spring snowmelt season. Other streams are often dry with sediment transport only occurring during intermittent rain events. Total annual flow is often utilized in determining the trap efficiency of reservoirs, which affects estimates of long-term reservoir sediment accumulation. Because sediment transport is highly non-linear (much more sediment is transported at higher flows proportional to the amount carried at lower flows) it is important to capture peak flows if possible within the discharge hydrograph.

The time step of the flow hydrograph is an important consideration which will vary depending on available data, the model computational time step, the mathematical scheme being used within the model, and the magnitude of the flow as well as potential operational policies under consideration (e.g., Cunge et al., 1980). While full treatment of this topic is beyond the scope of this paper, many models allow a larger time step for low flows (when less sediment is moving and changes are very gradual) and smaller time steps for larger flows (when changes happen much more quickly due to the non-linearity of sediment transport).

Because hydrologic patterns and associated sediment loads can vary considerably from year to year, several decades of stream flow data are ideal for hydrologic analysis. During low rainfall or snowpack years (below average), limited sediment accumulation may occur. In contrast, during wet (above average) rainfall or snowpack years higher rates of sediment accumulation may occur. Without long-term stream discharge records for context, a short period of data could result in over- or under- estimation of sediment accumulation. In locations with limited or no gaging station data, stream flow must be estimated using empirical approaches based on drainages of similar character, or better still, derived from a calibrated basin runoff model, either an event type or a long-term series. Regardless of available stream discharge data, uncertainty should be characterized in hydrologic analysis.

2.2.4 Boundary conditions

Subcritical flows require the flow discharge at the upstream boundary and the stage at the downstream end, while supercritical flows require both the discharge and the stage at the upstream boundary (the analysis leading to this result can be found in any hydraulics textbook, such as Henderson, 1966). Most practical problems for rivers and reservoirs include subcritical or critical flow. Supercritical flow, as an average channel condition, normally only occurs in spillways or very steep channels.

For two- and three-dimensional models of rivers and reservoirs, flow velocity vectors are specified at the upstream boundary and water surface elevation is specified at the downstream boundary. When only the upstream discharge is known, average flow velocity can be specified with vectors normal to the upstream boundary. Velocity can also be specified in the same proportion as the upstream boundary conveyance. For a three-dimensional model, the vertical profiles can be specified as logarithmic. Upstream and downstream model boundaries should be specified far away from the reach of interest (e.g., a minimum distance equal to ten channel widths).

The downstream stage can be specified by using stage-discharge rating curves or elevation hydrographs. Water-surface-slopes and the assumption of normal depth can also be specified, but this may be problematic for a mobile-bed sediment transport model because erosion or deposition at the downstream boundary may become unstable. For models where the downstream boundary corresponds to the dam, the pool elevation at the dam is often used. Depending upon model capabilities and problem complexity, the reservoir operational scheme may be specified for the downstream boundary. When the dam outlet works are used, relationships for the gates and spillways may have to be specified. These relationships are a function of the head at the dam, and more complex iterative schemes need to be used. In tidal regions, the tide will have to be specified as a hydrograph or a constant high or low tide could be specified.

In some models, especially if steady-state solutions are sought, special downstream boundary conditions are employed. These boundary conditions, generally known as non-reflective boundary conditions, prevent wave forms generated by spurious numerical solutions from being reflected back into the computational domain, as would happen in the case of a clamped down, free surface elevation. The use of these techniques allows the spurious waves to flow out of the computational domain and may significantly increase numerical convergence rates. A description of such techniques can be found in Keller and Givoli (1989).

2.3 Sediment Properties

Required input data for a sediment model typically consist of parameters to describe the sediment particle grain size of the streambed material and the upstream sediment load. Specific sediment properties required for model computations vary with the model and problem complexity.

2.3.1 Sediment Characteristics

Sediments may be classified by the grain size distribution, shape, specific gravity, and unit weight. Sediment load can be described with a variety of terminology (illustrated in Figure 4; USACE, 1995a). *Total load*, defined based on mode of transport, consists of *bed load* (material rolling and saltating along the channel bed) and *suspended load* (material carried in suspension). Alternatively, *total load* may be expressed based on measurement methods as *measured load* and *unmeasured load*. The *unmeasured load* usually includes the entire *bed load* and a portion of the *suspended load*.

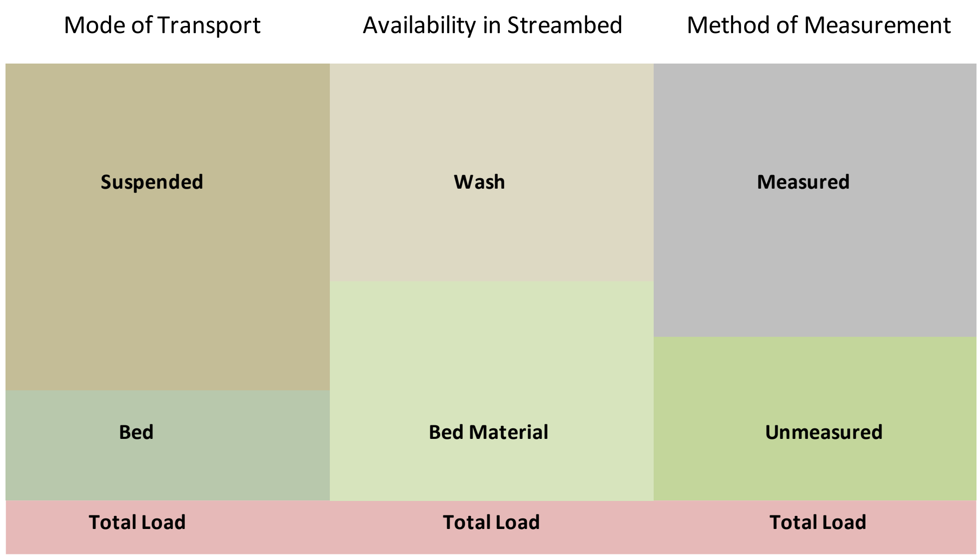

Figure 4. Different Classifications of Total Sediment Load (after USACE, 1995a)

Total load can also be defined based on availability of certain grain sizes in the streambed and banks. *Wash load* is the portion of the sediment load composed of grains smaller than those found in appreciable quantities in the movable bed, often taken as the smallest 10 percent of the bed material by weight. The wash load is normally transported in suspension. In most streams, these fine-grained sediments are washed through the fluvial system without significant interaction with the streambed and do not need to be considered for the purposes of simulating changes in the streambed. However, in a reservoir system, the wash load volume can be a significant contribution to reservoir sedimentation and should be simulated by the model. *Bed material load* is that portion of the total sediment load composed of material found in appreciable quantities on the streambed and banks, whether transported in suspension or as bed load.
The size of sediment particles transported by water ranges over seven orders of magnitude from individual clay particles to boulders. Sediment deposits have a range of grain sizes, and both field and laboratory techniques can be used to separate sediment grains according to their size. Grain size is the most important parameter describing sediment behavior in water, and a variety of terms may be used to describe the size characteristics of individual grains and composite samples. The term *coarse sediment* normally implies sand and larger grain sizes; *fine sediment* normally refers to silt and clay-size particles.

Sediment particles are classified, based on their size, into six general categories: *Clay, Silt, Sand, Gravel, Cobbles,* and *Boulders*. Because such classifications are essentially arbitrary, many grading systems are to be found in the engineering and geologic literature (USACE, 1995a). Sands and fine gravels are normally measured with sieves, and the reported diameter is characteristically the sieve diameter. Coarse gravels or cobbles can be directly measured by hand and the intermediate axis length is reported as the nominal diameter. Sediment within shallow areas can often be sampled by hand with sieves or lab processing (Bunte and Abt, 2001; Edwards and Glysson, 1999), while deeper areas require more equipment including grab samplers, or even drill rigs mounted on a boat if over a few meters of water depth. If sediment stratigraphy is important to distinguish sedimentation history or variation in vertical characteristics, core samplers are needed to preserve the spatial representation of the sample, which can then be interpreted by layers.

Bulk density measurements of reservoir sediment may also be needed to convert the volumetric based measurements of reservoir sedimentation to mass. The size, length of time within the reservoir, and compaction of sediments can affect bulk density computations, so unique measurements are needed to represent the vertical and lateral spatial distribution of reservoir sediment. Typical reservoir bulk density values are not widely available, but some data documentation exists to provide guidance (Lara and Pemberton, 1963).

2.3.2 Cohesive vs. Non-Cohesive Sediments

There is no clear boundary between cohesive sediment and non-cohesive sediment. The definition is usually site-specific. In general, finer sized grains are more cohesive. Clay-sized sediments, smaller than 0.002 mm, are generally considered cohesive sediment.

Clay is too fine for its structure to be detected between a person's teeth. However, a moist sample containing a significant percentage of clay can be rolled into a ribbon by hand. Sand-sized sediments (0.062 to 2 mm) are normally measured by sieve analysis. Silt-sized sediments (0.004 mm – 0.062 mm) are considered to be between cohesive and non-cohesive sediment. All but the largest silt particles are too small to be individually discerned with the naked eye, but a small sample placed between a person's teeth will feel gritty. The cohesive properties of fine sediment deposits are primarily due to the existence of clay. Thus, in engineering practice, silt and clay are both considered to be potentially cohesive sediment (Reclamation, 2006).

The mechanics of sediment transport for cohesive and non-cohesive materials are different. When the sediment particles are non-cohesive, mechanical forces dominate the behavior of the sediment in water. Particle hydrodynamics refers to the propensity of a particle to remain immobile or to become entrained if it is on the bed surface, and to remain in suspension or to cease movement if it is in motion. The three most important properties that govern the hydrodynamics of non-cohesive sediments are particle size, shape, and specific gravity.

Cohesive sediment behavior is dominated by electrochemical forces. Cohesive sediment behavior is primarily dependent on the particle size, water chemistry, and sediment mineralogy (USACE, 1995a). A *cohesive sediment* is one which contains a concentration of fines and colloids sufficient to impart plastic properties at some water content, and the ability to resist shear stress at some other water content, a property termed *cohesion*. The plastic and cohesive properties of clay are due to colloids, particles with a specific surface area (area per unit weight) so large that behavior is controlled by surface rather than gravitational forces (Morris and Fan, 1998). Clays have extremely low settling velocities, and without turbulence or Brownian (thermal) motion a 0.001-mm clay particle will require about 2 weeks to settle 1 m. However, as a result of Brownian motion, individual clay particles may be very stable even in quiescent water, and remain dispersed for months (Morris and Fan, 1998). Colliding fine particles stick together to form agglomerates having settling velocities orders of magnitude larger than those of the individual particles. Thus, the floc rather than the individual particle becomes the settling unit. These same physico-chemical surface forces provide the main resistance to erosion of cohesive sediment deposits.

2.4 Sediment Model Inputs

In addition to the sediment properties described in the previous section, other inputs are needed to execute a sediment transport model simulation.

2.4.1 Supply

Most sediments enter reservoirs as a consequence of rainfall or snowmelt erosion and subsequent transport by streams. Eroded sediments may be flushed downstream through stream channels over a period of decades or longer. It is essential to differentiate between the volume of material eroded from the land surface and the amount which is actually transported into the reservoir, the sediment yield. Both erosion and delivery processes must be understood to assess sediment supply to downstream reservoirs.

The majority of the sediment is delivered to reservoirs in pulses by periods of high inflow separated by prolonged periods of low flows and smaller sediment loads. The pulsed nature of sediment delivery may be recorded in reservoir deposits as alternating layers of coarse and fine sediment. Sediment layers may be either absent or not readily perceptible at the upstream end of the delta, or in areas close to the dam with low sediment loading. A typical pattern is for lenses of sandy sediment delivered during high inflow to be interbedded between layers of fines deposited during periods of low flow.

Sediment supply is typically difficult to determine due to limited available measurements and changing land use conditions in the upstream watershed. If reservoir bathymetry at different points in time is available, the average annual supply between those points in time can be determined by computing the difference in volumes of the reservoir for a given pool level. If there is an upstream gage with sediment and discharge measurements, sediment hydrographs can be computed and integrated over time to determine sediment inflows. Many watershed precipitation-runoff models include a sediment yield component that can be used to estimate inflows. Empirical models such as the Universal Soil Loss Equation (USLE, and variants MUSLE and RUSLE) or physically based models such as AGNPS, ANSWERS, CREAMS, and WEPP are sometimes used to estimate yield (ASCE, 2008). Caution should be used to differentiate between yield from the watershed and actual delivery to the reservoir. Additional information on this subject is given in the Sediment Delivery to Reservoirs section of this paper.

2.4.2 Boundary conditions

Downstream. Typically there are no special downstream boundary conditions for sediment transport modeling other than as required for the hydrodynamic calculations.

Upstream. Water and sediment yields are typically used for the upstream model boundary conditions describing the flow and accompanying amount of sediment entering a reservoir project. Sediment load denotes the material that is being transported, whereas sediment discharge denotes the rate of transport. Model boundary conditions refer to the description of the inflowing water discharge and accompanying sediment discharge. Depending upon model capability, water discharge entering the reservoir may be specified with a steady, quasi unsteady, or an unsteady flow hydrograph. For quasi-unsteady and unsteady flow models, model time step is another consideration, although outside the scope of this paper. Most models pair this data with a sediment rating curve that may also include specification of sediment size distribution. For multi-dimensional models, sediment concentration and a scheme for specifying the spatial distribution of the sediment discharge at the boundary is also required. Sediment delivery to a reservoir, which may be a model boundary condition, is addressed later in this paper.

2.5 Commonly Available Models

Numerical sediment transport models are available in one, two, and three dimensions. However, more modeling is performed with one-dimensional (1D) models which tend to be more robust than their two- and three-dimensional counterparts and require less input data and computation time. Two-dimensional (2D) sediment transport models are much more common than three-dimensional (3D) models. Recent advances in computing power and model code have resulted in the increased use of multi-dimensional models.

Public domain models are available for free or a nominal processing charge with varying degrees of documentation, support, and training. Proprietary models are available from private vendors for a fee. Pricing levels vary with the software, support, and training provided. Although there is no single comprehensive list of available and current models, some attempts have been made over the years to track the various models available (e.g., http://hydrologicmodels.tamu.edu/models.htm)

Guidance pertaining to the selection of the appropriate model is gained from professional experience and from the literature. Papanicolaou et al. (2008) present a detailed review of representative 1D, 2D, and 3D models and describe their main applications, strengths, and limitations. Between 10 and 15 models of each category are presented and discussed within the article. Model complexity and capability varies with the ability to handle unsteady flows, bed load and suspended load, sediment exchange processes, type of sediment (cohesive versus non-cohesive), and multifractional sediment transport. Caution should be used when applying riverine transport models to reservoir transport as the former often ignore the finest size fractions which are important for the latter. Also, while a few models have the capability to simulate the formation of the density currents, most cannot.

Fifteen U.S. Federal agencies participated in a Federal Interagency Stream Restoration Working Group (1998) to produce a handbook on *Stream Corridor Restoration Principles, Processes, and Practices.* They selected the following eight models for comparison: CHARIMA (Holly et al., 1990), FLUVIAL-12 (Chang, 1990), HEC-6 (USACE, 1993), TABS-2 (MacAnally and Thomas, 1985), MEANDER (Johannesson and Parker, 1985), USGS (Nelson and Smith, 1989), D-0-T (Darby and Thorne, 1996, Osman and Thorne, 1988), and GSTARS (Molinas and Yang, 1986). Most of these models have either been substantially updated or superseded since the handbook was published.

As an additional reference aid for model selection, Reclamation provides a summary comparison of these eight models (Reclamation, 2006; Table 5-12). HEC-6, HEC-RAS, TABS-2, USGS, and the GSTARS models are Federal models in the public domain; CHARIMA, FLUVIAL-12, MEANDER, and D-0-T are academic or privately owned models. Recent model releases that provide updates to the above model list include the SRH suite of models by Reclamation, which replaces the GSTARS series (www.usbr.gov/pmts/sediment/model/index.html), HEC-RAS with sediment by USACE (www.hec.usace.army.mil/software/hec-ras/), and ADH by USACE (adh.usace.army.mil). ICOLD Bulletin 140 (ICOLD, 2007) describes the MIKE and GSTARS models as applied to five case studies.

Sediment transport models incorporate a certain degree of simplification to be computationally feasible. Simplified models run into the risk of not obtaining a reliable solution, whereas increasing the model complexity can complicate the problem formulation and incur more input data preparation, calibration, and verification costs.

The choice of the engineer or scientist applying the model is more important than the choice of the model.

3.0 APPLICATION OF MODELS TO SEDIMENT IN RESERVOIRS

Broadly speaking, sediment models can be classified by application range such as bed-material load versus wash load or physical versus chemical transport, and also their spatial / temporal formulation such as one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D) and steady versus unsteady. Model selection for solving a specific problem depends on the problem scope and complexity, data availability for model calibration and verification, and overall available time and budget for solving the problem (Papanicolaou et al., 2008).

Most of the commonly used numerical sediment transport models were originally developed for the analysis of movable bed rivers having coarse sediments and employ sediment transport equations developed from flume and river data where the effect of fine or wash load on fall velocity, viscosity, and relative density can be ignored. In contrast, reservoir problems may involve the analysis of grain sizes ranging from cobbles in the upstream delta area to clays near the dam. The silts and clays which normally behave as wash load in most rivers, and which are ignored in many river sedimentation models, often constitute the majority of the total sediment load in a reservoir. Unlike riverine systems, reservoirs are normally depositional environments. However, during drawdown, reservoirs may experience erosion of the exposed sediment.

Many of the sediment transport computational methods are based on simplifying assumptions such as conditions of steady uniform flow in prismatic channels, and have been developed to analyze non-cohesive sediment (Yang, 1996; Julien, 1995). Transport computations also assume that the exchange between the fluid and the bed has reached equilibrium conditions. These conditions often do not apply in reservoirs. Streams entering a reservoir are depositing sediment load, thereby violating the assumption of equilibrium between the bed and fluid. In many reservoirs, sediment deposits consist largely of cohesive sediments. These deposited sediments present a sediment transport challenge because of the difficulty in characterizing the erodibility of cohesive materials since erodibility will vary as a function of time, depth, consolidation, reservoir operations, and other factors. Both inflow and flushing procedures may involve a wide range of grain sizes, with clays through gravels being eroded and transported simultaneously. The configuration of the channels through the delta may also result in complex geometry and distribution of flow, which in turn affects the amount of erosion.

During prolonged drawdown events, channel incision and lateral bank erosion can happen concurrently, resulting in complex and rapidly changing geometry. Example documentation of channel adjustments during a drawdown event were recorded on the Elwha River in northwest Washington State (Childers et al., 2000).

For practical applications in reservoirs, the characterization of cohesive sediment properties is complicated by the nonuniform nature of the deposits. Different inflow events will produce deposits having different thicknesses and grain size, and mineralogy can vary as a function of the sediment source area for different inflow events. Differences will also be caused by the fraction of coarse sediments or organics. Variations will occur along the length of the reservoir due to the differential settling rates of the inflowing sediment and other factors. Sediments will become compacted by consolidation and dewatering over time, and deposits which are exposed to the air will experience accelerated compaction and desiccation. As cohesive sediments compact, they become more difficult to erode (Morris and Fan, 1998, ch 9.11).

In summary, the sediment transport conditions associated with reservoirs are extremely complex. Detailed analysis of many of these problems lies beyond present knowledge, and only qualitative or rough quantitative estimates can be provided. Caution should be used in the application of numerical techniques in either hand calculations or computer models.

3.1 Sediment Transport Functions

There are dozens of sediment transport functions that are available within many sediment models. Computed transport can vary by an order or magnitude or more depending on the equation selected. Selection of a transport function or functions should compare the project sediment and hydraulic conditions to those used to develop the transport equation. Available references such as the HEC-RAS hydraulic reference manual (USACE, 2010, chap 13 and App E), Reclamation (2006, Table 3.8, 3.11), ASCE (1975) and Morris and Fan (1998 Table 11.2) provide a review of various transport functions, notes regarding data used for development, recommended applications, and sensitivity. A procedure for selecting a transport function is also available for consideration in Reclamation (2006) Section 3.8.4.3, Procedures Selecting Sediment Transport Functions.

If measured sediment transport rates are available, results from the selected sediment transport function(s) should be verified against the measured data. In the absence of measured sediment transport rates, transport functions can be used to estimate the sediment transport rate at the upstream boundary. For many applications, a sensitivity analysis is suitable to evaluate and compare output from each of the potentially suitable transport functions for project conditions.

Within a typical 1D sediment transport model, computations of the mean velocity and mean bed shear stress are averaged over a cross section of the river. Bed-load transport is typically computed for each sediment size class, assuming a varying critical bed shear stress for the initiation of motion. Computations often include a hiding factor. This hiding factor includes two main effects of a nonuniform mixture: fine sediments are protected by coarser sediments, and coarser sediments are more exposed and may also move more easily because of the presence of fine sediments. Simplified models may use a single diameter which describes the behavior of a sediment sample containing a range of grain sizes. The median *(d_{50})* diameter is most frequently used to describe a sediment sample. Fifty percent of the sample weight is composed of grains smaller than the median diameter. However, different researchers have proposed using "representative" sizes to describe the transport and related properties of sediment mixtures (Morris and Fan, 1998, p.5.1.3).

Most 1D sediment transport models, and transport functions, are designed for non-cohesive sediment transport. Models often include the addition of simple cohesive sediment computational procedures to enhance model capability. These procedures can often require input of additional parameters to describe cohesive sediments separately such as settling velocity, critical shear stress, and other factors to describe the material properties related to the erosion and deposition of cohesive sediments.

3.2 Sediment Delivery to Reservoirs

Sediment delivery to the reservoir can be computed from reservoir surveys, stream gage monitoring data, and watershed sediment yield computational models. Although sediment supply estimating methods have potentially important sources of error, reservoir survey data generally represent a more reliable measure of the long-term basin sediment yield. However, reservoir surveys can only provide data on the average sediment yield over the period between surveys (short-term variations in sediment delivery are not captured). Ideally, all available types of data will provide a convergence of answers.

Most storage reservoirs act as sediment traps, and successive reservoir surveys can be compared to determine the sediment volume accumulated during the survey interval. However, a portion of total incoming sediment load can be transported through the reservoir, particularly during high flows. By correcting for trap efficiency, and converting the volume of sediment deposits into sediment mass on the basis of dry bulk density, the total sediment yield from the watershed can be computed. Reservoir surveys measure the total sediment load, including bed load. A method for estimating reservoir trap efficiency can be found in Strand and Pemberton (1982). In smaller reservoirs, storage capacity may have been lost long ago and the pool is already full of sediment. In these cases, sensitivity tests can be done with varying assumptions of how many average annual years it may have taken to fill the reservoir pool with sediment. Although there is more uncertainty in these cases, it may still provide a useful context for possible sediment supply rates that can be tested against other methods.

Mean-daily or continuous measurement of stream water discharge is often available from USGS gaging stations. However, relatively few measurements are made of suspended sediment concentration or bed load. Research is underway to develop less costly methods to estimate suspended sediment concentration and bed load. Most of the new techniques utilize acoustic or optical methods. In the absence of measurements, bed load can be estimated as a percentage of the suspended sediment load or computed from stream hydraulics and bed load equations (Morris and Fan, 1998, para 7.3).

Sediment concentration measurements may be used to compute the sediment load using extrapolation assumptions. These assumptions are inherent in the utilization of *Concentration-Discharge* relationships or sediment rating curves, which are frequently determined from a few years of data and then applied to a much longer discharge record to estimate long-term sediment yield, and which are also frequently extrapolated to cover discharges larger than those actually measured. Many available references provide additional information regarding development of a sediment rating curve from measured stream data (e.g., Morris and Fan, 1998, sec 7.4).

The ratio between the erosion rate and sediment yield to the reservoir is the sediment delivery ratio. Sediment yields are highly variable, and most of the sediment entering a reservoir is delivered from only a small fraction of the landscape during short periods of time. Eroded sediments may be flushed downstream through stream channels over a period of decades or longer. The sediment delivery ratio differentiates between the volume of material eroded from the land surface and the amount which is actually transported into the reservoir (the sediment yield).

The volume of sediment delivered to a reservoir may also be estimated with watershed sediment yield models (USACE, 1995b). Watershed erosion models may be grouped into categories as empirically based models such as RUSLE (Renard et al., 1997), physically based modes such as WEPP (Nearing et al., 1989), and mixed empirical and physical based models such as GSSHA (Downer et al., 2002). A multitude of models are available, with recent advances in GIS capabilities significantly expanding model capabilities along with available national databases for soil, vegetation, and precipitation. Links to many other soil erosion models can be found on the internet (e.g., http://soilerosion.net/doc/models_menu.html).

3.3 Types of Deposition

When a river or tributary stream enters a reservoir pool and flow velocity decreases, the sediment load begins to deposit. The bed load and coarse fraction of the suspended load are deposited first to form delta deposits, while fine sediments with lower settling velocities are transported deeper into the reservoir by either stratified or nonstratified flow. Depositional patterns vary with differences in hydrologic conditions, sediment grain size, and reservoir geometry. In reservoirs with fluctuating water levels, previously deposited sediments may be extensively eroded and reworked by streamflow, failure of exposed slopes, and wave action. Most sediments are transported within reservoirs to points of deposition by three processes: (1) transport of coarse sediment as bed load along the delta surface or topset, (2) transport of fine sediment in turbid density currents, and (3) transport of fine sediment as nonstratified flow (Morris and Fan, 1998, chap 10). Of these three processes, most sediment computational models were designed to model the reservoir delta. Annandale (1996) explores both empirical and numerical techniques to predict distribution of both fine- and coarse-grained sediment deposits in a reservoir.

Sediment deposition in a reservoir, and the longitudinal deposition areas, are commonly divided into three main zones as shown in Figure 5. *Topset beds* correspond to delta deposits of rapidly settling sediment. The downstream limit of the topset bed corresponds to the break in slope between the topset and foreset beds, which is also the downstream limit of bed material transport in the reservoir. *Foreset deposits* represent the steep face of the delta advancing into the reservoir and are differentiated from topset beds by an increase in slope and decrease in grain size. *Bottomset beds* consist of fine sediments which are deposited beyond the delta by turbidity currents or nonstratified flow. They may also include organic material produced by algae or aquatic plants within the reservoir. Whereas delta deposits may contain both coarse and fine material, the bottomset beds are characteristically fine-grained. However, tributary inflows, reservoir drawdown, slope failures, and extreme floods can all deliver coarser material into zones where finer-grained material normally predominates, resulting in layering of deposits or localized variations in grain size (Morris and Fan, 1998, Chap 10).

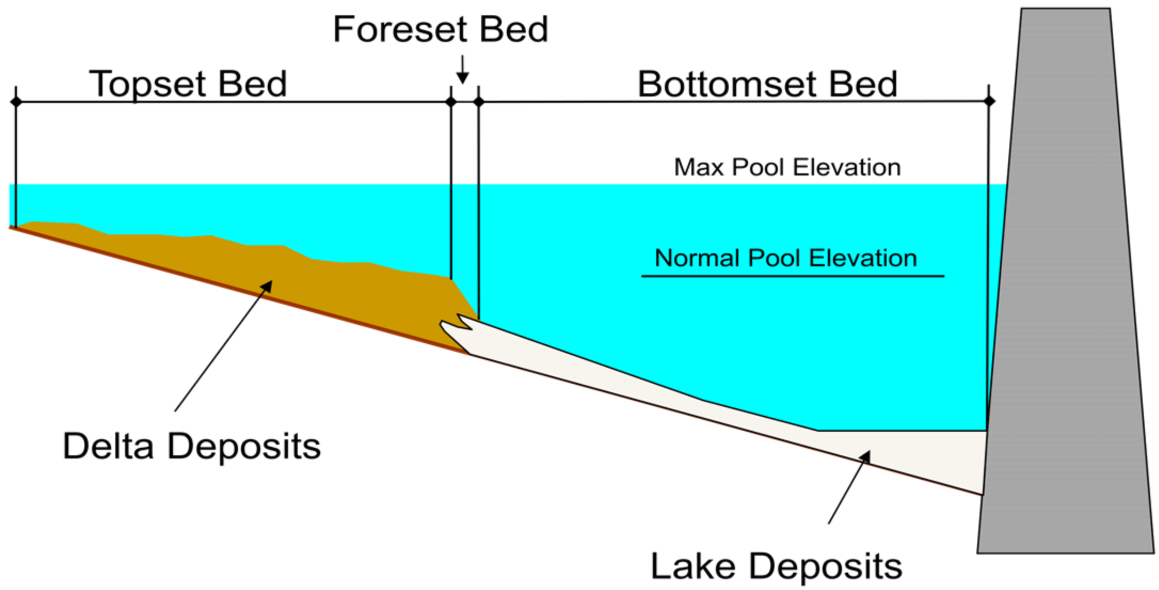

Figure 5. Conceptual View of Reservoir Deposition Zones

Delta deposits may constitute the majority of the sediment accumulation at hydrologically small reservoirs with low sediment trap efficiencies where coarse-grained material predominates. However, for hydrologically large reservoirs with high sediment trap efficiencies, the delta more commonly accounts for only a portion of the total sediment accumulation. Because delta deposition is focused in the shallow upstream reaches of reservoirs where the width tends to be the narrowest and storage volume is small, even small reservoir deltas can be problematic from the standpoint of upstream aggradation. Delta deposits are also the most visible component of sedimentation and can extend upstream beyond the reservoir pool.

In deep reservoirs which have been operated at different levels, distinct deltas may be formed at different water levels. Conversely, in long, narrow reservoirs, the bathymetric profile commonly associated with delta deposits may be absent, but an area characterized by a rapid shift in grain size marking the downstream limit of coarse material deposition may still be present. Reservoir deltas always grow in the downstream direction, and in some cases their vertical and upstream growth may also be significant. Sediment deposition is initially focused in the deepest part of each cross section, creating deposits having a near-horizontal surface regardless of the original cross section shape. Because the upstream area of the reservoir is shallow and has little storage capacity the longitudinal growth of the delta may initially be very rapid (Morris and Fan, 1998). Sedimentation can also result in deltas becoming exposed above the reservoir pool, after which vegetation can grow and affect channel configuration through the delta. In some cases, vegetation combined with large wood may form at the head of the delta, resulting in channel(s) forming along the reservoir margins (Figure 6).

Figure 6. View of vegetation, wood, and channels formed on the Lake Mills delta on the Elwha River, Washington. Photograph courtesy of Bureau of Reclamation, March 2010.

3.4 Modeling Sediment Management Strategies

Reservoir models can be applied to evaluate potential volumetric and spatial distribution changes when implementing sediment management strategies. Typically a mathematical model is constructed for a baseline condition, and then a series of “what if” analyses are performed to see how changes to the system will affect the results. One common example in reservoir modeling is to create a model (and calibrate it, if possible) of an existing project for some point in time. Once the existing conditions model is complete, a future prediction is made assuming that no changes are made to current conditions (e.g., hydrologic inputs, sediment loading, vegetation, sediment properties within reservoir deposits, operation & maintenance). This becomes the “no action” result. Then, one or more scenarios will be simulated for the same time period assuming that some change is made to the system inputs. The following sections describe some of these commonly modeled “what if” analyses.

3.4.1 Sediment Yield Change

If a project is proposed in the contributing watershed to a reservoir, it is often of interest to know how it will affect the rate of sedimentation and/or movement of sediment in the reservoir. Although numerical watershed models are available to compute sediment input to a system (see section on sediment model inputs), often, at least as a first step, a percent change in currently estimated loading is assumed and that is applied in the input to the model. Examples of sediment yield changes include:

- An afforestation project might reduce sediment contributions by a certain percentage
- An increase in construction activities may increase sediment loading by a certain percentage
- Stabilization of road cuts or landslide areas could reduce source areas from the watershed
- Construction and operation of upstream reservoirs or check dams to trap bed load could reduce coarse sediment contribution to downstream areas.

3.4.2 Sediment Routing

Sediment routing refers to movement of sediment around or through the reservoir. One mechanism is to take sediment at the upstream end of the reservoir and move it to below the dam (e.g., sediment slurry in a pipeline, excavating and trucking deposited sediment downstream to below the dam). Modeling this scenario would entail computing the quantities of sediment (and perhaps size fraction distribution as well) at the point of extraction and then taking those quantities as inputs to the system at a point below the dam.

A bypass tunnel is a sediment management method that diverts reservoir inflows of high sediment concentration around the reservoir and downstream of the dam. A numerical model could be used to simulate time periods where sediment concentrations exceed a certain threshold. For those time periods, all or a portion of the inflowing water could be diverted through the bypass tunnel, along with the corresponding sediment load. The remaining sediment inflow can be simulated to enter the reservoir. The sediment transport capacity of the bypass tunnel can computed to verify that diverted sediments will be transported through without deposition. Coarse sediment loads can be expected to cause abrasion of the tunnel lining at some rate, and should be anticipated during design.

Routing of sediment through the pool is somewhat more complex as the erosion, transport, and deposition processes will need to be simulated and these will change in space and time during the simulation. Strategies such as reservoir draw-down are typically modeled by varying the reservoir pool elevation over time either by changing model boundary conditions or performing computations of releases made through the outlet works [although the amount of sediment leaving with flow through orifices and gates is difficult to quantify accurately]. For modeling reservoir drawdowns, the rate of upstream headcutting and subsequent lateral erosion must be incorporated. If the drawdown is rapid, it may also require incorporation of mass failure of sediment deposits. Siphoning or use of hydro-aspirators are also techniques that would fall under this category.

Formation of density currents is another strategy to move sediment either through the reservoir or farther downstream towards the dam, depending on the system in question. A few models may be able to simulate the formation of the density currents while most cannot. References on modeling density currents include Han and He (1996), Morris and Fan (1998) and ICOLD (2007).

3.4.3 Mechanical Removal

To simulate mechanical removal such as by dredging or movement with heavy machinery, many models will allow some reshaping of topography at given points in time to reflect the removal. Some models will allow the modeler to specify a template reflecting the volume and distribution of sediment to be removed, and have additional options such as overdredging (e.g., HEC-6 and HEC-RAS). Depending on the rate of sediment removal, the location of dredging may have to be periodically moved throughout the reservoir. In addition, fluctuations in reservoir levels may also require different locations of dredging. Dredged areas may also serve as traps for future sediment inflows.

3.4.4 Combination of Strategies

It is common to examine sediment management strategies that implement more than one of the options described in the preceding paragraphs. In this case, the different strategies may be combined as yet another scenario to be modeled. Examples of combined strategies include reducing sediment inflow via yield reduction while flushing sediment based on water inflow and/or concentration, or using machinery to not only excavate in the dry during pool drawdowns but to also push sediment into the stream to increase load through the reservoir during the same time.

4.0 SUMMARY

A great deal of information is available on sediment transport, deposition and erosion in reservoirs. One of the tools available to the practitioner to predict sedimentation in and around reservoirs is mathematical (or numerical) modeling. Mathematical modeling, however, needs to be undertaken with great care as sediment transport in reservoirs tends to vary greatly both in time and in space. As sedimentation problems in reservoirs are very difficult and costly to remedy afterwards, dam designers need to use a conservative approach for sedimentation problems in dam design and consider management strategies that may include large capacity, low-level gates for sluicing, flushing, or the venting of turbidity currents.

Suitable mathematical models developed for reservoir sedimentation, describing the physical processes involved as accurately as possible, should be used for reliable simulations. Such models need to be able to simulate the hydrodynamics involved to some level of accuracy before one can hope to effectively predict sediment movement by water. Once a hydraulic model has been prepared which is judged to accurately predict movement of water (and hopefully has been calibrated), sediment characteristics, supply and transport can then be considered. Simulation of sedimentation processes is notoriously full of uncertainties. In many cases, however, accurate prediction of long-term sedimentation yield is as important as modeling of sediment deposition patterns in a reservoir.

Multiple numerical modeling programs are available; some of these have been reviewed by third parties as noted in this paper. For many areas, one-dimensional mathematical models are still often used with success for long-term sediment deposition predictions. However, for detailed studies two-dimensional or quasi-3D models are increasingly used, incorporating a fully hydrodynamic approach (quasi-steady for long-term simulations), and modules for erosion and deposition in cohesive and non-cohesive sediments, to be able to simulate storage, sluicing or flushing reservoir operations. Where density currents form in a reservoir, Navier-Stokes 2D vertical or 3D models should be used to describe the formation, movement and sediment transport of the density current. These models should be calibrated on local reservoir field data, especially when dealing with cohesive sediments.

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