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Estimation of sediment deposition in reservoir using one dimensional simulation models

Estimation du dépôt de sédiments dans le réservoir en utilisant des modèles de simulation à une dimension

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Foreword

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The committee responsible for this document is ISO/TC 113, *Hydrometry*, Subcommittee SC 6, *Sediment transport*.

Introduction

Storage reservoirs built across rivers or streams lose their capacity on account of deposition of sediment. Surveys indicate that world-wide reservoirs are losing their storage capacity, at an annual rate of about one percent, due to accumulation of sediments. The impacts of sedimentation on the performance of the reservoir project are manifold. Some of the important aspects are the following:

a) reduction in live storage capacity of the reservoir;

b) accumulation of sediment at or near the dam may interfere with the functioning of water intakes and hence is an important parameter in deciding the location and level of various outlets;

c) increased inflow of sediment into the water conveyance systems and hence to be considered in the design of water conductor systems, desilting basins, turbines, etc;

d) sediment deposition in the head reaches may cause rise in flood levels;

e) the location and quantity of sediment deposition affects the performance of the sediment sluicing and flushing measures used to restore the storage capacity.

Hence, prediction of sediment distribution in reservoirs is essential in the following:

a) feasibility studies during planning and design of various components of new projects;

b) performance assessment of existing projects.

The most simple and earliest models to predict the sedimentation processes in reservoirs are the empirical ones. The trap-efficiency curves derived from records of existing reservoirs are among the most commonly used empirical methods. Recently, due to better understanding of the fundamentals of reservoir hydraulics and morphology, along with the rapid growth of computational facilities, development and application of mathematical models have become a normal practice.

Compared to empirical methods, the mathematical approach of the sediment distribution enables more time and space dependent and more accurate modelling. A large number of mathematical models have been developed during the past few decades. Flow in the reservoir can be represented by the basic equations for conservation of momentum and mass of water and sediment.

Estimation of sediment deposition in reservoir using one dimensional simulation models

1 Scope

This Technical Report describes a method for estimation/prediction of sediment deposition within and upstream of a reservoir using numerical simulation techniques through one-dimensional flow and sediment transport equations.

Numerical simulation models for predicting sediment distribution are applicable for reservoirs, where the length of the reservoir greatly exceeds the depth and width and the reservoir has a significant through flow.

This Technical Report includes the theoretical basis and fundamental assumptions of the technique and provides a summary of some numerical methods used to solve the unsteady flow and sediment transport equations. Also provided are details on the application of the model, including data requirements, procedures for model calibration, validation, testing, applications and identification of uncertainties associated with the method. This Technical Report does not provide sufficient information for the development of a computer program for solving the equations, but rather is based on the assumption that an adequately documented computer program is available.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 748, *Hydrometry — Measurement of liquid flow in open channels using current-meters or floats*

ISO 772, *Hydrometry — Vocabulary and symbols*

ISO 1100-2, *Hydrometry — Measurement of liquid flow in open channels — Part 2: Determination of the stage-discharge relationship*

ISO 2425, *Hydrometry — Measurement of liquid flow in open channels under tidal conditions*

ISO 2537, *Hydrometry — Rotating-element current-meters*

ISO 3454, *Hydrometry — Direct depth sounding and suspension equipment*

ISO 4363, *Measurement of liquid flow in open channels — Methods for measurement of characteristics of suspended sediment*

ISO 4364, *Measurement of liquid flow in open channels — Bed material sampling*

ISO 4365, *Liquid flow in open channels — Sediment in streams and canals — Determination of concentration, particle size distribution and relative density*

ISO 4373, *Hydrometry — Water level measuring devices*

ISO 6416, *Hydrometry — Measurement of discharge by the ultrasonic (acoustic) method*

ISO 18365, *Hydrometry — Selection, establishment and operation of a gauging station*

ISO/TS 3716, *Hydrometry — Functional requirements and characteristics of suspended-sediment samplers*

ISO/TR 9212, *Methods of measurement of bedload discharge*

3 Definitions

For the purposes of this document, the terms and definitions given in ISO 772 apply.

4 Units of measurement

The units of measurement used in this Technical Report are SI units.

5 Principles of quasi-unsteady sediment modelling

Many early and contemporary sediment models simplify hydrodynamics of sediment transport models by invoking a "quasi-unsteady" flow assumption. Instead of solving the Saint-Venant equations explicitly or implicitly, the hydrodynamics are represented by a series of steady flow backwater computations and associated with temporal durations. Most generalized sediment transport models still utilize this approach. Because sediment transport and hydraulic processes respond on different time and distance scales and because of the inherent uncertainties associated with sediment simulations, the simplification provided by this approximation often justify the error introduced. However, because the quasi-unsteady approach does not route water, it can be difficult to implement for reservoir modelling. Quasi-unsteady models have been used successfully to model reservoir sedimentation but they require external hydrologic routing computations to define reservoir stage. This process often has to be iterative because the hydrologic routing parameters change in time as the capacity of the reservoir changes with sediment deposition. Therefore, an unsteady approach can be advantageous.

6 Principles of unsteady flow models

6.1 General

Numerical models are used to solve sedimentation problems in river engineering, especially for long-term simulation of long river reaches. The modelling cycle is schematically represented in Figure 1. The prototype is the reality to be studied and is defined by data and by knowledge. The data represents boundary conditions, such as bathymetry, water discharges, sediment particle size distributions, vegetation types, etc. The knowledge contains the physical processes that are known to determine the system's behaviour, such as flow turbulence, sediment transport mechanisms and mixing processes. Understanding the prototype and data constitute the first step of the cycle.

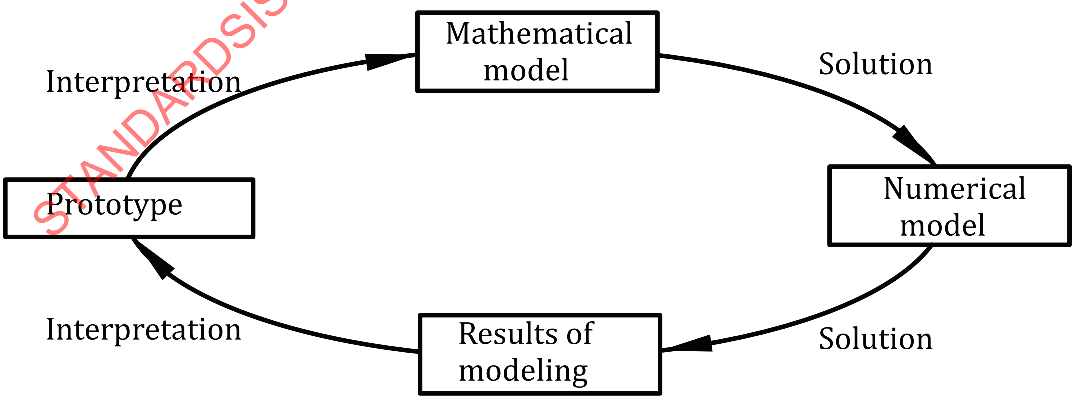

Figure 1 — Modelling cycle

In the first interpretation step, all the relevant physical processes that were identified in the prototype are translated into governing equations that are compiled into the mathematical model.

A mathematical model therefore constitutes the first approximation to the problem. It is the prerequisite for a numerical model. At this time, many simplifying approximations are made, such as steady versus unsteady and one- versus two- versus three-dimensional formulations, simplifying descriptions of turbulence, etc. In water resources, one usually (but not always) arrives to the set-up of a boundary value problem whose governing equations contain partial differential equations and nonlinear terms.

Next, a solution step is required to solve the mathematical model. The numerical model embodies the numerical techniques used to solve the set of governing equations that forms the mathematical model. In this step, one chooses, for example, finite difference versus finite element versus finite volume discretization techniques and selects the approach to deal with the nonlinear terms. This is a further approximating step because the partial differential equations are transformed into algebraic equations, which are approximate but not equivalent to the former.

Another solution step involves the solution of the numerical model in a computer and provides the results of modelling. This step embodies further approximations and simplifications, such as those associated with unknown boundary conditions, imprecise bathymetry, unknown water and or sediment discharges and friction factors.

Finally, the data needs to be interpreted and placed in the appropriate prototype context. This last step closes the modelling cycle and ultimately provides the answer to the problem that drives the modelling efforts.

The choice of model for each specific problem should take into account the requirements of the problem, the knowledge of the system, and the available data. On one hand, the model must take into account all the significant phenomena that are known to occur in the system and that will influence the aspects that are being studied. On the other hand, model complexity is limited by the available data. There is no universal model that can be applied to every problem. The specific requirements of each problem should be analysed and the model chosen should reflect this analysis in its features and complexity.

6.2 Governing equations

The governing equations are the one-dimensional, cross-sectionally averaged expressions for (1) the conservation of mass (or equation of continuity), (2) conservation of linear momentum and (3) continuity of the bed material.

The following one-dimensional flow equations are solved to get the hydraulic parameters such as energy slope, velocity and depth of flow at each cross-section at each time step. The sediment transport capacities at each cross-section are then computed and compared with the sediment inflow. The scour or deposition at each section is computed using sediment continuity equation and new cross-section bed levels are determined accordingly. The computations then proceed to the next time step and the cycle is repeated with the updated geometry.

Conservation of mass (or equation of continuity),

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q \tag{1}$$

Conservation of linear momentum

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\beta \frac{Q^2}{A}\right) + gA\frac{\partial y}{\partial x} + gA(S_f - S_0) = qu' \tag{2}$$

Equation of Continuity of the Bed Material

$$\frac{\partial G_b}{\partial x} + \frac{\partial G_s}{\partial x} + \frac{\partial}{\partial t}(C_s A) + \rho_* \frac{\partial}{\partial t}(B_d z) = 0 \tag{3}$$

where

A is the cross-sectional area of the channel, and varies with *x, t,* and *z*;

t is the time;

Q is the discharge, and varies with *x* and *t*;

u' is longitudinal component of the lateral inflow velocity and varies with *x* and *t*;

x is the longitudinal position along the channel axis;

y is the depth of flow, and varies with *x* and *t*;

g is the acceleration of gravity;

β is the momentum coefficient and varies with *x, z,* and *t*;

q is the lateral inflow per unit length of channel, and varies with *x* and *t*;

S_0 is the bed slope, and varies with *x*;

S_f is the friction slope, and varies with *x, t* and *z*;

G_b is the bed load;

G_s is the suspended load;

C_s is the average spatial sediment concentration in the cross-section;

ρ_* is the density of sediment in the bed;

B_d is the deformable bed width and varies with *t*;

z is the bed elevation and varies with *t*.

The momentum coefficient may be computed using Formula (4):

$$\beta = \int \frac{u^2 dA}{U^2 A} \tag{4}$$

where

- u is the velocity in some elemental area dA;
- U is the mean velocity in the same cross-section having a total area A.

The friction slope, S_f, accounts for the resistance due to external boundary stresses. The friction slope is generally represented by Chezy or Manning's equations.

For the Chezy equation, the bed resistance term in the momentum formula is described as:

$$S_f \frac{gQ|Q|}{C^2 AR} \tag{5}$$

where

- Q is the discharge;
- A is the flow area;
- R is the resistance or hydraulic radius.

For the Manning description, the term is:

$$S_f = \frac{gQ|Q|}{M^2 AR^{4/3}} \tag{6}$$

The Manning number, M, is equivalent to the Strickler coefficient. Its inverse is the more conventional Manning's, n. The value of n is typically in the range 0,01 (smooth channel) to 0,10 (thickly vegetated channel). The corresponding values for M are from 100 to 10.

The Chezy coefficient is related to Manning's n by

$$C = \frac{R^{1/6}}{n} = MR^{1/6} \tag{7}$$

Both R and n can vary as a function of x, z, and t. Formula 6 is based on the assumption that the Manning equation for steady, uniform flow provides a reasonable approximation for S_f in unsteady, non uniform flow.

Formula (2) can be modified to include a term accounting for the momentum imparted to the water by a temporally and spatially varying wind. Formulae (1) and (2) also can be written with (1) depth and velocity, (2) stage and velocity, or (3) stage and discharge as the dependent variables.

Formulae (1) and (2) apply to the unsteady, spatially varied, turbulent free-surface flow of an incompressible, viscous fluid in an open channel of arbitrary cross-section and alignment. The equations are solved simultaneously for the unknowns, z (depth of flow) and Q (discharge) as a function of time *(t)* and longitudinal position *(x).*

Formula (3) accounts for the sediment transport and thus the changes in bed levels. Various equations are available for the calculation of sediment transport rate and alluvial roughness, e.g. the Meyer-Peter and Muller and the DuBoys' transport function for the calculation of bed load; the Engelund and Hansen model, the Ackers and White model, the Yang model and the Smart and Jaeggi model for determination of the total load and the Engelund and Fredsoe and van Rijn models for the computation of bed load and suspended load separately. All these models/equations can be applied using a single representative grain size or using a number of grain sizes representing grain size fractions in graded material.

Formulae (1) and (2) are derived from first principles and may be obtained directly from the three dimensional equation of mass continuity and the Navier-Stokes equations, which are general, three dimensional statements of the conservation of momentum for any fluid flow. A number of assumptions are required to derive Formulae (1) and (2). An unsteady flow model should generally be applied to those conditions in which none of the major assumptions is severely violated. The assumptions are as follows:

a) flow is approximately one-dimensional, meaning that the predominant spatial variation in dynamic conditions of hydraulic parameters (discharge, velocity and stage) is in the longitudinal direction;

b) fluid density is homogeneous throughout the modelled reach;

c) vertical accelerations are negligible, i.e. the hydrostatic pressure distribution is applicable;

d) velocity is uniformly distributed in a given cross-section. Inclusion of the momentum coefficient in Formula (2) allows this assumption to be violated somewhat, however, there should be no flow separation and streamlines should not be highly curvilinear;

e) neither aggradation nor degradation of the river bed occurs during computational time step;

f) turbulence and energy dissipation can be described by resistance laws formulated for steady, uniform flow [required for Formula (4)];

g) there are no abrupt changes in channel shape or alignment;

h) velocity is zero at the channel boundary;

i) there is no super elevation of the water level at any cross-section;

j) surface tension and density of air at the free surface are negligible.

6.3 Numerical techniques for solution of governing equations

No known analytical solutions exist for Formulae (1) and (2). Consequently, numerical techniques are used to convert Formulae (1) and (2) into algebraic equations that may be solved for z and Q at finite, incremental values of x and t. This solution depends on the proper description of the cross-sectional area as a function of x and t, and on the availability of accurate boundary condition data.

A variety of numerical techniques have been proposed and used to solve the unsteady flow equations. The techniques of interest are those based on some type of gridded discretization of the problem at hand, in which the continuous variables for which the solution is sought are solved only at specific discrete locations of the physical domain. The algebraic equations that form the numerical model are functions of those discrete quantities. For the same problem (i.e. the same set of differential governing formulae and boundary conditions), it is possible to obtain very distinct sets of algebraic numerical equations, depending on the technique used to discretize the equations. The broad categories of numerical techniques are method of characteristics, finite differences, finite elements and finite volumes. Generally, finite-difference techniques are preferred for the solution of the one-dimensional partial differential equations describing unsteady open-channel flow. The finite difference method includes

a) explicit finite-difference methods, and

b) implicit finite-difference methods.

Numerous variations of each of these general categories of techniques exist. The methods are briefly reviewed to provide some perspective on advantages and disadvantages of each method.

6.3.1 Explicit finite-difference methods

Finite-difference methods are probably the most simple and most common methods employed in fluid flow models, as well as in other disciplines requiring the numerical solution of partial differential equations. They are based on the approximation of the individual derivative terms in the equations by discrete differences, thus converting them into sets of simultaneous algebraic equations with the unknowns defined at discrete points over the entire domain of the problem.

Explicit numerical schemes convert the governing equations to a system of linear algebraic equations from which the unknowns may be solved directly (explicitly) without iterative computations. Dependent variables on the advanced time level are determined one point at a time from known values and conditions at the present or previous time levels. Explicit schemes are only conditionally stable, meaning that errors may grow as the solution progresses, and the errors are a function of the time and distance step sizes. Explicit schemes are generally stable when the Courant condition is met, which results in limitations on the distance step and maximum time step, which can be used.

In order to meet numerical stability requirements, the computational time step must decrease as the hydraulic depth increases. Consequently, computational time steps may be required to be on the order of a few minutes for unsteady flow models of large rivers, which make the models somewhat computationally inefficient. Explicit finite-difference schemes also require that the computational distance steps be equal throughout the model domain, which may be a disadvantage for some systems.

6.3.2 Implicit finite-difference methods

Implicit numerical schemes convert the governing equations to a system on nonlinear algebraic equations from which the unknowns must be solved iteratively. Consequently, a system of 2N algebraic equations is generated for a model having N cross-sections along the x-axis. All of the unknowns within the model domain are determined simultaneously, rather than point-by-point as with explicit methods.

Weighting factors are typically required in the application of implicit schemes. These factors determine the time between adjacent time levels at which (1) the spatial derivatives and (2) functional quantities are evaluated; functional quantities are such features as cross-sectional area, top width and hydraulic radius, all of which are functions of the computed depth of flow. Some judgment is required in selecting these weighting factors and the weighting factors often are adjusted as part of the model calibration process. The accuracy of the numerical scheme generally decreases as the factor approaches one, where the terms in the governing equations are expressed entirely in terms of the future time step.

Fewer numerical stability problems are encountered with implicit schemes than with explicit schemes. Numerical instabilities can occur when modelling rapidly varying flows if the time step is large and if the spatial derivatives are not sufficiently weighted toward the future time step. Nonlinearities caused by irregular cross-sections having widths that vary rapidly along the channel or with depth also can cause numerical instabilities in implicit models.

6.3.3 Finite element methods

Finite element methods have been used successfully for fluid flow problems since the 1960s. They are particularly useful to solve problems with complex geometries, as they do not require the structured grid system needed in finite difference techniques. In an unstructured grid, the computational nodes do not need to be defined in an ordered manner, as opposed to structured grids where each node is identified by an (i - j) pair.

There are two main approaches for the formulation of finite element methods: variational methods and weighted residual methods. In variational methods, the variational principle for the governing equation is minimized. In general fluid mechanics problems, exact forms of the variational principles for the governing nonlinear equations are difficult to find (unlike in the linear equations encountered in solid mechanics); therefore, weighted residual methods are much more popular. Residual methods are based on minimizing some sort of error, or residual, of the governing equations.

6.3.4 Finite volume methods

Finite volume methods use conservation laws, i.e. the integral forms of the governing equations. The domain of computation is subdivided into an arbitrary number of control volumes, and the equations are discretized by accounting for the several fluxes crossing the control volume boundaries. There are two main types of techniques to define the shape and position of the control volumes with respect to the discrete grid points where the dependent variables are calculated: the node-centred scheme and the cell-centred scheme. The node-centred scheme places the grid nodes at the centroids of the control volume, making the control volumes "identical" to the grid cells. In cell-centred schemes, the control volume is formed by connecting adjacent grid nodes.

The main advantage of finite volume methods is that the spatial discretization is done directly in the physical space, without the need to make any transformations between coordinate systems. It is a very flexible method that can be implemented in both structured and unstructured grid systems. Because the method is based directly on physical conservation principles, mass, momentum and energy are automatically conserved by the numerical scheme.

Under certain conditions, the finite volume method is equivalent to the finite difference method or to particular forms of lower order finite element methods.

6.4 Sediment transport

Sediment transport rates are calculated for each flow in the hydrograph for each grain size. The transport potential is calculated for each grain size and multiplied by the corresponding fraction present in the bed at that time to obtain the transport capacity component. Computations of sediment transport are carried out using control volume concept.

The basis for adjusting the bed levels for scour or deposition is the continuity equation for sediment, i.e. the Exner equation. The sediment continuity equation is written for the control volume for each cross-section. The control volume width is usually equal to the movable bed width and its depth extends from the water surface to the top of bed rock or other geological control beneath the bed surface. In areas where no bed rock exists, an arbitrary limit called the model bottom is assigned.

The solution of the continuity of sediment equation assumes that the initial concentration of suspended bed material is negligible. Therefore, no initial concentration of bed material load needs to be specified in the control volume. The hydraulic parameters, bed material gradation and calculated transport capacity are assumed to be uniform in the control volume. The inflowing sediment load is assumed to be mixed uniformly with sediment existing in the control volume. The model accounts for two sediment sources, the sediment in the inflowing water and the bed sediment. The inflowing sediment load is specified as the upstream boundary condition. The bed sediment control volume provides the source –sink component and is specified in the input data.

The transport capacity is calculated at each cross-section using hydraulic parameters obtained from the water surface profile computations and the bed material gradation. The difference between the inflowing sediment load and the reach's transport capacity is converted to a scour/deposition volume. After each time step, the cross-section coordinates are lowered/raised by an amount which, when multiplied by the movable bed width and the representative reach length equals the required scour/deposition volume.

The process of scour and deposition is converted for numerical algorithms for computer simulation. The basis for simulating vertical movement of the bed is the continuity equation for sediment material viz., the Exner equation.

$$\frac{\partial G}{\partial X} + B_0 \frac{\partial Y_s}{\partial t} = 0 \qquad (8)$$

where

B_0 is width of movable bed;

t is time;

G is average sediment discharge rate during time step;

X is distance along the channel;

Y_s is depth of sediment in control volume.

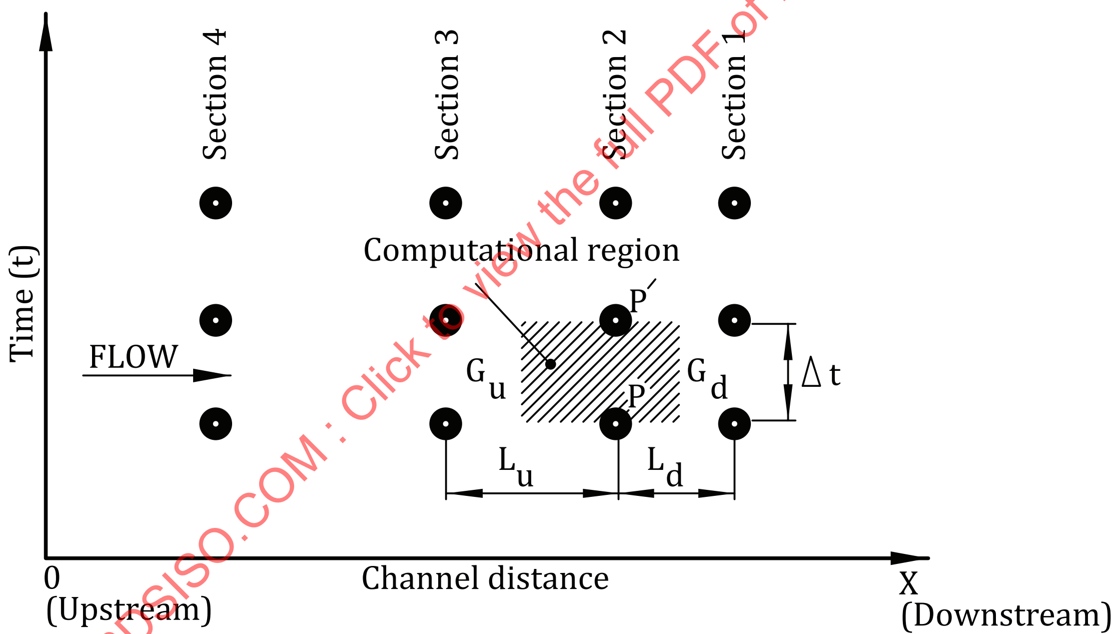

Figure 2 — Computation grid

The following formulae represent the Exner equation expressed in finite difference form for point P shown in Figure 2

$$\frac{G_d - G_u}{0{,}5\left(L_d + L_u\right)} + \frac{B_{sp}\left(Y'_{sp} - Y_{sp}\right)}{\Delta t} = 0 \qquad (9)$$

$$Y'_{sp} = Y_{sp} - \left[\frac{\Delta t}{(0{,}5)\,B_{sp}}\right]\left[\frac{G_d - G_u}{(L_d + L_u)}\right] \quad (10)$$

where

B_{sp} is the width of movable bed at point P;

G_u, G_d are the sediment loads at the upstream and downstream cross-sections respectively;

L_u, L_d are the upstream and downstream reach length respectively between cross-sections;

Y_{sp}, Y'_{sp} is the depth of sediment before and after time step, respectively at point P;

0,5 is the 'volume shape factor' which weights the upstream and downstream reach lengths;

t is the computational time step.

The initial depth of bed material at point P defines the initial value of Y_{sp}. The sediment load, G_u, is the amount of sediment, by grain size, entering the control volume. For the uppermost reach, this is the inflowing load boundary condition. The sediment leaving the control volume, G_d, becomes the G_u for the next downstream control volume.

The sediment load, G_d, is calculated by considering the transport capacity at point P, the sediment inflow, availability of material in the bed and armoring. The difference between G_d and G_u is the amount of material deposited or scoured in the reach and is converted to a change in bed level.

The transport potential of each grain size is calculated for the hydraulic conditions at the beginning of the time interval and is not recalculated during that interval. However, the gradation of the bed material is recalculated during the time interval because the amount of material transported is very sensitive to the gradation of bed material.

7 Data requirements

In general, the basic data requirements for loose boundary hydraulic models can be grouped in three broad categories: geometric data, hydraulic data and sediment data. These data establish the boundary conditions necessary to solve the governing equations and are an integral part of a model. The term "model" thus refers to the ensemble of the set of governing equations, their numeric solution technique, their implementation in a computer program, and the data that define the prototype. Data are required to construct, calibrate, test, validate and apply unsteady flow and sediment deposition models. Data collection and preparation often play the dominant role in determining the accuracy and applicability of the final numerical solutions generated by the computer.

The geometry data defines the topography of the reach to be simulated, i.e. the channel bed, banks and flood plains. In two and three-dimensional models, the data are most often presented as a set of points given by its x, y and z coordinates. The data are then interpolated to the locations of the grid nodes used in the discretization of the problem. In one-dimensional models, the geometry is usually defined by cross-sections. Each cross-section is a line representing a particular section of the modelled reach and is given by a set of points, each defined by a lateral distance and a bed elevation above a common datum. This line provides the information about the section shape and the locations of the sub-channels, and should be taken between locations above the highest stage levels. It should be perpendicular to the flow streamlines. Additionally, the distance between the cross-sections needs to be specified, and this distance should be measured along the flow streamlines. In addition, the movable bed portion of each cross-section and the depth of sediment material in the bed are required in some models.

Hydraulic data encompasses the necessary upstream and downstream flow conditions, as well as friction factors and local head losses. 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.

Stage-discharge rating curves, an elevation hydrograph, or a water-surface-slope hydrograph are common ways to define the stage. In the case in which the downstream boundary is a dam, the reservoir operational scheme may be used to define the stage. When the dam outlet works are used, relationships for the gates and spillways may have to be employed. These relationships are a function of the head at the dam, and more complex iterative schemes need to be used. Some models include capabilities to specify gate operations either a priori or as a user specified function of simulated hydraulic parameters (e.g. gates are opened and closed during the simulation in response to the reservoir stage in the previous time step).

Friction factors play an important role in determining stages and flow velocities. They can vary spatially (laterally and longitudinally) and temporally as a function of flow, hydraulic depth, season, temperature and changes in sediment transport conditions. Friction factors shall 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-usually using hydraulic and/or sediment quantities. Local energy loss coefficients should also be given, such as those due to channel bends, natural or manmade obstacles to the flow such as bridge piers and abutments. Once again, these may be prescribed or may be calculated, and they commonly require iterative procedures which many software packages automate. It is also important to note that bed roughness generally changes dramatically during the course of a reservoir simulation as the substrate fines due to fine sediment settling and coarsens due to the formation and advancement of the delta. Therefore, it is important to either select a method that computes a roughness parameter based on the substrate during a simulation or to select a roughness parameter that represents conditions during most of the simulation (not necessarily the initial conditions).

Sediment data encompass all the necessary information for sediment transport computations. The sediment inflow hydrograph shall be defined at the inflow boundaries. It is also necessary to specify the sediment concentration distribution along those boundaries. This data are rarely available, so a rating curve is commonly used and honed during the calibration process. The sediment particle-size distributions of these sediment inflows are also required. The particle size distribution of sediment boundary condition often varies as a function of the load (e.g. larger loads may have a higher percentage of sand and gravel). However, this data are rarely available and often has to be generated by engineering judgment. Because it is usually among the least certain parameters, the gradation of the inflowing load is often an effective calibration parameter.

Bed material gradations also need to be determined for each computational grid node (or for each cross-section, in the case of one-dimensional models). However, it is common practice to associate bed gradation samples with multiple nodes or cross-sections or to interpolate gradations between those that have data. Additionally, especially in the case of scour computations and bank widening, it is also necessary to provide the underlying bed-material size distribution. Alluvial sediments are often stratified so the sampling process should be informed by the modelling objectives. However, because reservoir sediment models tend to be depositional models, they are often far less sensitive to the starting bed gradation and bed mixing dynamics than other types of sediment models. It is often sufficient to simply estimate the original bed gradations within the backwater region of the reservoir.

Water temperature variations should also be prescribed or modelled because they have an indirect impact on sediment transport via the fall velocities of the sediment particles. Reservoir sedimentation models tend to be more sensitive to temperature data than other sediment modelling applications because they are strongly dependent on the fall velocity of fine materials.

In practice, it is difficult to determine a priori some of the hydraulic parameters necessary for a successful simulation. For that reason, usually there is a model calibration stage in which stage and discharge observations along the study reach are used to adjust the values of those parameters, such as bed roughness, discharge coefficients or other parameters particular to the model employed. Similarly, there should be a calibration stage for the sediment transport calculations. Observations of the sediment outflow quantities, of variations in channel width and bed elevation, and of changes in sediment particle-size distributions can be used to properly adjust model parameters.

International Standards for the measurement of velocity (ISO 748) and discharge (ISO 6416), for collection of water level and discharge records (ISO 4373), measurement of bed load and suspended load transport and bed material, bed load and suspended load, gradation curve (ISO/TS 3716, ISO 4363, ISO 4364, ISO 4365, ISO/TR 9212) should be followed.

In general, data are required at model boundaries for the entire period for which flow and sediment deposition is to be computed using the simulation model. Short-term records and discrete measurements are needed at locations within the model domain for the period, which are used for model calibration, testing and validation.

7.1 Selection of model boundaries

Reliable, accurate and appropriate boundary condition data are required for successful computation of stream flow and sediment deposition using the model. In a river system, there are three types of boundaries: upstream, downstream and internal. The upstream and downstream boundaries are at the cross-sections that are at the upstream most and downstream most cross-sections, respectively. There are three types of internal boundaries: a local inflow point, a tributary junction point and a hydraulic control point. Model boundaries should be selected prior to the installation of data-collection instrumentation. Boundaries should be in locations where there are a minimum of flow disturbances, such as sharp bends, rapid changes in cross-sectional geometry and major inflows. The modelled reach length also should be sufficiently long to permit accurate determination of the longitudinal water-surface slope so that adverse effects of measurement errors are minimized. Moreover, as subsequently discussed, discharge records are preferable as the upstream boundary condition to the extent possible. Thus, it may be expedient to extend the model domain beyond the reach for which stream flow computations are actually needed in order to obtain the necessary data for model boundary conditions.

There are two common methods of modelling the dam itself. The dam operation can be built into a downstream stage boundary condition. In this case, the time series of reservoir stage just upstream of the structure is the downstream boundary condition of the model. However, if the downstream effects of the dam (e.g. scouring or armoring) are of interest the dam can be modelled as an internal boundary condition, often using customized routines for simulating dam operations.

A common error in reservoir sediment modelling is to select an upstream boundary condition that is too close to the reservoir. Many reservoirs generate backwater effects far upstream of the flat water portion of the hydraulic profile. A mild backwater effect can generate substantial deposition, particularly of sand and gravel, far upstream of the reservoir itself.

7.2 Cross-section data

7.2.1 General

The topographical description of the area to be modelled is achieved through the specification of cross-sections of the channel (and flood plain) which lie approximately perpendicular to the direction of flow. Cross-sections are specified by a number of *x-z* coordinates where x is the transverse distance from a fixed point (often left or right bank top) and z is the corresponding bed elevation. The transverse extent of each cross-section depends on the requirement of flood simulation and method of simulation. The number of cross-sections required is determined from both physical and mathematical requirements. A measured cross-section is typically required at each computational node within the model reach. The exact spacing of the computational nodes, however, depends on criteria of the numerical scheme of convergence testing and stability.

Physically, there should be a sufficient number of cross-sections to define adequately the variation in channel shape along each model branch. Numerical solutions of the governing equations generally use the average of the measured cross-sections at the upstream and downstream ends of a reach to represent the cross-sectional geometry of the entire reach bounded by the two measured sections. Further, measured cross-sections should be fairly representative of conditions upstream and downstream of the measurement. The measured sections also should be spaced sufficiently close so that large changes in channel geometry do not occur between the sections.

Longitudinal distances should be measured along the centerline of the channel.

Cross-sections should be measured in accordance with ISO 748. Cross-sections should be referenced to the same datum as the stage records.

7.2.2 Manning's n values

The Manning's n values for each subsection are to be specified. The variation of n values either with discharge or elevation of water surface in the main channel and overbank/flood plain areas can be specified. In some models, a relative resistance can also be specified for each pair of coordinates.

7.2.3 Movable bed and dredging

The movable bed limits, the bottom elevation and lateral limits of dredged channel, as well as the depth of advanced dredging can also be specified in the input records.

7.3 Stage data

Stage data are required at all external boundaries of the modelled system in order to specify boundary conditions. Stage data are not required at internal junctions, where channels join within the model domain. In case of a hydraulic control point, three options are available to specify the stage as the internal boundary condition. The first option is to specify a rule-curve to establish a constant operating elevation of a reservoir/navigation pool within the model domain. This is accomplished by specifying a water surface elevation and a head loss. The second option allows users to specify a rating curve as an internal boundary. The third option, available in most generalized models, is to use customized routines to simulate the operation of hydraulic structures. This option is used for modelling weirs, gated spillways and drop structures. Stage also should be measured in at least one, and preferably multiple, locations within the model domain to provide data for model calibration and validation.

It is critically important that all stage measurements be referenced to a common datum. Errors in gauge datum translate into errors in water-surface slope which greatly affects computed stream flow through the third term in Formula (2). The use of discharge as the upstream boundary condition removes much of the uncertainty associated with potential errors in gauge datum.

Except in very large rivers (widths of several hundred meters or more), stage should be measured at 1 h intervals or less for reliable modelling of flow transients. If possible, the stage measurement interval should be a whole multiple of the computational interval, and should not be more than about five times the computational interval.

Synchronous measurement of stage at all recorders is also required for application of unsteady flow models for computing stream flow. Asynchronous measurements, like datum errors, translate into errors in water-surface slope and, hence, errors in computed stream flow.

Stage should be measured following procedures outlined in ISO 18365 using equipment described in ISO 4373.

7.4 Velocity data

Measurements of velocity in the study reach are required to (1) evaluate the assumption of one dimensional flow and (2) compute the momentum coefficient [Formula (3)]. Stream velocities obtained during discharge measurements generally are adequate for these purposes.

Velocities should be measured following procedures outlined in ISO 748 or ISO 2425 using equipment described in ISO 2537 and ISO 3454.

7.5 Discharge data

Discharge data are required for model calibration, and are needed as boundary data. Discharge data may be either (1) a continuous time series obtained from a stage-discharge rating or by using the *in situ* velocity meters, such as ultrasonic velocity meters or (2) discrete measurements. Time series of discharge are generally required only at the upstream boundaries. Discrete measurements are made within the model domain for the purposes of model calibration and testing.

Discharge should be measured using methods described in ISO 748, ISO 1100-2, ISO 2425, ISO 6416 and ISO 18365.

7.6 Lateral inflows and withdrawals

Time-varying records of major inflows into and withdrawals from the modelled reach must be included in the model to maintain mass balance. Inflows or losses which are relatively constant throughout the modelled reach, such as ground-water inputs or losses, can be lumped into a few discrete points in the reach or can be included at each computational node. Inflows from major streams should be gauged. Inflows from minor streams and local areas along the channel can be estimated using data from nearby gauged streams and drainage area ratios. In the absence of flow data, watershed or hydrologic modelling can be utilized if there is a rainfall record.

7.7 Sediment data

Sediment data required for the simulation model includes the incoming sediment load data, sediment properties and the grain size distribution. The transport capacity relationships and unit weights of deposited material are also required to be input in some models.

The sediment load (total load) entering the upstream boundary of the model and at local inflow points can be expressed as a function of water discharge vs sediment load or as a time series of water and sediment discharge data. When expressed as a function of water discharge vs sediment load, this data are specified as a table of sediment load by grain size class for a range of water discharges. The discharges should encompass the full range found in the inflow hydrograph. When expressed as a time series data, grain sizes representing grain size fractions are to be specified separately. Some models specify a load series and then the gradation is picked off a rating curve keyed to the load.

The basic sediment properties to be specified in the input data are grain size, specific gravity, grain shape factor, unit weight of deposits and fall velocity.

Depending on the software used for simulation, different methods are available for the calculation of sediment transport rate of clays, silts, sand and gravels. Some of the relationships available for sand and gravel transport in different models are listed below.

a) Engelund and Fredsoe (1976),

b) van Rijn functions (1984),

c) Toffaleti's (1968) transport function,

d) Madden's (1963) modification of Laursen's (1958) relationships,

e) Yang's (1973) stream power for sands,

f) DuBoys' transport function (Vanoni 1975),

g) Ackers-White (1973) transport function,

h) Colby (1964) transport function,

i) Engelund and Hansen Formula (1967),

j) Smart and Jaeggi model (1983),

k) Toffaleti (1968) and Schoklitsch (1930) combination,

l) Meyer-Peter and Muller (1948),

m) Toffaleti and Meyer-Peter and Muller combination,

n) Copeland's (1990) modification of Laursen's relationship(Copeland and Thomas 1989), and

o) User specification of transport coefficients based on observed data.

However, it should be noted that most of these relationships were developed to compute transport of sand and gravel in cases of unobstructed river flow. For small reservoirs and debris basins, results can be highly sensitive to the selection of a transport equation (Gist et al. 1996). However, deposition in large reservoirs often involves settling of silt and clay at flow depths and velocities outside of the range of these transport functions, they are useful for the reach upstream of the reservoir, but do not tend to be applicable within large reservoir pools. Sediment dynamics within large reservoirs with cohesive deposits tend to be driven by fall velocity more than transport capacity. Therefore, fine sediment dynamics can either be simulated using a dedicated cohesive method like the coupled Krone (1962) and Parthenaides (1965) method (which essentially uses fall velocity to compute deposition) or a fall velocity limiter should be added to the capacity calculation.

8 Formulation, calibration, testing and validation of models

Modelling is based on abstraction of a physical system to a mathematical expression and replication of the system using theses expressions and appropriate field data. The analyst should identify the important features of the flow system and ensure that these features are reflected in the model selected for application to the study reach. Important general model attributes include the following:

a) ability to simulate a wide range of flow conditions;

b) ability to represent a range of complex channel conditions and geometries;

c) stable, numerically-convergent, efficient computational scheme;

d) system for processing model input data and output simulation results.

All numerical models should be mathematically verified first by analytic solutions linear or nonlinear. Once the model is proven mathematically correct, it should be evaluated through a series of physical process validations, which are based on laboratory experimental results for the purpose of determining whether the model is capable of reproducing the basic physical processes relevant to the real-life problems to be studied by the selected model. Before a mathematically correct and physically capable numerical model is to be applied to an investigation of a real-world problem, one more step, the application case and site-specific validation, is required.

8.1 Formulation of numerical models

The behaviour of the sediments in the reservoir is mainly determined by the various forms of three-dimensional water circulation and the characteristics of the sediment and water mixture (e.g. chemical regimes, grain size distribution, stratification and three dimensional density currents, flocculation and consolidation of clay, re-entrainment of fine particles). Many varied dynamic forces and mechanics are involved and many of the phenomena are still not well defined. The use of mathematical models makes it possible to analyse the time dependent processes and spatial behaviour of flow and sediments.

A large number of mathematical models for the time and space dependent sediment distribution are available. Almost all models that are developed for practical purposes are one-dimensional, i.e. cross-sectional averaged. The main aspects of preparing and calibrating one-dimensional models are outlined below.

8.1.1 Hydrology

In most one-dimensional models, the inflowing hydrograph is specified as a series of constant discharge intervals. Since sediment transport is concentrated in periods of higher discharge, low flows may be simulated by a long period of constant discharge.

8.1.2 Geometry

To represent the behaviour of a fluvial system in a one-dimensional model, the system geometry should be specified such that, it reproduces the essential prototype hydraulic behaviour. Model geometry should be configured to simulate a one-dimensional flow path followed by sediment and water moving towards the dam, and cross-section locations should be selected to reflect reach averaged hydraulic conditions.

The distance between the cross-sections should be selected to reproduce the hydraulic characteristics of the reach. Cross-section geometry at a specific point may require adjustments to better simulate the hydraulic characteristics of the reach. Hydraulically ineffective areas of the reservoir lying outside the main flow path should be identified and designated as zero flow zones. Most models have the capability to identify portions of the cross-section that are ineffective. If the model does not include this capability, the cross-section can be truncated, but this will introduce an error due to the loss of storage in that portion of the cross-section.

In addition to defining the initial hydraulic geometry of the cross-section, it is also necessary to define the width and depth of the movable bed. These should be defined based on field inspection.

8.1.3 Selection of transport equation

The use of different bed material transport equations in a numerical model can produce significant differences in the simulation results. When measured bed material load data are available, transport equations should be compared to the measured values to select the applicable equation. If historical deposition patterns are available, the transport relation that best reproduces the observed historical pattern should be selected. Some models use parameters of the classic transport equations, like the reference shear, that allows the user to refine the behaviour of the best available equation during the calibration stage of the project.

A customized sediment transport equation can be used, if none of the equations provide a good fit. Using existing data collected from a river station, sediment load or concentration can be plotted as a function of water discharge, velocity, slope, depth, shear stress, stream power and unit stream power. The best fitting curve should be selected as sediment rating curve for the station.

When no field data or historical deposition patterns are available, transport equations may be selected based on the comparison of conditions in the study area against the data set used in the development of each equation. While selecting the correct transport equation will be essential to represent the sediment dynamics upstream of the reservoir, sediment models are often relatively insensitive to the transport equation selected in the reservoir itself. Because the water velocity in most reservoirs is so low, the capacity calculated by all equations approaches zero. Therefore, the sediment dynamics in the reservoir is more dependent on simulation of how fall velocity limits deposition in these low capacity cross-sections.

8.1.4 Bed mixing and armoring algorithm

Most models subdivide the bed sediments into layers (e.g. active and inactive layers) in order to compute transport capacity based on the sediment most likely to be transported. This is most important for erosion models, so reservoir deposition is not very sensitive to the mixing algorithm selected. However, erosion downstream of the dam will be strongly affected by bed mixing and armoring processes. If these processes are of interest, a bed mixing algorithm should be selected that is capable of simulating them.

8.2 Preliminary tests

In many cases, it is appropriate to conduct preliminary tests using simplified channel geometry and boundary conditions.

Tests should be conducted using a channel which has a uniform, rectangular cross-section, and with the model configured for the study reach. Tests using the rectangular cross-section model could include the following:

a) No inflow and no bed slope–no flow should be generated within the model domain.

b) Steady and unsteady inflow–mass should be conserved.

c) Triangular-shaped inflow hydrograph in channel with no bed slope–peak flow should not be significantly attenuated.

After the model for the study reach has been formulated using the measured cross-sectional data, tests to be performed include the following:

a) No inflow or water surface slope — no flow should be generated in the model domain; this test also determines if unintentional openings in the boundaries are present.

b) Steady and unsteady flow — mass should be conserved.

c) Rapid change in inflow boundary conditions — no numerical instabilities should be generated.

d) The 'robustness test' is used to find numerical oscillations or computational artefacts. A long-term sediment simulation should be conducted with the project geometry (without the dam) and a constant flow and sediment load. Generally the channel forming discharge and the corresponding sediment load is used. This simulation should converge to a stable solution if the channel forming discharge is correct and the original channel is in equilibrium.

e) Change in boundary conditions from one steady flow to another flow — the amount of time required for all flows within the model domain to reach the new steady-state condition is an indication of how long initial conditions persist within the model domain; model results generally are not accepted until effects of the initial conditions are transported out of the model domain so that model is responding to boundary conditions only.

Other tests may be performed as needed, but these simple tests can be used to document general model performance and should allow users to gain a better understanding of model capabilities and limitations prior to application to the study reach.

8.3 Computational grid and time step

The computational grid is used to represent the physical system in the simulation model. Junctions, hydraulic structures, inflows and outflows shall be represented by the computational grid.

Selection of the computational grid is an important task in the modelling process. A carefully selected computational grid will avoid many problems during the calibration and application phase. The design of the computational grid should be based on a thorough insight into the hydraulics of the area to be modelled and understanding of how the model works. Some general guidelines for selection of the computational grid are given below:

a) topographical/bathymetric data should be available for the entire study area;

b) at the model boundaries time series of water level or discharge or a rating curve should be available;

c) the boundary should be located at a sufficient distance from the area of interest to ensure that changes in the area of interest being investigated do not affect the boundary.

The channel system is subdivided into a number of finite segments for solution of the numerical approximation of the governing equations. The solution points are either at the end or the midpoint of each segment. The computational grid should be established such that computations of stage and discharge coincide with locations of data collection, or at locations where computed data are required. Measured cross-sectional data should be available at the end of each computational grid cell.

Some models allow non-uniform segment lengths, but others require that all segment have the same length. Segment lengths should be at least three times greater than the width of the channel and are frequently 5 to 10 times the channel width. Exact segment length is determined during convergence testing.

The computational time step should be sufficiently small to accurately represent flow transients, which occur in the modelled system. Generally, the computational time step is reduced to meet stability criteria rather than adjusting the spatial discretization interval. However, cross-section interpolation is sometimes used to improve the spatial discretization when both need to be reduced. As with the computational grid, convergence testing helps to define the maximum time step that can be used.

8.4 Convergence testing

A finite-difference solution to a partial-differential equation is spatially convergent if the numerical solution approaches the true solution of the differential equation, as the finite-difference spatial discretization approaches zero. Spatial convergency can be tested by repeatedly applying the model with a fixed set of boundary conditions for successively smaller computational discretizations. The model is spatially convergent if no further change in model results is observed, as the spatial step is refined. Likewise, a model is temporally convergent if model results remain substantially unchanged as the computational time step is decreased. Convergence testing should be conducted prior to model calibration to determine the effects of spatial discretization and time step on model results.

8.5 Boundary and initial conditions

Two initial conditions (Q and z for the formulation of the unsteady flow equations used in this Technical Report) are required at each computational node in the model domain. For the initial application of the model to a study reach, common initial conditions are a steady flow, equal to the initial boundary-condition flow, and a water surface, which slopes linearly from a measured upstream stage to a measured downstream stage. It is more common in most generalized models to simply compute a steady flow backwater based on the boundary conditions at the first time step. This gives a Q and a z at every node and is usually a better approximation of the Q and z for the first time step. Output from a previous unsteady flow model application also may be used to determine initial conditions for a simulation that follows sequentially in time.

The model may only be applied for periods, which have measured boundary conditions. Boundary conditions include a time series of measured stage at the downstream boundaries, measured stage or discharge at the upstream boundaries, measured lateral inflows, and measured sediment discharge at the upstream boundaries and inflow points.

8.6 Calibration

The common practice of applications of numerical models to the investigation of sedimentation problems relies heavily on the calibration of model parameters using the measured data from the site under investigation. Therefore, before the application of a model to the investigation of a real-life problem in nature, it has to be tested by field data. The application of a model to each real-life problem has to have its parameters representing the unique characteristics of the study site determined by data measured at the site. This is called site specific calibration. The user should not use all measured data in calibration. Instead, at least half or more data should be kept for validation to confirm whether and how close or adequate the model can predict the natural phenomena. Because of the uncertainty inherent in the sediment transport processes, data and equations it is essential to calibrate a sediment model if is expected to make useful predictions of the future.

Calibration is accomplished by adjusting model parameters until model results agree with observations within the specified tolerance. Essentially, all components of the model are subject to adjustment during model calibration. Components that are directly measurable and physically well defined, however, are typically less subject to adjustment than are the parameters that might not be directly measured. This results in a non-unique solution. Therefore, the calibration process should target a few highly sensitive and highly uncertain parameters to adjust. The most common calibration parameters for a reservoir sediment model are the coefficients (i.e. m and b in $Qs = m\ Q^b$) of the flow-load curve, the inflowing sediment gradations, and the temperature. Measures for quantifying the calibration are discussed in 8.7.

Before attempting a sediment calibration, a good hydraulic calibration should be completed. Use fixed bed model to perform hydraulic calibration for low, bankful and high flows before calibrating for sediment. Initially, the resistance coefficient, momentum coefficient, and weighting coefficients for the numerical scheme should be varied, because these parameters cannot be measured. In order to achieve an acceptable calibration at low and high flows, a vertical variation (or flow dependence) in the resistance coefficient is often required. Boundary gauge datum may be adjusted slightly if there is some uncertainty about the accuracy of the datum. Cross-sectional geometry also may be adjusted during the calibration process. Adjustment of channel geometry is justified because the measured cross-sections are used to represent the average conditions within a computational segment, rather than the actual conditions at the measured cross-section. Calibration adjustments should be performed proceeding in the same direction as the computational sequence. Thus, for sub-critical standard step hydraulic computations, one may start hydraulic adjustments at the downstream limit of the model and proceed upstream. When calibrating for sediment, adjustments can start at the upstream end of the model and proceed downstream. The upstream limit of the model should consist of a reach having stable characteristics throughout simulations under existing and proposed conditions.

In existing reservoirs, calibration may be performed using the available data of grain size and geometric change over time. In rivers lacking transport data and at proposed reservoirs sites, the model should be calibrated by simulating the existing condition. For proposed reservoir site, the numerical model may be used to simulate a similar existing reservoir in the region. This exercise can demonstrate the model's ability to simulate the pertinent processes and aid in the selection of the transport equations and parameters values.

The most common approach to reservoir model calibration is to collect repeated cross-sections and try to simulate the change in sediment mass or volume associated with each computational node. Often, the sediment calibration proceeds in two iterative steps. First, the flow load curve is adjusted to replicate the total mass or volume change in the reservoir. Second, the gradational distribution of the inflowing load is adjusted to match the longitudinal distribution of the deposited sediments. Coarser sediment will deposit upstream and finer sediments will deposit closer to the dam, so the relative distribution of the sediment can be adjusted to match the spatial depositional pattern in the reservoir. It is often necessary to iterate between these two steps a few time to refine the calibration. Finally, if gradation data of the sediment deposits is available the gradational distribution of the computed deposits can be used to check and refine the gradational break down selected for the inflowing load. It is important to note when the reservoir gradation data was collected however, because reservoir deposits are the result of a prograding front which is coarse at the top and fine at the bottom. So these deposits tend to stratify and the surficial gradations change over time (coarsening at a given location).

8.7 Validation

An appropriate portion of field data collected at the study site is used to calibrate the site-specific values of the model parameters. Then, the calibrated model is used to predict field characteristics and processes under prescribed forcing. The predicted results are then compared with those measured data at the same site under the same forcing conditions. If a reasonable agreement between the model simulations and the field measurements is achieved, the numerical model is validated for the application to the study case at the specific site. During the validation test(s), it is very important that the calibrated model parameters cannot be changed or tuned.

To conduct an application case and site-specific validation successfully, one should have a sufficient amount of high quality field data collected at well-designed locations with proper spatial distribution. Due to the fact that the numerical model represents an idealized and simplified system of the real-life problem, it is not expected that the numerically simulated results and the field measurements are in perfect agreement. The more important or useful results are the trend of spatial and temporal variations of the natural systems. Therefore, one should make certain that the trends of spatial and temporal variations of the system predicted by the computational model are reasonably accurate and reliable.

Graphical comparisons of measured and simulated information are often used for validation of numerical models, but these may be misleading. Measures of deviation between model results and data include absolute and relative error and root mean square deviations.

Statistical tests of significance are necessary to determine whether deviations are meaningful or whether they are simply related to variability in data. However, statistically independent data are needed to test for significance. Consequently, data and model results should be sampled at intervals greater than the correlation time scale before applying certain statistical tests, such as the *t*-test.

If possible, the model should be validated over the range of flow conditions for which the model is to be applied. The model may be applied to flows reasonably outside the range for which the model was tested, as long as conditions do not change appreciably.

Since the sediment transport model has more physical parameters than the flow model, such as sediment transport capacity, and they most likely vary in different river reaches in different seasons, the flow model should pass the above verification and validation tests first, and then, the sediment transport model should go through a similar procedure.

8.8 Predictive simulation

Once the model is calibrated and validated, it can be used to predict with some confidence. Predictive sediment modelling usually poses management questions about the rate of reservoir sedimentation. These are usually long term simulations (commonly 30 to 50 years) that predict the sediment elevation at an intake or the changes in the hydrologic capacity (e.g. storage-volume curves) over time. This requires selection of a representative future hydrologic time series, which is often the largest source of uncertainty in a reservoir sedimentation study. It is common to simply repeat historic flows to represent future hydrology. However, this approach can under or over predict deposition if the historic record is not representative of the system hydrology. Therefore, it is generally useful to perform statistical hydrology as well as a regional and historical analysis to evaluate how representative the historical flow record is. Stochastic time series can be generated to approximate the expected future deposition and quantify the uncertainty of the results related to the uncertainty of the future hydrology.

8.9 Sensitivity testing

Sensitivity testing consists of evaluating the change in model results to changes in selected model parameters. Parameters, or conditions, which should be included in the sensitivity testing include the resistance coefficient, the weighting coefficients used in the numerical scheme, the momentum coefficient, sediment transport function and channel geometry. The usual procedure is to successively increment the parameters by small amounts, apply the model, and compare the results with results from the calibrated model. A model which is highly sensitive to small changes in one or more parameters may become unstable for conditions outside those used for model calibration, and greater care must be taken when applying such a model. The generalized sensitivity of one-dimensional sediment transport models to input parameters are given in Table 1.

8.10 Specific models

Some of the specific models and case studies of their application where they have been successfully applied for reservoir sedimentation are given in Annex A along with their references.

Table 1 — Relative influence of input parameters on sediment simulation models

Description of data	Relative importance of data		
	High	**Medium**	**Low**
Physical parameters:			
Roughness coefficients		X	
Sediment inflow	X		
Water inflow	X		
Variation of bed evaluation		X	
Sediment size distribution (bed)			X
Sediment size distribution (Inflowing load)	X		
Water temperature		X	
Cross-section geometry	X		
Active layer thickness			X
Coefficients of losses			X
Operational parameters:			
Sediment transport equation		X	
Time step duration	X		
Number of time iterations			X
Roughness equation			X

9 Uncertainties

9.1 Model parameters

A number of physical processes that are not explicitly expressed in the momentum equation [Formula (2)] are combined into the channel rugosity coefficient (Manning's *n,* in this case). The Manning's *n* is an empirically derived coefficient which approximates channel rugosity in a steady uniform flow. The parameter in Formula (2), however, is applied to unsteady flow, and, from the physical perspective, includes the effects of turbulent dissipation of energy by several processes.

The Manning's *n* value, as well as weighting factors used in certain numerical schemes, cannot be measured, and these parameters are adjusted during model calibration to obtain agreement between model results and prototype measurements. Consequently, these model parameters also may include the effects of (1) the deviation of the modelled system from model assumptions; (2) the effects of numerical approximations to the governing equations, and (3) errors in field measurements. The uncertainties associated with combining these processes into a few model parameters is difficult, if not impossible, to quantify. However, model parameters selected during the calibration and testing phase of model development should be within the range of previously published values. Otherwise, the unrealistic model parameter values may be masking some serious errors within the model errors which may result in poor simulations for conditions, which were not evaluated during model testing.

9.2 Data for model development, testing and application

The collection of hydraulic and sediment field data are subject to a number of uncertainties. Quantification of uncertainties associated with the measurement of stage, velocity, discharge, suspended and bed load discharge, bed material grain size distribution and cross-sectional data are discussed in previously-published International Standards.

Uncertainties associated with estimation of lateral inflows and withdrawals should be minimized by accurately measuring as many of the inputs and losses as possible.

The effects of uncertainties associated with sediment transport function can be minimized by selecting a transport function developed using parameters suitable for the reservoir system.

9.3 Governing equations

Formulae (1), (2) and (3) strictly apply to an infinitesimally small volume at an instant in time. For the development and application of unsteady flow models, the equations are assumed to apply to some finite volume, which may have a length on the order of hundreds of meters, a width of tens of meters, and a depth of several meters; the equations are also assumed to apply to some finite duration, which may be as much as one hour. Uncertainties associated with the extrapolation of the differential equations to these finite volumes and times exist and are difficult to exactly quantify. However, the previously described convergence testing does provide an indication, along with the satisfaction of numerical stability criteria, that the appropriate time and distance discretization has been selected.

Flow in open channels is three-dimensional in nature, but is approximated by the governing equations as having only variations in the longitudinal direction. In addition to assumption of one dimensional flow, a number of other assumptions were used in the development of the unsteady flow equations. Some of these assumptions are restrictive and deviations from the assumption (such as no channel geometry change and no density gradients) are likely to produce erroneous simulations. Other assumptions, such as negligible surface tension effects, might not be violated in open-channel flow. All deviations from model assumptions should be clearly documented. And model testing should be used to assist in quantifying the effects of the deviations on flow computations. Further, the sediment transport parameter of Formula (3) has uncertainties inherent due to the assumptions made during the development of the transport function used in the model. A generalized idea of the range of parameters used for development of some of the sediment transport functions is given in Table 2.

9.4 Numerical approximations to governing equations

Formulae (1) and (2) are simplified mathematical expressions for the complex three-dimensional turbulent flow field in an open channel. The expressions are further simplified by making numerical approximations of the partial differential equations. These approximations introduce further uncertainty into the computations. The uncertainty, which is difficult to quantify for any given application, can be evaluated through testing and documentation of the numerical scheme.

Clear documentation of the numerical scheme, including equations, discretization and results of tests of the scheme, should be available. Certain numerical schemes, including variations of the method of characteristics, explicit and implicit schemes for one-dimensional unsteady flow modelling, have general testing and documentation that is widely available. However, many schemes, which have been devised for specific problems, may require extensive evaluation by model users.

Documentation of a numerical scheme should include a discussion of the relations among grid size, time step, and the stability and accuracy of the scheme. Numerical dispersion introduced by the scheme, which can result in the damping of a steep wave front, should be quantified. The uncertainty in the governing equations and numerical approximations is generally small compared to the uncertainty inherent in the sediment algorithms and parameters.