SEDIMENT PHENOMENA

G. R. Basson
Department of Civil Engineering, University of Stellenbosch, Stellenbosch, South Africa

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Contents

Summary

In the operation of water supply projects and the design of hydraulic structures, sediment phenomena play an important part. Where the continuity of the natural flow of water and the material it carries along is interrupted for good reasons, such as the building of a dam creating a storage reservoir, or a bridge reducing the river cross-section and increasing scour, the balance of nature is also upset. This creates challenges to the ingenuity of humankind to overcome these threats and still reap the benefits of developing these essential facilities. This article describes the means available to analyze a given situation, through modeling—either physically or numerically, through theoretical analysis, field studies, data collection, and engineering design. Typical modeling techniques, in one-, two-, or three-dimensions are alluded to, and the reasons for their choice and their theoretical background are given, with examples. Sediment transport equations, erosion, channel deformation, and consolidation, are other aspects addressed. Two case studies are presented as further examples. The first deals with the investigations for the design of a major bridge crossing over a wide braided river carrying heavy sediment loads during the monsoon season in Bangladesh. The second presents the case of a water supply storage reservoir in South Africa which had lost 85% of its capacity in twenty years due to sediment accumulation. Successful partial sediment flushing exercises led to constructive suggestions towards possibly reinstating half the lost capacity. The future of analysis and modeling techniques for representing sediment behavior is seen as being with hybrid modeling, which optimally combines physical and numerical models.

1. Introduction

Sediment transport, erosion and deposition are ongoing processes, continuously active and reshaping the surface of the earth. However, they are not uniform processes, nor proceeding at constant definable rates. Coupled to hydraulic stream power and hence to hydrology, they can also be considered stochastical processes, that often defy exact comprehension and prognosis (see *Probabilistic Methods and Stochastic Hydrology*).

Humanity, dependent on life-support systems associated with water availability, has to contend with threats such as reservoir sedimentation and loss of storage, scour and damage to hydraulic structures such as bridges, and water intakes due to sediment phenomena as yet not completely understood.

The hydraulic engineer entrusted with the design of vital life-support structures for storing and conveying water, has to ensure that they would be safe, sustainable and meet the requirements under all foreseeable situations. Technology and expertise is available, and also information regarding sediment behavior and its influence on hydraulic design.

The design of major new hydraulic structures may be approached in one of three ways:

by theoretical reasoning and the use of numerical (mathematical) models;
by scale model experiments (physical modeling); and
on the basis of previous experience of similar systems, often using empirical relationships.

Even with modern computing facilities, many complex problems still defy complete theoretical analysis. A combination of past experience, theory and physical modeling will provide partial or complete solutions to a number of problems. However, there still remain many problems which are tractable only through experimentation, especially where there are unsteady three-dimensional flow patterns with movable bed conditions, such as at flow through hydraulic structures or at intakes on a river bend (see *Sediment Exclusion at River Intakes*; *Design of Water Intakes for Sediment Exclusion*).

2. Physical Modeling

Physical models are extensively used to study sedimentation processes in rivers and reservoirs. Distorted scale movable bed models are mostly used, and it is important to simulate the prototype behavior in terms of similarity criteria—gravity, resistance, settling, suspension, incipient motion, concentrations, and bed deformation. In practice, only the main similarity criteria are satisfied, and the others to a lesser extent (see *Hydraulic Methods and Modeling*).

For movable beds, lightweight materials such as polystyrene, bakelite, talcum, crushed walnut shells, and fly-ash, have been used in models. Distortion of the geometric scales is often necessary for a model with a movable bed to provide large enough water depths and velocities within limited laboratory space.

Verification of model output with prototype data is of great importance. Deposition in the Danjianghou Reservoir, China, over a fourteen-year period, was verified, and differences of less than 20% were noted.

In a physical model of the Gezhouba project, China, suspended loads and bed load, as well as density currents, were simulated, and results compared well with prototype data. The volumes and distribution patterns of deposits, particle size distribution, and efficiency of scouring, could be verified with field data.

For the Three Gorges project, China, nine models have been constructed to simulate six key reaches over a total distance of 230 kilometers, as shown in Figure 1. Horizontal and vertical model scales used in these models were, respectively, as given by Tan during 1994:

Horizontal *and* vertical: $\frac{1}{250}$ *to* $\frac{1}{300}$ *and* $\frac{1}{100}$ *to* $\frac{1}{125}$

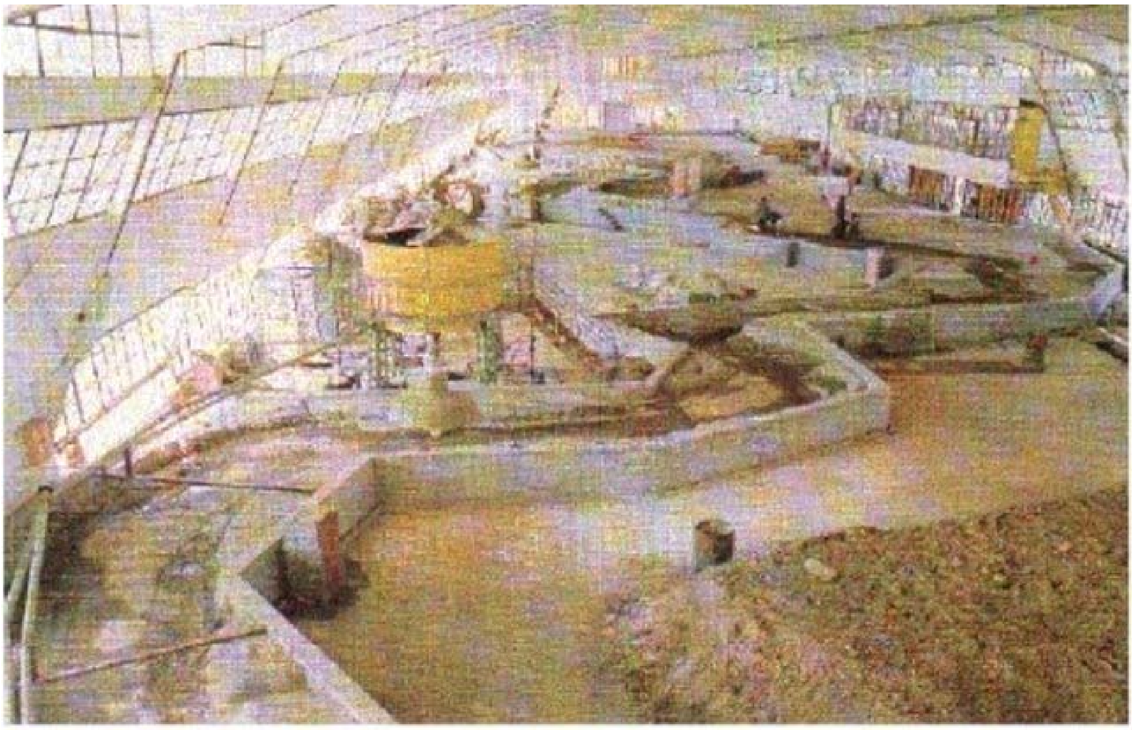

Figure 1. The Three Gorges, Yangtze River Model

The combined use of physical and mathematical models is practiced on large projects, and the results obtained are often used to complement results from other modeling techniques, so as to compensate for their shortcomings (see *Experimental Methods and Physical Modeling*).

3. Mathematical Modeling

Mathematical modeling in applied hydraulics involves the use of numerical computer programs for solving the mathematical equations representing the physical relationships, such as the equations of continuity, energy and momentum (see *Fluid Mechanics*). These relationships can be developed for one-, two- or three-dimensional boundary conditions, requiring accordingly higher levels of computing power, time and cost, and can be extended to include many other hydraulic phenomena (see *Hydro-informatics*).

3.1. Background

One-dimensional mathematical modeling of river and reservoir sedimentation based on the equations of motion and continuity of water and sediment, together with sediment transport equations, are widely used and give good results. Most mathematical models are based on coupled or sequential application of one-dimensional equations of motion for the water phase and the equation of mass conservation for the sediment (see *Hydraulics of Two-phase flow: Sediment and Water*).

Properly developed, calibrated, and verified mathematical models, can be used with confidence to analyze sediment transport phenomena. Field data are often used to calibrate empirical coefficients in mathematical models, and they are, therefore, of great importance in analyses (see *Sedimentation Data Acquisition*).

These models often require special technical and data inputs and computational skills, and are usually applied in investigations of large and important projects. Most important in the use of mathematical models, however, is an understanding of the sedimentation processes.

One-dimensional (1D) models use vertically and horizontally averaged hydraulic calculations at a number of selected cross-sections along a river. Vertically averaged two-dimensional (2D) models are often used for river applications, while (2D) models in the vertical can simulate phenomena such as density current formation. The 2D models use a rectangular grid or curvilinear grid, which follows the river plan morphology, or a triangular grid. The latter grid has the benefit that some areas can be modeled in more detail by using a smaller triangular grid in that area.

Because of the use of empirical relationships based on field data, their application is limited to those conditions for which these relationships were calibrated. Several models using equations of sediment transport under nonequilibrium and nonuniform conditions have been developed and have incorporated the following conditions:

- size distribution changes due to deposition and scouring;
- interchange between suspended particles and bed material; and
- sediment concentration not equal to sediment-carrying capacity adjustments in space and time.

Such a model has been used on the Yangtze River, China. Although such models should provide more accurate results for river conditions, the required amount of field data is extensive and the computations highly complicated (see *Gauging of Sediment-laden Rivers*).

Three-dimensional (3D) river and reservoir sedimentation models have been developed, but their use is limited because they require extensive field data sets for verification.

These models are mostly applied in coastal engineering studies (see *Dredging in Rivers and Estuaries*).

Several mathematical models have been developed in the past to simulate river and reservoir sedimentation processes. Reservoir conditions vary, and as a result sedimentation modeling differs from river modeling, as there are factors such as fine sediment transport, cohesive sediment deposits, and consolidation of the bed, as well as different modes of reentrainment of sediment, which all need to be accounted for.

For modeling of sedimentation processes, a model should be able to simulate both short-term (flood) and long-term deposition events, often with noncohesive and cohesive sediments. It should be borne in mind that the “ideal” mathematical model is only as good as the theory it is based on.

3.2. Typical Numerical Model to Simulate Sediment Transport Processes

The advantage of a numerical model is that it can be tailored to fit the situation, whereas a physical model is less flexible, time-consuming, and needs careful calibration and verification. A disadvantage is that a numerical model is coarser in scaling small elements, and merely simulates rather than actually reproduces flow behavior. Nevertheless, the expertise that is constantly developing is rapidly narrowing the gap.

The ideal numerical river and reservoir model should have at least the characteristics described in following sections 3.2.1-3.2.9.

3.2.1. Dimensionality Considerations

Models, both physical and numerical, can be constructed in one, two or three linear dimensions, and can be steady-state or time-dependent, thus involving the fourth dimension, time. The degree of sophistication necessary for solving the problem will decide which one of these options is to be used.

One-dimensional (1D) models are mostly used in river and reservoir applications around the world; although computationally “heavy”, two-dimensional (2D) and even 3D models have been developed. The main constraints in using a 2D model with sediment transport are often a lack of data for calibration of the model, and secondly, the uncertainty of the sedimentation processes. It is generally believed that modeling with a 2D approach often does not give more accurate or reliable results than one-dimensional modeling.

However, two- or three-dimensional numerical, as well as physical, models can be of specific benefit when considering the following cases:

- sediment deposition outside the main channel in flood plains (see *Flood Control Works*);
- sediment buildup at a specific location, such as at a tunnel intake (see *Sediment Exclusion at River Intakes*); and

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Biographical Sketch

Gerrit Basson is Professor and Head of the Water Division at the Department of Civil Engineering of the University of Stellenbosch, South Africa. He obtained the degrees B.Eng. (cum laude) and B.Eng. (Hons.) Civil from the University of Pretoria, South Africa, and the degrees M.Eng. and Ph.D. from the University of Stellenbosch, South Africa. He is a registered Professional Engineer in South Africa and Member of the South African Institution of Civil Engineers (SAICE). He has fifteen years' experience in consulting engineering, mainly in the fields of Hydraulic Engineering and Water Resources Planning. He is a specialist in the subjects of reservoir sedimentation and its control and the dredging of reservoirs, on which he has coauthored several reports. His other publications number about twenty. He is also active in research and data analysis on the hydraulic roughness of tunnels. He has served on the SAICE Water Division Committee since 1999. He is the representative for the International Association of Hydrological Sciences (IAHS), on the International Commission on Continental Erosion (ICCE). He is a member of the South African National Committee of the IAHS (SANCIAHS) for 2000 to 2003.