

SELECTION OF APPROPRIATE MATHEMATICAL MODELS TO SIMULATE SEDIMENT FLOW AND RESERVOIR SEDIMENTATION

Nguyen Thu Hien¹, Le Thi Thu Hien¹

Abstract: *Nowaday, mathematical (or numerical) models are very useful tools to predict sediment flow to reservoir and reservoir sedimentation. The prediction sedimentation flow to reservoirs and reservoir sedimentation are very important for reservoir design and sustainable reservoir management. This paper will review the existing popular mathematical models available to predict sediment flow to a reservoir. The study shows that existing models can successfully simulate reservoir sedimentation, however, each model has limitations and depending on the problem scope and complexity and data availability they require good understanding and judgment to choose an appropriate model.*

Keywords: Mathematical models, sediment flow, sedimentation, reservoirs.

1. INTRODUCTION

Reservoirs play an important role in the economic development of a region, especially for those areas with high vulnerability to flood and drought. Year by year, reservoir sedimentation is the gradual accumulation of the incoming sediment load from watershed and rivers. Estimation shows that about 0.5% to 1% of the total volume of global reservoir storage is lost annually (Atkinson, 1996). Reservoir sedimentation reduces the gross storage capacity and also negatively impacts water supply, hydropower plant and dam safety. Effective management of a reservoir system requires a model which can predict future behavior and response to perturbation (Morris et al., 1998). Therefore, the prediction sedimentation flow to reservoirs and reservoir sedimentation are very important for reservoir design and sustainable reservoir management.

Temporal and spatial information of soil erosion process and sediment transport is always required to describe the change of productivity of land and water quality of river, watershed or reservoir. Due to the increasing use of computer

applications and computing power in recent decades, the investigations of soil erosion and sediment transport through the development of mathematical models has been rapidly increased. However, each model has different strengths and weaknesses. Model selection for solving a specific problem depends on many factors, including (i) the problem scope and complexity, (ii) data availability (hydro-meteorology, topography and sediment data, geomorphological characteristics of the reservoir) for model calibration, verification and computation with different scenarios (iii) and overall available time and budget for solving the problem (Papanicolaou et al., 2008). Also, there are many problems that the existence models have been suffered such as the model uncertainty, the unreliable assumptions of models. Therefore, it should be noted that this it is impossible to choose the best model among those available, because each model has been developed for a particular purpose and is unable to solve the problem in every situation.

This paper reviews the existing popular mathematical models available to predict sediment flow to a reservoir and reservoir sedimentation. The paper attempts to distill accepted and applied

¹ *Hydraulics Department, Thuyloi University*

(rather than theoretical) available models engineers and soil and water conservation managers who are working on erosion and sediment transport phenomena to reservoirs. This should be helpful for readers to identify and generally characterize the types of available models, their limitations, strengths and their basic scope of applicability to simulate the processes of sediment transport to reservoirs.

2. SOIL EROSION AND SEDIMENT TRANSPORT MODELS TO RESERVOIRS

2.1. Soil erosion and sediment transport processes to reservoir

The sources and processes of sediment transport to reservoirs include sediment erosion from watershed, transport and erosion in streams and to reservoirs (see Figure 1). Generally, based on the equations to describe the physical processes of sediments erosion and transport the mathematical can be developed and applied to predict sediment flow and deposition in the reservoir.

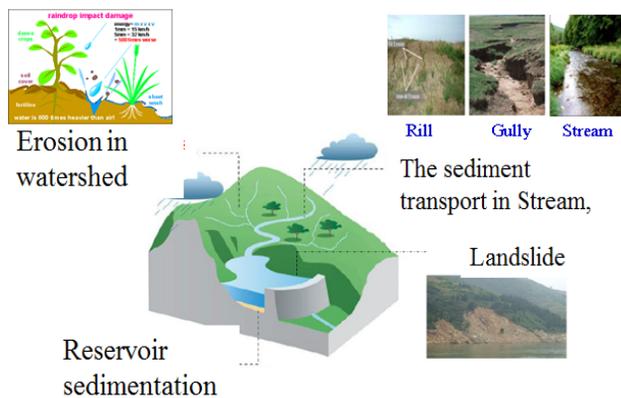


Figure 1. Soil erosion in watershed and reservoir sedimentation

Most sediments enter reservoirs as a consequence of rainfall erosion from upstream watershed and subsequent transport by streams/rivers. 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. Sediment flow to

reservoirs is typically difficult to determine due to limited available measurements and changing land use conditions in the upstream watershed. If sediment and discharge measurements are available at upstream boundary, sediment flow can be computed. However, many watershed precipitation-runoff models include a sediment yield component that can be used to estimate inflows of water and sediment to the reservoirs.

For sediment transport in the main rivers and reservoir sedimentation, usually fully hydrodynamic models are applied. These models allow not only to estimate the total quantity, but also determine the bed changes to space and time of the sedimentation process. The below sections will discuss more detail about the models applied to compute the erosion, sediment transport to the reservoir and reservoir sedimentation.

2.2. Sediment overland

If reservoir bathymetry at different points in time is available, the average annual supply between those points can be determined by computing the difference in volumes of the reservoir for a given pool level. If sediment and discharge are measured at upstream gage, sediment hydrographs can be computed and integrated over time to determine sediment 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, WEPP and conceptual models (combination of empirical and physically-based models) such as SWAT are usually used to estimate sediment yield. Many watershed precipitation-runoff models including a sediment yield component used to estimate inflows are reviewed by Mohammad et al. (2018).

2.3. Sediment transport in rivers/reservoirs

The models to compute the sediment transport in rivers/reservoirs are hydro-dynamic model and sediment transportation. The governing equations are the fully dynamic equations of such as one-dimensional (1D), two-dimensional (2D), or three-

dimensional (3D) depending on different models. The sediment in channels is usually divided into two types: suspended sediment and bed sediment. For suspended material, the basic equation is the advection-dispersion equation which based on the equation of conservation of mass of dissolved or suspended sediments (e.g., fine sediments). The module requires the output from the hydrodynamic module. For bed load, the Bed Sediment Mass Conservation equation and the empirical formulas are used. There are many empirical equations computed this component, for example: Engelund & Hansen; Yang; Meyer-Peter & Müller Parker; Wilcock & Crowe in HECRAS (USACE, 2021). White; Ashida and Michue; Engelund & Hansen; Lane & Kalinske; Meyer-Peter & Müller; Van Rijn; Smart & Jaeggi formulas used in MIKE, (DHI, 2017). Simplified Stream Power Eq; Yang sand & gravel; Molinas & Wu are used in SWAT, (SWAT, 2020).

In one-dimensional modeling, the solution of the sediment continuity equation provides a change in the cross-sectional area at each cross section and allocates changes to each wetted coordinate point across the cross section. The most widely used one-dimensional computer models are HEC-6 (USACE, 1993) or HEC-RAS (USACE, 2021), MIKE11 (DHI, 2017), GSTARS (Yang et al., 2001) covering a wide range of conditions, such as fractional transport, bed sorting and armoring, sediment transport functions for sizes ranging from clay to gravel, and non-equilibrium sediment transport.

A major advantage of multi-dimensional models over one-dimensional models is that they provide more details within an area-of-interest by their gridding capabilities. 2-D models can fairly simulate lateral but hardly simulate vertical particle movements in a reservoir as the fall velocity term is ignored (Yang et al., 2001). Recently, there are many 2-D models predicted the total sediment transport load, e.g., MOBED2 (Mobile BED), USTARS (Unsteady Sediment

Transport models for Alluvial Rivers Simulations), MIKE21, FLUVIAL 12, DELFT-2D, TELEMAC-2D and CCHE2D. However, some of them can separate the total sediment load into bedload and suspended load and they are limited to uniform sediment sizes such as MOBED2, USTARS, FLUVIAL 12, DELFT-2D, and CCHE2D (Papanicolaou et al., 2008).

Three-Dimensional Models are suitable for simulating local three-dimensional phenomena (Yang, 2006). Turbulence is an essentially three-dimensional phenomenon, and three-dimensional models are particularly useful for the simulation of turbulent heat and mass transport. These models are usually based on the Reynolds-averaged form of the Navier–Stokes (RANS) equations. Among the three-dimensional models, the commercial codes MIKE3 (DHI, 2008), ANSYS FLUENT (ANSYS, 2011), FLOW-3D (Castillo et al., 2015) and SSIIM (Papanicolaou et al., 2008).

2.4. Sediment from landslide in reservoir location

In addition to the amount of sediment erosion and transport to reservoirs the amount of sediment caused by bank erosion at reservoir location is also one of the significant sources causing the sedimentation in reservoirs (Figure 1). Bank damage usually occurs due to a combination of hydraulic processes that erode the cleft palate as well as geological processes that cause landslide and erode due to gravity. However, there are not many formulas available in the models to determine this quantity. Moreover, the analysis of bank stability mechanism is often not considered in the mathematical equations of conservation of mass, momentum as well as the calculation of sediment transport. Among the mathematical models of sediment transport including bank erosion and/or landslide, ANSWERS can determine the extension of the cross-section to the non-eroding bottom, CCHE-1D defines a new depth and breadth based on the concept of critical

shear stress and transport capacity. The HECRAS model with the BSTEM (the bank stability and toe erosion model) module is an effective tool for calculating vertical shoreline erosion based on physical mechanisms, (USACE, 1993). BSTEM includes two major, interacting components: a bank failure model and toe scour algorithms:

1. Bank failure: A geotechnical bank failure model computes failure planes through the bank to determine if the gravitational driving forces exceed the frictional resisting forces (and the interaction of pore water pressure).

2. Toe Scour: An erosion model simulates lateral bank migration, hydraulic forces that undercut the bank. As the toe scours, the bank becomes less stable, so toe scour can initiate bank failure.

Select and apply transport functions with extreme caution recognizing the intent and range of applicability of each. Transport functions are notoriously uncertain, computing transports that commonly differ by at least one order of magnitude. Engelund and Hansen (1967) and Yang (1996) work best for sand. Meyer-Peter and Müller (MPM) (1948) will probably perform best for coarse materials. Parker (1990) and Wilcock and Crowe (2003) are both surface based methods, intended for heterogeneous soil mixtures with sand and gravel components. Also, it should be noted that most of these transport functions are derived for one-dimensional alluvial transport at the cross section scale. BSTEM applies these transport functions to bank scour at the node scale. This makes transport functions, already uncertain

in their intended setting, loose process analogies in toe scour. The transport functions often over predict scour substantially and results should be interpreted carefully.

Table 1 summarizes some common models to simulate the process of erosion and sediment transport that are commonly used in recent times in the world and Vietnam that can be applied to calculate and forecast sedimentation. They are classified according to their scope of application in space and time, the type of equations used in the model, and the type of output.

3. APPLICATION OF MODELS TO SEDIMENT IN RESERVOIRS

3.1. Studies of models to sediment in reservoir

Many studies using watershed erosion models to estimate sediment flow to reservoirs. For examples, Mohammad et al. (2016) computed the annual sediment flow to Duhok reservoir using SWAT and WEPP. The results showed that both models gave good result compare to the observed data. Similarity, Sohoulane (2018) assessed sediment inflow to Somerville reservoir, Texas, USA using the SWAT model and gave very good matching with observed data. Mohammad et al. (2013) applied SWAT model to estimate the sediment load to of Mosul reservoir that is the biggest dam in Iraq. Among the reviewed watershed erosion models to estimate the sediment to reservoirs, SWAT model is the most successful and widely applied. However, these model can only provide the sediment yield to reservoir.

Table 1. Some common mathematical models to compute soil erosion, sedimentation flow to reservoirs and reservoir sedimentation

Model - Type	Spatial Scale	Temporal Scale	Flow Eqs	Overland erosion Eq.	Suspended load eq.	Bed load in stream	Sediment Outputs			
							Over land	In stream	Bed geometry	Failure bank
<i>Catchment</i>										
SWAT	Small Catchment	Daily	Kinematic wave	MUSLE	Kinematic wave	Yes	Detail of sediment transport, net erosion	Yes	No	No

Model - Type	Spatial Scale	Temporal Scale	Flow Eqs	Overland erosion Eq.	Suspended load eq.	Bed load in stream	Sediment Outputs			
							Over land	In stream	Bed geometry	Failure bank
WEPP	Hillslope/Catchment	Daily	Kinematic wave	Continuity Eq	Delivery Eq.	Yes	Erosion and sediment yield, runoff	No	No	No
ANSWER	Catchment	Event	Manning equation	USLE		Yes	Overland erosion, Sediment transport	Yes	No	No
Main river and reservoir										
MIKE 11	River/ reservoir	Event/Daily	1D shallow water Eq.	No	AD eq.	Yes (empirical formula) No bank failure	No	Yes	Bed profile	No
GSTARS	River/ reservoir	Event/Daily	1D quasi-steady Eq.	No		Yes (empirical formula) No bank failure	No	Yes	Semi-3D variation	No
HECRAS (1D & 2D)	River/ reservoir	Event/Daily	1D & 2D shallow water Eq.	No	AD eq.	Yes (empirical formula) Bank failure; Toe Scour; BSTEM model	No	Yes	Bed profile/ 2D variation	Yes
MIKE21	River/ reservoir	Event/Daily	2D shallow water Eq. 2D shallow water Eq.	No	AD eq.	Yes (empirical formula) No bank failure	No	Yes		No
CCHE-2D	River/ reservoir	Event/Daily		No	AD eq.	Yes (empirical formula) No bank failure	No	Yes		No
TELEMAC (2D and 3D)	River/ reservoir	Event/Daily	2D and 3D Navier–Stokes (RANS) Eq.	No	AD eq.	Yes (empirical formula) No bank failure	No	Yes	2D variation	No
FLOW3D (2D and 3D)	River/ reservoir	Event/Daily		No	AD eq.	Yes (empirical formula) No bank failure	No	Yes	3D variation	No
MIKE 3	River/ reservoir	Event/Daily		No	AD eq.	Yes (empirical formul) No bank failure	No	Yes	3D variation	No
DELFT-3D	River reservoir	Event/Daily		No	AD eq.	Yes (empirical formula)	No	Yes	3D variation	No

The longitudinal profile and/or bed geometry variation of a reservoir is very useful for reservoir sediment management. For this purpose, hydrodynamic models 1-D and multidimensional models have been used. One-dimensional codes are suitable for long-term simulation. Gibson and Pridal (2015) used HEC-RAS 1D to simulate a 50-year bed elevation profile for Argandab reservoir. Mohammad et al. (2016) estimated sediment load on Mosul reservoir (Iraq) by HECRAS model. Trần Kim Châu (2017) applied HEC-RAS to compute the reservoir sedimentation of the cascade reservoir in the upstream of Da River. Other codes such as GSTARS3 have been successfully used to simulate the long-term longitudinal profile by Nohani and Afrous, (2015). Launay et al. (2019) simulated the spatial and temporal dynamics of suspended particulate matter during floods. For this long-term simulation, they used the Rhone 1-D model.

2D and 3D models usually applied to simulate the bed variation and assess the effect of sediment management methods. For example, SRH-2D was applied by Lai and Wu (2018) to simulate the sediment desilting processes at the Shihmen reservoir under various bypass tunnel plans. Moussa (2013) applied CCHE-2D to simulate sediment transport along 150 km of Aswan reservoir. Omer et al. (2015) predicted the evolution of the bed topography using Delft3D to simulate the time variations of the bed level of Roseires Reservoir (Sudan). Ermilov et al. (2018) simulated flushing by TELEMAC. Sediment pass-through strategies such as venting of turbid density currents through a low-level outlet have been simulated by (Mohammadnezhad et al., 2010) using Mike 3. Pham Thi Huong Lan (2020) applied Mike11 and MIKE3 to simulate the bed variation of Dak Uy reservoir.

The combination of watershed models and hydro-dynamic model to simulate reservoir sedimentation is also applied. For example, Tadesse and Dai (2018) used SWAT model for the estimation of erosion at the catchment level, and the HEC-RAS model for the estimation of the sediment transport in the river channel to predict sedimentation in Awash River basin at the Koka Dam Reservoir in Ethiopia. Bulti (2021) used the hydrologic routing method was applied at an upstream part of a river basin through a SWAT model. HECRAS model was applied at the middle and downstream areas of the basin based on hydraulic routing principle.

The amount of sediment caused by the reservoir bank erosion/failure also contributes a significant part to reservoir sedimentation that should be considered. However, very few mathematical models include this module. One of the models that consider bank failure and toe scour is the HECRAS model with the BSTEM module that could help to estimate the amount of sediment from reservoir bank failure (USACE, 2021).

3.2. Model selection

Model selection for solving a specific problem depends on many factors, including the problem scope and complexity, data availability and overall available time and budget for solving the problem. Sediment yield to reservoir can be determine if there is an upstream gage with sediment and discharge measurements. However, these data are not available in many watersheds. In these cases, precipitation-runoff models including a sediment yield component that can be used such as SWAT, WEPP... to estimate inflows of water and sediment to the reservoirs. However, caution should be used to differentiate between yielding from the watershed and actual delivering to the reservoir.

For sediment reservoir management, longitudinal profile and/or the bed geometry

variation is very useful for understanding the sedimentation processes in a reservoir. The hydraulic 1-D and multidimensional models should be used for these purposes.

One-dimensional codes are appropriated for narrow reservoirs and suitable for long-term simulation or multiple alternative analyses. One-dimensional models generally require the least amount of field data for calibration and testing and numerical solutions are more stable. Furthermore, the combination of watershed models with 1D models is very useful for long-term simulation or different scenarios analyses, especially for predicting the impact of climate change and land use change of the upstream on the variations of reservoir bed profile.

On the other hand, when the reservoir pool is wide and without a clear, single flow direction multi-dimensional models must be used. Multi-dimensional models can better evaluate the measures for reservoir sediment management such as flushing, passway tunnel or turbidity current venting... (Razieh et al., 2020). However, the higher the dimension of the model, the more field data required for verification and calibration. Moreover, the excessive run time for multi-dimensional codes limits their application to short-term simulation or where the detailed solutions for critical points within the reservoir is more important than computational cost.

Furthermore, sediment from the reservoir bank erosion/failure also contributes a significant part to reservoir sedimentation that should be considered. For this purpose, the HECRAS model with the BSTEM module could be a good choice (USACE, 2021).

4. CONCLUSION

Mathematical models are very useful tools to predict sedimentation flow to reservoir and reservoir sedimentation. This paper reviewed mathematical models to simulate reservoir sedimentation. When there is no data to measure

sediment into the reservoir, watershed models or the combination of these model and hydrodynamic models can be applied to estimate sediment flow to the reservoir. For sediment reservoir management, longitudinal profile and/or the bed geometry variation is very useful for understanding the sedimentation processes in a reservoir. For these goals, the hydraulic 1-D and multidimensional models have been used. For many case studies, 1-D mathematical models have been applied successfully for long-term sediment deposition predictions. However, when the detail bed geometry variations are required and

sufficient data to calibrate and verify the model are available, multi-dimensional models should be used. Moreover, for reservoirs suffered landslide problem, a model that takes into account bank failure can be selected to assess the reservoir sedimentation.

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Tóm tắt:
**LỰA CHỌN MÔ HÌNH TOÁN THÍCH HỢP ĐỂ TÍNH TOÁN
DÒNG CHẢY BÙN CÁT ĐẾN HỒ VÀ BỒI LẮNG HỒ CHỨA**

Ngày nay, mô hình toán là một trong những công cụ rất hữu ích để dự báo bồi lắng đến hồ chứa. Việc xác định dòng chảy bùn cát đến hồ chứa và quá trình bồi lắng hồ chứa là rất quan trọng đối với việc thiết kế hồ và quản lý hồ chứa bền vững. Bài báo này đã nghiên cứu tổng quan các mô hình toán phổ biến hiện có để xác định bồi lắng hồ chứa. Nghiên cứu cho thấy các mô hình hiện có có thể mô phỏng thành công quá trình bồi lắng hồ chứa. Tuy nhiên, mỗi mô hình đều có những hạn chế, tùy thuộc vào phạm vi, sự đòi hỏi chi tiết của vấn đề nghiên cứu và số liệu sẵn để có, việc lựa chọn mô hình phù hợp cần có sự hiểu biết và đánh giá tốt về mô hình.

Từ khóa: Mô hình toán, dòng chảy bùn cát, bồi lắng, hồ chứa.

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