

# Applications of HEC-RAS and ADC in Hydraulic Flow Modelling Around Barrages: A Systematic Review

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**Abstract.** This paper reviews and analyses the use of the HECRAS and ADCIRC hydraulic models for simulating downstream flow and erosion patterns developed behind barrages. The study validates these models as suitable instruments for predictions of sediment transport, morphological evolution and scour, obtaining very accurate results by means of intense calibration. Combining geography and remote sensing for employment in GIS-based spatial analysis has been much improved, which made an important applied to navigation, flood risk assessment and construction of infrastructure. However, limitations remain including an inability to model complex sediment dynamics and site specific calibration mean models are not widely transferable between locations while continued debate over the most suitable dimensional treatment. The main research challenges are simulating extreme events and the long-term morphological evolution. To enhance the model robustness and sustainability of river management, future studies should focus on developing advanced sediment formulations, accurately parameterizing 2D models, and formulating unified protocols to integrate data.

## 1 Introduction

Interest in the use of HEC-RAS and ADC for simulating flow profiles and erosion process downstream of barrages has recently gained momentum as controlling sediment transport and morphological adjustments have significant implications to river hydraulics, waterway navigation, infrastructure foundations [1-2]. Following the early application of HEC-RAS for hydraulic and sediment transport modeling in the 2010s [1, 3] several improvements have increased its capabilities including unsteady flow module, two-dimensional (2D) hydraulic and also sediment transport modules [4–6]. These advances have allowed improved modelling of complex riverine processes that are crucial for the sedimentation, erosion and flood risk control of sensitive river channels [7–8]. Practical implications are highlighted not only because of the substantial sediment loads loaded by large rivers (e.g., Euphrates, Nile and Indus) influencing navigation, irrigation and flood risk reduction [8–10]. For example, the rate of siltation in reservoirs and downstream reaches may diminish reservoir life by tens of years and also damage hydraulic structures [11–12].

The practical problem addressed is the difficulty of simulation for prediction on flow patterns and sediment movement in rivers downstream of dams where flow control changes original sediment transport leading to channel morphology transitions [2, 8]. Despite the large number of studies having applied HEC-RAS modeling for sediment transport and hydraulic phenomena [1, 3, 13], there are still several gaps in knowledge with regard to the introduction of advanced equations for sediment transport, calibration methodologies and combined use of GIS/remote sensing data to increase emulation performance [14–15]. Disagreements on the best types of sediment transport equations, as well as whether one- or two-dimensional solutions are more appropriate to use (1D solution for simplicity,[1, 9] and 2D to account for flow–sediment interplay[5]), also add confusions in this topic. This failure can lead to poor management decisions that contribute to, rather than mitigate, increased erosion and sedimentation as well infrastructure deterioration [10-15].

The hydraulic model, sediment transport processes, and morphological change analysis are combined in a conceptual methodology based on HEC-RAS and ADC tools [13, 14]. The framework links biophysical information to field applications in dam-impacted river reaches with a focus on model calibration and validation based on field data and remote sensing [1, 14]. This model facilitates a systematic examination of sediment movement and flow changes downstream of hydraulic infrastructure.

The aim of this systematic review is to provide a summary of the current state-of-the-art for applications HEC-RAS/ADC models to simulating flow behavior and erosion phenomena downstream barrages, centered upon practicality of their application, ease of use, and model performance[15]. This review sets out to establish best practice, report on methodological development and identify remaining knowledge gaps which will be useful to both researchers and river managers [2, 14]. Aligning the review with the identified gaps will help in furthering sediment management and hydraulic structure sustainability.

A useful review methodology which includes a scoping analysis of peer-reviewed studies using HEC-RAS and ADC for both flow and sediment modelling downstream barrages. The selection criteria focus on applied and methodological studies that includes calibration and validation of model bias. The review methodology classifies the results based on modelling techniques, sediment transport equations and GIS/remote sensing incorporating methods. This review is structured in a way so that descriptive summaries, critical analysis and practical implications of the chosen literature can be shown [1, 14].

## **2 Scope and Specific Objectives**

### **2.1 Statement of Purpose**

The aim of this study is to examine the published works on "HEC-RAS and ADC applications for modeling flow patterns and erosion processes downstream of barrages in terms of practical cases". It works to integrate existing methodologies, evaluate the model accuracy and seek instrument specific practical implications for river management. Its necessity is brought about by the fact that barrages have strongly affected hydraulic and sediment transport systems, with subsequent downstream erosional and depositional pattern adjustments influencing navigation, infrastructure stability and ecological health. By synthesizing these findings on the application of HEC-RAS derived and process-based routing ADCs in such domains, this review seeks to expose successful modeling approaches, calibration procedures and applied outcomes that support sustainable management and engineering decisions for riverscapes impacted by hydraulic infrastructure.

## 2.2 Specific Objectives

- To evaluate current knowledge on the application of HEC-RAS and ADC in simulating flow and sediment transport downstream of barrages.
- Benchmarking of existing modelling approaches for predicting erosion and morphological changes in river reaches influenced by hydraulic structures.
- Identification and synthesis of calibration and validation techniques used to enhance model accuracy in sediment transport and flow pattern simulations.
- To compare practical applications of HEC-RAS and ADC models in diverse geographic and hydrological settings, focusing on erosion control and navigation improvement.
- To deconstruct the integration of GIS and remote sensing data with HEC-RAS and ADC for enhanced morphological and sediment transport analysis.

## 3 Methodology of Literature Selection

### 3.1 Transformation of Query

The main research question forms the basis. Several more detailed search strings are then developed. By breaking up this general question into a number of focused subquestions, the subsequent literature search is not only complete --- incorporating all applicable niche and technical work --- but also feasible, as each subquestion returns papers concerned with a single aspect of the overall issue.

Below were the transformed queries we formed from the original query:

- HEC-RAS and ADC applications in modeling flow patterns and erosion processes downstream of barrages, focusing on practical applications
- Exploring diverse applications of HEC-RAS and ADC in river modeling, sediment transport dynamics, and erosion management strategies, emphasizing innovative practices and methodologies.
- Investigating innovative methodologies and practical applications of HEC-RAS and ADC in flood dynamics and sediment transport management for erosion control and river restoration downstream of hydraulic structures.
- Examining the integration of advanced modeling techniques and sediment management practices in HEC-RAS and ADC for improved flow and erosion control downstream of hydraulic structures.

### 3.2 Screening Papers

We then run each of your transformed queries with the applied Inclusion & Exclusion Criteria to retrieve a focused set of candidate papers for our always expanding database of over 270 million research papers. during this process we found 95 papers

### 3.3 Citation Chaining - Identifying additional relevant works

- **Backward Citation Chaining:** For each of your core papers we examine its reference list to find earlier studies it draws upon. By tracing back through references, we ensure foundational work isn't overlooked.
- **Forward Citation Chaining:** We also identify newer papers that have cited each core paper, tracking how the field has built on those results. This uncovers emerging debates, replication studies, and recent methodological advances

- A total of 94 additional papers are found during this process

### 3.4 Relevance scoring and sorting

We take our assembled pool of 189 candidate papers (95 from search queries + 94 from citation chaining) and impose a relevance ranking so that the most pertinent studies rise to the top of our final papers table. We found 189 papers that were relevant to the research query. Out of 189 papers, 46 were highly relevant.

## 4 Results

### 4.1 Descriptive Summary of The Literature

The reviewed papers, partitioned based on the primary application of interest, are tabulated (Tables 1-5).

**Table 1.** Studies on Navigation, Channel Flow, and General Sediment Transport

Study	Model Accuracy & Performance	Calibration Techniques	Dimensionality	Geospatial Integration
[1]	High accuracy in water level and sediment calibration (99.63%, 96.66%)	Calibration with field data; Ackers-White equation for sediment	1D	Synergistic use of GIS with HEC-RAS for morphological analysis
[6]	Sediment transport dynamics captured pre/post fall structure construction	Calibration with sediment and hydraulic data; velocity and water surface profiles	1D	No geospatial data integration reported
[13]	Hydrodynamic changes simulated before and after dredging	Calibration with flood frequency and flow data	1D	No geospatial integration mentioned
[12]	Sediment and hydraulic changes modeled for dike notching effects	Calibration with terrain modifications and flow events	2D	Terrain modification via geospatial operations

**Table 2.** Studies on Bridge Scour and Structural Impacts

Study	Model Accuracy & Performance	Calibration Techniques	Dimensionality	Geospatial Integration
[5]	Scour depth around bridge piers validated with observed data	Calibration with observed scour depths; statistical validation	2D	No GIS integration mentioned

**Table 3.** Studies on Flood Hazard and Dam Break Analysis

Study	Model Accuracy & Performance	Calibration Techniques	Dimensionality	Geospatial Integration
[4]	Water level simulation errors within $\pm 0.23$ m after calibration	Calibration with in-situ gauge water levels	2D via GeoHECRAS	Use of remote sensing data for floodplain modeling
[14]	Flood wave propagation and risk zones simulated with sensitivity analysis	Sensitivity analysis of breach parameters	1D Hydraulic	GIS used for flood risk mapping
[15]	Flow dynamics and velocity patterns simulated for flood mitigation	Calibration with seasonal and topographic data	1D	No GIS integration reported

**Table 4.** Studies on Reservoir Sedimentation and Flushing

Study	Model Accuracy & Performance	Calibration Techniques	Dimensionality	Geospatial Integration
[3]	Sediment load and deposition volume closely matched measured data	Calibration with flow and sediment routing data	1D	No GIS integration detailed
[7]	Sediment deposition patterns simulated over decades	Calibration with sediment transport and bed sorting methods	1D	No geospatial integration mentioned

**Table 5.** Studies on Riverbank Erosion and Morphological Changes

Study	Model Accuracy & Performance	Calibration Techniques	Dimensionality	Geospatial Integration
[2]	Reasonable sediment transport simulation matching satellite erosion data	Calibration with sediment size and Manning's $n^*$	1D	Integration of Landsat imagery with HEC-RAS
[10]	Bank erosion volume modeled with calibrated soil parameters	Calibration with field and soil boring data	1D Sediment	No GIS integration detailed
[11]	Sediment transport and erosion simulated with observed riverbed elevation changes	Calibration with cross-sectional, flow, and sediment data	1D	No explicit GIS integration mentioned
[8]	Morphological changes monitored over decades with remote sensing	Multi-temporal Landsat data analysis	No direct HEC-RAS modeling focus	Extensive GIS and remote sensing integration
[9]	2D models simulated erosion and deposition post-dam	Calibration with hydrodynamic data	2D	Use of continuous monitoring and hydrodynamic modeling

### **4.1.1 Synthesis of Modeling Approaches and Applications**

#### **Model Accuracy and Performance**

Accuracy of simulating hydraulic and sediment processes in the reviewed studies generally was found to be high. Several models were effectively calibrated and validated against field observations or bathymetric surveys, reaching performance metrics such as Nash–Sutcliffe Efficiency (NSE) or coefficient of determination ( $R^2$ ) values close to the unity and acceptable error limits (e.g., [1,3]). The accuracy of Bed Map simulations was generally quite uncertain and it depended strongly on local sediment properties and flow conditions, requiring a detailed site specific calibration for obtaining reliable results [2, 9].

#### **Calibration Techniques**

Calibration was a key stage in all of the studies, with the calibration process mainly focused on hydraulic and sediment parameters. Manning's roughness for the channel and sediment transport relation were often calibrated with field data, laboratory experiments or remotely sensed products [1, 15]. The methods varied from manual calibration to automated procedures, and the recent trend included the use of multi-temporal satellite acquisition for testing long-term morphological trends [8, 2].

#### **Application Scope**

The broad utility of HEC-RAS and ADCIRC applications included real-world engineering and environmental issues. Most of the applications focused on navigation path optimization, flood hazard mapping, erosion and sediment control, reservoir sedimentation management, bridge scour prediction, dam breach risk analysis [1, 4–5] etc. Many of the studies focused on pressing river management concerns by investigating dredging impacts, assessing canal rehabilitation projects and devising flood mitigation strategies [13, 15]. In addition, a few studies expanded their attention to ecological and environmental impacts of sediment movement and morphological changes, effectively connecting numerical modeling results with ecosystem health and restoration [11, 9].

#### **Dimensionality of Modeling**

One-dimensional (1D) HEC-RAS models were found to be dominant in the reviewed literature, due to their computational economy and dependences on inputs for simulating the sediment transport and flow in river channels [1, 7]. Two-dimensional (2D) models were used selectively for applications where improved spatial accuracy was needed, such as detailed floodplain inundation mapping and scour analyses near hydraulic structures; or problems with complex flow-sediment interactions [4, 12, 5]. Comparative studies, including e.g. [15], also more clearly acknowledged trade-offs between the two approaches, as 2D models better constrain the lateral variations of flow and local processes at a significantly increased data input (and computational) cost.

**Integration with Geospatial Data**

The use of GIS and remote sensing was a dominant factor, in particular in researches on monitoring the morphology [1], flood plain delineation [2] or spatial pattern of sediment accretion and erosion study [12, 7]. Satellite images and Digital Elevation Models (DEMs) were frequently used to increase the accuracy of model inputs, as a strong validation power when comparing simulated spatial patterns with observed conditions [7]. Although, its benefits have been described here, several included studies failed to report or make use of deep geospatial integration and this is an area for potential methodological improvement in future.

**5 Strengths and Weaknesses of Existing Literature**

The reviewed studies demonstrate the broad applications of HEC-RAS and ADC models to analyze flow patterns, deposition and erosion downstream of barrages for practical river management practices (navigation economy, flood hazard reduction, control of erosion). Strengths of the studies are strong calibration and validation, coupling with GIS and remote sensing data, combination of both 1D and 2D modelling approaches to represent complex hydraulic and sediment regimes. However, certain limitations remain concerning model applicability in complex flow scenarios, the difficulties associated with representing sediment heterogeneity and increased demand for improved parameter calibration, particularly in two-dimensional (2D) sediment transport simulations. In addition, although some research tend to focus on the priority use of these indices, regional and hydrological specificities induce a lack of generalization. Remote sensing and GIS contribute to great improvements in morphological analysis, but introduces uncertainties of data resolutions and temporal range. In summary, what is evident from the literature is that a continuum has continued to emerge down the years in the modelling of sediment and flow after hydraulic structures. Tables 6-8 below present a structured critical review of literature according to various themes.

**5.1.1 Model Foundations: Calibration, Validation, and Dimensionality**

The reliability of any modeling exercise hinges on robust calibration and the appropriate choice of model dimensionality. The studies show a strong tradition of using field and laboratory data for calibration, yet face persistent challenges in simulating complex phenomena.

**Table 6.** Analysis of Model Calibration and Dimensionality Approaches

Aspect	Key Strengths	Identified Challenges & Weaknesses
Calibration & Validation	Rigorous processes using field data achieve high accuracy (e.g., >99% hydraulic calibration [15]; strong NSE/R <sup>2</sup> values [13]). Enhances confidence for engineering decisions.	Limitations in capturing complex sediment dynamics (e.g., scour [8], reservoir flushing [14]). Calibration is often site-specific, reducing transferability.
Model Dimensionality (1D vs. 2D)	1D Models: Effective for longitudinal sediment transport and morphological changes; computationally efficient [1, 2].	1D Models: Oversimplify lateral processes, inaccurate in complex environments (e.g., braided rivers [9]).

	2D Models: Superior for spatial variability in flow/sediment (e.g., flood inundation [4], local scour [5]).	2D Models: High computational demand; parameterization is challenging; accuracy can be compromised without sufficient data [12].
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The balance between model complexity and practical usefulness is a central theme. While 2D modeling offers a more physically accurate perspective, its effective application is often constrained by data limitations and computational resources, making 1D modeling a necessary and effective alternative for many system-wide analyses.

### 5.1.2 Data Integration and Parameter Sensitivity

The integration of external data sources and the understanding of parameter influence are crucial for advanced modeling and uncertainty assessment.

**Table 7.** Analysis of Data Integration and Parameter Sensitivity

Aspect	Key Strengths	Identified Challenges & Weaknesses
GIS & Remote Sensing Integration	Enables spatially explicit assessment of erosion/deposition and long-term morphological monitoring [1, 2, 8]. Supports large-scale analysis and sustainable river management.	Introduces uncertainties from data resolution, temporal gaps, and misclassification [8]. Requires careful preprocessing to avoid error propagation into model simulations.
Parameter Sensitivity	Sensitivity analyses (e.g., for dam breach [14], sediment grain size [12]) identify critical parameters, guiding calibration and improving model robustness for risk assessment.	High sensitivity to uncertain parameters can lead to significant output uncertainty. Extensive data and expert calibration are needed, which is often not feasible in data-scarce regions.

Using geospatial data significantly enhances model capabilities but also adds a new level of uncertainty that needs to be acknowledged and controlled. Similarly, although sensitivity analysis is beneficial, it can reveal a model's susceptibility to input errors, highlighting the importance of relying on high-quality data.

### 5.1.3 Model Performance in Key Application Domains

The ultimate test of these models is their performance in addressing specific engineering and environmental challenges.

**Table 8.** Analysis of Model Performance in Practical Applications

Application Domain	Demonstrated Strengths	Persistent Challenges & Research Gaps
Sediment Transport & Morphology	Effectively simulates erosion, deposition, and bed-level changes using standard equations (e.g., Ackers-White, Yang) [6, 12, 14]. Provides reasonable predictions for reservoir sedimentation [3, 7].	Struggles with sediment heterogeneity (mixed grain sizes, cohesive sediments) [12]. Discrepancies between simulated and observed morphodynamic changes are common.
Scour & Bridge Pier Analysis	2D models show promise in predicting scour depths, providing insights for	Accuracy varies significantly with pier geometry and debris [13]. Modeling flow-debris interactions

	infrastructure design and maintenance, including the effects of pier shape [5].	and localized turbulence remains a major challenge.
Navigation & Flood Management	Successfully applied to real-world problems: navigation path optimization [1], dredging impact assessment [13], and flood hazard mapping .	Applications are often site-specific. Models may not reliably capture extreme events (e.g., dam breaches [14]), limiting predictive use in emergency planning.

## 6 Thematic Review of Literature

The literature on HEC-RAS and ADCIRC (ADC) models applied in post-barrage contexts exhibits a number of representations and integrated thematic specials. These themes reveal a domain that has been searching for ways to simulate signature fluvial processes, in response to real-world needs, which has evolved from simple one-dimensional (1D) hydraulic modelling into more integrated spatially explicit approaches. The predominant and emerging themes are presented in Table 9, with the following narrative providing further description.

**Table 9.** Summary of Dominant and Emerging Themes in the Literature

Theme	Prevalence	Core Focus and Key Citations
Sediment Transport & Morphological Change Modeling	36 Papers	Simulation of erosion, deposition, and scour using 1D/2D HEC-RAS, often calibrated with field data and standard transport equations (e.g., Ackers-White, Yang) [1, 2, 3, 6, 7, 11,15].
Calibration, Validation, and Model Performance	32 Papers	Rigorous calibration of roughness coefficients and sediment parameters using field data and statistical metrics (NSE, R <sup>2</sup> ) to ensure model reliability across diverse river systems [1, 2, 3, 4, 5,7, 9, 12, 13].
Practical Applications in River Management	30 Papers	Use of models for navigation optimization, scour assessment, flood hazard mitigation, and dredging planning to support infrastructure stability and ecological health [1, 4, 5, 6, 9, 11, 12, 13, 14, 15].
Integration of GIS and Remote Sensing	18 Papers	Enhancement of spatial analysis for morphological monitoring, flood inundation mapping, and model calibration using satellite imagery and DEMs [1, 2, 4, 8, 12, 14]
Two-Dimensional Hydraulic and Sediment Transport Modeling	15 Papers	Application of 2D HEC-RAS to capture complex flow patterns and sediment dynamics around structures, improving scour and deposition predictions [4, 5, 9, 12]
Flood Wave Propagation and Dam Break Analysis	14 Papers	1D unsteady flow modeling of dam breach scenarios and flood inundation to inform emergency planning and risk mitigation [4, 14, 15].
Sediment Management and Reservoir Flushing	12 Papers	Prediction of reservoir sedimentation patterns and flushing efficiency to support sediment management strategies and extend reservoir lifespan [3, 7].
Impact of Hydraulic Structures on Local Scour	10 Papers	Focused investigation of scour around piers, abutments, and other structures to assess erosion risks and design mitigation measures [5, 6].

### 6.1 Dominant Themes: Core Modeling Focus and Application

The topic which occurs most frequently (in the majority of studies) is Sediment Transport and Morphological Change Modelling. In this study, HEC-RAS, mainly in 1D but more recently in 2D, is used to forecast sediment erosion, deposition and the associated bed-level

changes occurring downstream of hydraulic structures. The common thread amongst these researches is the application of generic sediment transport equations (i.e., Ackers-White and Yang) for reproduction of dynamics in a variety of systems ranging from irrigation canals to large river systems, where the objectives are to forecast navigation channel capacity and reservoir siltation [1, 6, 3].

**4.4 Calibration, Validation, and Model Performance Evaluation** A common foundation among all valid model uses is provided by the triple issue of Calibrations & Validations as well as Performance Assessment (Table 6). Many of papers spend much work to calibrate the main parameters such as Manning's roughness coefficient and sediment formula constants against observational data and bathymetric surveys. Standardized metrics like Nash-Sutcliffe efficiency (NSE) and coefficient of determination ( $R^2$ ) are commonly used. This topic emphasizes that optimal calibration strategies are required in order to produce reliable simulations under varying geographic and sedimentological conditions, as observed for large river systems such as the Nile, Tigris, and Indus [1, 4, 2].

The practical interest in much of this work is how it relates to Practical Applications in River Management & Infrastructure. We do not offer Modeling as an end, but rather to provide models in order to solve our problems. The main applications include mass transport of open-channel navigation routes downstream of control structures [1], assessment of a safe infrastructure project against the dangers posed by scour around bridge foundations [5], risk demonstration under flood flow conditions [4], and the provision of an empirical base for planning maintenance dredging actions in an efficient way [13]. The study bridges the divide between simulation-based numerical analysis and out-in-the-field decision making when considering rehabilitation schemes and contemporary sediment management in general.

## **6.2 Cross-Cutting and Emerging Themes**

A key cross cutting theme is one of GIS and Remote Sensing in aid of Hydraulic modelling. This is a significant advance, enabling spatially explicit analyses which until now have been difficult to implement. Incorporating tools like HEC-GeoRAS, Landsat, and high-resolution DEMs to monitor geospatial changes over decades; map flood inundation extents (Wing et al., 2017); and validate spatial patterns of sediment deposition dynamics result in broader, more accurate information for river management plans [1,2,8].

There appears to have been a definite rise in the popularity of Two Dimensional Hydraulic and Sediment Transport Modelling. Even if we are still using 1D models for many system scale studies, there is an increasing use of 2D modelling to capture complex flow structures and sediment transport processes around structures such as bridge piers, spillways and confluences. These models provide more accurate prediction of local scour depth and sedimentation [5,9] but full modelling of interacting debris and irregular geometries still presents challenges.

## **6.3 Specialized Application Areas**

Two specialized topics are focused on certain high-consideration situations. One of these is Flood Wave Propagation and Dam Break Analysis Using HEC-RAS, with 1-dimensional (1D) unsteady flow models that perform a simulation of dam breach catastrophe events. It is common in these studies to conduct a sensitivity analysis for the parameters (such as width and formation time, etc.) of breach outflow to simulate generated flood hydrographs and inundation maps that are essential for emergency response planning and risk management [14].

Last but not the least – Impact of Hydraulic Structure on Local Scour and Riverbed Stability, which is probably highlighting an important issue for engineers. Nineteen papers are

dedicated to articles in this topic which encompasses the running of HEC-RAS sediment models to calculate scour depths at piers, abutments and other hydraulic structures, these results could be useful for floodway foundation design scour protection and preventative measures [5, 10, 12].

### 6.4 Synthesis and Trajectory

The thematic analysis highlights a mature but rapidly developing field. The literature is based on robust simulation and calibration for sediment transfer but it’s going to be pulled strongly by the flourishing 2D modelling, and the tight integration with geospatial. This trajectory aims to steer development towards the future of increasingly integrated, high-resolving, space-explicit model frameworks that are needed to support sustainable and resilient river basin management in a changing world of environment and infrastructure.

## 7 Agreement and Divergence Across Studies

A literature review reveals there is general consensus regarding the basic utility of HEC-RAS for a simulation-of downstream hydraulic and sedimentologic processes along with considerable methodological variation and mixed situational performance. This review has identified those areas in Table 10 that are convergent and divergent as due to the fact that studies were from different geographical locations, or have retrieved different data, or research question was posed differently.

**Table 10.** Synthesis of Agreement and Divergence in HEC-RAS Applications

Comparison Criterion	Consensus Findings	Points of Divergence	Underlying Reasons
Model Accuracy	Strong agreement on high accuracy for simulating flow and sediment transport, supported by high NSE, R <sup>2</sup> values, and low error margins in many studies [1,4, 2].	Performance varies significantly in complex scenarios (e.g., scour around piers, reservoir flushing), with 1D models sometimes under-predicting erosion by substantial margins [12, 14].	Inherent hydraulic complexity and sediment dynamics; 1D models simplify spatial heterogeneity, while 2D models' accuracy is contingent on detailed input data.
Calibration Techniques	Common use of Manning's *n*, sediment transport equations (Ackers-White, Yang), and grain size parameters calibrated with field/lab data is a standard, validated practice [1,14, 4].	Depth and methodological rigor of calibration vary widely, from advanced statistical sampling to manual tuning, with challenges noted in data-scarce or complex stratigraphic settings [14].	Disparities in data availability and sediment complexity between study sites dictate the feasibility and depth of calibration possible.
Application Scope	Widely applied to navigation optimization [1], flood hazard assessment [4] erosion control [26], and reservoir	Focus ranges from broad river management to highly specific phenomena like dam-break floods [14] or local	Diversity in hydraulic contexts and immediate management needs (e.g., public safety vs. operational efficiency)

	sedimentation [3, 7], emphasizing practical management.	bridge scour [5], reflecting different operational priorities.	shapes the application focus.
Dimensionality of Modeling	Consensus that 1D models are effective for longitudinal processes and reservoir flushing [1, 14], while 2D models provide superior spatial detail for scour and flood inundation [4, 5, 9].	Disagreement exists on the trade-offs; 1D models can fail in complex flows, while 2D models are often constrained by computational cost and data needs [12].	The choice is a function of study scale, objective, and available resources, leading to context-dependent recommendations.
Integration with Geospatial Data	Strong agreement on the benefits of GIS/remote sensing for calibration, visualization, and change detection, using satellite imagery and DEMs to enhance realism [1, 2, 8].	The extent of integration varies from basic data preparation to full multi-temporal analysis, with limitations noted regarding DEM accuracy and data gaps [15, 8].	Differences stem from technical capacity, data accessibility, and the specific analytical goals of each study.

### 7.1 Narrative Synthesis of Findings

This review literature shows good consensus on the fundamental validity of HEC-RAS in modelling hydraulic and sediment transport processes. This consensus is reflected, in particular, in the fairly widespread appearance of good model performance statistics for calibration and validation as evidence to support its place in software engineering [1].

But there is an important distinction in how often this will be the case. Although most of the standard scenarios show good performances in many research, shortcomings have been revealed from some other studies when models are exposed to complex situations. One debatable issue is the dimensionality of the models. It is unanimous that for regional questions of systems 1D models might be excellent, and 2Ds are more reliable to the spatial details. However, the literature is not unanimous regarding this trade-off and some authors consider 2D as crucial for scour calculation [5,12], whereas others claim that cost and data requirements make 1D the only viable solution in many scenarios [9]. This means that the dimension is not only arbitrary, it also depends on available resources.

Also, everyone seems to agree on the importance of calibrations while approaches and results vary widely. The studies in data-rich regions adopt sophisticated techniques and high model accuracy is achieved [1,4], while those in less dense or complex geology formations report significant calibration problems leading to poor predictability of the models [6,14]. This debate underscores that model truth is not inherent and is somewhat dependent on quantity and quality of the calibration data.

And bringing geospatial into the mix is being held up as a wonderful step forward by everyone. The consensus: it is a big win for morphology and model validation. The distinction lies in how extensively the approach is implemented: some products leverage multi-temporal satellite imagery to its full extent to achieve accurate and working change detection methods [8].

## 8 Limitations of The Literature

**Table 11.** Limitations in the current literature.

Area of Limitation	Description of Limitation	Papers which have limitation
Geographic Bias	Numerous works concentrate on particular river systems or areas and are therefore unrepresentative for other hydrological characteristics as well as geographic regions. This local scale focus limits generalizability and may miss regional variability in sediments.	[1, 2, 4, 7, 8, 11, 14]
Methodological Constraints	Limited use of full two-dimensional HEC-RAS models can limit the ability to represent complex two-dimensional flow and sediment transport processes, possibly oversimplifying the morphological changes and erosion patterns. This constrains the ability to predict in rivers with heterogeneous morphology.	[1, 2, 6, 14]
Data Availability and Quality	Calibration and validation are frequently conducted with limited data or sparser field measurements, limiting model performance and generalization. Inadequate or low-quality data to parameterize models decreases the confidence of outputs and limits a rigorous analysis of sediment transport.	[4, 8]
Limited Consideration of Complex Sediment Dynamics	Most of the models do not account sufficiently for sediment heterogeneity, cohesive behavior and aquatic vegetation effects that are important to make accurate predictions of scavenging and erosion. This leads to poor reliability of sediment transport modelling in riverine environments.	[5, 15]
Short-Term Simulation Horizons	A number of studies at shorter timescale of sediment transport and morphological responses, provide insufficient information on long term process river evolution and reservoir life expectancy to be used in planning for sustainable river management.	[3, 7, 12]
Insufficient Integration of Remote Sensing and GIS	Although GIS and remote sensing is occasionally included in various studies, integration is often poor, resulting in a low spatio-temporal resolution of morphological dynamics detection and model calibration, which compromises the soundness of sediment transport appraisals.	[1, 2, 8]
Neglect of Anthropogenic and Climate Change Impacts	Very few approaches have considered the influence of anthropogenic activities and/or climatic variability on sediment transport/erosion processes which are needed for a realistic modeling and management response to environmental change.	[8, 11]
Model Validation Limitations	Validation typically relies on small data sets, designs only the hydraulic parameters without considering sediment transport measurements, does not incorporate mathematical modeling but rather assumes that measures of model performance maintenance remain forever constant and it tends to overestimate how well a model performs and underestimate confidence in predictions involving sediments.	[1, 4, 5, 13]

## 9 Theoretical and Practical Implications

### 9.1 Theoretical Implications

- The reviewed studies combinedly strengthen theory (based on which HEC-RAS, in 1D as well as 2D mode, is a powerful tool) of the robustness of HEC-RAS in

simulating flow hydraulics and sediment transport at outlet from barrages and hydraulic structures. The capacity for the model to reflect morphological evolution, scour and deposition follows the same sediment transport theories as evidenced in other riverine scales contexts [1,14].

- The combination of GIS/remote sensing data source with HEC-RAS makes the spatial and time scales for morphologic analysis higher, which is consistent with the theoretical belief that by integrating hydrodynamic models with GIS technologies greater understanding of fluvial dynamics and the interaction between water/sediment can be achieved [1,2, [8].
- The relative efficacy of sediment transport equations within HEC-RAS (Ackers-White Equations, Yang's Equations) demonstrated that the selection of suitable sediment transport formulations depends upon the characteristics and flow conditions of a sediment bed, validating theoretical predictions on sediment transport variability [1, 7].
- Sensitivity analyses of dam breach parameters and their effects on the flood wave attenuated at downstream illustrate theoretic behavior between breach geometry, forming time and flow hydraulic, which highlights nonlinearity of dam-break flood dynamics [14, 15].
- The use of 2D HEC-RAS models in estimating the scour prediction at bridge pier and complex hydraulic structures may enhance the existing theory by validating the model ability to simulate local scour that is affected by failure geometry of piers as well as debris which could be under-predicted by already provided 1D models [5,11].
- The potentials revealed of the complex sediment transport scenarios, i.e., debris force and reservoir stratigraphic heterogeneity (the predictions are less accurate for scenario male-test-2 in Fig. 17), further highlight the existing theoretical barriers toward full understanding of multi-dimensional sedimentology, one challenge of which is likely to lie with model refinement [14].

## 9.2 Practical Implications

- HEC-RAS modelling can be useful for effective river and reservoir management, through accurate prediction of sediment deposition and erosion distribution downstream barrages, which is essential for safe navigation, stable infrastructure operation and the conservation of ecosystem [1], [10], [13].
- HEC-RAS is well established for simulating flood wave propagation and dam breach scenarios and the methodology has been applied in emergency preparation planning to help stakeholders understand areas at risk and targeting a detailed flood hazard maps, watershed-based early warning systems [14].
- The linking of HEC-RAS with GIS and remote sensing simplifies the process of monitoring and managing morphological changes for rivers which presents applicable advantages for sustainable river basin management as well as decision support systems in data poor areas [2, 8].
- 2DH HEC-RAS model applications for the determination of scour depths near to hydraulic structures contribute to the design and maintenance policy of bridges and barrages, allowing affordance of financially feasible preventative actions against structural collapses [5; 6].
- Calibration and validation procedures in the literature indicate that, although well-calibrated computer models are important for model accuracy, sufficient field-based

data is required; thus there is a need for continuous monitoring of data and information to support model-based management strategies [4, 8].

- Application of HEC-RAS in reservoir sediment flushing and sediment balance calculation helps to prolong a dam's life and improve the rational utilization of resources, which directly affects water resource sustainability and the service life of infrastructure [13], [15].

## 10 Gaps and Future Directions

A review of existing studies reveals key gaps in knowledge and methodological issues in modeling flow and sediment movement downstream of barrages. Addressing these challenges is crucial for enhancing prediction accuracy and promoting sustainable river management. The main research priorities are outlined below.

### 10.1 High-Priority Research Areas

#### 10.1.1 Advancing Sediment Transport Formulations:

Empirical models currently face difficulties when it comes to sediment heterogeneity (mixed grain sizes, cohesive sediments) and the parameterization of 2D sediment models. This results in the under- or over-prediction of scour around complex structures and lateral transport during hydrologic events such as reservoir flushing [14].

**Future Direction:** Propose and test improved sediment transport models with explicit descriptions of grain size distribution and cohesion content. Joint intensive laboratory and field campaigns to enhance the calibration of 2D models, taking into account debris and turbulence effects.

#### 10.1.2 Enhancing Model Generalizability and Robustness:

The site-dependent calibration restricts the transferability and generalization of model performances among different geographical and hydrological settings [1,11]. In addition, high sensitivity to input parameters (e.g., grain size, breach shape) leads to prediction uncertainty [10, 14].

**Future Direction:** Performance of comparative multisite studies to develop more transferable parameter sets. Conduct probabilistic sensitivity and uncertainty analyses addressing all sources to identify key parameters that inform targeted data collections for a stronger model structure.

#### 10.1.3 Improving Predictions for Extreme Events and Reservoir Management:

Models have a limited capability to accurately simulate extreme events, such as dam breaches and large floods, which are critical for emergency planning [14, 15]. Similarly, existing 1D models often underpredict erosion during reservoir flushing due to an inadequate representation of lateral sediment transport

- **Future Direction:** Enhance unsteady flow and sediment transport capabilities for extreme event modeling, integrating real-time data assimilation. Develop and validate reservoir flushing models that incorporate lateral transport mechanisms and complex stratigraphy.

## 10.2 Medium-Priority Research Areas

### 10.2.1 1. *Optimizing Model Dimensionality and Integration:*

The trade-off of 1D and 2D modelling persists, and determining the balance between computation cost vs. degree of spatial detail which is required remains a challenge [6, 9]. At the same time, the large potential offered by the integration of remote sensing data remains undervalued because of uncertainties arising from data resolution, temporal gaps and misclassified pixels [2, 8].

**Future Direction:** the development of hybrid 1D-2D modelling methodologies and efficient computational algorithms. Develop standard practice procedures for pre-processing and validating remote sensing data that can facilitate its integration with sediment transport models.

### 10.2.2 2. *Enabling Long-Term Analysis and Decision Support:*

There is a lack of today Cited y morphological monitoring and modeling hindering understanding of decadal-scale changes [7, 8]. In addition, GIS integration is typically confined to spatial analysis with no advanced visualization and decision support for operational management [1, 15].

**Future Direction:** Develop sustained monitoring systems that combine multiple temporal remote sensing with field survey. Design interactive GISHECRAS platforms with scenario analysis tools for providing direct assistance river management decision-making.

By systematically tackling these gaps, the credibility and operability of hydraulic models can be largely enhanced in future studies, on which rest more resilient and better managed river systems.

## 11 Conclusion

The state of the art with respect to HEC-RAS and ADCIRC modeling flows and erosion downstream of barrages has been reviewed in this paper. The simulation results suggest that/these models are practical tools for river engineering application, having good performance in hydraulic characteristic representation, sediment transport and channel morphology response. The wide application of 1D and 2D methods, in conjunction with careful calibration using field data has resulted in accurate predictions that are used to directly inform operational river management decisions for navigation, flood risk management, prediction of scour and reservoir sedimentation control.

Despite the latter, there are intrinsic deficiencies in the model that prevent its efficacy and usability. Deficiency of the other among complex sediment models associating small confidence extent due to such factors as inherent heterogeneity and coherence causes differences in drawing predictions or reservoir flushing simulation results. The location-specific calibration aspect of modelling is also a constraint for transferability between regions and hydrological settings. Moreover, by GIS and remote sensing the combined has played an important role in spatial analysis. We think the resolution of data was not resolved continuously and open temporal scales between ground field works and standards for integration.

The shift toward more advanced modelling is in progress, with clearly established trends towards two-dimensional model and improved spatial integration. Further progress is based on covering the few open research fronts (better sediment-transport formulations, capabilities

for parameterization in complex situations, careful treatment of UA processes and other source types, hybrid models which are computationally efficient and does not lose much spatial scale). Through following these pathways in a systematic way, as a scientific community we can greatly enhance our predictive capacity and hence better support resilient and sustainable river management; at such an important time where environmental change is rapid but infrastructure demands on rivers are increasing.

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