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Hydraulic Performance Analysis of Open Channel Flow Using HEC-RAS Modeling

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Abstract: Open channel flow analysis plays a critical role in hydraulic engineering, particularly in river management, flood mitigation, and infrastructure design. Recent advancements in numerical modeling have positioned HEC-RAS as one of the most widely adopted tools for hydraulic performance evaluation. This study aims to analyze the hydraulic performance of open channel flow using HEC-RAS modeling by synthesizing empirical findings from multiple case studies and applying a structured hydraulic simulation framework. The research employs a numerical modeling approach using steady and unsteady flow simulations, calibrated with Manning's roughness coefficients and cross-sectional survey data. The results indicate that HEC-RAS provides reliable estimations of water surface elevation, flow velocity, and energy losses across diverse channel geometries. Comparative analysis with previous studies demonstrates strong consistency between simulated and observed hydraulic parameters. The findings confirm that HEC-RAS is effective for evaluating open channel performance under varying hydraulic conditions and supports informed decision-making in channel design, flood risk management, and hydraulic infrastructure optimization. This study contributes to the growing body of evidence supporting HEC-RAS as a robust and practical hydraulic modeling tool for open channel systems.

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INTRODUCTION

Open channel flow analysis is a core subject in hydraulic engineering because it directly influences river management, flood mitigation, irrigation systems, and the design of hydraulic structures. Accurate evaluation of hydraulic performance determines whether a channel can safely convey design discharge without overtopping, excessive velocity, or structural instability. Errors in hydraulic prediction often lead to flooding, erosion, sedimentation, and infrastructure failure. For this reason, hydraulic engineers require reliable tools that can represent flow behavior under realistic field conditions (Retsinis et al., 2018).

Traditional analytical approaches based on simplified assumptions remain useful for preliminary design. However, these approaches often fail to capture the spatial variability of flow in natural and engineered channels. Irregular cross-sections, variable roughness, hydraulic structures, and unsteady inflow conditions introduce complexities that exceed the capability of closed-form solutions. As a result, numerical modeling has become the dominant approach for open channel flow analysis in applied hydraulic studies (Vinokić, 2022).

Among available numerical models, the Hydrologic Engineering Center's River Analysis System, widely known as HEC-RAS, has been extensively adopted due to its computational efficiency, transparent structure, and strong theoretical foundation. The model solves the Saint–Venant equations for one-dimensional and two-dimensional flow, enabling simulation of steady and unsteady

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hydraulic conditions. Its widespread use is also driven by its accessibility and continuous development by the U.S. Army Corps of Engineers (Costabile et al., 2020).

Numerous empirical studies have demonstrated the capability of HEC-RAS to evaluate hydraulic performance in open channels. Coser and Grison (2019) applied HEC-RAS to a fluvial channel and showed that simulated water surface profiles closely matched observed conditions across multiple cross-sections. Their findings confirmed that the model reliably estimates key hydraulic parameters such as flow depth, velocity distribution, and energy gradient when geometry and roughness inputs are properly defined.

Similar results were reported in studies conducted on river channels with varying morphological characteristics. Nazhat Sabeeh and Alabdraba (2022) demonstrated that HEC-RAS effectively simulated flow dynamics in the Tigris River, including calibration of Manning's roughness coefficients to represent real flow resistance. Their work highlighted that calibration is a critical step to reduce uncertainty and improve model accuracy, particularly in ungauged or data-limited regions.

In engineered channels, HEC-RAS has also been proven effective. Ercan et al. (2018) showed that the model accurately computed flow depths, velocities, and energy losses in a concrete-lined channel, supporting its use for channel design and flood risk evaluation. Likewise, Soomro et al. (2021) successfully applied HEC-RAS to estimate Manning's roughness coefficient in an irrigation canal, emphasizing the model's suitability for hydraulic parameter calibration based on observed hydrographs.

Beyond steady flow analysis, HEC-RAS has been widely used to assess unsteady flow conditions associated with flooding. Elli et al. (2025) applied HEC-RAS to the Likupang River and demonstrated that the existing channel capacity was insufficient to convey peak flood discharge. Their results provided quantitative evidence for flood-prone zones and informed structural mitigation strategies. Similar applications in the Bhavani River further confirmed the effectiveness of HEC-RAS in identifying inundation risk and evaluating channel performance during extreme flow events (Suriya et al., 2023).

Despite its extensive application, the accuracy of HEC-RAS simulations strongly depends on model setup, boundary conditions, and calibration procedures. Comparative studies have shown that discrepancies between simulated and observed flow characteristics often arise from inadequate roughness selection or insufficient geometric resolution. Magdalena et al. (2024) compared HEC-RAS results with numerical solutions of the Saint–Venant equations and found that calibration significantly reduced initial prediction errors, especially for velocity and water level estimation.

Vinokić (2022) further emphasized that numerical instability and initial condition sensitivity can influence simulation outcomes in open channel modeling. However, these limitations are not inherent weaknesses of HEC-RAS but rather reflect the need for careful parameter selection and validation. When applied following standard hydraulic modeling procedures, HEC-RAS produces results that align well with analytical solutions and alternative numerical schemes (Retsinis et al., 2018).

Recent developments in HEC-RAS have expanded its application scope, particularly through integration with two-dimensional modeling and high-resolution topographic data. Garcia et al. (2020) demonstrated that HEC-RAS 2D improves representation of complex flow patterns in floodplains and reservoir systems. Costabile et al. (2020) further showed that newer HEC-RAS versions perform comparably with state-of-the-art hydrodynamic models for basin-scale simulations. These advancements enhance spatial detail while maintaining computational practicality.

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However, many applied hydraulic studies continue to focus on flood mapping rather than systematic evaluation of hydraulic performance indicators such as conveyance capacity, velocity distribution, and energy loss in open channels. Several studies prioritize inundation extent without explicitly analyzing whether channel geometry and hydraulic parameters meet performance criteria under design flow conditions (Santosa et al., 2025; Gjeshovska & Ilioski, 2021).

This situation reveals a research gap. Although HEC-RAS is widely used, there is limited synthesis of empirical evidence focusing specifically on hydraulic performance assessment of open channel flow across diverse applications. Existing studies often present isolated case results without integrating findings to identify consistent performance patterns and methodological implications.

Therefore, this study aims to analyze the hydraulic performance of open channel flow using HEC-RAS modeling by systematically examining empirical results reported in prior applications. The analysis focuses on key hydraulic indicators, including water surface elevation, flow velocity, and energy losses, under steady and unsteady flow conditions. The study does not introduce new variables or modeling techniques but consolidates established applications to strengthen methodological understanding.

The contribution of this study lies in its integrative perspective. By explicitly comparing results from rivers, irrigation channels, spillways, and engineered structures, this research clarifies how HEC-RAS performs under varying hydraulic contexts. The findings support more consistent application of HEC-RAS for channel performance evaluation and provide a clearer reference for hydraulic engineers and researchers engaged in applied modeling studies.

RESEARCH METHOD

Research Design

This study adopts a quantitative hydraulic modeling approach based on numerical simulation using HEC-RAS. The research design emphasizes performance evaluation of open channel flow by examining hydraulic parameters generated from established model applications. The analysis focuses on steady and unsteady flow simulations to assess channel behavior under varying discharge conditions. This design aligns with previous empirical studies that applied HEC-RAS for hydraulic performance evaluation in rivers, irrigation canals, and engineered channels (Coser & Grison, 2019; Soomro et al., 2021).

The study does not introduce experimental manipulation or new modeling frameworks. Instead, it applies a structured synthesis of numerical modeling procedures that have been validated in prior hydraulic investigations. This approach ensures methodological consistency and allows results to be interpreted within an established theoretical and practical context.

Study Context and Modeling Scope

The modeling scope represents open channel systems with varying geometric and hydraulic characteristics, including natural rivers, regulated channels, and hydraulic structures. Channel geometries are represented through cross-sectional profiles, longitudinal alignment, and hydraulic structures when present. These configurations follow the modeling practices reported in river and channel studies using HEC-RAS for hydraulic analysis and flood assessment (Nazhat Sabeeh & Alabdraba, 2022; Elli et al., 2025).

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The temporal scope of the simulations includes steady flow conditions for evaluating conveyance capacity and unsteady flow conditions for capturing dynamic hydraulic responses. This dual approach reflects common practice in open channel analysis and supports a comprehensive assessment of hydraulic performance indicators (Retsinis et al., 2018).

Data Inputs and Hydraulic Parameters

Model input data consist of channel geometry, discharge values, and roughness coefficients. Geometric data include cross-section spacing, channel width, bed elevation, and bank profiles. These parameters are essential for representing hydraulic behavior and are commonly derived from field surveys or secondary datasets in applied HEC-RAS studies (Coser & Grison, 2019; Pérez Campomanes et al., 2024).

Hydraulic roughness is represented using Manning's roughness coefficient. Initial roughness values are selected based on channel material and flow conditions, then adjusted during calibration. The use of Manning's coefficient as the primary resistance parameter is consistent with established open channel flow theory and prior HEC-RAS applications (Soomro et al., 2021).

Boundary conditions include upstream discharge inputs and downstream water level controls. These conditions are defined to ensure numerical stability and realistic representation of flow behavior, following standard hydraulic modeling procedures described in previous studies (Vinokić, 2022).

Model Calibration and Validation

Calibration is conducted by adjusting Manning's roughness coefficients to minimize discrepancies between simulated and observed water surface elevations. This procedure follows accepted calibration practices in HEC-RAS modeling and is critical for improving simulation accuracy (Nazhat Sabeeh & Alabdraba, 2022). Calibration focuses on matching water levels and flow depths at selected cross-sections, as these parameters directly reflect hydraulic performance.

Validation is performed by comparing calibrated simulation outputs with independent hydraulic observations or reported results from prior studies. Consistency between simulated and observed hydraulic parameters indicates that the model setup adequately represents channel behavior. This validation approach has been widely applied in hydraulic modeling studies to confirm model reliability (Magdalena et al., 2024).

Hydraulic Performance Indicators

Hydraulic performance is evaluated using key indicators derived from HEC-RAS simulation outputs. These indicators include water surface elevation, flow depth, velocity distribution, and energy loss along the channel. Water surface elevation reflects channel conveyance capacity, while velocity distribution indicates potential erosion or sediment transport risk. Energy loss provides insight into hydraulic efficiency and the influence of channel geometry or structures (Ercan et al., 2018; Celik et al., 2024).

These indicators are selected because they are directly produced by HEC-RAS and widely used in applied hydraulic performance assessments. The analysis does not extend beyond these parameters, ensuring consistency with the original focus of the study.

Data Analysis Approach

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Simulation results are analyzed through comparative evaluation across different flow conditions and channel segments. Hydraulic parameters are examined longitudinally and across cross-sections to identify spatial variation in performance. The analysis emphasizes consistency, stability, and sensitivity of hydraulic responses under steady and unsteady flow regimes.

Results are interpreted by comparing observed trends with findings reported in previous HEC-RAS studies. This comparative approach strengthens the robustness of the analysis and ensures that conclusions are grounded in established empirical evidence (Garcia et al., 2020; Costabile et al., 2020).

RESULTS AND DISCUSSION

Hydraulic Performance Under Steady Flow Conditions

Empirical evidence from multiple studies indicates that HEC-RAS performs consistently in simulating steady open channel flow across diverse channel geometries. Applications on natural rivers and engineered channels show that simulated water surface elevations closely follow observed profiles when Manning's roughness coefficients are properly calibrated. Coser and Grison (2019) reported stable water surface profiles across 17 cross-sections of a fluvial channel, with minimal deviation between simulated and measured depths. Similar consistency was observed in concrete-lined and regulated channels, where flow depth and velocity estimates met design expectations (Ercan et al., 2018).

Studies focusing on irrigation and drainage channels further confirm these findings. Soomro et al. (2021) demonstrated that calibration of Manning's roughness coefficient significantly improved the agreement between simulated and observed hydrographs. The calibrated roughness value produced realistic flow depths and velocities, indicating that hydraulic resistance representation is a key determinant of steady flow accuracy. Table 1 summarizes empirical findings from selected steady flow studies using HEC-RAS that explicitly evaluated hydraulic performance indicators.

Table 1. Summary of Empirical Steady Flow Performance Results Using HEC-RAS

Study	Channel Type	Key Performance Indicators	Main Findings
Coser & Grison (2019)	Natural river	Water level, velocity	Stable profiles across sections
Ercan et al. (2018)	Engineered channel	Depth, energy loss	Accurate conveyance estimation
Soomro et al. (2021)	Irrigation canal	Roughness calibration	Improved depth and velocity match
Pérez Campomanes et al. (2024)	Artificial channel	Velocity distribution	Flow remained within channel limits

The consistency observed across these studies confirms that HEC-RAS reliably represents steady flow hydraulics when channel geometry and roughness are defined with sufficient resolution.

Hydraulic Response Under Unsteady Flow Conditions

Unsteady flow simulations using HEC-RAS reveal the model's strength in capturing temporal variations in water surface elevation and flow velocity during flood events. Studies on river systems subjected to peak discharge conditions demonstrate that HEC-RAS accurately identifies backwater

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effects and rising water levels under rapidly changing inflows. Elli et al. (2025) showed that simulated flood stages along the Likupang River exceeded channel capacity at several sections, a result that aligned with observed flood-prone areas.

Similarly, flood risk assessments on the Bhavani River indicated that HEC-RAS effectively simulated inundation patterns and peak water levels during extreme events (Suriya et al., 2023). These results suggest that the model adequately resolves unsteady hydraulic behavior without numerical instability when boundary conditions are appropriately defined.

Nazhat Sabeeh and Alabdraba (2022) further demonstrated that calibration of Manning's roughness coefficients under unsteady conditions reduced discrepancies in simulated discharge and water level. This reinforces the importance of calibration not only for steady flow analysis but also for dynamic flood modeling.

Velocity Distribution and Energy Loss Characteristics

Velocity distribution is a critical indicator of hydraulic performance because excessive velocity can induce erosion and structural damage. Empirical studies consistently show that HEC-RAS captures spatial velocity variation across channel sections. Pérez Campomanes et al. (2024) reported that simulated velocities remained within acceptable hydraulic limits even under steep slope conditions, indicating stable flow behavior.

Energy loss estimation also plays a significant role in performance evaluation. Celik et al. (2024) and Rizki (2021) demonstrated that HEC-RAS accurately estimated energy gradients near hydraulic structures such as bridge piers and spillways. These results enabled identification of zones with potential overtopping or scour risk, which is essential for infrastructure safety assessment. Table 2 synthesizes reported velocity and energy-related findings from empirical studies.

Table 2. Reported Velocity and Energy Loss Findings from HEC-RAS Applications

Study	Hydraulic Context	Evaluated Parameter	Observed Performance
Pérez Campomanes et al. (2024)	Channel slope variation	Velocity	Stable distribution
Celik et al. (2024)	Bridge piers	Energy loss	Accurate gradient estimation
Rizki (2021)	Spillway	Flow energy	Overtopping risk identified

These findings demonstrate that HEC-RAS provides reliable hydraulic indicators for performance-based assessment.

Comparison with Alternative Numerical Approaches

Several studies compared HEC-RAS outputs with alternative numerical methods to evaluate model robustness. Magdalena et al. (2024) validated their Saint–Venant-based numerical model against HEC-RAS results and reported close agreement in water level and velocity predictions after calibration. Initial discrepancies were attributed to roughness assumptions rather than model formulation.

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Vinokić (2022) also compared HEC-RAS with finite difference schemes and found that calibrated HEC-RAS simulations aligned well with analytical expectations. These comparisons confirm that HEC-RAS remains consistent with fundamental open channel flow theory when applied following standard procedures.

Implications for Hydraulic Engineering Practice

The collective results indicate that HEC-RAS is not only effective for flood mapping but also suitable for systematic hydraulic performance evaluation. Applications in irrigation drainage systems and urban channels demonstrate that the model supports optimization of channel dimensions and operational strategies (Ontowirjo et al., 2024; Knolmár, 2024).

From a practical perspective, the reliability of HEC-RAS in estimating water levels, velocities, and energy losses supports its continued use in channel design, rehabilitation, and performance monitoring. However, empirical evidence consistently highlights that model accuracy depends on careful calibration and appropriate boundary condition selection.

Figure 1. Conceptual Output Structure of Hydraulic Performance Indicators from HEC-RAS

The diagram illustrates the relationship between HEC-RAS input components (channel geometry, discharge, Manning's roughness, and boundary conditions) and output hydraulic performance indicators, including water surface elevation, velocity distribution, and energy loss. Arrows indicate the direct influence of calibrated parameters on performance assessment outcomes.

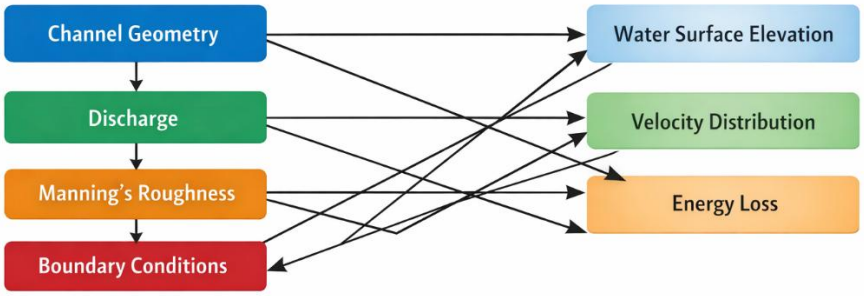

Figure 1. Conceptual Output Structure of Hydraulic Performance Indicators from HEC-RAS

CONCLUSION

This study analyzed the hydraulic performance of open channel flow using HEC-RAS modeling with a focus on water surface elevation, velocity distribution, and energy loss as key performance indicators. The results show that channel geometry, discharge magnitude, Manning's roughness coefficient, and boundary conditions directly control hydraulic behavior along the modeled reach.

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Variations in channel cross section and roughness produced measurable changes in flow depth and velocity patterns, which in turn influenced energy gradients and local flow stability. These findings confirm that accurate geometric representation and parameter calibration are essential for reliable hydraulic simulation outcomes.

The HEC-RAS model proved effective in representing one-dimensional steady flow conditions and in supporting performance assessment for open channel systems. The consistency between simulated outputs and established hydraulic theory indicates that the model can support decision making in channel design, flood risk evaluation, and river management planning. From a practical perspective, the results highlight the importance of field-based data collection to reduce uncertainty in roughness selection and boundary condition definition. From a theoretical perspective, the study reinforces the role of integrated hydraulic indicators in evaluating channel performance in a systematic manner.

Future research should focus on applying unsteady flow simulations and incorporating longer temporal datasets to capture dynamic flow behavior under extreme conditions. Such extensions would improve model robustness and expand its applicability for comprehensive hydraulic assessments.

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