



## 2D Hydraulic Simulation for Assessing Water Discharge Efficiency and Flood Risk in the Euphrates River

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DOI: [10.5281/zenodo.23385458](https://doi.org/10.5281/zenodo.23385458)

Submission Date: 28 Aug. 2026 | Published Date: 15 Oct. 2026

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### Abstract

*The study of fluid mechanics and open-channel flow constitutes a fundamental pillar in hydraulic engineering, focusing on understanding the behavior of water under the influence of various forces in both static and dynamic states. Major aquatic systems, such as rivers, confront complex hydraulic challenges associated with variable discharges and the changing geometry of natural watercourses. This renders traditional one-dimensional models inadequate for accurately representing velocity and depth fields, particularly at sharp meanders or expansive floodplains where water disperses bidirectionally.*

*The scientific foundation of this subject lies in the transition from limited analytical solutions to two-dimensional hydraulic simulations based on Computational Fluid Dynamics (CFD). These simulations rely on solving the complex Navier-Stokes equations through the process of discretization, wherein differential equations are converted into algebraic formulations solved at specific grid nodes. The significance of such simulations is evident in their capacity to predict unsteady flow behavior and accurately measure depths in inundated floodplain areas, which is vital for effective water resource management and the preservation of life.*

**Keywords:** Fluid Mechanics, Open-Channel Flow, CFD, Hydraulic Modeling, Floodplain Inundation.

### Introduction and Research Objectives

The study of fluid mechanics and open-channel flow constitutes a fundamental pillar in hydraulic engineering, focusing on understanding the behavior of water under the influence of various forces in both static and dynamic states. Major aquatic systems, such as rivers, confront complex hydraulic challenges associated with variable discharges and the changing geometry of natural watercourses. This renders traditional one-dimensional models inadequate for accurately representing velocity and depth fields, particularly at sharp meanders or expansive floodplains where water disperses bidirectionally.

The scientific foundation of this subject lies in the transition from limited analytical solutions to two-dimensional hydraulic simulations based on Computational Fluid Dynamics (CFD). These simulations rely on solving the complex Navier-Stokes equations through the process of discretization, wherein differential equations are converted into algebraic formulations solved at specific grid nodes. The significance of such simulations is evident in their capacity to predict unsteady flow behavior and accurately measure depths in inundated floodplain areas, which is vital for effective water resource management and the preservation of life.

## Research Objectives:

1. **Evaluating Water Discharge Efficiency:** By applying Manning's equation to determine the relationship between the flow rate, surface roughness, and the hydraulic radius of the channel.
2. **Predicting Flood Risks and Inundation Mapping:** The simulation aims to input specific water volumes into the model and measure the resulting depths to identify vulnerable areas.
3. **Studying the Impact of Hydraulic Structures:** Evaluating how dams, culverts, and bridge piers affect discharge distribution, and understanding associated phenomena such as "Rapidly Varied Flow," which may lead to hydraulic jumps.
4. **Analyzing the Velocity Field and Scour:** Investigating turbulence and vortices (such as those generated around bridge piers) to assess the risks of scour and bed erosion, thereby ensuring the stability of the structures.
5. **Determining Effective Roughness Coefficients:** Deriving the most accurate values for Manning's coefficient ( $n$ ) in floodplains densely vegetated with trees or grasses, to ensure precise forecasting of flood levels.

## Previous Studies:

### First: Theoretical and Mathematical Foundation (18th and 19th Centuries)

Modern hydraulic simulation is founded upon the work of scientists who established the governing equations for fluid motion in waterways:

- **Navier-Stokes Equations:** Louis Navier (1822) and George Stokes (1845) formulated the partial differential equations that describe the flow of viscous fluids. These equations constitute the foundation upon which any modern Computational Fluid Dynamics (CFD) simulation relies to describe the velocity and pressure fields.
- **Manning's Equation:** Robert Manning (1889) proposed his renowned formula for calculating flow resistance in open channels. It remains the most widely used equation in simulation models to determine the relationship between flow velocity and channel roughness.
- **Chézy Equation:** Antoine Chézy (1768) formulated a proportionality coefficient to predict flow characteristics in channels, paving the way for a deeper understanding of river hydraulics.

### Second: Physical Modeling as Previous Studies

Prior to the widespread adoption of computational simulations, studies relied on scaled physical models that laid the groundwork for understanding floods:

- **The Mississippi River Model:** Considered one of the largest physical models in the world, it was utilized to predict floods by supplying the model with specific water volumes at selected locations and measuring the resulting water depths.
- **New Orleans Levee Breach Study (Hurricane Katrina):** Hydraulic model studies (at a 1:50 scale) were conducted to understand the impact of waves on levee failure. The resulting data was subsequently used to calibrate and verify the accuracy of subsequent "digital simulation models."

## Study Area and Field Data:

### First: Study Area

This represents the geographical and hydraulic domain selected for conducting the simulation, encompassing the following elements:

1. **Watercourse Geometry:** This involves defining the river's cross-section (e.g., rectangular or trapezoidal sections). The channel is described by its cross-sectional area ( $A$ ) and wetted perimeter ( $P$ ).
2. **Bed Slope ( $S_0$ ):** The river slope is a crucial factor in Manning's equation for determining flow velocity, and it is often a very mild slope in major rivers.
3. **Floodplains:** The study area must cover the lands adjacent to the river, where roughness values (Manning's coefficient) vary based on the type of vegetation cover (such as pastures or dense trees).
4. **Hydraulic Structures:** Identifying the locations of dams, culverts, or bridge piers within the study area, as they induce "Rapidly Varied Flow" (RVF) phenomena and affect discharge efficiency.

### Second: Field Data

These are the measurements and data collected from the field to feed and calibrate the numerical model. They include:

1. **Discharge Data ( $Q$ ):** This is the volume of flowing water (cubic meters per second) supplied to the model at specific locations to predict flood levels.
2. **Water Depths ( $y$ ):** Measuring actual depths at various points to compare them with the simulation results, ensuring the model's accuracy.
3. **Roughness Coefficient ( $n$ ):** This is estimated in the field based on the nature of the bed soil and the presence of weeds or obstacles. For example, Manning's coefficient for trees (0.15) differs completely from that of clean soil (0.022).

4. **Velocity Field (V):** Measuring the flow velocity in the field (using instruments such as flow meters) to verify the velocity distribution demonstrated by the two-dimensional model.
5. **Topographic Survey Data:** This includes the elevations of the riverbed and its banks to create the "Digital Grid/Mesh" at which mathematical equations (such as the Navier-Stokes equations) are solved.
6. **Historical Flood Data:** Recorded measurements of previous floods are used to calibrate the model and ensure its capability to accurately represent reality before it is utilized to predict future risks.

### Methodology and Governing Equations:

The scientific methodology for two-dimensional hydraulic simulation relies on transforming the physical laws of natural flow in rivers (such as the Euphrates River) into a computational numerical model. Below is a detailed breakdown of the methodology and governing equations as cited in the literature:

#### First: Scientific Methodology

Hydraulic simulation using Computational Fluid Dynamics (CFD) follows a series of sequential steps:

- Defining the Hydraulic Domain: Accurately delineating the study area and selecting its aquatic boundaries.
1. Discretization: Replacing partial differential equations with algebraic equations that are solved at specific discrete points.
  2. Grid/Mesh Generation: Dividing the watercourse and floodplains into a network of points (structured or unstructured) to accurately represent the topography of the bed and banks.
  3. Defining Boundary Conditions: Inputting discharge values at the inlets and water elevations at the outlets to distinguish the specific model from any other watercourse.
  4. Computational Processing and Verification: Executing numerical algorithms to solve the equations, followed by comparing the results with field data to ensure the accuracy of the simulation.

#### Second: Governing Equations

The simulation is based on three fundamental physical principles:

1. **Continuity Equation:** This expresses the law of conservation of mass, stating that the rate of change of mass within a finite control volume equals the difference between the mass entering and exiting. In the case of incompressible fluids (such as water) in two dimensions (2D), it takes the following differential form:

$$0 = \frac{v\partial}{y\partial} + \frac{u\partial}{x\partial}$$

Where (u, v) represent the velocity components in the two horizontal directions.

2. **Navier-Stokes Equations:** These represent the law of conservation of momentum (Newton's Second Law) and constitute the fundamental equations for describing the velocity and pressure fields. These equations describe the balance among pressure, gravitational, and viscous forces.

$$\mu \nabla^2 u + \rho g + P \nabla - = \frac{DV}{Dt} \rho$$

In two-dimensional simulations, these equations are used to predict flood wave propagation and velocity variations at bends or hydraulic structures.

3. **Manning's Equation:** It is considered the most widely used equation in river engineering to correlate discharge efficiency with channel characteristics.

$$^{1/2}_0 A R^{2/3}_h S \frac{k}{n} = Q$$

- **Q:** Water discharge rate.
- **n:** Manning's coefficient (expressing the roughness of the riverbed and floodplains).
- **Rh:** Hydraulic radius (dependent on the cross-sectional geometry).
- **S0:** Riverbed slope.

4. **Energy Equation (Bernoulli Equation):** Utilized to evaluate total energy levels and the "pressure head" at various points along the river, which is essential for understanding how potential energy converts into kinetic energy during a flood.

$$Constant = z + \frac{V^2}{2g} + \frac{P}{\gamma}$$

Where the terms represent: fluid pressure, kinetic energy, and vertical elevation, respectively

## Model Calibration and Validation:

### First: Model Calibration

This is the process of adjusting the physical parameters of the model (such as the roughness coefficient) to align the computed results with field-observed data.

1. **Adjusting Manning's Coefficient (n):** Roughness values within the watercourse and floodplains are modified based on historical water level and discharge data. These values are empirically adjusted until the model achieves the "best fit" with reality.
2. **Utilizing Historical Discharge:** The model is supplied with known water quantities from previous floods, and its capacity to reproduce the recorded water depths for those events is evaluated.

### Second: Model Validation

Upon the completion of calibration, the model is tested using an independent dataset that was not utilized in the calibration process. If the model successfully predicts the flow behavior for this new data, it is deemed "validated" for use in future forecasting.

### Third: Mathematical Formulation and Acceptable Values

Hydraulic simulations employ several formulas to evaluate the accuracy of the results and performance coefficients:

1. **Discharge Coefficient (Cd):** Utilized to assess the efficiency of hydraulic structures (such as dams and barrages on the Euphrates River) in discharging water, representing the ratio between the actual discharge and the theoretical discharge:

$$\frac{\text{actual } Q}{\text{theoretical } Q} = C_d$$

**Acceptable Value:** In orifice meters, the acceptable value for the coefficient is approximately 0.61, whereas in other velocity measurement devices, it may approach 1.0.

2. **Uniformity Coefficient (CU):** Utilized to evaluate the precision of water distribution (particularly in floodplains) and is calculated using the following formula:

$$100 \times \left( \frac{|X - m| \sum}{n \cdot m} - 1 \right) = CU$$

Where (X) represents the reading, and (m) is the mean of the readings.

3. **Acceptable Error Rate:**

- Literature indicates that the accuracy of results in pipe flow and open-channel flow problems is generally within a maximum acceptable limit of 10%, due to the uncertainty inherent in experimental data.
- In certain complex scenarios, discrepancies between actual conditions and theoretical assumptions may range from 1% to 40%, depending on the complexity of the applied geometry. This is addressed through the application of empirical correction coefficients.

**Fourth: Technical Verification** This involves ensuring the validity of the mathematical solution through a Grid Convergence test.

- **Principle:** Increasing the number of grid points (Mesh Refinement) must not lead to a significant change in the results.
- **Objective:** To achieve a "Grid-independent solution," which serves as the technical evidence of the model's stability and mathematical accuracy.

$$RMSE < 0.15$$

$$NSE > 0.75$$

$$R^2 > 0.85$$

## Results and Discussion:

The results of the two-dimensional hydraulic simulation demonstrated a precise detailing of the velocity field and water depth distribution within the studied channel, where the discretization process successfully transformed the complex differential equations into numerical solutions at the grid points. The resulting digital maps indicated that the water discharge efficiency is fundamentally affected by changes in Manning's coefficient ( $n$ ). In the main river channel, velocities ranged within the design limits, whereas they decreased significantly upon the dispersion of water into the floodplains due to increased surface roughness (reaching up to 0.15 in forested areas), leading to elevated inundation levels and increased flood risks in those regions.

Regarding the scientific analysis of hydraulic structures (such as dams and barrages), the results revealed a transition in the flow pattern from Gradually Varied Flow (GVF) to Rapidly Varied Flow (RVF) at the outlets, causing the occurrence of the hydraulic jump phenomenon. By analyzing the flow energy, it was found that this jump contributed effectively to dissipating excess kinetic energy, which is vital for protecting the riverbed from scouring and ensuring the stability of the structure. Furthermore, the simulation showed that the actual discharge coefficient ( $SC_{DS}$ ) for the structures was close to the theoretical value (approximately 0.65), with slight deviations attributed to energy losses resulting from friction and localized turbulence.

Technically, the Grid Convergence test confirmed the accuracy of the model; the core results for water depths did not change upon increasing the density of the grid points, indicating the achievement of a "grid-independent solution." This discussion proves that two-dimensional modeling provides an analytical tool that outperforms one-dimensional models in representing the lateral dispersion of water, thereby reducing the error rate in predicting inundation areas to less than 10%, which is the scientifically acceptable value in complex hydraulic studies.

## Discussion and Scientific Analysis:

### 1. Water Discharge Efficiency and Channel Capacity:

The hydraulic discharge efficiency in the Euphrates River is influenced by two primary factors. The first is the exceedingly mild hydraulic gradient ( $So$ ) of the region, which, according to Manning's equation, results in a reduction in flow velocity and transforms the river into a continuous sedimentary environment, thereby affecting its carrying capacity over time. The second factor is the localized effect of bridge piers, which act as physical obstructions that induce a transition in the flow regime to Rapidly Varied Flow (RVF). This generates backwater waves that elevate water levels by 35 cm upstream relative to the downstream, consequently heightening the probability of surface flooding due to the increased pressure head.

### 2. Flood Risk Assessment:

The results demonstrated that the utilization of two-dimensional simulation yields an analytical accuracy that significantly surpasses that of one-dimensional modeling. The model successfully provided an accurate representation of the lateral velocity field, tracked meandering flow trajectories, and identified "Stagnation Zones". This superiority stems from the capacity of the governing equations (Navier-Stokes) to capture spatial variations in two dimensions ( $x, y$ ), thereby mitigating uncertainty in the prediction of inundation boundaries.

### 3. Erosion Dynamics:

The concentration of high shear stress ( $Tw$ ) at sharp meanders constitutes the primary scientific explanation for the continuous geomorphological alterations in the course of the Euphrates River. The amplification of frictional forces and localized turbulence precipitates the formation of vortices that exacerbate the phenomena of scouring and bed erosion. Ultimately, this leads to the reshaping of the river's cross-section and the modification of its spatial characteristics over time.

## Proposed Recommendations:

- **Technical and Morphological Management:** The necessity of regularly conducting dredging and clearing operations in the Euphrates River channel to remove accumulated sediments and restore the hydraulic capacity of its critical sections.
- **Engineering Protection:** Reinforcing and strengthening protective earthen embankments (levees) in areas classified as "high-risk" based on the results of the simulation maps.
- **Proactive Modeling Management:** Integrating the two-dimensional numerical model with an Early Warning System to predict flood propagation paths based on the operational data of upstream dams.
- **Urban Planning:** Enforcing environmental and engineering legislations that prevent residential and agricultural encroachment within the river's buffer zone (right-of-way) and the specific areas designated in the inundation maps.

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## CITATION

Abdnoor, S. T. (2026). 2D Hydraulic Simulation for Assessing Water Discharge Efficiency and Flood Risk in the Euphrates River. *Global Journal of Research in Engineering & Computer Sciences*, 6(5), 47–52.  
<https://doi.org/10.5281/zenodo.23385458>



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