CHEMICAL ENGINEERING TRANSACTIONS
VOL. 114, 2024

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Min Zeng, Yee Van Fan, Xuechao Wang

ISBN 979-12-81206-12-0; **ISSN** 2283-9216

DOI: 10.3303/CET24114135

Importance of Eddy Viscosity and Advection in Hydrodynamical Models for Simulating Flash Floods on Steep Sloped Watersheds

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Flash floods in steeply sloped watersheds pose significant human life and infrastructure. Accurate prediction of these events relies on key parameters such as peak flow, time to peak flow, and the total overland flow volume. Numerical models are highly effective tools for predicting flash floods. The accuracy of hydrodynamic models is determined mainly by the solver equations used. Depth-integrated models offer various equation sets, with the full hydrodynamic equation providing the most detailed, though computationally intensive, solution. Eddy viscosity is another critical factor in simulating turbulent overland flow. Still, increased equation complexity leads to longer computational times and the need for smaller time steps to maintain model stability. Simulating turbulent overland flow in steep watersheds is particularly challenging because maintaining stability in these conditions is difficult. This study examined overland flow using artificial watersheds and model rainfall events, testing multiple solvers within the Hydrologic Engineering Center – River Analysis System (HEC-RAS). By keeping geometry, mesh, and rainfall inputs consistent, the study compared solver performance, identifying potential errors that arise under different conditions. Nonlinear advection, rather than gravity and roughness, was found to govern flow around obstructions. These findings are critical for improving the reliability of models that simulate the complex dynamics of flash floods, ultimately aiding in the reduction of risks posed by these hazardous events.

1. Introduction

Numerical simulation of flash floods on steeply sloped watersheds and natural channels presents significant challenges due to steep terrain, irregular distribution of obstructions, and the complex behavior of shallow turbulent flow. Calibration and mesh distribution in hydrodynamic models become intricate due to these factors. Various parameters such as gravity, turbulence, roughness inducts, and solver methods can significantly impact the hydrodynamic model results. The comparison of these parameters is still a gap in studies and engineering practice.

Flash flood-prone watersheds, often lacking hydrological data, necessitate using alternative methods like hydrodynamic depth-integrated models to accurately model flow behavior (Blöschl et al., 2013). The simulation of turbulent flow requires stable methods to capture flow dynamics precisely (Ámon et al., 2024). While fluid dynamic models offer various flow processes in hydraulic engineering, depth-integrated models are reasonable choices for smaller watersheds to simulate turbulent shallow flow (Ismailov et al., 2023). Methods that solve the full depth-averaged shallow water equations or closely approximate them are necessary (Huang et al., 2015). The accuracy of results improves as the numerical model better approximates the shallow water equations (SWE). Discrete solvers are based on the Reynolds-averaged Navier-Stokes (RANS) method (Yu and Duan, 2012). However, the presence of subcritical and supercritical flow regions necessitates careful consideration of stability, time steps, cell size adaptivity, and volume error during simulations, which is the focus of this research.

In modeling environments like HEC-RAS, different methods are available for solving or approximating shallow water equations. The local inertia (LIA) model, which neglects nonlinear advection, offers higher stability than

Paper Received: 20 May 2024; Revised: 1 August 2024; Accepted: 27 November 2024
Please cite this article as: Ámon G., Bene K., 2024, Importance of Eddy Viscosity and Advection in Hydrodynamical Models for Simulating Flash Floods on Steep Sloped Watersheds, Chemical Engineering Transactions, 114, 805-810 DOI:10.3303/CET24114135

the full equations. Despite its complexity, the LIA model has limitations compared to the full shallow water equations.

In steep watersheds, shallow flow is primarily governed by shear stress, transitioning to gravity dominance with increased steepness and lower turbulence. Achieving a balance between shear stress, slope, and gravity is crucial during simulation (Zhao and Liang, 2022), with the LIA method providing a reasonable approximation (Almeida and Bates, 2013). Large-eddy simulations (LES) can be employed where obstructions hinder proper eddy formations, adding complexity but enhancing simulation accuracy (Mehta et al., 2018).

The research compares multiple SWE solvers, specifically addressing the gap in the literature regarding the impact of nonlinear advection and turbulence on flow behavior in steep, flash flood-prone watersheds. While previous studies have focused on the accuracy of depth-integrated models and the limitations of simplified methods, this study incorporates LES to capture the complexities of turbulent flow around obstructions. It provides insights into the trade-offs between model stability and computational efficiency. The study developed a model watershed and channel bed to simulate overland and channel flow across varying slopes, incorporating obstructions to mimic meandering flow patterns. The primary objective was to evaluate the effects of advection and LES in capturing highly turbulent, shallow flows while identifying the strengths and limitations of different modeling approaches. Gaining a deeper understanding of these complexities is essential for the practical application of depth-integrated models in simulating flash floods accurately, particularly in smaller, steeply sloped watersheds. The results of this research will increase flash flood prediction accuracy, contributing to improved safety and more effective flood management strategies.

2. Methodology

This study comprehensively evaluated and compared four depth-integrated solvers designed for shallow water equations. Utilizing an artificial watershed featuring two slopes and obstructions, model simulations were performed to assess the performance of the solvers under a 60 min rainfall event. The results were compared based on the following key aspects:

- Analysis of flow behavior, including accurately representing eddy movements and comparing flow time series derived from overland flow simulations.
- Examination of volume errors to gauge the stability of the simulations and ensure reliable results.

2.1 Applied solvers

HEC-RAS provides different 2D methods for flow simulation. According to Huang et al. (2015), representing overland flow, highly turbulent flow requires full hydrodynamic calculations by the full 2D SWE. An alternative option is the local inertia approximation (LIA) model, a modified form of SWE that neglects nonlinear advection to enhance stability. A large eddy simulation component is added to the LIA model to capture turbulence effects. Surface shear stress significantly influences flow dynamics in watersheds with shallow water depths, necessitating heightened roughness calibration. The LES component in the model assumes high transversal and longitudinal mixing due to steep slopes, rough surfaces, and obstructions. While LES are sensitive to cell sizes, reducing them can lead to instability, highlighting the importance of stable calculations. Large eddy simulation proves beneficial for particle tracing in areas with high turbulence, walls, and obstructions (Montante and Paglianti, 2014). However, these models are sensitive to input parameters and model structures such as surface roughness, slope steepness, and mesh size. Additional simulations were performed: model 3 to assess potential overcomplexity issues and model 4 as a control calculation with reduced cell size (0.5x0.5 m) to address sensitivity around walls. Iteration steps are allowed in model 4 if the dynamic time step cannot be further lowered during the simulation process. The summary of the four simulations with the solver-type model cell size is shown in Table 1.

Table 1: Primary and additional simulations

Primary simulation			Additional control simulations		
No.	Solver	Cell size [m]	No.	Solver	Cell size [m]
1	Full SWE	1x1	3	Full SWE+LES	1x1
2	LIA+LES	1x1	4	LIA+LES smaller cells	0.5x0.5

2.2 Model summary

The experimental watershed is an artificially created rectangular area. In the middle is a trapezoid-shaped channel with a bed width of 5 m, a depth of 2 m, and side slopes of 1:1. The lower part of the watershed has a longitudinal slope of 5 %, while the upper region has a slope of 20 %. The cross-directional slopes are 5 % in

the lower part and 20 % in the upper region (Figure 1). The width of the area is 200 m, and each of the 5 % and 20 % sloped sections is 100 m long. Some obstructions are 1 m wide and 10 m long on both sides of the watershed. Additionally, there are obstructions in the channel bed, each 1 m wide and 4.5 m long (Figure 1). All obstructions are high enough to prevent overflow, forcing the flow to move around them.
An adaptive mesh, with cell sizes of 1x1 m, concentrated around the obstructions and break lines (such as the bed over banks and the bed's lowest points). Sections 1-1, 2-2, and 3-3 in Figure 1 are control sections where flow time series were evaluated.

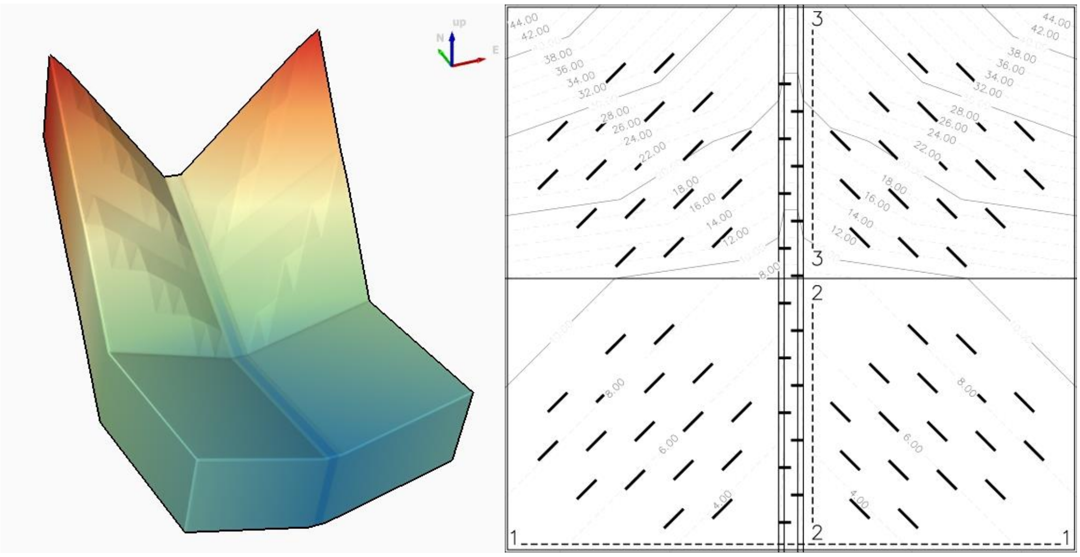

Figure 1: 3D view of the study area with 10x vertical scale (left) and the upper view with the obstruction placements and control cross sections (right)

The land use is uniform in the model area, with Manning's roughness coefficient of 0.06 applied to every cell. The high roughness value was applied to simulate a natural watershed in a forested area, ensuring the surface accurately represents a quasi-natural environment.

2.3 Boundary conditions

The watershed area is initially dry, and the channel is initially empty. For the duration of the simulation, a steady flow of 10 m^3/s is introduced at the inflow section of the channel. Concurrently, uniform rainfall occurs across the watershed. The rainfall distribution is linear, with its intensity peaking at 3/8 of the total rainfall duration, which is 60 min (Figure 2). At the outflow boundary, a friction slope of 0.05 is defined.

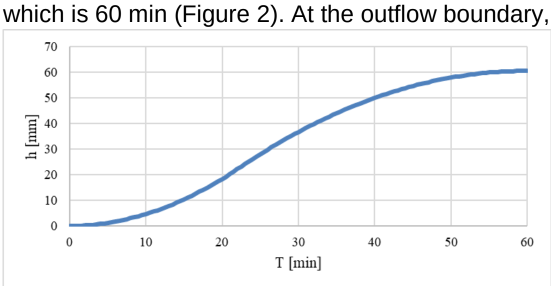

Figure 2: Artificial rainfall event's depth in 60 min

2.4 Time steps and stability

The numerical modeling process is sensitive to the time step, which can lead to numerical errors and a substantial number of iteration steps. No iterations were allowed during the simulation to ensure stability. The initial time step was set to 0.1 s. Dynamic adjustments to the time steps were made based on a Courant number criterion, ensuring the Courant value remained between 0.2 and 0.9. With these conditions, all the different solving methods remained stable.

3. Results

The effects of turbulent flow were examined through the outflow hydrograph, velocity distribution overland and around obstructions in the channel, and volume error. Figures 3 and 4 illustrate the differences in the outflow hydrograph (Q [m3/s]) at three different locations: at the outlet point (section 1-1) at the outflow of the steep slope (section 2-2), and the outflow of the milder slope (section 3-3).

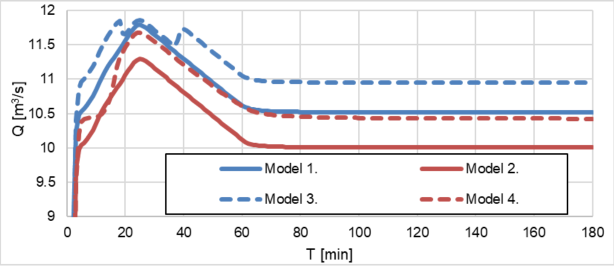

Figure 3: Flow time series at sections 1-1 (outflow)

Figure 3 shows the outflow hydrographs for the four models. Model 1 served as the baseline for comparison. In Model 1, after the recession limb flattens out, the outflow is slightly higher than the inflow following the rainfall, indicating a small volume error. In Model 2, the outflow characteristics are similar. Still, the predicted flows are lower by 0.5 m^3/s, and the final outflow value remains around 10 m^3/s, matching the steady inflow value. Model 3 exhibits two jumps in the outflow due to numerical errors, likely caused by the solver's overcomplexity. Model 4 shows intermediate results, with a smaller volume error than Model 1. Outflow hydrographs were compared at the outflow from 1-1 and 2-2 sections, as shown in Figure 4.

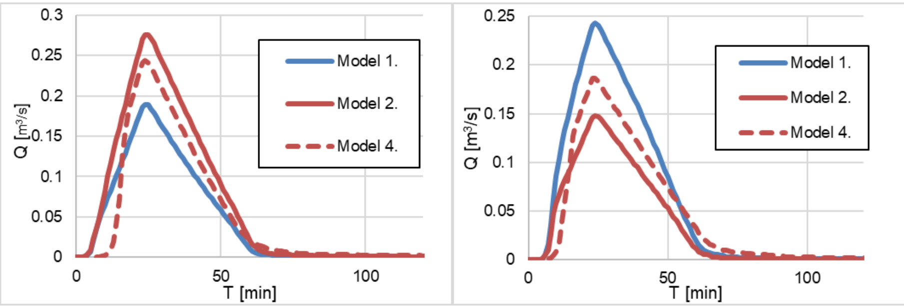

Figure 4: Rainfall inducted outflow time series a section 2-2, steep area (left) and section 3-3 steeper area (right)

The flow time series in sections 2-2 and 3-3 show flows originating solely from rainfall on one (Figure 4). The results of Models 1 and 3 were similar, and only Model 1 is shown in the graph. Model 2 shows a smaller peak flow in the steeply sloped area, but for steeper slopes (from 5 % to 20 %), Model 1 shows a higher peak. Model 4 produces results between Models 1 and 2, although closer to Model 2 in both areas. As the slope increases in the watershed, advection becomes more dominant in governing the flow's motion, resulting in a smaller peak flow. Additionally, Table 2. shows the volume error for the four model types.

Table 2: Volume error for the final investigated models

Simulation	Solver	Volume error [%]
1	SWE	4.968
2	LIA+LES	0.00006
3	SWE+LES	8.807
4	LIA+LES smaller cell	4.061

Model 2 resulted in zero errors. The error is around 4-5 % with Models 1 and 4; in Figure 3, these two hydrographs were also closest. The volume error at Model 3 was high, caused by the numerical errors. As the LES part increases its influence on the smaller cells (Model 4), not just the results but also the volume errors start getting closer, even without iterations.

Figure 5 shows the velocity distribution (color scale from 0-4 m/s) and particle tracing (white lines representing the motion of moving particles) on the overland and in the channel.

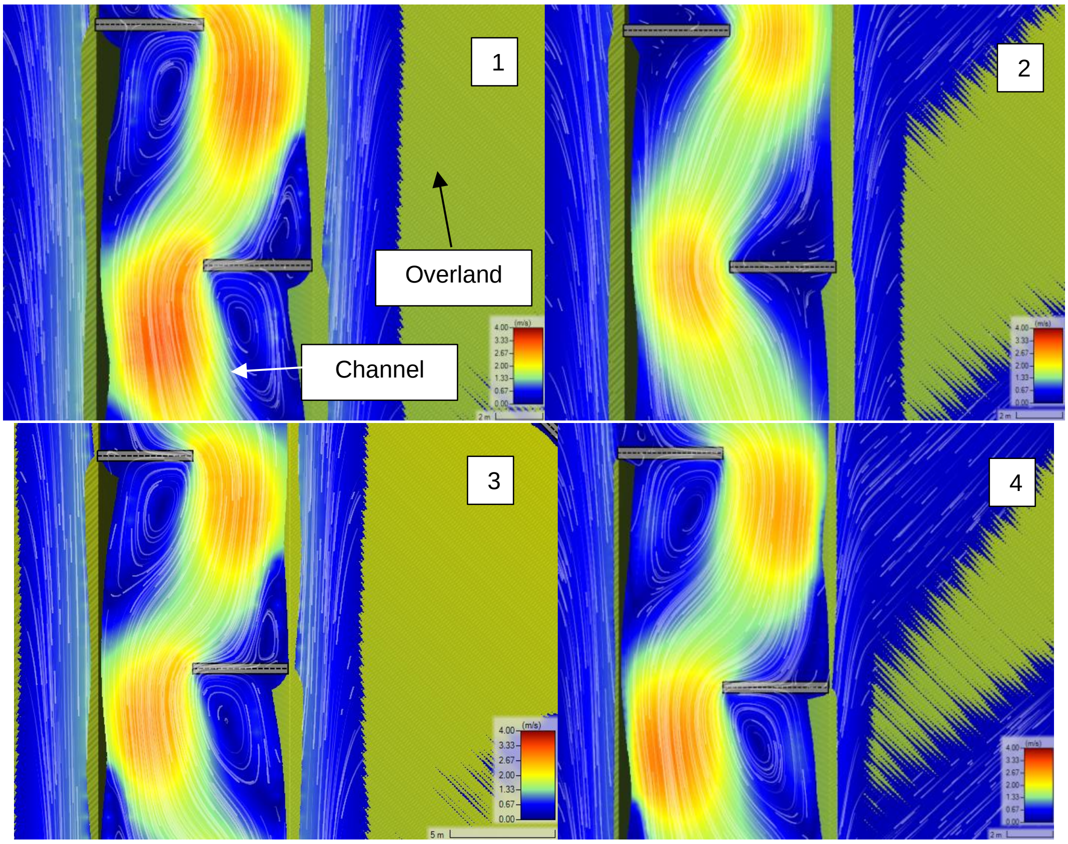

Figure 5: Velocity distribution (0-4 m/s) and particle tracing (white lines) around obstructions in bed and on the watershed, although the visualization shows that the overland flow on the side of the bed is specified more accurately with the LIA models

The velocity distribution and the appearance of eddy structures show that Model 1 gives the most realistic picture of the flow in the channel. At the same time, the approximation of overland does not appear visually correctly (Figure 5). Although the LIA+LES model (Model 2) gives more accurate results based on volume calculation, the eddy structures and channel flow are less refined. Particle tracing shows that the eddy structures created by the advection can be reproduced with LES using smaller cells (Model 4). Models 1 and 3 are less refined, and Models 2 and 4 are more detailed when comparing the velocity distribution on the overland.
Model 3 results can be neglected due to the numerical errors caused by overcomplexity. Model 4 shows the best distribution of shallow flow on the overland portion of the watershed visually and on flow time series. The particle tracing shows similar eddy movement, and the visualization shows similar velocity distribution in Model 4 and Model 1. Both parts, the proper representation of the overland flow and appropriate simulation of movement in bed around obstructions, make Model 4 the overall best working model from the four simulations.

4. Discussion

The study developed a model watershed and channel bed to simulate overland and channel flow on two slopes, incorporating obstacles to mimic meandering movements. The primary aim was to evaluate the advantages and disadvantages of four different solvers of the Shallow Water Equations (SWE) while examining the impact and effectiveness of large eddy simulations (LES) and advection simulations on highly turbulent and shallow flows within the watershed and channel bed. Findings revealed that highly turbulent flow within the channel bed generated circular flows around obstacles, both upstream (steep slope) and downstream (milder slope), driven by the nonlinear nature of the equations. Model 1 emerged as the most suitable for channel flow among the tested solvers, offering the most accurate hydraulic solution despite some volume errors. This model successfully captured the flow dynamics around obstructions with optimal complexity. Model 3 faced challenges related to its extreme complexity, leading to numerical errors, which could have been shown by comparing it with the other results. Also, Model 3 velocity field differs from Model 1 because of LES. The velocity distribution resembles better with Model 4.

On the other hand, Model 4 provided a reliable approximation of eddy movement and velocity distribution with smaller cell sizes, but nonlinear effects still induced volume errors. However, Model 4 seems to produce a reliable solution in this situation. The influence of surface roughness and gravity varied with slope steepness for shallow overland flow in the watershed. The study determined that Model 1 simulations were predominantly influenced by gravity for steeper slopes, whereas Models 2 and 4 (a simplified method) emphasized surface roughness. LES's impact on flow rate produced intermediary results, enhancing the visual representation of shallow flow.

5. Conclusion

The study highlights the inherent challenges in modeling turbulent and shallow flows using various SWE solvers. The principal implication drawn from the study is the potential appearance of volume errors around obstructions in the bed, where instead of gravity and roughness, the nonlinear advection governs the flow motion. It was also determined that the SWE simulation (Model 1) leaned towards gravity dominance for steeper slopes at overland shallow flow, while the simplified method (Model 2) continued to emphasize roughness. Additionally, the influence of the LES on flow rate displayed an intermediary outcome, offering an improved visual representation of the shallow flow. This research provides valuable insights into the behavior of flow dynamics in the presence of obstacles and varying slopes, helping future efforts in hydraulic modeling and simulation. It also enhances our understanding of complex flow interactions, which can lead to more effective flood mitigation measures and infrastructure planning.

Acknowledgments

The research presented in the article was carried out within the framework of the Széchenyi Plan Plus program with the support of the RRF 2.3.1 21 2022 00008 project.

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