JTAM (Jurnal Teori dan Aplikasi Matematika)
http://journal.ummat.ac.id/index.php/jtam
p-ISSN 2597-7512 | e-ISSN 2614-1175
Vol. 10, No. 3, July 2026, pp. 1090-1103

Development of Leapfrog-Hansen Numerical Model to Simulate One-Dimensional Dam-Break Flow

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Article History:
Received : 28-02-2026
Revised : 06-06-2026
Accepted : 08-06-2026
Online : 01-07-2026

Keywords:
Dam-break;
Finite-Difference;
Hansen Filter;
Leapfrog;
Numerical Model.

ABSTRACT

This study is a computational study aimed at developing and validating a numerical model for simulating one-dimensional dam-break flow. Dam construction, in addition to providing benefits to the community in terms of flood control, irrigation, and clean water sources, also carries the potential for disaster. Disasters can occur when dams fail or collapse. Dam failures can generate catastrophic flooding that threatens infrastructure, the environment, and human life. Therefore, numerical modeling is an important approach for understanding the characteristics of dam-break flow to support flood mitigation efforts following dam failure. The proposed model is developed using the Leapfrog finite-difference method, known for its simplicity. However, the conventional Leapfrog method is prone to numerical oscillations when handling discontinuities and shock waves in dam-break simulations. The novelty of this research lies in the development of a Leapfrog–Hansen numerical model for one-dimensional dam-break flow simulation by integrating the Hansen numerical filter into the conventional Leapfrog finite-difference scheme to improve stability while maintaining computational simplicity. The governing shallow water equations were solved using the proposed Leapfrog–Hansen model and applied to several hypothetical one-dimensional dam-break scenarios with varying downstream water depths. The performance of the developed model was evaluated by comparing its numerical simulation results with Stoker's analytical solution, which is often used as a benchmark in numerical modeling of one-dimensional dam-break flow. The comparison results show that the Leapfrog–Hansen model accurately reproduces the water surface profiles predicted by the analytical solution. The Leapfrog-Hansen model yielded relatively small Mean Absolute Error (MAE) values of 0.032 to 0.062, indicating high accuracy in reproducing dam-break flows. In addition, the developed model successfully reduces numerical oscillations in the conventional Leapfrog scheme and accurately captures flow discontinuities, shock-wave propagation, and wet-dry conditions, while maintaining simulation stability. These findings demonstrate that the proposed Leapfrog–Hansen model provides a simple, stable, and accurate alternative for simulating one-dimensional dam-break flows and has potential applications in flood-propagation analysis, preliminary dam-break hazard assessment, and other hydraulic studies related to flood risk mitigation.

https://doi.org/10.31764/jtam.v10i3.38595

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A. INTRODUCTION

Dams are infrastructure built to provide benefits to society, such as providing clean water, generating hydroelectric power, supplying irrigation water, and controlling flooding (Mellivera et al., 2020; Mirauda et al., 2020; Simsek & Islek, 2023). However, these benefits also carry the potential for severe risks and disasters when a dam collapses, either partially or completely

(Qian et al., 2018). Several factors, including earthquakes, structural failure, or planning errors, can cause such collapses (Harlan et al., 2019; Zendrato et al., 2019). When a dam fails, the large volume of water it holds is suddenly released, triggering devastating flooding downstream (Latrubesse et al., 2020).

Floods resulting from dam failure, or dam-break flows, are complex because they involve flow discontinuities, rapid water-level changes, and shock waves (Gu & Lai, 2026; M. Zhang & Wu, 2011). Furthermore, these flows are characterized by high propagation velocities, which severely limit evacuation times. Dam-break flow is also destructive, causing economic losses, infrastructure damage (Harlan et al., 2019; Yakti et al., 2018), loss of life (Dai et al., 2025; Huang et al., 2017; Mellivera et al., 2020), and environmental damage (Zendrato et al., 2019; Y. Zhang et al., 2022) if not properly addressed. Based on this, an efficient and accurate tool is needed to study dam-break flow behavior for mitigation planning.

One widely used approach to studying dam-break flow behavior is numerical modeling (Issakhov & Imanberdiyeva, 2019; Ravena Maitsa et al., 2020; Simsek & Islek, 2023). Compared to physical laboratory models, numerical models offer several advantages, including cost and time efficiency (Magdalena et al., 2021; Rehman & Cho, 2019; Zendrato et al., 2019). Numerical models also allow faster analysis and broader domain coverage than laboratory experiments. These advantages make numerical models an appropriate tool for analyzing flooding caused by dam failures or dam-break flow.

Several previous studies have developed numerical models to simulate dam-break flow using various methods, including the finite-difference method (Adityawan et al., 2023; Hafiyyan et al., 2023; Mellivera et al., 2020; Pratama et al., 2025; Putri et al., 2020). This method is widely used for its algorithmic simplicity (Magdalena et al., 2020; Magdalena & Eka Pebriansyah, 2022), making it easy to implement across a variety of flow scenarios. Several researchers have applied the finite-difference method to simulate dam-break flow in both wet and dry bed conditions (Hafiyyan, Adityawan, et al., 2021; Magdalena & Eka Pebriansyah, 2022). However, finite-difference models still suffer from weaknesses, such as instability and numerical oscillations, when handling shock waves and flow discontinuities (Mellivera et al., 2020; Tseng & Chu, 2000; Zendrato et al., 2019). These weaknesses also reduce the accuracy of finite-difference model simulations.

In addition to the finite-difference method, previous research has widely used the finite-element (Hafiyyan, Harlan, et al., 2021; Mao et al., 2016) and finite-volume methods (Magdalena et al., 2024; Salamttalab et al., 2023; Wang et al., 2011) to simulate dam-break flow. Both methods are known to handle flow discontinuities well and maintain numerical stability (Hafiyyan, Adityawan, et al., 2021; Liu et al., 2013; Zendrato et al., 2019). However, these methods generally require more complex computational algorithms than the finite-difference method (Magdalena & Eka Pebriansyah, 2022). This complexity makes the finite-element and finite-volume methods difficult to implement. Furthermore, algorithmic complexity also increases computational costs. Therefore, developing finite-difference models with simple algorithms that provide stable, accurate solutions remains a key topic in dam-break flow simulation.

One explicit finite-difference method with a relatively simple algorithm is the Leapfrog method. This method uses a central-difference approach to solve the spatial and temporal derivatives of a governing equation (Iserles, 1986; Sukhinov et al., 2020), achieving a fairly good level of accuracy. However, the Leapfrog method is susceptible to numerical oscillations when used to model flows with sharp gradient changes, such as dam-break flow. To address this issue, the Leapfrog method requires a stabilizer that dampens numerical oscillations without significantly compromising model accuracy. One such stabilizer is the Hansen numerical filter. With a relatively simple algorithm, the Hansen filter has been shown to improve the stability of numerical models (Harlan et al., 2019; Mellivera et al., 2020; Putri et al., 2020).

Based on the description above, this study aims to develop a simple alternative numerical model that accurately and stably simulates one-dimensional dam-break flow. Model development is carried out by combining the Leapfrog finite-difference method with the Hansen numerical filter as a stabilizer. The developed Leapfrog-Hansen model is expected to provide stable and accurate solutions without compromising the main advantage of the finite-difference method, its simplicity. In addition, the developed model is expected to serve as an alternative tool for accurately representing dam-break flow behavior and to support flood mitigation efforts following dam failure.

B. METHODS

1. Governing Equation

This study is a computational study focused on developing a numerical model based on the finite-difference method to simulate dam-break flow in a one-dimensional domain. The model was developed using the shallow-water equation as the governing equation. Many researchers have utilised the shallow water equations to simulate dam-break flows (Ferrari et al., 2023; Holzbecher, 2022). These equations are derived from the Navier-Stokes equation. The shallow water equations comprise the continuity and momentum equations. For one-dimensional cases, the shallow water equation can be expressed in vector form under the assumption that factors such as wind force, Coriolis force, and turbulence effects are ignored.

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{F}}{\partial x} = \boldsymbol{S} \tag{1}$$

where $\boldsymbol{U}$ is the unknown (conserved) variable vector, $\boldsymbol{F}$ is the flux vector representing transport of mass and momentum, and $\boldsymbol{S}$ is source-term vector accounting for external effects such as bed slope and friction. These vectors are defined as

$$\boldsymbol{U} = \begin{Bmatrix} h \\ hu \end{Bmatrix};\ \boldsymbol{F} = \begin{Bmatrix} hu \\ hu^2 + \frac{1}{2}gh^2 \end{Bmatrix};\mathbf{S} = \begin{Bmatrix} 0 \\ gh(\,S_o - S_f\,) \end{Bmatrix} \tag{2}$$

In shallow water equations, h represents flow depth, u represents flow velocity, S_o represents bed slope, and S_f represents the friction slope. The friction slope can be calculated using the Manning equation as follows.

$$S_f = \frac{q^2 n^2}{h^{\frac{10}{3}}} \tag{3}$$

where n denotes the Manning roughness coefficient and $q = hu$ represents the unit width discharge. Then, the channel bed slope, So, can be obtained using the following equation:

$$So = -\frac{dz}{dx} \tag{4}$$

where z is the channel bed elevation.

2. Leapfrog Method

The Leapfrog method is an explicit finite-difference method for solving differential equations, particularly for time-dependent problems such as dam-break flow. The name "leapfrog" comes from the method's approach to solving time derivatives. The Leapfrog method uses a central difference approach to handle spatial and temporal derivatives, achieving second-order accuracy. The spatial and temporal derivatives in equation (1) are discretized using the central difference approach, as shown in equations (5) and (6).

$$\frac{\partial \boldsymbol{U}}{\partial t} = \frac{\boldsymbol{U}_i^{t+1} - \boldsymbol{U}_i^{t-1}}{2\Delta t} \tag{5}$$

$$\frac{\partial \boldsymbol{U}}{\partial x} = \frac{\boldsymbol{U}_{i+1}^{t} - \boldsymbol{U}_{i-1}^{t}}{2\Delta x} \tag{6}$$

where t+1 represents the state of the variable at the next time step, t represents the state at the current time step, t−1 represents the state at the previous time step, Δt represents the time step, and Δx represents the spatial step. When equations (5) and (6) are substituted into the governing equation, the following new equation is obtained.

$$\frac{\boldsymbol{U}_i^{t+1} - \boldsymbol{U}_i^{t-1}}{2\Delta t} + \frac{\boldsymbol{F}_{i+1}^{t} - \boldsymbol{F}_{i-1}^{t}}{2\Delta x} = \boldsymbol{S}_i^t \tag{7}$$

Multiplying equation (7) by 2Δt and rearranging the equation yields the following:

$$\boldsymbol{U}_i^{t+1} = \boldsymbol{U}_i^{t-1} - \frac{\Delta t}{\Delta x}(\boldsymbol{F}_{i+1}^{t} - \boldsymbol{F}_{i-1}^{t}) + 2\Delta t \boldsymbol{S}_i^t \tag{8}$$

Expanding the vector form yields the following continuity equation.

$$h_i^{t+1} = h_i^{t-1} - \frac{\Delta t}{\Delta x}((hu)_{i+1}^t - (hu)_{i-1}^t) \tag{9}$$

Meanwhile, the momentum equation is as follows:

$$\begin{aligned}(hu)_i^{t+1} = (hu)_i^{t-1} - \frac{\Delta t}{\Delta x}\left(\left(hu^2 + \frac{1}{2}gh^2\right)_{i+1}^t - \left(hu^2 + \frac{1}{2}gh^2\right)_{i-1}^t\right) \\ + 2\Delta t\left(-gh(S_o - S_f)\right)_i^t\end{aligned} \tag{10}$$

If the channel is assumed to be flat and frictionless, equation (10) can be simplified as follows.

$$(hu)_i^{t+1} = (hu)_i^{t-1} - \frac{\Delta t}{\Delta x}\left(\left(hu^2 + \frac{1}{2}gh^2\right)_{i+1}^t - \left(hu^2 + \frac{1}{2}gh^2\right)_{i-1}^t\right) \tag{11}$$

The numerical parameters used in this model are the time step size (Δt) and the spatial step (Δx). In numerical modeling, these two parameters will affect the stability and accuracy of the modeling results. Therefore, this study will select a combination of Δt and Δx by trial and error to produce a stable, accurate simulation.

3. Hansen Filter

In this study, a Hansen numerical filter is incorporated as an artificial dissipation mechanism. Its primary purpose is to reduce numerical oscillations and enhance the computational stability of the Leapfrog-Hansen Model. One of the key advantages of the Hansen filter is its algorithmic simplicity. The Hansen filter employs an equation to update a flow parameter on each computational node at every simulation time step. The equation can be expressed as follows.

$$\boldsymbol{U}_{filter} = C \cdot \boldsymbol{U}_i + (1 - C)\left(\frac{\boldsymbol{U}_{i+1} + \boldsymbol{U}_{i-1}}{2}\right) \tag{12}$$

with C is the Hansen correction factor which has a value from 0 to 1, $\boldsymbol{U}$ is a the unknown variable vector (depth and flow velocity) before filtering, and $\boldsymbol{U}_{filter}$ is the filtered unknown variable vector. In this study, a Hansen correction factor of 0.99 is applied. Previous research has demonstrated that this value enhances model stability (Hafiyyan, Adityawan, et al., 2021; Harlan et al., 2019; Mellivera et al., 2020).

4. Simulation Setup

In this study, the developed Leapfrog model was used to simulate a hypothetical one-dimensional dam-break flow. In this case, the dam failure was assumed to occur completely and suddenly, with the dam located at the center of the computational domain. The computational domain for this case was a 2,000-m-long straight channel with no slope or friction (n=0). The boundary condition applied in this simulation was a slip boundary condition, meaning no flow enters or exits through the channel walls. The initial simulation conditions were assumed to be still water. The upstream water depth (h_u) was set at 10 meters, while the downstream water depth (h_d) varied between 5 m, 1 m, and 0.0001 m (as shown in Figure 1). These variations were used to represent conditions ranging from a wet bed to a near-dry bed. Simulation results obtained using the Leapfrog-Hansen model were then compared with Stoker's analytical solution and other numerical results to evaluate the accuracy and performance of the developed model.

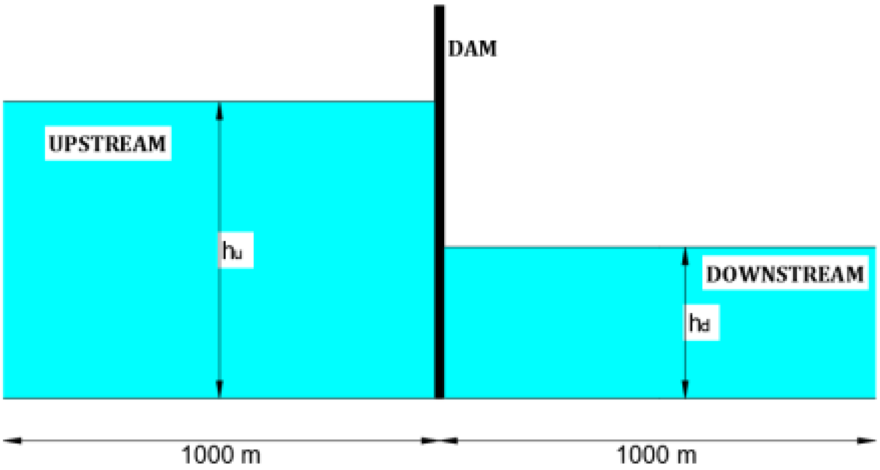


Figure 1. Initial Condition

5. Model Validation and Performance Evaluation

In this study, model validation was conducted by comparing the Leapfrog-Hansen model's simulation results with Stoker's analytical solution. Stoker's solution is an exact solution commonly used as a reference for assessing a model's ability to represent one-dimensional dam-break flow phenomena in frictionless flat channels. The variable being compared is the flow depth (h) at a specific simulation time. Quantitatively, model accuracy was evaluated using the Mean Absolute Error (MAE), defined as the average absolute difference between the numerical model results and the analytical solution at all computational points. The Mean Absolute Error value is calculated using equation (13). The smaller the Mean Absolute Error, the better the agreement between the numerical and analytical solutions, indicating greater model accuracy in simulating one-dimensional dam-break flow.

$$\mathrm{MAE} = \frac{1}{\mathrm{N}} \sum_{i=1}^{N} \left| h_{numerical} - h_{analytical} \right| \tag{13}$$

where $h_{numerical}$ represents the depth of the numerical solution flow, $h_{analytical}$ represents the depth of the analytical solution flow, and N represents the number of computation points.

In addition to quantitative analysis, model evaluation was conducted qualitatively through a visual comparison of the simulation results from the proposed model and Stoker's analytical solution. This evaluation was conducted by comparing water surface profiles at specific simulation times. Through this approach, the proposed model's ability to reproduce dam-break flow characteristics, such as propagation, can be visually evaluated. The model performance was then analysed based on the level of conformity of the water surface profile to the analytical solution, the Mean Absolute Error value obtained in each scenario, and the ability of the proposed model to produce a stable solution without significant numerical oscillations. Thus, the evaluation of the proposed model was carried out not only by considering the magnitude of the numerical error but also by assessing its ability to reproduce the dam-break flow stably and accurately.

C. RESULT AND DISCUSSION

The comparative results of the 1D dam-break flow simulation using the Leapfrog-Hansen model and Stoker's analytical solution for various downstream water depths are presented in Figures 2 to 4. Figure 2 also compares the Leapfrog-Hansen model's simulation results with those of the conventional Leapfrog model. Based on these figures, the Leapfrog-Hansen model produces water surface profiles that are very close to the analytical solution and superior to those of the conventional Leapfrog model. Furthermore, the Hansen filter in the Leapfrog-Hansen model successfully reduces the numerical oscillations that occur in the conventional Leapfrog model.

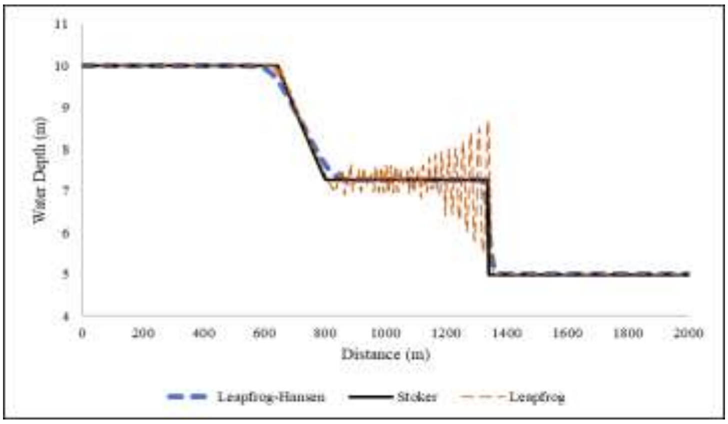


Figure 2. Water surface profile for h_d = 5 m at simulation time 7.2 s (Δt = 0.003 s; Δx = 4 m)

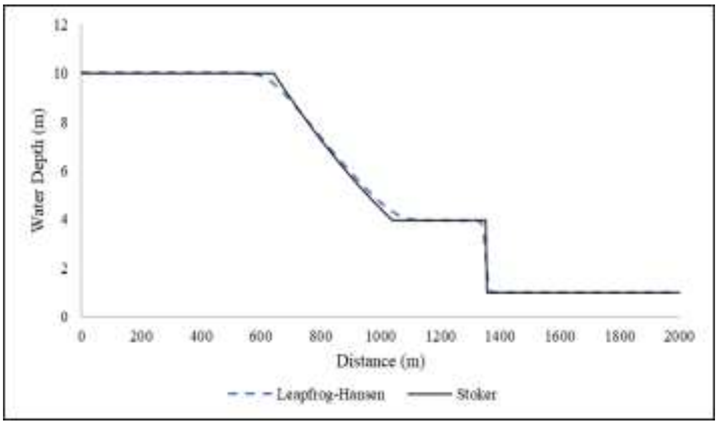


Figure 3. Water surface profile for h_d = 1 m at simulation time 7.2 s (Δt = 0.002 s; Δx = 4 m)

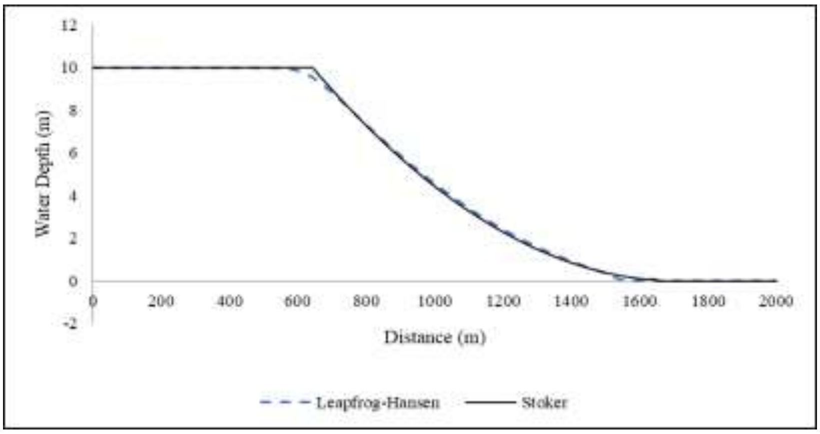


Figure 4. Water surface profile for hd = 0.0001 m at simulation time 7.2 s (Δt = 0.001 s; Δx = 4 m)

Furthermore, Tables 1 until 3 present the Mean Absolute Error (MAE) values for the Leapfrog and Leapfrog-Hansen models under various downstream water depth conditions. The MAE values for h_d = 5m, h_d = 1m, and h_d = 0.0001m conditions are 0.032, 0.055, and 0.062, respectively. These values are smaller than the MAE values of the Leapfrog model in all test scenarios. This finding indicates that applying the Hansen filter consistently improves model accuracy across a range of hydraulic conditions in one-dimensional dam-break flow. The increased accuracy of the Leapfrog-Hansen model solution is due to the Hansen filter's ability to damp numerical oscillations that often occur in the Leapfrog scheme, thereby improving the numerical solution. By reducing these unwanted numerical oscillations, the Leapfrog-Hansen model produces a more stable solution that is closer to the analytical solution.

Table 1. Absolute Error of The Leapfrog Model and Leapfrog Hansen Model for h_d = 5m

x	Stoker's Solution	Leapfrog Model	Leapfrog-Hansen Model	Absolute Error	
				Leapfrog Model	Leapfrog-Hansen Model
0	10.000	10.000	10.000	0.000	0.000
4	10.000	10.000	10.000	0.000	0.000
⋮	⋮	⋮	⋮	⋮	⋮
660	9.693	9.572	9.476	0.121	0.217
664	9.619	9.733	9.429	0.114	0.191
668	9.546	9.532	9.380	0.014	0.166
672	9.473	9.490	9.330	0.017	0.143
676	9.400	9.518	9.280	0.118	0.121
680	9.328	9.275	9.228	0.053	0.100
684	9.256	9.412	9.175	0.156	0.081
688	9.184	9.191	9.121	0.007	0.063
692	9.113	9.168	9.067	0.055	0.046
696	9.041	9.184	9.012	0.142	0.030
700	8.970	8.952	8.956	0.019	0.014
704	8.900	9.043	8.901	0.143	0.001
708	8.829	8.907	8.844	0.078	0.015
712	8.759	8.776	8.788	0.017	0.029
716	8.689	8.857	8.731	0.168	0.042
⋮	⋮	⋮	⋮	⋮	⋮
1996	5.000	5.000	5.000	0.000	0.000
2000	5.000	5.000	5.000	0.000	0.000
		MAE		0.110	0.032

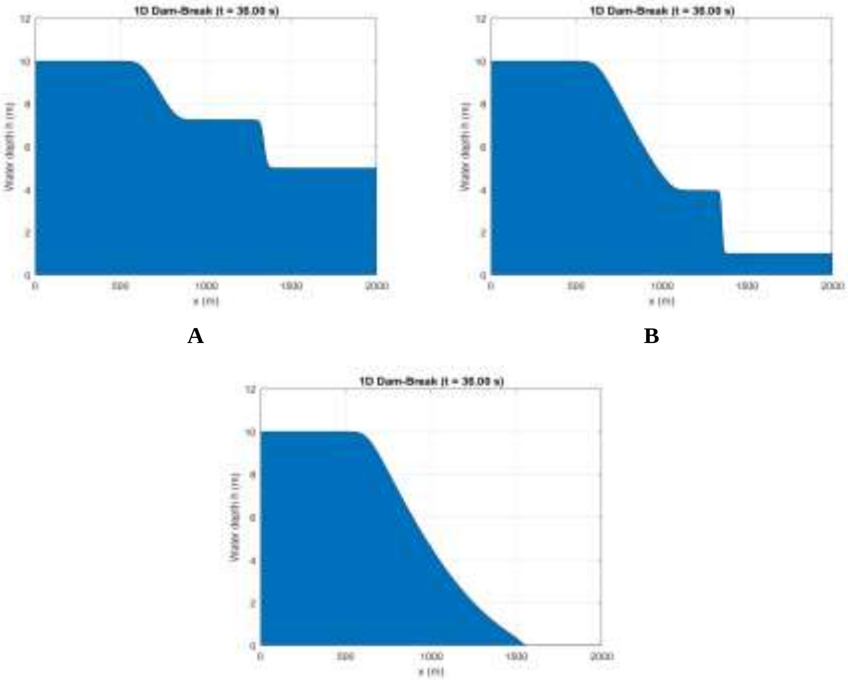
Table 2. . Absolute Error of The Leapfrog-Hansen Model for h_d = 1 m

x	Stoker's Solution	Leapfrog-Hansen Model	Absolute Error
0	10.000	10.000	0.000
4	10.000	10.000	0.000
8	10.000	10.000	0.000
⋮	⋮	⋮	⋮
608	10.000	9.832	0.168
612	10.000	9.808	0.192
616	10.000	9.781	0.219
620	10.000	9.753	0.247
624	10.000	9.723	0.277
628	10.000	9.690	0.310
632	10.000	9.656	0.344
⋮	⋮	⋮	⋮
1992	1.000	1.000	0.000
1996	1.000	1.000	0.000
2000	1.000	1.000	0.000
		MAE	0.055

Table 3. Absolute Error of The Leapfrog-Hansen Model for Wet-Dry Condition (h_d = 0.0001m)

x	Stoker's Solution	Leapfrog-Hansen Model	Absolute Error
0	10.000	10.000	0.000
4	10.000	10.000	0.000
8	10.000	10.000	0.000
⋮	⋮	⋮	⋮
628	10.000	9.687	0.313
632	10.000	9.652	0.348
636	10.000	9.616	0.384
640	10.000	9.577	0.423
644	9.989	9.537	0.453
648	9.915	9.495	0.420
652	9.841	9.451	0.389
⋮	⋮	⋮	⋮
1992	0.0001	0.0001	0.000
1996	0.0001	0.0001	0.000
2000	0.0001	0.0001	0.000
		MAE	0.062

This study also found that variations in downstream water depth significantly influence the characteristics of the dam-break flow (Figure 5). Changing the downstream water depth from 5 m to 0.0001 m increases the h_u/h_d ratio. As this ratio increases, the potential energy difference between the upstream and downstream sides of the dam also increases. As a result, waves propagate faster, and the wave front moves further downstream. This condition is clearly visible in the downstream water depth (h_d) scenario of 0.0001 m, which produces the longest wave propagation among the three scenarios. In the h_d = 0.0001m scenario, which represents the wet-dry condition, the Leapfrog-Hansen model still produces a stable solution without significant numerical oscillations. These results indicate that the proposed model can handle sharp discontinuities between upstream and downstream areas, which is a major challenge in dam-break flow modeling.



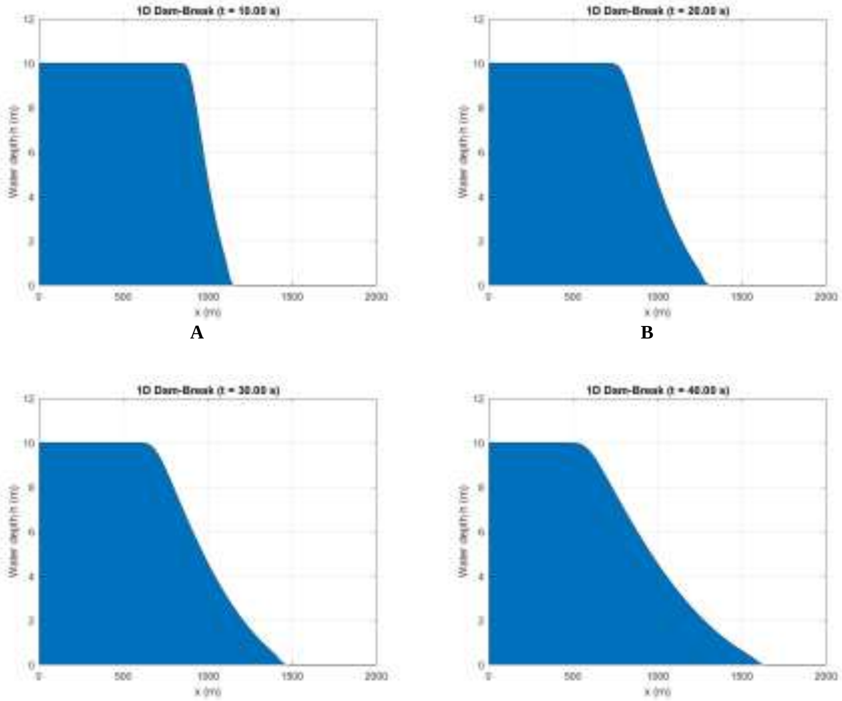
A

B

C

Figure 5. Dam-Break Flow for h_d (A) 5m (B) 1m (C) 0.0001m at t = 36s

In this study, the evolution of the water surface profile at several simulation times is presented in Figure 6. The figure shows that as time increases, the wave front moves downstream while the water level in the upstream area decreases. This phenomenon indicates the formation of positive waves propagating downstream and negative waves propagating upstream. The success of the Leapfrog-Hansen model in reproducing both types of waves indicates that it can capture the physical phenomena in dam-break flow.



A

B

C

D

Figure 6. Dam-Break Flow During Simulation Time (A) 10s (B) 20s (C) 30s (D) 40s

The results of this study indicate that the developed Leapfrog-Hansen model produces water surface profiles that are very close to the analytical solution, with a relatively small MAE across all test scenarios. This finding aligns with the study by previous researchers (Harlan et al., 2019; Maitsa et al., 2021; Mellivera et al., 2020; Putri et al., 2020), which shows that applying a numerical filter can reduce numerical oscillations and increase model stability. In addition, the proposed model maintains simulation stability under wet-dry conditions, supporting the study by Magdalena & Eka Pebriansyah (2022), which emphasizes the importance of handling wet-dry conditions in dam-break simulations. The good agreement between the numerical simulation results and the analytical solution in this study is also consistent with the findings of Seyedashraf & Akhtari (2017), Hafiyyan, Adityawan, et al. (2021), and Magdalena et al. (2020), which show that a stable and accurate numerical model can reproduce the characteristics of dam-break flow. However, unlike those studies that used finite-element and finite-volume schemes, this study developed a combination of the Leapfrog method and the Hansen filter for one-dimensional dam-break flow simulation. Thus, the results of this study not only support previous studies on the importance of model stability in dam-break flow modeling but also demonstrate that the developed Leapfrog-Hansen model can serve as a simple alternative for producing stable, accurate one-dimensional dam-break flow simulations.

D. CONCLUSION AND SUGGESTIONS

In this study, a numerical model has been successfully developed to simulate one-dimensional dam-break flow. The developed model combines the Leapfrog finite-difference scheme with the Hansen filter to improve model stability while maintaining algorithmic simplicity. The comparison of water surface profiles with Stoker's analytical solution showed that the developed model can stably and accurately reproduce the characteristics of dam-break flow under various downstream water-depth conditions. The good accuracy of the Leapfrog-Hansen model is seen in the relatively small Mean Absolute Error (MAE) values, which range from 0.032 to 0.062. In addition, the Leapfrog–Hansen model can capture flow discontinuities, shock wave propagation, and wet-dry conditions well without producing excessive numerical oscillations. The findings in this study indicate that applying the Hansen filter to the conventional Leapfrog scheme can improve numerical stability while preserving the method's computational simplicity. Thus, this study contributes to the development of a finite-difference method-based numerical model for dam-break flow simulation and offers a simple, stable, and accurate alternative model for analyzing flood propagation due to dam failure.

The Leapfrog–Hansen model developed in this study needs to be further applied to more complex and realistic hydraulic conditions. The simulations in this study are limited to a hypothetical one-dimensional dam-break flow case, assuming a flat channel bed without slope or friction. They are validated only against Stoker's analytical solution. Therefore, further research can be conducted by considering the effects of friction and complex topography, developing a two-dimensional model, and validating it using experimental and field data. With these developments, the performance of the Leapfrog–Hansen model to support the understanding of dam-break flow characteristics and dam failure mitigation can be evaluated more comprehensively.

ACKNOWLEDGEMENT

This research is supported by DIPA Polnep 2025.

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