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A Unique Volume Balance Approach for Verifying the Three-Dimensional Hydrodynamic Numerical Models in Surface Waterbody Simulation

Hussein A.M. Al-Zubaidi and Scott A. Wells

Abstract

The hydrodynamic numerical modeling is increasingly becoming a widely used tool for simulating the surface waterbodies including rivers, lakes, and reservoirs. A challenging step in any model development is the verification tests, especially at the early stage of development. In this study, a unique approach was developed by implementing the volume balance principle in order to verify the three-dimensional hydrodynamic models for surface waterbody simulation. A developed and verified three-dimensional hydrodynamic and water quality model, called W3, was employed by setting a case study model to be verified using the volume balance technique. The model was qualified by calculating the error in the accumulated water volume within the domain every time step. Results showed that the volume balance reached a constant error over the simulation period, indicating a robust model setup.

Keywords: hydrodynamic model, lakes and reservoirs, model verification, model simulation, numerical model, volume balance, water quality modeling, W3 model

1. Introduction

Many 3D hydrodynamic and water quality models have been developed since the 1960s, and different numerical solution techniques have been used to solve the governing equations. The most popular numerical models and the basis that other models has been built based on are POM [1, 2], ECOM [1, 3], NCOM [4, 5], FVCOM [6, 7], EFDC [8], TRIM-3D [9], UnTRIM [10], GLLVHT [11], and DNS [12].

During the development stage of any numerical model, verification tests need to be performed to ensure that model foundations are valid. The 3D simulation models available in market have been tested either by comparing the predictions with the analytical solution, field data, or both. As a result, each verification approach has its advantages and disadvantages depending on the model complexity (governing equations used to develop the model and assumptions used to simplify the problem).

All three-dimensional models available to simulate surface waterbodies do not have outputs related to the model of volume balance performance (see the user manuals of the above popular models). Therefore, the user does not know the model preserves volume or not during the simulation period even though the model gives results. In addition, most 3D users run the simulation for a very short time (even for seconds), thinking the model is stable, since the 3D numerical models require long computation time to run. Thus, the need to develop a new volume balance tool arises based on these issues related to 3D hydrodynamic numerical models used in practice for surface waterbodies.

In this work, the volume balance approach was used as a tool to measure how a model preserves volume during the simulation time by calculating the accumulated error over time as a percent. Therefore, the modeler can monitor the model performance over time and decide whether the model is robust or not while running the model rather than waiting until the end of simulation.

2. Methods

To implement the volume balance approach, the three-dimensional model W3 developed by [13] for modeling hydrodynamics, temperature, and water quality in surface waterbodies was employed. Using the finite differences, the model solves the governing equations of continuity, free surface, momentums, and mass transport. Comparisons with analytical solutions and field data were carried out for verifying and validating the W3 model [13–17].

The model of volume balance was performed by comparing the water volume in the model domain during a time period with the water volume entering and leaving the same domain during the same period of time.

Let Vol be the accumulated water volume in the model domain over time. Then,

$$\text{Vol} = \text{Vol}_{\text{initial}} + \text{Vol}_{\text{in}} - \text{Vol}_{\text{out}} \quad (1)$$

where $\text{Vol}_{\text{initial}}$ = the initial water volume within the domain; Vol_{in} = the accumulated water volume entering the domain; and Vol_{out} = the accumulated water volume leaving the domain.

Thus, the error over time can be calculated as follows:

$$\% \text{Error} = (\text{abs}(\text{Vol} - \text{Vol}_{\text{internal}})) / \text{Vol}_{\text{internal}} \times 100 \quad (2)$$

where $\text{Vol}_{\text{internal}}$ is the water volume within the domain at any time during the simulation period.

A subroutine was added to the model to check the volume preservation by calculating % error at every time step. A lower % error represents more accurate model predictions. The error should reach a constant value with time and should not grow with time. If % error grows with time exponentially, this implies that the model goes unstable (blows up). Two tests implementing the volume balance check were performed. One of these tests examined the volume balance over a rectangular domain, and the other tests evaluated the volume balance over an irregular domain. Both tests were performed over a period of 100 days based on the same real meteorological data, calculated solar short radiation, and constant inflow and outflow. The meteorological data are shown in **Figures 1–5**.

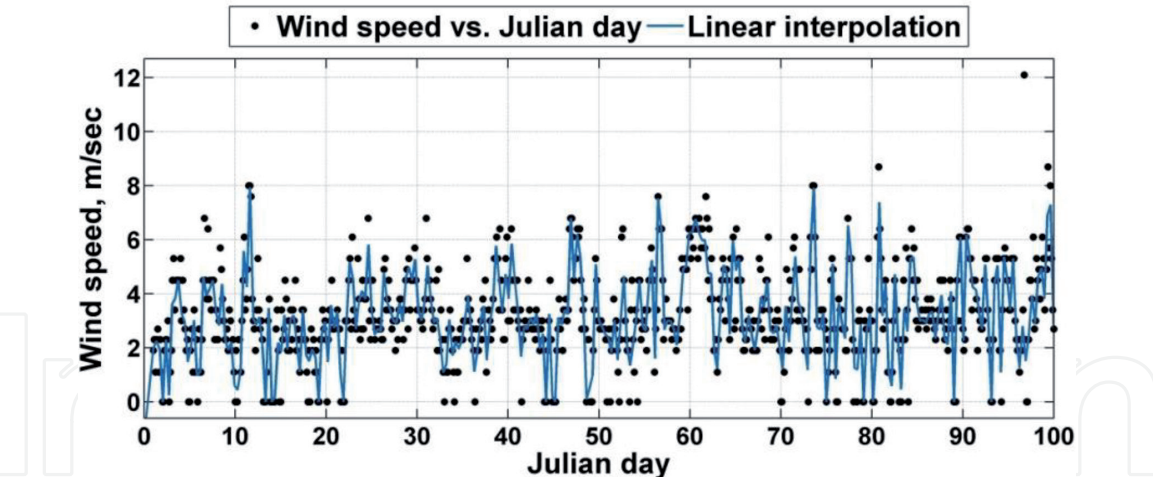


Figure 1.
Wind speed input data.

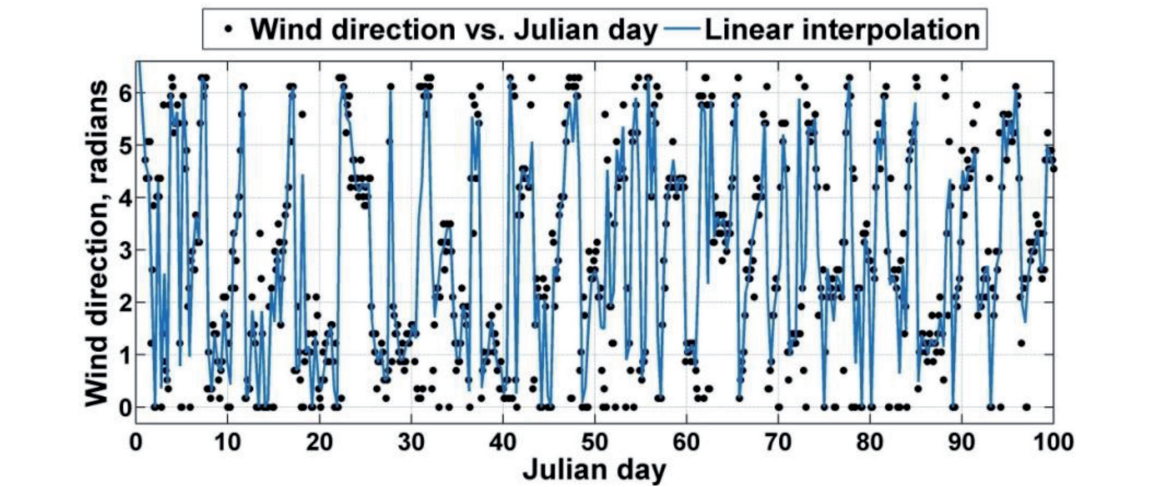


Figure 2.
Wind direction input data.

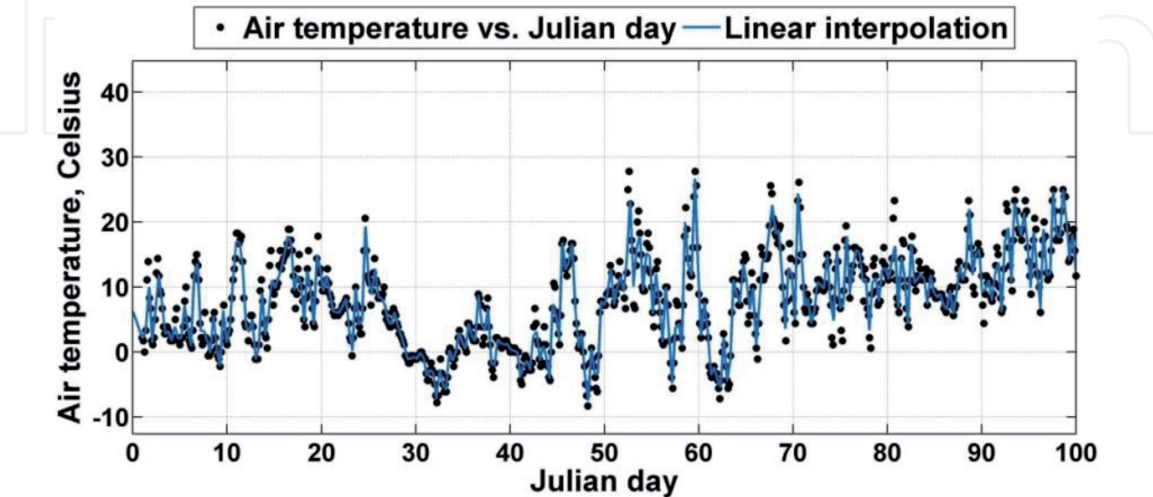


Figure 3.
Air temperature input data.

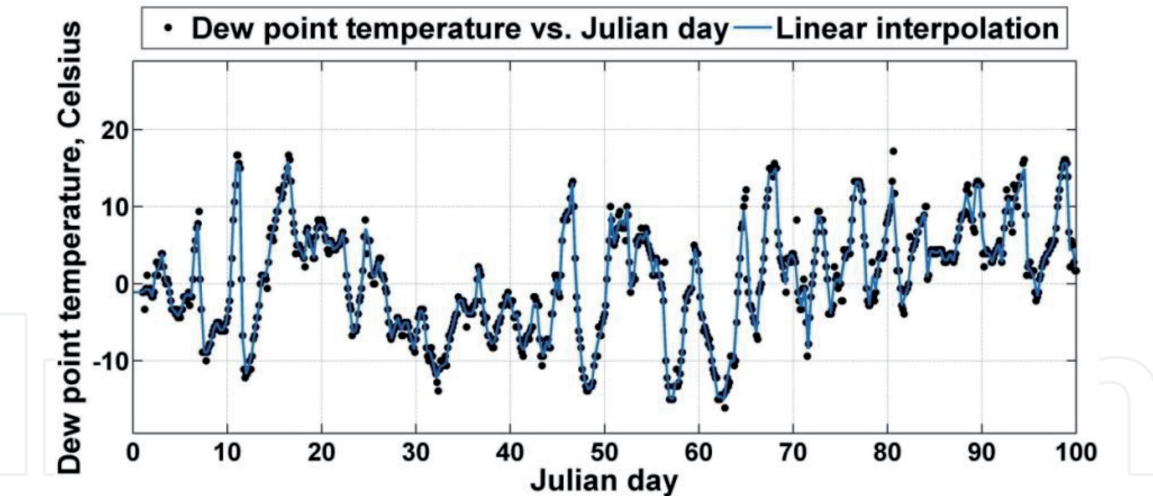


Figure 4.
Dew point input data.

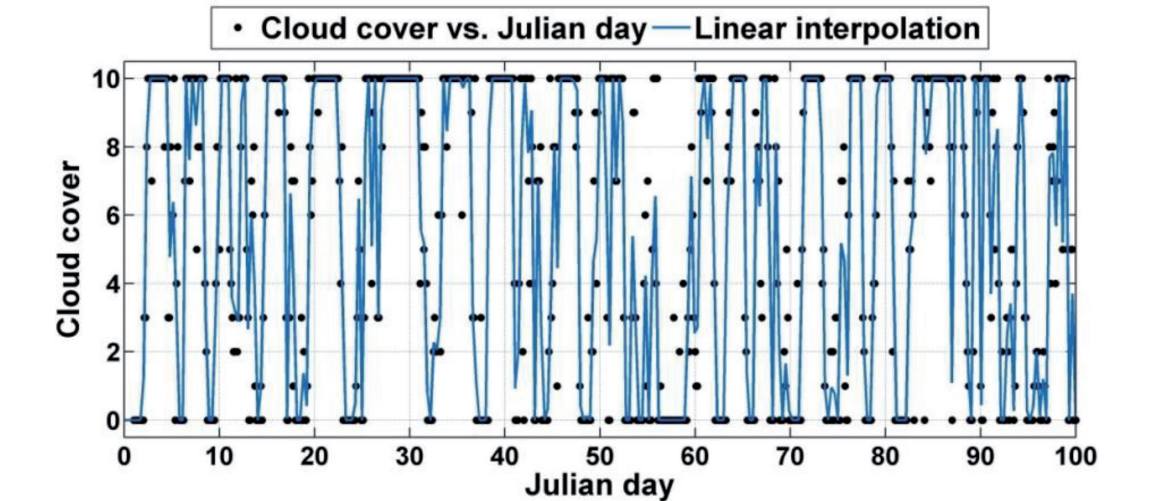


Figure 5.
Cloud cover input data.

3. Results and discussion

The physical domain was divided into computational cells of $1000 \times 500 \times 1$ (x,y,z) m and oriented perpendicular to the north direction as shown in **Figure 6**, in which there are bends at the boundaries to check how the model catches the flow field variability. The code was run without assuming a frictionless fluid, with the Coriolis force, with wind variable in magnitude and direction at 10 m height above

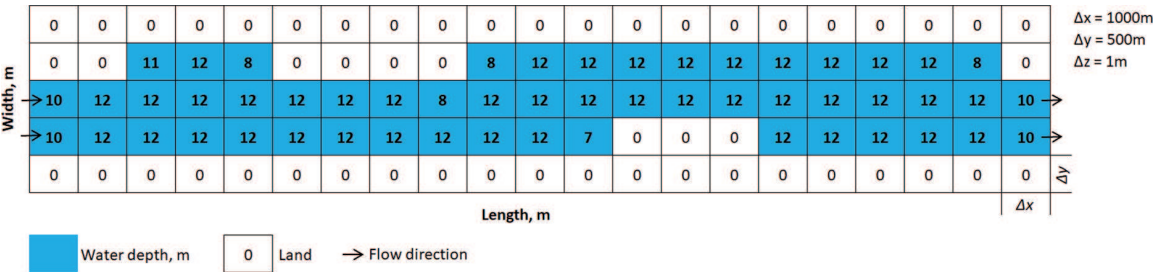


Figure 6.
Irregular physical domain and the input bathymetry.

the water surface, with a constant inflow and outflow of $0.8 \text{ m}^3/\text{s}$, and with variable water temperature over time by solving the heat transport equation. Additionally, the adding/subtracting layers algorithm (see [18]) was turned on to examine the surface layer thickness over the simulation period.

Using a time step of 35 s and a degree of implicitness (θ) of 1, the code was run for the simulation period. **Figure 7** presents the model predictions of the surface velocity field at Julian day 100. The model results showed good performance in following the bends at the boundaries. Furthermore, the volume balance error gave a good agreement in preserving volume in which the percent error reached a constant low value over time as shown in **Figure 8**, which is a semilog plot of the percent error with time. The corresponding water levels at three locations over time were shown in **Figure 9**, denoting a very small change ($\cong 0.005 \text{ m}$) in the surface layer thickness resulting from the free water surface waves.

Since the W3 model uses the degree of implicitness to switch between the fully implicit numerical scheme and the fully explicit scheme, the effect of the degree of implicitness on the accumulated error was evaluated by running the code using $\theta = 0.5$ with the same inputs that were used with $\theta = 1$. The results showed that using the semi-implicit scheme of $\theta = 0.5$ produces less percent error than using $\theta = 1$. **Figure 10** shows the percent error after running the code for day 100 using two degrees of implicitness ($\theta = 1$ and $\theta = 0.5$).

In addition and in order to make sure that the numerical answers do not depend on the grid resolution, a grid refinement was performed, and the associated volume

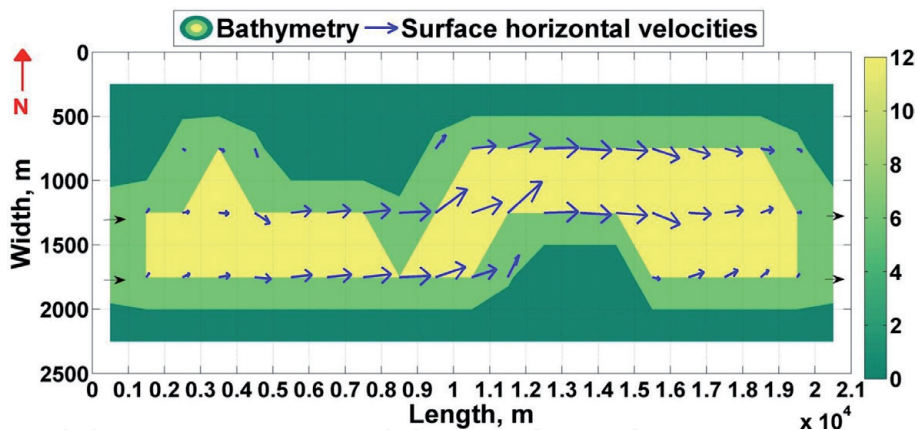


Figure 7.
Surface velocity field for the irregular domain at Julian day 100.

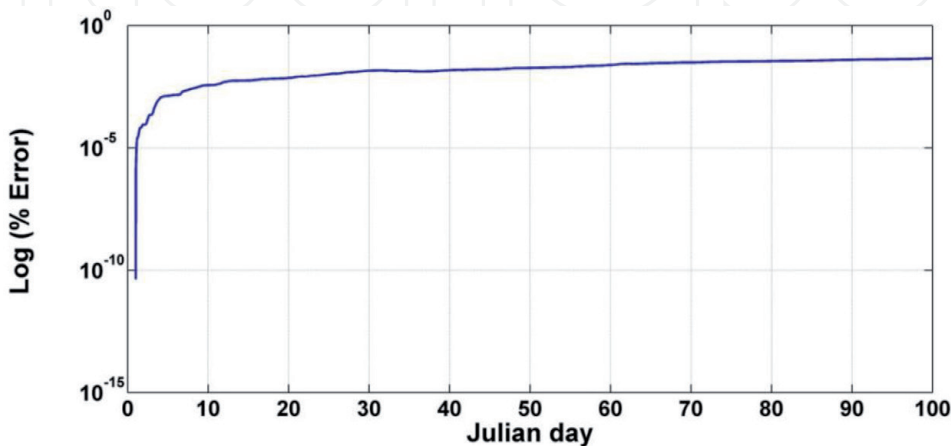


Figure 8.
Volume balance for the irregular domain using $\theta = 1$.

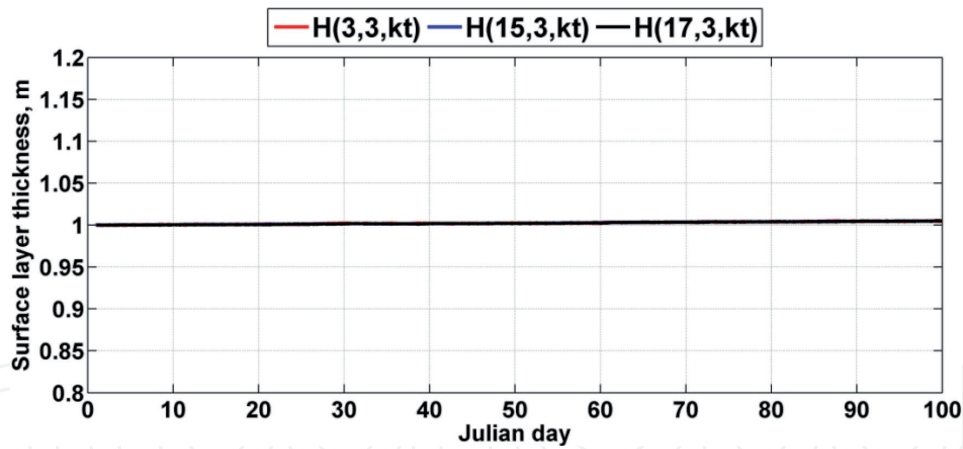


Figure 9.
Surface layer thickness over time for the irregular domain using $\theta = 1$.

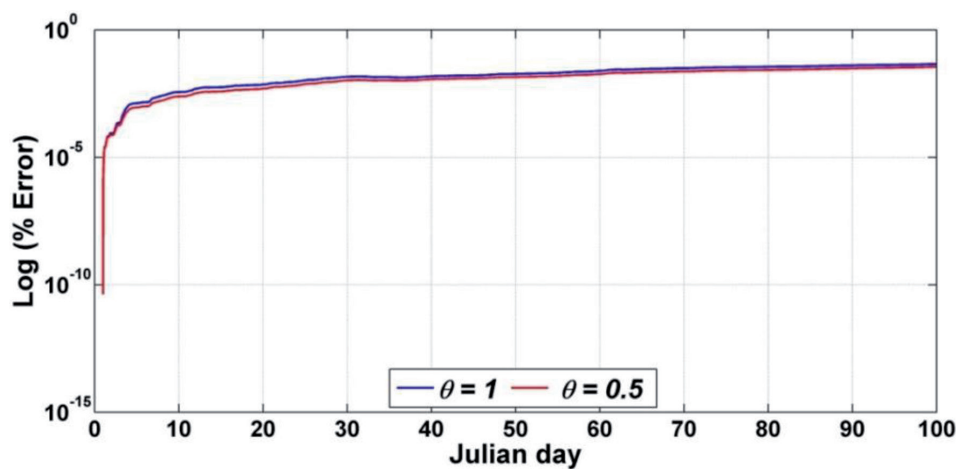


Figure 10.
The volume balance for the irregular domain using $\theta = 1$ and $\theta = 0.5$.

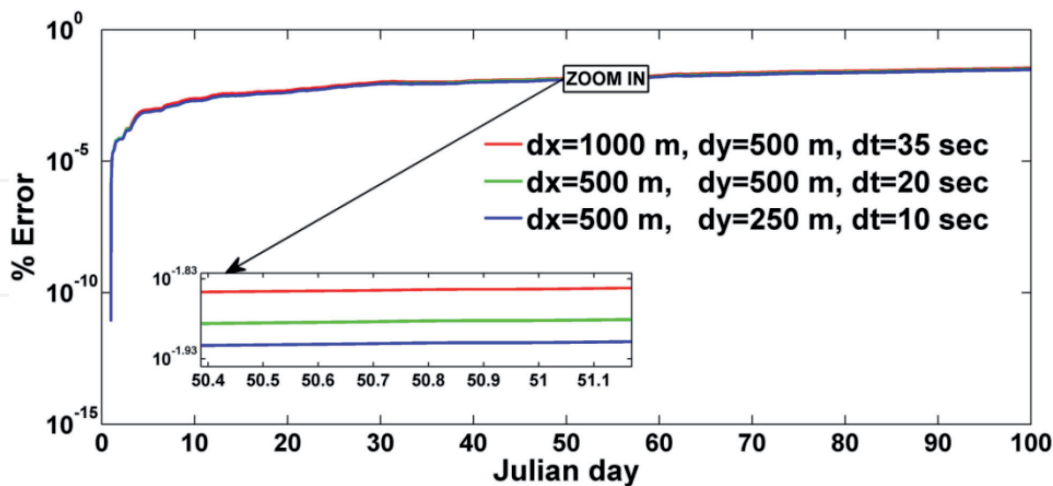


Figure 11.
The effect of grid refinement.

error was assessed. The code was run using $\theta = 0.5$ with three horizontal grid resolutions 1000×500 , 500×500 , and 500×125 (x,y) m in which the model was stable numerically. To maintain the stability, three different time steps were chosen to run the code because the refinement lowers the time step (Δt). All resolutions were applied on the same initial water volume in **Figure 6**. Therefore, the initial water volume of the waterbody was fixed, while the grid resolution was varied.

Figure 11 shows the percent error over time for the three considered grid resolutions, indicating that the error in volume has the same order of magnitude for the three resolutions.

4. Conclusions

Model verification is the first step after building any new hydrodynamic numerical model for surface waterbody simulation. In this chapter, a new volume balance approach was introduced for verifying the three-dimensional hydrodynamic numerical models in surface waterbody simulation. This technique provides information about whether the code preserves fluid mass or not by calculating the volume balance percent error over time during a model simulation. The model results indicated that the model is considered numerically stable if the volume balance error reaches a constant value over time. In addition, even though the model degree of implicitness had a reasonable volume balance error (less than 0.1%), the semi-implicit numerical scheme had slightly better volume balance error than the fully implicit scheme.

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