第Ⅱ部門　Improving a Kinematic Wave-Based Model Using Hillslope Surface Flow Observations

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1. Introduction

Kinematic wave-based distributed models have effectively simulated slope lateral flows and reproduced flood hydrographs in mountainous catchments. However, these models typically lack vertical infiltration schemes, and relying on downstream hydrographs often fails to reveal structural limitations. To address these limitations, the study utilized time-lapse camera observations that directly captured the occurrence and duration of hillslope surface flow from 2021 to 2023. This study aims to test and improve the structure of a 1-km distributed hydrological model (1K-DHM) by comparing slope surface flow duration and downstream discharge responses in the Shigaraki Experimental Catchments incorporating Green-Ampt (GA) model as a vertical percolation scheme.

2. Study Area and Observation Data

This study focuses on the Shigaraki Experimental Catchment (24.6 hectares) located in Shiga Prefecture, Japan (Figure 1). Since the catchment is less than 1 km^2, the study applied a 5-m resolution of DEM to generate a model grid. Slope surface flow on the hillslope was monitored using time-lapse cameras. Cameras took images every 10 minutes, allowing the assessment of slope surface flow duration. Due to limited space, this paper focused on an event in 2022 from August 16 to 18 when the most rainfall happened. Rainfall was measured using two tipping bucket gauges, one in an open space and another under the canopy to account for vegetation interception. River discharge was monitored at a triangular weir located at the downstream outlet.

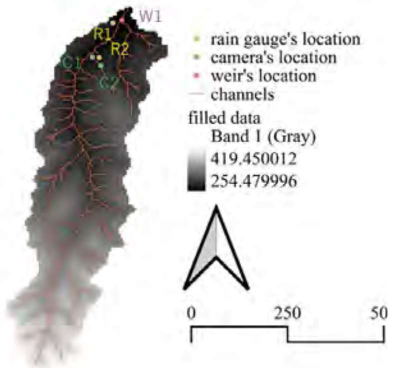

Fig. 1 Catchment map showing the 5-meter DEM, river channels, observation stations, and catchment boundary

3. 1K-DHM Simulation for the 2022 Event

The model was applied to simulate a flood event in 2022 using seven parameter sets (PS 1-7). Figure 2 compares the observed and simulated hydrographs and duration of slope downstream surface flow. All sets achieved moderate to high NSE values (0.49-0.63); among them, PSs 1,3, and 4 showed relatively accurate peak reproduction with small peak discharge errors (PDE -1.6%, -8.9%, and -5.6%, respectively), while PSs 2 and 7 provided the best overall hydrograph fit (NSE: 0.629 and 0.601; RMSE: 0.044 m^3/s for both parameters). On the other hand, peak discharge was overestimated across the board (PDE: -30.586% for PS 2 and 2.072% for PS 7), indicating performance sensitivity to parameter selection.

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To evaluate the model's ability to reproduce the slope flow duration, we calculated the Jaccard Index based on the overlap period of slope surface flow observed by time-lapse cameras. The index for PS 2 and PS 7 were remarkably low (0.399 and 0.518, respectively) showing overestimation of the surface flow duration.

These results indicate that although the model reproduces the river discharge hydrograph, it fails to capture the slope surface flow explicitly. This limitation results from models intended to represent the whole runoff processes (even losses) by only slope lateral flows. As a result, capillary layers are set deep, and non-capillary layers are too thin to suppress saturation realistically, resulting in excessive slope surface flow.

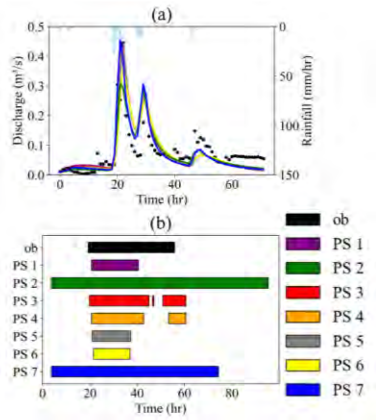

Fig. 2 Simulation results of PS 1-7, ob means observation data (dots in hydrographs): (a) hydrograph, (b) slope surface flow bar chart

4. Improvement by Green-Ampt

To address the overestimation of slope surface flow in the original model, the GA model was integrated into 1K-DHM as a vertical percolation loss scheme. Originally designed for infiltration, GA was applied here to simulate percolation. The study fixed k, Ψ and θ_d as 3.2×10^{-7} m/s, 0.25 m and 0.26, respectively (PS 8 hereinafter).

A new parameter set (PS 8) was defined by manually calibrating based on PS 1. Simulation with PS 8 is shown in Figure 3. Peak discharge was slightly overestimated (PDE = 10.57%), but the hydrograph shape was reasonable (NSE 0.507, RMSE = 0.050 m^3/s). The Jaccard Index increased to 0.745, better capturing the duration of slope surface flows. These results suggest that the introduction of vertical percolation losses reduces the unrealistic saturation tendency of the original model and mitigates the excessive persistence of the slope surface flow.

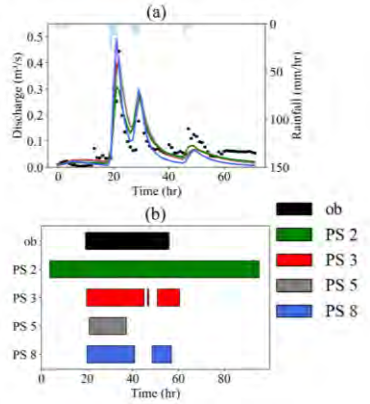

Fig. 3 Comparison of PS 2, 3, 5 and 8 at slope downstream ob means observation data (dots in hydrographs): (a) hydrograph, (b) slope surface flow bar chart

5. Conclusion

This study evaluated the 1K-DHM model using both river discharge and slope surface flow duration. The original model showed good discharge reproduction but tended to overestimate the surface flow persistence due to structural limitations. To improve this, the study introduced the GA model as a vertical percolation scheme. The modified model showed better agreement with observations, especially in recession behavior and surface flow duration, which was reflected in improvements in performance metrics. Although based on short-term data, these results support the benefits of incorporating physical-based vertical losses. Future studies should apply the model over longer periods and in diverse catchments to further assessment.

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Reference

T. Tanaka, Y. Tachikawa: Testing the applicability of a kinematic wave-based distributed hydrologic model in two climatically contrasting catchments, Hydrological Sciences Journal, 60(7-8), pp. 1361-1373, 2015.