Title
The Influence of Model Spatial Resolution on Rainfall-Induced Landslide Prediction for a Basin in Utuado, Puerto Rico

Journal
GEO-EXTREME 2025: DIFFERENT CLIMATES AND THE COASTAL ZONE, 372(GSP 372)

ISSN
0895-0563

Authors
Kassem, Mirna
Zekkos, Dimitrios

Publication Date
2025-10-30

DOI
10.1061/9780784486528.008

The Influence of Model Spatial Resolution on Rainfall-Induced Landslide Prediction for a Basin in Utuado, Puerto Rico

Mirna Kassem, S.M. ASCE[1] and Dimitrios Zekkos, Ph.D., P.E., M. ASCE[2]

[1]Deptartment of Civil and Environmental Engineering, University of California, Berkeley, CA; E-mail: kassem_mirna@berkeley.edu

[2]Department of Civil and Environmental Engineering, University of California, Berkeley, CA; E-mail: zekkos@berkeley.edu

ABSTRACT

Rainfall-induced landslides are driven by intense storms in mountainous regions. However, drainage basin-scale modeling faces challenges due to uncertainties in input parameters and computational limitations. Particularly, the Digital Elevation Model (DEM) resolution used in the hydrological and slope stability models can impact the prediction of landslides. Hence, understanding the influence of the domain's resolution on the results is critical. This study uses a pseudo-three-dimensional slope stability approach coupled with the Parallel Integrated Hydrological model (ParFlow) to predict failures by Hurricane Maria in a watershed in Utuado, Puerto Rico. A 1-m resolution pre-hurricane DEM is used as the base scenario for both ParFlow and the slope stability analyses. The DEM resolution was then varied, and the results were compared to the base scenario with a focus on the landslide area density, timing of failures, and associated failure mechanisms. Results demonstrated that a coarser DEM for the slope stability analysis significantly affected the predicted landslides, whereas it had minimal impact in the hydrologic model. Resampling the DEM for the hydrological model while maintaining a high-resolution DEM for the slope stability model reduced the required computational resources significantly without compromising the validity of the results in regional-scale applications.

INTRODUCTION

Slope failures, induced by natural or human-induced factors, result in significant life and infrastructure losses globally, with rainfall being the major natural cause of landslides (Mansour et al., 2011). Climate change and shifting land use practices are driving more frequent and intense extreme weather events, which, in turn, are exacerbating the occurrence and severity of rainfall-induced landslides. Predicting rainfall-induced landslides is crucial for managing landslide risk and alleviating the severe socio-economic impacts associated with slope failures, particularly at a regional scale (Haque et al., 2016). The high number and high spatial variability of the input parameters, as well as the complexity of advanced mechanistic predictive models, increase the computational resources needed for regional slope stability analyses (van Asch et al., 2007). To reduce these computational requirements, simplifying approximations are often made, including adopting coarser Digital Elevation Models (DEMs), smaller study areas, spatially constant subsurface properties, steady-state and one-dimensional (1D) flow conditions, 1D slope or 2D stability calculations, and assuming hydrostatic spatial water table levels. Particularly, using a coarser DEM resolution can reduce the required computational time and resources significantly (Qiu et al., 2022). Hence, understanding the impact of these simplifications is crucial for assessing the validity of results and for focusing on the most critical factors that affect them. This can help scale up landslide predictions to a regional scale without compromising on the validity of the results or the detail level of the generated output.

Hurricane Maria hit Puerto Rico on 20 September 2017 at 6:15 a.m. (Atlantic Standard Time), triggering more than 70,000 landslides and debris flows, most of them on the same day (Hughes and Schulz, 2020). Utuado, in central Puerto Rico was the most severely affected by the hurricane with a landslide area density exceeding 100 landslides/km^2 (Hughes and Schulz, 2020).

A rainfall-induced landslide regional predictive model that couples the Parallel Integrated Hydrological model (ParFlow) and a pseudo-three-dimensional (3D) slope stability approach is introduced. The model integrates the effects of different processes, including 3D transient subsurface groundwater flow in the saturated and vadose zones, overland flow, and slope stability. The model outputs a set of predicted landslides across the topography with well-defined locations, areas, volumes, and timing of failures. It was applied to a watershed in Utuado to study the impact of the DEM resolution of both ParFlow and the slope stability analyses on the predicted landslide area density, timing of failures, failures spatial distribution, and the associated failure mechanisms.

STUDY AREA AND EVENT

This analysis focused on a 10,312 m² watershed in Utuado, central Puerto Rico (Figure 1), the easternmost island of the Greater Antilles.

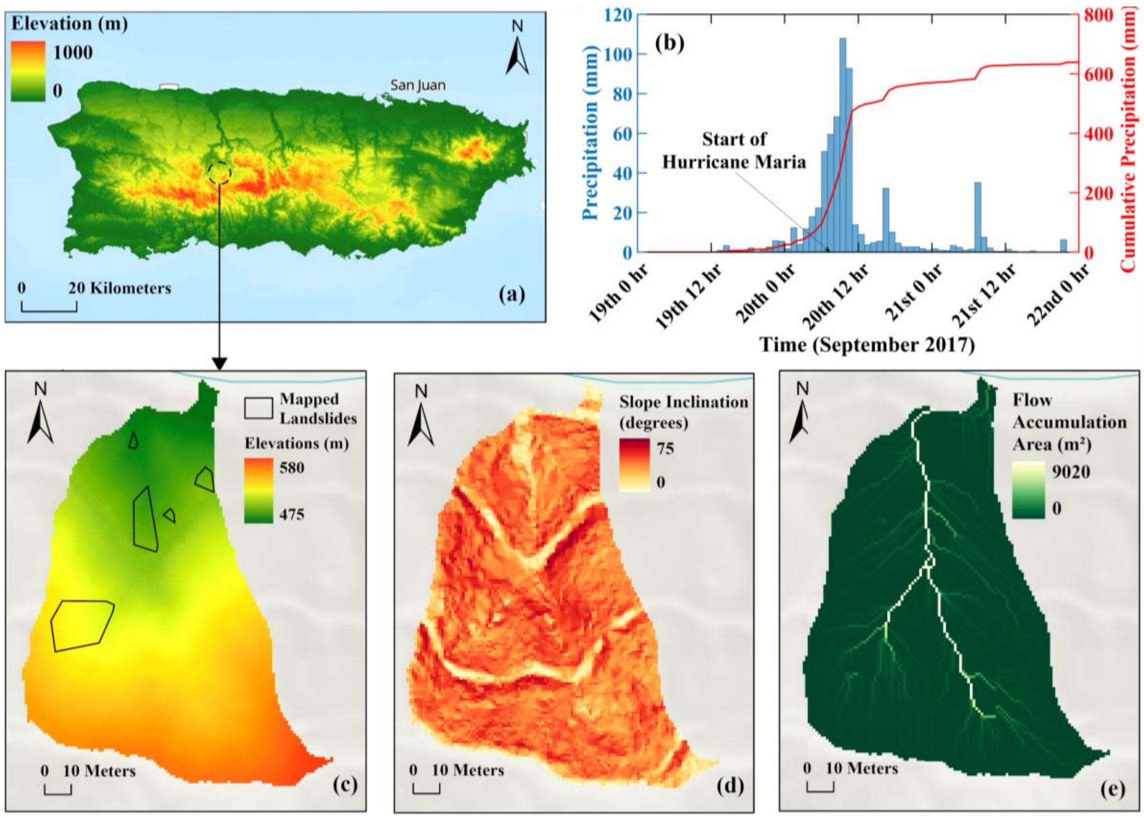

Figure 1. (a) Puerto Rico Topography, (b) Precipitation time history of Hurricane Maria (2017) using the NCEP Stage IV dataset, and (c) Elevations, (d) Slope inclinations, and (e) Flow accumulation areas of the studied watershed in Utuado, central Puerto Rico.

The soil in Utuado is silty sand originating from granodiorite-quartz diorite, part of the plutonic rocks of the Utuado batholith formed during the Cretaceous period (Learned et al., 1981). Frequent intense rainfall, widespread weathered hillslope soils, and evolving land use practices play a key role in triggering rainfall-induced landslides and debris flows in Puerto Rico (Bessette-Kirton et al., 2019). This study focused on the Category 4 Hurricane Maria that triggered over 70,000 landslides and debris flows in at least three-fourths of the island's municipalities (Hughes and Schulz, 2020). Most of the landslides were shallow and translational in soil or saprolite with a thickness that varied from a few decimeters to a few meters (Bessette-Kirton et al., 2019). Figure 1 shows the watershed's elevations (Figure 1c), slope inclinations (Figure 1d), and flow accumulation areas (Figure 1e). Elevations are based on a 1-m resolution pre-hurricane DEM (U.S. Geological Survey, 2017). A high-quality landslide inventory is used, incorporating mapped landslide locations, source areas, and volumes estimated through Light Detection and Ranging (LiDAR) differencing (Bayouth-Garcia and Hughes, 2023). The studied watershed includes five mapped landslides with a mapped landslide area density of ~5.5% (Figure 1c). Rainfall estimates for Hurricane Maria varied significantly amongst the available datasets, but records confirm that the mountains of Puerto Rico received at least 250 mm of rain (Bessette-Kirton et al., 2019). This study used the National Centers for Environmental Prediction (NCEP) Stage IV rainfall dataset, as it most closely matched the partially available gauge data (Du, 2011). Rainfall was measured at a spatial resolution of 0.2° by 0.2°, every 1 hour, with a cumulative total of 640 mm recorded by the end of the hurricane (Figure 1b).

METHODS

Model

The mechanistic model used for this analysis integrates ParFlow (Kollet and Maxwell, 2008) with a pseudo-3D slope stability approach (Gong et al., 2023) to predict regional-scale 3D landslides with well-defined locations, areas, volumes, and timing of failures. ParFlow models the 3D groundwater subsurface flow in both the saturated and vadose zones as well as the overland flow. It uses the van Genuchten model to describe the variation of hydraulic conductivity and soil moisture in the unsaturated zone. Land surface processes, including precipitation and evapotranspiration, are accounted for by integrating ParFlow with the Community Land Model (CLM) (Dai et al., 2003). To estimate the initial groundwater table level, ParFlow offers a "spinup" feature, starting with a constant recharge until steady state hydrologic conditions are reached.

The pseudo-3D slope stability approach consists of two main steps. First, it identifies potential triggering cells where the factor of safety (F_s) is ≤1, using a 1D infinite slope stability analysis (Duncan et al., 2014) (Figure 2a). The F_s for each cell in the DEM is computed at each depth and time step as follows:

$$F_s(z,t) = \frac{\tan(\phi')}{\tan(\beta)} + \frac{c' - \psi(z,t)\,\gamma_w \tan(\phi')}{\gamma\, z\, sin(\beta)\cos(\beta)}$$

where c' and ϕ' are the effective cohesion and friction angle, respectively; β is the slope angle; γ and γ_w are the respective material and water unit weight; z is the vertical depth at the center of each subsurface layer; $\psi(z,t)$ is the pressure head at a given time and depth calculated by ParFlow.

The triggering depth is determined as the shallowest or deepest depth relative to the ground surface, depending on the user's preferences, where F_s ≤1.

Second, the model extends each triggering cell into a 3D landslide using a geometric projection (Figure 2b). Starting with the triggering cell with the highest flow accumulation within the topography, the model includes upslope cells that meet certain criteria, including: having a higher elevation than the triggering cell, having a lower flow accumulation than the downslope cell of interest, and not being part of another landslide. The process continues until the failure plane daylights to the ground surface, forming a 3D cone-shaped landslide. The model assumes that the slope of the failure plane becomes steeper as the distance from the triggering cell increases. Remaining triggering cells, not part of formed landslides, with lower flow accumulations are then processed similarly to form additional landslides across the topography.

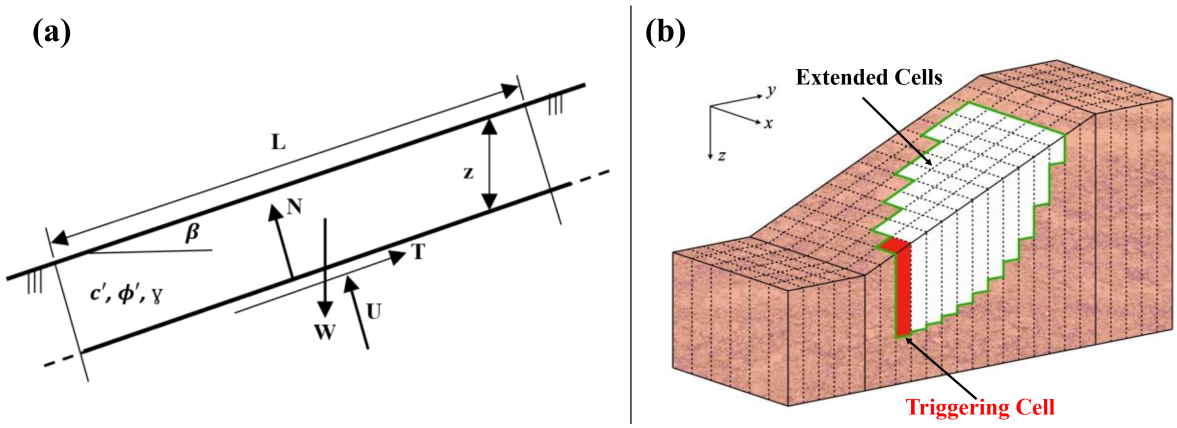

Figure 2. (a) Infinite slope stability limit equilibrium method, (b) Schematic of pseudo-3D slope stability approach.

Study Domain and Input Parameters

Most of the hurricane-induced landslides were shallow and translational (Bessette-Kirton et al., 2019) with an average mapped landslide thickness of 1 m in our studied watershed (Bayouth-Garcia and Hughes, 2023). Thus, a 2 m subsurface domain was defined and subdivided into eight layers ($D_z = 0.25\ m$). A 1-m resolution pre-hurricane DEM ($D_x = D_y = 1\ m$) was used for the base scenario of the analysis (U.S. Geological Survey, 2017).

This study examined the impact of DEM resolution, in both ParFlow and slope stability analyses, on the predicted landslides across the topography. We explored five scenarios by varying the DEM resolutions ($D_x = D_y$): (1) 1-m resolution in both ParFlow and the slope stability analysis (base scenario), (2) 3-m in both, (3) 10-m in both, (4) 3-m in ParFlow and 1 m in slope stability, and (5) 10-m in ParFlow and 1-m in slope stability. In scenarios 4 and 5, the DEM was resampled to a coarser resolution for ParFlow using the Nearest Neighbor method in ArcGIS Pro, while the original 1-m resolution was retained for the slope stability analysis. In scenario 4, for example, a pore pressure head estimated by ParFlow for a 3×3 m cell was uniformly applied to all nine 1×1 m cells within that area and was used as input in the slope stability analysis, while elevations and slopes were derived from the original 1-m resolution DEM.

No-flow boundary conditions were applied at the domain's bottom and sides, reflecting minimal water movement from the watershed, while an overland flow boundary was assigned at the top. Given the relatively small size of the study area, input parameters were constant spatially and in-depth, except for k_s, which only varied with depth. Table 1 summarizes the input parameters that remained consistent across all five scenarios.

Table 1. Model input parameters.

Input Parameter	Value	Source
Saturated hydraulic conductivity (k_s)	3e-06 m/s (shallowest), halving per layer to 2e-08 m/s at 8th layer	Baum et al., 2023
Hydraulic conductivity tensor	Isotropic	--
Specific storage	1e-05 m^{-1}	--
Porosity (n)	0.45	Thomas et al., 2020
van Genuchten α	1.0	Baum et al., 2023
van Genuchten N	1.5	Thomas et al., 2020
Saturated volumetric water content (θ_s)	0.45	Thomas et al., 2020
Residual volumetric water content (θ_r)	0.1	Thomas et al., 2020
Manning's coefficient	5.6e-05 $hr/m^{1/3}$	--
Constant recharge for the "spinup" ParFlow simulation	1e-08 m/s	--
Rainfall dataset	NCEP Stage IV hourly rainfall rates	Du, 2011
Cohesion (c')	20 kPa	Baum et al., 2023
Friction angle (ϕ')	37°	Baum et al., 2023
Saturated soil unit weight (γ)	22 kN/m^3	U.S. Department of Agriculture, 2019

Analysis Steps

For each scenario, the analysis started with a ParFlow "spinup" simulation to set the initial groundwater table level for the main ParFlow simulation. The ParFlow main simulation estimated pore pressure heads that evolved spatially, temporally, and with depth in response to the hurricane. These pressure heads were subsequently inputted into the slope stability analysis. Potential triggering cells were identified, and 3D landslides were generated at each time instant using the pseudo-3D procedure. The shallowest depth at which the triggering was initiated was used to define the onset of a landslide.

RESULTS

Landslide Area Density Over Time

Figure 3 illustrates the model's predicted landslide area density over time for the five scenarios studied. For the base scenario (blue solid curve), which used a 1-m resolution DEM for both ParFlow and the slope stability analyses, the model predicted a maximum cumulative landslide area density of 30%, with landslides initiating eight hours before the hurricane's onset (September 19, 2017, 10:00 p.m.). Conversely, with a 3-m resolution DEM (red solid curve), landslides were triggered three hours after the hurricane started (September 20, 2017, 9:00 a.m.), with a maximum cumulative landslide area density estimated at 6.5%. No landslides were predicted for a DEM resolution of 10 m (green solid curve). The 1-m resolution DEM significantly overpredicted landslides compared to the mapped landslide area density (5.5%), whereas the 3-m resolution DEM generated a closer alignment between the predicted and mapped landslide area densities.

The previous three scenarios used the same DEM resolution for both ParFlow and the slope stability components of the model. On the other hand, analyses were conducted where the DEM resolution was resampled to 3 m for ParFlow while maintaining a 1-m resolution for the slope stability analysis (red dashed curve). In this case, the model predicted a maximum cumulative landslide area density of 29%, which closely matched the base scenario (blue solid curve). Moreover, landslides in the scenario using a 3-m resolution DEM for ParFlow and a 1-m resolution DEM for slope stability were triggered starting on September 19, 2017, at 6:00 p.m. The temporal evolution of the predicted landslide area density in this scenario closely resembled that of the base scenario. Similarly, resampling the DEM to a 10-m resolution for ParFlow while maintaining a 1-m resolution for slope stability predicted a maximum cumulative landslide area density of 27.5% (green dashed curve), which is also closely comparable to the base scenario (blue solid curve). In this scenario, landslides were initiated starting on September 20, 2017, at 3:00 a.m., and the temporal variation of the landslide area density closely aligned with that of the base scenario. This indicates that coarser resolution hydrogeologic modeling can be adequate, and can result in significant computational efficiencies, as long as landslide triggering remains at high resolution.

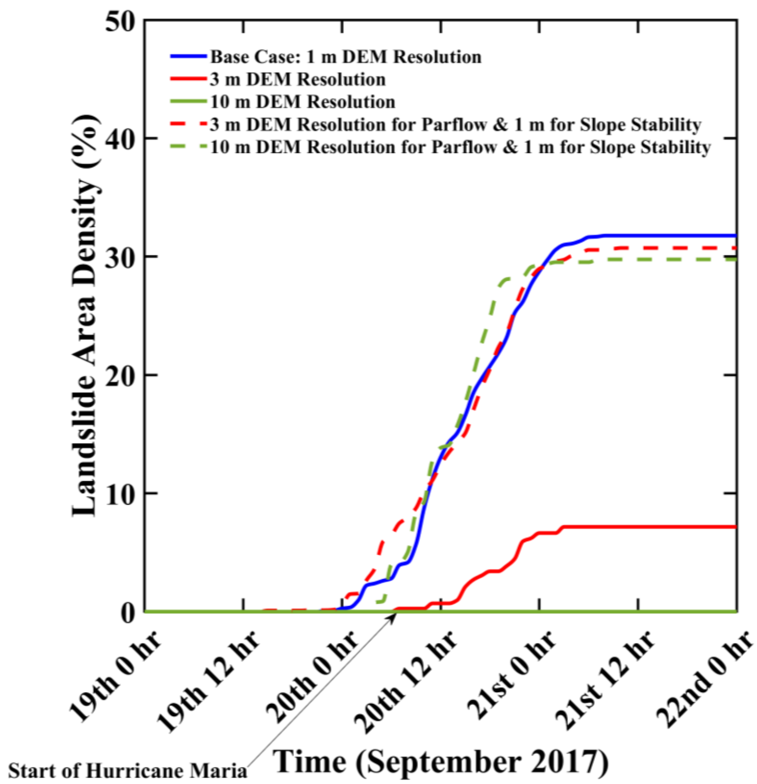

Figure 3. Predicted cumulative landslide area density over time for the five scenarios.

Spatial Distribution of Failures

Figure 4 shows the spatial distribution of the predicted landslides at different time instants for three scenarios: (a) the base scenario with a 1-m resolution DEM for both ParFlow and the slope stability analyses, (b) the scenario with a 3-m resolution for ParFlow with the original 1-m resolution DEM for the slope stability analysis, and (c) the scenario using a resampled 3-m resolution for both ParFlow and the slope stability analyses. Predicted landslides are overlaid on a background showing the flow accumulation area, a proxy of the geomorphic position across the topography.

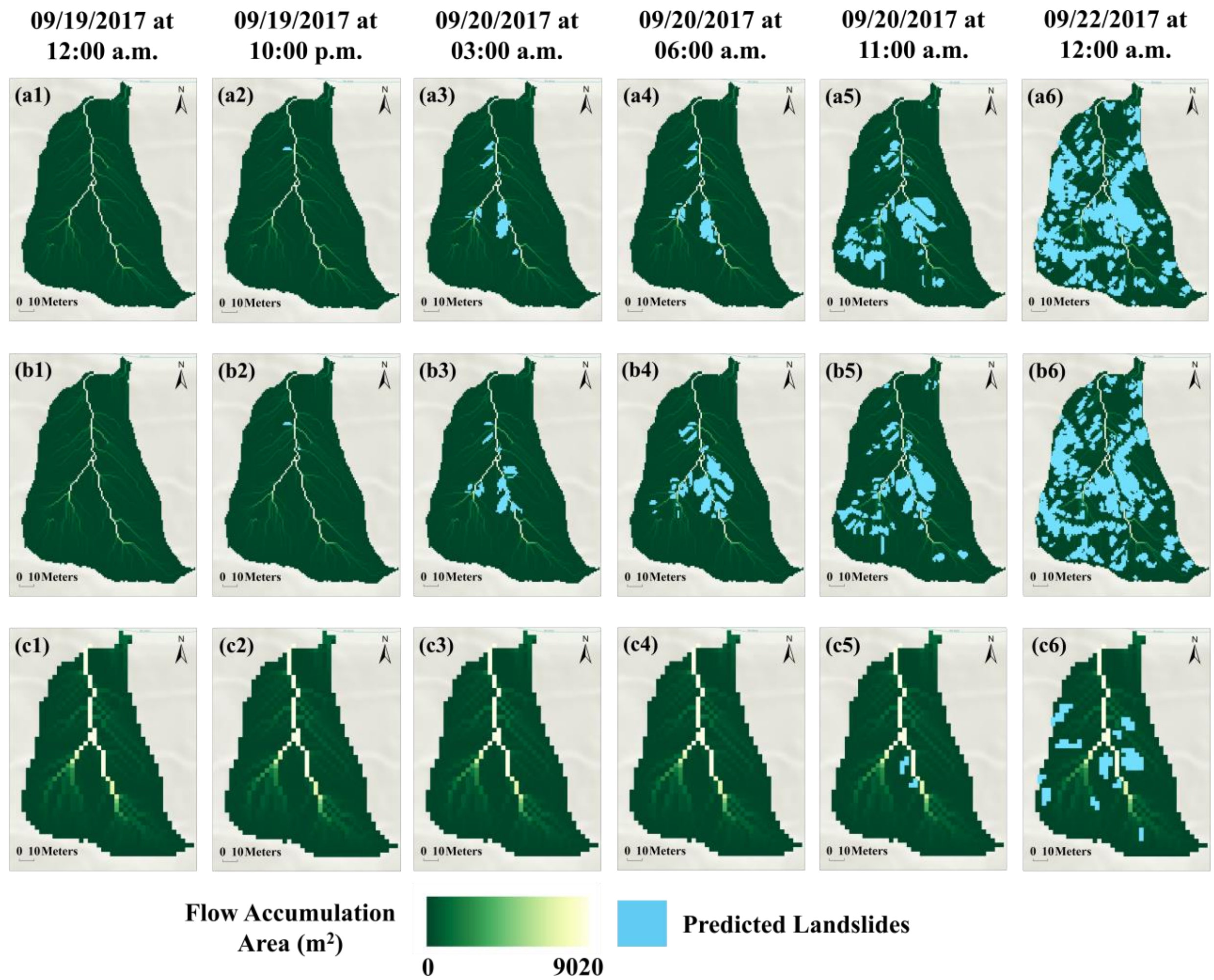

Figure 4. Spatial distribution of predicted landslides over time for the (a) base scenario, with a DEM resolution of 1 m applied to both ParFlow and the slope stability analyses, (b) scenario with a resampled DEM resolution of 3 m applied to ParFlow and the original 1 m DEM resolution for the slope stability analysis, and (c) scenario with a resampled DEM resolution of 3 m applied to both ParFlow and the slope stability analyses.

The predicted number of failures and their spatial distribution over time were largely similar in both the base scenario (Figure 4a), which utilized the original 1-m resolution DEM for both ParFlow and the slope stability analyses, and the scenario where ParFlow used a DEM resampled to 3-m resolution while the slope stability analysis maintained the original 1-m resolution DEM (Figure 4b). The resampled DEM scenario tended to trigger more failures at earlier time instants (e.g., Figures 4a4 and 4b4). However, by the end of the hurricane, the total number of failures, their spatial distributions, and the corresponding cumulative landslide area densities were nearly identical in both scenarios (Figures 4a6 and 4b6).

On the other hand, a significantly higher number of failures and a higher cumulative landslide area density were predicted across the topography by the end of the hurricane for the 1-m resolution DEM (Figure 4a6) compared to the 3-m resolution DEM scenario (Figure 4c6). The spatial distributions of the predicted failures across the topography were also significantly different between the two scenarios. Furthermore, the individual areas of the predicted landslides in the 3-

m resolution DEM scenario (Figure 4c) were noticeably larger than those in the 1-m resolution DEM scenario (Figure 4a). Moreover, landslides were triggered earlier in the 1-m resolution DEM scenario (Figure 4a) compared to the 3-m resolution DEM (Figure 4c). For the 1-m resolution DEM scenario, landslides were initially predicted on September 19 at 10:00 p.m. (Figure 4a2), near valley bottoms in locations with high flow accumulation areas. By September 20 at 6:00 a.m. (hurricane's onset), the most vulnerable slopes in lower geomorphic positions had already failed due to the rise in the groundwater table level (bottom-up failures), leading to prediction of additional landslides at higher geomorphic positions, where top-down failures started to emerge due to the formation of a perched water table (Figure 4a4). On the other hand, the 3-m resolution DEM scenario (Figure 4c) triggered exclusively top-down failures, initiated by the formation of a perched water table in locations near ridge tops with low flow accumulation areas. This is because resampling the DEM to a coarser resolution for the slope stability model smooths the topography, potentially removing steep slopes near valley bottoms and, as a result, reducing or eliminating bottom-up failures due to rise in the water table.

For all the three scenarios, the model overpredicted the mapped failures, and the spatial distribution of the modeled and mapped landslides (shown in Figure 1c) did not match well. This can be attributed to the assumption of spatially constant shear strength parameters (cohesion and friction angle) across the topography, which fails to account for the landscape's complexities.

Simulations Run Time

Reducing the spatial resolution in simulations can substantially decrease computation time (Table 2). All simulations were run on a local computer equipped with an Intel Core i9 vPro processor (8 physical cores, 16 logical processors, base clock speed 2.61 GHz), using one processor.

Table 2. Comparison of model run times for different cases.

Case	ParFlow "Spin-up" Run Time	ParFlow Main Simulation Run Time	Slope Stability Analysis Run Time	Total Run Time
1-m DEM resolution for both ParFlow and slope stability analysis	150 minutes	540 minutes	60 minutes	750 minutes
3-m DEM resolution for ParFlow; 1-m for slope stability analysis	12 minutes	140 minutes	60 minutes	212 minutes
3-m DEM resolution for both ParFlow and slope stability analysis	12 minutes	140 minutes	1 minute	153 minutes
10-m DEM resolution for ParFlow; 1-m for slope stability analysis	8 minutes	30 minutes	60 minutes	98 minutes
10-m DEM resolution for both ParFlow and slope stability analysis	8 minutes	30 minutes	0.5 minutes	38.5 minutes

DISCUSSION

This study showed that lowering the DEM resolution for both ParFlow and slope stability analyses resulted in a significantly different predicted cumulative landslide area density, its temporal evolution, the spatial distribution of the predicted landslides, and the associated failure mechanisms. However, when resampling the DEM to a lower resolution for ParFlow only, while retaining the original high resolution for the slope stability analysis, the landslide area density temporal curves, the spatial distribution of the predicted landslides, and the associated failure mechanisms showed a close match to the base scenario.

Given the input parameters used, reducing the DEM resolution for the hydrological model had a minimal effect on the predicted landslides because pore pressure gradients and soil saturation levels were found to change gradually over distances of 3 to 10 m. This is primarily because the initial groundwater table varied smoothly, precipitation was nearly uniform, and material properties were relatively consistent across these scales. Therefore, assigning the same pore pressure head to all 1×1 cells within a larger 3×3 or 10×10 cell was not a significant compromise. Conversely, the slope stability analysis required a high DEM resolution to account for shallow landsliding, as well as terrain-driven differences, especially in a highly mountainous region like Puerto Rico. Using a coarse DEM resolution for slope stability analysis resulted in smoothening the topography, potentially disregarding small-scale features such as steep slopes that can be essential in triggering landslides. This emphasized the importance of using a high-resolution DEM for slope stability analysis, while it was not as critical for the hydrological model. Adopting this approach can result in significant reduction in the computational time and resources required for running the model. Resampling the DEM to 10 m for ParFlow, while retaining the original 1-m resolution for slope stability analysis, reduced computational time from 750 minutes (when both used 1-m resolution) to 98 minutes for this study area and domain (Table 2).

CONCLUSIONS

A regional predictive model for rainfall-induced landslides, which integrates ParFlow with a pseudo-3D slope stability approach, was introduced. Applied to a watershed in Utuado, central Puerto Rico, during the 2017 Hurricane Maria event, the study aimed to examine the influence of the DEM resolution used for the hydrological and slope stability components of the model on the predicted landslides. Results showed that the reduction of DEM resolution from 1 m to 3 m and 10 m for the hydrological component of the model did not play a major role in the predicted landsliding, while changes in the DEM resolution used for slope stability analysis significantly influenced the predicted landslides. This is particularly important in reducing the computational time and resources needed when scaling up such analyses to a regional scale and in allocating the available resources efficiently.

REFERENCES

Baum, R. L., Brien, D. L., Reid, M. E., Schulz, W. H., and Tello, M. J. (2023). "Assessing Locations Susceptible to Landslide Initiation During Prolonged Intense Rainfall in the Lares, Utuado, and Naranjito Municipios of Puerto Rico." *Nat. Hazards Earth Syst. Sci. Discuss.*, 1-47. https://doi.org/10.5066/P9UXTQ4B

Bayouth-Garcia, D., and Hughes, S. (2023). "Mapped landslide inventory of the Lago Caonillas basin." [Unpublished dataset]. University of Puerto Rico

Bessette-Kirton, E.K., Cerovski-Darriau, C., Schulz, W.H., Coe, J.A., Kean, J.W., Godt, J.W., ... and Hughes, K.S. (2019). “Landslides triggered by Hurricane Maria: Assessment of an extreme event in Puerto Rico.” *GSA Today* 29(6):4-10. https://doi.org/10.1130/GSATG383A.1

Dai, Y., Zeng, X., Dickinson, R.E., Baker, I., Bonan, G.B., ... and Yang, Z.L. (2003). “The common land model.” *Bull. Am. Meteorol. Soc.* ,84(8):1013-1024. https://doi.org/10.1175/BAMS-84-8-1013

Du, J. (2011). “NCEP/EMC 4KM Gridded Data (GRIB) Stage IV Data. Version 10.” *UCAR/NCAR - Earth Observing Laboratory*. https://doi.org/10.5065/D6PG1QDD. Accessed 01 Jun 2024

Duncan, J.M., Wright, S.G., and Brandon, T.L. (2014). “Soil strength and slope stability.” *John Wiley & Sons*

Gong, W., Zekkos, D., and Clark, M. (2023). “A pseudo-3D methodology for regional-scale back-analysis of earthquake-induced landslides.” *Eng. Geol.*, 325:107277. https://doi.org/10.1016/j.enggeo.2023.107277

Haque, U., Blum, P., da Silva, P.F., Andersen, P., Pilz, J., and Chalov, S.R., et al. (2016). “Fatal landslides in Europe.” *Landslides*, 13, 1545–1554. https://doi.org/10.1007/s10346- 016-0689-3

Hughes, K.S., and Schulz, W. (2020). “Map depicting susceptibility to landslides triggered by intense rainfall, Puerto Rico.” (No. 2020-1022). *U.S. Geol. Surv.*. https://doi.org/10.3133/ofr20201022

Kollet, S.J., and Maxwell, R.M. (2008). “Capturing the influence of groundwater dynamics on land surface processes using an integrated, distributed watershed model.” *Water Resour. Res.*, 44(2). https://doi.org/10.1029/2007WR006004

Learned, R.E., Hickey, T.H., and Perez de Gonzales, I. (1981). “A geochemical reconnaissance of the Utuado Batholith and vicinity, Puerto Rico.” (open file report 81-1131) (p. 5). *Reston, VA: U.S. Geol. Surv*. https://doi.org/10.3133/ofr811131

Mansour, M.F., Morgenstern, N.R., and Martin, C.D. (2011). “Expected damage from displacement of slow-moving slides.” *Landslides*, 8:117-131. DOI 10.1007/s10346-010-0227-7

Qiu, H., Zhu, Y., Zhou, W., Sun, H., He, J., and Liu, Z. (2022). “Influence of DEM resolution on landslide simulation performance based on the Scoops3D model.” *Geomat. Nat. Hazards and Risk*, 13(1), 1663-1681. https://doi.org/10.1080/19475705.2022.2097451

Thomas, M. A., Mirus, B. B., and Smith, J. B. (2020). “Hillslopes in humid-tropical climates aren't always wet: Implications for hydrologic response and landslide initiation in Puerto Rico.” *Hydrol. Process.*, *34*(22), 4307-4318. https://doi.org/10.1002/hyp.13885

van Asch, T., Malet, J., van Beek, L., and Amitrano, D. (2007). “Techniques, advances, 1329 problems and issues in numerical modelling of landslide hazard.” *Bull. Soc. Géol. Fr.*, *178*(2), 65–88. https://doi.org/10.48550/arXiv.0709.2642

U.S. Department of Agriculture, Natural Resources Conservation Service. (2019). *Web Soil Survey*: https://websoilsurvey.sc.egov.usda.gov/app/WebSoilSurvey.aspx. Accessed 01 July 2023

U.S. Geological Survey. (2017). 2015-2016 USGS Puerto Rico lidar: *U.S. Geol. Surv.*: https://apps.nationalmap.gov/lidar-explorer/#/. Accessed 15 June 2023