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Analysis of the Influence of Manning's Coefficient in Dam Failure Flood Simulations Using Remote Sensing Data



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ABSTRACT

Dam failures pose significant risks to both life and infrastructure, making precise flood simulations essential to mitigate their impacts. This study investigates the influence of Manning's roughness coefficient on dam failure flood simulations, utilizing three freely accessible high-resolution Land Use and Land Cover (LULC) datasets: MapBiomass, ESRI Annual Land Cover, and Dynamic World, all processed via Google Earth Engine. The analysis encompasses two dams located in the semi-arid region of Pernambuco, Brazil, using the HEC-RAS 6.5 model to explore variations in key hydraulic parameters such as peak flow, flood propagation time, and inundated areas. Additionally, the study emphasizes the importance of accurately defining the Self-Rescue Zone (SRZ), a critical emergency response area defined within 30 minutes of flood wave propagation, typically as required by several dam safety legislations. Differences in SRZ dimensions were analysed based on the LULC datasets, revealing significant variations linked to Manning's coefficient. The results highlight the potential of LULC data in failure simulations, especially in data-deprived regions. However, they reinforce the substantial impact of LULC datasets on hydraulic modelling results, which may influence emergency planning.

Keywords: LULC datasets, Manning's coefficient, dam failure, LULC datasets, Self-Rescue Zone

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1. INTRODUCTION

Dam failures are technological disasters that can be catastrophic, posing serious threats to life and infrastructure. Accurate prediction of flood scenarios is crucial to mitigate these risks, and numerical models, especially two-dimensional (2D) simulations, have become indispensable tools. However, the calibration of roughness coefficients, particularly Manning's coefficient, remains a significant challenge due to the scarcity of historical data on extreme events [1]. This limitation is even more pronounced in dam failure studies, where the lack of comparable historical events significantly hinders the calibration process [2, 3].

Remote sensing data, such as Land Use and Land Cover (LULC) datasets, offer a promising alternative by providing detailed information on land use and surface cover. This study utilizes three high-resolution and freely accessible LULC datasets: MapBiomas [4], ESRI Annual Land Cover[5], and Dynamic World [6], all obtained through the Google Earth Engine platform (GEE).

Additionally, the study emphasizes the importance of accurately defining the Self-Rescue Zone (SRZ), a crucial region for emergency evacuations during the critical first minutes following a dam failure, as outlined in the legislation of Brazil and Portugal [7, 8]. The definition of the SRZ largely depends on the propagation characteristics of flood waves, which are influenced by the topography of downstream valleys and Manning's coefficient.

Two case studies were undertaken, comprising two dams with different sizes, both located in the semi-arid region of Pernambuco, Brazil. The HEC-RAS 6.5 model was used for these simulations, which focused on understanding the impact of varying Manning coefficients. The findings of this study aim to advance hydraulic modelling practices, strengthen emergency planning, and improve the accuracy of attenuation forecasts.

2. METHODOLOGY

2.1. Case Study Overview

This case study focuses on two dams situated in Brazil's semi-arid region, specifically in the state of Pernambuco. The area is defined by its semi-arid climate, which is characterised by sparse and irregular rainfall. Furthermore, the rivers downstream of the dams are intermittent, with flow occurring only during periods of rainfall. The geographic location of the two dams selected for the case study is presented in figure 1.

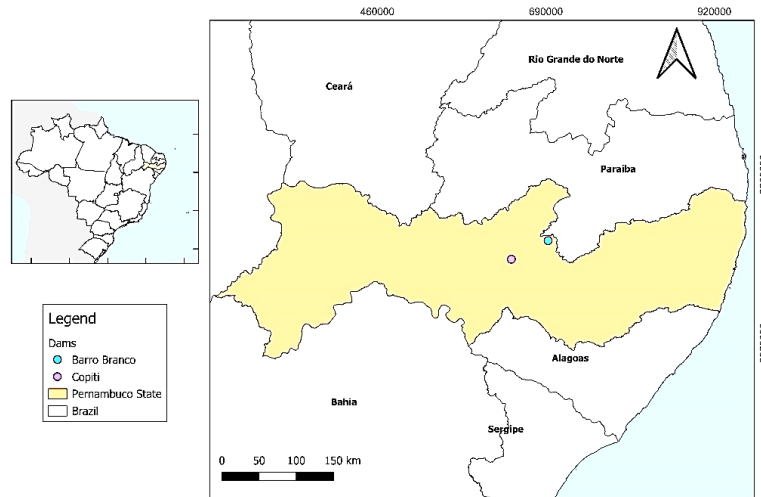


Fig. 1: Case Studies Localization Map

Table 1 presents information regarding the dams and, in addition, their classification according to the ICOLD criterion. This classification is determined by the values of the maximum height of the dam (H) and the maximum accumulated volume (V) [9].

Table 1 – Dams selected for the case study

Dam	Height (m)	Reservoir volume (hm ³)	$H^2\sqrt{V}$	Size
Copiti	17.22	6.33	746.05	Large
Barro Branco	12.56	0.27	81.97	Small

The Pernambuco region has a digital terrain model ranging from 0.5 to 1 meter, the PE3D model [10]. This accurate representation is used in urban planning, environmental management and water resource studies. [11].

2.2. Land Use and Land Cover

This study employed three high-resolution LULC datasets: Dynamic World (DW), MapBiomas 10m Collection BETA (MB), and ESRI 10m Annual Land Cover (ERSI). These datasets were chosen for their high spatial resolution and comprehensive temporal coverage, leveraging Sentinel-2 imagery to map land use and land cover at a 10-meter resolution.

MapBiomas is a dataset tailored to the Brazilian region, offering detailed annual maps for the period of 2016–2022 [4]. In contrast, ESRI provides global data from 2017–2023, generated through deep learning techniques applied to billions of labeled pixels [5]. Dynamic World stands out for its near-real-time updates (every 2–5 days), providing probabilistic labels for nine land cover classes, enhanced by cloud and shadow removal techniques [6].

A script was constructed on the Google Earth Engine platform to enable the retrieval and downloading of LULC data corresponding to the region of interest for each case study. Figure 2 presents an overview of the process for obtaining the datasets.

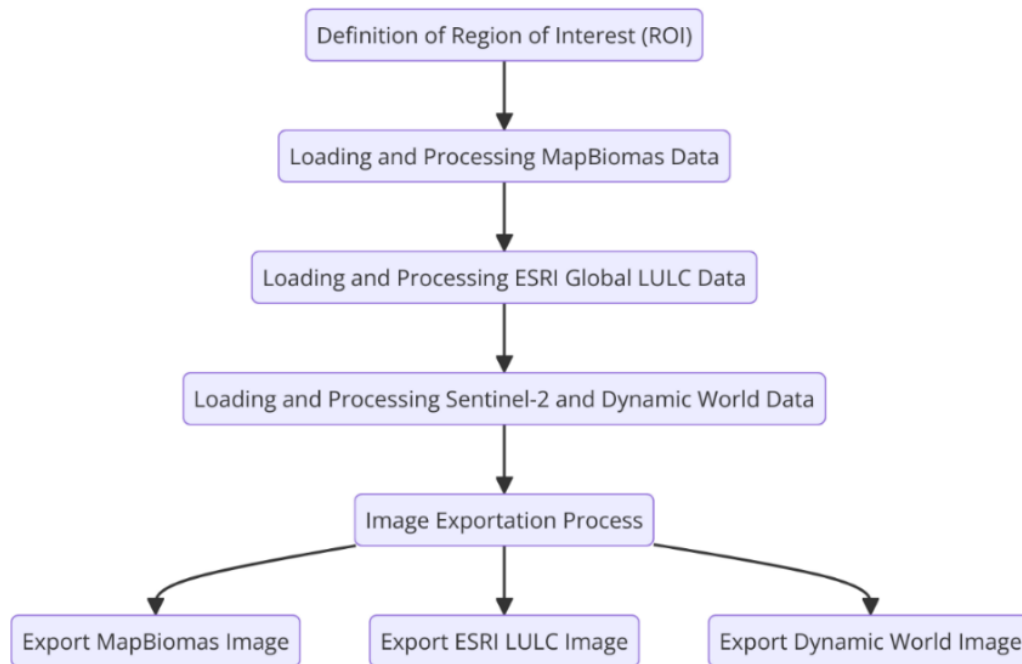


Fig. 2- Flowchart of processing Land Use and Land Cover (LULC) data in Google Earth Engine.

For the study, the 2022 MapBiomass and 2023 ESRI 10m Annual Land Cover datasets were used. Meanwhile, for Dynamic World, due to its cloud-related limitations, images from 11/2023 for Copiti valley and 07/2023 for Barro Branco valley were utilized.

The LULC data were employed as the foundation for determining Manning's roughness coefficient values, with consideration of the reference values presented in [12]. However, differences in the interpretation and classification of land cover classes, as well as for the selection of Manning value ranges, have been observed to result in varying Manning coefficients, even when analysing the same area.

In the study areas, Manning's roughness coefficient was predominantly observed to range between 0.04 and 0.08 for the MapBiomass dataset, around 0.08 for the Dynamic World dataset, and approximately 0.04 for the ESRI 10m Annual Land Cover dataset. Figure 3 illustrates these conclusions with the example of the Copiti dam.

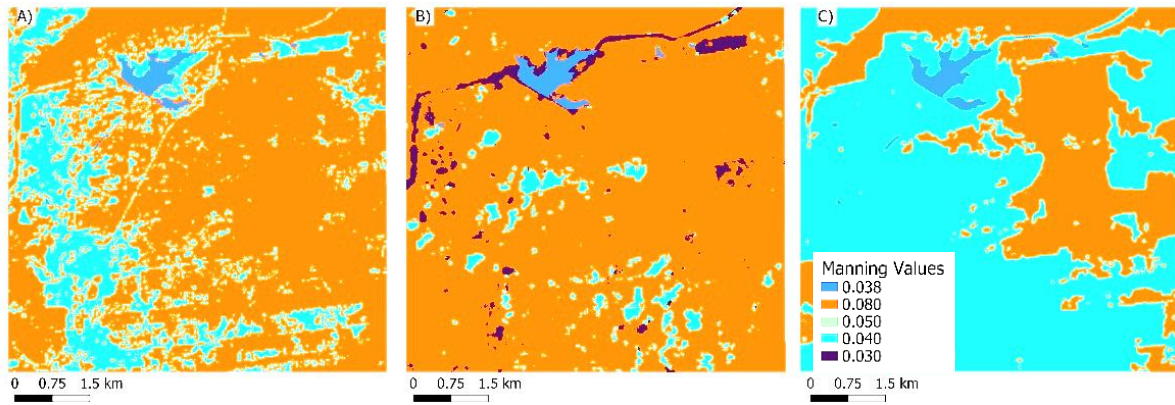


Fig. 3: Maps of Manning's roughness coefficients for Copiti Dam areas: A) MapBiomass 10m Collection BETA, B) Dynamic World, and C) ESRI 10m Annual Land Cover.

2.3. Dam Break Analysis

In the HEC-RAS model, the two-dimensional unsteady flow is solved using the mass conservation equation and the Saint-Venant momentum conservation equations along the x and y axes [13].

HEC-RAS 2D permits the specification of a default Manning's value for the entire 2D flow area and allows the designation of a Manning roughness coefficient via a Land Cover layer in RAS Mapper.

Each dam was evaluated under the assumption of a piping failure scenario, and the breach parameters were calculated using Froehlich's equations (1995), which are incorporated into HEC-RAS. The formulas used are as follows [14]:

$$t_f = 0,00254 V_w^{0,53} h_b^{-0,9} \quad (1)$$

$$B_{ave} = 0,1803 k_0 V_w^{0,32} h_b^{0,19} \quad (2)$$

where B_{ave} is the average breach width (m), t_f is the breach formation time (hours), k_0 is a constant (1,4-overtopping or 1,0-Piping), V_w is the volume of water in the reservoir (m^3) and h_b is height of water above the breach (m).

A simulation was conducted under identical conditions and consistent parameters for each dataset. For each LULC dataset, a dam-break simulation was performed to evaluate how different LULC configurations affect critical hydraulic parameters. The analysis focused on key hydraulic variables, including peak flow (Q_p), time to peak (t_p), depth (h_p), and flood area.

Flood propagation time is an important variable for planning emergency response, ensuring timely alerting of vulnerable populations and defining necessary actions. In fact, the estimated distance covered by the flood within 30 minutes defines the Self-Rescue Zone (SRZ), a

reference standard in countries like Portugal and Brazil, where rapid individual action is required.

Accordingly, the variations in distances travelled within a 30-minute period were analysed for the dams in the case study, with a specific focus on the influence of different LULC datasets.

3. RESULTS AND DISCUSSION

3.1. Flood propagation

Figure 4 illustrates the attenuation of flood discharge along the downstream valley for the Barro Branco and Copiti dams. The propagation of the hydrograph is related to the size of the dam, as simulations with Barro Branco show a rapid attenuation compared to Copiti, regardless of the LULC dataset used.

Simulations employing Manning's coefficients derived from the ESRI LULC dataset, noted for its lower roughness values, consistently produced the highest peak flows. In contrast, those using the Dynamic World LULC dataset, characterized by higher roughness, yielded significantly lower peak flows. Meanwhile, simulations based on the MapBiomas data presented results that were intermediate when compared to the aforementioned datasets, highlighting the varying impacts of land use and cover characteristics on hydrological responses.

For the Barro Branco dam, the flow rates estimated within a 5 km distance were 289.1 m³/s, 254.8 m³/s, and 206.8 m³/s, respectively, for simulations using the ESRI, MapBiomas, and Dynamic World datasets. These results indicate a 13.5% difference between MapBiomas and ESRI and a -19.0% difference between MapBiomas and Dynamic World simulations. At a 20 km distance, the difference between MapBiomas and ESRI is 12.7%, while the discrepancy between MapBiomas and Dynamic World increases to -25.1%.

For the Copiti Dam, the flow rates at a 5 km distance are approximately 1757.8 m³/s, 1705.4 m³/s, and 1617.64 m³/s for simulations using the ESRI, MapBiomas, and Dynamic World datasets, respectively. These results indicate a difference of 3.1% between MapBiomas and ESRI, and -5.1% between MapBiomas and Dynamic World.

At a 20 km distance, the simulation using ESRI shows a peak flow 11.5% higher, while the peak flow estimated using Dynamic World shows a difference of -31.1% compared to MapBiomas.

This variation can be explained by the rupture hydrograph, which was influenced by the size of the dams, resulting in lower flows for Barro Branco compared to Copiti. Additionally, the

different distribution patterns of Manning's coefficient (n) values also played an important role in this explanation.

Regarding Manning's coefficient, the average value in Dynamic World was approximately 0.08 in both analyzed regions. However, the mean values of n , considering the flooded area, were 0.06 in MapBiomass and 0.05 in ESRI 10m Annual for Barro Branco, while for Copiti, these values were 0.05 in MapBiomass and 0.04 in ESRI 10m Annual. Therefore, the distribution of Manning's coefficients in MapBiomass and ESRI 10m Annual in Copiti resulted in lower resistance to hydrograph propagation compared to Barro Branco. On the other hand, the Dynamic World simulations showed practically the same Manning's coefficient values in both areas.

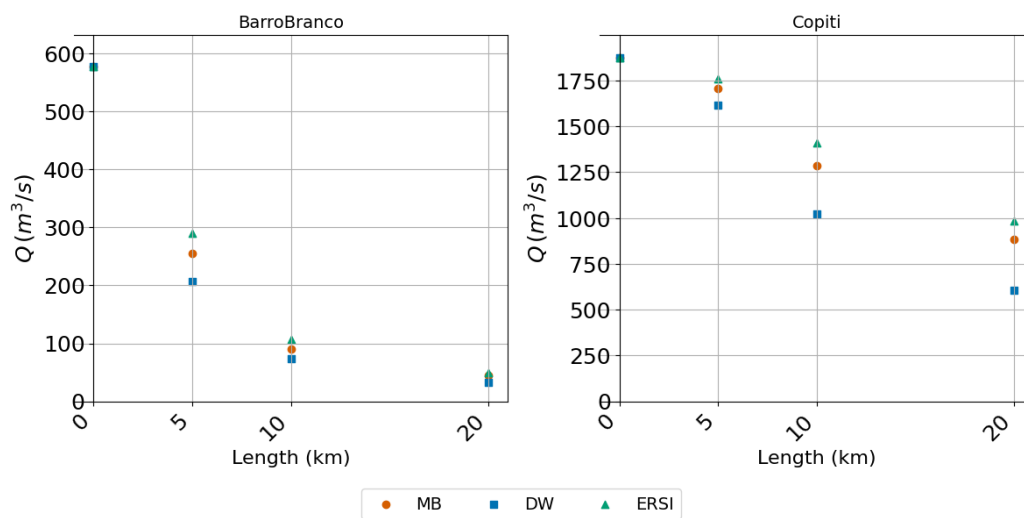


Fig. 4- Propagation of hydrographs at different distances and LULC data sets for the Barro Branco and Copiti dams - (MapBiomass (MB), Dynamic World (DW) and ESRI 10m Annual Land Cover (ERSI))

Figures 5 and 6 present the stage hydrographs of the dams under analysis and allow the evaluation of Manning's coefficient influence on the simulation results in terms of wave propagation time and depth.

The propagation of the flood wave was observed to occur at varying velocity in the simulations conducted using the three different datasets. The propagation was found to be slower in the simulations utilising the Dynamic World dataset, while the simulations employing the ESRI dataset indicated a faster propagation of the wave. The MapBiomass dataset produced intermediate results, falling between those observed for Dynamic World and ESRI.

The impact of Manning's values is evident in the comprehensive analysis conducted. The simulations utilising the Dynamic World set, which represents terrain with heightened resistance, demonstrate the lowest flow rates but record-high depth values, for instance, at 5 km in both dams. Additionally, they exhibit the second-highest value at 10 km in both dams.

However, the simulations with the ESRI dataset showed shallower depths, with the highest value occurring only at 20 km downstream of the Barro Branco dam. At this point, the distribution of Manning's values across the analyzed LULCs was very similar. The simulations using the MapBiomas dataset resulted in intermediate depth values at 5 km for both dams and at 20 km for the Barro Branco dam, but recorded the greatest depth at 10 km for both dams.

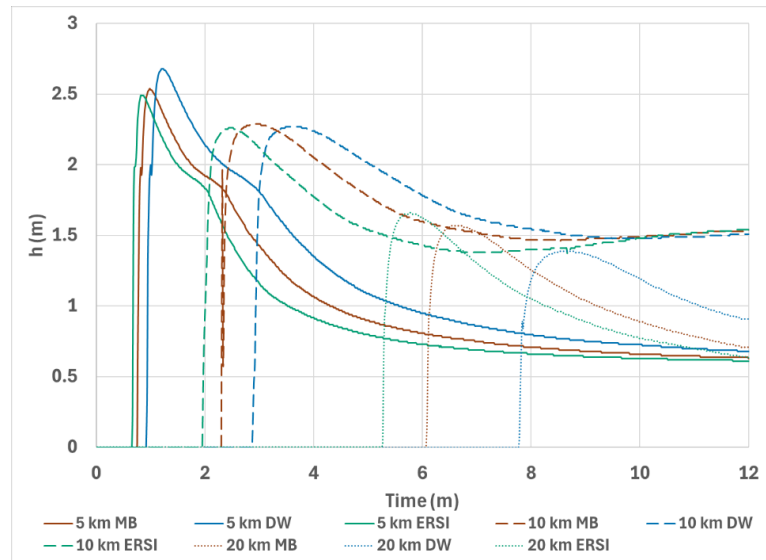


Fig. 5- Barro Branco dam stage hydrograph

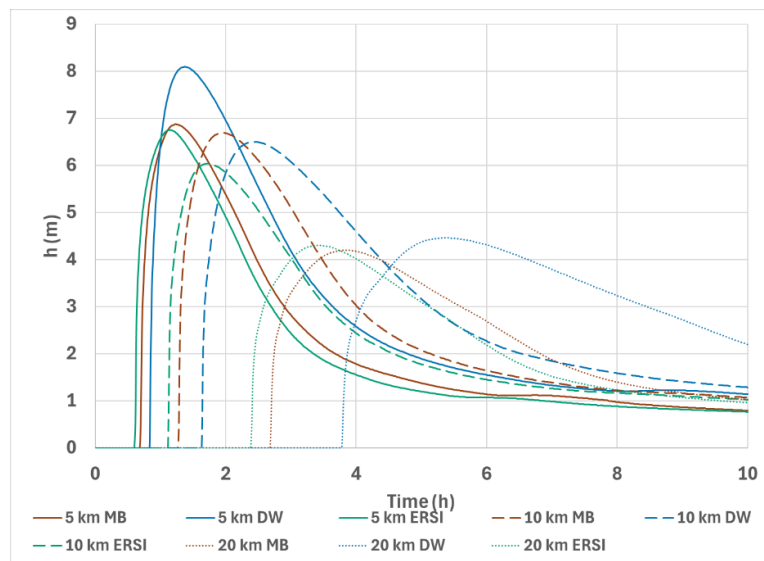


Fig. 6- Copiti dam stage hydrograph

The results indicate that flood propagation time could be a more critical factor than water depth when assessing the impact of roughness estimates in hydrodynamic modeling. While water depth is influenced by both flow rate and channel roughness, variations in roughness can significantly affect the extent of flooded areas.

These variations are primarily driven by differences in soil resistance, with simulations based on the Dynamic World dataset—which represents higher resistance—producing the largest flooded areas, followed by MapBiomas and ESRI, as shown in Table 2.

For the Barro Branco dam, the flooded area estimated by Dynamic World was 360.93 ha, which is 1.11% larger than the area simulated using MapBiomas and 1.61% larger than the area simulated using the ESRI dataset.

Similarly, for the Copiti dam, the flooded area estimated by Dynamic World was 885.27 ha, representing a 7.76% increase compared to the MapBiomas estimate and a 10.47% increase compared to the ESRI estimate.

Table 2 – Flooded Areas for Barro Branco and Copiti Dams Based on Different LULC Datasets

LULC Dataset	Barro Branco	Copiti
	Flood Area (ha)	Flood Area (ha)
Mapbiomas	356.93	816.57
Dynamic World	360.93	885.27
ERSI	355.13	792.58

3.2. Self-Rescue Zone

The analysis of simulations with different LULC datasets revealed significant differences in SRZ estimates for the dams, figure 7. The ESRI 10m Annual dataset consistently presented the highest SRZ values for both dams. On the other hand, the Dynamic World dataset produced the lowest values for both dams.

The MapBiomas dataset presented intermediate SRZ values for both dams, reflecting an intermediate response in terms of distance compared to the other LULC datasets. Figure 6 highlights the variability in SRZ distances for the Barro Branco and Copiti dams as a function of the different LULC datasets analyzed.

The differences in SRZ estimates among the LULC datasets for the Barro Branco dam are significant. The Dynamic World predicts a 16.4% reduction in the extent of the saturated zone (SRZ) compared to MapBiomas. On the other hand, the ESRI dataset shows the largest SRZ extent, with an increase of 10.4% compared to MapBiomas.

For the Copiti dam, the differences among the datasets are also notable. Dynamic World predicts the smallest SRZ extent, with an 18.3% reduction compared to MapBiomas. In contrast, the ESRI dataset estimates the largest SRZ extent, representing a 16.6% increase compared to MapBiomas.

The Copiti dam exhibited lower SRZ values across all datasets compared to the Barro Branco dam. This disparity can be attributed to the breach characteristics of the dams. Specifically, dams with faster failures, characterized by shorter breach formation times, result in a quicker onset of hydrograph propagation.

The discrepancy between the calculated distances for the SRZ illustrates the significance of establishing Manning coefficient values and formulating an effective emergency plan. In the Dynamic World simulation, when Manning values are higher and propagation is slower, the SRZ may appear to be undersized. However, simulations with faster propagation result in a greater distance from the SRZ, which, in theory, may enhance safety but may necessitate a considerable investment in rapid evacuation strategies.

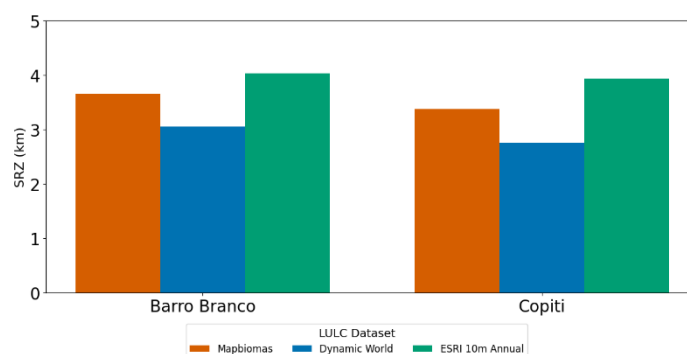


Fig. 7 – SRZ Estimates for dams using different LULC dataset

4. CONCLUSIONS

The results demonstrate that the employment of LULC datasets can serve as a valuable informational resource for the determination of Manning's coefficient in the hydrodynamic modeling of dam failures, particularly in regions where data is scarce. However, the differences observed between the LULC data indicate that they exert a considerable influence on estimates of critical hydraulic parameters, including peak flow, flood wave propagation time, flooded areas, and the delineation of the SRZ.

The analyses showed that the estimated flood areas varied significantly between the different LULC datasets, highlighting the direct effect of terrain roughness on modelling results. Simulations based on the Dynamic World set with higher Manning coefficients resulted in larger flood areas, potentially increasing the magnitude of impacts and the need for planning and mitigation.

However, the ESRI set, despite estimating higher flows due to the lower roughness coefficients, produced more restricted flood areas which may underestimate the real impact in certain scenarios.

In the case of the SRZ, higher Manning's coefficients, such as those observed in Dynamic World, resulted in smaller SRZ extensions, which could lead to under sizing of this area and compromise the effectiveness of emergency response. In contrast, the ESRI set resulted in larger SRZ extensions, which may increase safety, but could lead to higher costs in implementing evacuation strategies. These results reinforce the need to balance safety and operational costs in emergency planning. The choice of the LULC dataset also had an impact on the depth of the flows. Regions with greater roughness showed higher depths, even in low flow scenarios, showing that channel roughness plays a crucial role in flow dynamics. The use of LULC datasets from MapBiomass showed intermediate results in terms of flood areas, peak flows and SRZ delineation. This characteristic is directly related to the influence of the assumed Manning values derived from the detailed regional soil classification. These results may indicate a preference for regional LULC data, such as MapBiomass, whenever available. In this sense, the definition of the Manning coefficient is not merely a technical data point for models; it constitutes an indispensable element for public safety. Subsequent studies should prioritize refining LULC databases and their influence on downstream damage, including the population at risk, the affected infrastructure, and additional considerations.

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