INTEGRATED FLOOD MODELING FOR URBAN RESILIENCE PLANNING FOR MANDAUE CITY, PHILIPPINES

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ABSTRACT: Urban flood resilience planning in the Philippines is necessary due to the country's vulnerability to natural disasters and the effects of climate change, which increase the risk of flooding in urban areas. The high population density in urban cities further exacerbates this vulnerability making it crucial to have well-informed maps to serve as guides for disaster mitigation, prevention, and preparation. This study aims to create a 2D urban flood model for Mandaue City, Philippines integrating its urban aspects of road networks, drainage systems and other flood control structures to create a comprehensive hydrodynamic model. Data integration was created through Geographic Information System (GIS) and followed by 2D flood modelling in the Flo-2D program. The objective of the study aims to provide insights that can support the development of effective flood resilience planning. This planning will help prioritize tasks such as managing population growth, implementing measures to mitigate urban flooding, and integrating considerations of flood risks into urban development plans. Additionally, the results can help shed light into solutions to reduce the economic impact of flooding, ensure public health and safety, and foster environmental conservation.

1. INTRODUCTION

The Philippines is one of the most densely populated countries in the world with a significant portion of its population residing in urban centers. Urbanization trends continue to grow, and as more people migrate to cities, the concentration of infrastructure and economic activity in these areas intensifies. This underscores the paramount importance of urban flood resilience planning in the country due to its susceptibility to natural disasters and the escalating impacts of climate change. The archipelago's geographical location exposes it to various environmental hazards, with flooding being a particularly frequent and devastating occurrence. With the vulnerability to flooding exacerbated as urban areas expand, often without adequate urban planning and flood resilience measures in place, it becomes imperative to adopt proactive measures to mitigate and prepare for urban flooding, especially in densely populated urban areas.

Metro Cebu, nestled in the eastern region of Cebu Island, has emerged as a dynamic urban center within the Philippines, profoundly influenced by the forces of globalization. The transformative impact of globalization on Cebu's economy experienced a significant impetus during the 'Ceboom' phenomenon of the 1990s, characterized by the adoption of investment-oriented policies and a stance of openness (Ortega, 2012). These policies reshaped the urban landscape of Cebu City, leading to its expansion into the surrounding regions. However, this expansion, marked by urban sprawl, has brought about an exacerbation of inter-city traffic woes, partly fueled by rising incomes, which have enabled individuals to seek affordable single-detached homes in suburban areas. These residential choices, in turn, have given rise to bedroom communities, with extended commutes to employment hubs concentrated in special economic zones (SEZs) and export processing zones (EPZs) situated in core cities like Cebu, Mandaue, and Lapu-Lapu. This rapid urbanization, penetrating peri-urban territories and neighboring municipalities, has outpaced the limited planning, financial resources, and governance capacities of local government units, thereby precipitating a series of challenges encompassing disorganized land use, traffic congestion, environmental degradation, and stark socio-economic inequalities within and between cities. Evidently, the escalating urbanization in Cebu underscores the imperative for adept and vigilant urban management, recognizing that the absence of sound governance in metropolitan regions engenders profound social and environmental costs, ultimately jeopardizing the potential benefits of globalization (Sevilla, 2017). Moreover, the continued unchecked expansion of settlements, coupled with the degradation of hillside vegetation, heightens the vulnerability of low-lying and flatland areas to landslides and flooding, which have become increasingly severe during episodes of heavy rainfall (Sevilla, 2018).

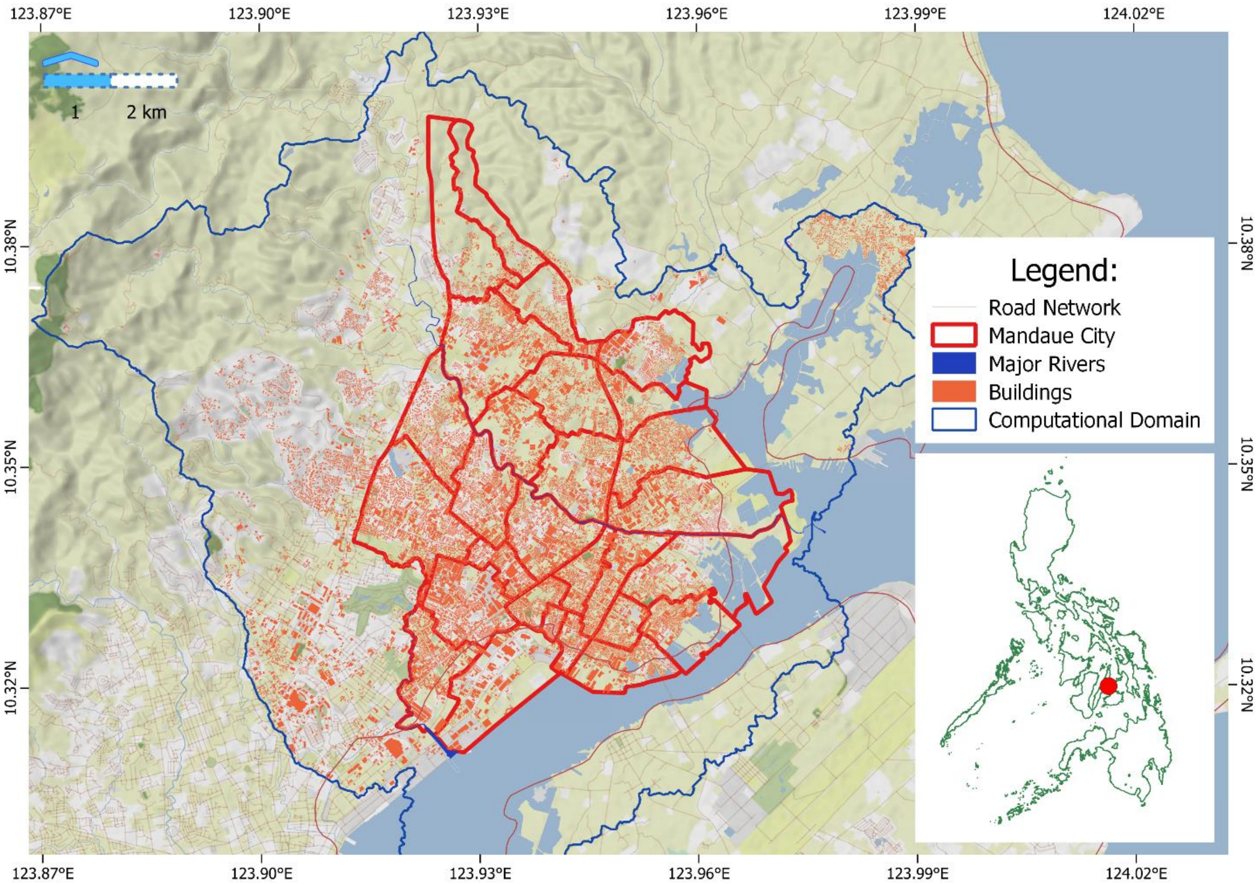

Figure 1. Study Area: Mandaue City, nestled in the plains of Metro Cebu

Perennial flooding stands as an enduring and pressing concern for Mandaue City (Figure 1), especially during the rainy season. Real estate experts have identified deficient urban planning practices as a root cause of this recurrent issue. Notably, the granting of development permits without the requisite infrastructure, such as proper sewerage systems, has been pinpointed as a contributing factor. Moreover, the present drainage system in the city is deemed inadequate for the contemporary urban landscape, necessitating an urgent expansion (Leyson, 2017). The problem is further compounded by improper waste disposal practices and an array of factors including increasingly extreme weather patterns, rampant urbanization in hilly terrains, and extensive construction in uptown areas. These elements collectively strain the already overburdened drainage system, exacerbating the problem of flooding. The consequences of such recurring flooding are not limited to environmental concerns alone; they extend to impeding economic growth within the urban areas. In addition, Illegal settlers residing along creeks and riverbanks in the city encroach upon the right-of-way of open canals reducing their width, compounded by improper waste disposal practices, and unchecked expansion of settlements and the degradation of hillside vegetation all heighten the vulnerability of low-lying areas to landslides and flooding (Sevilla, 2018).

The presence of these vulnerabilities underscores the critical need for well-informed maps that can serve as valuable tools for disaster mitigation, prevention, and preparedness. This study aims to develop a 2D urban flood model for Mandaue City, Philippines, which will encompass various urban elements, including road networks, drainage systems, and other flood control structures. This comprehensive hydrodynamic model will be instrumental in guiding various planning efforts, such as addressing population growth management, implementing strategies to mitigate urban flooding, and integrating flood risk considerations into urban development plans. Moreover, the outcomes of this study have the potential to provide insights into effective measures to minimize the economic impact of flooding, ensure public health and safety, and promote environmental conservation.

2. METHODOLOGY

The vulnerability of the Philippines to natural disasters and climate change, coupled with high population density in urban areas, underscores the necessity of urban flood resilience planning. The development of a 2D urban flood model for Mandaue City exemplifies a proactive approach to addressing these challenges by integrating critical urban elements into a comprehensive hydrodynamic model, ultimately helping informed decision-making and disaster risk reduction strategies.

The creation of a comprehensive hydrodynamic model means that the study will consider not just static flood maps but dynamic models that simulate the behavior of floodwaters over time. This allows for a more accurate prediction of flood extents, depths, and velocities during different rainfall and storm scenarios. This study aims to create a 2D urban flood model specifically tailored for Mandaue City, Philippines and integrate various urban aspects such as road networks, drainage systems, and flood control structures into a comprehensive hydrodynamic model.

2.1 Study Area

Mandaue City, Cebu(10.3321° N and 123.9357° E), is a high-income urban center within Cebu island, Philippines (Figure 1). It is a pivotal component of the Cebu Metropolitan area, located in the Central-Eastern coastal region of Cebu. As the second-largest city in the province, it has historically functioned as a hub for trade with other countries and presently serves as a source of social, recreational, and economic opportunities not only for its residents but also for those in the surrounding provinces (Mahoney and Klitgaard, 2019; Banados & Quijano, 2022). The city is characterized by a primary waterway, the downstream section of the Butuanon river, and it acts as a catchment area for various rivers and streams originating from a nearby densely populated city (Cortes et al., 2022). Given its equatorial proximity, the city experiences two distinct seasons - rainy and sunny - classified under the Coronas climate type 3. The rainy season typically spans from June to November, contributing to an average annual precipitation of 1,570 millimeters (JICA, 2010).

2.2 Flood Simulation

FLO-2D GDS Pro is a flood-routing software that employs a dynamic-wave momentum equation and finite-difference routing to create flood and debris flow hazard maps. This software, a GIS-integrated tool for modeling river and floodplain dynamics, is used to run the 2D Flood simulation for the study. This is accomplished by imitating the movement of water across a grid built up of square segments (UP TCAGP, 2015). 10-meter by 10-meter grids that cover the whole area of interest were created using GIS and FLO-2D. The area's boundaries can be established by either manually defining each component or by drawing a line around the subcatchment's perimeter. The computational domain for the flood simulation is made up of the grid components that are encircled by the defined boundary.

Elevation data was imported in the form of a LiDAR-generated DEM extrapolated into the model's grids, providing an elevation value foreach grid element. After which, streamlines were generated from the elevation raster to add to the stream shapefiles provided by the Mandaue City Local Government Unit (LGU). After which the corresponding Manning's roughness coefficient values, as shown in table 2, was assigned corresponding to the land use or land cover of the corresponding element based on Zhang et al’s (2013) study. The datasets used are outlined in table 2 below and the corresponding land use roughness coefficients are shown in figure 2.

Table 1. Datasets used and their corresponding sources

Dataset	Source
Rainfall	DOST PAG-ASA
Elevation	LiDAR Derived
Land Cover/ Land Use	Global Map of Local Climate Zones (Demuzere et al, 2022)
Road Networks	Mandaue City LGU
Building Datasets	Mandaue City LGU
Stream Networks	Elevation Generated
River Networks	Mandaue City LGU

The 25-year return rainfall intensity-duration-frequency (RIDF) data from the Mactan station was used due to its proximity to the area of interest and has the closest rainfall values to the available historical data for validation. For the infiltration parameters, the study uses the Green-Ampt infiltration method, with the initial saturation applied to the 25-year model being 0.8.

Table 2. Manning's Roughness Values for every Land Use Classification

No.	Land Use/ Cover	Roughness Coefficient (Zhang, 2013)
1	Compact highrise	0.13
2	Compact midrise	0.12
3	Compact lowrise	0.11
4	Open highrise	0.07
5	Open midrise	0.06
6	Open lowrise	0.05
7	Lightweight lowrise	0.04
8	Large lowrise	0.03
9	Sparsely built	0.05
10	Heavy industry	0.13
11	Dense Trees (LCZ A)	0.11
12	Scattered Trees (LCZ B)	0.1
13	Bush, scrub (LCZ C)	0.05
14	Low plants (LCZ D)	0.04
15	Bare rock or paved (LCZ E)	0.09
16	Bare soil or sand (LCZ F)	0.09
17	Water (LCZ G)	0.02

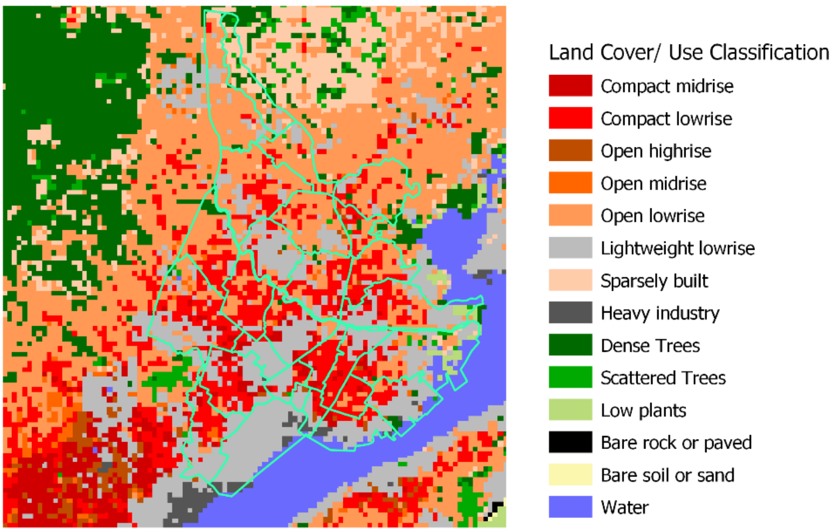

Figure 2. Urban land cover/ use map for Mandaue City

2.3 Urban Flood Model Dynamics

In recent decades, fluvial and coastal flood modeling, along with inundation mapping, have been extensively studied and have become standard procedures, hinging on the precision of topographic and hydrological data inputs (Neelz et al., 2013). In contrast to the comparatively straightforward terrains observed in river and rural catchment areas, urban landscapes are set apart by intricate and irregular topography, which includes buildings, drainage networks, and critical infrastructure. The complex dynamics and nonlinear interactions of hydrological, hydrodynamic, and hydro-morphological processes throughout this urban context present substantial modeling challenges. Furthermore, the diversity of urban surface characteristics makes modeling of urban flood models more challenging (Guo et al, 2021).

Beyond the topographical characteristics, an accurate depiction of the urban infrastructure is crucial for realistic urban flood modeling to capture the dynamics of flow wave propagation. All buildings within the domain, totaling 72,369 features, were integrated into the FLO-2D computational domain (Figure 3). These polygon vectors were translated as Reduction Factors, designating the grid element surface area as impervious and excluding it from potential water interactions. In addition, the study adds these building features and road/ street networks into the roughness computation in the model to evaluate street flow and account for flow path obstructions.

Figure 3. Urban Flood Elements

To get the better floodplain scenario, the study utilizes the drainage network map of the local government unit of Mandaue City with 1,369 storm water drains as inlets and 44 outfalls flowing to the nearby waterbodies (Figure 3). The exact location of the storm drain inlets and outfalls in the study's two-dimensional grid system was determined using the Flo-2d QGIS plugin, and flood routing and two-dimensional inundation analysis were performed using the FLO-2D GDS. We do this to accurately portray the influence of buildings and roads on flood waves and to describe the complex floodplain topography. The overflows of the city's storm drain system was estimated using EPA-SWMM and introduced into the input file of FLO-2D, which assisted in the setup of our 2D models.

3. RESULTS

This study developed a complete 2D urban flood model designed for Mandaue City, Philippines, effectively integrating important urban aspects such as building structures, road networks, and drainage networks within its floodplain. Fieldwork validation was done in August – September 2022 to get accurate historical flood depth values from communities in Mandaue City. 150 points randomly generated all over the computational domain in Mandaue City was validated through in-person interviews (Figure 4). After comparing the flood depth map to the nearest rainfall event, which corresponds to the calculated rainfall of 208.5mm in 24 hours, the resulting model has an RMSE value of 0.5657 meters. Figure 5 and 6 shows the flood hazard and flow depth obtained from the simulation of the 25- year rain return period (208.5 mm) in accordance to the set of roughness used.

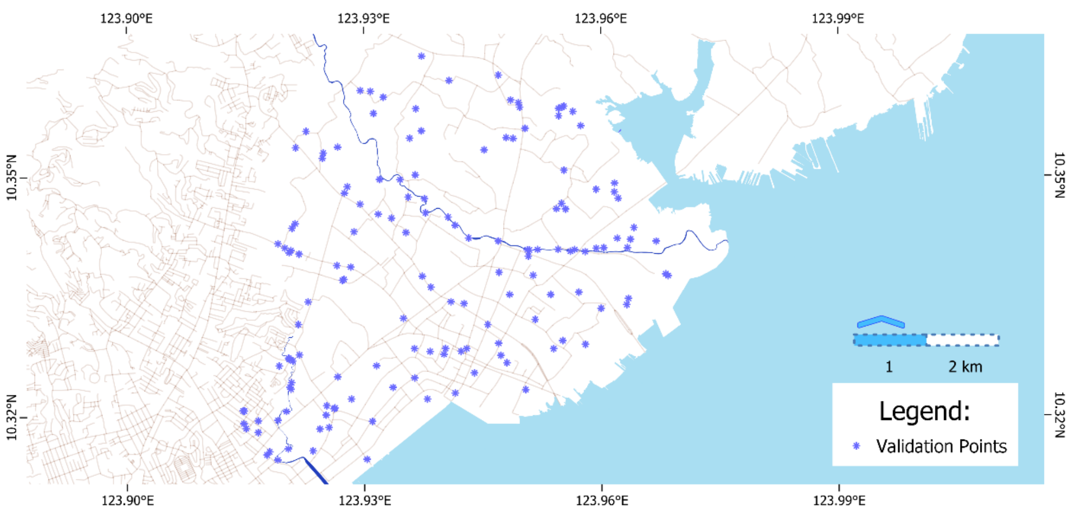

Figure 4. Flood validation points generated throughout the floodplain

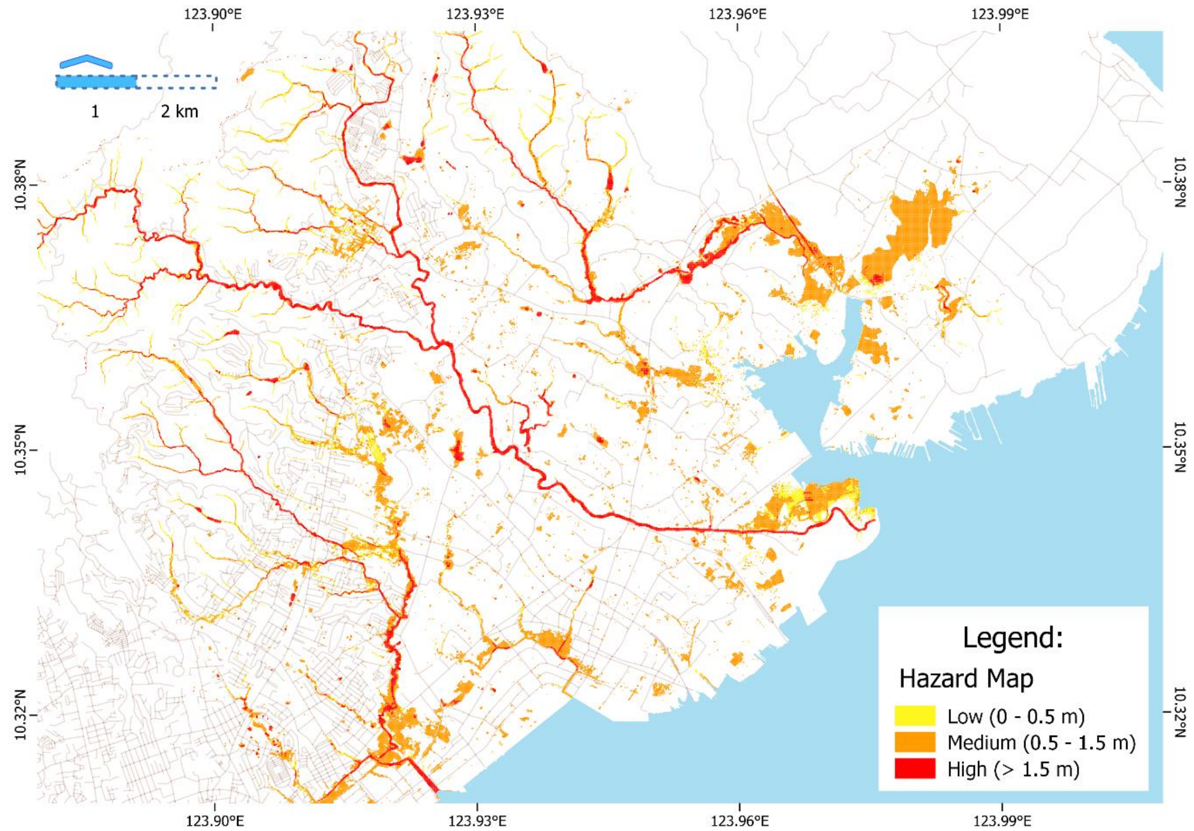

Figure 5. 25-year Urban Flood Hazard Map of Mandaue City

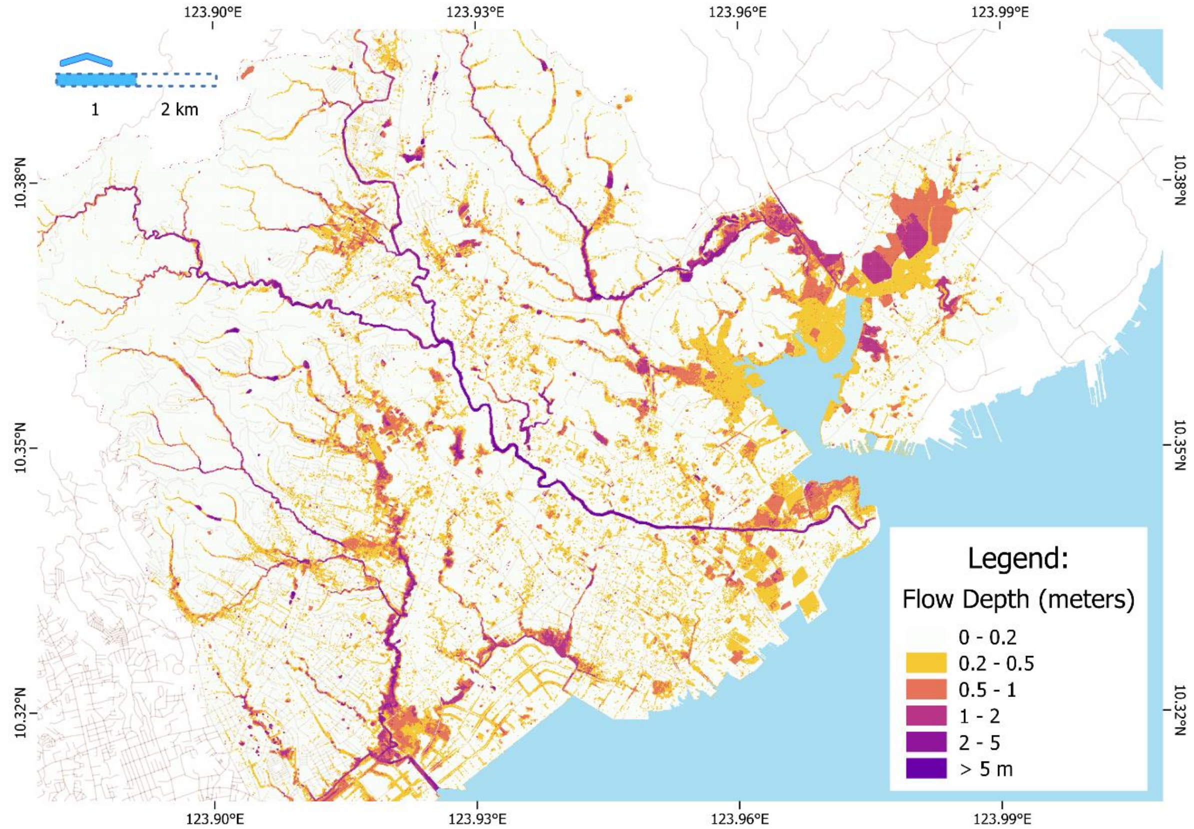

Figure 6. 25-year Urban Flood Depth Map of Mandaue City

4. CONCLUSION

This study developed a complete 2D urban flood model designed for Mandaue City, Philippines, effectively integrating important urban aspects such as building structures, road networks, and drainage networks within its floodplain. The utilization of Geographic Information System (GIS) in tandem with 2D flood modeling within the Flo-2D program, along with the incorporation of EPA-SWMM for storm drain network integration, has proven to be instrumental in this endeavor.

The FLO-2D model has emerged as a versatile and adaptable tool for predicting flood hydraulics, delineating inundation zones, and formulating flood containment strategies. It has effectively forecasted floodplain inundation, encompassing flood hydrograph routing, the projection of street-level inundation, and the intricate dynamics of urban flooding, accounting for factors like building obstructions that amplify flow depths in surrounding areas.

Furthermore, the study's simulation of a 25-year rain return period using FLO-2D demonstrated a strong correlation with historically observed inundation extents, as verified through field validation. This alignment underscores the model's reliability and its potential as a valuable resource for flood risk assessment and management in Mandaue City.

Overall, the developed 2D urban flood model and its successful application provide an essential foundation for enhancing flood resilience and informed decision-making in the city. The outcomes of this study hold significant promise in bolstering urban flood preparedness, safeguarding public safety, and promoting sustainable urban development practices while mitigating the adverse impacts of flooding.

FLO-2D serves as a valuable tool for generating urban flood hazard maps and can be applied to various urban areas in the Philippines, offering crucial insights into urban inundation risks amid ongoing urban expansion. The unchecked growth of settlements and hillside vegetation degradation heighten the vulnerability of low-lying areas to landslides and flooding, necessitating targeted interventions. To enhance the reliability of simulations, it's essential to validate results with historical data. The combination of numerical modeling, remote sensing, and field validation can significantly reduce the expenses associated with comprehensive hazard mapping in urban regions.

The primary goal of this research was to provide valuable insights that can inform the formulation of effective flood resilience plans. These plans are essential for addressing critical tasks such as managing population growth, implementing strategies to mitigate urban flooding, and integrating flood risk considerations into urban development plans. Furthermore, the study's findings offer potential solutions to minimize the economic repercussions of flooding, enhance public health and safety, and promote environmental conservation within the city. Overall, this research contributes to the advancement of flood risk management strategies in urban areas and underscores the importance of proactive planning in the face of increasing flood risks.

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