

Flood Risk Assessment in the Sungai Senggarang Catchment Using InfoWorks ICM

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Abstract

Flooding poses a significant threat to low-lying areas, affecting lives, infrastructure, and ecosystems, and is further intensified by climate change, urbanization, and extreme weather. This study investigates flooding in the Sungai Senggarang catchment, Batu Pahat, Johor, using InfoWorks Integrated Catchment Modelling (ICM). A 3D terrain model from GIS, river survey data, and historical rainfall records from the 2006/2007 flood were integrated to simulate flood maps under current and projected future land use scenarios. Design storms with 20-, 50-, and 100-year ARIs for a 6-hour critical storm were applied. The results indicate a substantial increase in runoff and flood extent with increasing ARI and future development. Under present land-use conditions, the flood-affected area increases from approximately 13% for the 20-year ARI to about 33% for the 100-year ARI. This proportion further increases under future land-use scenarios, reaching approximately 41% for the 100-year ARI. The software's effectiveness was validated by the close similarity between the simulated present-day 50-year ARI flood map and the historical 2006/2007 flood event. This study demonstrates that advanced flood modelling software can provide critical insights into the extent and severity of flooding under varying development and climate conditions, supporting the integration of hydrological, hydraulic, and topographic data for more effective flood risk management.

1. Introduction

A flood refers to the occurrence where an unusually high volume of water exceeds the capacity of a river or stream channel, causing it to overflow its banks. River flooding is the most common type of freshwater flood worldwide [1], with monsoonal rainfall playing a particularly significant role in regions such as Asia. Malaysia experiences two main monsoon seasons: the southwest monsoon from late May to September and the northeast monsoon from November to March. The transitional phase between these monsoons occurs in October and is flanked by two inter-monsoon periods, from April to May and October to November [2]. While the monsoon seasons bring prolonged, widespread, and heavy rainfall, the inter-monsoon periods are known for short-duration but intense convective storms, typically marked by variable winds and afternoon thunderstorms.

The combination of high equatorial heat, regional pressure differences, and Malaysia's maritime climate contributes to the development of extreme weather events [1]. Globally, flooding has become increasingly severe due to rising sea temperatures and levels, as well as the increasing frequency and intensity of storms. This situation is further exacerbated by rapid urbanization and climate change [3], [4]. Consequently, human displacement is forecasted to increase in the future as severe floods compounded by rising sea levels are expected to submerge some cities [5]. The district of Batu Pahat in Johor is among the areas repeatedly affected, particularly in low-lying areas such as the Sungai Senggarang catchment. Previous studies have identified three major floods in 1984, 2006, and 2007 as the most severe recorded in the area. In 2006 and 2007, consecutive unexpected rainfall events caused floods with depths ranging from 0.3 m to 1.0 m, resulting in substantial damage to local communities and infrastructure, with stagnant water persisting for more than two months. Recurring flood events, including the most recent in 2023 [6], highlight the urgent need for detailed flood mapping and modelling, as well as improved flood risk assessment and mitigation strategies.

Flood modelling software serves as a valuable tool for forecasting floods and evaluating the performance of existing channels under varying storm conditions. The use of 2D hydrodynamic models has become increasingly crucial in flood studies, as they enable accurate simulation of overland flow and floodplain dynamics, particularly in complex catchments. While several open-source hydrology and hydraulic models are available, InfoWorks ICM was adopted in this study due to its integrated 1D–2D modelling framework, which enables the simultaneous simulation of river channels, floodplains, and surface runoff processes. The model has been widely applied and validated in previous flood studies, particularly for urban and semi-urban catchments, where accurate representation of flow interactions between channels and floodplains is required. InfoWorks ICM combines hydrological and hydraulic modelling with detailed spatial data, allowing for a more reliable representation of flood extents, depths, and runoff behaviour under diverse land-use and climate scenarios [7], [8]. Although flood modelling studies in Malaysia have increasingly adopted advanced tools such as InfoWorks ICM, the majority have focused on larger, more urbanised basins, including the Damansara [7] and Gombak [8] catchments. In contrast, smaller coastal and low-lying catchments such as Sungai Senggarang, which experience recurrent flooding, remain underexplored despite their high vulnerability. Moreover, previous studies often faced calibration limitations due to the absence of continuous gauging data [9], [10] and did not fully exploit high-resolution LiDAR terrain and GIS-based datasets to improve model accuracy [7], [10].

To address these gaps, this study integrates hydrological, hydraulic, and high-resolution spatial data within a coupled 1D–2D framework, validated against historical flood records, to provide detailed flood maps and risk insights for Sungai Senggarang. Therefore, this study aims to develop flood maps for the Sungai Senggarang catchment using InfoWorks ICM under present and future land-use conditions, and to evaluate the model's effectiveness for flood risk management in small, low-lying catchments.

2. Methodology

2.1 Study Area

The Sungai Senggarang catchment, located in Batu Pahat, lies along the western coastal zone of Johor Barat. Sungai Senggarang is generally a low-lying coastal area with slightly raised interiors, as illustrated in Fig. 1, which makes it prone to flooding and vulnerable to multiple major flood events over the past two decades. Historical records documented that the most severe flood event occurred in 2006/2007 [9], during which thousands of residents were severely affected and had to seek temporary shelter for several weeks [11].

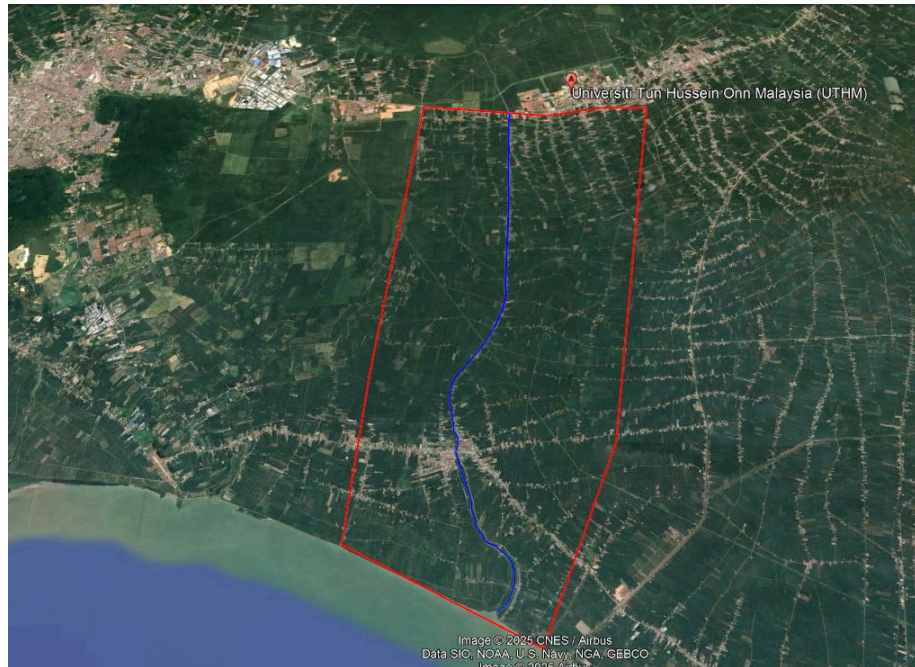


Fig. 1 Location of the study area

2.2 Climate and Rainfall Characteristics

The study area has a warm and humid climate with minimal seasonal variation in temperature, persistently high humidity, irregular cloud cover, low wind speeds, and abundant but seasonal rainfall. The average annual temperature is approximately 27°C, with monthly fluctuations ranging from 30°C in May to 25°C in December. The Sungai Senggarang catchment receives substantial annual rainfall, ranging from 2000 to 2300 mm, influenced by several climatic factors. Heavy rainfall typically occurs during the southwest monsoon (March–May), with monthly totals reaching up to ~ 240 mm, while the highest rainfall is generally recorded during the westerly wind period (September–November), with monthly totals up to ~ 300 mm. In addition, the northeast monsoon (November–January) significantly affects rainfall variability in the basin.

To quantify these characteristics, intensity–duration–frequency (IDF) curves were developed using rainfall data from three monitoring stations within and around the basin, as listed in Table 1. The locations of these stations are illustrated in Fig. 2. IDF curves, widely used for peak discharge estimation, were applied to derive design rainfall intensities for average recurrence intervals (ARIs) of 20-, 50-, and 100- years, across storm durations ranging from 15 minutes to 48 hours. This analysis followed the methodology outlined in the Department of Irrigation and Drainage’s Hydrological Procedure No. 1: Estimation of Design Rainstorm in Peninsular Malaysia [12], which prescribes the use of IDF relationships for determining design storms. Complementary water-level and streamflow records were also analysed to assess hydraulic and hydrological characteristics and to establish the rainfall–runoff relationship of the river system.

Table 1 Rainfall stations near the study area

Station Index	Station Name	Data Period
1829003	Pintu Kawalan Parit Bintang	1979-2019
1931003	Empangan Sg. Sembrong di Air Hitam	1982-2019
1732004	Parit Madirono at Site 4	1978-2019

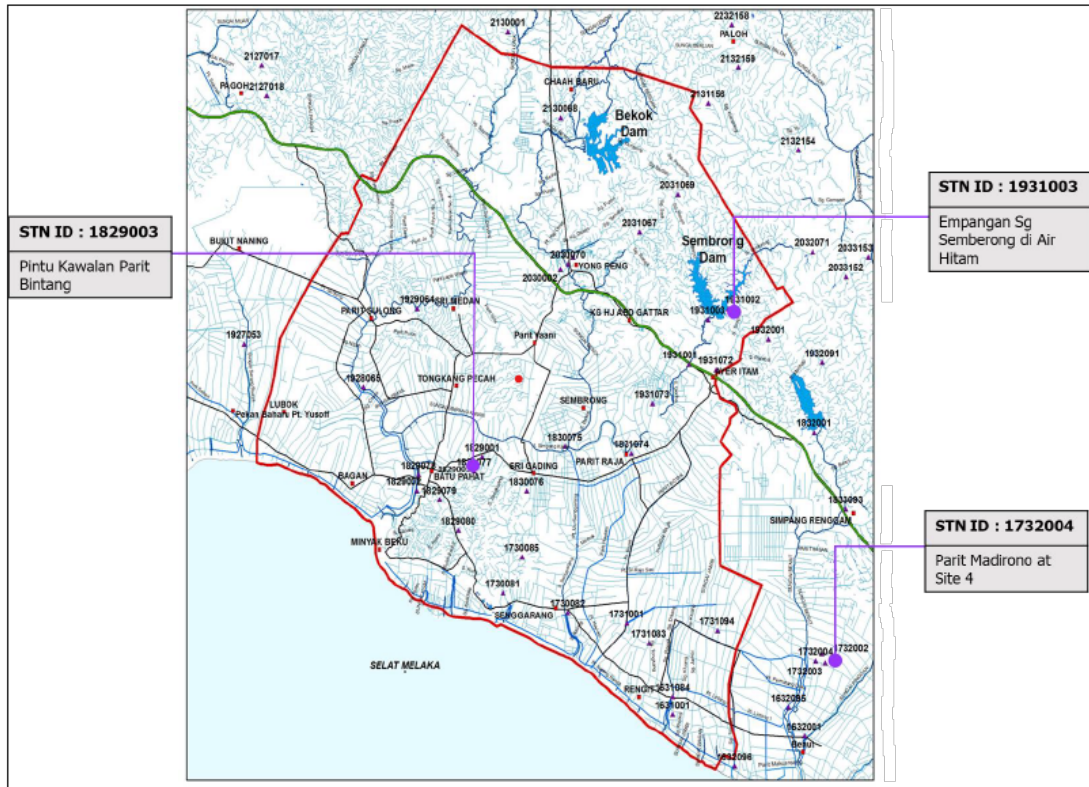


Fig. 2 Location of rainfall stations near the study area

2.3 Topography

The soil data was used in the study on determining soil infiltration of rainwater into soil. Based on soil classification and mapping, the area predominantly consists of clayey soils, specifically the Kranji, Linau-Sedu, and Selangor-Kangkong series as illustrated in Fig. 3. These soils are known for their low infiltration rates, typically in the range of approximately 0.004 – 0.007 mm/s, and high runoff potential, which contribute to the area’s vulnerability to flooding. When saturated, these soils significantly reduce natural drainage capacity, thereby worsening flood conditions. The study area is predominantly agricultural, with most of its terrain dedicated to farming and irrigation-based activities. Oil palm, coconut and fruit crops are crops that are planted in the study area. This long-standing agricultural focus has shaped the region’s infrastructure, including its drainage systems, which were initially designed to manage runoff from cultivated land rather than urban surfaces. As a result, the drainage network lacks the capacity and structure required to support effective urban flood control. According to the Department of Irrigation and Drainage Malaysia (DID) [13], the existing system in Batu Pahat was built to handle stormwater runoff for events up to a 10-year ARI. When rainfall exceeds this threshold, the limited capacity of the system leads to surface water overflow and increases the risk of flooding in surrounding areas.

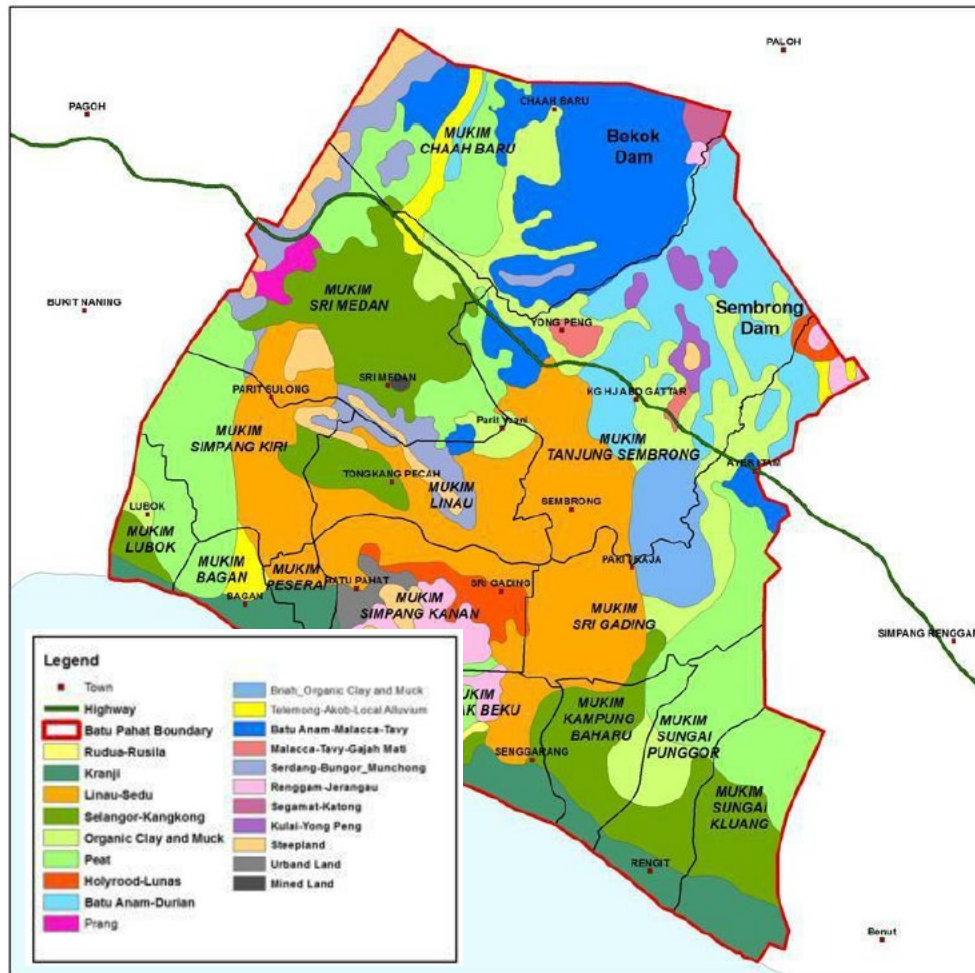


Fig. 3 Hydrology soil group map for Batu Pahat [9]

2.4 Flood Modeling

Flood modelling serves as a quantitative tool for planning, designing, and managing flood risks. The overall methodology followed a structured workflow as illustrated in Fig. 4. The process began with the collection of hydrological, river network, and terrain datasets, followed by hydrological analysis and river model development. These were integrated into an in-bank drainage/river model, which was calibrated and validated against historical flood records. The verified model was then extended to a 2D floodplain domain to simulate flood behaviour, generate flood maps, and export results into GIS format for spatial analysis and visualization [14]. This integrated workflow ensures a comprehensive and reliable approach to flood risk assessment and mapping.

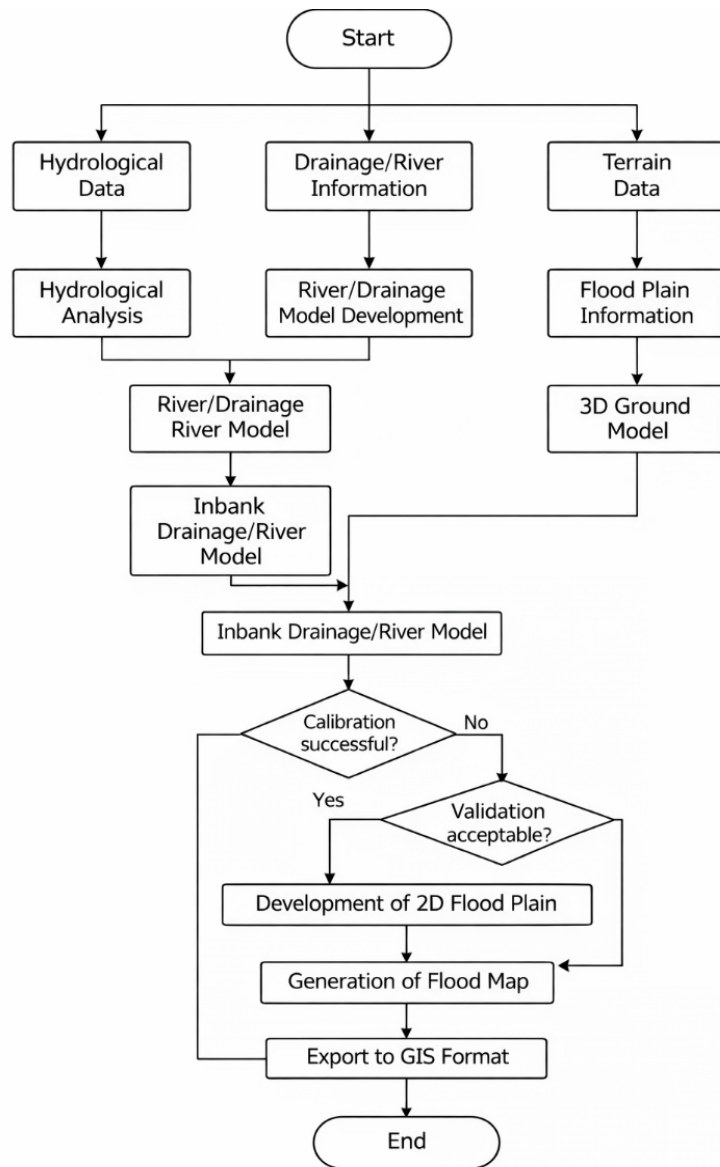


Fig. 4 2D hydrodynamic for flood plain and flood map development

2.4.1 Data Input

The development of the flood model relies on three key datasets: hydrological data, drainage and river network information, and topographic data (Table 2). Hydrological data, including rainfall and streamflow records, are essential for simulating runoff generation within the catchment. The rainfall data from the year 2006/2007 was referenced due to the significance of the flooding event during that period. Although the event is relatively dated, it provides valuable historical insight into extreme rainfall patterns and their impact on the study area, serving as a benchmark for analyzing flood risk and designing mitigation measures. These data are typically obtained from DID Malaysia and used to define storm events with varying average recurrence intervals (ARIs) for model input. The primary source of land use information was PLANMalaysia Johor, supplemented by data from the respective local councils. Future land use was referenced from the *Rancangan Struktur Negeri Johor 2030*.

Drainage and river network information form the foundation of the one-dimensional (1D) in-bank system. This dataset includes details of river cross-sections, channel geometry, hydraulic structures, and drainage connectivity. Accurate representation of these parameters is crucial for replicating the conveyance capacity and hydraulic behavior of the river system under different flow conditions. Topographic data, particularly the digital elevation model (DEM), is used to generate the two-dimensional (2D) floodplain domain. The DEM provides detailed terrain information that governs overland flow dynamics once water exceeds channel capacity. Integration of these three datasets enables the development of a coupled 1D–2D hydrodynamic model capable of simulating both channel flow and floodplain inundation [14].

Table 2 Data used in the data collection stage

Data for Hydrological Analysis	Land Use Maps (Present & Future (2030)) Satellite Map Rainfall 2006/2007 River Flow Location of Rainfall Stations
Data for Hydraulic Analysis	River Alignment Cross Sections Bunds Bridges Weirs Dam
Data to Generate Ground Model	LiDAR data Satellite Images Cadastral Lot Points of Interests

3. Results

3.1 Model Application

The hydrological component of the model simulates natural processes, including precipitation, land use, infiltration, evaporation, and runoff, to generate hydrographs that represent flow variations over time within the catchment. The Soil Conservation Service Curve Number (SCS-CN) method was employed to estimate runoff volumes. This widely adopted method in hydrological modelling accounts for soil classification, land use, vegetative cover, and antecedent moisture conditions (AMC) [15]. For this study, Curve Number (CN) values ranging from 78 to 79 were assigned to all sub-catchments (Table 3). This value reflects Hydrologic Soil Group C, which corresponds to the predominant clayey soil types, under AMC II conditions with average soil moisture, and a land use classification dominated by agricultural activity.

The hydraulic component of the model comprises two main parts: the one-dimensional (1D) and the two-dimensional (2D) domains. The 1D model simulates flow within riverbanks, representing in-bank flooding, while the 2D model captures overland flow across the floodplain, simulating conditions when the river overtops its banks. Sub-catchments were delineated using a Geographic Information System (GIS) based on the river network through the Thiessen polygon method, as illustrated in Fig. 5(a). The river network model was developed by integrating surveyed river cross-sections with a LiDAR-based digital terrain model, as shown in Fig. 5(b). Longitudinal sections along drainage lines were generated at 500-meter intervals to produce vertical profiles of terrain and water levels, illustrated in Fig. 5(c). Culverts beneath roads were modelled as simple conduits to simulate floodplain connectivity [16]. The catchment characteristics of the Sungai Senggarang are presented in Table 3.

Table 3 Catchment characteristics of the Sungai Senggarang

No.	Sub-catchment Name	Total Area (ha)	Channel Length (m)	CN	Time of Concentration, t_c (min)
1	33	286.872	3700	79	257.81
2	33a	685.046	4787	79	265.83
3	33b	567.266	5287	78	298.16
4	33c	892.47	4720	78	223.74
5	33d	536.565	5326	79	300.70
6	33e	1024.086	5840	79	334.46
7	33f	622.932	4094	78	76.31
8	33g	1093.016	4696	78	96.85
9	33h	901.828	5520	78	59.92
10	33j	658.903	3460	78	66.15

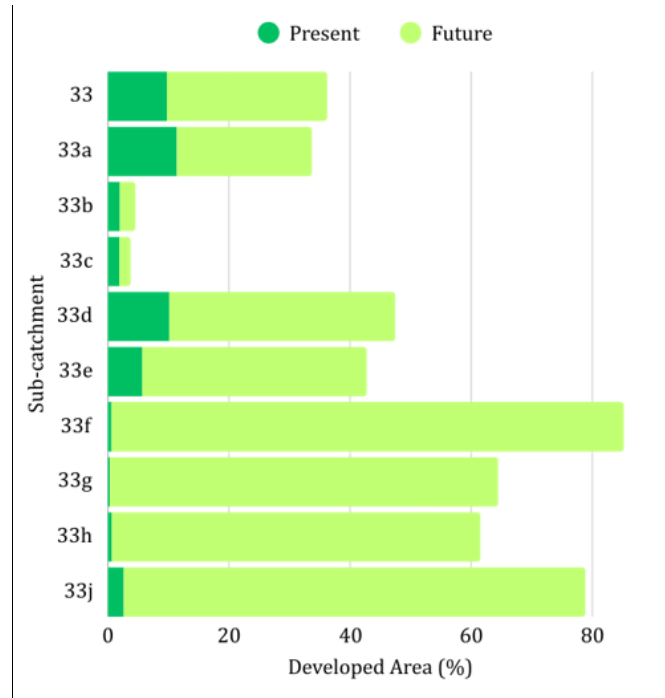


Fig. 6 Percentage of development for the present and future scenarios in each sub-catchment of Sungai Senggarang

Table 4 Present and future land use distribution

Sub Catchment Name	Land Use Distribution (ha)					
	Present			Future		
	Residential	Infra	Agriculture	Residential	Infra	Agriculture
33	27.99	2.22	256.66	75.94	2.22	208.71
33a	78.05	2.87	604.12	152.96	2.87	529.21
33b	11.25	3.17	552.84	14.64	3.17	549.46
33c	16.91	2.83	872.73	16.91	2.83	872.73
33d	54.57	3.20	478.80	200.17	3.20	333.20
33e	58.23	3.50	962.36	379.86	3.50	640.72
33f	3.67	2.46	616.81	527.10	2.46	93.37
33g	3.65	2.82	1086.55	701.27	2.82	388.92
33h	5.76	3.31	892.75	549.12	3.31	349.39
33j	17.25	2.08	639.58	502.40	2.08	154.43

Multiple simulation scenarios with varying rainfall intensities and storm durations were run to generate flood extent maps. Simulations for durations ranging from 15 minutes to 48 hours showed that the 6-hour storm produced the highest peak discharge. Consequently, the 6-hour duration was adopted for further hydrological analysis under both present and future scenarios. Runoff was routed to sub-catchment discharge points using infiltration and volume models. At the same time, hydrographs derived from flow accumulation were applied as upstream boundary conditions for the rainfall-runoff model of the river system [14], as illustrated in Fig. 7.

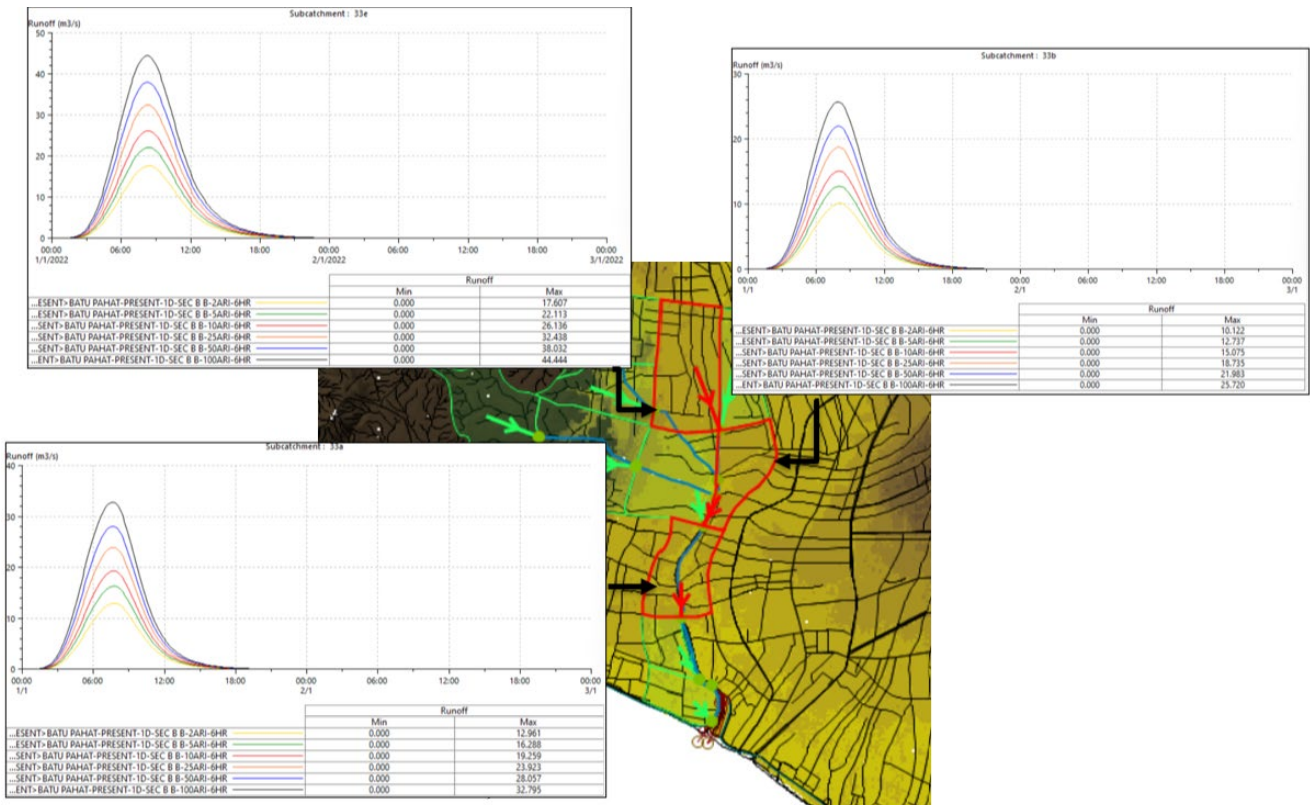
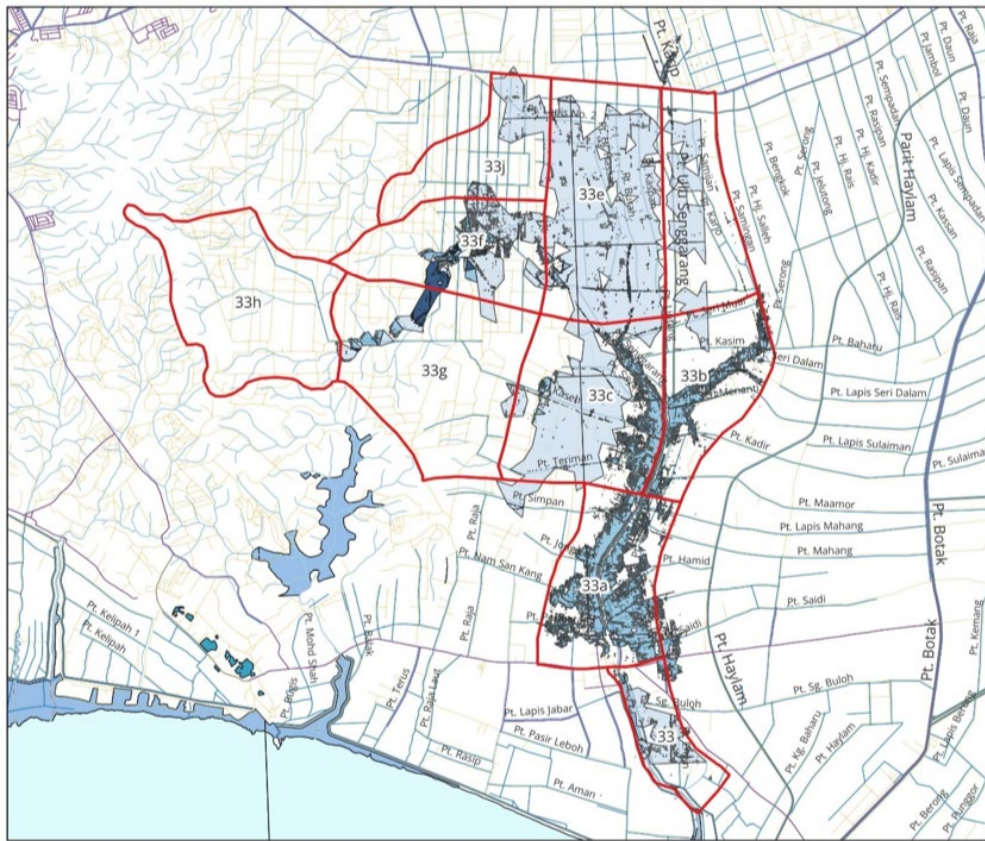


Fig. 7 Hydrological output of the sub-catchments under present conditions

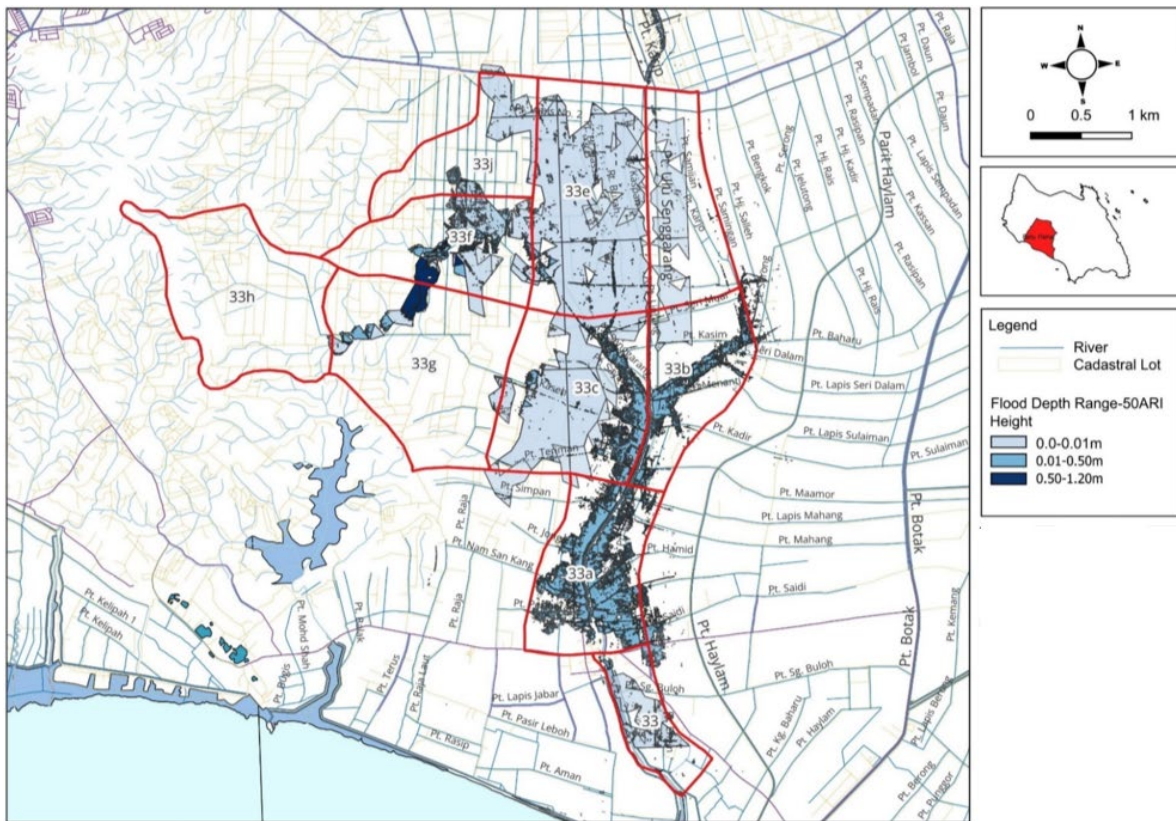
3.2 Scenario Analysis

Flood simulations for the 20-, 50-, and 100-year ARI events were carried out using a 6-hour critical storm duration. Present and projected land-use data were incorporated as baseline scenarios. Due to limited data availability, the model did not account for backwater effects from the adjacent coastal system. The outputs from the InfoWorks ICM simulations were transferred into GIS for spatial analysis and flood map generation, enabling assessment of flood distribution across the catchment. Flood depths were categorized into three ranges: 0–0.5 m, 0.5–1.2 m, and greater than 1.2 m. The corresponding inundated areas and runoff flows were quantified for each ARI scenario. These results are presented in Figs. 8, 9 and 10, and Table 5.

In general, the flood maps across various design storms indicate widespread inundation along the main river corridor, reflecting the low-lying topography features of the catchment. The centrally located sub-catchments, namely 33a, 33b, and 33c, experience heightened flood severity as they function as a hydraulic convergence zone. These areas receive cumulative runoff from adjacent sub-catchments (33h, 33g and 33f), in addition to concentrated flows from upstream river channels, resulting in increased flow volumes, prolonged inundation duration, and higher flood peak intensities. The projected rise in peak runoff, particularly in upstream sub-catchments (33f, 33g, 33j), aligns with observations by Liew et al. [14] in the Segamat River Basin and Ching et al. [2] in the Muar Basin, both of which reported that rapid urbanisation substantially increases flood risk. The most severely affected areas are concentrated within the downstream floodplains, where low-lying terrain and flow convergence significantly exacerbate inundation. Flood depths exceeding 1.2 m constitute a substantial proportion of the inundated areas, particularly under higher ARI scenarios, indicating elevated flood hazard levels. Overall, the results demonstrate a clear escalation in both flood extent and severity with increasing ARI values and intensified urban development.

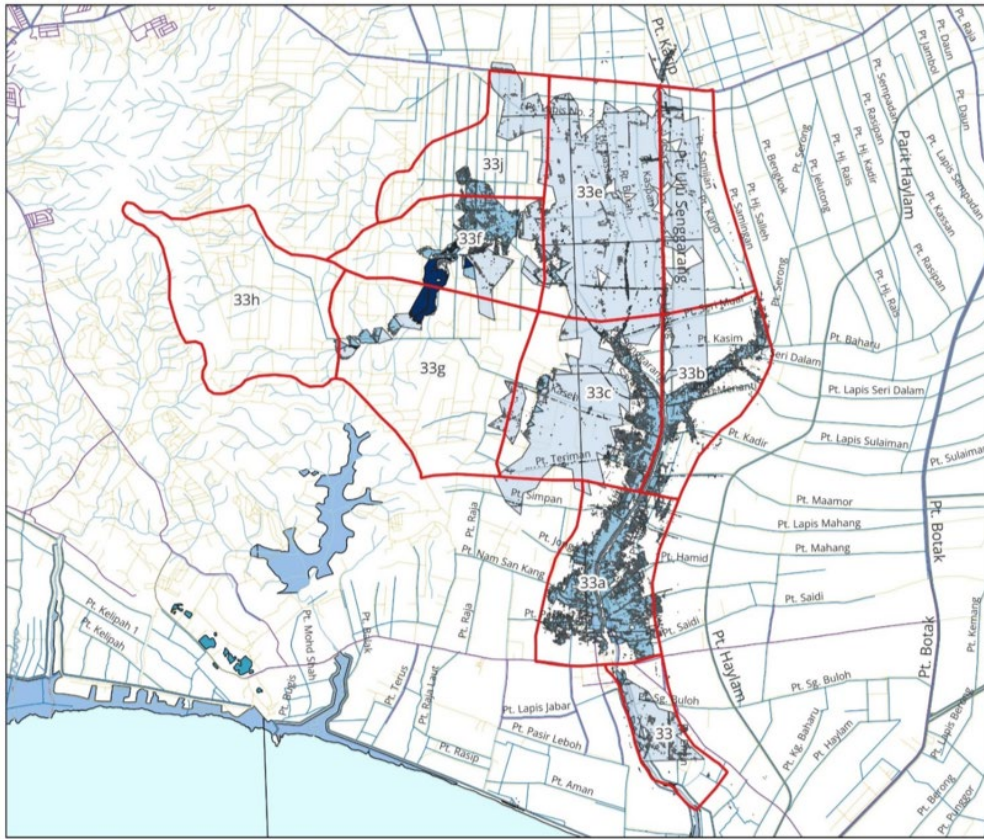


(a)

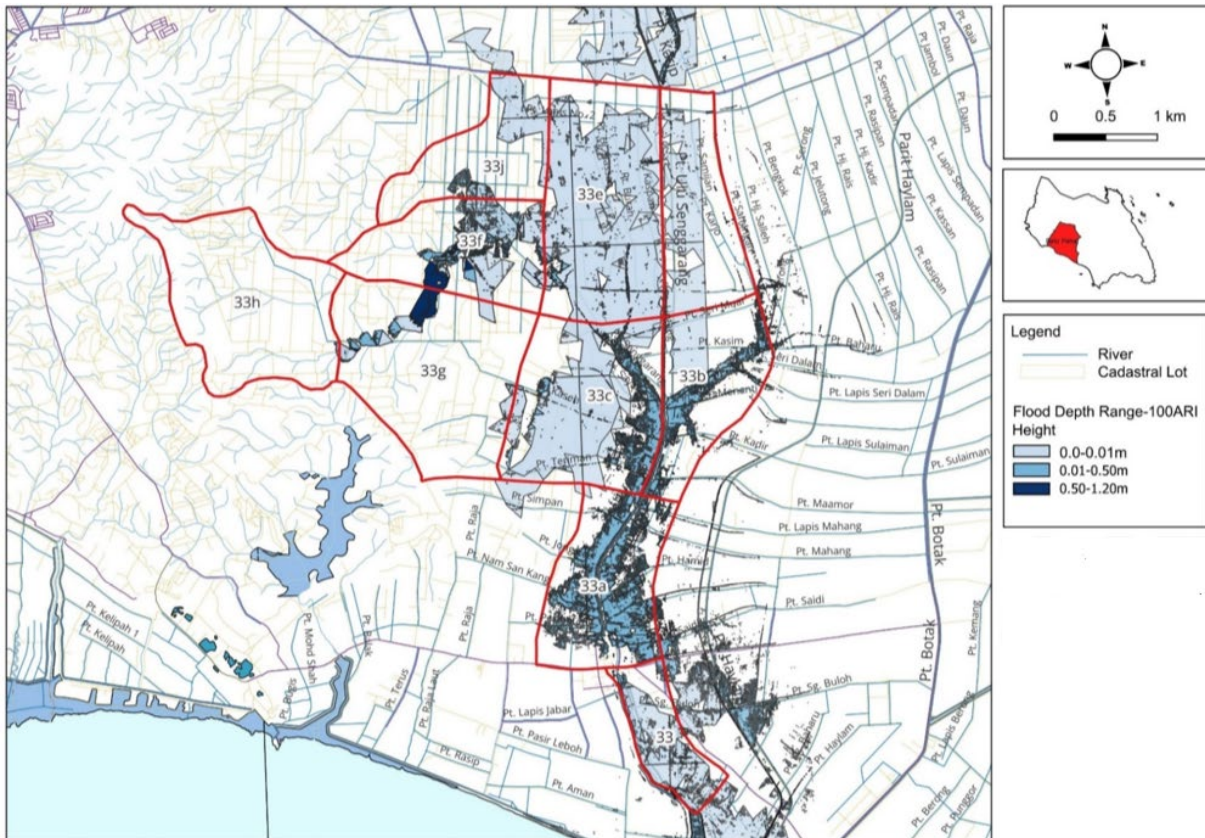


(b)

Fig. 9 Flood maps of the Sungai Senggarang catchment for the 50-year ARI under (a) present; (b) future land use conditions



(a)



(b)

Fig. 10 Flood maps of the Sungai Senggarang catchment for the 100-year ARI under (a) present; (b) future land use conditions

The estimated flood-inundated areas presented in Table 5 shows an increasing trend with higher ARI scenarios under both present and future land use conditions. For the Sungai Senggarang catchment, the percentage of flood-affected areas increases from approximately 13% under the present 20-year ARI scenario to about 33% under the 100-year ARI. Under future land-use conditions, this proportion increases further, reaching 41% for the 100-year ARI.

Table 5 Total flooded area and depths for various design storms under present and future land use conditions

Depth (m)	Total flooded area (m ²)					
	20 ARI		50 ARI		100 ARI	
	Present	Future	Present	Future	Present	Future
0–0.01 m	457	1586	1772	1830	2009	492
0.01–0.5 m	527	553	586	674	628	742
0.5–1.2 m	38	44	41	43	44	115

Hydrological analysis results indicate a consistent increase in peak runoff when comparing present and future land use scenarios, as shown in Table 6. In the downstream catchments, namely 33a, 33b, 33c, 33d and 33e, the peak flow during the 50-year ARI design storm increased by an average of approximately 5%. This modest rise is attributed to limited urban development and minimal land use change in these areas. In contrast, the upper catchments, particularly sub-catchments 33f, 33g, 33h, and 33j, exhibit a substantially higher increase in peak discharge, averaging around 15%. This significant rise is associated with intensive land development and shifts in land cover, which have reduced natural infiltration and accelerated surface runoff generation.

Table 6 Sub-catchment peak runoff under present and future land use conditions for 20-, 50-, and 100-year ARI

Sub Catchments ID	Peak Runoff (m ³ /s)					
	20 ARI		50 ARI		100 ARI	
	Present	Future	Present	Future	Present	Future
33	10.78	11.21	13.13	13.6	15.92	16.41
33a	23.92	24.91	28.06	29.11	32.79	33.91
33b	18.73	19.32	21.98	22.76	25.72	26.66
33c	33.45	34.54	39.18	40.65	45.74	46.12
33d	18.38	19.53	21.5	22.72	25.07	26.36
33e	32.44	34.52	38.03	40.25	44.44	46.79
33f	27.09	32.23	31.68	37.08	36.91	42.58
33g	46.87	53.96	54.79	62.26	63.87	71.68
33h	39.5	44.64	46.18	51.59	53.8	59.62
33j	22.4	26.18	26.18	30.19	30.51	34.75

3.3 Model Calibration

By comparing the 2007 flood event (shown in Fig. 11(a)) with flood maps from various design storms and site investigations, it can be concluded that the most severe event experienced in the study area corresponds to the 50-year ARI, as illustrated in Fig. 11(b). Due to the absence of recorded flow and water level data within the study area, hydrological model calibration could not be performed, thereby limiting the ability to validate the model against real-world conditions. To overcome this constraint, a hydraulic verification approach was adopted using previous reports and community surveys with residents who experienced the 2006/2007 flood events. The information gathered was then compared with model outputs (50-year ARI) to align simulated results with known flood extents and impacts (Table 7). This approach provided a practical means to assess the model's reliability, ensuring that the simulation could reasonably represent actual flood behavior despite the lack of empirical data. Fig. 12 illustrates the results of the community survey conducted with the most affected flood victims.

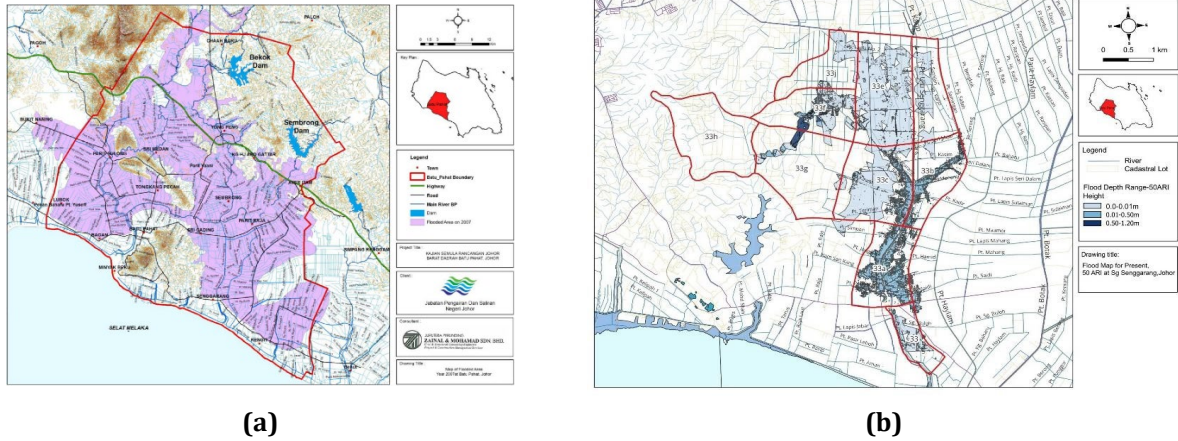


Fig. 11 (a) Flooded area during the 2007 flood event in Sungai Senggarang, Batu Pahat; (b) flood map for the present 50-year ARI in Sungai Senggarang, Batu Pahat

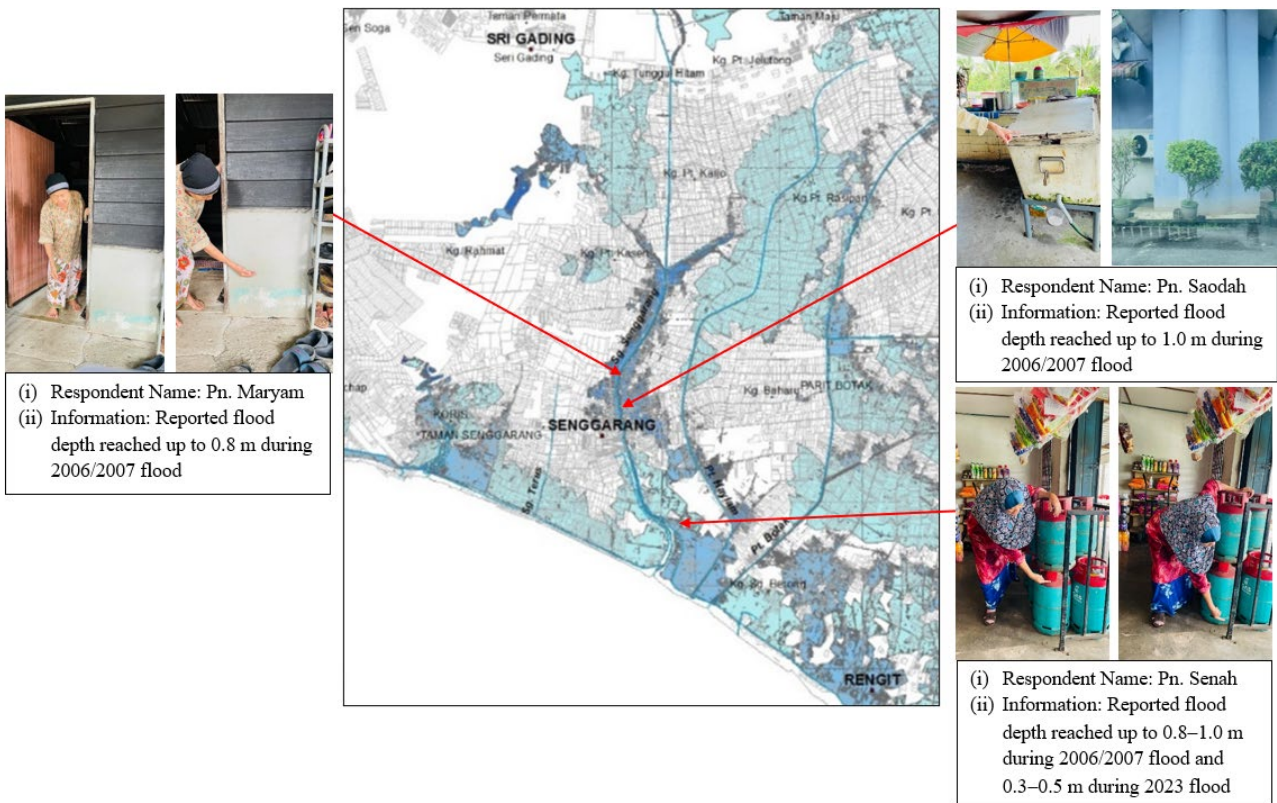


Fig. 12 Flood depth information during site investigation in 2025

Table 7 Observed and simulated flood depths for the calibrated event in the Sungai Senggarang catchment

	Flood Depths (m)
Observed	0.8 – 1 m
Simulated	0.01 – 1.2 m

4. Conclusion

This paper presents a study of flood risk assessment and mitigation in the low-lying areas of the Sungai Senggarang catchment in Batu Pahat District. Using the InfoWorks ICM hydrodynamic model, the historical rainfall event of December 2006–January 2007, and design storm events with 20-, 50-, and 100-year ARIs, flood depths and discharges were simulated and analyzed. The model was calibrated against historical flood records and field observations, following standard practices commonly adopted in similar studies. The resulting data on flood extents and flow rates were used to identify critical flood-prone zones, providing valuable insights into flood risks and the impacts of land use changes. In addition to model performance evaluation, this study highlights the projected increase in flood extent by 2030 under future land use conditions. The findings demonstrate that urban expansion significantly exacerbates both the spatial extent and severity of flooding, emphasizing the need for proactive flood mitigation and land use planning.

The simulations demonstrated that land use significantly influences runoff and flood risk, underscoring the importance of development control in flood management strategies. Without adequate mitigation measures, such as detention ponds or green infrastructure, the increased upstream discharge may exacerbate downstream flooding. The study recommends widening and deepening the channel, in addition to the existing tidal gates, to enhance flood conveyance capacity. The application of InfoWorks ICM proved effective in modeling flood behavior within a complex basin. By integrating hydrological and hydraulic components, the model simulated rainfall–runoff processes and surface water flow with high accuracy. Overall, this research highlights the potential of advanced modelling tools such as InfoWorks ICM to support local authorities in urban planning, flood mitigation, and policy development, thereby strengthening resilience for vulnerable communities amid rapid urbanisation and changing climate conditions. While this study demonstrates the capability of InfoWorks ICM for compound flood simulation, future research could incorporate advanced approaches reviewed in recent literature [17], such as machine learning–based early warning systems, sensor data assimilation, and multi-hazard frameworks, to further enhance flood resilience in Batu Pahat.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Siti Nazahiyah Rahmat, Mohd Daud A; **data collection:** Mohd Daud A, Nur Alia Mohd Daud; **analysis and interpretation of results:** Mohd Daud A, Nur Alia Mohd Daud, Alfi Rahmi; **draft manuscript preparation:** Siti Nazahiyah Rahmat, Nuryazmeen. All authors reviewed the results and approved the final version of the manuscript.*

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