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Assessment on the Efficiency of Flood Mitigation Measures

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ABSTRACT

Storms and floods are frequent occurrences that can disrupt communities and harm ecosystems. An effective flood management plan requires a decision-making process that balances financial, social, and environmental benefits. This paper provides an overview of a study that applied a decision-making process using engineering analysis to determine the most effective approach in selecting the most effective flood mitigation measures. This study used hydrodynamic modelling to determine the effectiveness of proposed measures, such as the construction of a flood wall and river improvement works. The results showed that the combination of both measures could provide 100 ARI level protection, reducing the flood area from 6.11 km^2 to 0.00 km^2 areas without flooding. The study highlights the importance of considering financial, social, and environmental benefits in selecting effective flood mitigation measures.

Keywords: Cost benefit analysis; decision-making framework; economic analysis; flood management

INTRODUCTION

Flood scenarios often have negative impacts on economic activity, and the economic activity will be paralysed if the flood phenomenon is not dealt with clearly, effectively and consistently. Therefore, flood protection has always received considerable attention, resulting in significant flood protection investment. Engineering analysis in floods such as hydrodynamic modelling will assess flood protection in current conditions and with mitigation plans. Managing storm floods requires an innovative system of flood control facilities distributed throughout the river basin since space and land are very limited. In order to balance up the need between society and the environment, it is crucial for the decision maker to comprehend that every alternative available has an opportunity cost. Therefore, to pertain to sustainable development, it is important to examine the costs and benefits of an investment involving flood management. This article aims to evaluate the effectiveness of flood mitigation measures by Integrating hydrodynamic modelling with Cost-Benefit Analysis (CBA) which will support and assist the decision-making process in selecting the optimum flood mitigation measures, considering their financial, social, and environmental benefits of it. The application of CBA has been widely practised, and it has proven to be a systematic and effective method in evaluating the strengths and weaknesses of alternatives in monetary terms.

The changing climate in Malaysia is currently causing a major rise in flood risk. Floods in Malaysia are due to the geographical characteristics of the region, bringing an abundance of rains during the monsoon seasons and convection rains during the hot yet humid periods. Malaysia will normally be in a stand-by mode between November and February as it is the monsoon climate that triggers flood. The worst major floods recorded in Malaysia started as early as 1926 and it became so prevalent for almost every year. It then continued with other major flood events reported in 1963, 1965, 1967, 1969, 1971, 1973, 1979, 1983, 1988, 1993, and 1998. Malaysia witnessed its massive 21st century floods in December 2006-January 2007 (Johor – the southern state), 2009/2010 (Kedah and Perlis – the northern states), 2014 (Kelantan, Terengganu and Pahang – the east coast states) and 2017 (Penang Island) (Abdullah et al. 2019; Amin & Othman 2018; DID, 2019a; Zakaria et al. 2017) The Malaysian government has allocated billions of ringgits to address the flood problem in its every Five-Year Malaysia Plan. A total of RM 5 billion was invested to mitigate flood risks, in urban and rural areas. This was announced in the 10th Malaysia Plan (2011-2015) (EPU 2010).

This paper presents a novel decision-making process that considers not only the financial benefits but also the social and environmental impacts of flood mitigation measures in order to select the most optimum and effective solution.

METHODS

In order to obtain the optimum flood mitigation measures design, a quantitative approach through hydraulic modelling application can evaluate the capacity and conveyance of the existing river system and hence the flood protection level of the river systems with respect to the design discharges (DID 2019b). The model will then be run to analyse various flood mitigation measures to evaluate their effectiveness. The evaluated analysis will therefore be the main input for the decision-making process. CBA, as a holistic economic assessment will look into the financial, social and environmental benefits and costs of the mitigation project per se. Hydraulic modelling combines CBA will then form a framework of decision-making on flood mitigation projects. Figure 1 illustrates the methodology flow

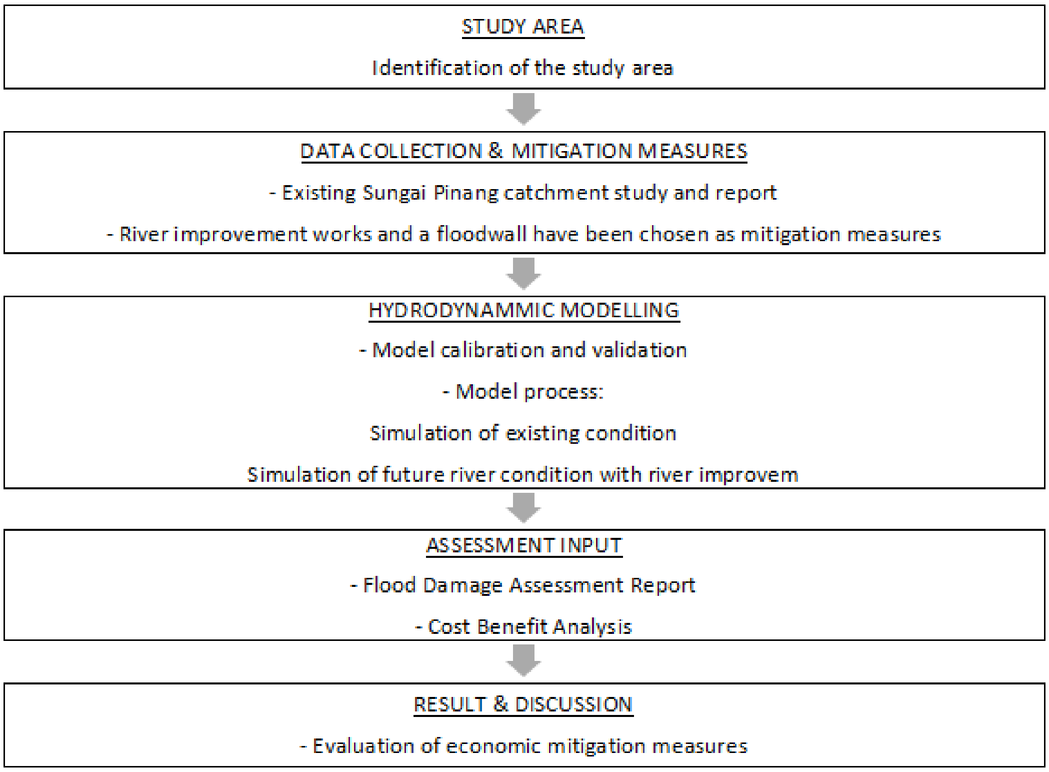


FIGURE 1. Methodology flowchart

STUDY AREA

The case study area used in the present work is in Sungai Pinang catchment, which is in Georgetown, Northeast District of Penang, Malaysia. It is a rapidly urbanizing region along the east coast of the Penang Island. Georgetown is the capital city of Penang, listed as a UNESCO World Heritage Site. Georgetown is renowned for its heritage, cultural and arts as the most popular tourist destination in Malaysia. Sungai Pinang catchment area is 51 km^2 and it is the largest most built-up river system on the island. Sungai Pinang flows originate from the central hilly to undulating part of the catchment. Figure 2 indicates the river map of Sungai Pinang catchment. Sungai Pinang is approximately about 3.6 km and its tributaries are Sungai Jelutong, Sungai Air Hitam, Sungai Air Terjun, Sungai Dondang, Sungai Air Putih, Sungai Kecil and Sungai Mati. Among these tributaries, Sungai Air Hitam is the largest tributary and Sungai Mati is the shortest tributary. Meanwhile, flow from Sungai Jelutong A, B, and C is diverted to Jelutong Diversion. Sungai Air Hitam is regulated by a water supply dam located at the upstream part. Flooding has occurred as a result of extensive developments and changes in the characteristics of the catchment area over time, combined with more intense rainfall over the catchment area. Recurrent flooding has been reported at this region. The flooding worsens when it occurs during high tides. Tidal effects had prevented or delay the discharge of the Sungai Pinang.

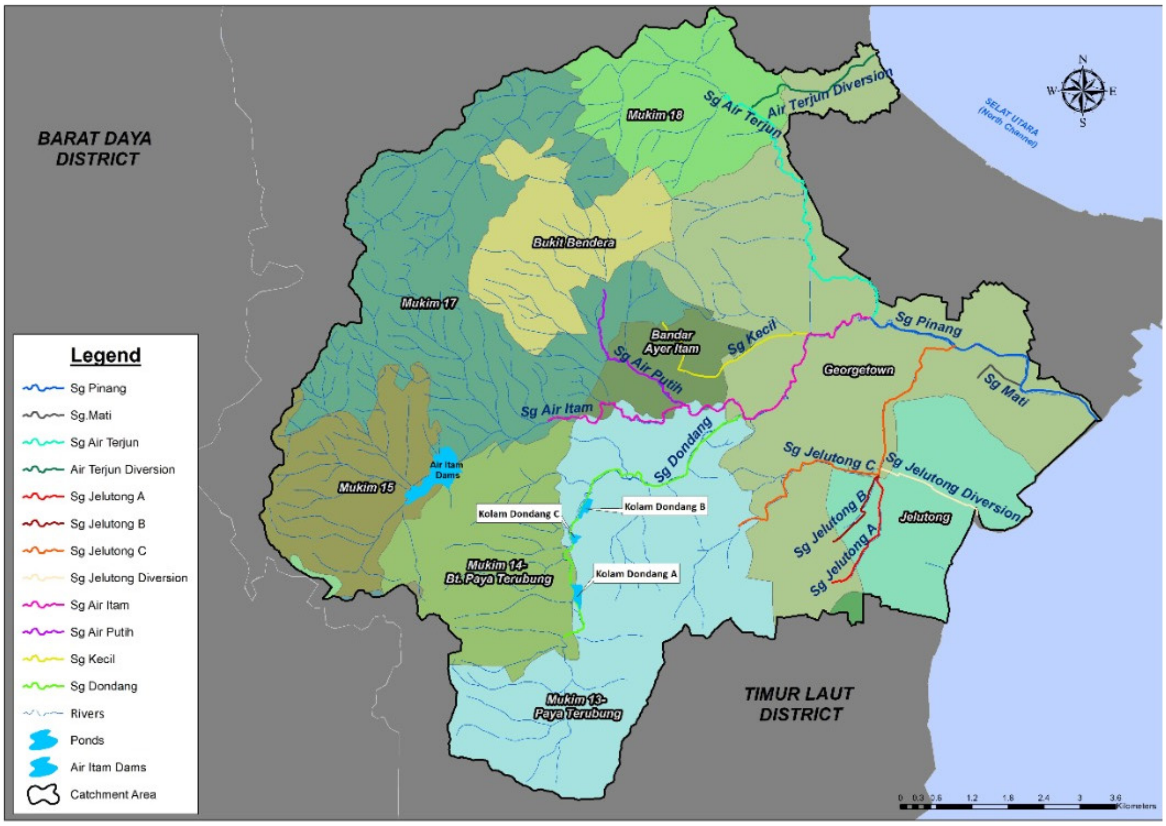


FIGURE 2. River map of Sungai Pinang catchment

SUNGAI PINANG'S CATCHMENT RAINFALL-RUNOFF

Most of Sungai Pinang and its tributaries have been channelized and lined during the development of the surrounding area. This channelization was done to accommodate the increase in surface runoff and changes in floodplain coefficient caused by development over the years (Saad et al. 2008; Misnan & Rindam 2012; Sabdul Hakim et al. 2020). The catchment receives on average of 2,540 mm of rainfall annually which varies over the years, with the lowest monthly average around 60 mm for January and February and the highest monthly average around 220 mm for August, September, October and November (DID 2018, 2019a). According to Table 1, the hydrological components of Sungai Pinang stated that the surface runoff is 1,102 mm and approximately 47 percent of runoff is lost to the sea. The remaining 53 percent recharges the ground and enters the atmosphere through evapotranspiration. Surface runoff is frequently captured by reservoirs, dams, and water treatment plants for the current water supply system in the Sungai Pinang basin to meet current water demand. River flows in Sungai Pinang for 1.99 m^3/s.

TABLE 1. Hydrological Components of Sungai Pinang River Basin

River Basin	Catchment Area (km^2)	Rainfall (mm)	Evapotranspiration (mm)	Surface runoff (mm)	Runoff / Rainfall ratio	River flow (m^3/s)
Sungai Pinang	51	2,540	1,235	1,102	0.47	1.99

CONVERSION OF LAND USE EXCHANGE

According to the land use information under Rancangan Tempatan Daerah 2018 obtained from Jabatan Perancangan Bandar dan Desa Negeri Pulau Pinang, the current land use area of 52.45 km^2 has been classified into twelve categories which are water body, forest, industrial, infrastructure and utilities, institution, commercial, transportation, agriculture, residential, non-development area and recreation area as indicated in Figure 3. Summarising the classes, the forest takes over the current land use with an area of 28.27 km^2, followed by residential land use of 9.63 km^2. The third largest land use are under institution and transportation with each total area of 4.09 km^2 and 4.05 km^2. The land use for recreation is 1.88 km^2 while non-development and commercial each cover 1.20 km^2 and 1.12 km^2 of land use area. Other land uses cover small area ranging from 0.18 km^2 to 1.06 km^2.

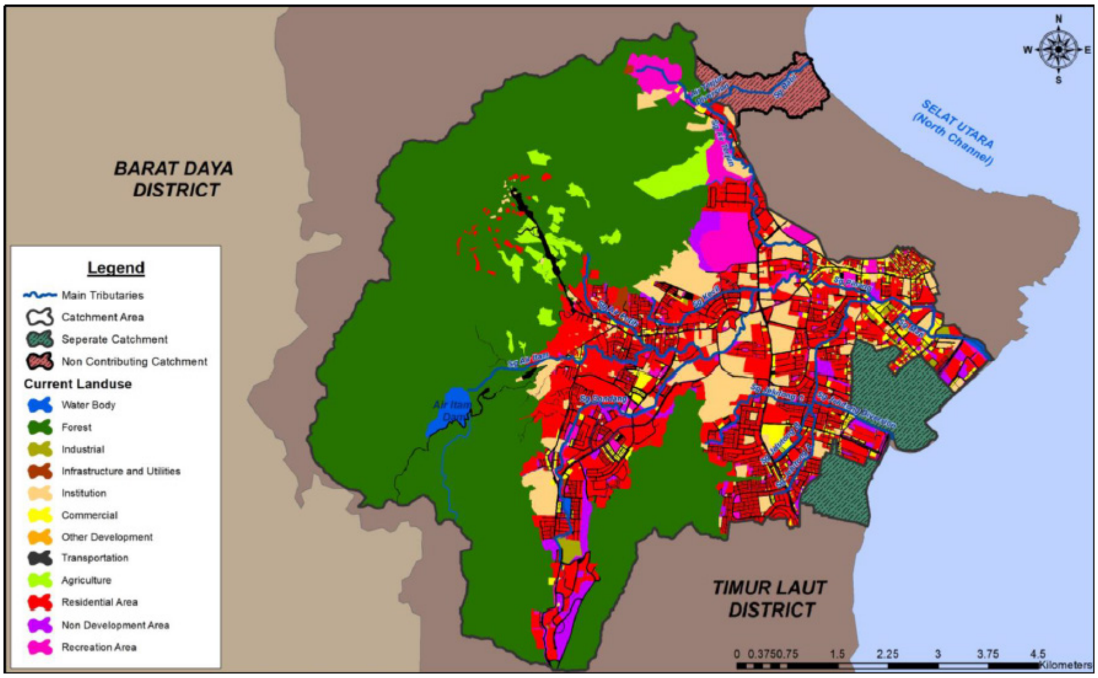


FIGURE 3. Land use of Sungai Pinang catchment area for 2018 (PlanMalaysia, 2018)

COMPLEXITY OF THE FLOOD RISK SYSTEM

Urbanisation has harmed ecological surfaces and the environment by replacing natural permeable surfaces with rooftops, highways, and other impervious surfaces. When the city drainage system does not hold the quantities of runoff offsite, high-intensity rainfall can trigger flooding. Flood mitigation literature highlighted that uncoordinated planning of developed land will cause greater frequency and severity of flooding. This situation will also be seen as a damage that will affect the economy, society and environment (Genovese & Thaler 2020; Kundzewicz et al. 2018; Shah et al. 2020). Figure 4 illustrates the impact of urbanisation on natural flooding.

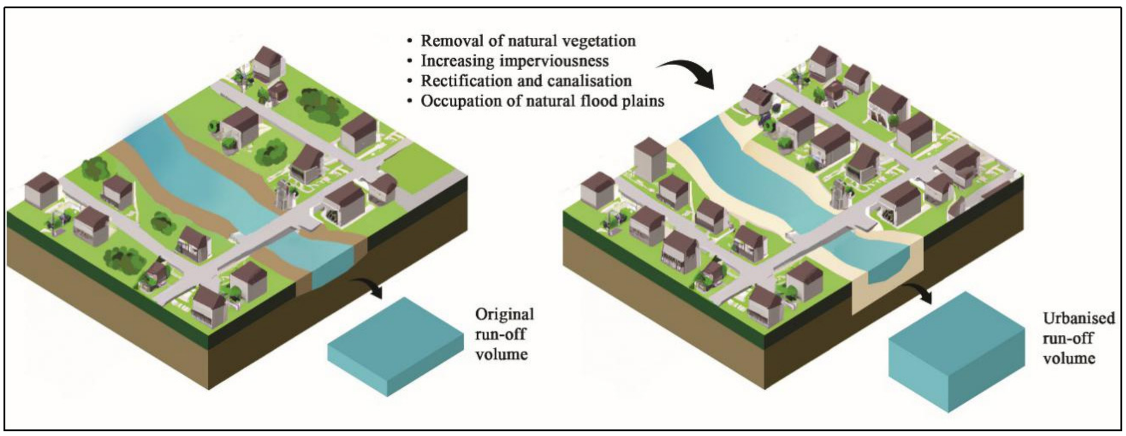


FIGURE 4. The impact of urbanisation on natural flooding Adopted from (Miguez et al. 2011)

DIMENSION OF FLOOD MITIGATION

The conventional modelling of floods is focused mainly on the supply of rainfall data from a network of rain stations in a basin. Rainfall stations are, however, very limited in Malaysia, as most of them are situated in remote and rural areas. The development of computational modelling technologies allows the river system to be developed and to conduct flood simulations. Hydrodynamic modelling is an efficient technique for understanding the forms of the river. Flow approximations are often used in hydrodynamic models to save computation time (Annis et al. 2020; Jahandideh-Tehrani et al. 2020; Nogherotto et al. 2019; Novak et al. 2018). Hydraulic and hydrodynamic modelling techniques can facilitate the analysis of particular rainfall design occurrences over a variety of different return periods in order to gain knowledge regarding flood trends in multiple scenarios (Moura Rezende et al. 2019). Modelling is important in terms of understanding the dynamics of urban development and in particular for predicting how it would influence the environment (Wicks et al, 2013). Thus, it is essential to understand and model the relation between precipitation, surface runoff, urbanization, climate change and urban pluvial floods in order to address flood risks and other problems related to water.

There are three approaches to solve the issue of hydraulic engineering design, which are by assumption and reasoning, by knowledge gained from previous related structures, or by examining the issue and evaluating the design on a model. The complexity of many fluid flow situations and restricted analytic skills even now, has allows for the rigid application of theory and the fundamental flow equations. Therefore, methods using models are needed to arrive at a solution or evaluate the effect of the said flow interpretation. In hydraulics, the description model is used to define a physical or mathematical simulation of a prototype or field-size situation (Novak et al. 2018).

HYDRAULIC MODELLING: ADOPTING INFOWORKS INTEGRATED CATCHMENT MODELLING (ICM)

InfoWorks Integrated Catchment Modelling (ICM) is adopted as the engineering assessment to generate the hydrological analysis impact for this study. It is a software application that integrates flow simulation in rivers, channels, and floodplains. It functions as a model-based flood mapping method that produces numerous simulation results of flood mitigation measures alternatives and it can incorporates both urban and river catchments. The software allows engineers to use one application to produce a fully integrated 1-D and 2-D model to simulate above ground and below ground river and drainage networks. The software will as well do the interaction between larger flows in the urban environment and local flows in rural environment in order to predict major flood event. The combination of these advanced modelling requirements can be done in a single application with one simulation in order to achieve reliable simulation within short period of time (DID, 2009).

The flood hazard maps for the Sungai Pinang basin were created using hydrological and hydraulic modelling. This article tries to evaluate the solution to the flood event in Georgetown, Pulau Pinang in 2017 using standard rain fall cycles for 100 years. An effective river flood model requires a representation of the river channel and floodplain geometry, as well as an accurate description of the model parameters, in order to appropriately estimate the magnitude of the flow and water levels along the reach (Alaghmand et al. 2012; Annis et al. 2020; DID, 2009b; Mardookhpour & Jamasbi 2017; Maskrey et al. 2021; Molinari et al. 2021; Novak et al. 2018; Zainalfikry et al. 2020). The flood hazard can be described by the spatial distribution of the calculated inundation depth as a function of the return duration (Olesen et al. 2017). River improvement works and the construction of flood wall as the mitigation measures, will be simulated with design hydrographs for 100ARI. the research will stimulate two different flood mitigation measures in Sungai Pinang sub-catchment using the InfoWorks Integrated Catchment Modelling; river improvement works and flood wall. The river and flood model development can be categorized into three major elements; hydrology, hydraulic and floodplain analysis. The three elements are incorporated and integrated in order to create an immersive and reliable hydrodynamic model. The aim of hydraulic modelling is to evaluate the capacity and conveyance of the existing river systems based on the design flood hydrographs derived from rainfall-runoff model so that the flood mitigation measures can be formulated (Abd Jalil et al. 2018; Amin & Othman, 2018; DID, 2009; King Kuok KUOK et al. 2020; Othman et al. 2013; Shahrulnizam et al. 2020)

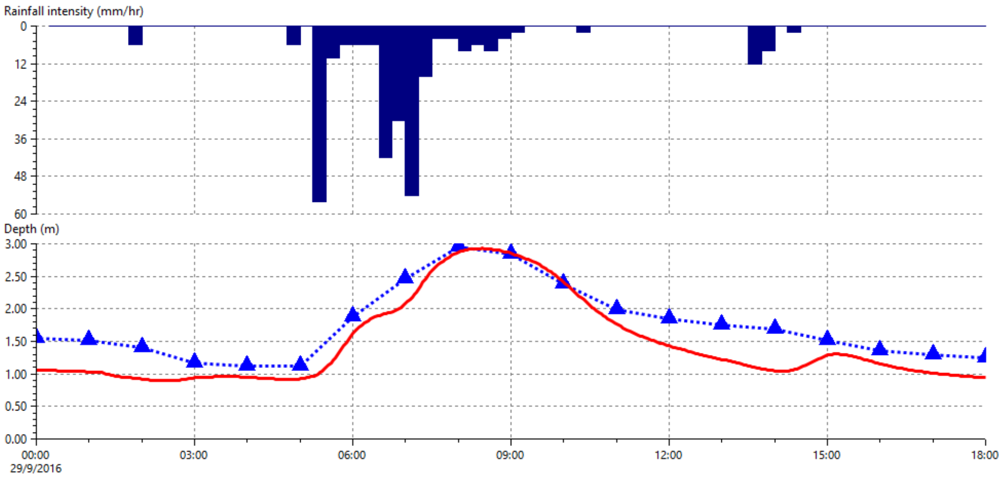
MODEL CALIBRATION AND VALIDATION

Calibration and validation procedure of a model are important steps in model application. For this study, the 100 return periods that was already set up will be used as a reference. In many practical hydrological and hydraulic modelling applications, models are calibrated against values estimated using Hydrological Procedure (HP) or other procedures. In this case, the process is more concerned with ensuring that the models' outputs are constrained by the HPs' estimates. It is all about avoiding major blunders when dealing with more complex models such as Infoworks ICM. Another way to ensure model behaviour is within bounds is to conduct a reality check with actual conditions on the ground. However, the actual system is complex and difficult to comprehend. Reality checks and cross-checks with HPs are procedures that can be implemented (DID 2009). Calibration of the hydrodynamic model was carried out using a flood event on 29th September 2016 at the telemetry water level station in Sungai Pinang at Jalan P. Ramlee. It is crucial to obtain a good calibration of the model to ensure that the current conditions correctly represent the actual site situation and that the proposed mitigation is successful and reliable. After the model has been calibrated, the model was validated by using two flood events on November 4th and 5th 2017 and May 28th 2018 at the water level station at Jalan P. Ramlee.

RESULTS AND DISCUSSION

CALIBRATION AND VALIDATION RESULTS

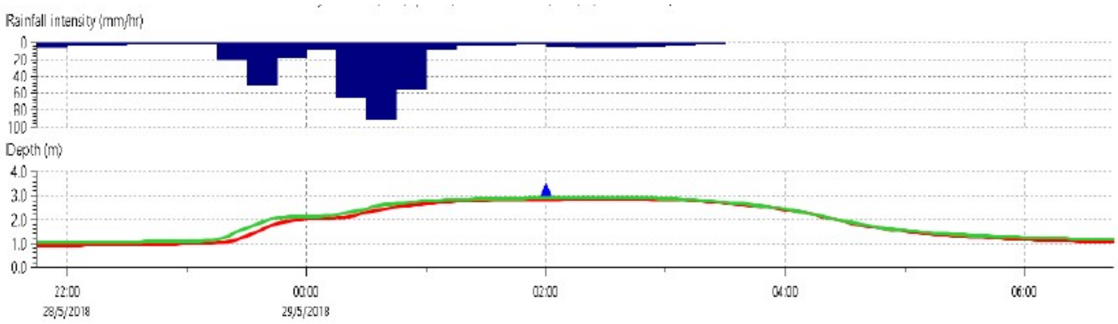
Once the model was calibrated, it was applied to predict the impact of future development to the flow hydrograph at the outlet. The result of the calibration simulation at water level station in Sungai Pinang at Jalan P. Ramlee station is shown in Figure 5.



	Rainfall			Depth	
	Depth (mm)	Peak (mm/hr)	Average (mm/hr)	Min (m)	Max (m)
Rain	74.500	56.000	4.139		
Observed				1.120	2.950
...Rainfall event-29/9/2016				0.893	2.930

FIGURE 5. Water level calibration at Jalan P. Ramlee for 29th September 2016 event

The model was validated using two flood events, including the recent major flood event on November 4th and 5th, 2017. Figures 5 and Figure 6 show the simulated and observed water levels at Station Sungai Pinang on Jalan P Ramlee for the validation events on November 4th and 5th 2017 and May 28th 2018, respectively. This indicates that the calibrated model likewise works effectively throughout the validation period.



	Rainfall			Depth	
	Depth (mm)	Peak (mm/hr)	Average (mm/hr)	Min (m)	Max (m)
Rain	89.100	91.200	14.850		
Observed				3.050	3.050
...5-Rainfall event-28/05/2018				0.915	2.865
...5-Rainfall event-28/05/2018				1.026	2.932

FIGURE 6. Water level validation at Jalan P. Ramlee for 28th May 2018 event

Looking into the sub-catchment properties, the model was calibrated and validated by adjusting these three parameters which are Time of Concentration, Curve Number, and baseflow until a satisfactory correlation between model response and historical data is achieved (Jahandideh-Tehrani et al. 2020). This was done to optimize the compatibility between observed data and data predictions made by the model. Variations are expected due to cross-sectional changes in rivers throughout time. The overall comparison indicates that the peak, peak level timing and shape of the hydrograph for the simulation were in good agreement.

SIMULATION RESULTS FOR FUTURE DEVELOPMENT FLOOD PROTECTION LEVEL OF 100 ARI

The flood mitigation measures will be consisted of a safety level, and the strategy for improving the Sungai Pinang will reduce the water level of the rivers to provide the desired level of safety. Figure 7 shows the flood hazard map for Sungai Pinang 100 years ARI with flood mitigation option of river improvement and flood wall.

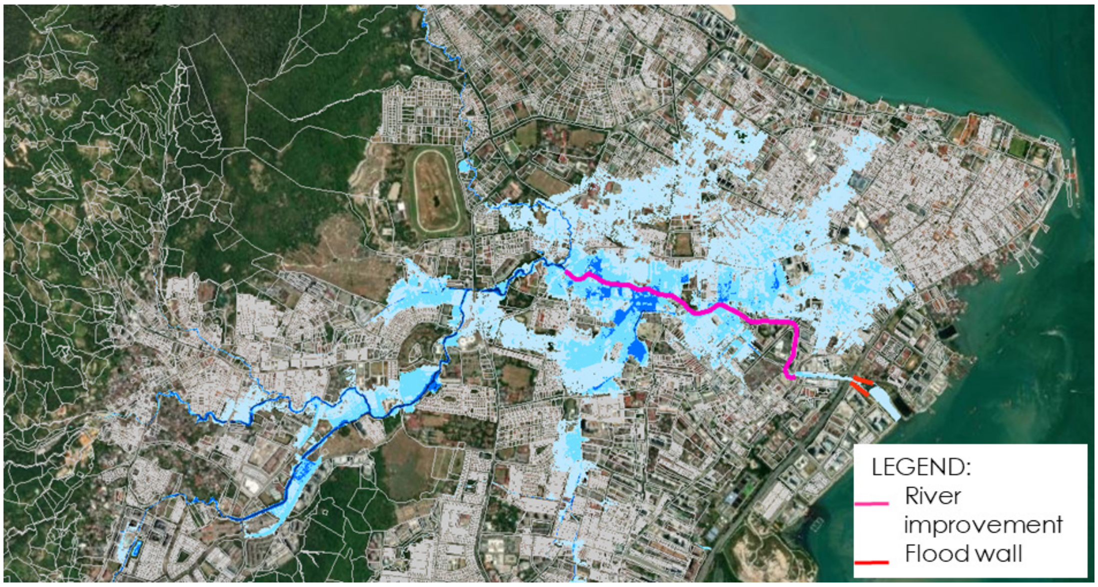


FIGURE 7. Flood hazard map for Sungai Pinang 100 years ARI with flood mitigation option of river improvement and flood wall

The river improvement works include river widening and deepening that will help increase the cross-sectional area of the river, thereby increasing its conveyance capacity indirectly. It will be done from CH 0 to CH 3650. Engineered channels will be designed to have enough capacity and freeboard to handle flood flows up to 100-year ARI, with detailed of design referring to the local design guidelines, 2nd edition Urban Stormwater Management Manual for Malaysia (MSMA 2nd Edition). The widening work will be up to 30m wide and will make use of previously acquired land for Sungai Pinang river improvement. Flood wall will be constructed with 3m in height. As illustrated in Figure 8, the 100 ARI water level was contained within riverbanks with the exception of a few areas. These areas are located on the left bank of Sungai Pinang between CH 450 and CH 540, and on the right bank between CH 1100 and CH 1200.

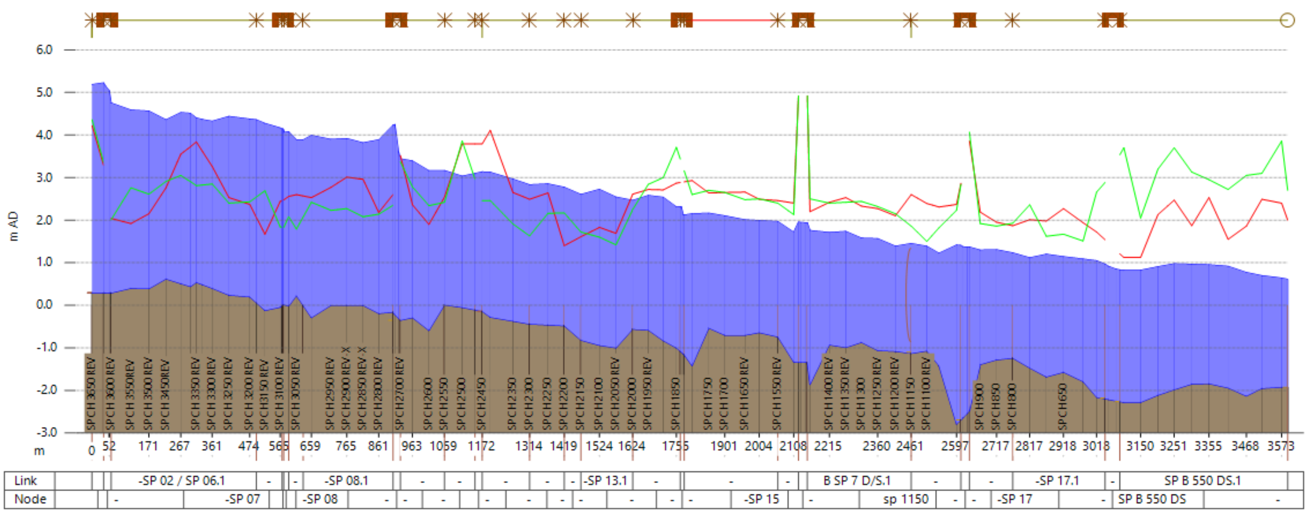


FIGURE 8. Water Level 100 ARI at existing Sungai Pinang from CH 0 to CH 3650

The river improvement and floodwall mitigation options simulated from the hydrodynamic modelling, were found sufficient and have been able to reduce the flood area from 6.11 km^2 to 0.00 km^2 areas without flooding. Table 2 indicates the flood area before and after mitigation. The flood map produced by the modelling demonstrated that the model could simulate the depth of the flood. Figure 9(a) and 9(b) displays the flood hazard map for the 2017 flooding events. It was generated for Sungai Pinang with 100 year ARI. The extended flood area is noticeable where the water had overflow. Figure 9(a) presents flood hazard map before mitigation measures and Figure 9(b) shows that mitigation measures of river improvement and floodwall significantly reduce flood levels from 1.2m to 0.0m.

TABLE 2. Flood area before and after flood mitigation

Flood area before mitigation		Flood area after mitigation		Flood reduction	
Depth (m)	Area (km^2)	Depth (m)	Area (km^2)	Depth (m)	Area (km^2)
< 0.5	2.91	< 0.5	0	< 0.5	2.91
0.5 – 1.2	2.31	0.5 – 1.2	0	0.5 – 1.2	2.31
> 1.2	0.89	> 1.2	0	> 1.2	0.89
	6.11		0		6.11

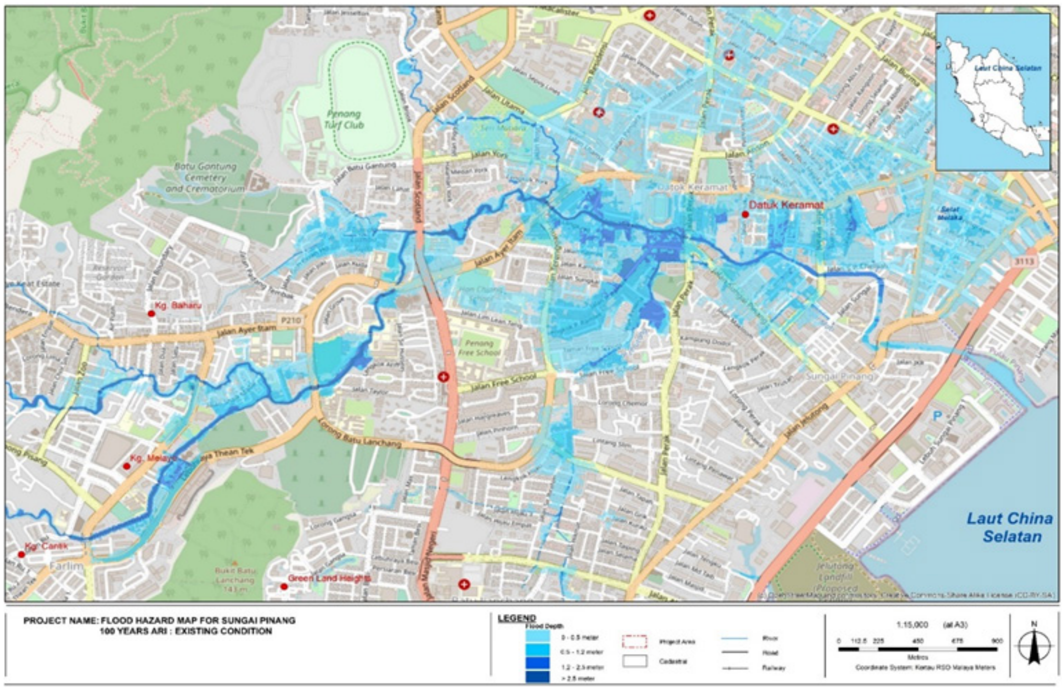


FIGURE 9(a). Flood hazard map for Sungai Pinang 100 years ARI before flood mitigation

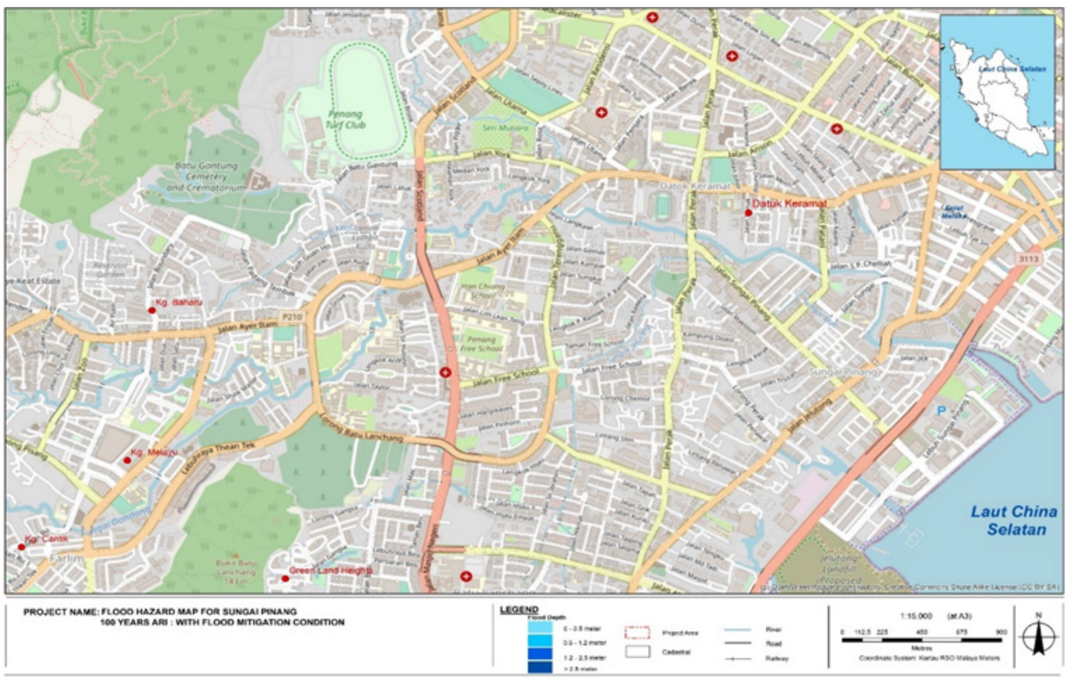


FIGURE 9(b). Flood hazard map for Sungai Pinang 100 years ARI after flood mitigation

COST BENEFIT ANALYSIS OF FLOOD MITIGATION MEASURES

The flood event for this study was the event on 3rd November 2017 to 6th November 2017 with total flood area of 6.11 km^2 and flood depth of 1.2m and above. Therefore, referring to the flood damage cost carried out by DID in 2012, the estimated flood damage for the 2017 flood event is RM 131,113,298. The construction and maintenance cost are provided by DID. The construction costs consist of project cost of RM 150,000,000.00. Maintenance costs are RM 3,000,000.00. Cost estimates are typically performed during the design phase of a flood mitigation measure (Aerts, 2018). In this study cost estimates will look into the construction of river improvement works and floodwalls.

The amount of compensation and flood assistance fund, paid to flood victims by the Government for the social benefits is RM 7,000,000.00. Referring to the Final Design Report of the project from DID, the environmental benefits associated with constructing flood walls RM 8,153,600, widening and deepening rivers RM 147,600,000 and land acquisition costs is RM 213,089,500. The total cost for environment benefit is RM 368,843,100.

The CBA results are reported as in Table 3. They indicate the total cost and total benefit of flood mitigation measures of river improvement and floodwall. The Net Present Value (NPV) were calculated with the discounting rate of 4%. The score table shows that the B/C ratio is 1.34. As mentioned in Chapter 2, according to (Jonkman & Kok, 2004) an activity is attractive if the benefits outweigh the costs when it generates an increase in economic welfare and a lower benefit activity is otherwise unattractive. Therefore, if the Government's decision to proceed with the project based on the cost benefit analysis, the flood mitigation measures resulted from the hydrodynamic modelling would be adopted.

The cost-benefit analysis is based on calculating the Net Presetn Value (NPV), taking the discount rate into account. The NPV value is calculated using secondary data obtained from the Department of Irrigation and Drainage and the Pulau Pinang Timur Laut District Office. The data included the cost of assessing flood damage and the government's social compensation. The discount rate used for CBA of flood damage mitigation is 4% (Jonkman & Kok, 2004), while the Malaysian discount rate by Central Bank of Malaysia is 3% (Raihan & Said, 2021).

The benefit and cost of implementing flood mitigation measures are represented by the equations below (Hudson & Botzen 2019).

TABLE 3. Cost and benefit for flood mitigation measures of river improvement and floodwall

Total cost (Million RM)	Total benefit(Million RM)	B/C ratio
153	Flood damage: 131 Societal: 7 Environmental: 368	1.34

NPV at discounting rate of 4% over 100 years

$$\text{NPV}_\text{B} = \sum_0^T \left(\frac{1}{1+r}\right)^t b \tag{1}$$

$$\text{NPV}_\text{C} = \sum_0^T \left(\frac{1}{1+r}\right)^t c \tag{2}$$

$$\text{CBA} = \begin{cases} \text{Yes if } \frac{B}{C} > \text{x} \\ \text{No if } \frac{B}{C} \leq \text{x} \end{cases} \tag{3}$$

Equations 1 and 2 show the flood mitigation project's costs and benefits effects in the t. The present value is calculated by multiplying the benefits and costs of a year by a discount factor that depends on time (t) and the discount rate (r) (Hudson & Botzen, 2019; Jonkman & Kok 2004; Raihan & Said 2021). A flood mitigation project's CBA determines whether it benefits the society. Equation 3 states that a project should proceed if its discounted life-time benefits (B) exceed its costs (C). The benefit–cost ratio may also need to meet a certain criterion (x). The flood mitigation project is beneficial if B - C exceeds one. Most studies used the benefit–cost ratio with x = 1 as the decision rule (Hudson & Botzen, 2019)

CONCLUSIONS

The hydrodynamic modelling is greatly useful in determining the effectiveness of flood mitigation measures employed on a project. The simulation results done for Sungai Pinang sub-catchment suggested that the river improvement works, and the construction of flood wall is the solution. The combination of both mitigation measures provide 100 ARI level of protection would significantly reduce the whole flood areas of 6.11 km^2. The decision-making process in flood management has been economically evaluated which also takes into account social and environmental benefits.

RECOMMENDATION AND FUTURE RESEARCH

More refined scenario analysis of flood forecasting and economic development in various vulnerable areas are required in the near future to support policy and decision-making in the context of flood risk management, spatial planning, and further economic development. Adequate understanding and a well-informed decision-making process will make the flood management process more viable and cost-effective. Given that flood mitigation projects can often be expensive, risk reduction strategies should be a key aspect of flood management efforts. As the cost of flood mitigation projects is often high, risk reduction management needs to be practiced in flood management. Risk reduction is concerned with minimizing possible losses by lowering the likelihood and severity of a potential loss. It focuses on reducing the effects of floods through measures implemented within the vulnerable area. Flood preparation can also help to mitigate the effects of flooding when both structural and non- structural measures are applied for example flood forecasting and warning systems, disaster management, and evacuation plans.

In conclusion, a systematic approach is required to create consistent and credible flood economy estimates for essential decision-making. For a developing country like Malaysia, flood damage is severe. Flood danger is rising in frequency, area, and population. Critical flood catastrophe decisions must be backed by a detailed cost-benefit analysis that appropriately reflects the national and local circumstances. A thorough and all-encompassing strategy is needed to assess flood economics reliably. This will also help the Federal and State governments accurately analyse and distribute resources for the public good.

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DECLARATION OF COMPETING INTEREST

None

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