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AN EVALUATION OF FLOOD MITIGATION USING SWMM MODEL IN A RESIDENTIAL AREA IN MUAR, JOHOR.

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ABSTRACT

Flood risk has been on the rise over the years globally. In Malaysia, 10% of the land is susceptible to flooding. The Muar River basin in Johor is one of Malaysia's major rivers prone to severe flooding. Hence, it is crucial to conduct an evaluation of flood mitigation measures on developed sites periodically to minimize the risk. This study aims to offer an assessment of the flood mitigation measures at a residential area in Muar, Johor. A storm water management model by EPA-SWMM is adopted to analyse potential flood issues in the area. During the analysis, the stormwater runoff behavior associated with the rainfall precipitation and the land uses of the study site was analysed and discussed. The event-based simulation would be based on the most severe hourly rainfall precipitation from year 2020 to 2022. The simulation outcome showed signs of flooding at the study area under 2 hours of consecutive rainfall averaging 60mm/hr, and with the inclusion of the proposed solution, results showed improvement of the storm drainage network in flood mitigation capability. The improvement saw a decrease in bottleneck stormwater drainage utilisation from maximum capacity to about 80% under the most severe stormwater runoff volume.

Keywords:
Flood Mitigation, Flood Prevention, Flooding root cause, Stormwater Runoff, Peak Flow, SWMM

INTRODUCTION

Compared to the annual average flood occurrences from 2009 to 2018, the occurrence of flood events worldwide has seen a 30% increase, with 5,110 casualties. In addition, it has caused the world an estimated loss of 155 billion Malaysian Ringgit. In Malaysia, 10.1% of the land, home to 5.7 million people, is exposed to the risk of flooding. States like Sarawak, Selangor, and Perak were among the most affected by flooding in 2020 (CRED, 2021). In Johor, the Muar River basin has also been one of the major rivers in Malaysia that is prone to major flooding. The flood event on 19th December 2006 holds the record for the highest flood depth in the state over the past 40 years.
The rise in flood event occurrences has raised concerns about whether the existing flood mitigation system design is sufficient to handle rainfall runoff due to surrounding urban development and climate change. The increase in precipitation may render the current drainage system ineffective, as the excess water will overflow the banks, leading to flooding (Syed and Mohammad, 2023). The Urban Stormwater Management Manual for Malaysia (MSMA) used to determine rainfall patterns and intensities may not reflect recent rainfall trends in the study area (Bong et al., 2021). Findings by Abustan et al. (2008) indicate that rainfall-runoff behavior varies between sites, and careful planning of land applications should be considered. Hence, the lack of studies evaluating flood mitigation in the study area may understate the risk of future flooding.

From a global perspective, floods occur more frequently than other natural disasters such as droughts, earthquakes, extreme temperatures, storms, and wildfires. In 2019 in particular, flood events increased by 30% compared to the annual average from 2009 to 2018. Furthermore, floods were the deadliest natural disaster in 2019, causing 5,110 casualties and resulting in an estimated global economic loss of 155 billion Malaysian Ringgit (CRED, 2021). Previous research found that 5.7

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million Malaysians were exposed to the risk of flooding, occurring in 10.1% of Malaysia's land area. The annual monetary loss is estimated at RM1.15 billion. Based on the records, Sarawak had the highest number of recurring flood events at 225 cases, followed by Selangor (132 cases) and Perak (100 cases) (Pusat Ramalan dan Amaran Banjir Negara, 2021).

Manual calculation procedures for stormwater runoff are tedious and complex, often time-consuming and prone to errors. Fortunately, advances in information technology have enabled complex stormwater runoff analysis through computerized calculations. Numerous software programs in the market, such as HEC-HMS, HEC-RAS, and SWMM-based programs, provide solutions for stormwater design and analysis in complex terrain conditions. Each program has its advantages and disadvantages, and users should understand the program's limitations when analyzing the study area. According to Febrianto et al. (2023), the SWMM model is the most suitable for representing flood conditions. The SWMM model recommends implementing a polder system as a drainage improvement, as it can divide flow into two collectors and reduce load accumulation.

In this study, EPA-SWMM is selected for flood mitigation evaluation due to its excellent program stability, high compatibility with add-on modules for advanced analysis, and its open-source platform, which allows customization to meet specific engineering requirements. Considering the availability of long-term data that may influence the analysis, an event-based rainfall-runoff approach will be applied. Event-based rainfall-runoff has also been shown by Hossain et al. (2019) to produce better outcomes when using EPA-SWMM.

The objectives of this study are to identify the potential root causes of flooding in the study area, located in a residential neighbourhood in Muar, Johor. During the analysis, the peak flow rate will be determined using event-based rainfall-runoff modeling with EPA-SWMM. Then, the flood mitigation measures in the area will be evaluated.

THE STUDY AREA

The study area is situated in a residential area in Taman Maharani Ayu, Muar, Johor, at latitude 2°04'23.9"N and longitude 102°33'41.0"E, as stated in Figure 1. This study area covers approximately 29 acres and consists mostly of residential development in the form of double-storey landed residential units and low-rise apartments, with a small portion allocated to commercial and light industrial use nearby.

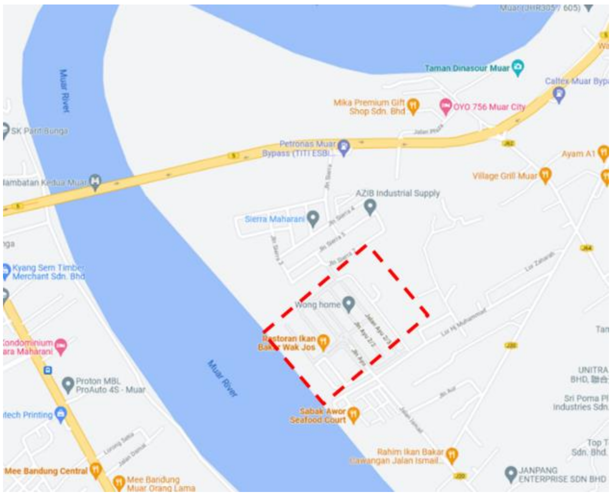

Figure 1: The location of study area

In the state of Johor, the Muar River Basin is an important subject of research due to its geological position and frequent flooding. It is one of the major rivers in Malaysia, with a 6,600 km² catchment area and spanning 329 km in length. The river crosses the states of Pahang, Melaka, and Negeri Sembilan, and discharges through the southwest of Johor into the Malacca Straits. Between 1980 and 2010, a total of 29 severe flood events occurred in the river basin. Based on the analysis, most of these floods took place during the North-East Monsoon season between November and March. The study recorded the highest rainfall intensity on 19th December 2006, with a staggering 301 mm in a single day. This was one of the most severe floods in Johor over the past 40 years, reaching a maximum flood depth of 6.56 m (Yuen Chen et al., 2013; Syed and Mohammad, 2023).

Flood events with occurrence intervals greater than the return period of current flood protection measures are projected to increase across all continents under all considered specific warming levels, leading to a widespread rise in flood hazard. The monsoons are significant factors in determining rainfall patterns in Malaysia. Each monsoon affects the coasts directly facing it and produces intense convectional rain, accompanied by highly variable winds and thunderstorms (Yuen Chen et al., 2013). It is evident that most regions in Peninsular Malaysia experience the highest total number of rainfall days in August. Among these, the eastern region recorded a greater total number of rainfall days compared to other regions (Tan and Yusoff, 2022). A survey by Diya (2014) showed that improper drainage systems, pollution, mismanaged urbanisation, and environmental factors are the top three perceived causes of flooding by the public. Moreover, the characteristically flat terrain limits the rapid drainage of surface water. Combined with extensive impervious paving, this often results in the rapid accumulation of standing water following heavy rainfall (Onifade et al., 2023).

STORMWATER MANAGEMENT MODELLING IN THE MARKET

The EPA Storm Water Management Model (SWMM) has been widely adopted as a runoff modelling tool by water specialists and academic researchers. It is a simulation model developed by the United States Environmental Protection Agency to utilise computers for analysing either single rainfall events or long-term simulations of runoff quantity and water quality in both urban and rural areas. The advantages of SWMM include being freely available to the public, offering strong programme stability, highly customisable modelling, and compatibility with various add-on components for detailed analysis. Nevertheless, SWMM has certain limitations, such as the inability to input data in DWG format, limited compatibility with GIS compared to alternative programmes, and an inability to process calculations when pipelines have a reverse slope (Hlustik, 2017).

EPA-SWMM was used by Junaidi et al. (2018) to evaluate the adequacy of the urban drainage system at a hospital in Padang, located in the Sungai Sapih District. Due to the availability of hourly rainfall data, the authors adopted the Mononobe Method to generate IDF curves for subsequent analysis using a hyetograph. Parameters were simulated using EPA SWMM 5.1 under several scenarios representing current and potential future conditions in terms of land-use changes and drainage upgrades. The simulation outcomes indicated that the current design could not accommodate present and future runoff scenarios. Based on the SWMM results, the authors concluded that Indonesia’s current design guidelines require improvement and recommended the collection of more rainfall and drainage data to enhance the accuracy of outcomes.

EPA-SWMM was also adopted by Gambi et al. (2011) to assess potential solutions for reducing flow peaks in receiving waters as part of a redevelopment plan for the old fruit and vegetable market in the city centre of Bologna. The implementation of retention basins, green roofs, and infiltration tanks was simulated using SWMM. The findings demonstrated that the proposed solutions were effective in reducing water volume flows by up to 50%, allowing a reduction in the diameter of discharge pipes leading to the wastewater treatment plant. However, the authors noted that proper maintenance of the implemented solutions is essential to ensure their long-term effectiveness in managing runoff.

It was also used by Kian et al. (2021) to analyse stormwater runoff rehabilitation for an integrated bio-ecological drainage system located at the academic complex of Universiti Teknologi Petronas. Two bioretention ponds and a new diversion channel were proposed for the flood-prone study area. The simulation results indicated that the mitigation strategy effectively attenuated flow discharge through the integration of the implemented structures. The authors recommended applying best management practices within the EPA-SWMM parameters to generate results that comply with the MSMA standard.

METHODOLOGY

Overall Approach

The study area was modelled using EPA-SWMM 5.2, one of the most widely used software tools among academic researchers and engineering consultants due to its ability to simulate hydrological processes in both rural and urban settings. Hourly rainfall precipitation data from the years 2020 to 2022 was selected and used to simulate the runoff behaviour of the study area, as provided by the Department of Drainage and Irrigation Malaysia (DID). The model requires several parameters to simulate flooding in the study area, such as topographical data, soil data, drainage layout, and rainfall data. The overall approach undertaken in this study is illustrated below:

1. Literature review
2. Data collection from relevant parties and departments
3. Delineation of the drainage network and sub-catchments within the study area
4. Calibration of the SWMM model
5. Execution of SWMM simulation
6. Analysis of simulation outcomes
7. Outlining the main findings of the research
8. Presentation of conclusions and recommendations

For data collection, the topographical data and drainage layout were retrieved from the infrastructure designer. The soil data from the site investigation report was obtained through relevant geotechnical consultants. Rainfall data was accessed via the online portal of the Department of Irrigation and Drainage (DID).

In SWMM, flow routing is governed by the momentum equations and the conservation of mass to analyse unsteady flow. In this study, Dynamic Wave Routing is adopted for modelling the study area due to its performance in producing the most accurate theoretical outputs. It offers advantages over other routing options in determining overflow within the drainage system, whereby the overflow quantity is converted into a constant surface area, which then acts as input to the downstream junction.

For infiltration modelling, the Curve Number Method has been selected due to its relatively simple data requirements. This method only requires input values such as the curve number and the time required for fully saturated soil to dry completely. It is particularly suitable for studies with limited data availability and where less time is available for computation and calibration.

The drainage layout was subsequently imported into SWMM, sub-catchments were delineated, and the drainage system was established in accordance with the design, as shown in Figure 2.

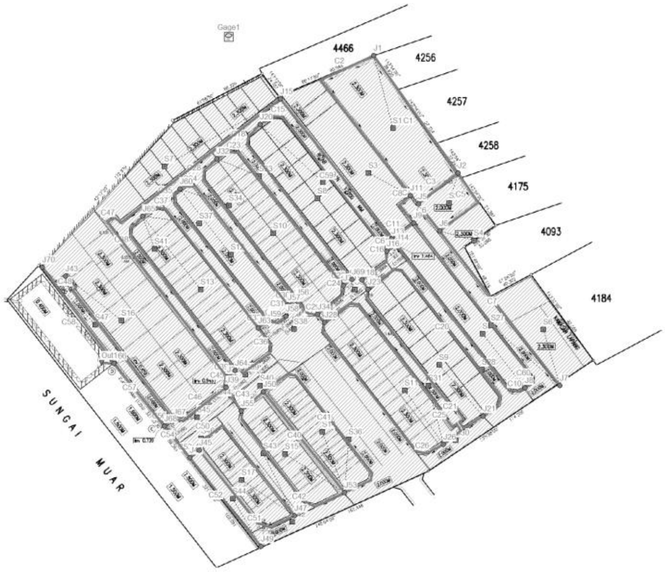

Figure 2: SWMM Modelling

Runoff Equation and Calculation in EPA-SWMM

The EPA-SWMM treats each sub-catchment surface as a non-linear reservoir. As shown in Figure 3, rainfall precipitation and flows from upstream catchments are used as inflow parameters. Surface runoff, infiltration, and evaporation are categorised as outflows. Hence, the runoff is calculated according to the equation below: -

$$Q_{net} = Q_{inflow} - Q_{outflow}$$

Where:-

Q_{net} is net flow under the effect of inflow and outflow.
Q_{inflow} is the inflow expressed in m^3/s
$Q_{outflow}$ is the outflow express in m^3/s

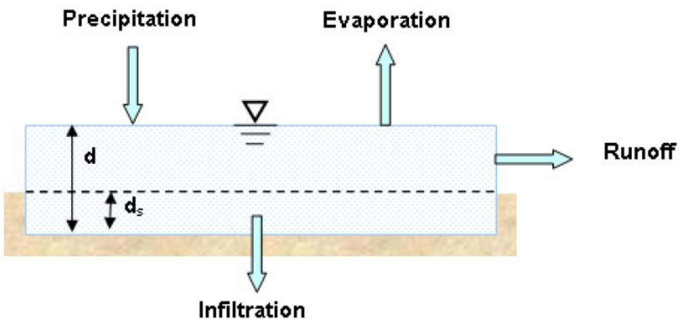

Figure 3: Runoff Model Concept

In SWMM, the flow rate for drainage, pipe culvert and sub-catchment are determined using manning equation: -

Q = (1/n) *A* R^(2/3) * S^(1/2)

Where:
n is manning roughness coefficient;
A is the cross-sectional area of flow;
R is the hydraulic radius of flow;
S is the gradient/slope

RESULT AND DISCUSSION

Simulated Result

The rainfall-runoff data for the simulation were recorded over two consecutive rainy days, beginning at 2:00 p.m. on 12/07/2020 and ending at 10:00 a.m. on 13/07/2020. This period represents the highest rainfall intensity recorded throughout the year 2020. During this time, 22 low-lying areas around the research site were affected by flash floods, resulting in damage to property and infrastructure (Astro Awani, 2021). In addition, the rainfall station is located 2 km from the project site, which is sufficiently close to accurately reflect the rainfall intensity at the research location. For these reasons, the selected rainfall data is deemed suitable for evaluating the flood mitigation capability of the research area.

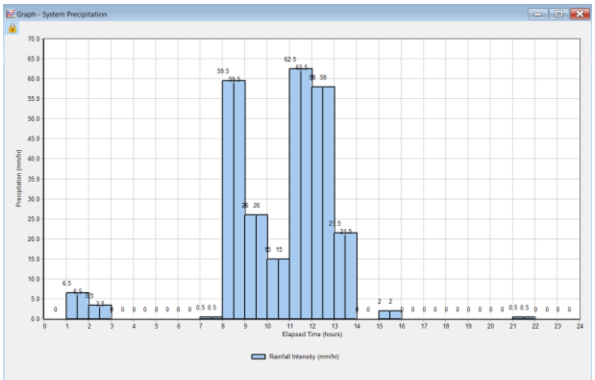

Figure 4: Rainfall Intensity Data

Referring to Figure 4, the total precipitation during the simulation period was 255 mm/day, with the highest hourly rainfall intensity of 62.5 mm occurring between the 12th and 13th hour of the dataset. This intensity is categorised as "Very Heavy" under the Rainfall Intensity Categorisation by the Department of Irrigation and Drainage Malaysia (DID, 2022).

```
**************************        Volume         Depth
Runoff Quantity Continuity     hectare-m            mm
**************************     ---------       -------
Total Precipitation ......         2.658       255.500
Evaporation Loss .........         0.000         0.000
Infiltration Loss ........         0.089         8.595
Surface Runoff ...........         2.572       247.300
Final Storage ............         0.001         0.052
Continuity Error (%) .....        -0.175

**************************        Volume        Volume
Flow Routing Continuity        hectare-m      10^6 ltr
**************************     ---------     ---------
Dry Weather Inflow .......         0.751         7.511
Wet Weather Inflow .......         2.572        25.721
Groundwater Inflow .......         0.000         0.000
RDII Inflow ..............         0.000         0.000
External Inflow ..........         0.000         0.000
External Outflow .........         3.292        32.922
Flooding Loss ............         0.012         0.118
Evaporation Loss .........         0.000         0.000
Exfiltration Loss ........         0.000         0.000
Initial Stored Volume ....         0.000         0.000
Final Stored Volume ......         0.019         0.193
Continuity Error (%) .....        -0.002
```

Figure 5: Simulation Analysis

From the simulation outcome, 96.7% of the rainfall was discharged primarily through surface runoff, while the remainder infiltrated into the soil layer. This implies that the surface area of the research site is largely impervious and requires an efficient stormwater drainage system to manage off-site discharge. As the site is developed, with buildings and paved roads, the observed rainwater discharge pattern corresponds with the nature of such a development mix. As the proportion of impervious surfaces increases, both total runoff and peak runoff gradually rise, while infiltration decreases. This pattern is commonly observed in urban environments, where greater imperviousness reduces soil absorption and increases surface runoff (Zhao et al., 2021).

In this simulation, the runoff continuity error was less than 1%, and the flow routing continuity error showed minimal difference between total inflow and outflow. Both continuity errors are within acceptable limits for application in this study.

Potential Root Cause of Flooding

Impervious Area

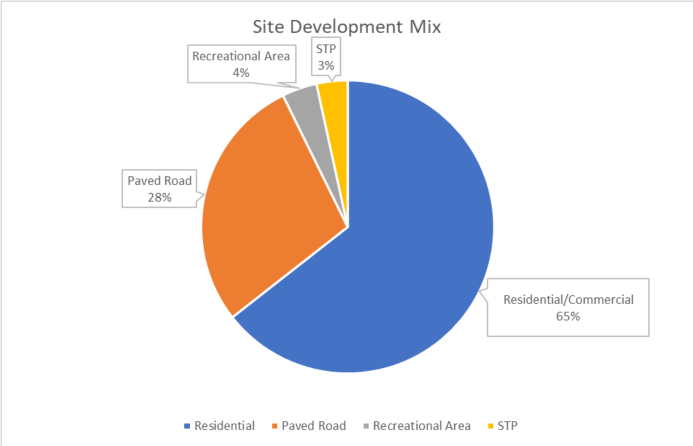

Figure 6: Site Development Mix

Research findings from Figure 6 show that 65% of the land use comprises residential and commercial buildings, while 28% is allocated to paved roads. Both types of land use are conventionally constructed with impervious materials such as roof tiles, road pavements, concrete flooring, glass awnings, and similar surfaces. As a result, 93% of the land use in the study area is classified as highly impervious.

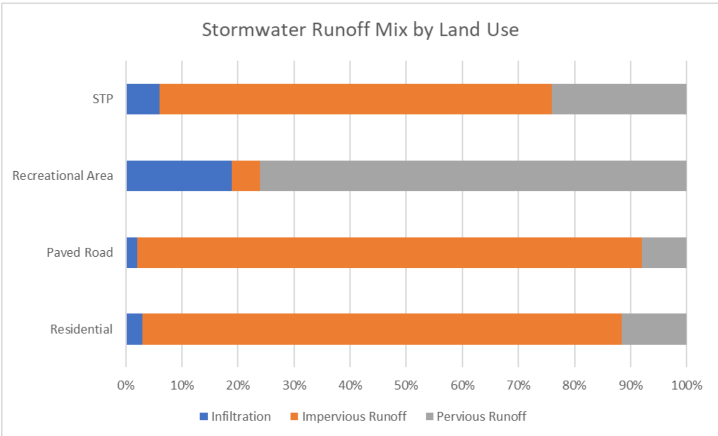

Figure 7: Stormwater Runoff Mix by Land Use

As shown in Figure 7, more than 80% of stormwater from residential, commercial, and paved road areas experienced direct runoff into the nearby drainage system. In contrast, for recreational areas with 95% pervious surface, approximately 20% of the stormwater infiltrated into the soil layer, while about 70% ran off through the pervious surface. Research findings from Iqbal, M. (2022) indicate that urbanisation has a direct relationship with impervious surface coverage—higher proportions of impervious areas significantly increase stormwater runoff rates, especially during heavy rainfall events. From a macroscopic perspective, the excess water can exceed river capacity and cause flooding in adjacent low-lying areas. When combining the analysis of the site development mix and the stormwater runoff characteristics, it is evident that the research site is susceptible to flooding due to a lack of pervious surfaces and water retention facilities, which are essential for acting as detention mechanisms to moderate the stormwater runoff rate before it is discharged into the drainage system. As a result, flash floods may occur during consecutive heavy rainfall.

Drainage Design

Figure 8: Bottleneck Stormwater Mitigation Path

Referring to Figure 8, the simulation based on the rainfall data showed that stormwater runoff from the sub-catchments is routed through their respective drainage networks and converges at Node J39. The nodes marked in red and drainage segments highlighted in yellow indicate sections of the stormwater mitigation path that are approaching or have reached their maximum depth during the period of 62.5 mm/hr rainfall intensity. The drainage lines highlighted in green also exhibit higher flow depths compared to other segments of the drainage system.

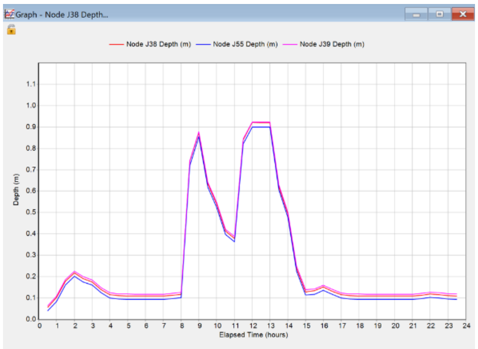

Figure 9: Node J38, J39 and J55 vs Elapsed Time

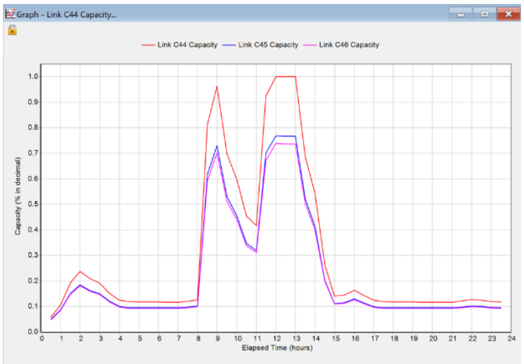

Figure 10: Bottleneck Drainage Capacity

Referring to Figure 9, the nodes (manholes) J38, J39, and J55 are experiencing higher water depth levels compared to other manholes in the network. The flow depth peaked between the 12th and 14th hour of the rainfall dataset. The total rainfall precipitation of 120.5 mm nearly saturated the capacity of the nearby drainage system, resulting in elevated water depth levels as observed in the simulation output.

The capacity of the drainages (conduits) relative to the manholes is illustrated in Figure 10. It shows that Drainage C44, located between nodes J39 and J55, was operating at maximum capacity during the period of heavy rainfall.

This aligns with the flooding analysis, which indicated that Node J55 experienced flooding, with a total flood volume of 117 m^3. Flooding at this node occurred at the 12th hour, when the inflow exceeded the maximum capacity that Drainage C44 could handle. As a result, the total flood volume of 117 m^3 is expected to impact part of the nearby residential area and paved road.

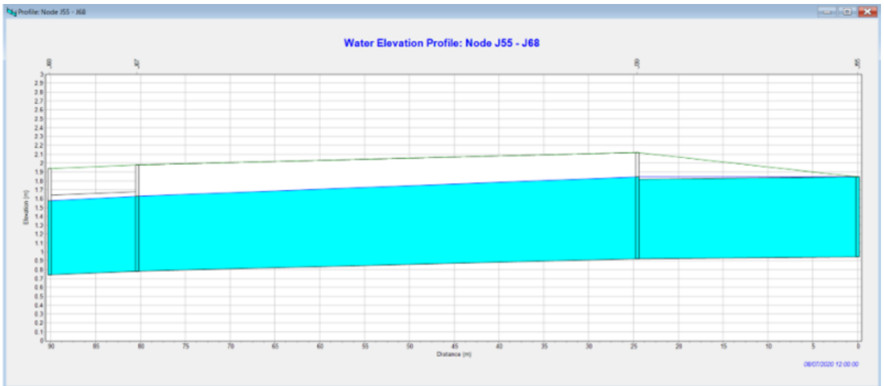

Figure 11: Water Profile from Node J55 to J68

Figure 11 shows the water level profile of the drainage system from the flooded node to the second-last discharge point at Node J68. The figure indicates high water depth in the drainage segments between Node J55 and J39, as well as between Node J67 and Node J68. These drainage segments consist of box culverts located beneath the paved road.

Based on the analysis of drainage utilisation during heavy rainfall, several drainages are also approaching high utilisation, and a bottleneck has been identified around the manhole (Node) J39. Therefore, it is necessary to address this bottleneck by either proposing a diversion or upgrading the drainage capacity to reduce the volume of flow routed through this critical section. Additional mitigation measures, such as permeable pavements, green roofs, infiltration trenches, and other water retention solutions, should also be considered to reduce the volume of runoff being discharged directly into the drainage network.

Peak Flow Rate

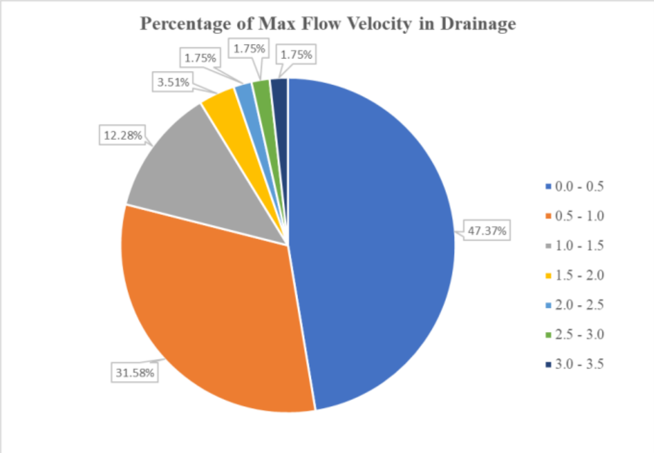

Figure 12: Peak Flow Velocity

The peak flow rate for all drainage paths mostly occurred between the 11th and 12th hour of the rainfall simulation data, during which total precipitation reached 120 mm. During this period, the inflow generated by precipitation was approximately 12,500 m³. The peak flow velocities for the drainages were determined through simulation using the rainfall data. According to the results shown in Figure 12, 78.95% of the drainages exhibited flow velocities below 1.0 m/s.

The maximum velocity identified was 3.14 m/s, occurring at Drainage C55. Flow velocity is a critical factor that can contribute to soil erosion and scouring within the drainage system. It is important to monitor this parameter and reduce it if velocities exceed 4.0 m/s. In this simulation, all velocities were within the recommended maximum average flow velocity of 4.0 m/s, as specified in Table 16.3 of the MSMA 2nd Edition (DID, 2012).

Effectiveness of Flood Mitigation Measures

The research site may be exposed to the risk of major flooding due to the high proportion of impervious surfaces and the current drainage design. Therefore, it is necessary to review the existing flood mitigation measures in the study area and explore possible methods to improve the site's preparedness against flood risk. The water table at the site is generally high, primarily because the study area is located close to the Muar River. As a result, the high-water table and soil saturation levels render the implementation of most Best Management Practices (BMP) unsuitable (DID, 2012). An upgrade of the stormwater drainage system, particularly at the bottleneck flow path, is proposed to enhance the site's flood resistance capability.

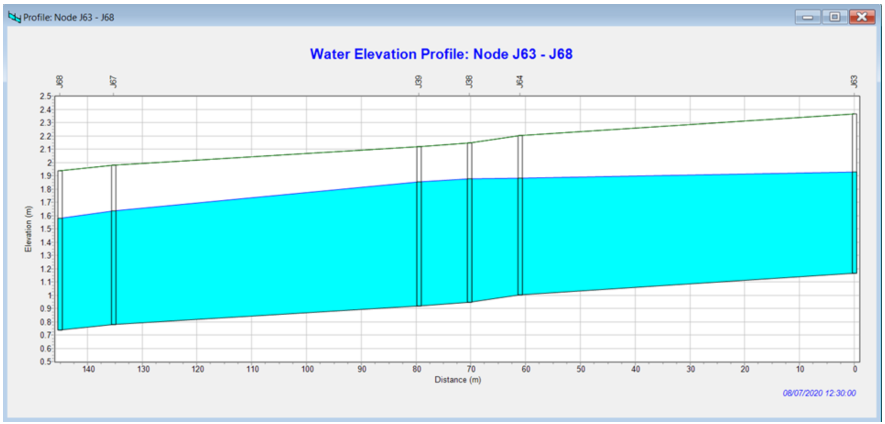

Figure 13: Water Profile after Upgrade (Node J63 -J68)

By upgrading the drainages at the bottleneck section between Node J63 and J68 from a depth of 0.9 m to 1.2 m, the maximum utilisation rate of the bottleneck drainage path was reduced from 100% to approximately 80%, as shown in Figure 13. As a result, the proposed drainage upgrade will enhance the resilience of the stormwater mitigation network, allowing it to better withstand even heavier rainfall events than those modelled in this research study.

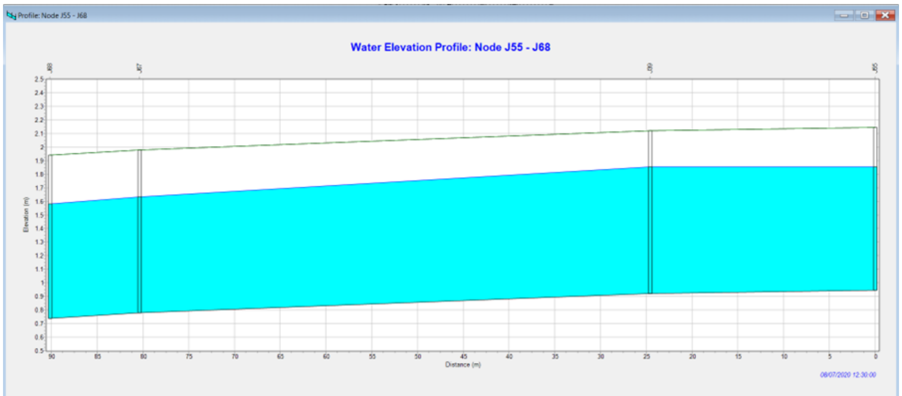

Figure 14: Water Profile after Upgrade (Node J55 - J68)

On the other hand, the utilisation of Drainage Link C44, as shown in Figure 14, also improved after being upgraded from the original depth of 0.9 m to 1.2 m. With the increased depth, the box culvert drainage is no longer constrained in handling the volume of stormwater runoff generated from the respective sub-catchments, which comprise residential, commercial areas, and paved roads.

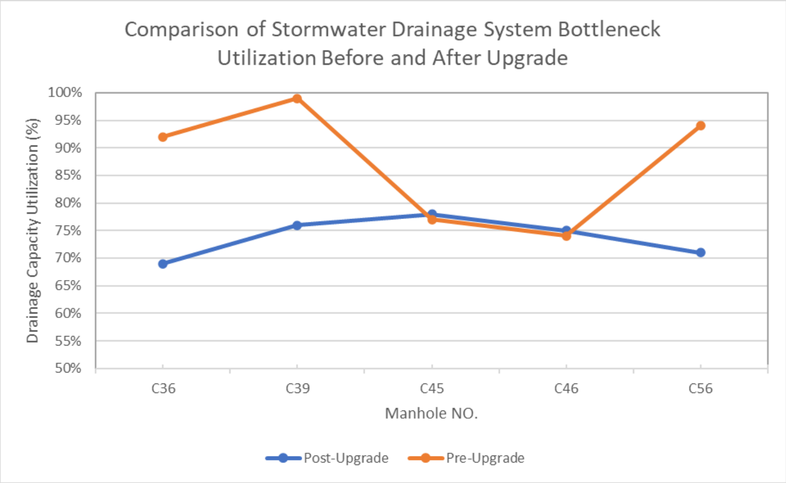

Figure 15: Comparison of Drainage Utilization

`The comparison in Figure 15 shows that overall utilisation after the stormwater drainage upgrade has been reduced by approximately 20%, providing additional capacity in the event of rainfall intensities exceeding the 62.5 mm/hr applied in this research study. Nevertheless, although the existing flood issue has been minimised through the upgrade, the runoff path remains a bottleneck, as there is no alternative mitigation route within the network leading to the outlet.

CONCLUSION AND RECOMMENDATIONS

Based on the analysis of the study area and the simulation results assessing peak flow and flood mitigation effectiveness, it can be concluded that the area is highly vulnerable to flooding, primarily due to the extensive impervious surface coverage and limitations in the existing drainage system design. However, the flood risk can be mitigated through drainage system upgrades, particularly at bottleneck sections such as Manhole (Node) J39.

The analysis showed that 79% of the drainages exhibited flow velocities below 1.0 m/s under the most intense rainfall event used in this study. The peak velocity recorded was 3.14 m/s, which remains well within the allowable limit of 4.0 m/s as specified in the MSMA 2nd Edition.

Furthermore, future studies should incorporate a broader range of rainfall data and collect more comprehensive site-specific information to enhance model calibration. This will ensure more accurate flood risk assessments and the development of more effective mitigation strategies.

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