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Can Nature-Based Solutions Reduce Pluvial Flood Risk? A Case Study on an Institutional Complex.

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ABSTRACT

Flood control systems are experiencing increasing pressure and growing threats from the impacts of climate change and urbanization. Nature-based solutions (NbS) provide flood-risk mitigation and ancillary benefits, but their quantitative effectiveness remains inadequately evaluated. This paper aims to provide quantified benefits of risk reduction benefits of having NbS implementation through micro-scale analysis. An institutional compound at Kota Bharu, Kelantan was chosen for the sensitivity analysis, with consideration of green roofs and permeable pavements as the NbS adaptation. Hydrology and hydraulic simulations of flood events show that the implementation of NbS yields a notable reduction of peak flow at high-frequency events, as high as 44.2% from a 5-year return period and 24-hour rainfall duration. Meanwhile, a lower percentage was found for low-probability of occurrence events, with only 0.4% from a 100-year return period. For flood depth, damage, and risk across the range of flood events, the quantified effects of NbS diminish with only less than a 1% reduction of expected annual damage between base and NbS scenarios. The findings suggest that despite the acceptable reduction of runoff, flood damage and risk are not significantly reduced. Thus, integrating NbS with grey infrastructure is essential for effective flood-risk reduction.

Keywords: Nature-based solutions, Urban Flooding, Flood Mitigation, Grey infrastructure.

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INTRODUCTION

The expansion of urban development, which significantly increases impervious surfaces, is a principal driver of urban flooding. This augmentation of impervious surfaces alters the hydrological response within a catchment, primarily by increasing surface runoff. As urban densification continues, the construction of additional roadways and roofs in already populated areas renders these regions increasingly impermeable, thereby contributing to a higher volume of runoff (Zölch et al., 2017).

The predominant approach to urban flood mitigation in engineering involves using grey infrastructure, which focuses on promptly redirecting excess runoff from

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the impacted region and storing it in downstream facilities. However, the continuous expansion of grey infrastructure capacity is increasingly considered environmentally unsustainable, particularly when facing the combined pressures of climate change and ongoing urbanization (Kordana et al., 2017). Despite these sustainability concerns, it is crucial to recognize that grey infrastructure remains pivotal in efficiently mitigating the effects of extreme precipitation events (Hanak & Lund 2012).

In recent years, the academic and policy focus has shifted away from a sole reliance on grey infrastructure towards the implementation of nature-based solutions (NbS). The International Union for Conservation of Nature (IUCN) defines NbS as “actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (IUCN 2016). NbS, such as green infrastructure, can help minimize the pollutant discharge from the stormwater, reducing erosion and maintaining the stream’s base flow (Mei et al., 2018). This approach marks a crucial departure from the unsustainable expansion of grey infrastructure, promoting flood mitigation strategies that reestablish the connection between societal well-being and the environment (Chee et al., 2021). The growing international adoption of NbS is reflected in the development of guiding policy frameworks, including the Convention on Biological Diversity (2014), the Sendai Framework for Disaster Risk Reduction (2015), and the Ramsar Convention on Wetlands (2015) (IUCN 2016). NbS are recognized for its significant influence on flood events, particularly through its capability of reducing the peak of flood hydrographs (Adams et al., 2018). NbS for flood mitigation ranged from large scale intervention, such as land recovery (Manes et al., 2024) to local implementations, such as swales, ditches, and small ponds, and floodable parks (Martín Muñoz et al., 2024) that enhance storage capacity and trap sediments. By increasing water attenuation, NbS effectively reduces flood flows. Furthermore, large-scale natural landscapes like wetlands, floodplains, and forests are vital components of water infrastructure, mitigating the impacts of urban development, such as river pollution and environmental degradation along riverbanks. Consequently, the widespread utilization of NbS has the potential to decrease reliance on conventional grey infrastructure for stormwater and combined sewer overflow management (Grant et al., 2010). Previous studies have demonstrated that NbS can effectively complement conventional flood control infrastructure, supporting a more integrated and resilient flood management framework in Malaysia. By incorporating natural hydrological processes, NbS have been shown to reduce flood risks while simultaneously enhancing environmental sustainability (e.g., Rosmadi et al., 2024).

In urban environments, common NbS features include green roofs and permeable pavements. A green roof, for instance, consists of three primary components: the roof structure, the substrate, and the vegetation. Depending on the substrate depth, green roofs are classified as either intensive or extensive. Permeable pavements offer another effective method to reduce overland runoff by collecting and storing water. The water stored within these pavements is filtered, which reduces suspended particles and chemical contaminants, thereby improving its quality (Kharat et al., 2019).

NbS have great potential to bring forth diverse environmental benefits as compared to conventional grey solutions. Despite the well-known benefits of NbS, little is known on its effects in reducing flood losses on a protected area. The high cost of long-term NbS implementation necessitates a robust understanding of the degree to which these solutions can prevent flood damage. This information is crucial for guiding effective investment decisions. This study aims to address this gap by analyzing the reduction of runoff, flood depth, and flood risk through the application of NbS within an institutional compound in a small catchment in the Kota Bharu region. The research utilizes hydrological and hydrodynamic models to simulate flood inundation for various return periods (i.e., 5, 10, 20, 50, and 100 years) under three distinct scenarios: a baseline without NbS, a lack of maintenance scenario (sedimentation), and a scenario with NbS implementation (green roofs and permeable pavements). The first two scenarios are to understand the status-quo conditions whilst the third is to analyse the effects of NbS implementation in the area.

STUDY AREA AND DATA

Study area

Malaysia frequently experiences floods that cause significant flood damage. Several states in Malaysia were impacted by floods in late 2021 and early 2022, resulting in aggregate losses of RM6.1 billion, according to the Special Report on the Impact of Floods in Malaysia 2021 produced by the Department of Statistics Malaysia (DOSM 2022). Malaysia has 189 water basins and an average annual rainfall of more than 2000 mm (Husna et al., 2017). Prolonged and heavy rainfall, particularly during the southeast monsoon season (November to March), is a primary cause of widespread flooding, especially in states like Kelantan and Terengganu (Rehan et al., 2024). The occurrence of widespread flooding in several states of the peninsula, particularly Kelantan and Terengganu, can be attributed to an extended period of incessant and heavy rainfall.

Kelantan state, located on the east coast of Peninsular Malaysia, is one of the states exposed to floods in Malaysia, as shown in Figure 1. It receives a high amount of rainfall during the northeast monsoon season, which occurs from around November to March every year (Rehan et al., 2024) and leads to frequent occurrences of floods during the period (Ismail & Haghroosta 2018; Soomro et al., 2022). The river basin of the Kelantan River has a mean annual temperature of 26.8˚C (1984-2014) and a mean annual rainfall of 2510 mm (Faizalhakim et al., 2016; Ghorbani et al., 2015). The Kelantan River, which is the state's main river basin, is approximately 248 km long. It drains an area of 13,100 km^2

from its catchment that has a maximum of 150 km in length and 140 km in width, which is more than 85% of the State of Kelantan (Ibbitt et al., 2002).

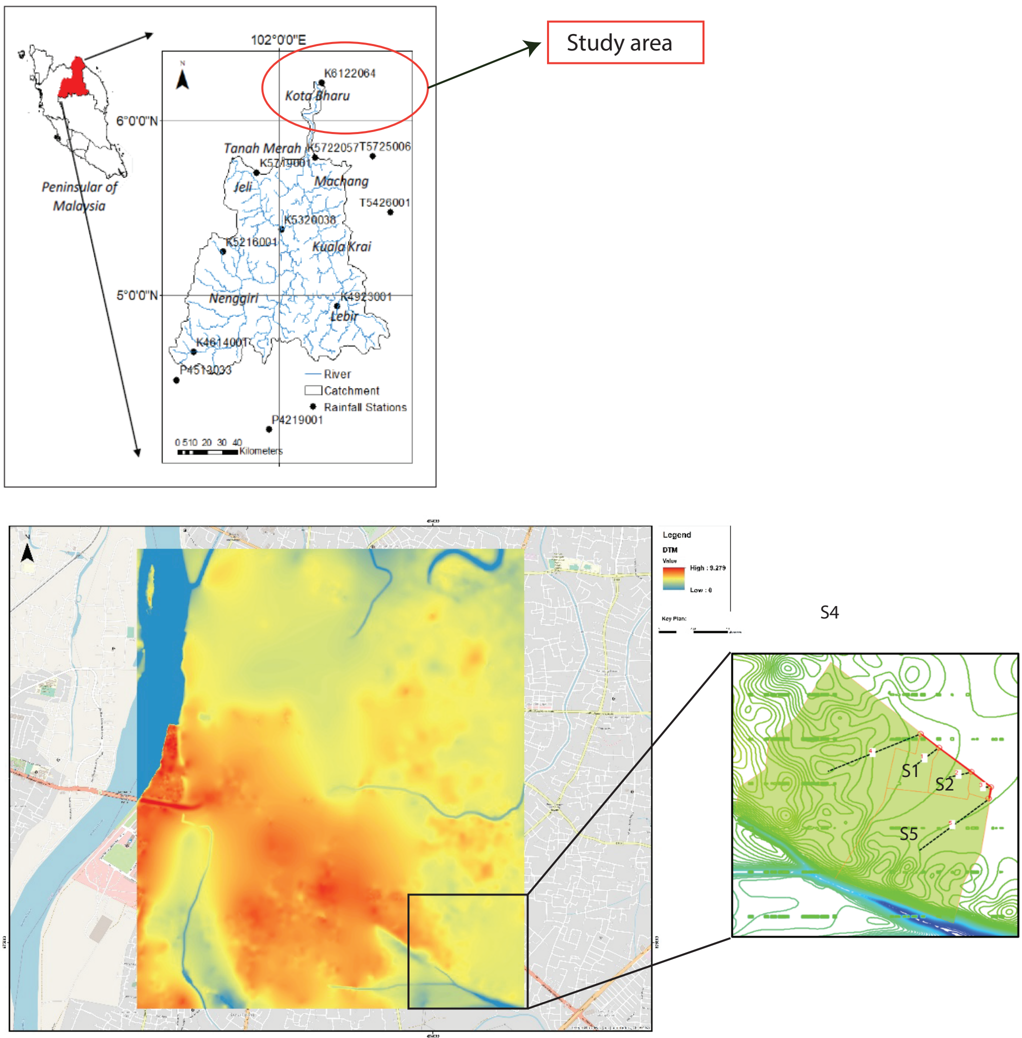


Figure 1. (a) Kelantan River Basin with locations of rainfall station ID:6122064 (Hassan & Kamarudzaman, 2023), and (b) elevation map of IFSAR DEM with superimposed study area and delineated sub-catchments (i.e., S1 to S5)

This study focuses on localized flood damage and risk to institutional buildings and their compound located in an upstream subbasin of the Kelantan River basin and within the state's capital city, Kota Bharu. Kota Bharu is an urbanized area and serves as the center for administrative and commercial operations in Kelantan. Based on the infiltration analysis performed by (Shaari et al., 2016), about 70% of the soil in the Kota Bharu region has been found to have low permeability. When the runoff is excessive, and the soil's capacity to absorb the water is low, this circumstance can lead to flooding. The low permeability of the soil is aggravated by the urbanized condition of the area, further increasing the possible inundation during the heavy downpour.

The specific area chosen for the exploration study is an institutional complex that situates one of the state's administrative headquarters. According to state agency reports, the specific area of the present study is frequently flooded, which is attributed to inadequate drainage capacity and drainage infrastructure in the aging system (DID,2018). The catchment area selected for the study is 0.361 km^2, which was delineated into five sub-catchments (Figure 1(b)) based on the information from DEM, drainage network, and land uses. A raster image with a 4.6 m by 4.6 m resolution was provided and subsequently processed to produce the sub-catchments and the XYZ spatial data in preparing for the modeling (Figure 1 (a)).

The study area was divided into five sub-catchments based on the DTM information, land uses, and drainage layout (Figure 1.b). Sub-catchments 1 (S1) and 2 (S2) mostly consist of buildings, while sub-catchment 3 (S3) is the parking space of the institutional compound (Refer Fig.1 (b)). Following the DEM information, sub-catchment 4 (S4) and sub-catchment 5 (S5) contribute runoff to the S1, S2 and S3. The model was configured according to the characteristics of and links between the five sub-catchments. DTM for ground elevations, drainage system, survey data of invert level, and drain size were obtained from authorities to help establish important information for the modeling.

Hydrometeorology

The design storms used for the simulations were the projected rainfall intensities for five storm durations, i.e., 60, 180, 360 and 720, and five different return periods. Design storm is essential for the design, development, and construction of hydraulic infrastructure such as dams, water retention reservoirs, and levees to enhance flood protection (Bezak et al., 2018). Numerous hydrological studies necessitate design storm values, especially for the indirect estimation of design flood levels. One of the essential relations of rainfall characteristics for the design storm is the intensity-duration-frequency (IDF) that is constructed based on available historical rainfall extremes and used for flood risk analysis (Alemaw & Chaoka, 2016). This study adopts the IDF relationship of the nearest station located 600m from the study area (Station ID: 6122064) for the extreme rainfall simulations, which the characteristics are provided in the Malaysia National Guideline on stormwater management (DID 2012). Table 1 shows the rainfall intensity and rainfall depth for 24-hour storm duration, while the IDF curve is shown in Figure 2.

Table 1
Rainfall intensity (mm/hr), depth (mm), and duration from IDF of the study area region

Return Period (Year)	**Storm Duration (24-hour)**	
	Rainfall intensity (mm/hr)	**Rainfall depth (mm)**
5	12.11	290.52
10	14.04	336.98
20	16.29	390.86
50	19.81	475.53
100	22.98	551.57

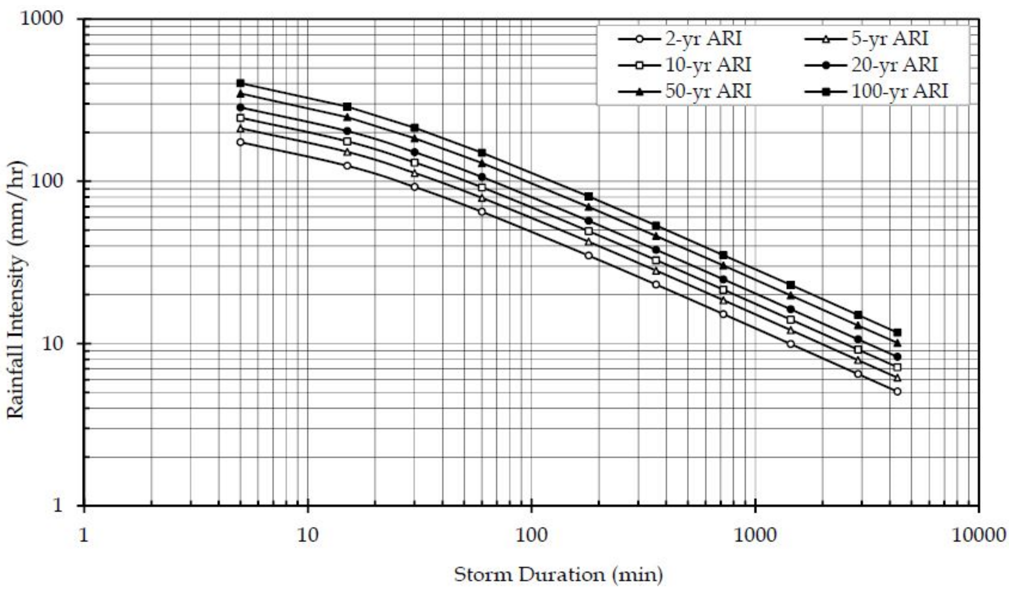


Figure 2. IDF curve at rainfall station Setor JPS Kota Bharu (DID 2012)

METHODOLOGY

The methodological framework applied in this study is divided into four modules (Figure 3). The first and the second modules are dedicated for the rainfall-runoff and hydrodynamic processes simulation for the pluvial extremes. They involve storm hydrographs characterization to simulate the maximum water level on the floodplain of interest. Meanwhile, the third module is on flood damage quantifications to capture the monetary losses by integration of flood events probability. The output is monetary flood risks in expected annual damage. Modeling chain to quantify flood risk in terms of expected annual damage is well-established and has been widely used over more than two decades in research and planning (Fatdillah, 2022; Merz et al., 2009). The final module, i.e., the fourth module, aims to evaluate flood risk reduction benefits considering all scenarios.

Three scenarios were considered to address the NbS potential to reduce flood risk against the status-quo and against the channel capacity reduction: (1) A base or status-quo condition, where it is assumed that the land cover conditions remain unchanged. (2) A condition with implementation of NbS at suitable areas in the study area, namely green roof and permeable parking space. The selection and specification of the NbS types and their potential locations are tailored to the actual sub-catchments land covers. (3) A condition considering sedimentation in the drainage system due to depositions of sediments from runoffs and aggravated by the lack of maintenance. The reduction capacity of drains due to insufficient drainage maintenance has been acknowledged as a common problem in the area (DID, 2018). While the channel capacity of the base and NbS cases were assumed to be unaffected by sedimentation and channel performs to its design capacity, the third case assumed reduction in the drainage capacity. Explanation on the setup is further provided in Section 3.3. All cases were simulated in the XP-Storm Water Management Model (XP-SWMM) (XPSolutions 2014) through interfaces that enable simulations of floods for urban areas. The input information is stored, and the simulation output is retrieved to allow further analysis of the events (e.g., Li et al., 2019).

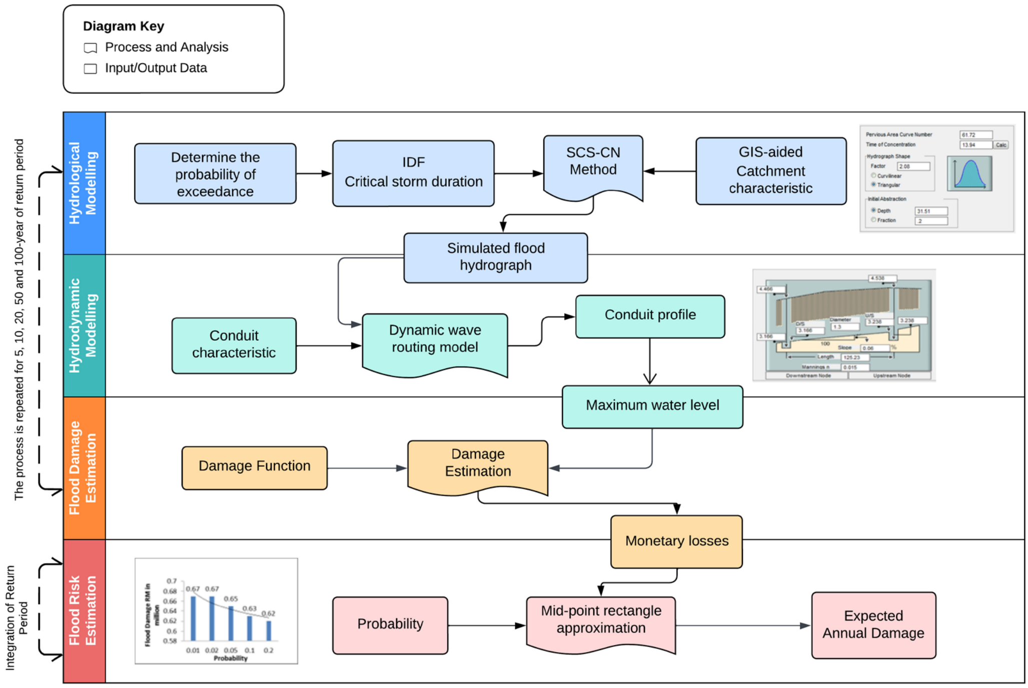


Figure 3. Simulation process for a scenario

Hydrological Model

The inbuilt rainfall-runoff modeling in XP-SWMM used in the present study was the Soil Conservation Service Curve Number (SCS-CN) method. The simulation employed a Horton roughness coefficient of n = 0.015 to represent the predominance of paved surfaces within the predominantly institutional area. The equation for runoff generated is:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (1)$$

where:

Q = depth of runoff, in mm

P = depth of rainfall, in mm

S = maximum potential retention

where maximum potential retention, S, is:

$$S\ (mm) = \frac{25400}{CN} - 254 \quad (2)$$

For the runoff generation quantification, the initial abstraction rate was set to the constant value, λ=0.2, following the commonly used value. The initial abstraction (Ia) was calculated using Equation 3.

$$\text{Initial abstraction } (I_a) = S\ (\text{mm}) \times \lambda$$

Runoff hydrograph at the outlet of a catchment is calculated in XP-SWMM by convolving the rainfall hyetograph with a unit hydrograph. Multiplying each ordinate of the rainfall design storm by each ordinate of the unit hydrograph produces a series of smaller hydrographs. Each hydrograph corresponds to a single rainfall amount throughout the period. The final runoff hydrograph is the sum of all the hydrographs. The rainfall pattern used was obtained from the National Stormwater Manual (DID Malaysia 2012), while the unit hydrograph of SCS-CN was selected for this study. In order to calculate the peak of the unit hydrograph, this study used a formula from the SCS method following Equation 4:

$$Q_p = 0.208A/t_p \quad (4)$$

in which:

Q_p is the peak discharge in m^3/s

A is the drainage area ha and

t_p is the time to peak in hours

The time needed for runoff to travel from each sub-catchment's hydraulically farthest point to the outlet, i.e., the time of concentration (), was computed using the Velocity Method (Equations 5, 6, and 7) (DID Malaysia 2012).

Overland Flow, : t_o

$$t_o = \frac{107.n^{*}.L^{\frac{1}{53}}}{S^{\frac{1}{5}}} \qquad (5)$$

t_o = Overland sheet flow travel time (minutes)

L = Overland sheet flow path length (m)

For Steep Slope (>10%), L ≤50 m

For Moderate Slope (<5%), L ≤100 m

For Mild Slope (<1%), L ≤200 m

n^* = Horton's roughness value for the surface

S = slope of overland surface (%)

Drain Flow, : t_d

$$t_d = \frac{n.L}{60R^{\frac{2}{3}}S^{\frac{1}{2}}} \qquad (6)$$

n = Horton's roughness value for the surface

R = Hydraulic radius (m)

S = Friction slope (m/m)

L = Length of reach (m)

t_d = Travel time in the drain (minutes)

Time of concentration, : t_c

$$t_c = t_d + t_o \qquad (7)$$

Hydrologic characteristics of each sub-catchment that is required to run the rainfall-runoff model were carefully specified and pre-processed according to the site information, such as the area, land use, and soil type. For example, the data from the land use and soil type determine the CN value, and the present catchment is within the Kelantan River Basin with soil classified under the Hydrologic Soil Group A and D based on the TR-55 tables (Faizalhakim & Shafuan, 2016). Since the catchment area is considered urban and mainly impermeable with a very low infiltration rate, it was specified as Group D for soil type.

The CN for each sub-catchment was further associated with the land use types within the sub-catchment, and the area-weighted average CN was finally quantified for each sub-catchment. Rows 1 until 5 in Table 2 show the hydrologic parameter values determined for each sub-catchment.

Table 2
Input data for each sub-catchment

No.	Data/Sub-catchment	S1	S2	S3	S4	S5
1	Area (km²)	0.0182	0.0144	0.0039	0.1985	0.1284
2	Type of Land Use	Commercial & Business Area	Commercial & Business Area	Parking Lot	Residential Area	Residential Area
3	Imperviousness (%)	85	85	100	65	65
4	CN Value	95	95	98	92	92
5	Maximum potential retention, S	10.88	9.61	5.18	22.09	22.09
6	Initial abstraction	2.18	1.92	1.04	4.42	4.42
7	Slope of overland slope (%)	0.05	0.05	0.03	0.14	0.28
8	Time of Concentration (min)	13.94	17.02	14.02	19.70	16.56
9	Friction slope(m/m)	0.0007	0.0007	0.0008	0.0008	0.0060
10	Flow path Length (m)	180.46	145.36	66.09	605.82	525.00
11	Hydraulic Length (m)	69.80	125.23	76.40	0.00	38.68
12	Hydraulic Radius (m)	0.4952	0.4952	0.4952	0.4952	0.4952
13	Overland flow (min)	12.90	15.11	12.90	19.70	16.36
14	Drain flow (min)	1.04	1.91	1.11	0.00	0.20

This study considers rainfall events of 6-hours, 12-hours 24-hours, and 48-hours to determine the critical storm duration for the hydrological system. The design storm was used to find critical storm duration for the simulation study. The simulation results concluded that the maximum critical duration for the Islamic Hall Complex is 24 hours, hence being used for all considered storm probability. The rainfall depths used are as shown in Table 1.

Hydrodynamic Model

The hydrodynamic simulations applied the dynamic wave routing of Saint Venant equations, where spatial features in the XP-SWMM have to be specified as 1D and 2D. 1D was set for flows along the main channels and 2D for floodplain areas. The total grids for the 2D computation are 3,624 grids with a mesh size of 4 m by 4 m. Links for 1D modeling to represent the main drain for S1, S2, and S3, and the 2D mesh for the flood inundation is displayed in Figure 4. Following the average channel depths of drains from site surveys, all drains and nodes were designated as concrete rectangular drain with dimension 1.3 m deep and 1.6 m wide. The drainage network within the catchment predominantly comprises concrete-lined channels; therefore, a Manning's roughness coefficient of n = 0.015 was adopted in the hydraulic simulation to represent the flow resistance characteristics of concrete surfaces.. Rows vii until xii in Table 2 show the input data for sub-catchments. Upon verifying the simulated flood depth, it was found that the simulated flood depth range of the base case coincides with the reported flood depth from historical reports of flood events in the study area, which is between 0.1 and 1.0m (DID, 2018).

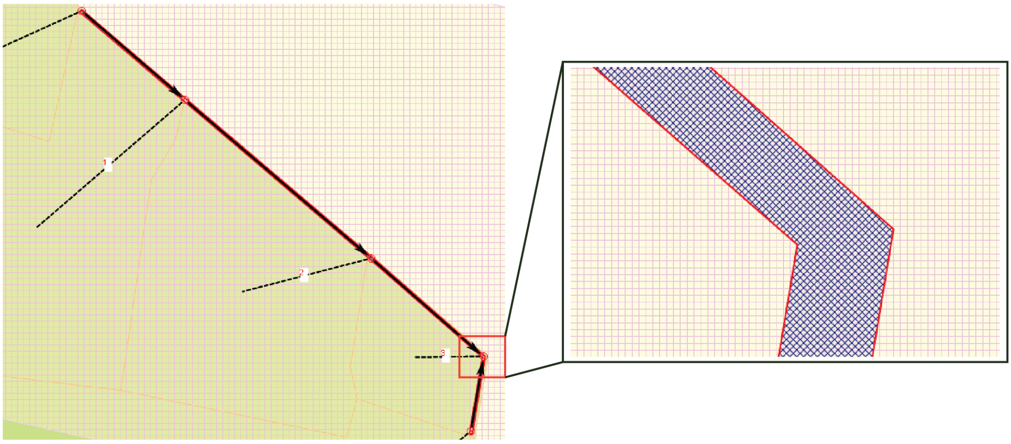
Model calibration was undertaken through an iterative adjustment of sensitive hydraulic parameters, primarily the Manning's roughness coefficient and infiltration rates, to achieve optimal agreement between simulated and observed flood depths and extents. The calibration process utilized historical flood records and surveyed water levels to ensure realistic model behaviour under representative storm events. Subsequently, model validation was performed using an independent rainfall event to assess the robustness and predictive reliability of the calibrated model. The validation results demonstrated satisfactory correspondence between simulated and observed inundation patterns, indicating that the model configuration is suitable for application in subsequent flood assessment scenarios

Flood Management Scenarios

Flood modeling for the all scenarios were undertaken using the same rainfall characteristics, but with different rainfall excess generation due to the different land covers and characteristics. For the base case and with NbS scenarios, the drainage system is expected to perform to its design capacity, and built-up sedimentation is negligible. This means that the drainage system is assumed to be maintained during the appraisal period. Meanwhile, the third scenario that represent the depleted capacity of the drainage system reflects a lack of maintenance scenario that can influence flood inundation on the floodplain and consequent damage and risk. The built-up sediment was set to be three inches (0.07 m) along the conduit, which roughly represents the actual site's condition obtained during site visits. Despite the relatively low sediment depth used in the flood modeling, the module was included to relate the cause and effects of sedimentation to flooding that has been speculated to be one of the factors aggravating flood impacts.

Figure 4. Example of links represented by arrows for hydrodynamic modeling and grids of 2D modeling

with dashed lines indicating flows from sub-catchment into nodes. Also shown is the superimposed interface of 1D-2D regimes (right)



The scenario with NbS assumes that a large number of institutional buildings within the vicinity have been upgraded with green roofs, and the parking lots have been upgraded with porous pavement. Green roofs help to reduce runoff volume, while porous pavement improves the permeability of the area. Approximately 8.7% of the total catchment area is covered by NbS interventions, with the spatial distribution across the respective sub-catchments presented in Table 3. The hydrologic parameters used for the simulation of floods, given the assertion of NbS measures, are also given in the table. In terms of CN input for the modelling, the interpolation approach is used; The green roof's CN value is 78, considering that 70% of the area remains impervious (Sena 2015). On the other hand, the porous pavement's CN is 45, which is a pragmatic approach when consider CN range between 45 and 89 (Bean et al., 2007).

Table 3
Area and CN for sub-catchments in the study area. Note that institutional buildings refer to the area where green roofs are applied.

Sub-catchment	Land Use (%)	Area %	Imp (%)	CN	CN Product	Maximum potential retention, S (mm)	Initial abstraction (mm)
S1	Paved parking lots	8,360 m²= (49.7%)	45.92%	45	22.37		
	Buildings with green roofs	8,463 m² = (50.3%)	70%	78	39.35		
	Total	16,824 m²	50.5%		CN=61.72	157.54	31.51
S2	Paved parking lots	6,802 m²= (45.16%)	45.92%	45	20.32		
	Buildings with green roofs	8,261 m² = (54.84%)	70%	78	42.91		
	Total	15,063 m²	50.55%		CN=62.23	154.16	30.83
S3	Paved parking lots	3,733 m² = (100%)	45.92%	45	45		
	Total	3,733 m²	45.92%	45	CN=45.00	310.44	62.09

Flood Damage and Risk

A flood damage equation that utilizes maximum flood depths as one of the determinant factors for damage to an institutional building was adopted from DID (2012) in the present study (Equations 8 and 9). Maximum inundation depths from the rainfall excess simulations were used to determine the possible losses of assets during flood events. Flood depth is widely used as the main flood indicator in flood risk assessment studies that provides estimates of economic damage based on the degree of susceptibility of the elements at risk. This means that areas with higher property values will possess greater losses from flooding. The damage equation used the mean values of flood depth and duration suggested by DID (2012) (i.e., 0.76 m depth and 2.45 days) based on their extensive data collection of flood damages. These were used to obtain the constant damage factor. Meanwhile, the mean damage value (i.e., RM 401,500) was used in the overall computation of flood damage on the institutional building.

$$\text{Flood damage (RM)} = \text{Affected properties (ha) x Unit property values (RM/ha) x Damage factor (\%).} \quad (8)$$

$$\text{Damage Factor} = ((\text{Depth in meter} - \text{Mean Depth}) \text{ x } 0.32)) + ((\text{Duration in days} - \text{Mean Duration}) \text{ x } 0.08)) + 1 \quad (9)$$

Flood risk was quantified in terms of Expected Annual Damage (EAD), which represents the expected degree of losses considering the likelihood of storm events. It is calculated by integrating the damage with the probability of occurrences over the range of considered flood probability (Equation 10) (Fatdillah et al., 2022).

$$\text{Risk} = \sum_{T=1}^{N} (P_{T+1} - P_T).\frac{D_{T+1} + D_T}{2} \qquad (10)$$

where; P is the probability of a flood event, T and D is the damage of the flood event

$$\text{Expected annual benefits} = \text{EAD}_{\text{without NbS}} - \text{EAD}_{\text{with NbS}} \qquad (11)$$

Flood risk with and without NbS implementation was compared to obtain the Expected Annual Benefits (EAB) of risk reduction (Equation 11) and the percentage of EAD reduction(Equation12)

$$\text{Expected annual damage reduction} = \frac{\text{EAD}_{\text{without NbS}} - \text{EAD}_{\text{with NbS}}}{\text{EAD}_{\text{without NbS}}} \times 100 \qquad (12)$$

In order to highlight the magnitude of the change independent of its direction, the absolute value of the disparity can be calculated. This facilitates a uniform method for comparing numbers and displaying the discrepancy as a percentage following Equation 13.

$$\text{Percentage Difference} = \frac{Absolute\ Difference}{Average} \text{ x } 100\% \qquad (13)$$

RESULTS

Results were analyzed in terms of the peak runoff and consequent maximum water levels, flood damage, and risk associated with the design storms and considered scenarios. The highlight is on the analysis of EAD reduction benefits related to the NbS implementation. Due to the micro-level simulations being applied, results were analyzed at sub-catchment level focusing on sub-catchments S1, S2, and S3, where upgraded features of NbS is considered on the institutional compound.

Runoff and flood depth

Table 4 and Figure 5 show the reduction of peak discharges and flood depth across all return periods when considering NbS implementation against the base case. Among all sub-catchments analyzed, S3 demonstrates the most notable reductions in both peak flow and maximum depth. This is attributed to the improved pavement porosity applied in this area and its downstream location that leads to flow attenuation. In contrast, NbS offers little measurable benefit in S1 and S2 under high return period events (50- and 100-year) reflecting the limited capacity of the proposed measures under extreme storm conditions.

Across the entire sub-catchments, it can be seen that when NbS is considered and design storms are at relatively low probability of occurrence, i.e., 20-, 50- and 100-year return periods reduction in runoff is small. The reduction in runoff is higher for higher probability of occurrence, i.e., 5- and 10-year return periods. The highest reduction of runoff is 44% at sub-catchment S3 under 5-year return period design storm, while the lowest reduction of runoff is 10% at S1 under the 100-year return period storm. The simulated flood depths are within the range of 0.44 m to 0.87 m for base scenario. NbS contributes to lessening the runoff and depth of flooding, but only marginally, i.e., ranging from none to 2.22% for S2, and not as pronounced as what is found from the peak runoff comparisons. The minor differences are also apparent from the inundation map of different return periods shown in Figure 6.

Table 4
Percentage reduction of discharge and percentage reduction of maximum water depth compared to the status-quo condition.

Sub-catchment/ Return Period	S1		S2		S3	
	Flow reduction (%)	Maximum water depth reduction (%)	Flow reduction (%)	Maximum water depth reduction (%)	Flow reduction (%)	Maximum water depth (%)
5-year	24.82	1.47	24.78	2.22	44.20	2.13
10-year	21.66	1.37	21.64	2.00	39.06	1.92
20-year	18.86	1.28	18.86	1.82	34.40	1.75
50-year	15.67	0	15.69	1.59	28.94	1.56
100-year	10.46	0	10.51	0	18.71	1.47

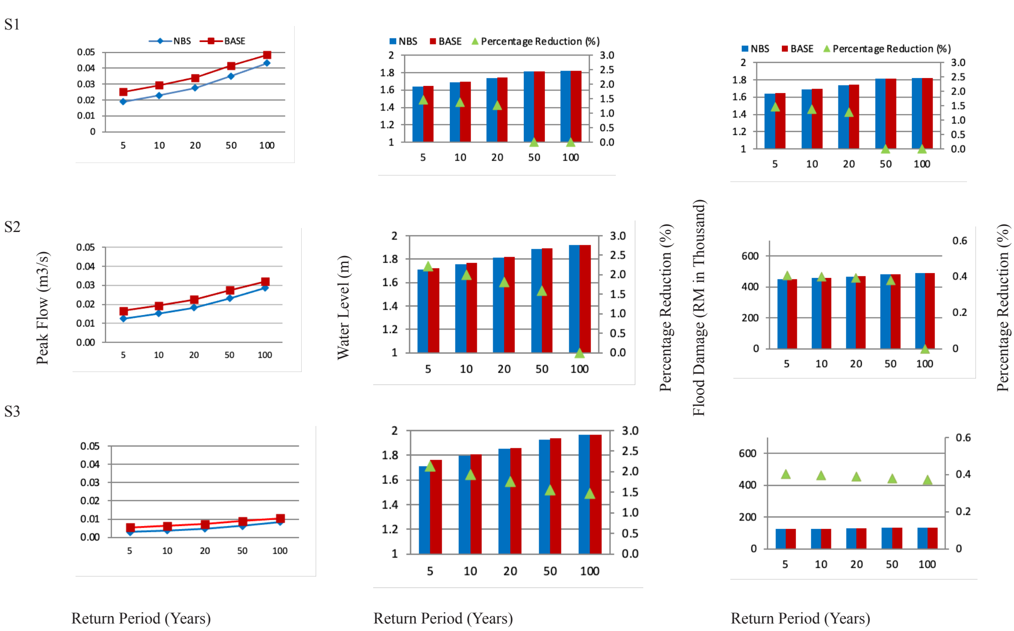


Figure 5. Peak flow, water level and flood damage for subcatchment S1, S2 and S3

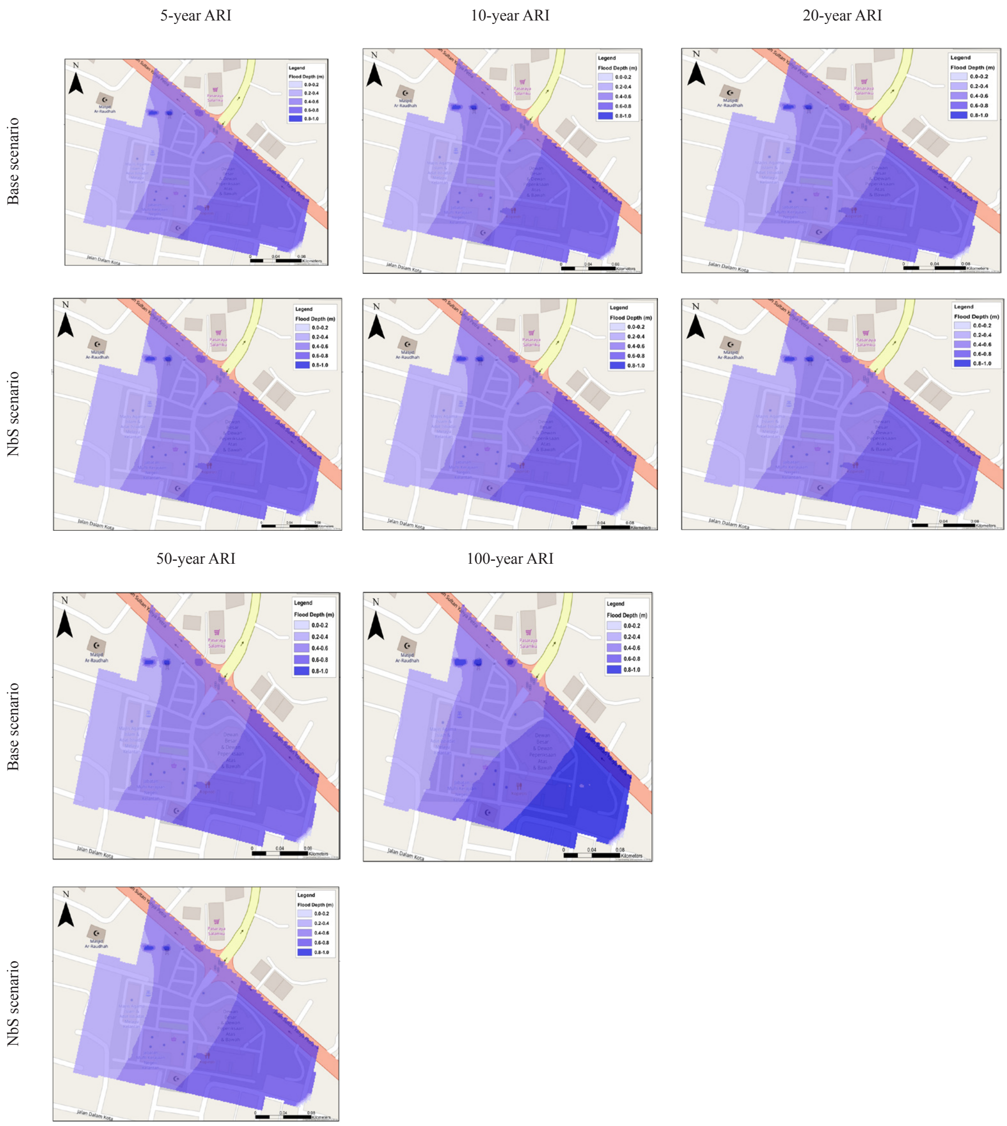


Figure 6. Flood map for base and NbS scenario for Islamic Hall Complex

Flood Damage and Risk Reduction

Further analysis was made on the flood damage and risk reduction of the different scenarios (Figure 5). In the base case, there is an increase in flood damage over low probability of exceedance floods given the greater flood magnitude. The maximum flood damage can be observed from S1 at RM 670 thousand, while the least is from S3 at RM 120 thousand, both corresponding to a 100-year return period. A comparison of damage over the return periods between the status-quo condition and NbS shows a small difference. This is influenced by the minimal difference in flood depths between the two scenarios. The highest flood damage reduction is 0.4% at S3, which is located at the most downstream area in the subbasin. There is no reduction of damage from the low probability of exceedance floods at S1 and S2, i.e., 50- and 100-year return periods for the former and 100-year return period for the latter. The no difference in damage is primarily caused by the indifference flood depths of the low probability of exceedance flood events.

The extremely small differences in flood damage between the high return periods are translated into small differences in the expected annual damage, i.e., risk. The highest benefits (i.e., EAD reduction) is 0.44% from S3, followed by 0.39% and 0.32% from S2 and S1. In terms of monetary risk-reduction benefits, the highest is from S1 with RM 385, followed by S2 with RM 340 and S3 with RM 105.95. Overall, the risk reduction benefit to the institutional compound is only RM830 despite the NbS implementation. It can be found that the flood event that the NbS is most beneficial to reduce the flood damage from is the 5-year return period event. For flood events that are rare, such as the 100-year return period, the NbS does not yield reduction in EAD, except at S3 subbasin. This is because the NbS type considered in S3 subbasin is a parking lot with porous pavement that is dominating the land cover of the subbasin result in greater abstractions. However, it only yields less than 0.5% risk reduction as compared to the base case.

DISCUSSION ON NBS EFFECTIVENESS AND CHANNEL CAPACITY REDUCTION

The present study shows that small-scale implementation of NbS at the institutional building compounds in subbasins S1, S2, and S3 covers only a cumulative 10% of the total basin. The small area and localized NbS implementations have resulted in insignificant flows and depth reductions as compared to the base case, for example, 12.98% reduction in flow and 0.54% in depth at the downstream subbasins where the NbS are considered. Note that the upstream subbasins, i.e., S4 and S5, were not include NbS, hence have led to the same runoff generation from the upstream to the downstream S1, S2 and S3 subbasins as the base case scenarios. While NbS typically excels at lowering peak discharges (e.g., Adam et al., 2018), its limited effect on flood depth in disproportionate areas is an expected outcome as quantified in the present study. Nature-based Solutions (NbS) can offer valuable space and time for water retention and release; however, their effectiveness is highly dependent on their scale and location of implementation. Small-scale, localized NbS implementations often do not significantly reduce flood risk, a finding consistent with previous research (Matczak et al., 2019; Seddon et al., 2020). The insignificance is even more expected when the NbS implementation area is not in proportional to the rest of the catchment (Futter, 2019).

NbS ecological and social co-benefits, coupled with lower implementation costs, make them compelling additions to flood mitigation portfolios (e.g., Rehan et al., 2023). While NbS promotes environmental sustainability and can offer a lower-cost intervention than traditional engineered measures (Reid & Bourne, 2018), their effectiveness are clearly diminishing over the higher return period events. Similar to the present study, studies have shown that NbS can be a more cost-effective solution than engineered alternatives when it comes to less extreme hazard scenarios (Collentine et al., 2018), but not for most extreme events (Dadson et al., 2017). The fundamental obstacle to relying entirely on NbS over structural measures remains the insufficient volume capacity within catchments to fully manage the most extreme events.

Since flood impacts are subject to the hazard probability and magnitude as well as the damaging consequences, it is imperative to consider the range of flood hazards and not only a specific target design standard when deciding upon investment allocations (e.g., Rehan, 2018). A key area for improvement also lies in how the benefits of NbS, ranged from quality of life to water environment (Wang et al., 2022), are accounted for in risk assessments. At the moment, there remains a knowledge gap around how the cost-effectiveness of NbS compares to or alongside other alternatives (Seddon et al., 2020). There is an ongoing challenge in quantifying the diverse benefits of NbS implementation in monetary terms. For instance, Mulatu et al. (2022) have attempted to monetize the wetland eco-system services, which may be adopted in flood risk management context. Integrating these benefits into monetary evaluations would help to highlight the true value of NbS alongside engineered measures during benefit-cost analyses.

In terms of the reduction of channel capacity due to sedimentation, it was found that the effects to flood depths between the base case scenario and the sedimentation scenario are apparently infinitesimal with less than a 1% (Figure 7). The reason for the indifference between the two conditions is the small difference in the conveyance capacity of the drain. As a result, the maximum flood depth on the ground resulting from the storm events is not influenced much by sedimentation. Note that sedimentation here does not represent clogging, which the consequences will be much greater to the extent that more than 50% of the capacity might be reduced. Moreover, the analysis considers a relatively small basin which, if extend to a much larger basin, the effects are possibly exponential.

The overall results produced were based on a modelling approach that does not satisfy robustness in simulation studies. Uncertainties in rainfall inputs, parameter selection, model structural limitations, or the long-term performance of NbS features (e.g., clogging or maintenance deficiencies) are inherent in the modelling steps. Therefore, the reported benefits should be interpreted with caution, and future studies are encouraged to incorporate uncertainty analysis or probabilistic flood modeling to improve confidence in expected NbS performance under a range of possible events.

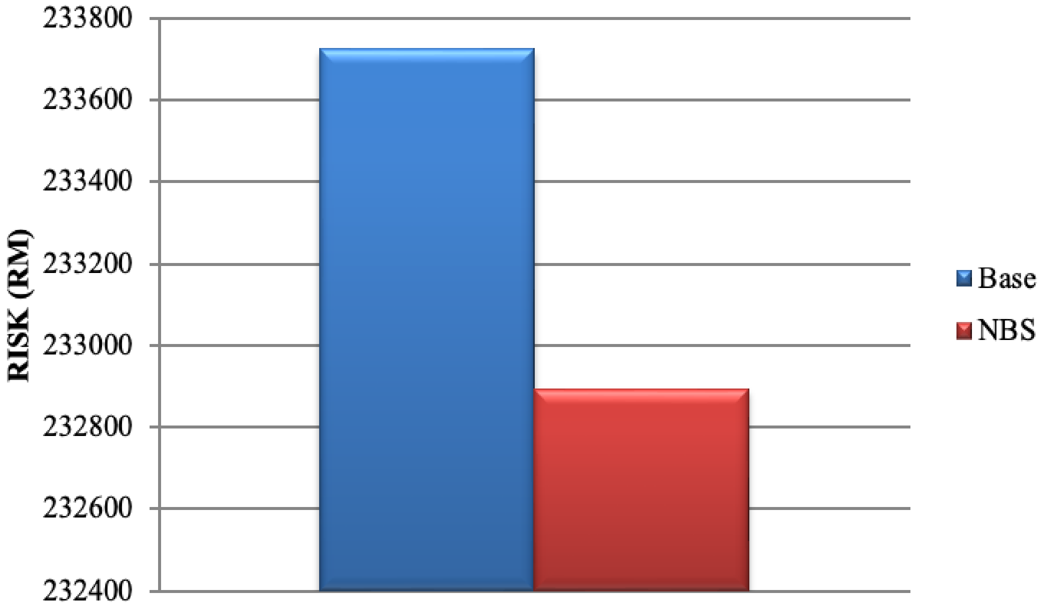


Figure 7. Total risk for base and NBS scenario

CONCLUSION

This paper analyses the effects of NbS on risk reduction if it is implemented at an institutional building in a flood-prone area of Kelantan, northeast of Peninsular Malaysia. Hydrologic and hydrodynamic models were employed to simulate localized pluvial flooding under scenarios with and without NbS interventions. Application of NbS in a limited area at the downstream area of the basin caused only small effects in runoff reduction and to the resulting flood depths. The effects cascade to the flood damage, the risk estimates and the risk reduction, highlighting the insignificant effectiveness of NbS if not being implemented rigorously over a large area of the basin, and if not being integrated with structural measures. The findings are consistent with previous studies and highlight the potential risks of depending exclusively on flood mitigation measures without integrating broader adaptation strategies, but the extent or degree of their contribution in the tropical region remains to be investigated. Understanding the implications of integrated measures under different scale of implementation would enhance development of sustainable solutions in flood risk management. It is also understandable that the effectiveness of NbS is also influenced by the amount and intensity of rainfall in a region. In tropical countries, rainfall is generally much higher than in other regions, which can substantially affect NbS performance. This study is constrained by its focus on a single institutional compound and a micro-scale modelling framework, which limits the transferability of the results to larger, interconnected urban catchments where hydrological responses and infrastructure interactions may be more complex. The analysis is based on a selected set of rainfall return periods and a 24-hour event duration, and therefore may not fully capture the influence of shorter- or longer-duration, and high-intensity convective storms that are common in tropical climates. Furthermore, the coupling between NbS and existing grey infrastructure is treated conceptually rather than through fully integrated system modelling, which may underestimate synergistic or threshold effects under extreme flood scenarios. Finally, the study prioritizes hydrological and risk-based indicators, while broader economic valuation, social vulnerability, and ecosystem service benefits of NbS were not quantitatively assessed, potentially understating the full contribution of NbS to sustainable urban flood management. Nonetheless, the present study is one of the few studies that have highlighted the effectiveness of NbS in Peninsular Malaysia. Future research should explore how the scale, spatial configuration, and intensity of NbS interventions influence risk reduction. A clearer understanding of these relationships will help policymakers design more effective, climate-adaptive flood management strategies tailored to local rainfall regimes.

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