Ecological Indicators 160 (2024) 111850

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Stormwater characterisation and modelling for Sungai Air Hitam in Selangor, Malaysia using model for urban stormwater improvement conceptualisation (music)

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A R T I C L E I N F O

Keywords:
Water Quality
Pollution Sources
Stormwater Modelling
MUSIC
BMPs
Land Use Change

A B S T R A C T

The aim of this study is to evaluate the current water quality status of one of the urban rivers in Malaysia, called Sungai Air Hitam. The river's water supply is not only unsuitable for the inhabitants but also hazardous to the aquatic species that depend on it. In order to simulate the water quality formulation of the river, the Model for Urban Stormwater Improvement Conceptualization (MUSIC) was used. The effects of various best management practices (BMPs) components have been examined to improve the river's water quality. This study also investigated different scenarios of the expected future changes in the land cover and the quality of the river. As the proportion of impervious surfaces increases, the urban hydrology cycle can be significantly altered, resulting in an increase in volumes and peak flows, and a decrease in storage, infiltration, and interception. The MUSIC results have shown significant reductions in biochemical oxygen demand (BOD), total suspended solids (TSS), total phosphorus (TP), and total nitrogen (TN) after introducing BMPs. It was also noticed that the prediction of pollutants falls within the acceptable range set by the Urban Stormwater Management Manual for Malaysia (MSMA) 2nd edition. For the land cover, it was found that the total reduction of BOD, TSS, TP, and TN for existing land use is 92.5 %, 94.5 %, 90.7 % and 91.9 %. Meanwhile, the total reduction in future land use is 81.6 % for BOD, 86.2 % for TSS, 80.9 % for TP and 80.8 % for TN. From the simulation results, it was observed that the application of BMPs has successfully reduced the observed mean BOD concentration from 92.38 mg/L (Class V) to 6.93 mg/L (Class IV) of the national water quality standards, NWQS, water quality index. As a result, the water quality index of the overall catchment has improved from Class IV to Class III (WQ1, WQ3, and WQ4) and from Class V to IV (WQ2) with the application of the BMPs. This assessment aims to raise awareness within the Sungai Air Hitam community regarding the importance of preserving river cleanliness and understanding the long-term environmental impact of water quality. These findings underscore the importance of an integrated system in managing urban water systems, which can offer valuable insight to the decision-makers.

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https://doi.org/10.1016/j.ecolind.2024.111850
Received 18 October 2023; Received in revised form 20 February 2024; Accepted 4 March 2024
Available online 14 March 2024

1. Introduction

Urbanization refers to the expansion of residential, industrial, and commercial areas in response to a 68 % growth in the human population by 2050 (United Nations, 2018). This process leads to the conversion of vegetated areas into impervious surfaces for instance, parking areas, roads, and rooftops (Mangangka, 2013). Consequently, the natural water cycle is disrupted, resulting in negative impacts on both the quantity and quality of surface runoff. Additionally, urbanization exacerbates issues related to climate change, for example, increased runoff (Miller and Russell, 1992), urban flooding, and sea level rise. Furthermore, human activities like farming and agricultural leaching contribute to an increase in pollutant runoff, which contaminates water bodies. Water pollution poses a significant challenge that threatens the deterioration of our environment (Osman et al., 2019).

Nonpoint source (NPS) pollution, specifically stormwater runoff, is a key contributor to water pollution (Osman et al., 2019). It consists of various contaminants such as trash, debris, floatable materials, suspended solids, organic compounds, nutrients, pathogens, and heavy metals (Akan, 1993). Duncan (1999) conducted an evaluation of pollutant concentrations, including total suspended solids (TSS), total phosphorus (TP), and total nitrogen (TN), based on different land uses, which indicate that land use can influence the concentration and load of pollutants. Typical land uses such as lawns, commercial streets, parking lots, highways, and industrial areas contribute significantly to high stormwater runoff concentrations. However, Osman et al. (2019) highlights that agricultural lands contribute more sediment and nutrient loads, particularly nitrogen. This finding aligns with the review conducted by Goh et al. (2019), which identifies agricultural lands as having the highest average concentrations of TSS, TP, and TN. In an urban agglomeration watershed, the combined effects of agricultural activity and urbanisation result in more severe NPS contamination, therefore the load levels and pollution process must be taken into account (Zong et al., 2021).

The characteristics of urban runoff vary across countries due to differences in development level, land use, soil properties, and rainfall patterns. Agricultural, plantation, and industrial land use changes have happened throughout time. In Malaysia's perspective, many elements of land use have been altered by Malaysia's fast urbanisation and the establishment of new cities (Rahman, 2021). In comparison to countries like the USA and Australia, being a tropical country, Malaysia, experiences frequent and extreme rainfall through the year. Consequently, this leads to a low event mean concentration (EMC) and a weak first flush, resulting in a low rate of pollutant removal (Wang et al., 2017). Furthermore, development level alters the features of runoff within the same climate region. Phosphorus and nitrogen are the most prevalent nutrients in stormwater runoff, and they are generally derived from soil erosion, farming, wildfire ash, and fuel burning (Mangangka, 2013). Farming activities in emerging country such as Malaysia is more extensive than in developed countries, resulting in higher quantities of runoff pollutants, particularly nutrients. According to Chow and Yusop (2014), Malaysian average pollutant concentrations for TSS, TP, and TN are 204 182 mg/L, 0.9 0.2 mg/L, and 3.0 1.2 mg/L, respectively, which are higher than in developed countries such as Australia, where the levels of TSS (36.5–54.4 mg/L), TP (0.21–0.34 mg/L), and TN (1.36–1.57 mg/L) are reported lower (Lucke et al., 2018).

Agriculture and palm oil plantation were the original land uses in the basin of Sungai Air Hitam (KDABB, 2019) in Selangor, Malaysia before it became a mixed development region with residential and urban areas. This has resulted in significant deterioration of the river's water quality and detrimental to the creation of a long-term urban environment. Its water supply is now not only unsuitable for the inhabitants, but also dangerous to the aquatic species that depends on it. The river and its tributaries are foul-smelling, based on dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and ammoniacal nitrogen (AN) alarming value. It is also unattractive and unsuited for water sports and recreational activities over large sections of their lengths. In addition, some squatter settlements rely on the river for everyday use. Therefore, it is pressing to monitor and rehabilitate the water quality of the river. Construction of trash traps, new waste disposal places, and urban area management are the most straightforward solutions. However, the decreasing water quality will not be solved by any of these short-term fixes.

It also has been reported that changes in monsoon weather conditions worsen the declining water quality of Sungai Air Hitam. Sungai Air Hitam's water quality cannot be reliably maintained by this environmental strategy due to the unpredictable rainfall patterns associated with the monsoon season. Land use changes in the Sungai Air Hitam watershed region are linked to urbanisation.

Stormwater planning and management, with the aid of computer simulation, offers solutions for decision-makers. Nowadays, incorporating green technologies or best management practices, BMPs, in computer simulation can assess the BMPs' effectiveness, optimize their placement, and estimate their impact on stormwater runoff and water quality (Jajarmizadeh et al., 2016; Al-Ani et al., 2012). While traditional stormwater modeling software has focused on engineered systems, there is a growing need for software tools that can accurately simulate and evaluate the performance of nature-based solutions (Noh et al., 2018).

Stormwater management tools can be used to study the effectiveness of the BMPs in reducing urban pollutants. The Model for Urban Stormwater Improvement Conceptualization (MUSIC) is one of the tools that serves as a pivotal conceptual and decision-making tool in the realm of stormwater management. Its primary objective is to facilitate the conceptualization of potential stormwater BMPs and determine appropriate sizing to attain specific water quality objectives. In Australia, this model is renowned as the most widely utilized numerical stormwater model package. It offers a visual interface and accommodates single and continuous event-based simulations (Li et al., 2021). MUSIC offers a high degree of flexibility using rainfall inputs and allowing the incorporation of synthetic or natural event-based simulations, a feature deemed crucial for understanding how BMPs respond to specific storm events (Lisenbee et al., 2021). From a technical standpoint, the model executes water quality simulations by considering essential inputs such as soil parameters, catchment, and rainfall data. The simulation of water quality is based on the event mean concentration (EMC) methodology (Duncan, 1999). A notable instance of MUSIC's practical application involves its deployment to evaluate the performance of stormwater management facilities by the Brisbane City Council. This evaluation focused on the pollutants' reduction, serving as a tangible demonstration of the model's utility in real-world scenarios (Wong et al., 2002). MUSIC model supports the green infrastructure (GI) component or the BMPs widely used worldwide. GI component that also applies in Urban Stormwater Management Manual for Malaysia or *Manual Saliran Mesra Alam* (MSMA) second edition (Sidek et al., 2013). MSMA offers guidance to all stakeholders involved in the planning and design of stormwater management. It concentrates on managing stormwater through a control approach that is environmentally sustainable (Zakaria et al., 2014) within urban areas across Malaysia. MUSIC conveys the functionality of BMPs introduced for the catchment, such as infiltration systems, bioretention, gross pollutant traps and rainwater harvesting (Zahari et al., 2017; Shahzad et al., 2022; Woon et al., 2023). Moreover, MUSIC may assess drainage systems with treatment devices to improve water quality, hydrology, and cost at the lowest possible cost (Lisenbee et al., 2021). Overall, integrating green stormwater management practices, user-friendly modelling software, and stakeholder involvement can lead to more sustainable and effective stormwater management strategies that benefit both the environment and the community. Sidek et al. (2013) utilized MUSIC to simulate the characteristics of the Langat River in Malaysia and its catchment aimed to rehabilitate the river and improve its water quality index, WQI, to national water quality standards, NWQS, Class II. The results of the study indicate that implementing a combination of wetlands, bio-retention systems, and ponds significantly reduced pollutant loadings in the river. Specifically, TSS were reduced by 85.1 %, TP by 69.1 %, and TN by 37.5 %. The researchers also conducted an assessment during dry seasons to determine the minimum river flow necessary to protect habitats and the river's ecology. Muha et al. (2016) used the MUSIC model to assess the performance of water quality for a small scale bioretention system in a tropical climate. TSS (more than 80 %), TP (more than 50 %), and TN (both more than 50 %) reductions were found using the MUSIC software. The forecast of pollution reduction via MUSIC is in accordance with MSMA requirements. The findings of this study may help to improve the existing MSMA guidelines for the use of bioretention systems.

Using water quality modelling with the MUSIC software, Zahari et al. (2017) predicted the water quality of the Connaught Bridge Power Station (CBPS), Klang River, Malaysia, and forecasted pollutant concentrations. The model anticipated that BOD5 and TSS concentrations will decrease at Station 1, suggesting improved water quality. The concentration of BOD5 was reduced from Class IV to Class III, while the concentration of TSS was reduced from Class III to Class II. At Station 1, the model predicted mean reductions in TSS, TP, TN, and BOD5 concentrations by 0.17 %, 0.14 %, 48 %, and 0.31 %, respectively. Noh et al. (2018) investigated the pollutant loading composition of TSS, TP and TN in urban stormwater in Cameron Highlands, Malaysia. The MUSIC model was used in the study to evaluate pollution transport and stormwater treatment using various BMPs such as wetlands, bioretention, on-site detention, sediment basins, and gross pollutant traps, resulted in TSS, TP and TN reductions from 65 % to 83 %, 40 % to 66 %, and 52 % to 78 %, respectively. The comparison of observed and computed data revealed that stormwater runoff quantity modelling was accurate, but stormwater runoff quality modelling was more challenging and dependent on watershed characteristics and land uses. Imteaz et al. (2022) conducted a detailed analysis of the literature as well as mathematical simulations using the MUSIC software and demonstrate that the daily maximum concentrations of TSS, TP, and TN can be significantly decreased with the use of rainwater tanks. The MUSIC simulation results revealed that a rainwater tank can reduce TSS by 50 %, TP by 33 %, and TN by 29 % (mean daily concentrations) and TSS by 80 %, TP by 75 %, and TN by 63 % in terms of highest daily maximum concentrations.

To address contaminated runoff in a tropical climate, Woon et al. (2023) provide the calibration of bioretention model parameters using MUSIC software. The bioretention model was generated using data from a pilot study, conducted at the Universiti Sains Malaysia (USM) engineering campus in Malaysia, to assess the flow rate and pollutant reduction efficacy. The bioretention model parameters were calibrated and the MUSIC model performed good or very good of TSS, TN, and TP elimination percentages with reductions of −13 %, −4%, and −39 %, respectively. At 17 %, the flow rate reduction was likewise judged to be satisfactory.

There is a noticeable gap of information on the effectiveness of best management practices (BMPs) in Malaysia. To address this gap, hence, MUSIC is proposed in this study and various best management practices (BMPs) components have been examined based on four water quality parameters of the WQI, namely BOD, TSS, TP and TN where Sungai Air Hitam was chosen as study area. In additional to that, different scenarios of the expected future changes in the land cover and the quality of the river were also investigated. Finally, the water quality parameters from the developed method then will be compared to the range provided by the Urban Stormwater Management Manual for Malaysia (MSMA) 2nd edition. The WQI results obtained from this investigation offer valuable insights for BMPs implementation to rehabilitate Sungai Air Hitam.

2. Methodology

2.1. Study area

Sungai Air Hitam is located in Selangor's south and central regions within the Sepang district (Fig. 1 (a)). The Sepang District is in the southern part of the state of Selangor in Malaysia. Sungai Air Hitam's total length, including tributaries, is 4.9 km. The first tributary, about 1.07 km, originates in the southern section of the basin's hills. With a length of 1.86 km, the second tributary is covered in the northern half of the basin, including Malaysian Universiti Tenaga Nasional and training centers. Putrajaya Presint 14, Kampung Abu Bakar Baginda, training centers, and Bandar Baru Bangi are the primary localities within the Air Hitam River Basin. Most of the river's upstream water originates from a pond adjacent to Putrajaya's Nashrul Quran. The river flows naturally through a village, Kampung Dato' Abu Bakar Baginda (KDABB), then crosses the PLUS North-South highway to Bandar Baru Bangi, where it meets Cempaka Lake and merges into Ramal river. Majlis Perbandaran Sepang is the local council for the basin. Three river water treatment plants are nearby: Semenyih 2 Water Treatment Plant, Labuhan Dagang Water Treatment Plant and Bukit Tampoi Water Treatment Plant.

2.2. Methods

2.2.1. Sampling and water quality monitoring

The standard procedures of sample preparation and preservations, and laboratory analysis method by Code of Federal Regulations (CFR, 2021) were used in this study. Key parameters of calculating the national water quality standard (NWQS) water quality index are dissolved oxygen (DO, mg/L), biochemical oxygen demand (BOD, mg/L), chemical oxygen demand (COD, mg/L), ammoniacal nitrogen, (AN, mg/L), total suspended solid (TSS, mg/L) were measured following the CFR standards, and pH. Temperature (°C) and pH were measured using ProDSS multiparameter digital water quality meter. The meter was placed in a wastewater sample and briefly stirred for few seconds to remove any air bubbles. Measurement of temperature and pH of a sample was performed 10 cm underwater.

At sample ID WQ1, as shown in Fig. 1 (b), Sungai Air Hitam collected discharge from the dry detention pond of Presint 14 Putrajaya. Sungai Air Hitam at KDABB stops at a detention pond in the river's downstream section (WQ4). The present river conditions are tabulated in Table 1, along with the river's primary drain (exit) and sampling sites.

2.2.2. Water quality index

Water quality index (WQI), which is based on the national water quality standards (NWQS) is a set of standards created based on beneficial uses of water, is one of the two main approaches used to categorize the river water quality measured (Mohiyaden et al., 2018). The NWQS is a great benchmarking tool and has many useful applications. As a result, it can serve as a foundation for the target water quality in efforts to restore rivers, making it simple to understand for populations living along the river and for river basin management (Zainudin, 2010). The classification for water quality index, WQI, and based on national water quality standards (NWQS) is used as shown in Table 2. The descriptions of WQI classes which comprised 5 classes are tabulated in Table 3.

In Malaysia, water quality may remain consistent with some fluctuations during the dry season. Whereas, when precipitation is at its peak during the rainy season, water quality can improve or deteriorate depending on runoff or non-point source pollution intake. Therefore, four sampling locations were chosen as illustrated in Fig. 1: WQ1, WQ2, WQ3 and WQ4, which covers from the upstream point of the river towards downstream together with point sources detected along the stretch. To calculate the NWQS water quality index, six crucial parameters: pH, total suspended solids (TSS), ammoniacal nitrogen (AN), biological oxygen demand (BOD), chemical oxygen demand (COD), and dissolved oxygen (DO) were measured.

The water quality index, WQI, was then determined using the subsequent Equation (1) based on six tested parameters from laboratory and on-site testing:

(a)

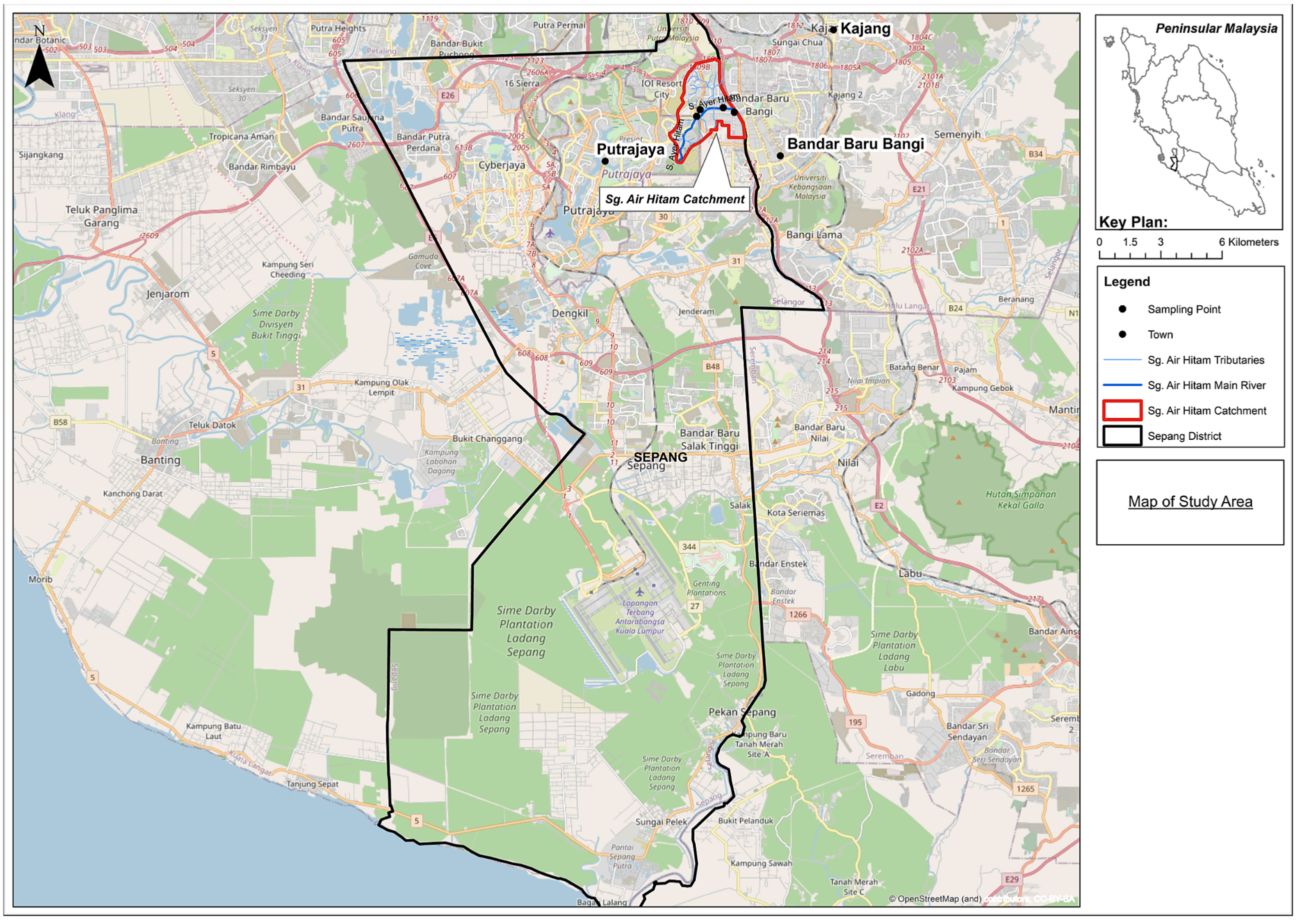

Fig. 1a. Study area at Sungai Air Hitam.

$$WQI = (0.22xSIDO) + (0.19xSIBOD) + (0.16xSICOD) + (0.15xSIAN) + (0.16xSISS) + (0.12xSIpH) \quad (1)$$

Where SIDO is Subindex DO (% saturation), SIBOD is Subindex BOD, SICOD is Subindex COD, SIAN is Subindex NH_3-N, SISS is Subindex SS, SIpH is Subindex pH, $0 \leq WQI \leq 100$. WQI of 81–100, 60–80 and 0–59 are considered clean, slightly polluted, and polluted, respectively (DOE, 2020**)**.

Sampling was conducted at two different times, morning, and night, for two weeks each. Fig. 3 demonstrates the (a) TSS (mg/L), (b) AN (mg/L), (c) COD (mg/L), (d) BOD (mg/L), (e) pH, (f) DO (mg/L), (g) temperature (°C), and (h) WQI results of the four study locations.

Fig. 2 illustrates that DO, BOD, COD and AN are measured higher than other parameters, especially DO and BOD with Class V for all sites, at both sampling times. In Malaysian rivers and lakes, the predominant pollutants are biochemical oxygen demand, BOD, ammoniacal nitrogen (NH_3-N), and suspended solids (SS). Elevated BOD levels primarily result from the discharge of untreated or inadequately treated sewage, particularly from manufacturing and agro-based industries. Domestic sewage, livestock farming, and various liquid organic waste products are key contributors to the presence of ammoniacal nitrogen. Suspended solids, on the other hand, mainly originate from earthworks and land clearing activities. The mitigation of suspended solids often involves employing sedimentation and water filters to achieve effective removal. Addressing these pollution sources is crucial for the preservation and improvement of water quality in Malaysian water bodies (Huang et al., 2015).

These parameters are non-compliant, surpassing the limits set for Class II. Among these parameters, BOD is of parameter of concern, as it exhibits an inverse relation with DO levels, as depicted in Fig. 3 (f) and in Class V for all sites, at both sampling times. The decline in DO levels (Fig. 2 (d)) reflects elevated BOD levels. On average, WQ2 demonstrates higher concentrations of non-compliance parameters compared to other sampling locations. This may be attributed to the improper disposal of solid waste and garbage into the river, originating from sources such as a nearby mini-market, workshops, and potentially a sewage treatment plant (STP). Additionally, the water channel flowing from residential areas significantly impacts the river's water condition. The proximity of sampling points to residential housing, roads, and commercial areas suggests the potential for untreated sullage to enter the drainage systems, contributing to river pollution.

The findings from the sampling, as detailed in Fig. 2, lead to the conclusion that the water quality status at the selected sampling locations (WQ1 – WQ4) in Sungai Air Hitam falls within the polluted range. According to the WQI classification by the Department of Environment (DOE, 2020), where a WQI of 0–59 is categorized as polluted, all sampled locations are classified as polluted. Moreover, the WQI results presented in Fig. 2 (h) provide insights into the water classes and designated uses according to the NWQS criteria (DOE, 2020). Notably, only location WQ2 is classified under Class V, indicating water unsuitable for any type of beneficial usage, with an average index value of 23.0. In contrast, the remaining locations are categorized under Class IV, signifying suitability solely for irrigation purposes, with average index values ranging from 39.2 to 40.1.

Class II represents the least acceptable category of clean water for general uses, particularly in the context of fisheries (aquatic habitat), water supply, and recreational activities. The analysis of sampling results reveals several non-compliance parameters, indicating that the water does not meet at least Class II standards as specified in the NWQS.

(b)

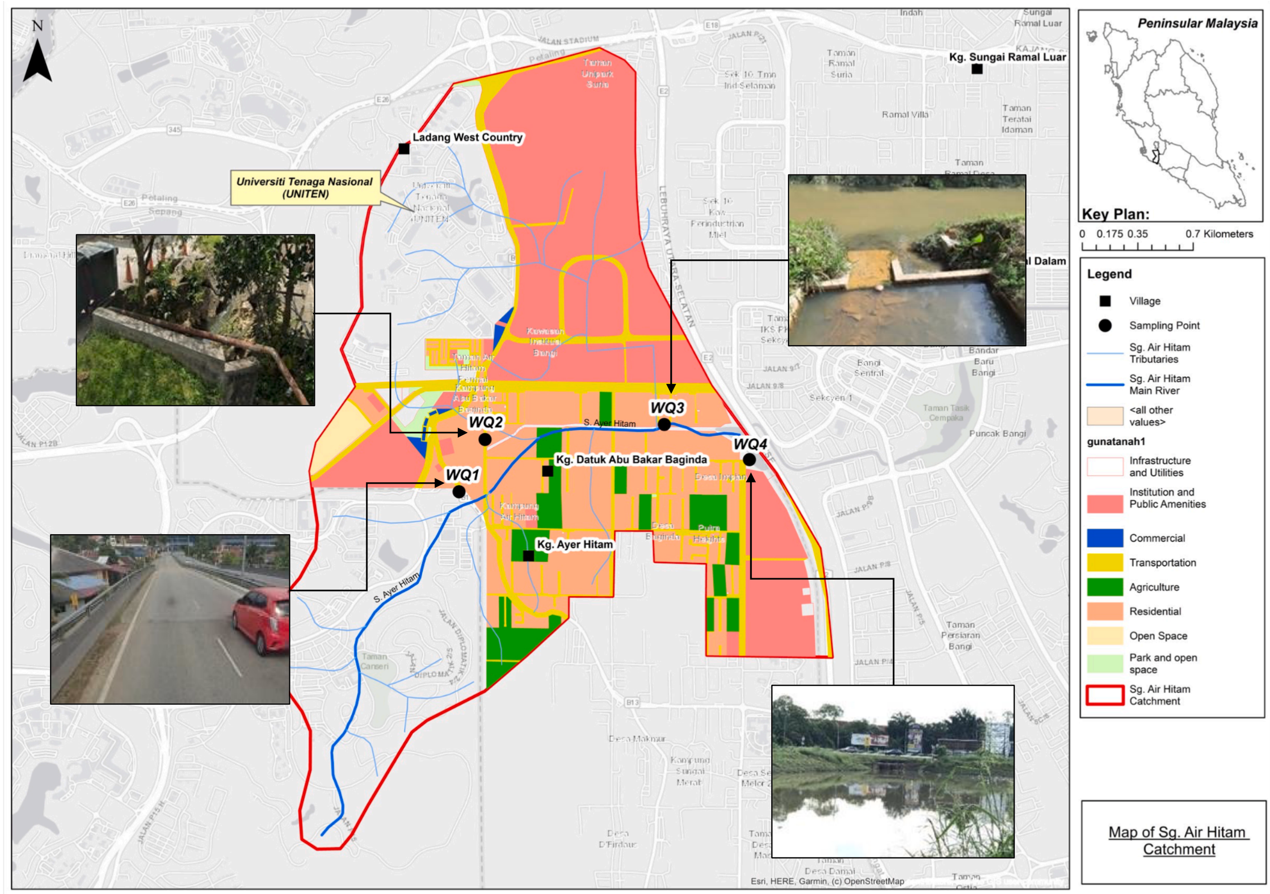

Fig. 1b. Sampling locations of tributaries of Sungai Air Hitam (WQ1), main drainage at Jalan Anggerik (WQ2), main drainage at Jalan Desa Baginda (WQ3) and Tasik Baginda pond (WQ4).

Table 1
Water Quality Sampling Location Details.

Sampling ID	Location	Latitude	Longitude	Types
WQ1	Tributaries of Sungai Air Hitam	2.95504	101.73120	Upstream
WQ2	Main drainage at Jalan Anggerik	2.95803	101.73267	Point Source
WQ3	Main drainage at Jalan Desa Baginda	2.95891	101.74287	Point Source
WQ4	Tasik Baginda (Pond)	2.95691	101.74772	Downstream

2.2.3. *MUSIC water quality modelling*

A simple stochastic hydrological model such as MUSIC was used to conceptually design the BMPs that comply with MSMA second edition in Malaysia. It quantified outflow from the catchment and the performance of BMPs devices that can be implemented in the catchment. The water quality simulation conducted for the Sungai Air Hitam catchment determined the percentage pollutant reduction that was achieved by applying of BMPs in the simulation. Parameters considered in the MUSIC simulation are BOD, TSS, TN, TP.

To run MUSIC model network, respective steps were determined: 1) nearest rainfall rain gauge and evaporation DID stations to develop meteorological template, 2) source nodes or the catchment areas to be incorporated into the model, 3) input of soil properties (rainfall-runoff properties), and 4) the input of pollutant generation characteristics for selected source nodes. The working procedure of MUSIC water quality modelling is demonstrated in Fig. 3 which require data input of hydrology/catchment characteristic of the study area to accurately calculate reduction percentage of target pollutants TSS, TP and TN based on land use characteristics.

To achieve the water quality objectives, magnitude of the overall catchment pollutant exports, and the pollutant loads reduction are required to identify acceptable pollutant loads in the receiving water. Within a catchment, pollutant loads are accumulated because of

Table 2
NWQS water quality index, WQI (DOE, 2020).

Parameter	Unit	NWQS Class				
		I	II	III	IV	V
Ammonia nitrogen, AN	mg/L	< 0.1	0.1–0.3	0.3–0.9	0.9–2.7	>2.7
Biochemical oxygen demand, BOD	mg/L	< 1	1–3	3–6	6–12	>12
Chemical oxygen demand, COD	mg/L	< 10	10–25	25–50	50–100	>100
Dissolved oxygen, DO	mg/L	> 7	5–7	3–5	1–3	<1
pH	–	> 7.0	6.0–7.0	5.0–6.0	<5.0	>5.0
Total suspended solids, TSS	mg/L	<25	25–50	50–150	150–300	>300
Water quality index, WQI	–	>92.7	76.5–92.7	51.9–76.5	31.0–51.9	<31.0

Table 3
Water classes and uses (DOE, 2020).

Classes	Uses
Class I	Conservation of natural environment.
	Water Supply I – Practically no treatment necessary.
	Fishery I – Very sensitive aquatic species.
Class IIA	Water Supply II – Conventional treatment.
Class IIB	Fishery II – Sensitive aquatic species.
	Recreational use body contact.
Class III	Water Supply III – Extensive treatment required.
	Fishery III – Common, of economic value and tolerant Species; livestock drinking.
Class IV	Irrigation.
Class V	None of the above.

stormwater runoff, caused by anthropogenic activities and practices. The load estimation by event mean concentration, EMC, method was calculated using Equation (2) (DID, 2012) and tabulated in Table 9 and Table 10 for existing and future land uses, respectively.

$$L = R^*EMC^*A^*C_V/100 \quad (2)$$

Where L is the annual pollutant load (kg/year), R is the mean annual rainfall – MAR (mm/year), EMC is the event mean concentration (mg/L), A is the catchment area (ha), and C_V is the area-weighted volumetric runoff coefficient as shown in Equation (3) (TxDOT, 2002) for the whole catchment.

$$C_V = \frac{\sum_{j=1}^{m} C_j A_j}{\sum_{j=1}^{m} A_j} \quad (3)$$

Where C_j is the runoff coefficient for area j, A_j is the area for land cover j, and m is the number of distinct land use.

The hydrology/catchment characteristic data was obtained from the Department of Environment and Meteorology Department of Malaysia. A meteorological template was created by using the following input: (i) rainfall data (hourly) in 2022 (Station number 2616135, Ldg. Telok Merbau, Selangor) (ii) rainfall runoff parameter for each defined land use, (iii) event mean concentration (EMC) values of BOD, TSS, TP and TN adopted from the second edition of MSMA (DID, 2012), and (iv) average monthly potential evapotranspiration (PET) data. The average monthly PET values, as summarized in Table 4, obtained from the Malaysian Department of Irrigation and Drainage (DID) evaporation station named Loji Air Kuala Kubu Bahru. The incorporation of Table 4 was crucial for the development of stormwater modeling. It necessitated the input of meteorological data, including rainfall and potential evapotranspiration (PET) values, to precisely depict the catchment in the software.

$$\%Impervious(orpervious)SurfaceArea = \frac{TotalofImpervious(orpervious)SurfaceAreas}{TotalofCatchmentArea} \times 100 \quad (4)$$

Next, the catchment area was delineated, and the attributes of the catchment were included in the source nodes windows. According to the percentage of pervious and impervious area, source nodes reflected each form of land use in the catchment, including residential, commercial, transportation, forest, and agricultural. Each source node was incorporated with the EMC value to introduce the pollutant generation from the catchment. The EMC values for BOD, TSS, TN and TP pollutants and land uses are set out in Table 5. A list of runoff generation parameters used in the modeling is shown in Table 6.

Stormwater BMPs constructed or installed will enhance the catchment's water quality. Various stormwater BMP applications in MUSIC have been integrated into the software. The available BMPs in MUSIC are bioretention systems, infiltration systems, media filtration systems, gross pollutant traps, buffer strips, vegetated swales, ponds, sedimentation basins, rainwater tanks, wetlands, and detention basins (Muha et al., 2016; Haris et al., 2016). All stormwater BMPs has their applications and ability in pollutant removal as well as other function, such as a component in flood control. The targeted parameter reduction is based on pollutant reduction targets set by MSMA 2nd Edition (DID, 2012). The MSMA manual states that the pollutant reduction target for gross pollutants is 90 %, TSS must be 80 %, and TN and TP must achieve at least 50 % reduction after considering the application of stormwater BMPs.

In situations where the application of best management practices (BMPs) falls short of meeting the targets outlined in the MSMA 2nd edition, the development of an appropriate treatment train becomes necessary. A treatment train is characterized by a series of treatment devices arranged sequentially. In this setup, the effluent from one treatment device seamlessly transitions into the next, ultimately discharging to a specified receiving node. The rationale for implementing a treatment train stem from the acknowledgment that a singular treatment device is seldom effective in addressing all contaminants associated with stormwater flow. By organizing a sequence of treatment devices, each equipped with specific capabilities, a more comprehensive and efficient strategy is employed to mitigate diverse contaminants (ewater, 2020).

3. Results and discussion

3.1. Water quality modelling using MUSIC

The MUSIC water quality modelling was conducted to support the analysis and provide the proposed solution for the Sungai Air Hitam catchment. This analysis is based on the non-point sources of pollution generated from the overall Sungai Air Hitam Catchment. The final outlet or discharge in the simulation is also defined as the actual sampling location, which flows into Sungai Air Hitam. The water quality simulation was established with four existing and future land use scenarios. The scenarios are listed as follows:

i) Scenario 1: Existing land use without proposed BMPs
ii) Scenario 2: Existing land use with proposed BMPs
iii) Scenario 3: Future land use without proposed BMPs
iv) Scenario 4: Future land use with proposed BMPs

Table 7 showcases the existing and future land-use surface areas, both in hectares and percentage, within the Sungai Air Hitam catchment. The data was obtained from the Malaysian Town and Rural Planning Department (PLANMalaysia), Ministry of Local Government Development, computed and integrated into the MUSIC modeling process. The existing and future land uses were categorized into impervious and pervious surfaces, and their respective percentage surface areas were determined using Equation (4). The distribution of these percentages is tabulated in Table 8.

Fig. 4 (a) and Fig. 4 (b) demonstrate the MUSIC model setup of no BMPs and with BMPs, respectively. BMPs proposed for the Sg. Air Hitam are constructed wetland (CW), sediment basin (SB), and bioretention (BIO). These three BMPs are mainly proposed to cater for water quality improvement. Constructed wetland and bioretention system are commonly utilize the function of plant roots to remove the pollutant in water while the sediment basin, is a pond like structure to detent the water and let the sediment to settled down at specific parts of the basin.

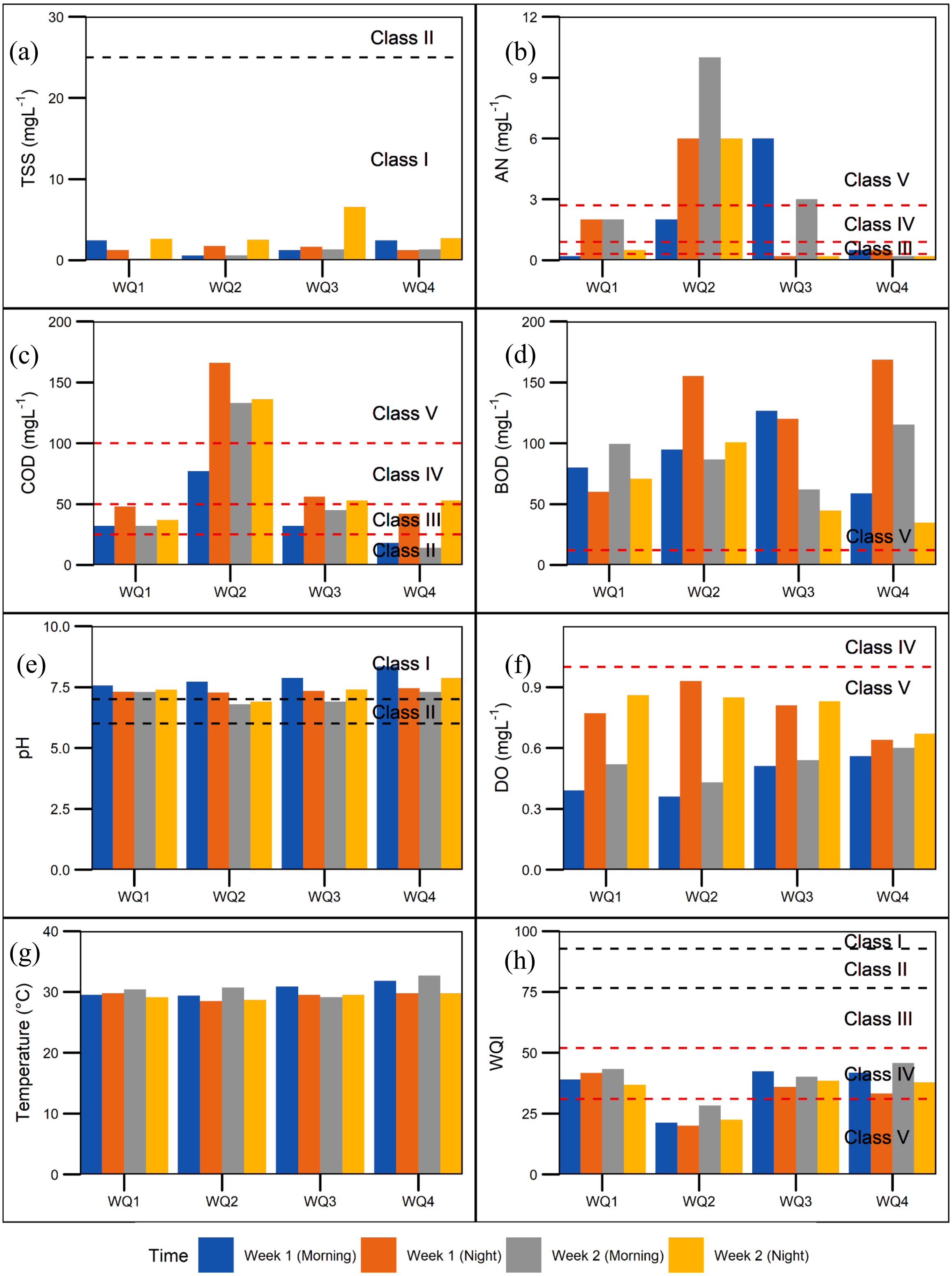

Fig. 2. Sampling results of (a) total suspended solids (TSS, mg/L), (b) ammoniacal nitrogen (AN, mg/L), (c) chemical oxygen demand (COD, mg/L), (d) biochemical oxygen demand (BOD, mg/L), (e) pH, (f) dissolved oxygen (DO, mg/L), (g) temperature (°C), and water quality index (WQI), of each sampling location WQ1-WQ4, and their corresponding classification.

These BMPs aim to mitigate the impact of urban development on water quality by reducing pollutant loading. The simulation results are expected to demonstrate the effectiveness of these BMPs in controlling BOD, TSS, TP and TN levels, leading to a potential improvement in overall water quality in the Sungai Air Hitam catchment under Scenario 2 and Scenario 4.

Simulation takes place with the BMPs by identify and characterize the details of the BMPs structure including the sizing, flow input and filtration area. Details pollutant reduction of individual BMPs is tabulated in Table 11. The simulation results of different BMPs cases showed

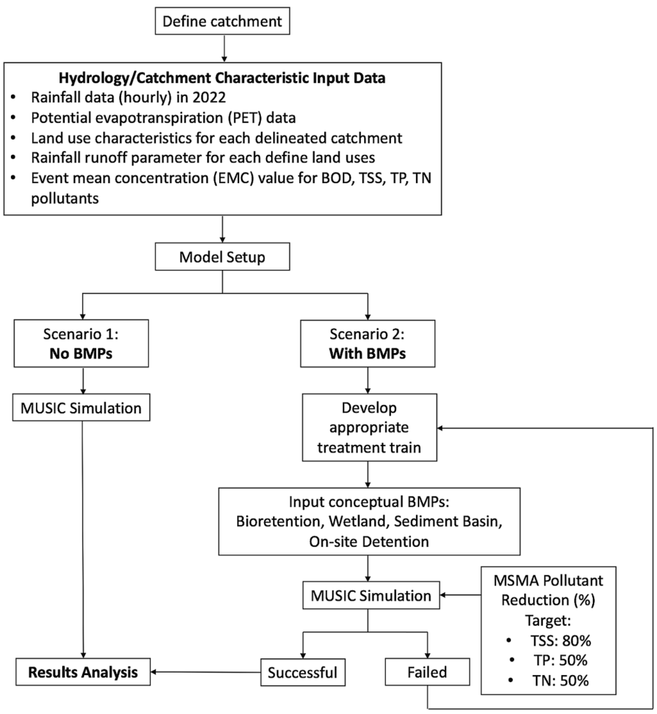

Fig. 3. MUSIC stormwater quality methodology.

Table 4
Average monthly PET values for 10 years (unit:mm).

Month	Average Evaporation
January	114.5
February	111.0
March	107.9
April	89.5
May	92.2
June	88.8
July	84.0
August	93.9
September	89.0
October	81.2
November	66.3
December	74.4

Table 5
Mean EMC (mg/l) values for selected land uses from MSMA second edition (DID, 2012).

Parameters	Residential	Commercial	Open Spaces	Roads and Highway	Park and Agriculture
BOD	17.90	22.90	0.00	14.90	0.00
TSS	128.00	122.00	68.33	80.00	220.89
TP	0.34	0.32	11.54	0.16	0.90
TN	4.21	4.84	2.65	2.25	5.15

that in the case with only one BMP measure, constructed wetland had the best reduction effect, with average reductions of 74.3 % for TP, 75.6 % for TN, 75.7 % for BOD, and 76.4 % for TSS. Constructed wetland can tremendously remove various types of pollutant from the stormwater runoff and can efficiently treat wastewater. Based on previous study, with a relatively slight seasonal variability, constructed wetland is able to remove approximately up to 92 % of TSS, elimination of organic compounds with 96.6 % of BOD and 95 % of COD parameters (Gizinska-Gorna et al., 2020). A case study conducted by **Md.** Akhir et al., (2016) for wastewater also achieved 52 % of reduction which comply with the Standard A (guideline produced by Department of Environment, Malaysia).

Table 6
MUSIC runoff generation parameters (Noh et al., 2018; DOE Australia, 2009).

Parameters	Urban Residential	Commercial	Rural Residential	Forested
Field Capacity (mm)	200	80	80	80 (250)
Infiltration Capacity Coefficient *a*	50	200	200	200 (200)
Infiltration Capacity Exponent *b*	1	1	1	1(1)
Rainfall Threshold (mm)	1	1	1	1(1)
Soil Capacity (mm)	400	120	120	120 (300)
Initial Storage (%)	10	25	25	25 (30)
Daily Recharge Rate (%)	25	25	25	25 (25)
Daily Baseflow/ Drainage Rate (%)	5	5	5	5 (5)
Initial Depth (mm)	50	50	50	50 (10)
Deep Seepage (%)	0	0	0	0 (0)

Table 7
Existing and future land use for various land use types within the Sungai Air Hitam catchment.

Land Use Type	Existing Land Use		Future Land Use	
	Hectares (ha)	Percentage (%)	Hectares (ha)	Percentage (%)
Residential	164.00	23.14	211.90	32.82
Commercial	410.30	57.89	411.70	63.76
Open Spaces	13.10	1.85	5.60	0.87
Roads and Highway	81.30	11.47	10.30	1.60
Park and Agriculture	40.10	5.66	6.20	0.96
Total	**708.80**	**100.00**	**645.70**	**100.00**

Table 8
Total of pervious and impervious areas for existing and future land use.

Existing Land Use		Future Land Use	
Pervious (%)	Impervious (%)	Pervious (%)	Impervious (%)
7.51	92.49	1.83	98.17

In the case with a combination of multiple BMP measures for future land use, the combination of bioretention, sediment basin, and constructed wetland performed better than the individual BMP, achieving average reductions of 80.9 % for TP, 80.8 % for TN, 81.6 % for BOD, and 86.2 % for TSS (Table 13). Simulation results revealed notable variations in peak flow (m^3/s) across each simulation, consequently yielding distinct values for pollutant reduction. Thus, simulation of individuals BMPs only give insight on its effectiveness and does not represent the overall percentage reduction. Given that optimization design frequently entails the implementation of multiple best management practices (BMPs) to attain reduction goals for various pollutants, it is imperative to design BMP combination settings. This approach is crucial for assessing the overall effectiveness of different BMPs in achieving the desired outcomes across multiple pollutant parameters (Zhang et al., 2023). Furthermore, it is compulsory to propose different types of BMPs in meeting the target set by MSMA guidelines. It also important to take note that, the BMPs propose must be suitable with the actual site condition including the space constraint and the flow of the drainage at the site to be proposed.

The calculated and simulated total annual pollutant load (of all BMPs combination) for the existing land use and future land use are tabulated in Table 12 and Table 13, respectively. Tables 12 and 13 present the pollutant loading values derived from EMC-based calculations and

Table 9
Annual loading pollutant for existing land use. Mean Annual Rainfall, MAR = 1811.06 mm.

Land Use	Area (ha)	Volumetric Runoff Coefficient (C_v)	Pollutants	EMC (mg/L)	Annual Runoff (mm)	Annual Loading (kg/year)	(tonne/year)
Residential	164.00	0.80	**BOD**	17.90	1448.85	42,532	42.53
			TSS	128.00		304,142	304.14
			TP	0.34		808	0.81
			TN	4.21		10,003	10.00
Commercial	410.30	0.90	**BOD**	22.90	1629.95	153,148	153.15
			TSS	122.00		815,900	815.90
			TP	0.32		2140	2.14
			TN	4.84		32,368	32.37
Open Spaces	13.10	0.30	**BOD**	0.00	543.32	0.00	0.00
			TSS	68.33		4863	4.86
			TP	11.54		821	0.82
			TN	2.65		189	0.19
Roads and Highway	81.30	0.95	**BOD**	14.90	1720.51	20,841	20.84
			TSS	80.00		111,902	111.90
			TP	0.16		224	0.22
			TN	2.25		3147	3.15
Park and Agriculture	40.10	0.30	**BOD**	0.00	543.32	0.00	0.00
			TSS	220.89		48,125	48.13
			TP	0.90		195	0.19
			TN	5.15		1122	1.12

Table 10
Annual loading pollutant for future land use. Mean Annual Rainfall, MAR = 1811.06 mm.

Land Use	Area (ha)	Volumetric Runoff Coefficient (C_v)	Pollutants	EMC (mg/L)	Annual Runoff (mm)	Annual Loading (kg/year)	(tonne/year)
Residential	211.90	0.80	**BOD**	17.90	1448.85	54,954	54.95
			TSS	128.00		392,974	392.97
			TP	0.34		1044	1.04
			TN	4.21		12,925	12.93
Commercial	411.70	0.90	**BOD**	22.90	1629.95	153,670	153.67
			TSS	122.00		818,684	818.68
			TP	0.32		2147	2.15
			TN	4.84		32,479	32.48
Open Spaces	5.60	0.30	**BOD**	0.00	543.32	0.00	0.00
			TSS	68.33		2079	2.08
			TP	11.54		351	0.35
			TN	2.65		81	0.08
Roads and Highway	10.30	0.95	**BOD**	14.90	1720.51	2640	2.64
			TSS	80.00		14,177	14.18
			TP	0.16		28	0.03
			TN	2.25		399	0.40
Park and Agriculture	6.20	0.30	**BOD**	0.00	543.32	0.00	0.00
			TSS	220.89		7441	7.44
			TP	0.90		30	0.03
			TN	5.15		173	0.17

MUSIC-simulated values for parameters BOD, TSS, TP, and TN for both existing and future land uses. Given the inherent methodological disparities and variances in data inputs between the two approaches, the computation of pollutant loading relies on the utilization of Equation (2), while the MUSIC simulation necessitates a more intricate dataset. This dataset encompasses a time series comprising rainfall and monthly evaporation data, detailed land-use descriptions (including contributing area measured in hectares and percentages of pervious and impervious areas for each land use), and logarithmically expressed event mean concentration (EMC) values in units of log/mg/L for each specific parameter. Despite these methodological distinctions, both approaches share commonality in the application of identical parameters and EMC values, establishing a fundamental basis for comparability. The consistency in pollutant loading outcomes facilitates an assessment of simulation reliability, even when confronted with divergent data inputs and complexities inherent in the calculation and simulation processes.

Based on the MUSIC simulation results for Scenario 1 and Scenario 3, it is anticipated that the pollutant loading of BOD, TSS, TP, and TN will experience an increase of 48.20 %, 49.30 %, 51.72 %, and 55.40 %, respectively, in the absence of BMP implementation for future land use. Conversely, a direct comparison of pollutant loading between Scenario 2 and Scenario 4 is challenging due to their distinct land cover usage. The selection of best management practices (BMPs) is guided by the availability of on-site BMPs or proposed suitable BMPs, with criteria taking into account available spaces and suitability.

By implementing the proposed BMPs, the simulation results as shown in Table 12 and Table 13, demonstrate that introducing BMPs to the catchment in the simulation allows the pollutant to be treated and reduced compared to when no BMPs are applied. The existing pond in the catchment helps in TSS reduction as well as other parameters. Referring to the analysis of the water quality of Sungai Air Hitam, TSS is not classified as a big issue to tackle. However, from the future land use details, there will be more open land for development that will be transformed from vacant land and agricultural areas. The development process promotes more construction work, indirectly leading to uncontrolled sediment production in the water body if there is no proper plan of erosion and sediment control.

Based on the simulation results, the corresponding total reduction of BOD, TSS, TP, and TN for existing land use is 92.5 %, 94.5 %, 90.7 % and 91.9 %. Meanwhile, the total reduction in future land use is 81.6 % for

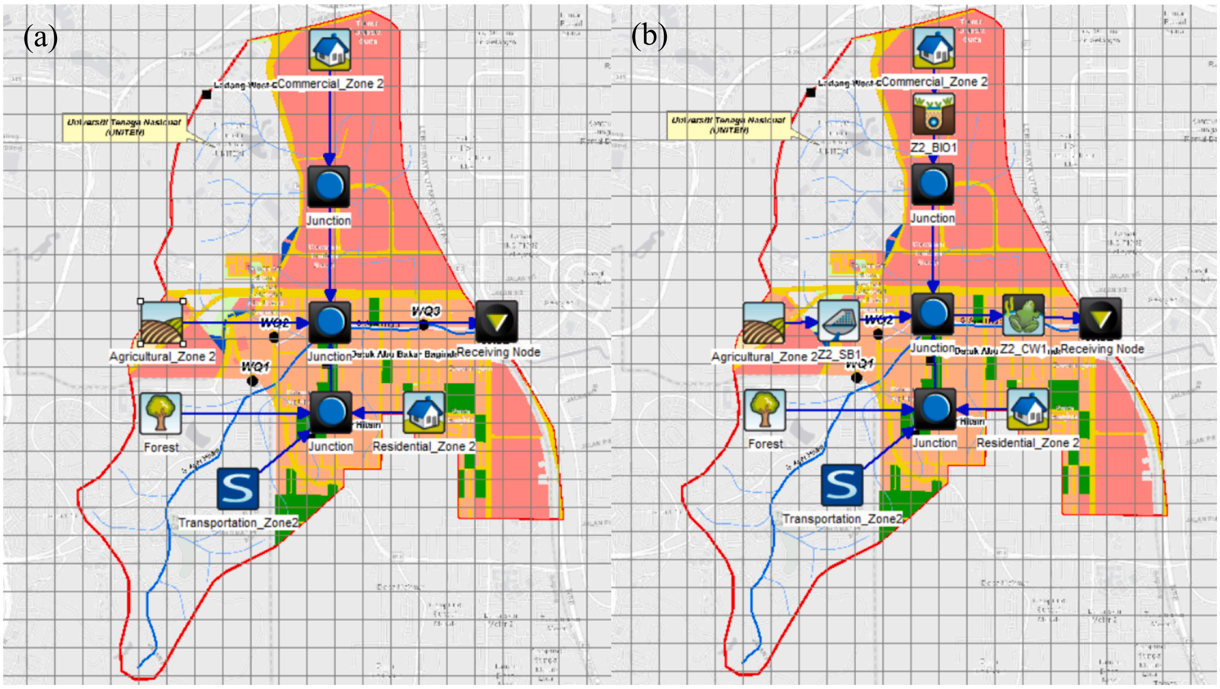

Fig. 4. MUSIC model setup for Sungai Air Hitam catchment of (a) without BMPs and (b) with proposed BMPs.

Table 11
Individual BMPs percentage of pollutant reduction based on future land use.

Parameters	Bioretention (BIO)	Sediment Basin (SB)	Constructed Wetland (CW)
Surface Area (ha)	2.2	1.5	3.0
Depth (m)	1.2	2.0	2.0
TP	8.5 %	0.8 %	74.3 %
TN	29.6 %	0.3 %	75.6 %
BOD	32.5 %	0.0 %	75.7 %
TSS	38.4 %	0.7 %	76.4 %

BOD, 86.2 % for TSS, 80.9 % for TP and 80.8 % for TN. The highest reduction of BOD, TSS, TP and TN were achieved in Scenario 2 a simulation of existing land use with proposed stormwater BMPs. However, the BMPs proposed for future land uses can increase pollutant reduction with the influence of land use changes.

As per the observed data collected for Sungai Air Hitam, BOD is the crucial parameter to be tackled since most of the data in every sampling point falls in Class V. The mean observed concentration for BOD is 92.38 mg/L which exceeds Class V of the NWQS water quality index. From the simulation results, the application of BMPs has successfully reduced BOD concentration from 92.38 mg/L (Class V) to 6.93 mg/L (Class IV) of the NWQS water quality index. It was not possible to compare MUSIC's reduction prediction regarding observed TP and TN concentrations because in the sampling, TP and TN were not measured. As a result, the water quality index of the overall catchment has improved from Class IV to Class III (WQ1, WQ3, and WQ4) and from Class V to IV (WQ2) with the application of the BMPs.

4. Conclusions

The significance of this study is heightened by the challenging

Table 12
Total annual pollutant loading of calculated and simulated values, BMPs, and pollutant reduction percentage for existing land use.

Type of Loading	Existing Land Use Calculated (without BMPs)		Simulated (without BMPs)		Simulated (with BMPs)		Reduction %
	kg / year	tonne / year	kg / year	tonne / year	kg / year	tonne / year	
BOD	216,521	216.52	91,100	91.10	6,800	6.80	92.5
TSS	1,284,932	1,284.93	552,000	552.00	30,300	30.30	94.5
TP	4,188	4.19	1,740	1.74	161	0.16	90.7
TN	46,830	46.83	21,300	21.30	1,720	1.72	91.9

Table 13
Total annual pollutant loading of calculated and simulated values, BMPs, and pollutant reduction percentage for future land use.

Type of Loading	Future Land Use Calculated (without BMPs)		Simulated (without BMPs)		Simulated (with BMPs)		Reduction %
	kg / year	tonne / year	kg / year	tonne / year	kg / year	tonne / year	
BOD	211,264	211.26	135,000	135.00	24,800	24.80	81.6
TSS	1,235,354	1235.35	824,000	824.00	113,000	113.00	86.2
TP	3,601	3.60	2,640	2.64	505	0.51	80.9
TN	46,057	46.06	33,100	33.10	6,340	6.34	80.8

impact of climate change, particularly alterations in monsoon weather conditions, which have further intensified the decline in water quality in Sungai Air Hitam. Continuous water quality monitoring over a two-week period at Sungai Air Hitam reveals that the most polluted area within the catchment is WQ2, situated at the point source of the main drainage at Jalan Anggerik. WQ2, located near a workshop, residential area, and mini market, is contaminated with waste from various sources. Despite this, water quality index assessments for all sampling points within Sungai Air Hitam indicate that the river falls within the polluted range. Thus, evaluating and preserving the water quality of the river is crucial.

According to the MUSIC modeling, the suggested best management practices (BMPs) can reduce pollutants like BOD, TSS, TP, and TN by over 80 % in current and future land use. The simulation underlines the importance of utilizing bioretention systems, sediment basins, and constructed wetlands within the Sungai Air Hitam catchment area. Implementing these BMPs can potentially improve the water quality index of the overall catchment from Class IV to Class III (WQ1, WQ3, and WQ4), and from Class V to IV (WQ2). This would make the river suitable for activities like fishing, livestock drinking, and irrigation, which could help boost the economy of the Sungai Air Hitam community.

The proposed best management practices (BMPs) are effective, but they require detailed design and construction work. Non-structural measures can complement these efforts. Measures such as installing trash racks or log booms, establishing new waste disposal sites, managing urban areas, and community engagement can also help address water quality issues. It is recommended to adopt a holistic approach by combining structural and non-structural measures for sustainable and long-term mitigation of water quality issues in the Sungai Air Hitam catchment. This assessment aims to raise awareness within the Sungai Air Hitam community regarding the importance of preserving river cleanliness and understanding the long-term environmental impact of water quality. These findings underscore the importance of an integrated system in managing urban water systems, which can offer valuable insight to decision-makers.

CRediT authorship contribution statement

Noorhayati Idros: Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Lariyah Mohd Sidek:** Writing – review & editing, Supervision, Resources. **Nur Anis Aishah M. Rahim:** Writing – original draft, Data curation. **Nurshahira Mohd Noh:** Writing – original draft, Software, Investigation, Data curation. **Amr M. Abdelkader:** Writing – review & editing. **Hairun Aishah Mohiyaden:** Writing – review & editing. **Hidayah Basri:** Writing – review & editing. **Mohd Hafiz Bin Zawawi:** Writing – review & editing. **Ali Najah Ahmed:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

This work was supported by Tenaga Nasional Berhad (TNB) and Universiti Tenaga Nasional (UNITEN) through the BOLD Refresh Postdoctoral Fellowships under the project code of J510050002-IC-6 BOLDREFRESH2025-Centre of Excellence. In addition, the authors would like to express our gratitude to MPKK Kg. Dato' Abu Bakar Baginda and UNITEN Institute of Energy and Infrastructure (IEI) for their support of this project.

Funding Sources

This work was supported by Tenaga Nasional Berhad (TNB) and UNITEN through the BOLD Refresh Publication Fund under the project code of J510050002-IC-6 BOLDREFRESH2025-Centre of Excellence. This work was also financially supported by the grant no. 202210054YCU Community Based Program for Denai Sungai Kebangsaan Sungai Air Hitam, Kg. Dato' Abu Bakar Baginda.

References

Akan, O.A., 1993. Urban stormwater hydrology: a guide to engineering calculations. Crc Press, PA, USA.
Md. Akhir, M. S. A., Amir, A. A., Mokhtar, M., Hooi, A. W. K., 2016. Constructed Wetland for Wastewater Treatment: A Case Study at Frangipani Resort, Langkawi. International Journal of the Malay World and Civilisation (Iman) 4 (Special Issue 1), 21 – 28. https://doi.org/10.17576/IMAN-2016-04SI1-03.
Al-Ani, I.A.R., Sidek, L.M., Desa, M.N.M., Ahmad Basri, N.E., 2012. Knowledge-based expert system for stormwater management in Malaysia. J. Environ. Sci. Technol. 5, 5, 381–388. https://doi.org/10.3923/jest.2012.381.388.
Kampung Dato Abu Bakar Baginda, KBADD, 2019. Sejarah Asal Kampung Dato Abu Bakar Baginda. https://bangi.pulasan.my/kg_air_hitam?s=air&s=hitam (Accessed 15 January 2024).
Chow, M.F., Yusop, Z., 2014. Characterization and source identification of stormwater runoff in tropical urban catchments. Water Sci. Technol. 69 (2), 244–252. https://doi.org/10.2166/wst.2013.574. PMID: 24473291.
Code of Federal Regulations, CFR, 2021. PART 136—GUIDELINES ESTABLISHING TEST PROCEDURES FOR THE ANALYSIS OF POLLUTANTS. 40 CRF Ch. I (7-1-21 Edition). https://www.govinfo.gov/content/pkg/CFR-2021-title40-vol25/pdf/CFR-2021-title40-vol25-part136.pdf (accessed 1 December 2023).
Department of Environment Malaysia, DOE, 2020. NATIONAL WATER QUALITY STANDARDS AND WATER QUALITY INDEX. https://www.doe.gov.my/en/national-river-water-quality-standards-and-river-water-quality-index/ (accessed 1 July 2023).
Department of Environment, Water, Heritage and the Arts, Australian Government, DOE Australia, 2009. WATER SENSITIVE URBAN DESIGN STORMWATER QUALITY MODELLING GUIDE FINAL. http://www.equatica.com.au/Darwin/reports-pdfs/Final%20Docs/8005_Darwin%20WSUD%20Modelling%20Guide%20FINAL%20_May09_.pdf (accessed 1 December 2023).
Department of Irrigation and Drainage Malaysia, DID, 2012. Urban Stormwater Management Manual for Malaysia. MSMA Second Edition. https://www.water.gov.my/jps/resources/PDF/MSMA2ndEdition_august_2012.pdf (accessed 1 July 2023).
Duncan, H.P., 1999. Urban Stormwater Quality: A Statistical Overview. Report 99/3, Cooperative Research Centre for Catchment Hydrology.
Ewater, 2020. MUSICX 1.0, Creating a Stormwater Treatment Train, Creating a Treatment Train. https://ewater.atlassian.net/wiki/spaces/MX1/pages/56328483/Creating+a+Treatment+Train (Accessed 15 January 2024).
Gizinska-Gorna, M., Jozwiakowski, K., Marzec, M., 2020. Reliability and efficiency of pollutant removal in four-stage constructed wetland of SSVF-SSHF-SSHF-SSVF type. Water 12, 3153. https://doi.org/10.3390/w12113153.
Goh, H.W., Lem, K.S., Azizan, N.A., Chang, C.K., Talei, A., Leow, C.S., Zakaria, N.A., 2019. A review of bioretention components and nutrient removal under different climates—future directions for tropics. Environ. Sci. Pollut. Res. 26, 14904–14919. https://doi.org/10.1007/s11356-019-05041-0.
Haris, H., Chow, M.F., Usman, F., Sidek, L.M., Roseli, Z.A., Norlida, M.D., 2016. Urban stormwater management model and tools for designing stormwater Management of Green Infrastructure Practices. IOP Conference Series: Earth and Environment Science 32, 012022. https://doi.org/10.1088/1755-1315/32/1/012022.
Huang, Y.F., Ang, S.Y., Lee, K.M., Lee, T.S., 2015. Quality of water resources in Malaysia. INTECH. https://doi.org/10.5772/58969.
Imteaz, M.A., Boulomytis, V.T.G., Yilmaz, A.G., Shanableh, A., 2022. Water quality improvement through rainwater tanks: a review and simulation study. Water 14, 1411. https://doi.org/10.3390/w14091411.
Jajarmizadeh, M., Sidek, L.M., Mirzai, M., Alaghmand, S., Harun, S., Majid, M.R., 2016. Prediction of surface flow by forcing of climate forecast system reanalysis data. Water Resour. Manag. 30 (8), 2627–2640. https://doi.org/10.1007/s11269-016-1303-0.
Li, G., Xiong, J., Zhu, J., Liu, Y., Dzakpasu, M., 2021. Design influence and evaluation model of bioretention in rainwater treatment: a review. Sci. Total Environ. 787 (13), 147592 https://doi.org/10.1016/j.scitotenv.2021.147592.
Lisenbee, W.A., Hathaway, J.M., Burns, M.J., Fletcher, T.D., 2021. Modeling bioretention stormwater systems: current models and future research needs. Environ. Model. Softw. 144, 105146 https://doi.org/10.1016/j.envsoft.2021.105146.
Lucke, T., Drapper, D., Hornbuckle, A., 2018. Urban stormwater characterisation and nitrogen composition from lot-scale catchments—new management implications. Sci. Total Environ. 619, 65–71. https://doi.org/10.1016/j.scitotenv.2017.11.105.
Mangangka, I. R., 2013. Role of Hydraulic Factors in Constructed Wetland and Bioretention Basin Treatment Performance [Doctoral dissertation, Science and Engineering Faculty, Queensland University of Technology]. https://core.ac.uk/download/pdf/17201966.pdf.

Miller, J.R., Russell, G.L., 1992. The impact of global warming on river runoff. J. Geophys. Res. 97 (D3), 2757–2764. https://doi.org/10.1029/91JD01700.

Mohiyaden, H.A., Sidek, L.M., Hayder, G., Noh, M.N., 2018. Water quality assessment Klang River water treatment plants. international journal of. Eng. Technol. 7, 4.35, 639–642. https://doi.org/10.14419/ijet.v7i4.35.23075.

Muha, N.E., Sidek, L.M., Jajarmizadeh, M., 2016. Water quality improvement through reductions of pollutant loads on small scale of bioretention system. IOP Conference Series: Earth and Environment Science 32, 012010. https://doi.org/10.1088/1755-1315/32/1/012010.

Noh, N.S.M., Sidek, L.M., Haron, S.H., Puad, A.H.M., Selamat, Z., 2018. Pollutant loading analysis of suspended solid, nitrogen and phosphorus at bertam catchment, Cameron Highlands using MUSIC. International Journal of Engineering & Technology 7, 743–748. https://doi.org/10.14419/ijet.v7i4.35.23100.

Osman M., Wan Yusof K., Takaijudin H., Goh H. W., Abdul Malek M., Azizan N. A., Ab. Ghani A., Sa'id Abdurrasheed A., 2019. A Review of Nitrogen Removal for Urban Stormwater Runoff in Bioretention System. Sustainability 11(19):5415. doi: 10.3390/su11195415.

Rahman, H.A., 2021. Water issues in Malaysia. International Journal of Academic Research in Business and Social Sciences 11, 8. https://doi.org/10.6007/ijarbss/v11-i8/10783.

Shahzad, H., Myers, B., Hewa, G., Johnson, T., Boland, J., Mujtaba, H., 2022. Characterizing the stormwater runoff quality and evaluating the performance of curbside infiltration systems to improve stormwater quality of an urban catchment. Water (switzerland) 14, 1. https://doi.org/10.3390/w14010014.

Sidek, L.M., Abidin, M.R.Z., Esfahani, F.Z., Basri, H., 2013. Stormwater quality modeling for upscaling MSMA stormwater management ecohydrology. IOP Conference Series: Earth and Environmental Science 16, 012048. https://doi.org/10.1088/1755-1315/16/1/012048.

Texas Department of Transportation, TxDOT., 2002. Hydraulic Design Manual. Bridge Division of TxDOT, Austin, Texas, USA. http://onlinemanuals.txdot.gov/TxDOTOnlineManuals/TxDOTManuals/hyd/rational_method.htm (accessed 2 December 2023).

United Nations, UN, Department of Economic and Social Affairs, 2018. 68% of the world population projected to live in urban areas by 2050, says UN. https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html (accessed 2 December 2023).

Wang, J., Chua, L.J.V., Shanahan, P., 2017. Evaluation of pollutant removal efficiency of a bioretention basin and implications for stormwater management in tropical cities. Environ. Sci. Water Res. Technol. 3, 78–91. https://doi.org/10.1039/c6ew00285d.

Wong, T H.F., Fletcher, T.D., Duncan, H.P., Coleman, J.R., Jenkins, G.A., 2002. A Model for Urban Stormwater Improvement Conceptualization. A. Rizzoli, and A. Jakeman, editors. Integrated assessment and decision support. Proceedings of the 1st biennial meeting of the International Environmental Modeling and Software Society, 1, 48–53.

Woon, K.L., Goh, H.W., Chang, C.K., Juiani, S.F., Zakaria, N.A., 2023. Bioretention model for urban runoff treatment in a tropical climate: a case study at the Universiti Sains Malaysia. Journal of Water Management Modeling 31, C498. https://doi.org/10.14796/JWMM.C498.

Zahari, N.M., Zawawi, M.H., Muda, Z.C., Sidek, L.M., Fauzi, N.M., Othman, M.E.F., Ahmad, Z., 2017. Klang River water quality modelling using music. AIP Conf. Proc. 1885, 020132 https://doi.org/10.1063/1.5002326.

Zainudin, Z., 2010. Benchmarking river water quality in Malaysia. Jurutera 12–15.

Zakaria, N. A., Ghani, A. A., Chang, C. K., 2014. MSMA 2nd Edition – Application of Green Infrastructures for Solving Sustainable Urban Stormwater Management Challenges Persidangan Air Kebangsaan (PAM 2014) (Kedah).

Zhang, X., Qi, Y., Li, H., Sun, S., Yin, Q., 2023. Assessing effect of best management practices in unmonitored watersheds using the coupled SWAT-BiLSTM approach. Sci. Rep. 13, 17168. https://doi.org/10.1038/s41598-023-44531-7.

Zong, M., Hu, Y., Liu, M., Li, C., Wang, C., Liu, J., 2021. Quantifying the contribution of agricultural and urban non-point source pollutant loads in watershed with urban agglomeration. Water (switzerland) 13, 10. https://doi.org/10.3390/w13101385.