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A Study of Total Maximum Daily Load (TMDL) by Using Water Quality Modelling as an Approach to Investigate the Quality of Water at Bentayan River, Muar

Anis Adibah Anuar Alsadat[1], Nor Maizzaty Abdulla[1]*, Hasnida Harun[1]

[1] *Department of Civil Engineering Technology, Universiti Tun Hussein Onn Malaysia, Pagoh Campus, KM 1, Jalan Panchor, Panchor, 84600, MALAYSIA*

*Corresponding Author: maizzaty@uthm.edu.my
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Abstract

This study evaluates the water quality of the Bentayan River in Muar, Malaysia, by integrating the Total Maximum Daily Load (TMDL) framework and water quality modelling using QUAL2K. The research aims to determine the current state of the river's health and assess the impact of industrial and urban activities on key water quality parameters. Field data were collected from five strategic checkpoints which is have upstream (stranded land), midstream (hotel, shop lot, industrial area) and downstream (foodcourt). Along the river, focusing on parameters such as pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), and total suspended solids (TSS). Laboratory analyses revealed significant pollutant levels, particularly high BOD and TSS at Checkpoint 4, an area with dense industrial activity. Conversely, the highest DO levels were observed at Checkpoint 1, which exhibited the largest discharge rate, indicating better water quality. The QUAL2K model was calibrated with the collected data, demonstrating its effectiveness in simulating the river's conditions under varying scenarios, including tidal influences. The TMDL calculations identified the maximum allowable pollutant loads that ensure compliance with water quality standards. This approach provided a basis for recommending pollution reduction strategies and regulatory measures to enhance the river's ecological health. The findings highlight the critical need for ongoing monitoring and the implementation of effective management practices to mitigate pollution and preserve the Bentayan River's environmental and economic roles. This study underscores the value of integrating TMDL and water quality modelling as robust tools for river management and sustainable development.

1. Introduction

Water quality is a crucial aspect of environmental health, impacting ecosystems, human health, and community sustainability. The Bentayan River in Muar, Malaysia, is a significant water body that supports biodiversity and human activities, including tourism [1]. However, rapid urbanization and industrial activities pose significant risks to its water quality. Total Maximum Daily Load (TMDL) is a key concept in water quality management, aiming to reduce pollution to acceptable levels [1]. The Bentayan River faces significant pollution challenges due to industrial discharges, urban runoff, and other anthropogenic activities. High pollutant loads can lead to severe ecological stress, disrupting the river's natural balance. This study aims to investigate the water quality of the

Bentayan River using TMDL and water quality modeling techniques. The objectives include determining water quality parameters, analyzing the impact of industrial and urban activities on water quality, and using the QUAL2K water quality model to simulate the river's conditions and assess the effectiveness of TMDL implementation [2]. The study involved a detailed water quality assessment at several checkpoints along the Bentayan River, which involved field sampling and laboratory analysis [1]. Five checkpoints were chosen based on 3 divisions of the river catchment which is upstream, midstream and downstream. The QUAL2K model will be calibrated and applied to simulate the river's water quality under various scenarios, including industrial discharges and tidal influences [2]. The findings will provide insights into the river's health and guide future water management and regulatory efforts to enhance the sustainability of the Bentayan River ecosystem. This research is significant in several respects, contributing to the understanding of how industrial and urban activities impact river water quality in rapidly developing regions [2]. By applying advanced water quality modeling techniques, the study offers a methodological framework for assessing and managing river ecosystems effectively [3].

2. Materials and methods

The water quality of the Bentayan River was examined using field surveys and laboratory analysis. Total suspended solids, pH, dissolved oxygen, and biochemical oxygen demand (BOD) were measured at five different checkpoints along the river. Laboratory analysis measured key factors such as biochemical oxygen demand (BOD) and total suspended solids (TSS). The QUAL2K model was used to mimic the Bentayan river's water quality, which allowed for extensive examination of contaminants and their interactions. The Total Maximum Daily Load (TMDL) was computed to estimate the highest permitted pollution loads while maintaining water quality criteria. Recommendations for reducing pollution and improving water quality were created, including regulatory measures and voluntary activities by stakeholders. Statistical methods were used to analyze the data and model outcomes.

2.1 Study Area

The Bentayan River, a significant tributary of the Muar River, is in the state of Johor, Malaysia. The river's geographical coordinates extend from latitude 2.050°N to 2.090°N and longitude 102.450°E to 102.530°E. The study area covers a 12-kilometer stretch of the river, with varying land uses ranging from residential and commercial areas to industrial zones. The river is subjected to various pollution sources, primarily from urban runoff and industrial discharges [1]. The Bentayan River study area in Malaysia is situated in Johor, a state in the southern portion of Peninsular Malaysia. This location is part of the broader Johor River Basin, which is critical to the local water supply, serving both the neighboring towns and sections of Singapore [1]. The research field is largely focused om numerous environmental issues, such as water pollution, water scarcity, and the effects of climate change [2].

Fig. 1 *Bentayan River, Muar.*

2.2 Data Collection and Testing

Based on EPA guideline, Water samples were collected and kept in at 5-litre high-density polyethene bottles using buckets and rope by grab sampling, as shown in Fig. 1. The bottles were stored in a cool room at Univerisiti Tun Hussein Onn, Campus Pagoh before being utilised for laboratory testing.

2.2.1 Water Quality Sampling

Water sampling was conducted in the Bentayan River, Muar, during high and low tides. The river area is flanked by commercial and industrial properties. Water samples were obtained from five different sites. As demonstrated in Fig. 2, five checkpoints along the Bentayan River have been chosen as sites for water sampling. Google Maps was used to identify the sampling location's latitude and longitude using the Global Positioning System (GPS).

Fig. 2 *Checkpoints marked on Bentayan River map*

2.3 Water Quality Modelling

The goal of utilizing water quality modelling tools is to simulate and calibrate water quality parameters. This study used the QUAL2K programmed to simulate and calibrate water quality models. The programmed requires three types of data: hydraulic, location, and water quality [4]. Each checkpoint's hydraulic data includes the river's velocity, breadth, and depth. To establish the position of each checkpoint, its latitude and longitude must be known. The degree of its impact may be shown by doing a Bentayan River water simulation on the ebb and tide flow with QUAL2K.

2.4 QUAL2K

The model's water quality input parameters include flow, pH, DO, BOD, and total suspended solids (TSS). The hydraulic properties of each sampling point were determined using the river's geometry, depth, and water velocities. The graphical user interface is created using Microsoft Excel.

QUAL2K is a water quality modelling software used to simulate water quality in rivers and streams [5] QUAL2K involves adjusting model parameters to ensure the model outputs match observed data as closely as possible, as illustrated in Fig. 3 is the interface of QUAL2K Software [7]. QUAL2K is a one-dimensional stream, steady-state hydraulic actuators, a diurnal heat budget, and daily water-quality dynamics were simulated utilizing meteorology, heat budget, temperature, load and abstractions on a diurnal time scale [7].

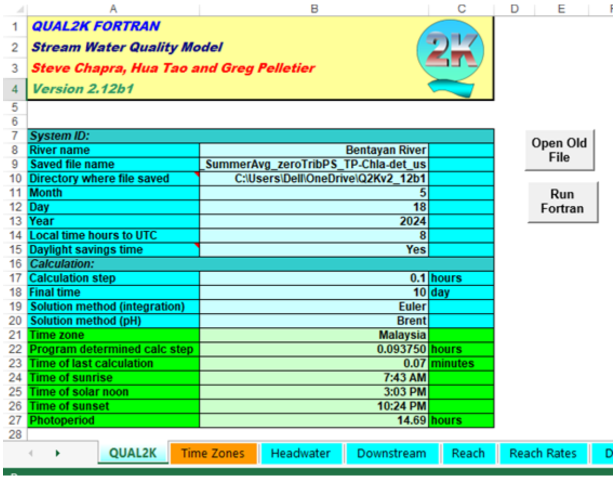


Fig. 3 *QUAL2K Software*

The QUAL2K model was created for the US Environmental Protection Agency [4]. QUAL2K model is one-dimensional; it is well-mixed in both the vertical and lateral dimensions [6]. It is does because of the steady-state model that the flow and Water quality do not change over time [7]. Water quality fluctuations during the day due to temperature variations throughout the day and sunshine may be reproduced [8]. A QUAL2K model divides the river into several reaches, each split into an optional number of segments [9]. Excavations and Discharges can be placed anywhere. point along the river. The model will incorporate a waterfall if a weir, dam, or reservoir [10]. This should be placed after reach, and that reach must include comprises only one ingredient [4].

The Kluang station recorded meteorological data such as air temperature, dew point temperature, wind speed, and cloud cover. Weather Underground provided information for 2024. Data from the 10th of each month is used to compute the daily average temperature, dew point temperature, and wind speed across the year. Weather Underground provides cloud cover data categorized by conditions (clear, smoke, partly cloudy, or mainly cloudy). Because the QUAL2K model required percentages for cloud cover, percent values were assigned to each situation (e.g., clear = 0%, smoke = 5%, partly cloudy = 20%, and mostly cloudy = 30%). Meanwhile, shade was considered to be 100% at night and 0% during the day.

2.4.1 Calibration and Validation

If the predicted values match the estimated values, the model is regarded as calibrated properly. This technique enabled the simulation to mimic the observed quality of water patterns in the river by assessing the simulated and observed data, and the primary kinetic parameters were changed until an acceptable match was discovered between the model outputs and the data [1].

2.5 TMDL Development

Total Maximum Daily Load or TMDL is a regulatory term in the United States established by section 303(D) of the Clean Water Act [12]. TMDL describes a value of the maximum number of pollutants that a water body can receive while still meeting water quality standards [13]. The formula of TMDL is shown in equation 3.7. This approach is to ensure the resultant receiving water quality is acceptable if the capacity of natural receiving water cannot cater to the discharge quantity rise due to development or limited in size [12].

The acquired value may then be used to determine the TMDL. The TMDL is calculated using eqn. 1. The Margin of Safety (MOS) is typically between 7% and 15% of the overall TMDL, providing a safety buffer between the predicted TMDL and the actual demand that will allow the water system to meet its beneficial usage. The MOS employed in this study is 15%, based on the most recent research in Sungai Semenyih [7].

$$TMDL = Point\ Sources\ (WLA) + Non + point\ Sources\ + MOS \quad (1)$$

Where:

WLA: Waste load allocation from point sources (kg/day)
LA: Load allocation from non-point sources (kg/day)
MOS: Margin of safety (%)

The flow of each WQM station is a non-point source of faecal coliform burdens to receivers. Equation 3.8 shows the pollution load formula. The data and LDC analysis suggest that the advantage in most WQM stations is the consequence of non-point source loading such as failing OSWD systems, leaks in sewage lines, cattle in the river, and faeces loading from land application fields, animals and pets transported by running events [5]. The pollution loading (Point Sources) formula is stated in eqn. 2:

$$Load\ (kg/day) = concentration\ (mg/L) \times flow\ rate\ (m3/s) \times 86.4 \qquad (2)$$

According to federal regulations, a MOS is necessary. The MOS is a conservative factor integrated into the TMDL calculation that accounts for the uncertainty in calculating the allowable faecal coliform pollutant loading to ensure that WQS are fulfilled [13]. The USEPA rules allow for the use of either implicit or explicit manifestations of the MOS, or both. The MOS is implied when conservative assumptions or conservative variables are used in the TMDL formulation or calculations [6].

3. Result and Data Analysis

Results of water quality parameters include pH, dissolved oxygen, biochemical oxygen demand (BOD) and total suspended solids (TSS). All results are tabulated and presented in graphic form. This chapter shows a detailed discussion of the results obtained from the Total Maximum Daily Load (TMDL) Study Using Water Quality Modeling as An Approach to Investigating Water Quality in the Bentayan River, Muar.

3.1 Water Quality Status

The water quality of the Bentayan River at all monitoring stations could be classified as Class III (Slightly Polluted) based on the standard identified. The pH is low, indicating acidic water, DO is at a very low level for aquatic life; BOD has high values for organic pollution and the level of TSS indicates severe particle pollution. This shows that there is a need for conservation to improve the water quality for ecological and potentially human uses. Table 1 shows DO levels were highest at checkpoint 1 and lowest at checkpoint 4. Checkpoint 1 is in a food court area with slow-flowing water, while Checkpoint 4 is in an industrial area with stagnant water, resulting in lower DO values.

Checkpoint 4 had the greatest BOD and TSS levels due to industrial operations, but moderate DO concentrations. In contrast, Checkpoint 1 had the lowest concentrations, which coincided with the river's condition. Checkpoint 1 also had the greatest discharge and DO concentration, demonstrating a significant association between industrial activity and BOD and TSS levels.

Table 1 *Water quality measurements of Bentayan River*

SITUATION	pH	DO	BOD (mg/L)	TSS (mg/L)
CHECKPOINT 1 (FOODCOURT)				
HIGH	5.08	4.99	2.75	50.0
LOW	5.65	5.49	3.25	51.6
CHECKPOINT 2 (HOTEL)				
HIGH	5.01	4.61	2.82	60.0
LOW	5.58	5.11	3.32	62.4
CHECKPOINT 3 (SHOP LOT)				
HIGH	5.30	4.56	3.76	80.0
LOW	5.87	5.06	3.84	81.3
CHECKPOINT 4 (INDUSTRIAL AREA)				
HIGH	5.93	4.46	2.77	80.0
LOW	6.30	4.96	3.99	83.4
CHECKPOINT 5 (STRANDED LAND)				
HIGH	5.02	4.73	2.80	50.0
LOW	5.59	5.23	3.30	52.3

3.2 Water Quality Impairments

The water quality statistics from the Bentayan River checkpoints display several deficiencies when compared to the Class II level as shows shown in Table 2. The pH is constantly acidic, the DO levels are low, the BOD levels show considerable organic pollution, and the TSS levels are significant. These data indicate that the river is somewhat contaminated and does not satisfy the requirements required to sustain a healthy aquatic ecosystem.

Interventions are required to address these problems and enhance the overall water quality of the Bentayan River

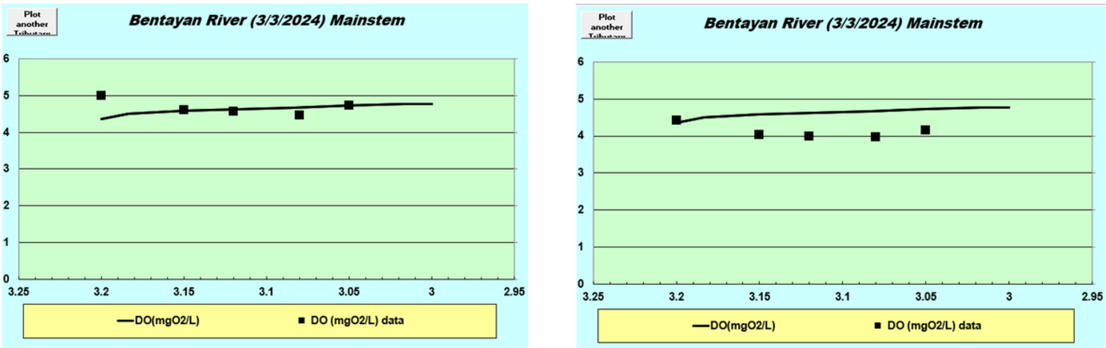
Table 2 *Comparison Of Water Quality Standard And Sampling Data*

Parameter	Standard Water Quality (Class II)	Sampling Data	Remarks
pH	6.5 - 8.5	5.01 - 6.30	Acidic conditions across all checkpoints
DO (mg/L)	> 7	4.46 - 5.49	Low dissolved oxygen levels
BOD (mg/L)	< 3	2.75 - 3.99	Moderate organic pollution
TSS (mg/L)	< 50	50.0 - 83.4	Moderate organic pollution

3.3 Water Quality Modelling

To meet the study's specifications, the model was established using QUAL2K software and the water quality measurements (BOD, pH, DO, and TSS). The simulation results for all parameters must be accurate to the observed data. The analysis suggests that the model was adequately calibrated. If the forecast closely matches the estimate, the model is said to be appropriately calibrated. The model was compared to observed data to mimic the water quality trends in the river. Key kinetic characteristics were altered to guarantee a good fit between the two.

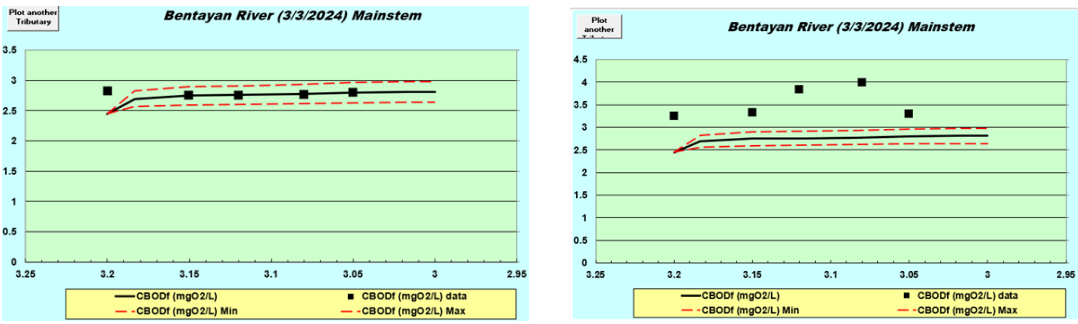
Fig. 4 (a) and (b) illustrate that the Bentayan River drops as it approaches mid-stream and then grows slightly downstream. This pattern happens during both low and high tides. Flow over high tide. The strong slope in the top stream accurately depicts the velocity, which gradually decreases as it approaches the mid-stream. The QUAL2K simulation shows that the content of DO is higher at high tide than throughout low tide flow. The DO level continuously falls until km 3.20 due to substantial BOD in the checkpoint 4 industrial sector. A decrease in DO value frequently suggests an increase in BOD value. However, the DO concentration rebounded at km 3.15 after confluence with the checkpoint 2 Hotel, where a higher volumetric input (5.11 m3/s) at high tide and (4.61 m3/s) during low tide flow and dilution led the BOD to decrease.



(a) (b)

Fig. 4 *(a) DO of Bentayan River during low tide; (b) DO of Bentayan River during high tide*

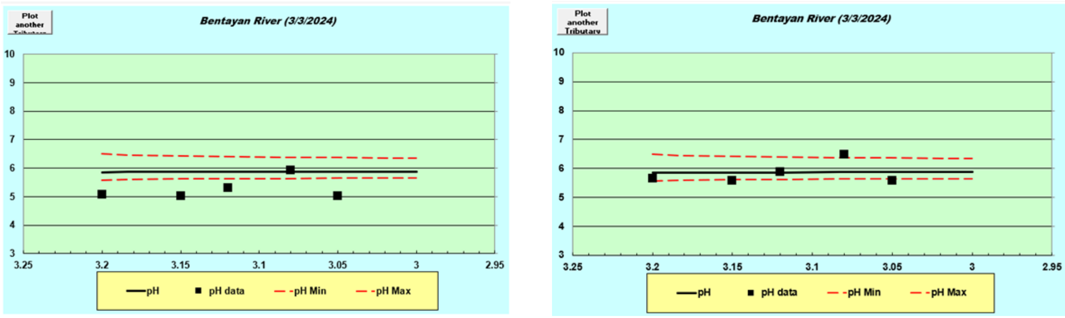
Fig. 5 (d) (high tide) and (c) (low tide) demonstrate a progressive increase in BOD content along checkpoint 3 Shop lot and a minor decrease downstream to checkpoint 4 industrials. However, BOD concentrations rise sharply upstream at the checkpoint 4 industrial area at high tide, reaching 3.99 mg/L and 2.77 mg/L at low tide, causing DO concentrations to fall. As considerable turbidity was reported, BOD began to fall sharply through kilometer 3.05 owing to denitrification.



(c) (d)

Fig. 5 (c) *BOD of Bentayan River during low tide; (d) BOD of Bentayan River during high tide*

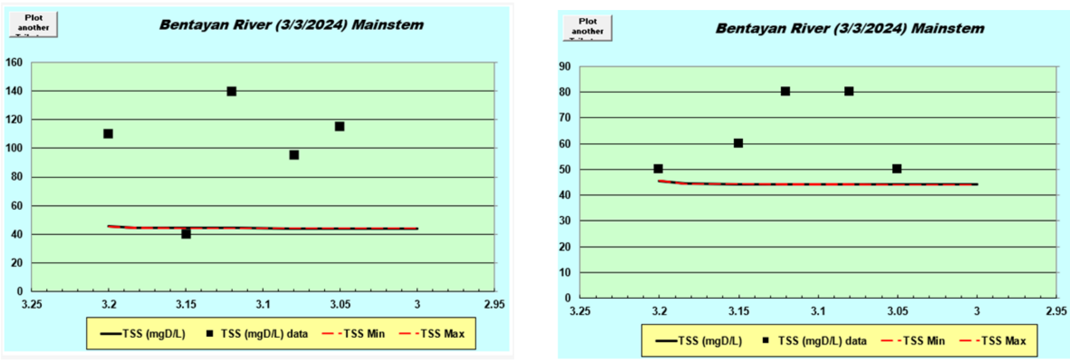
Fig. 6 (e) and (f) depict the Bentayan River's pH during low and high tides. The river generally, has an acidic pH ranging from 5 to 6. After a rainstorm, the pH is somewhat higher than on a sunny day. The lower the pH, the more active the hydrogen ion (H^+) and the more acidic the habitat. Uncontaminated streams often have a pH that is approximately neutral or slightly alkaline [14]. According to Malaysia's Department of Environment (DOE) water quality index categorization, the pH was greater than 5 and fell into class III.



(e) (f)

Fig. 6 *(e) pH of Bentayan River during low tide; (f) pH of Bentayan River during high tide*

Fig. 7 (h) (high tide) and (g) (low tide) indicate a progressive increase in TSS concentration from checkpoint 2 to checkpoint 4. TSS levels increased considerably during low tide (83.4 mg/L) and high tide (80 mg/L). The surge in TSS concentration is attributable to the involvement of checkpoint 4 industrial area and activities from along the river. However, the TSS concentration begins to fall sharply through checkpoint 5. TSS concentration decreased via checkpoint 5 during low tide and increased slightly during high tide. High TSS concentrations at points 1 and 3 can be caused by causes such as increased water flow, soil erosion, or human activity nearby. Furthermore, rainfall can cause increased runoff, which transports debris and suspended particles into bodies of water (James, 2021). According to the DOE's water quality index categorization, Malaysia's TSS content (50 mg/L - 90 mg/L) is classified as class III and requires significant treatment [5].



(g) (h)

Fig. 7 *(g) TSS of Bentayan River during low tide; (h) TSS of Bentayan River during high tide*

3.3.1 Calibration and Validation

To comply with the study's requirements, the model was calibrated using QUAL2K software using the water quality parameters (BOD, pH, DO, and TSS). It is critical to ensure that the simulated data for all parameters fit the observed data well. Based on the study, it appears that the model was properly calibrated. The model is deemed properly calibrated if the forecast fits the estimate well. The model was compared to observed data to replicate observed water quality patterns in the river. Key kinetic parameters were adjusted to ensure a reasonable match between the two.

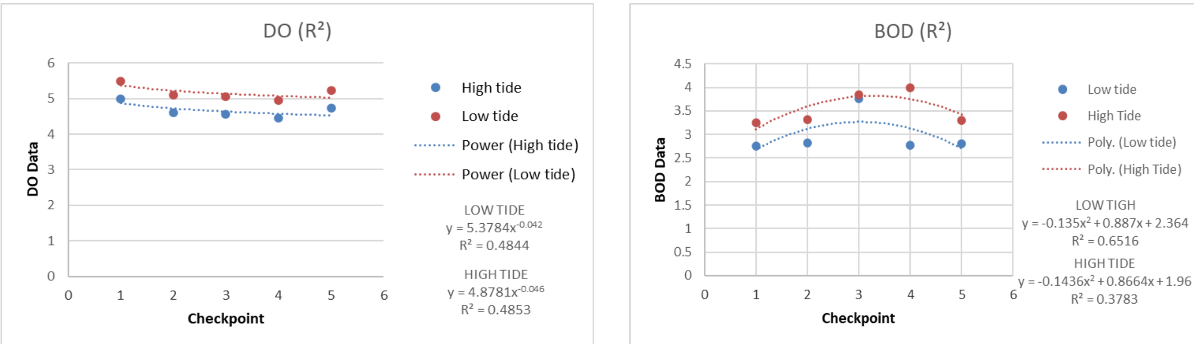
The Nash-Sutcliffe Efficiency (NSE) is a statistical tool for determining the prediction accuracy of hydrological models as shown in Table 3. It compares observed data to model-simulated data and assesses how closely the simulated outcomes match the observations. The NSE is especially important in hydrology for assessing the accuracy of models that forecast streamflow, rainfall-runoff, and other hydrological processes. In summary, the Nash-Sutcliffe Efficiency is useful for evaluating hydrological models because it provides a clear and interpretable statistic for determining how well model predictions match observed data.

Table 3 *Criteria of Nash- Sutcliffe efficiency*

NSE Value	Interpretation
NSE >0.75	Good
0.36<NSE<0.75	Qualified
NSE<0.36	Not Qualified

The model's performance was evaluated using R^2 based on calibration and validation findings. The difference between expected and observed values given DO data. The laboratory results were compared for high and low tides. The R^2 findings indicated an excellent match between the observed and projected DO levels. Similarly, the data show that there is very little fluctuation between calibration and validation. The QUAL2K model effectively predicts river water quality and supports decision-making, particularly in developing countries with limited access to high-accuracy data for frequent monitoring campaigns. Based on Figure (i), The R^2 score of 0.48 shows that the model or observed data performed, reached the minimal acceptable norms, and is thus labelled as Qualified.

The data is rated as Qualified, with a Low Tide (R^2 = 0.37) thought acceptable in general as shown in Fig. 8 (j). The High Tide (R^2 = 0.65) is rated as Qualified, which is closer to the "Good" range but still falls inside the "Qualified" category, suggesting relatively accurate model performance or data fit. Both R^2 scores are in the Qualified group, suggesting somewhat reasonable but not exceptional data or model predictions. The QUAL2K model, evaluated using R^2 and calibration and validation findings, effectively predicts river water quality and supports decision-making in developing countries with limited access to high-accuracy data for frequent monitoring campaigns. The model's R^2 findings match observed and projected DO levels, with minimal fluctuation between calibration and validation.



(i) (j)

Fig. 8 *(i) Stimulated DO for calibration; (j) Stimulated BOD for calibration*

3.4 Implementation of TMDL

The presented water quality model was used to calculate the waste load allocation (WLA) and load allocation (LA). Tables 4 shows pollutant loading statistics for the Bentayan River watershed during low and high tides, including BOD, pH, Do, and TSS. The margin of safety (MOS) employed in this investigation is 7%, 10% and 15%, based on the earlier TMDL study in Semenyih River [13]. With a margin of safety of 15%, commercial land uses will have a total maximum daily load (TMDL).

Table 4 *Data pollutant loading within the Bentayan River*

Parameter	High tide				Low tide			
	Current (kg/day)	MOS 7%	MOS 10%	MOS 15%	Current (kg/day)	MOS 7%	MOS 10%	MOS 15%
pH	130.901	9.163	13.09	19.64	131.52	9.206	13.51	19.73

DO	101.926	7.134	10.19	15.29	104.77	7.334	10.47	15.72
BOD	60.165	4.211	6.016	9.024	66.84	4.679	6.68	10.03
TSS	911.128	63.77	91.11	136.67	1435.01	100.45	143.50	215.2

According to the pollutant loadings presented in Table 4, the data contributed the most to pollution loadings among the sample stations examined in this study. Furthermore, the results were associated with low and high tidal flow conditions, indicating that TSS contributes the most pollution (kg/day) to the Bentayan River. It was also demonstrated that the overall load contributor from TSS much outweighs all other reported point sources due to the high pollutant effluent concentration released. The data show that low tidal flow causes more pollution than high tide flow. Water quality is better with high flow than it is during low flow. During low flow, there was less water to dilute the high pollution concentrations in the water body, resulting in a slower absorption process.

The ideal MOS percentage for situations with stable circumstances and low measurement uncertainty is 7%. This is insignificant assistance but it is problematic if conditions change abruptly. A balanced strategy, at 10%, is appropriate for moderate uncertainty and medium environmental sensitivity. A 15% MOS is ideal for extremely changeable situations, significant measurement errors, or delicate ecosystems, providing the greatest amount of protection. Given the high present BOD and TSS levels, and the possible environmental impact, 15% MOS is recommended, as it provides the most powerful safety buffer for efficiently maintaining water quality standards.

4. Conclusion

Bentayan River water quality was assessed. Water samples are taken at both low and high tide. pH, dissolved oxygen (DO), biochemical oxygen demand (BOD) and total suspended solids (TSS) are some of the characteristics tested for water quality. During this investigation, all of this data including in-situ and laboratory analytical data, contributed to the corpus of knowledge. This work provides a TMDL implementation plan strategy to assure river water quality restoration and conservation. The study provided TMDL values for various contaminants with a 15% margin of safety, serving as a standard for river management and pollutant load reduction. The TMDL values fluctuated with tide conditions, demonstrating the dynamic nature of pollution loading in the river environment.

The model produced a strong match between observed and simulated data, suggesting its ability to forecast water quality characteristics under various scenarios. Nevertheless, the findings indicate the crucial need of targeted pollution management efforts, particularly in industrial and commercial sectors, to improve the Bentayan River's water quality. The QUAL2K model's successful use shows that similar modelling methodologies may be used effectively in other river systems to enhance water quality management and policy-making.

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