

Simulation of Environmental Flow Assessment (EFA) using XPSWMM for Enhancing River Ecosystem Sustainability in Kenyir Lake Basin

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ABSTRACT

The study on Environmental Flow Values E-Flow found that existing river management practices could harm ecosystem health due to insufficient river flow rates. The main objectives of this study are to develop a hydrodynamic model using Expert Storm Water Management Model (XPSWMM) to determine E-Flow and to manage restoration and rehabilitation. Sampling activities commenced during both the dry and normal seasons, involving the collection of hydrology components, hydrodynamic data, and ecological samples. The giant snakehead fish species, *Sebarau*, and *Belida* were selected as bioindicator species out of the total 20 species of native fish sampled. Based on simulation, the 7Q20 low-flow analysis for both study rivers determined that minimum river discharge values with a 20-year frequency must be maintained in the Terengganu River. The

optimal discharge is 42.78 m³/s, depth is 3.94 m, and water velocity is 0.54 m/s, all of which are anticipated to satisfy fish species development needs. Based on the simulation in the Petuang River, with an optimum discharge of 0.08 m³/s, a depth of 0.4 m, and a water velocity of 0.04 m/s, the river can only accommodate a few individuals of small-sized fish species. Based on the optimal physical requirements for the indicator species, the study recommends a sustained minimum discharge of 505.72 m³/s in

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the Terengganu River to maintain optimal habitat for all native fish species. Both the lowest values obtained later were used as inputs for the low-flow analysis, with an output error of less than 20% compared to the real situation. The uses and implications of the E-Flow are highlighted through the green physical structure proposed in assessing river health based on the Integrated Water Resources Management IWRM concept as a basis for maintaining the optimum environmental flow level.

Keywords: Environmental flow values E-Flow, length-weight relationship LWR, Petuang river, Terengganu river, XPSWMM,

INTRODUCTION

The issue of lake management imbalance has persisted since the colonial era, with environmental discharge, water quantity, and quality being the main contributors to ecosystem degradation in Malaysia. Changes in catchment areas increase surface erosion and sedimentation, negatively impacting the hydrological cycle (Baig et al., 2022; Kamarudin et al., 2016). Increased sediment production disrupts river ecosystems, affecting fish populations and overall water quality (Rottier et al., 2020; Wahab et al., 2016). River ecological restoration plays a crucial role in improving water resources and maintaining ecosystem stability (Hossen et al., 2019; Hua, 2016), but large-scale implementation faces challenges, particularly due to economic constraints (Shao et al., 2017).

Kenyir Lake functions as a natural buffer, regulating water flow before it reaches the South China Sea (Wahab et al., 2018). However, environmental discharge imbalances caused by river regime changes, sedimentation, and declining water quality have been linked to extensive land use changes driven by development projects such as dam construction and tourism expansion (Ghurah et al., 2018; Saputra & Lee, 2019). Rapid development around Kenyir Lake has altered river flow, depth, and morphology, impacting the ecological characteristics necessary for sustaining aquatic life (Kim & Choi, 2019; Yao et al., 2018). Additionally, Kenyir Lake's unique microclimate and hydrodynamic properties influence hydrological patterns, requiring further study on water quality and flow regulation.

This study on Environmental Flow E-Flow found that unsustainable river management, particularly excessive water abstraction for domestic, industrial, and agricultural use, contributes to ecosystem degradation. The current fragmented approach to natural ecosystem management lacks a comprehensive framework, leading to inefficiencies in enforcement and conservation efforts (Zin et al., 2017). Integrating management models such as Integrated Water Resource Management IWRM, Integrated Lake Basin Management ILBM, and Integrated River Basin Management IRBM could provide holistic solutions to address issues like water pollution, scarcity, and flooding (Elfithri et al., 2019; Sukareman et al., 2022; Van et al., 2022). The construction of the Kenyir Dam has further altered the river ecosystem, affecting downstream fish populations and reducing natural

infiltration due to deforestation. Rainwater runoff, exacerbated by the lack of catchment areas, increases sedimentation and alters hydrological processes (Azmi & Geok, 2016). These changes disrupt the environmental balance, affecting fish survival, and leading to habitat shifts that may cause the emergence of invasive species.

Environmental flow imbalances are closely tied to climate variability, with monsoon seasons causing high discharge rates, while dry seasons result in reduced flow and inadequate water supply. Urbanisation exacerbates this issue by increasing surface runoff during heavy rainfall and reducing groundwater recharge (Schillinger et al., 2020; Stewart, 2024; Wahab et al., 2023). Moreover, the construction of Kenyir Dam II near the Tembat and Puah rivers has intensified hydrological changes, affecting fish activity, species distribution, and overall ecosystem health (Ramdas & Mohamed, 2017; Razali et al., 2018).

Unchecked development, including housing and tourism projects, further degrades water quality, disrupts the natural water cycle, and accelerates soil erosion. Without strategic intervention, these impacts may become irreversible, posing severe environmental and socio-economic consequences (Gidado et al., 2018). A systematic, well-planned management approach is necessary to restore ecological balance and ensure sustainable resource use. The changes to environmental flow, either through planned human activities or as a result of natural processes, can lead to shifts in ecosystems, particularly affecting the ecological components. The use of modelling and various hydrological, hydrodynamic, and statistical analyses in this study provides insights into the ecosystem imbalances occurring within the Kenyir Lake Basin and offers the best solution for characterising the natural attributes of the studied river system.

Modelling using Expert Storm Water Management Model (XPSWMM) software provides detailed information on river management development within the basin to ensure the sustainability of the natural ecosystem. The XPSWMM software was selected for the EFA in this study due to its comprehensive and integrated modelling capabilities, which are particularly advantageous for complex tropical river systems. Unlike single-purpose models, XPSWMM integrates 1D river hydraulics, 2D floodplain overland flow, detailed hydrologic, and water quality components within a single framework. This integration is crucial for the Kenyir Lake Basin, where E-Flow determination must account for the highly dynamic conditions characteristic of a tropical climate, including intense, short-duration rainfall events and rapid changes in runoff (Tügel et al., 2022; Wahab et al., 2025). While models such as HEC-RAS excel at steady or unsteady state hydraulic analysis, they typically require coupling with separate software for detailed runoff and water quality simulation. Similarly, Soil and Water Assessment Tool SWAT is highly effective for large-scale watershed hydrology and non-point source pollution, but its hydraulic resolution often lacks the detail necessary for site-specific habitat analysis and E-Flow cross-section evaluation (Gori et al., 2019; Javidi Sabbaghian et al., 2025; Jha & Afreen, 2020). MIKE 11 offers

robust hydrodynamic modelling but often requires more effort to seamlessly couple with high-resolution urban stormwater and water quality modules compared to XPSWMM's native integration of the EPA Storm Water Management Model SWMM engine (Anik et al., 2025; Baumann et al., 2022; Zhang et al., 2025). The particular suitability of XPSWMM for this tropical river basin lies in its ability to simulate the interplay between the natural river flow and surrounding catchment dynamics. The region's higher intensity of rainfall means that stormwater runoff significantly and rapidly impacts the river's physical habitat and water quality components. By natively handling both hydrology and hydraulics, XPSWMM allows for the accurate simulation of the 7Q20 low-flow condition while concurrently modelling the potential influence of upstream land use and effluent, ensuring a more holistic and realistic E-Flow calculation that considers both habitat needs and water quality constraints essential for the survival of the bioindicator fish species (Herison et al., 2025; Wahab et al., 2023). XPSWMM is necessary to provide a basin protection strategy for the Kenyir Lake Basin that includes conservation measures, a monitoring system, pollution assessment, pollution control, and special rules or regulations in order to lessen the effects of ecosystem imbalances (Hossen et al., 2019).

METHODOLOGY

This study focusses on two rivers in southeast Terengganu which are Terengganu River outlet from Kenyir Lake and Petuang River inlet to Kenyir Lake located between $5^{\circ}01'57.3''$ N to $5^{\circ}14'149.9''$ N and $102^{\circ}55'37.6''$ E to $102^{\circ}39'37.4''$ E. Figure 1 and Figure 2 show sampling stations of each river which was divided into three sampling stations (I, II, III) to facilitate the analysis of environmental flow. DGPS was used in this study to provide very accurate data from the Mean Sea Level MSL for the selection of sampling locations. For accuracy and rectification, the gathered data will be cross-checked with the Department of Survey and Mapping Malaysia JUPEM data system. The selected sites provide diverse data for determining optimal environmental flow values in Peninsular Malaysia. This research also aims to support the development of an environmental flow model integrating hydrology, hydrodynamics, and ecology.

There are more hundred supplier rivers in the Kenyir Lake Basin, which include the Siput River, Tembat River, Ketiar River, Besar River, Lepar River, Lawit River, Cenana River, Cicir River, Perepek River, Terengganu Mati River, Cacing River, Bewah River, Terenggan River, Lasir River, and Petang River refers in Figure 3. This study also assesses hydrological, hydrodynamic, and water quality characteristics in the Terengganu and Petuang Rivers using XPSWMM software to predict the optimum environmental flow level for ecosystem sustainability. Figure 4 outlines the key components integrated into the computerised analysis to estimate the environmental flow assessment of the basin area. Data collection focussed on hydrometric parameters, including river width, water depth,

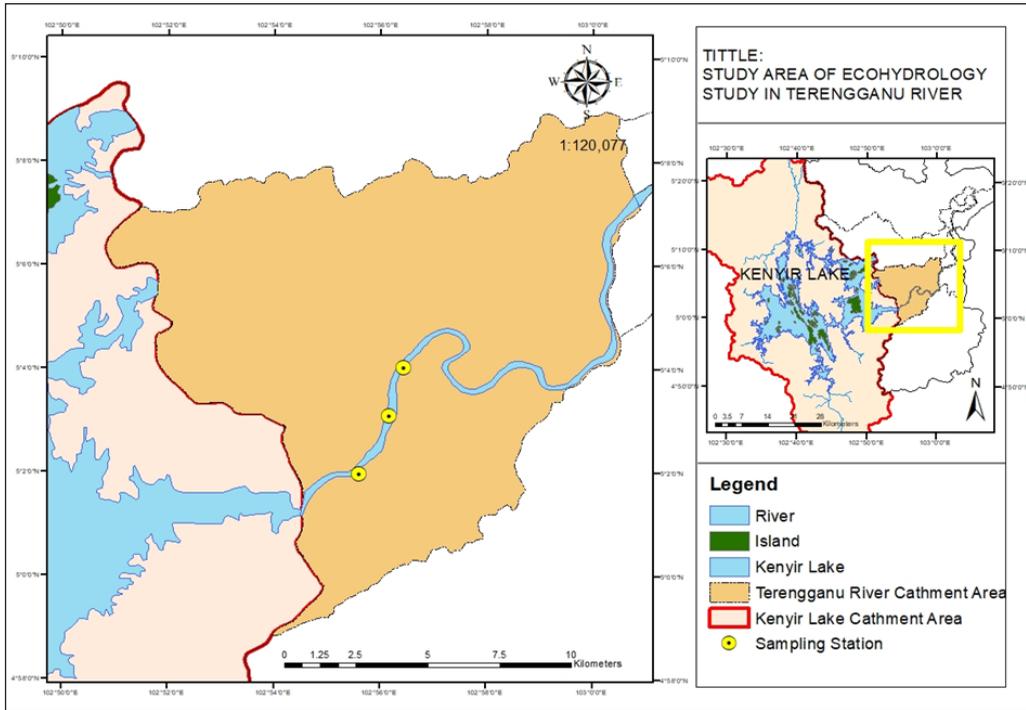


Figure 1. The sampling station map for the Terengganu River in the outlet area of the Kenyir Lake Basin, Malaysia

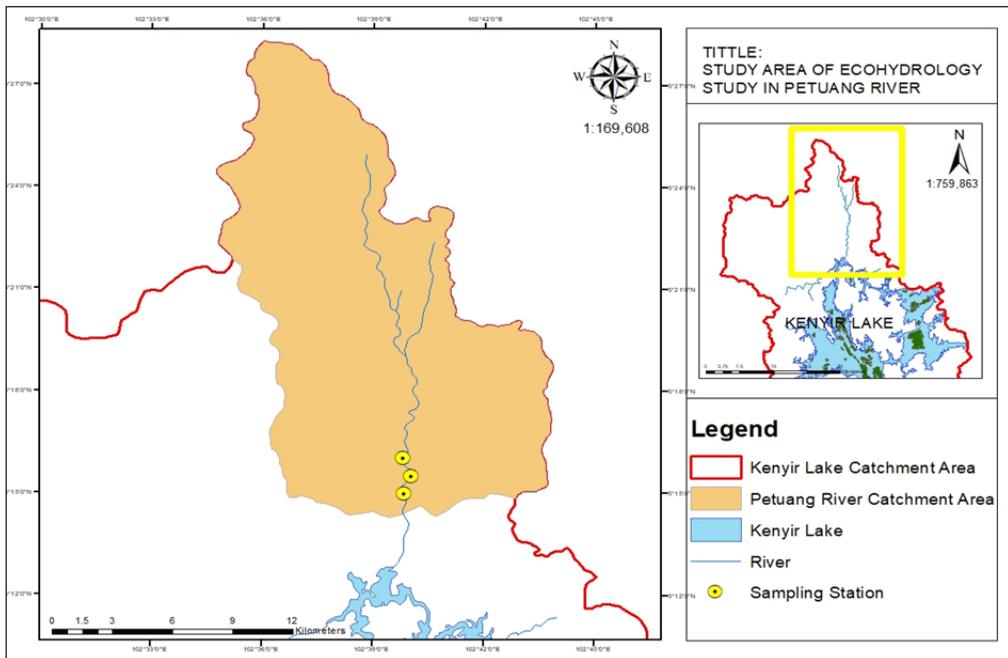


Figure 2. The sampling station map for the Petuang River in the inlet area of the Kenyir Lake Basin, Malaysia

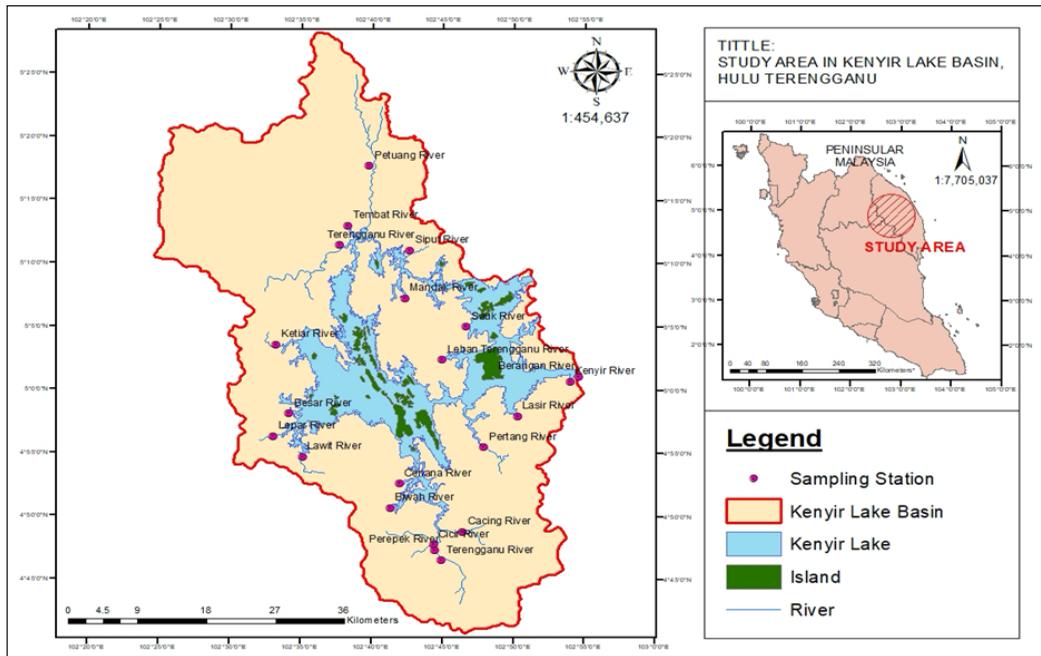


Figure 3. Illustration of the locations of several active supplier rivers in the Kenyir Lake Basin, Malaysia

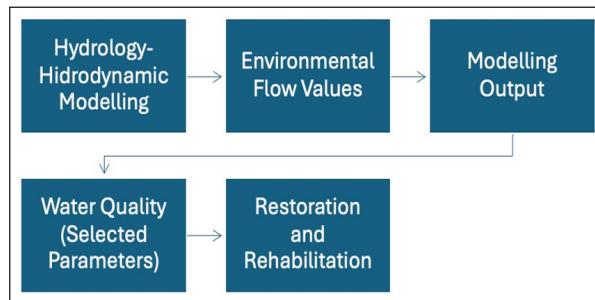


Figure 4. The environmental flow components are determined through the integration of modelling and the hydrological-hydrodynamic proportions for this study

velocity, and water level. Station locations were selected along straight river sections with minimal obstructions to ensure accurate cross-sectional measurements representative of the river’s physical conditions (Ebrahimian et al., 2018; Ng et al., 2019). Low flow discharge studies rely on these measurements, reflecting responses to various physical processes in the river channel (Baruah & Sarma, 2020; Kerr et al., 2016; Yao et al., 2018). XPSWMM was used to simulate environmental flow inputs from the Terengganu and Petuang Rivers, representing the inlet and outlet rivers of Kenyir Lake. The modelling phase followed a structured process based on hydrological and water quality parameters to estimate environmental flow levels in the basin.

Model Calibration and Validation

In the simulation, to ensure the reliability and predictive accuracy of the XPSWMM hydrodynamic model, a rigorous calibration and validation process was conducted. The model, parameterised with LiDAR-derived discharge data, was calibrated against observed hydrological data collected during a normal flow event and a low flow of 48 hours at the gauging station on the Terengganu River. For calibration, the model's key parameters, such as Manning's roughness coefficient, depression storage, and infiltration rates, were adjusted iteratively until the simulated discharge closely matched the recorded discharge hydrograph. Besides that, for validation, the calibrated model was then validated against a separate set of observed data for 48-hour flow events. The model's performance was statistically evaluated using the Coefficient of Determination, which describes the degree of correlation between observed and simulated values, with values close to 1 indicating a strong match. The hydrograph curve observed for 48 hours from the data records did not show a significant difference in terms of the pattern of discharge increase or decrease throughout the period. This was confirmed by recording an R^2 value greater than 0.50 indicating a significant relationship between time and both observed and simulated discharge, specifically 0.727 Figure 5 (a). Therefore, the user inflow registered for the normal discharge scenario in the Terengganu River is deemed acceptable for use in this simulation. For the low discharge scenario simulation in the Terengganu River, the procedure for registering the hydraulic information and physical drainage characteristics was the same as the base scenario normal discharge, except for the user's inflow hydrograph value. The validation between the observed data recorded observations over 20 years and the simulated data for the lowest discharge scenario in the Terengganu River is shown in Figure 5 (b), recording an R^2 value greater than 0.50, specifically 0.951. Similarly, for the Petuang River, the 48-hour normal discharge simulation achieved an R^2 of 0.714, while the validation against data

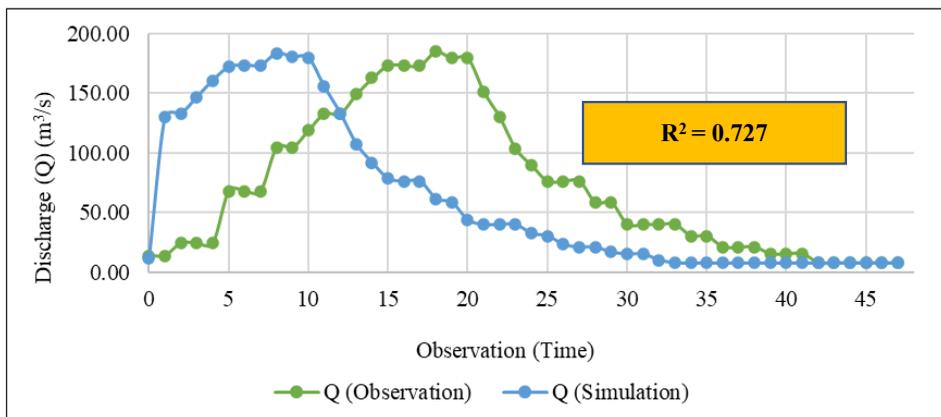


Figure 5 (a). Model validation for the normal discharge scenario in the Terengganu River

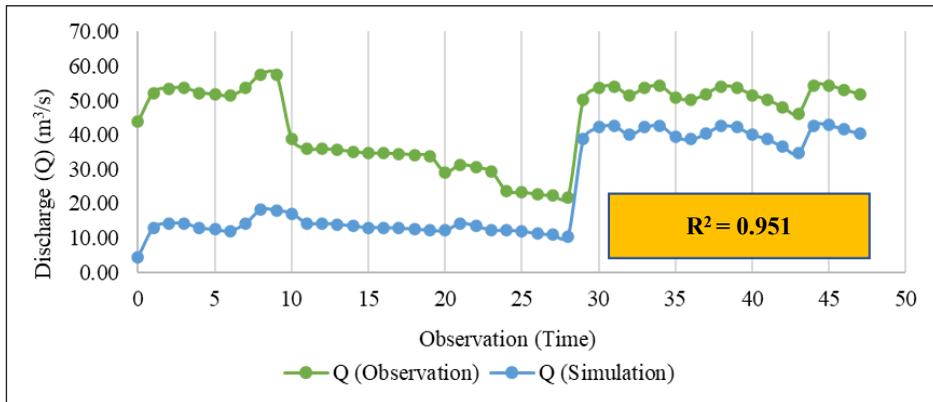


Figure 5 (b). Model validation for the low discharge scenario in the Terengganu River

for the lowest discharge scenario yielded a highly significant R^2 of 0.976. These statistical results, with all R^2 values substantially exceeding the 0.50 threshold, confirm that the model accurately replicates the hydrological behaviour of both river systems under both normal and extreme low-flow conditions, justifying the use of the registered user inflows for subsequent Environmental Flow simulations refers to Figure 6 (a) and Figure 6 (b).

The determination of the final E-Flow value was based on a combination of hydrological and hydraulic criteria, justified through established environmental flow assessment literature, specifically tailored for tropical river ecosystems. The primary hydrological threshold used was the 7Q20 low-flow value, which represents the lowest average seven-day flow expected to occur once every 20 years. This extremely low-flow indicator is mandated by Ng et al. (2019) and Wahab et al. (2025) and is critical for identifying the absolute minimum flow required to prevent catastrophic ecosystem collapse. The calculated 7Q20 flows for the Terengganu River and Petuang River were used as the basis for the minimum required E-Flow. The investigation of percentage-based flow scenarios such as 30%, 50%, 70% of Mean Annual Flow MAF, though not directly used in the final optimal E-Flow recommendation, which was based on habitat suitability and hydraulic-ecological criteria, served a critical role in the sensitivity analysis of the river's physical habitat. These scenarios are widely recognised in E-Flow literature, deriving conceptual justification from hydrological methods which link a river's natural flow volume to general stream health categories (Hairan et al., 2021; Mobadersani et al., 2022; Wahab et al., 2024; Zhao et al., 2021). By simulating these MAF percentages alongside the 7Q20 extreme low-flow, this study was able to quantify the hydraulic characteristics (depth, velocity) required to meet the optimal physical habitat needs of the bioindicator species (Toman, Sebarau, Belida) and provide a management gradient to policymakers, showing the trade-offs between water abstraction and ecological health, moving from the collapse threshold 7Q20 to the optimal condition (Herison et al., 2025; Khan et al., 2024; Shinozaki & Shirakawa, 2021).

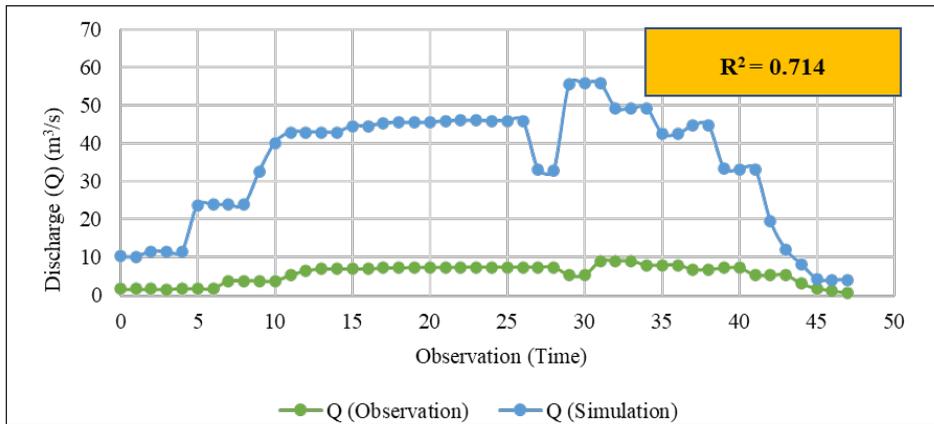


Figure 6 (a). Model validation for the normal discharge scenario in the Petuang River

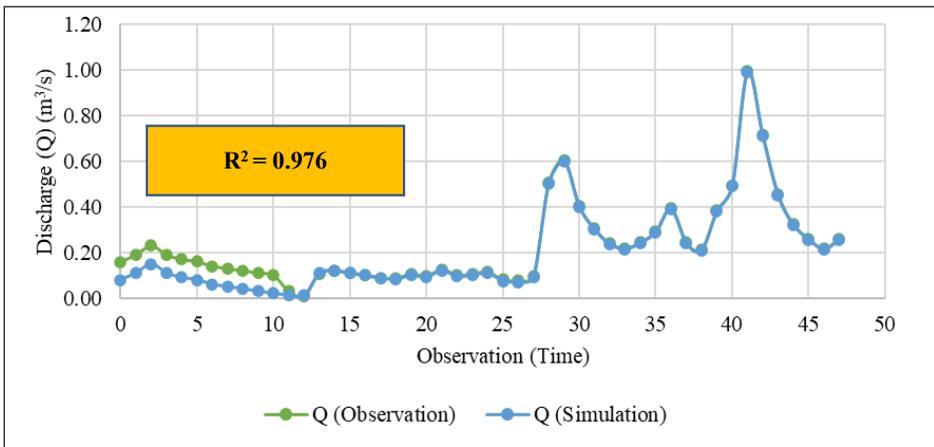


Figure 6 (b). Model validation for the low discharge scenario in the Petuang River

Although this study primarily utilised a Physical Habitat Simulation PHABSIM approach via XPSWMM coupled with hydrological analysis 7Q20, the resultant E-Flow values and methodology are conceptually aligned with established global E-Flow frameworks, ensuring the scientific defensibility of our findings (Razzaghi Rezaieh et al., 2025; Wahab et al., 2025). The study's approach implicitly follows the core of the Building Block Methodology BBM, defining the 7Q20 flow as the Critical Low Flow Component for the ecosystem, and grounding the optimal E-Flow in the maximisation of the Weighted Usable Area WUA for the bioindicator fish species. The process that links flow to specific ecological objectives, such as spawning and rearing habitat. Furthermore, by quantifying the relationship between varying flow rates and the resulting change in WUA, the study provides the necessary data to define the limits of acceptable hydrological alteration,

a key analytical step within the Ecological Limits of Hydrologic Alteration ELOHA framework. This alignment confirms that the XPSWMM-derived E-Flow is scientifically robust, globally relevant, and offers a defensible management gradient consistent with international best practices for sustaining river ecosystems (Gebreegziabher et al., 2023; Kimambo et al., Jain, 2025).

Model Simulation Method for the Basic Scenario and Low Flow Scenario

In the simulation, six main nodes were digitised to represent sampling stations along both rivers: ST1–ST3 for the Terengganu River and SP1–SP3 for the Petuang River. Each river also includes a dummy node to mark the outflow point and serve as a reference for linking segments. As illustrated in Figure 7 (a), three river channel links were constructed per river:

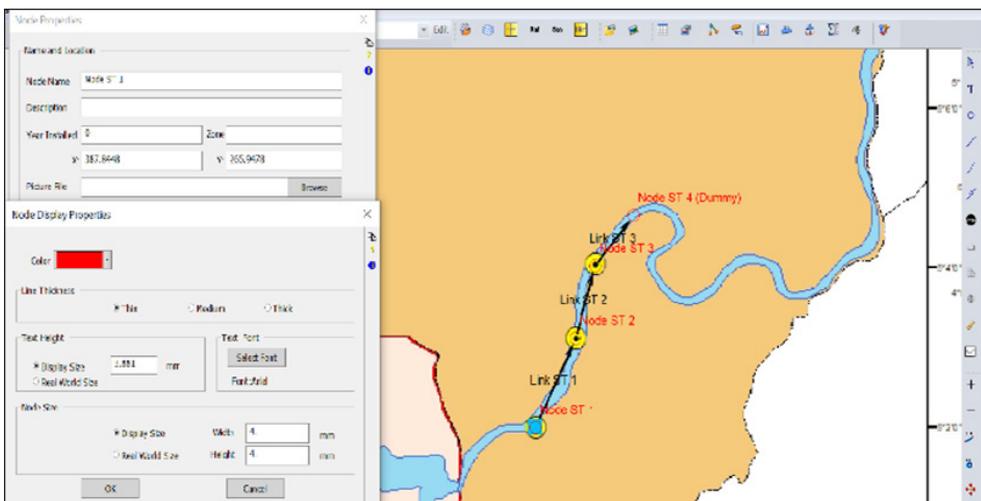


Figure 7 (a). The process of representing nodes and links for each sampling station in the Terengganu River

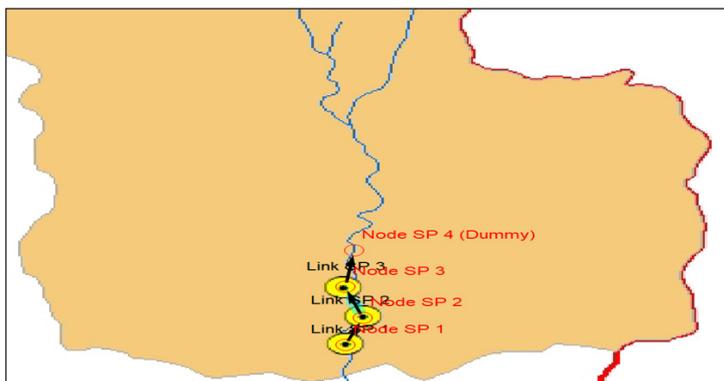


Figure 7 (b). The process of representing nodes and links for each sampling station in the Petuang River

ST1–ST2, ST2–ST3, and ST3–ST4 (dummy). Then Figure 7 (b) for the Terengganu River; and SP1–SP2, SP2–SP3, and SP3–SP4 (dummy) for the Petuang River, and Link SP 3 (representing the Petuang River channel connecting Node SP 3 and Node SP 4 (dummy)).

Hydraulic data were entered for each main node station (Node ST 1–ST 3 and Node SP 1–SP 3) as shown in Figure 8. For the dummy nodes (Node ST 4 and Node SP 4), Spill Crest and Invert Elevation values were set to the same as those of Node ST 3 and Node SP 3. User inflow data were also input for each river link (Link ST 1–ST 3 and Link SP 1–SP 3), as shown in Figure 9. These inflow values, collected during field sampling in the normal season, are used in simulations of normal and low flow conditions, assuming constant MSL and river width.

In the process of completing the hydraulic data for each conduit link, every link is constructed based on the natural form of the river, using field measurements of cross-sectional observations. According to Akoh et al. (2017), the appropriate value of Manning's Roughness coefficient used in this study is 0.025, which focusses on river or lake basin areas. The required data includes Upstream Invert Elevation, Downstream Invert Elevation, Length, and Roughness. Based on the calibration to the created nodes, the XPSWMM programme uses this input data to automatically determine the percentage of bank slope. Three segments are covered for each river channel under study: the Terengganu River (Link ST 1, Link ST 2, Link ST 3) and the Petuang River (Link SP 1, Link SP 2, and Link SP 3). Figure 10 shows the conduit link dialogue box and the procedure for registering the Conduit Profile data.

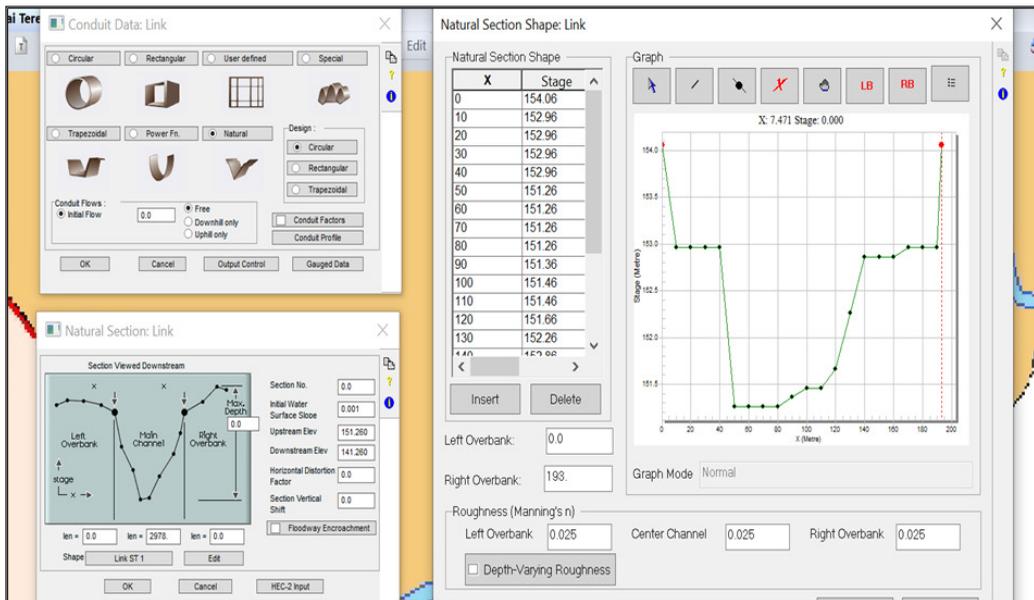


Figure 8. Dialogue box for hydraulic data registration for each node in the Terengganu River and Petuang River

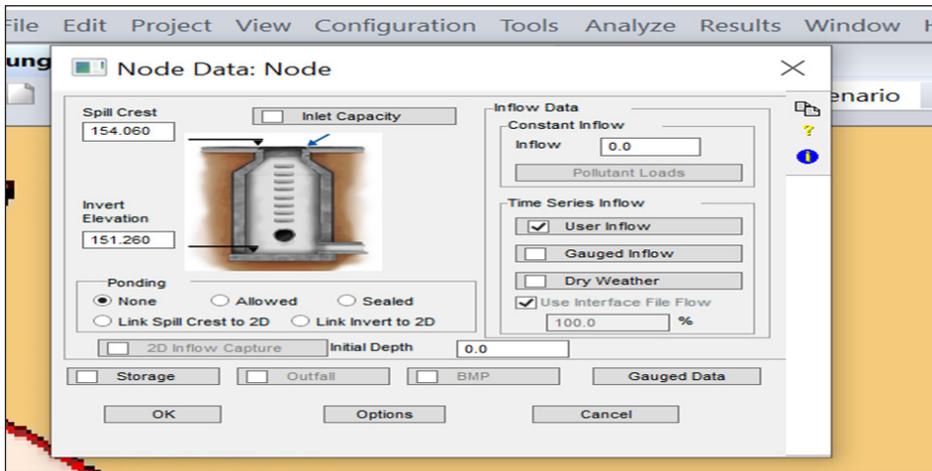


Figure 9. Dialog box for hydraulic data registration for each link in the Terengganu River and Petuang River

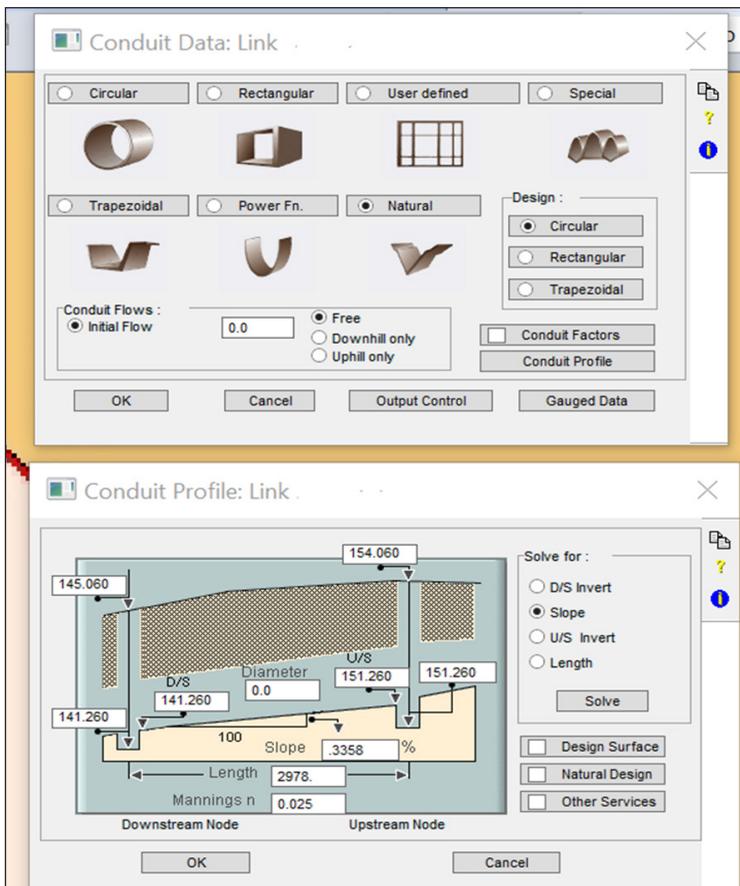


Figure 10. Illustration of conduit link dialogue box and conduit profile data entry for the Terengganu River and Petuang River channels

About the 48 hour Inflow Hydrograph data recorded during the normal flow season for each monitoring node along the Terengganu River (station ST 1 – ST 4) and the Petuang River (station SP 1 – SP 4) refers in Figure 11. These inflow datasets were subsequently incorporated into the XPSWMM hydrological-hydraulic modelling platform to stimulate river flow dynamics. In the analysis, the occurrence of minimum discharge is treated independently, which implies that the return periods can be established over varying time intervals such as daily, weekly, or monthly rather than being confined solely to annual events (Jamil et al., 2012; Ni et al., 2012). To further assess low-flow behaviour, frequency analysis was performed using complete discharge datasets. Even when discharge data exhibit statistical dependence, this approach remains valid by plotting flow values against the percentage of time that each discharge is equalled or exceeded, thereby providing flow-duration characteristics (Cheah et al., 2019). At the modelling stage, the 7Q20 low-flow statistic, defined as the minimum average flow observed over seven consecutive days with an estimated recurrence interval of 20 years, was applied. This statistic is widely adopted in hydrological and water quality studies, as it serves as a critical benchmark for identifying ecological stress periods, setting environmental flow requirements, and designing water supply management strategies. In this study, the 7Q20-derived inflow was used as a constant discharge input for each node station in the XPSWMM environment, thereby enabling the simulation of extreme dry-season scenarios. This ensures that the model reflects realistic drought-like conditions and allows subsequent analysis of system performance under critical stress situations. Figures 12 (a) and Figure 12 (b) illustrate the

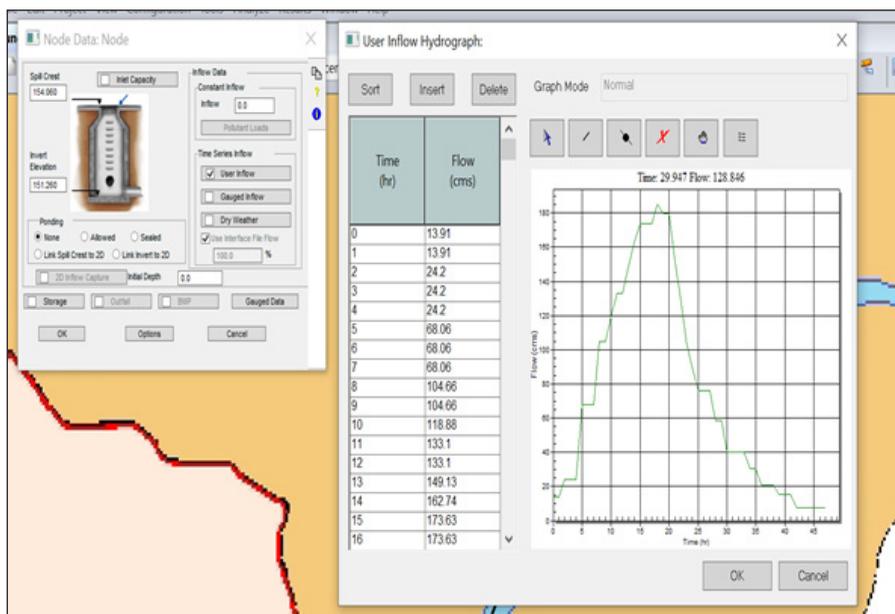


Figure 11. Inflow hydrograph data entry dialogue for each Node in the Terengganu River and Petuang River

input dialogue interfaces within XPSWMM, demonstrating how the 7Q20-based inflow values were incorporated into the model setup. This stage provides the foundation for later simulations, including low-flow impact assessments on river hydrodynamics, water allocation planning, and ecological sustainability evaluations (Baumann et al., 2019; Wahab et al., 2025).

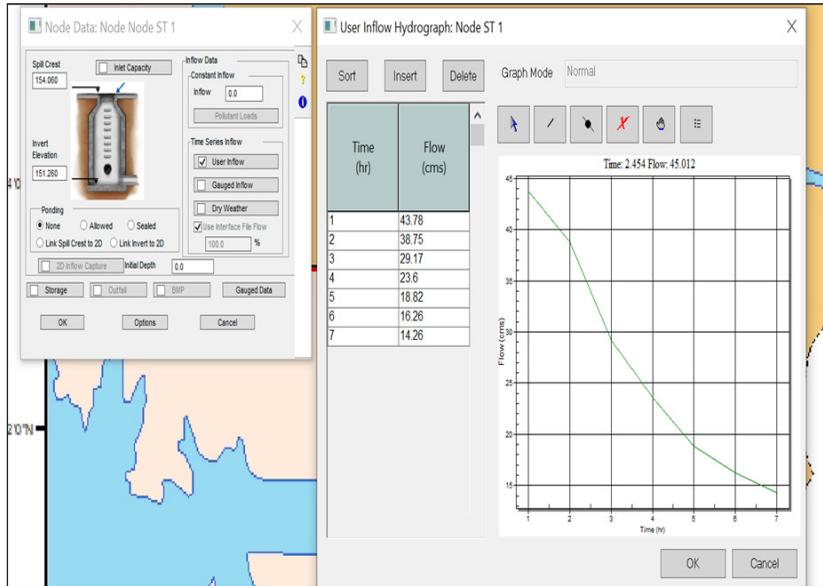


Figure 12 (a). Inflow hydrograph/cross-section data entry dialogue based on low flow frequency analysis for the Terengganu River

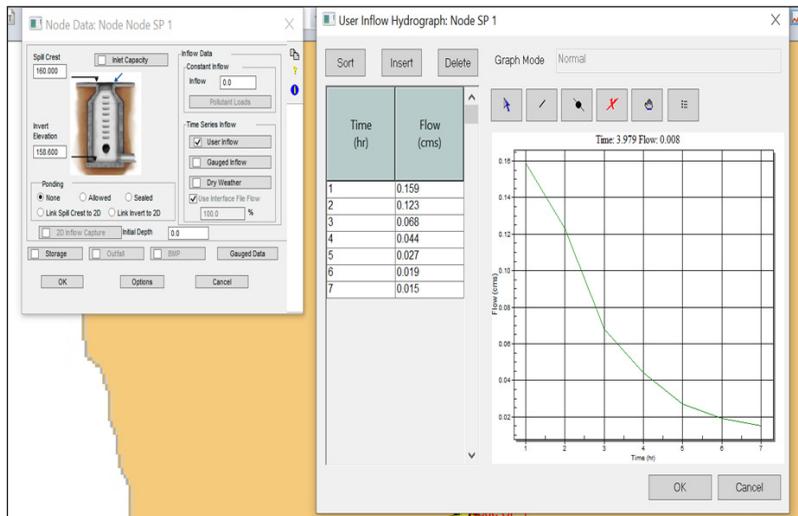


Figure 12 (b). Inflow hydrograph/cross-section data entry dialogue based on low flow frequency analysis for the Petuang River

RESULTS AND DISCUSSION

The Details Summary of Hydrological and Hydrodynamics for the Terengganu River and Petuang River

The values of average depth, velocity, width, and discharge for the Terengganu and Petuang Rivers during the dry and normal seasons are presented in Table 1 and Table 2. During the dry season, the Terengganu River recorded an average depth of 2.5 ± 1.1 m, velocity of 0.045 ± 0.010 m/s, width of 145 ± 138 m, and discharge of 8.520 ± 4.894 m³/s. Petuang River showed a depth of 2.3 ± 0.9 m, velocity of 0.200 ± 0.010 m/s, width of 81 ± 65 m, and discharge of 6.250 ± 4.921 m³/s. Despite dry conditions, water velocity remained moderate—likely influenced by scheduled water releases from Kenyir Lake by TNB in preparation for the monsoon season. Petuang River generally records shallower depths than the Terengganu River, which receives more consistent flow due to its role as the lake's primary outlet. In fact, about 80% of the Terengganu River's flow originates from Kenyir Dam's hydro turbines at Sultan Mahmud Power Station. During the 2014

Table 1

The average values of depth, velocity, and river width during the dry season for the Terengganu River and Petuang River

Sampling Station	Average of Depth (m)	Average of Velocity (m/s)	Width (m)	Discharge (m ³ /s)
Terengganu River I (ST 1)	2.1 ± 1.1	0.029 ± 0.011	141	5.671
Terengganu River II (ST 2)	2.2 ± 1.1	0.045 ± 0.010	145	8.520
Terengganu River III (ST 3)	2.5 ± 1.1	0.031 ± 0.011	138	4.894
Petuang River I (SP 1)	2.3 ± 1.1	0.200 ± 0.010	65	6.250
Petuang River II (SP 2)	2.2 ± 1.1	0.120 ± 0.061	71	6.235
Petuang River III (SP 3)	1.5 ± 0.9	0.110 ± 0.065	81	4.921

Note. Ecological Interpretation and Alignment with Global Standards

Table 2

The average values of depth, velocity, and river width during the normal season for the Terengganu River and Petuang River

Sampling Station	Average of Depth (m)	Average of Velocity (m/s)	Width (m)	Discharge (m ³ /s)
Terengganu River I (ST 1)	2.8 ± 1.1	0.056 ± 0.012	193	13.906
Terengganu River II (ST 2)	3.8 ± 1.1	0.060 ± 0.011	195	18.742
Terengganu River III (ST 3)	3.5 ± 1.1	0.053 ± 0.012	156	12.588
Petuang River I (SP 1)	1.4 ± 0.1	0.285 ± 0.226	65	10.401
Petuang River II (SP 2)	2.1 ± 1.1	0.214 ± 0.081	81	16.424
Petuang River III (SP 3)	2.0 ± 1.1	0.480 ± 0.142	95	16.174

Note. Ecological Interpretation and Alignment with Global Standards

monsoon season, despite record-high lake levels, the Ungated Spillway system prevented flooding by effectively controlling overflow (Sinar Harian, 2019). In the normal season, the Terengganu River showed increased depth (3.8 ± 1.1 m), velocity (0.060 ± 0.011 m/s), width (195 ± 156 m), and discharge (18.74 ± 12.588 m³/s). Petuang River recorded depth of 2.1 ± 0.1 m, velocity of 0.480 ± 0.081 m/s, width of 95 ± 65 m, and discharge of 16.424 ± 10.400 m³/s. The higher velocity in the Petuang River may result from receding lake levels and accelerating inflow from tributaries. Discharge trends align with rainfall patterns, though factors like sedimentation can reduce channel capacity and heighten flood risk. The Terengganu River, being the main outlet, is more prone to flooding than the Petuang River, especially during peak flows. Petuang River, at a higher elevation, is less affected. Post-monsoon, water levels often stabilise, but uneven water release, especially in the dry season, can disrupt aquatic habitats, particularly around the inlet and outlet zones of Kenyir Lake (Abdullah & Ismail, 2019; Sufiyan & Zakaria, 2018).

Total Suspended Solids and Dissolved Oxygen are key parameters influencing river discharge and the survival of native indicator fish species. High TSS levels can impair fish health by damaging gill tissues through excessive mucus production and pore blockage. In this study, a TSS threshold of >300 mg/L (Class V) was identified as the stress limit for sensitive species (Khan et al., 2023; Sulaiman et al., 2025; Zain & Hamid, 2025). However, seasonal TSS levels in both rivers remained below this threshold shows in Figure 13,

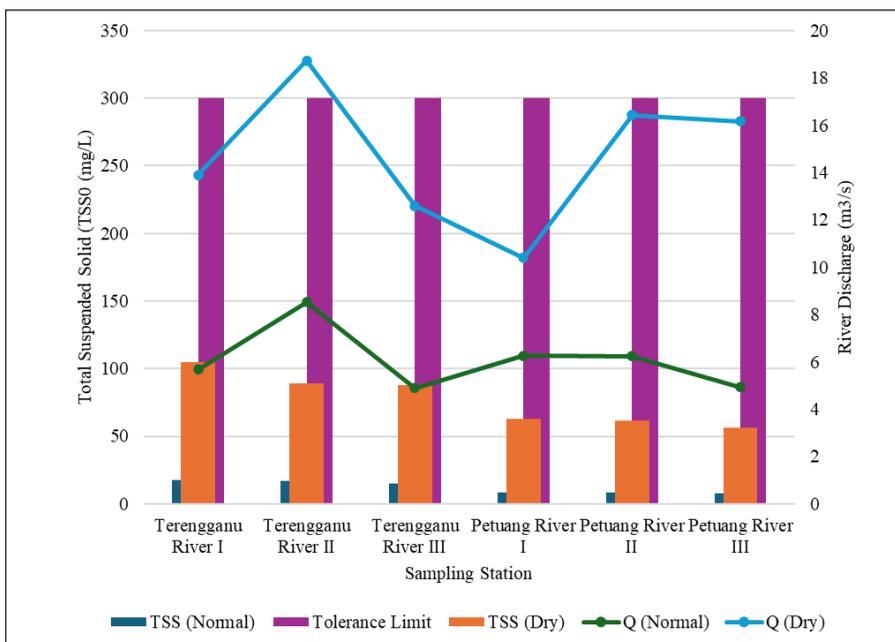


Figure 13. The trend of Total Suspended Solids (TSS) distribution and river discharge (Q) in the Terengganu River and Petuang River during the dry and normal seasons

suggesting suitable conditions for fish survival. Exceeding this limit can lead to reduced DO, habitat degradation, egg and juvenile mortality, organ damage, and loss of food sources (Kim & Choi, 2019; Rohalin et al., 2025). DO concentration plays a crucial role in determining aquatic habitat quality. DO levels below 6–7 mg/L can impair fish growth and reproduction, while concentrations below 3 mg/L can lead to mortality, despite some adult fish tolerating such conditions temporarily (Hashim et al., 2020; Rohalin, 2025; Rosle et al., 2018). Analysis Figure 14 showed that Terengganu River stations recorded Class I DO levels DOE, 2007 during the normal season, supporting healthy fish populations. In contrast, the Petuang River recorded lower DO levels (6.81 ± 5.98 mg/L), tolerable only for short periods. Indicator species like *Toman* and *Sebarau* tolerated DO levels of 7.34 ± 6.91 mg/L in the Terengganu River. *Sebarau*, in particular, showed high resilience due to its respiratory adaptations. However, *Belida*, a smaller species, was less present in the Petuang River, likely due to lower DO levels. Therefore, a DO threshold of 7 mg/L is used in this study to define optimal conditions for fish survival.

River discharge plays a vital role in the river's ecological system. River discharge controls several important drainage characteristics, such as depth, channel width, flow velocity, and substrate composition within the drainage area. The diversity in river discharge types is also found to have a high impact on aquatic fauna, such as the distribution and diversity of fish. The survival rate of an important fish species in a river environment reflects

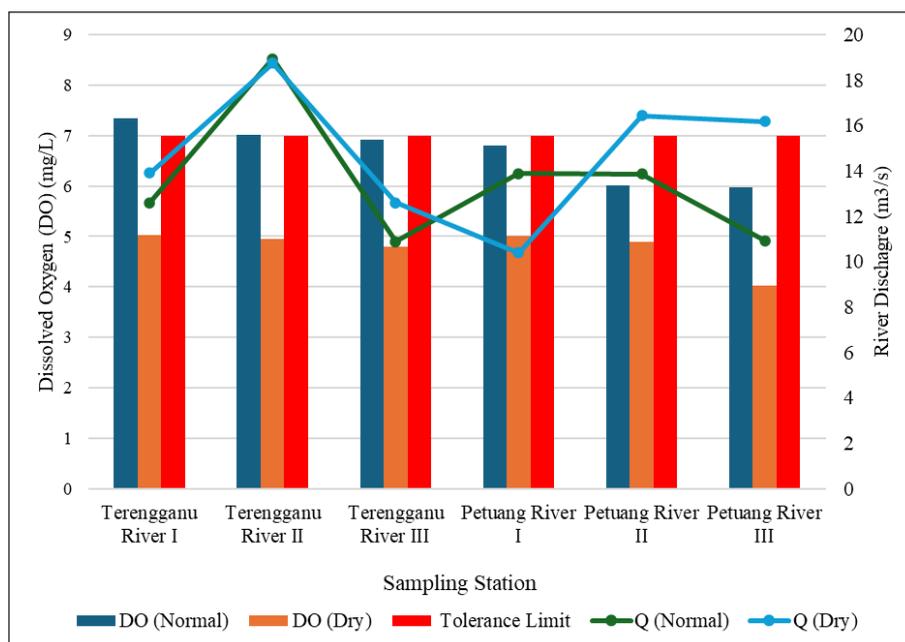


Figure 14. The trend of Dissolved Oxygen (DO) distribution and river discharge (Q) in the Terengganu River and Petuang River during the dry and normal seasons

the health status of that river channel. Fish communities are commonly used as biological indicators for water quality assessment, river network connectivity, and discharge regime analysis. Taking the Giant Snakehead fish *Toman* as the largest indicator fish species, the analysis found that the average width, length, and weight for all individuals captured during both scenarios were 6.72 ± 3.26 cm, 33.6 ± 7.25 cm and 280.97 ± 18.8 g (Terengganu River) and 4.83 ± 3.52 cm, 14.83 ± 6.00 cm dan 155.23 ± 264.58 g (Petuang River). The average lifespan of the *Toman* is up to 8 years, and it can reach a length of up to 2 meters and a weight of up to 20 kg. Based on the Length-Weight Relationship (LWR) analysis of the three indicator species, two of the species *Toman* and *Sebarau* exhibited good isometric growth characteristics recording the ideal b value between 2.5 and 3.5 during the normal flow base scenario in the Terengganu River. The respective b values were 2.943 *Toman* and 3.207 *Sebarau*. However, the *Belida* species showed non-ideal growth between the two parameters of length and weight, recording b value of 2.371 (< 3). This non-ideal growth is possibly due to slight pressure from environmental factors such as physical stressors and predation, leading to an imbalance between these two parameters (Mengistu et al., 2021). Furthermore, two indicator fish species, *Sebarau* and *Belida*, exhibited good isometric growth characteristics during the normal flow base scenario in the Petuang River, with respective b values of 2.975 *Sebarau* and 3.098 *Belida*. During the low flow additional scenario, only two indicator fish species, *Sebarau* and *Belida*, were successfully sampled in both rivers. The analysis showed that these two indicator fish species exhibited good isometric growth characteristics in the Terengganu River, with respective b values of 3.029 *Sebarau* and 2.965 *Belida*. Conversely, the Petuang River during the low flow additional scenario recorded non-ideal isometric values between the two parameters of length and weight, recording ideal b values less than 2.5, specifically 2.201 *Sebarau* and 2.222 *Belida*. The imbalanced growth observed in these two species in the Petuang River suggests a disruption to the ecosystem's condition resulting from the stress of environmental factors.

From the results of the length-weight regression, the R^2 coefficient values recorded for the Terengganu River during both scenarios were 0.881 ± 0.793 and 0.882 ± 0.621 , respectively. For the Petuang River, the values recorded were 0.629 ± 0.577 during the low flow additional scenario and 0.882 ± 0.778 during the normal flow base scenario. Overall, these regression values indicate that weight increased by approximately 62% to 88% in the Terengganu River and 57% to 88% in the Petuang River based on increases in length. The length–weight relationship obtained shows varying growth patterns, namely isometric, positive allometric, and negative allometric. The relationship between length and weight is classified as moderately strong at $90\% \pm 50\%$. The findings also show that all three native fish species were in good condition, as the mean condition factor values were greater than unity ($K > 1$). The average K value for the low flow additional scenario in both rivers was slightly lower than in the normal flow base scenario, indicating spawning and recovery

conditions for the fish. The calculation of the condition factor in this study describes the general health status of fish populations in a habitat. This indicates that the discharge level of 4.92 m³/s the minimum recorded at the Petuang River is insufficient to support the survival of most other native fish species, including the dominant indicator species of this study, the *Toman*, in the Petuang River during the low flow additional scenario. This is because such a low discharge value is unsuitable for most large-sized native fish species, refers to Table 3 and Table 4.

Table 3
Length-weight relationship (LWR) analysis during the normal flow base scenario

River	Item	R ²	Coefficient a	Coefficient a	Condition Factor (K)
Terengganu River	Toman (<i>Channa macropeltes</i>)	0.899	1.917×10^{-5}	2.943 (≈ 3)	1.409
	Sebarau (<i>Hampala macrolepidata</i>)	0.7646	8.7177×10^{-6}	3.2067 (> 3)	2.509
Petuang River	Belida (<i>Chitala lopis</i>)	0.6217	2.5811×10^{-5}	2.3713 (< 3)	1.118
	Sebarau (<i>Hampala macrolepidata</i>)	0.882	2.566×10^{-5}	2.976 (≈ 3)	2.326
	Belida (<i>Chitala lopis</i>)	0.778	3.820×10^{-5}	3.098 (> 3)	6.253

Note. R² the coefficient of determination, measures how much of the variation in the dependent variable is explained by the independent variables in a regression model

Table 4
Length-weight relationship (LWR) analysis during the low flow additional scenario

River	Item	R ²	Coefficient a	Coefficient a	Condition Factor (K)
Terengganu River	Sebarau (<i>Hampala macrolepidata</i>)	0.793	1.764×10^{-5}	3.029 (> 3)	2.056
	Belida (<i>Chitala lopis</i>)	0.881	1.269×10^{-5}	2.965 (≈ 3)	1.095
Petuang River	Sebarau (<i>Hampala macrolepidata</i>)	0.629	1.151×10^{-3}	2.200 (< 3)	2.301
	Belida (<i>Chitala lopis</i>)	0.577	4.689×10^{-4}	2.222 (< 3)	0.965

Note. R² the coefficient of determination, measures how much of the variation in the dependent variable is explained by the independent variables in a regression model

Simulation Results using the Base Scenario: Normal Flow and Additional Scenario: Low Flow for the Terengganu River

Simulation of the Normal Flow Base Scenario for the Terengganu River

Figure 15 shows a dynamic display illustration for Link ST 1, Link ST 2, and Link ST 3. Based on the normal flow simulation results in the Terengganu River, the maximum

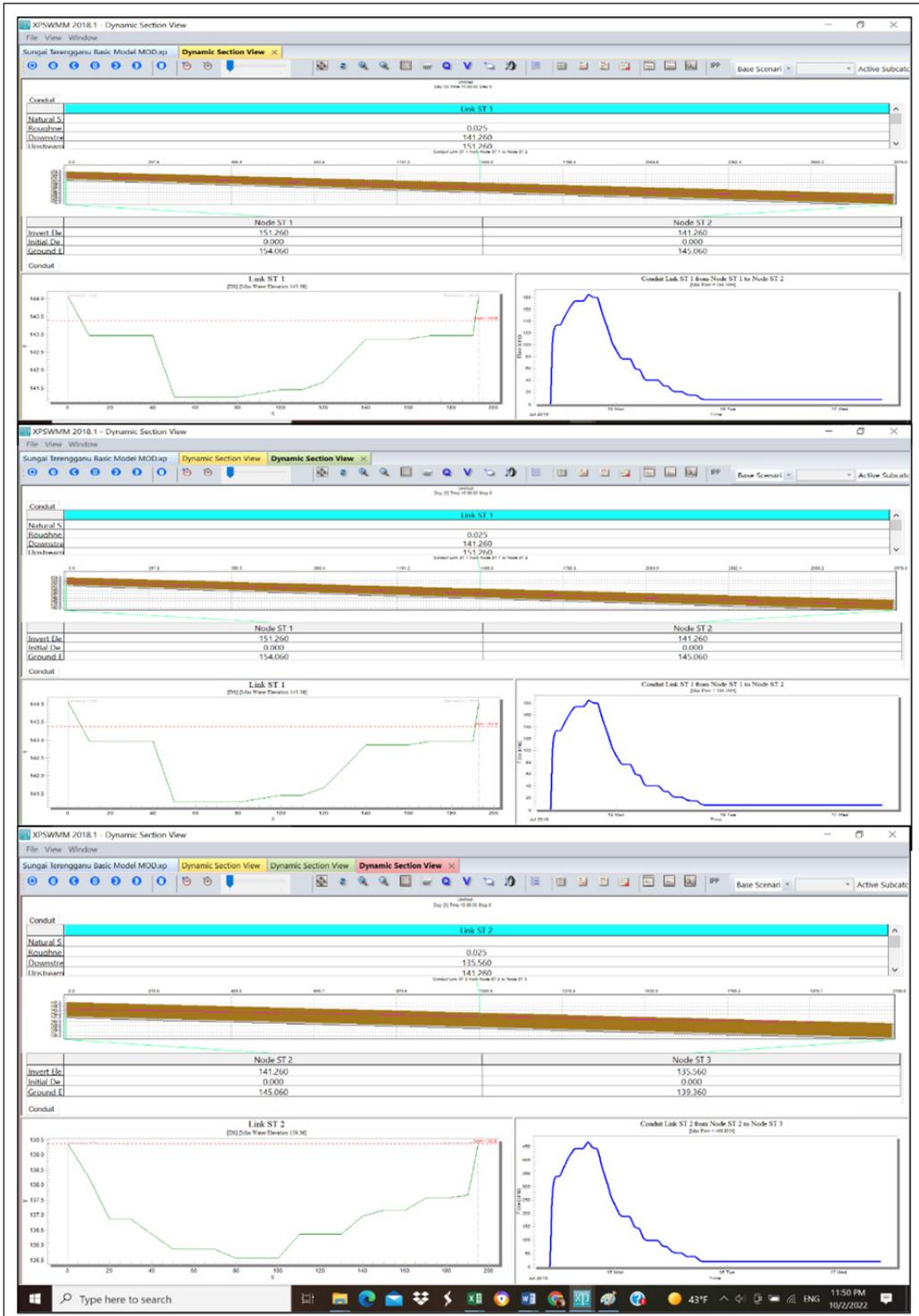


Figure 15. Dynamic simulation normal flow base scenario for the Terengganu River of Link ST 1, ST 2 and ST 3

depth that can be reached at each station during the normal season ranges between 3.74 m and 4.94 m, where the upstream station ST 1 records the lowest depth (3.74 m) and has the lowest discharge value of 184.196 m³/s compared to the other stations, with a maximum flow velocity of 1.91 m/s. It was found that the river flow velocity influences the discharge rate at each conduit link section. Although the midstream stations (ST 2 and ST 3) have higher depths compared to the upstream station, the river discharge rate at those sections is directly proportional to the flow rate (Rottler et al., 2020). This is due to the flow slowing down as it reaches the downstream section, primarily due to the presence of a dam structure in the area before entering the Terengganu River Basin. The structure acts as a barrier to water flow, where the flow is controlled by a spillway bank with a rate of 1.43 m/s during the normal season to ensure the water depth does not drop below 1.0 m, as shown in Table 5. During the normal season, selected water quality parameters, TSS and DO in this environmental flow study, showed good readings, not exceeding the tolerance limits needed for the growth of the three indicator fish species in the study (Ng et al., 2019; Razzaghi et al., 2025). To detect critical levels and ensure the acceptable discharge levels required by the river drainage system to prevent biological component failures, such as inadequate survival of fish, a low flow scenario was conducted (Kamarudin et al., 2023; Rohalin et al., 2025).

Table 5

Longitudinal characteristics for all nodes and links in the Terengganu River for the normal flow base scenario

Station	ST 1	ST 2	ST 3	ST 4
MSL (m)	151.26	141.26	135.56	135.00
Water Level (Normal) (m)	155.00	146.00	140.50	139.94
Maximum Velocity (m/s)	1.91	1.97		1.43
Maximum Discharge (m ³ /s)	184.1964	466.8354		505.7206
Maximum Depth (m)	3.74	4.74		4.94

Simulation of the Low Flow Additional Scenario for the Terengganu River

Simulation results during the dry season show that the maximum permissible depth at each station ranges from 3.64 m upstream, ST 1 to 3.94 m downstream, ST 3. ST 1 recorded the lowest discharge 14.26 m³/s and flow velocity 0.79 m/s refers to Figure 16. Flow velocity strongly influenced discharge, with midstream and downstream stations showing higher values due to dam releases. The dam maintained minimum depths above 1.0 m by releasing water through spillway banks at 0.54 m/s during dry conditions in Table 6. The downstream discharge peaked at 42.78 m³/s, supporting small to medium-sized fish species. During the normal season, lower discharges were recorded as 42.78 m³/s simulation and 8.52 m³/s fie. Fish caught included small to medium species such as *Kawan*, *Patung*,

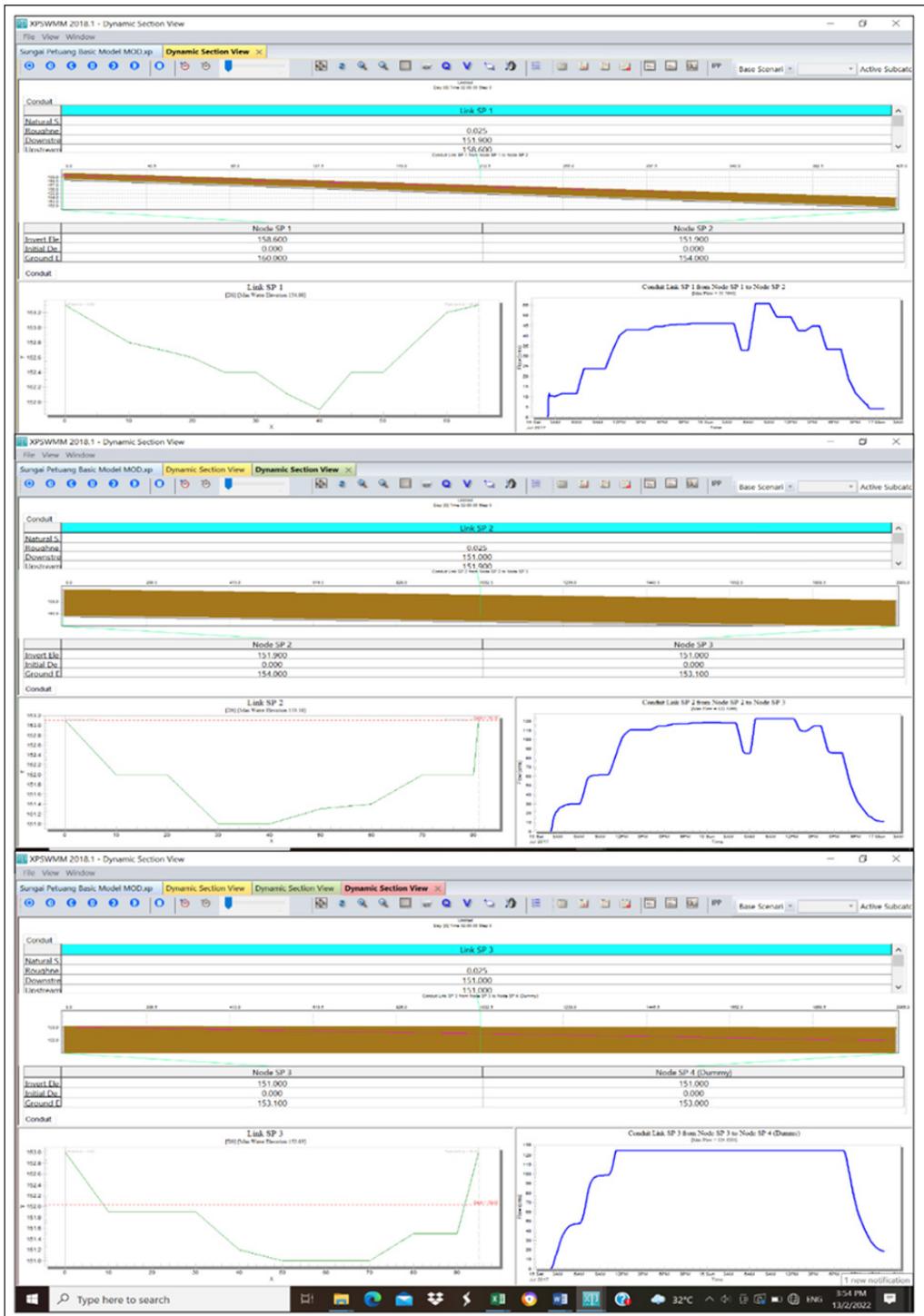


Figure 16. Dynamic simulation low flow additional scenario for the Terengganu River of Link ST1, ST2 and ST 3

Tengalan, Sebarau, and Belida, with a maximum weight of 92.5 g and length of 16.03 cm. However, these conditions were not suitable for sustaining the indicator species *Toman*. Low-flow simulations showed that while typical seasonal discharge levels can support key species, prolonged dry periods may threaten fish populations. Declines were observed in both rivers during the dry season, potentially affecting fish stocks, food security, and socio-economic activities in the Terengganu River Basin (Radzi et al., 2019; Shahimi et al., 2021; Toriman & Mohamad, 2004).

Table 6

Longitudinal characteristics for all nodes and links in the Terengganu River for the lowflow additional scenario

Station	ST 1	ST 2	ST 3	ST 4
MSL (m)	151.26	141.26	135.56	135.00
Water Level (Normal) (m)	154.90	145.50	139.50	138.94
Maximum Velocity (m/s)	0.79	0.80		0.54
Maximum Discharge (m ³ /s)	14.260	28.52		42.78
Maximum Depth (m)	3.64	4.24		3.94

Simulation Results using the Base Scenario: Normal Flow and Additional Scenario: Low Flow for Petuang River

Simulation of the Normal Flow Base Scenario for the Petuang River

Figure 17 illustrates the dynamic display for Link SP 1, Link SP 2, and Link SP 3. It was observed that the river flow velocity influences the discharge rate at each conduit link section, where the midstream and downstream stations SP 2 and SP 3 exhibit higher depths exceeding 0.5 m. However, the river discharge rates in these sections are directly proportional to the flow rate. The invert elevation of the riverbed at SP 2 and SP 3 is lower than that of SP 1, resulting in the downstream section receiving a greater quantity of water than the drainage capacity of the section allows. At the conclusion of the simulation, the maximum discharge magnitude at the downstream section of the river SP 4 was recorded at a rate of 0.91 m³/s, corresponding to a depth of approximately 0.9 m from the riverbed. Table 7 states that, albeit in modest numbers, a considerable number of medium and small

Table 7

Longitudinal characteristics for all nodes and links in the Petuang River for the normal flow base scenario

Station	SP 1	SP 2	SP 3	SP 4
MSL (m)	160.00	154.00	153.00	152.80
Water Level (Dry) m)	160.50	154.60	153.90	153.70
Maximum Velocity (m/s)	2.09	1.06		0.91
Maximum Discharge (m ³ /s)	55.7640	122.5366		124.623
Maximum Depth (m)	0.5	0.6		0.9

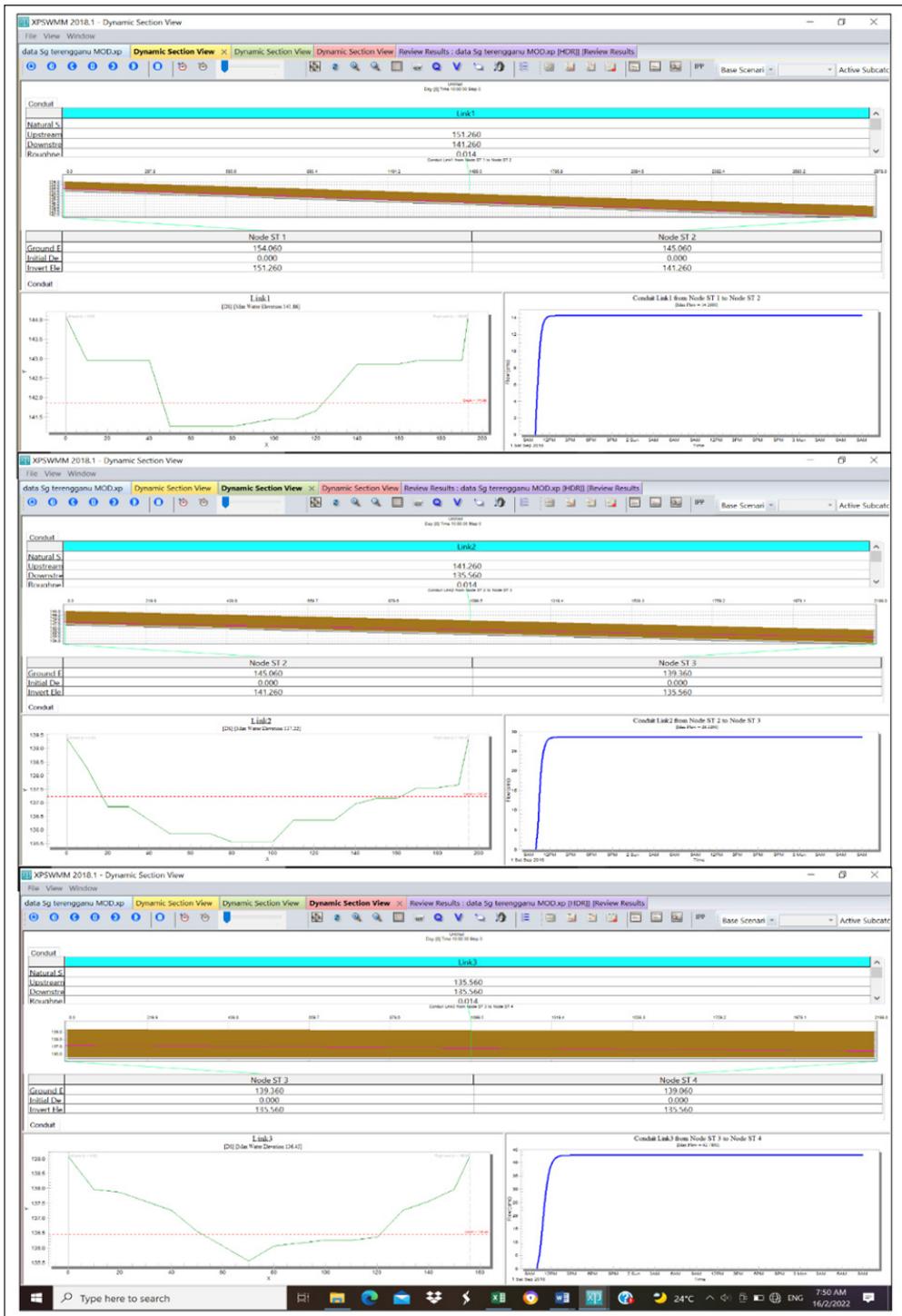


Figure 17. Dynamic simulation normal flow base scenario for the Petuang River of Link SP 1, SP 2, and SP 3

fish species can still live in this drainage ecosystem. Water leaving the lake basin's upstream drainage areas and flowing downstream towards the lake outlet, which is also close to the dam structure, is thought to be the cause of this phenomenon.

Simulation of the Low Flow Additional Scenario for the Petuang River

Link SP 1, Link SP 2, and Link SP 3 are shown dynamically in Figure 16 during the Petuang River's low flow scenario. The maximum depth that can be reached at each station during the dry season, according to the simulation results, is between 0.1 and 0.4 m. The upstream station SP 1 has the lowest depth, measuring 0.1 m, and the highest discharge value, 0.1063 m³/s, when compared to other stations. It also has the highest flow velocity, 0.56 m/s. At each conduit link section, the discharge rates were found to be influenced by the river flow velocity. Due to external environmental factors like human and climatic influences, the discharge rates in the midstream stations SP 2 and SP 3 are not directly proportional to the flow rate, especially downstream, despite their deeper depths. The highest flow velocity at the final station SP 4 is just 0.04 m/s, and it drastically drops as it approaches the downstream section. The water level at the river mouth does not surpass the spillway level of the dam structure, which results in extremely slow flow velocities. This suggests that the maximum recorded depth in the downstream section of the river offers a bigger wet perimeter region. This situation contradicts the original purpose of constructing such structures to prevent water levels from falling below a depth of 1.0 m. Table 8 illustrates the longitudinal profile for all nodes and links in the Petuang River during the low flow simulation, and Figure 18 shows the dynamic simulation of the low flow additional scenario for the Petuang River of Link SP 1, SP 2, and SP 3. In conclusion, at the end of the simulation, the maximum discharge magnitude recorded in the downstream section was at a rate of 0.886 m³/s with a maximum depth of 0.40 m. At this recorded depth, it was found that only small-sized fish individuals can be supported since most adult or larger species are unable to thrive in such an environment.

Table 8
Longitudinal characteristics for all nodes and links in the Petuang River for the low flow additional scenario

Station	SP 1	SP 2	SP 3	SP 4
MSL (m)	160.00	154.00	153.00	152.80
Water Level (Dry) (m)	160.10	154.20	153.40	153.20
Maximum Velocity (m/s)	0.56	0.13		0.04
Maximum Discharge (m ³ /s)	0.1063	0.1198		0.0886
Maximum Depth (m)	0.1	0.20		0.40

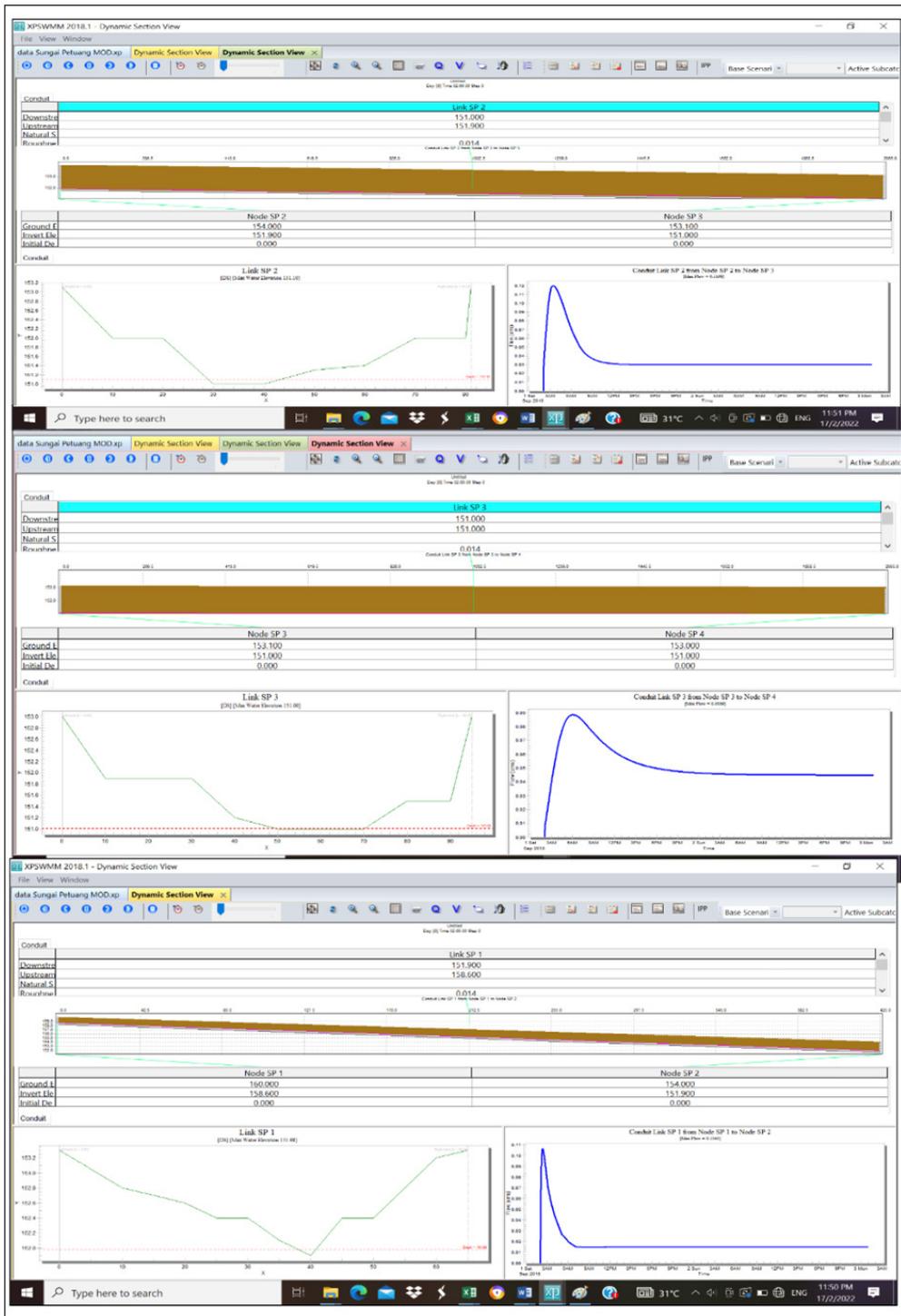


Figure 18. Dynamic simulation low flow additional scenario for the Petuang River of Link SP 1, SP 2 and SP 3

Overall, the river discharge constitutes a critical hydrological driver governing the structural and functional dynamics of riverine ecosystems. Variations in discharge regimes directly influence channel morphology, sediment transport processes, and habitat heterogeneity, which in turn determine the composition, diversity, and resilience of aquatic biota. Simulation outcomes further underscore the ecological risks associated with suboptimal flow regimes, wherein reduced discharge levels compromise habitat suitability, diminish fish stock productivity, and propagate cascading effects across trophic networks. Such hydrological alterations not only threaten biodiversity conservation but also pose significant implications for ecosystem services and the socio-economic security of dependent riparian communities (Sukereman et al., 2022; Van Tra et al., 2022). Accordingly, the maintenance of environmentally sustainable flow thresholds is imperative for safeguarding ecological integrity and ensuring adaptive capacity within river basin management frameworks. This has the potential to affect other components, such as food resources, and indirectly impact the socio-economic aspects of communities that depend on it (Radzi et al., 2019; Shahimi et al., 2019; Sukereman et al., 2022).

This demonstrates that preserving the equilibrium of a river ecosystem depends heavily on river discharge. This is because river discharge, whether it be high, low, or normal, contributes to the establishment of the appropriate river channel for the biotic components of the river system to remain in balance. River discharge influences a river's physiographic features, including depth, width, current velocity, sediment thickness, and substrate type. Fish and microbenthos are examples of aquatic fauna whose development is significantly impacted by river discharge, which also affects the species' abundance or diversity within the river habitat. As a predictor of the survival of other native fish species, the ability of critical species like Toman to survive in this study is crucial for demonstrating the degree of sensitivity of fish to any changes in discharge (Rahman et al., 2021). This is because a dam, which serves as a structure that releases water occasionally throughout the dry season, causes the flow to become slower as it approaches the downstream section as opposed to the upstream section. This is because the discharge level during the regular season is adequate to guarantee the three indicator fish species under study's survival all season long. The imbalance of environmental flow can be identified through the execution of the low-flow scenario model. Based on the catches in both rivers during the season, the yield was lower compared to the normal season. If the tolerant flow level fails to be maintained for the optimal development of the three species, it is expected that other fish species will also be threatened during the dry season.

Environmental Flow Requirements for Ecological Innovator in Kenyir Lake Basin

The health assessment of three indicator fish species revealed that optimal fish development in the Terengganu River occurs at a depth of 4.94 ± 3.74 m, velocity of 1.91 ± 1.43 m/s, and

discharge of $505.72 \pm 184.20 \text{ m}^3/\text{s}$ during normal seasons. In contrast, the Petuang River with a shallower depth $0.9 \pm 0.5 \text{ m}$, similar velocity $2.09 \pm 0.91 \text{ m/s}$, and lower discharge $124.62 \pm 55.76 \text{ m}^3/\text{s}$ supports only smaller species like *Sebarau* and *Belida*. During the dry season, both rivers show a significant drop in discharge, especially in Petuang $0.12 \pm 0.09 \text{ m}^3/\text{s}$, resulting in reduced fish abundance and size. The largest fish recorded during this time were 92.5 g and 16.03 cm in Terengganu, and 55.37 g and 14.83 cm in Petuang. These results highlight that dry season flows are insufficient to sustain most native fish, particularly larger species like *Toman*. The study recommends a minimum discharge of $505.72 \text{ m}^3/\text{s}$, a velocity of at least 1.43 m/s, and depths between 3.74 to 4.94 m in the Terengganu River to maintain suitable habitats for all native fish, while the Petuang River remains more limited in supporting only small-sized fish, especially in its downstream section Node SP 1.

Proposed Method for Controlling Environmental Flow Levels (Proposal for the Construction of a Water Retention Pond in the Downstream Section of the Petuang River)

A water retention pond based on the Monkey Cheek concept is proposed downstream of the Petuang River to support environmental flow E-Flow levels and aid in the development of a hydrodynamic hydrological model. This pond will store excess water during the wet season and release it during dry periods, maintaining stable river flow year-round.

Construction is scheduled before the wet season to minimise erosion and sedimentation. The plan includes an 800 m impounding structure at 17.5–20 m elevation, flooding approximately 1.5 km² of swampy land without affecting large dipterocarp trees. Over time, water will replace the existing grass and vegetation. A rip-rap structure is recommended to reduce erosion (Abidin et al., 2017).

While the structure may hinder fish movement if levels fall below the spillway, its main goal is to equalise lake and river levels to support fish migration. Small-scale floods could help retain 1.5–2.0 m of water at the base. The location is shown in Figure 19. According to Annear et al. (2002), controlled flows improve habitat quality, fish spawning, biodiversity, and sediment removal. Although concrete structures may reduce ecological friendliness and make the river semi-lotic, the system is expected to stabilise within 1–2 years, creating better conditions for native fish.

CONCLUSION

This study successfully determined the sustainable Environmental Flow (E-Flow) regime for the Kenyir Lake Basin using the XPSWMM hydrodynamic model, establishing an optimal flow of $505.72 \text{ m}^3/\text{s}$ with a critical minimum of $42.78 \text{ m}^3/\text{s}$ for the Terengganu River. This quantitative finding illustrates how river flow is essential to preserving the



Figure 19. Potential areas for the construction of water retention ponds in the Petuang River

equilibrium of riverine ecosystems, as normal, low, or high river flows create the required river channel conditions, including depth, width, flow velocity, and substrate composition, that are fundamental for the biotic components in the river system to be in equilibrium. The growth of aquatic fauna, including fish and microbenthos, is greatly impacted by this varied discharge, which in turn affects species richness and abundance. Since it acts as a standard for the sustainability of native species, the capacity of essential species like *Toman* to flourish in this study, validated by their good condition factor ($K > 1$) from the Length-Weight Relationship LWR analysis, is crucial for demonstrating fish sensitivity to any changes in discharge. Based on the physical appropriateness offered by all three indicator fish species, it is thought that both rivers sustain the sustainability of at least two native species under study throughout the year. While these results are robust, the model is subject to inherent data uncertainty stemming from reliance on input and historical gauging records, necessitating the acknowledgement of model limitations in data-sparse areas. To address the concerns raised, specific management recommendations are proposed, including the mandatory gazettement of the 505.72 m³/s optimal E-Flow for dam operation and the implementation of continuous ecological monitoring, especially in the Petuang River, where minimum flows pose a serious ecological threat. These suggestions, however, are based on this initial assessment, and each offered remedy needs to be thoroughly and in-depth researched before being put into practical implementation.

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REFERENCES

- Abdullah, S., & Ismail, M. (2019). The weather and climate of tropical Tasik Kenyir, Terengganu. In M. T. Abdullah et al. (Eds.), *Greater Kenyir landscapes* (pp. 3-8). Springer. https://doi.org/10.1007/978-3-319-92264-5_1
- Abidin, R. Z., Sulaiman, M. S., & Yusoff, N. (2017). Erosion risk assessment: A case study of the Langat River bank in Malaysia. *International Soil and Water Conservation Research*, 5(1), 26-35. <https://doi.org/10.1016/j.iswcr.2017.01.002>
- Anik, M. S. B. M., An, C., & Li, S. S. (2025). Evolution from physical process-based approaches to machine learning approaches for predicting urban floods: A literature review. *Environmental Systems Research*, 14(1), 1-17. <https://doi.org/10.1186/s40068-025-00409-3>
- Annear, T., Chisholm, I., Beecher, H., Locke, A., Aarrestad, P., Burkardt, N., & Wentworth, R. (2002). *Instream flows for riverine resource stewardship*. Instream Flow Council.
- Azmi, W. A., & Geok, H. A. (2016). Aquatic insect communities in relation to water quality of selected tributaries of Tasik Kenyir, Terengganu. *Journal of Sustainability Science and Management*, 11(2), 11-20.
- Baig, M. F., Mustafa, M. R. U., Baig, I., Takaijudin, H. B., & Zeshan, M. T. (2022). Assessment of land use and land cover changes and future predictions using CA-ANN simulation for Selangor, Malaysia. *Water*, 14(3), Article 402. <https://doi.org/10.3390/w14030402>
- Baruah, A., & Sarma, A. K. (2020). Ecological flow assessment using hydrological and hydrodynamic routing models in the Bhogdoi River, India. *Modelling Earth Systems and Environment*, 6(4), 1-10. <https://doi.org/10.1007/s40808-020-00982-9>
- Baumann, H., Ravn, N. H., & Schaum, A. (2022). Efficient hydrodynamic modelling of urban stormwater systems for real-time applications. *Modelling*, 3(4), 464-480. <https://doi.org/10.3390/modelling3040030>
- Cheah, R., Billa, L., Chan, A., Teo, F. Y., Pradhan, B., & Alamri, A. M. (2019). Geospatial modelling of watershed peak flood discharge in Selangor, Malaysia. *Water*, 11(12), Article 2490. <https://doi.org/10.3390/w11122490>
- Department of Environment (DOE). (2007). *Malaysia environmental quality report 2006* (Chap. 3, River water quality). Sasyaz Holdings Sdn Bhd.
- Ebrahimian, M., Nuruddin, A. A., Soom, M. A. M., Sood, A. M., Neng, L. J., & Galavi, H. (2018). Trend analysis of major hydroclimatic variables in the Langat River Basin, Malaysia. *Singapore Journal of Tropical Geography*, 39(2), 192-214. <https://doi.org/10.1111/sjtg.12234>

- Elfithri, R., Mokhtar, M. B., & Zakaria, S. (2019). The need for awareness raising, advocacy, and capacity building in integrated water resources management towards sustainable development: A case study in Malaysia. *World Water Policy*, 5(1), 43-54. <https://doi.org/10.1002/wwp2.12002>
- Gebreegziabher, G. A., Degefa, S., Furi, W., & Legesse, G. (2023). Evolution and concept of environmental flows (e-flows): A meta-analysis. *Water Supply*, 23(6), 2466-2490. <https://doi.org/10.2166/ws.2023.120>
- Ghurah, M. A., Kamarudin, M. K. A., Wahab, N. A., Umar, R., Wan, N. N., Juahir, H., & Hidayat, Y. (2018). Temporal change detection of land use/land cover using GIS and remote sensing techniques in South Ghor regions, Al-Karak, Jordan. *Journal of Fundamental and Applied Sciences*, 10(1S), 95-111.
- Gidado, K. A., Kamarudin, M. K. A., Firdaus, N. A., Nalado, A. M., Saudi, A. S. M., Saad, M. H. M., & Ibrahim, S. (2018). Analysis of spatiotemporal land use and land cover changes using remote sensing and GIS: A review. *International Journal of Engineering and Technology*, 7(3.14), 56-60. <https://doi.org/10.14419/ijet.v7i4.34.23850>
- Gori, A., Blessing, R., Juan, A., Brody, S., & Bedient, P. (2019). Characterizing urbanisation impacts on floodplains through integrated land use, hydrologic, and hydraulic modelling. *Journal of Hydrology*, 568, 82-95. <https://doi.org/10.1016/j.jhydrol.2018.10.053>
- Hairan, M. H., Jamil, N. R., Azmai, M. N. A., Looi, L. J., & Camara, M. (2021). Environmental flow assessment of a tropical river system using hydrological index methods. *Water*, 13(18), Article 2477. <https://doi.org/10.3390/w13182477>
- Hashim, Z., Setyowati, D. L., Ramli, E. Z., & Nayan, N. (2020). Land use impact on the water quality of the Liwagu River, Sabah. *Journal of Tourism, Hospitality and Environment Management*, 5(19), 118-133. <https://doi.org/10.35631/JTHEM.519009>
- Herison, A., Romdania, Y., Kusumastuti, D. I., & Adama, R. A. (2025). Experimental investigation on hydraulic jump characteristics at the downstream of a dam with varying stilling basins. *Jurnal Teknologi (Sciences & Engineering)*, 87(4), 819-826. <https://doi.org/10.11113/jurnalteknologi.v87.23127>
- Hossen, M. A., Rafiq, F., Kabir, M. A., & Morshed, M. G. (2019). Assessment of water quality scenario of the Karnaphuli River in terms of water quality index, south-eastern Bangladesh. *American Journal of Water Resources*, 7(3), 106-110.
- Hua, A. K. (2016). Malacca River as a new Malacca tourist attraction: A critical review. *Geografica*, 12(1), 108-117.
- Jain, S. K. (2025). Environmental flows: Concept, methods, case studies, and implementation challenges in India. *Ecohydrology*, 18(7), Article e70114. <https://doi.org/10.1002/eco.70114>
- Jamil, N. R., Toriman, M. E., Idris, M., & How, N. L. (2012). Analysis of streamflow characteristics in normal, wet, and post-flood periods of Sungai Chini and Sungai Paya Merapuh, Tasik Chini, Pahang. *e-Bangi*, 9(1), 1-16.
- Javidi Sabbaghian, R., Fereshtehpour, M., & Goli Hosseinabad, M. R. (2025). Integrated hydrologic-economic modelling for urban flood risk mitigation using SWMM, HEC-RAS, and HAZUS: A case study of the Bronx River watershed, NYC. *Sustainable Water Resources Management*, 11(5), Article 97. <https://doi.org/10.1007/s40899-025-01263-y>

- Jha, M. K., & Afreen, S. (2020). Flooding urban landscapes: Analysis using combined hydrodynamic and hydrologic modelling approaches. *Water*, *12*(7), Article 1986. <https://doi.org/10.3390/w12071986>
- Kamarudin, M. K. A., Toriman, M. E., Abd Wahab, N., Samah, M. A. A., Maulud, K. N. A., Hamzah, F. M., ... Sunardi, S. (2023). Hydrological and climate impacts on river characteristics of the Pahang River Basin, Malaysia. *Heliyon*, *9*(11), Article e21573. <https://doi.org/10.1016/j.heliyon.2023.e21573>
- Kamarudin, M. K. A., Toriman, M. E., Idris, M., Juahir, H., Azid, A., Gasim, M. B., ... Rwoo, M. A. (2016). Environmental management of a natural lake using sediment and hydrology hydraulic models. *Malaysian Journal of Applied Sciences*, *1*(2), 9-26.
- Kerr, J. R., Manes, C., & Kemp, P. S. (2016). Assessing hydrodynamic space use of brown trout (*Salmo trutta*) in a complex flow environment: A return to first principles. *Journal of Experimental Biology*, *219*(21), 3480-3491. <https://doi.org/10.1242/jeb.134775>
- Khan, I., Zakwan, M., Pulikkal, A. K., & Lalthazula, R. (2024). Environmental flow assessment for the Musi River, India. *Environment, Development and Sustainability*, *26*, 1-15. <https://doi.org/10.1007/s10668-024-04927-5>
- Khan, K., Zeb, M., Younas, M., Sharif, H. M. A., Yaseen, M., Al-Sehemi, A. G., ... Qasim, M. (2023). Heavy metals in five commonly consumed fish species from the River Swat, Pakistan, and their implications for human health using multiple risk assessment approaches. *Marine Pollution Bulletin*, *195*, Article 115460. <https://doi.org/10.1016/j.marpolbul.2023.115460>
- Kim, S. K., & Choi, S. U. (2019). Comparison of environmental flows from a habitat suitability perspective: A case study of the Naeseong-cheon Stream in Korea. *Ecohydrology*, *12*(6), Article e2119. <https://doi.org/10.1002/eco.2119>
- Kimambo, O. N., Mbungu, W., Massawe, G. D., Hamad, A. A., & Ligate, E. J. (2023). Rapid environmental flow assessment for sustainable water resource management in Tanzania's Lower Rufiji River Basin: A scoping review. *Heliyon*, *9*(11), Article e22509. <https://doi.org/10.1016/j.heliyon.2023.e22509>
- Mengistu, S. B., Palstra, A. P., Mulder, H. A., Benzie, J. A., Trinh, T. Q., Roozeboom, C., & Komen, H. (2021). Heritable variation in swimming performance in Nile tilapia (*Oreochromis niloticus*) and negative genetic correlations with growth and harvest weight. *Scientific Reports*, *11*(1), Article 90418. <https://doi.org/10.1038/s41598-021-90418-w>
- Mobadersani, A., Hosseinzadeh Dalir, A., Yasi, M., Arvanaghi, H., & Kennard, M. J. (2022). New integrated hydrologic approach for the assessment of river environmental flows into Lake Urmia. *Scientific Reports*, *12*(1), Article 8110. <https://doi.org/10.1038/s41598-022-10262-4>
- Ng, C. K. C., Ooi, P. A. C., Wong, W. L., & Khoo, G. (2019). Adaptation of an assessment system for establishing a river physical quality index and testing its effectiveness with fish-based metrics in Malaysia. *River Research and Applications*, *35*(9), 1540-1553. <https://doi.org/10.1002/rra.3528>
- Ni, L. W., & Khin, M. W. (2014). Low flow frequency analysis on selected rivers in Malaysia. *International Journal of Earth Sciences and Engineering*, *7*(4), 1316-1322.
- Radzi, M. R. M., Nashrudin, M. N., Zawawi, M. H., Abas, A., Azman, A., & Hassani, A. (2019). Effect of free surface water level of Kenyir Dam on spillway structure using fluid-structure interaction (FSI) analysis. In *AIP Conference Proceedings*. AIP Publishing. <https://doi.org/10.1063/1.5118051>

- Rahman, M. N. E. A., Lola, M. S., Ramlee, M. N. A., Abdullah, M. T., & Ariffin, M. S. A. (2021). Ecological balance towards a sustainable index of Tasik Kenyir. In M. T. Abdullah, C. V. Bartholomew, & A. Mohammad (Eds.), *Resource use and sustainability of Orang Asli: Indigenous communities in Peninsular Malaysia* (pp. 215-224). Springer Nature. https://doi.org/10.1007/978-3-030-64961-6_14
- Ramdas, M., & Mohamed, B. (2017). Perceptions of visitors and residents on the impact of tourism activities on water quality in Redang and Perhentian Islands, Malaysia. *Asian Journal of Technical Vocational Education and Training*, 2(1), 1-7.
- Razali, A., Ismail, S. N. S., Awang, S., Praveena, S. M., & Abidin, E. Z. (2018). Land use change in highland areas and its impact on river water quality: A review of case studies in Malaysia. *Ecological Processes*, 7(1), Article 12. <https://doi.org/10.1186/s13717-018-0126-8>
- Razzaghi, A. R., Ahmadi, H., Hessari, B., & Haghdoost, N. A. (2025). Environmental flow assessment of rivers using ecohydrology methods: A case study of Mahabad Chay, Lake Urmia Basin. *Water and Environmental Challenges*, 1(1), 12-19.
- Rohalin, W. M., Abd Wahab, N., Yaakub, N., & Fatah, F. A. (2025). Application of chemometric analysis for water quality assessment in Bukit Goh, Kuantan. *Malaysian Journal of Fundamental and Applied Sciences*, 21(4), 2479-2491. <https://doi.org/10.11113/mjfas.v21n4.4311>
- Rosle, S., Ibrahim, S., & Yusof, M. N. (2018). Relationship between water quality parameters, depth, and fish density in Kenyir Lake, Malaysia. *International Journal of Advanced Science and Research*, 3(4), 22-25.
- Rottler, E., Francke, T., Bürger, G., & Bronstert, A. (2020). Long-term changes in Central European river discharge for 1869–2016: Impact of changing snow cover, reservoir construction, and an intensified hydrological cycle. *Hydrology and Earth System Sciences*, 24(4), 1721-1740. <https://doi.org/10.5194/hess-24-1721-2020>
- Saputra, M. H., & Lee, H. S. (2019). Prediction of land use and land cover changes for North Sumatra, Indonesia, using an artificial neural network-based cellular automaton. *Sustainability*, 11(11), Article 3024. <https://doi.org/10.3390/su11113024>
- Schillinger, M., Weigt, H., & Hirsch, P. E. (2020). Environmental flows or economic woes—Hydropower under global energy market changes. *PLOS ONE*, 15(8), Article e0236730. <https://doi.org/10.1371/journal.pone.0236730>
- Shahimi, S., Salam, R., Salim, J. M., & Ahmad, A. (2019). Species richness of riparian vegetation after three decades of Kenyir Dam establishment. *Data in Brief*, 25, Article 104045. <https://doi.org/10.1016/j.dib.2019.104045>
- Shao, Q., Cao, W., Fan, J., Huang, L., & Xu, X. (2017). Effects of an ecological conservation and restoration project in the Three-River Source Region, China. *Journal of Geographical Sciences*, 27(2), 183-204. <https://doi.org/10.1007/s11442-017-1371-y>
- Shinozaki, Y., & Shirakawa, N. (2021). A comparative study of 100 major Japanese rivers: Multi-objective evaluations and environmental flow practices. *River Research and Applications*, 37(7), 979-987. <https://doi.org/10.1002/rra.3830>
- Sinar Harian. (2019, December 9). *Empangan Kenyir: Ini fakta menarik anda perlu tahu!*

- Stewart, J. P. (2024). Potential storage augmentation impacts on hydropower production, irrigation water supply, and environmental flows in the Indus Basin in Pakistan. *Journal of Hydrology: Regional Studies*, 51, Article 101618. <https://doi.org/10.1016/j.ejrh.2023.101618>
- Sufiyani, I., & Zakariya, R. B. (2018). Impacts of flood simulation in 3D and SWAT environments of the Terengganu River catchment. *Advances in Research*, 13(1), 1-14. <https://doi.org/10.9734/AIR/2018/38886>
- Sukereman, A. S., Suratman, R., & Ab Rahim, N. O. R. B. A. Y. A. (2022). Applying good governance practices in the implementation of integrated water resource management: Analysing the relationship. *Journal of Sustainability Science and Management*, 17(3), 243-265. <https://doi.org/10.46754/jssm.2022.03.019>
- Sulaiman, F. R., Azhar, N. A., & Sulaiman, N. (2025). Pollution level and assessment of a tropical river in Pahang, Malaysia. *Environmental Forensics*, 26(3), 425-434. <https://doi.org/10.1080/15275922.2024.2431320>
- Toriman, M. E., & Mohamad, S. (2004). Effects of the Sungai Chini gateway on wetland hydrology and tourism activity in Tasik Chini, Pahang: A preliminary survey. In *Proceedings of the International Conference on Social Sciences and Humanities* (pp. 330-338). Penerbit FSSK.
- Tügel, F., Hassan, A., Hou, J., & Hinkelmann, R. (2022). Applicability of literature values for Green-Ampt parameters to account for infiltration in hydrodynamic rainfall-runoff simulations in ungauged basins. *Environmental Modelling & Assessment*, 27(2), 205-231. <https://doi.org/10.1007/s10666-021-09788-0>
- Van Tra, T., Nguyen, T. A., Linh, L. V., Bach, N. H., & Son, D. H. (2022). The degree of integrated water resources management implementation in the Mekong River Delta in Viet Nam. *World Water Policy*, 8(1), 51-64. <https://doi.org/10.1002/wwp2.12071>
- Wahab, N. A., Kamarudin, M. K. A., Al Qassem, A., Rahayu, M., & Mamat, A. F. (2023). Environmental flow assessment model for sustainability planning strategies in the Kenyir Lake Basin, Malaysia. *Planning Malaysia*, 21(6), 282-296. <https://doi.org/10.21837/pm.v21i30.1401>
- Wahab, N. A., Kamarudin, M. K. A., Ata, F. M., Ismail, I. N., & Sunardi, S. (2024). Integrated lake basin management (ILBM) of hydrological assessment characteristics in the Kenyir Lake Basin, Terengganu, Malaysia. *Planning Malaysia*, 22(6), 261-275. <https://doi.org/10.21837/pm.v22i34.1628>
- Wahab, N. A., Kamarudin, M. K. A., Gasim, M. B., Umar, R., Ata, F. M., & Sulaiman, N. H. (2016). Assessment of total suspended sediment and bed sediment grain size in upstream areas of Lata Berangan, Terengganu. *International Journal on Advanced Science, Engineering and Information Technology*, 6(5), 757-763. <https://doi.org/10.18517/ijaseit.6.5.994>
- Wahab, N. A., Kamarudin, M. K. A., Sukki, F. M., Ata, F. M., Breckwoldt, A., & Rohalin, W. M. (2025). Ecohydrological indicators and environmental flow assessment (EFA) in the inlet and outlet reaches of the Kenyir Lake Basin, Malaysia. *Malaysian Journal of Fundamental and Applied Sciences*, 21(4), 2492-2512. <https://doi.org/10.11113/mjfas.v21n4.4224>
- Wahab, N. A., Kamarudin, M. K. A., Toriman, M. E., Juahir, H., Gasim, M. B., Rizman, Z. I., & Damayanti, P. P. (2018). Climate change impacts on sedimentation rates in the Terengganu River, Terengganu, Malaysia. *Journal of Fundamental and Applied Sciences*, 10(1S), 33-51.

- Wahab, N. A., Kamarudin, M. K. A., Toriman, M. E., Juahir, H., Samah, M. A. A., Azinuddin, M., ... Sunardi, S. (2023). Assessment of sedimentation problems in the Kenyir Hydropower Reservoir, Malaysia. *Water*, *15*(13), Article 2375. <https://doi.org/10.3390/w15132375>
- Yao, Y., Zheng, C., Tian, Y., Li, X., & Liu, J. (2018). Eco-hydrological effects associated with environmental flow management: A case study from the arid desert region of China. *Ecohydrology*, *11*(1), Article e1914. <https://doi.org/10.1002/eco.1914>
- Zain, A. M., & Hamid, M. S. A. (2025). Assessing water quality in the Kelantan River Basin using WQI: Suspended solids and ecosystem health. *Journal of Science and Technology*, *17*(1), 23-32. <https://doi.org/10.30880/jst.2025.17.01.003>
- Zhang, Z., Zhang, K., Luo, Y., Hinkelmann, R., & Yang, X. (2025). A review on the coupled hydrological and hydrodynamic modelling for watershed floods. *Wiley Interdisciplinary Reviews: Water*, *12*(6), Article e70038. <https://doi.org/10.1002/wat2.70038>
- Zhao, C. S., Pan, X., Yang, S. T., Xiang, H., Zhao, J., Gan, X. J., ... Yang, Y. (2021). Standards for environmental flow verification. *Ecohydrology*, *14*(1), Article e2252. <https://doi.org/10.1002/eco.2252>
- Zin, M. S. M., Juahir, H., Toriman, M. E., Kamarudin, M. K. A., Wahab, N. A., & Azid, A. (2017). Assessment of water quality status using univariate analysis at the Klang and Juru Rivers, Malaysia. *Journal of Fundamental and Applied Sciences*, *9*(2S), 93-108. <https://doi.org/10.4314/jfas.v9i2s.7>