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RESEARCH ARTICLE

Ecohydrological Indicators and Environmental Flow Assessment (EFA) in the Inlet and Outlet Reaches of the Kenyir Lake Basin, Malaysia

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Abstract The balance of environmental flow in basin-maintained ecosystems is crucial for sustaining biodiversity and the environment. Maintaining optimal environmental flow in rivers ensures the sustainability of natural ecosystems. An Environmental Flow Assessment (EFA) was conducted in the Terengganu River (outlet) and Petuang River (inlet) to assess whether river flow is sufficient to support ecological and biodiversity needs. The study aimed to develop a hydrological-hydrodynamic model to determine Environmental Flow Values (E-Flow) and to use ecohydrological indicators for restoration and rehabilitation in the Kenyir Lake basin. Sampling was carried out during both the dry and normal seasons. Data were collected on hydrology (water level and river discharge), hydrodynamics (using XPSWMM software), and ecology (fish sampling and Length-Weight Relationship (LWR)). Three sampling stations were selected on each river, with the fish species Toman (*Channa micropeltes),* Sebarau (*Hampala macrolepidota*), and Belida (*Chitala lopis*) chosen as bioindicators. These species were selected based on their size (width, length, and weight), which indicates their tolerance to Environmental Flow Values. A 7Q20 low-flow analysis revealed that in the Terengganu River, the optimum discharge was 42.78 m^3/s, with a depth of 3.94 m and a water velocity of 0.54 m/s, supporting the needs of larger fish species. Meanwhile, the Petuang River's optimum discharge was 0.08 m^3/s, with a depth of 0.4 m and a water velocity of 0.04 m/s, which could only accommodate small fish species. These low-flow values, with an error margin of less than 20%, were used as inputs in the low-flow analysis. The study highlights the importance of E-Flow in maintaining river health. This holistic assessment, based on Integrated Water Resources Management (IWRM), supports sustainable ecosystem management using green physical structures to optimize environmental flow.

Keywords: Ecohydrological Indicators, Environmental Flow Assessment (EFA), *Channa micropeltes*, *Hampala macrolepidota*, *Chitala lopis*, Environmental Flow Values (*E-Flow*).

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Introduction

Water resources are a critical component in sustaining life on Earth and supporting regional development. Malaysia, endowed with abundantnatural water resources, experiences a tropical climate influenced by both the Southwest and Northeast monsoon throughout the year, resulting in an average annual rainfall exceeding 2500 mm. Based on its land area of approximately 330,000 km², Malaysia's total annual water resource is estimatedat around 990 billion m³. However, only 7% (approximatelt 64 billion m³) of this total contributes to groundwater, while 36% (around 360 billion m³) is lost to the atmosphere through evapotranspiration [1]. The effective management of river water resources requires a systematic management system to ensure a sustainable supply of balanced quality and quantity of water. Various plans regarding water resource management have been implemented to address the issues affecting natural ecosystems [2–3]. The concept of environmental flows has been specifically introduced to protect aquatic life, particularly in the downstream areas of rivers, from potential hazards. The construction of dams is one such structure aimed at managing freshwater supplies, contributing to socio-economic development, and generating electricity. However, negative impacts have been identified with the presence of dams, including changes in downstream water flow, degradation of water quality, sedimentation in lake basin areas, disruption of aquatic species migration, and loss of biodiversity [4]. Therefore, hydrological aspects are the most crucial factor in maintaining the stability of river and lake ecosystems [5–6]. The environmental flow regime refers to the flow rate or discharge of a river in cubic meters per second (m³/s). In open channel flow studies, determining the detailed cross-sectional profile of the channel and the water velocity in meters per second (m/s) are also considered important aspects. Variations in both velocity and time provide basic guidelines for classifying flow standards. Most quantitative analyses in hydrological research require basic information on the quantity of water flowing in rivers. Accurate discharge measurements are essential because the discharge-stage relationship forms the basis for managing irrigation systems. River flow data typically consists of recorded water levels and river discharge measurements over a specific period. Most rivers exhibit a unique relationship between water level and discharge at a given location, known as a discharge rating curve. There are three basic steps in obtaining river flow data: measuring water levels, calculating river discharge, and defining the relationship between water level and river discharge [7–8]. In many developed countries, such as Japan, Australia, and Europe [9–11], the environmental flow regime paradigm has gained widespread acceptance over the past decade, particularly in river research and management, as a necessary approach for achieving a balanced natural ecosystem. However, information on the diversity of environmental flow regimes and surface water resources remains limited among researchers, especially in developing countries, where awareness of the importance of maintaining optimal environmental flows is still lacking. Figure 1 illustrates the application of the environmental flow regime paradigm, along with other hydrological parameters, to maintain ecological balance within the field of ecohydrology. Additional criteria, such as river drainage geomorphology, water quality, and biological diversity, are also used to assess the environmental flow capacity and ecological characteristics of a river, reflecting the overall balance of its habitat and ecosystem. The concept of environmental flows remains relatively new in this field and requires complete and consistent hydrological records, along with the application of globally accepted analytical methods, to ensureaccurate interpretation of environmental data in the study area [11–14].

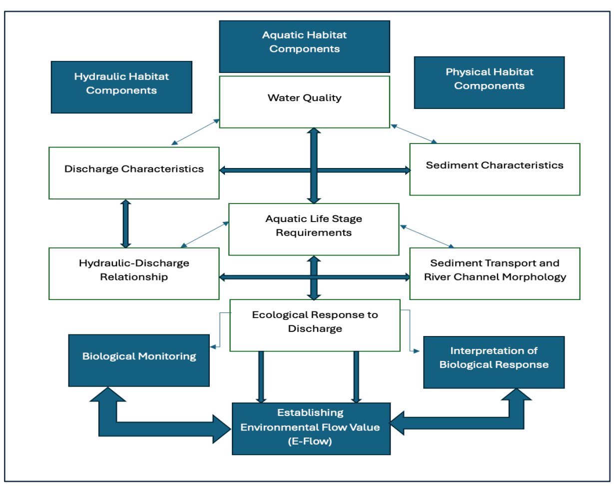


Figure 1. Application of the environmental flow regime paradigm for maintaining ecological balance [12, 13]

Based on research and the recommendations by the Ministry of Environment and Water (KASA) through the National Hydraulic Research Institute of Malaysia (NAHRIM), regarding the use of a minimum environmental/ecological flow rate (E-Flow) in river management in Malaysia, this can serve as a benchmark in this study [15]. The study on E-Flow by NAHRIM in 2018 found that existing river management practices can negatively impact ecosystem health due to insufficient river flow rates resulting from river water abstraction activities for domestic/industrial water supply, agricultural irrigation (paddy and non-paddy), and use in livestock and aquaculture. The determination of E-Flow aims to ensure that the river flow quantity is always sufficient for ecological and biodiversity needs, to increase the dilution factor of pollutant loads from domestic, industrial, and other wastewater discharges, to reduce saltwater intrusion caused by tidal phenomena, and to ensure that water transportation can continue functioning.

Based on results from eight river basins, namely the Muda River, Kelantan River, Pahang River, Johor River, Linggi River, Selangor River, Padas River, and Sadong River, it was found that three river basins have a high Water Exploitation Index (WEI), exceeding 40% of the average annual water availability in their basins. These rivers are the Muda River (75.3%), Selangor River (45.9%), and Johor River (41.4%). These three river basins are also classified as being in severe water stress conditions (scores exceeding 40%). The WEI analysis for the remaining five river basins shows that the Linggi River is in a low-stress condition (scores between 10% - 20%) with an index score of 18.4%, while the Kelantan River, Pahang River, Padas River, and Sadong River are in a non-stress condition (scores below 10%) with respective index scores of 8.6%, 4.7%, 3.3%, and 2.3%. This indicates that the water abstraction rate in these river basins remains low and controlled, and does not adversely affect the river ecosystem. Several methods for determining E-Flow are used worldwide. NAHRIM has determined the average minimum E-Flow rate based on five methods, such as the Class D Hydrological Method, 10% of the Average Annual Flow (AAF), 10% of the median river flow (Q50), 10% of the average annual water availability (AWA), and the base flow (Q95). The basic method used is the hydrological method adapted from the Montana/Tennant method [16–17]. Based on the above method analysis, the proposed minimum E-Flow rate at the release point is 0.4 m3/s for every 100 km2. In this case, the remaining river flow after permitted abstraction activities must be maintained at least at the same rate for the preservation of the ecosystem, biodiversity, navigation, and other related purposes (Refer to Table 1(a)). For example, the E-Flow requirement for the Selangor River at the Bestari Jaya barrage is 537 million liters per day (MLD) based on the minimum E-Flow rate proposed according to the catchment area at the location. Since there is a water abstraction requirement of 3,000 MLD for several water treatment plants (WTP) there, the state water management or dam operator needs to ensure that sufficient river flow is available at the WTP intake of 3,537 MLD to meet the water abstraction needs as well as the E-Flow requirement.

Table 1(a). Application of environmental flow regime paradigm for maintaining ecological balance

Basin	Dam	The catchment area of the dam	E-Flow Class D Hydrological Method	E-Flow 10% of the Average Annual Flow (AAF)	E-Flow 10% of the median river flow (Q50)	E-Flow 10% of the average annual water availability (AWA)	E-Flow base flow (Q95)	Average E-Flow based on all methods
Muda River	Muda	984	0.8	0.2	0.1	0.2	0.3	0.3
	Beris	116	0.8	0.2	0.1	0.2	0.3	0.3
Kelantan River	Pergau	224	1.5	0.4	0.2	0.4	0.9	0.7
Pahang River	Sultan Abu Bakar	183.4	0.9	0.2	0.1	0.2	0.5	0.4
	Susu (Ulu Jelai)	158	0.9	0.2	0.1	0.2	0.5	0.4
Johor River	Linggi	220	0.4	0.1	0.1	0.3	0.3	0.2
Selangor River	Selangor River	197	1.4	0.3	0.2	0.4	0.6	0.6
	Tinggi River	40	1.4	0.3	0.2	0.4	0.6	0.6

Table 1(b) and Table 1(c) show the results obtained for the 7-day minimum flow rates at different recurrence intervals for selected rivers (before and after dam construction). It can be observed that the 7-day minimum flow rate settings for the 2-year, 5-year, 10-year, 20-year, 25-year, 50-year, and 100-

year recurrence intervals are higher after dam construction at these locations (the Muda River, Johor River, and Selangor River). This demonstrates that the higher minimum flow rate setting is due to the impact of the dam structure, which controls river flow rates. Furthermore, the dam structure also acts as an indicator for regulating river flows not only during the flood season but also during the dry season. During the dry season, water is released from the dam to maintain river flow for the health of the ecosystem along the river basin. Without the formal enforcement of minimum flow rate settings, it is expected that the river ecosystem's health will be affected, including problems such as insufficient water quantity and the degradation of raw water quality [17–19]. This situation is expected to worsen in the future if extreme drought episodes occur and there is a reduction in the average annual rainfall due to climate change and the El-Nino phenomenon [20–21]. The proposed minimum E-Flow rates will help the government maintain the ecosystem and preserve biodiversity for environmental sustainability. However, it is a complex process aimed at preserving key characteristics of natural flow patterns. Therefore, it requires regular and systematic monitoring and strong collaboration among many stakeholders in forming the framework for E-Flow implementation in Malaysia.

Table 1(b). 7-day minimum flow rates at different recurrence intervals for selected study rivers (before and after dam construction)

T (year)	Johor River		Selangor River		Muda River	
	7-Day Rate Minimum Flow (before dam construction)	7-Day Rate Minimum Flow (after dam construction)	7-Day Rate Minimum Flow (before dam construction)	7-Day Rate Minimum Flow (after dam construction)	7-Day Rate Minimum Flow (before dam construction)	7-Day Rate Minimum Flow (after dam construction)
2	7.14	10.01	17.02	24.02	17.14	25.05
5	4.77	6.81	10.81	19.24	9.75	17.99
10	3.83	4.95	7.42	15.66	7.70	15.10
20	3.21	3.33	4.60	11.89	6.67	13.17
.25	3.06	2.86	3.79	10.62	6.46	12.69
50	2.70	1.47	1.51	6.46	6.03	11.52
100	2.45	0.23	0.45	1.94	5.80	10.69

Table 1(c). 7-day minimum flow rate at different recurrence intervals for selected study rivers

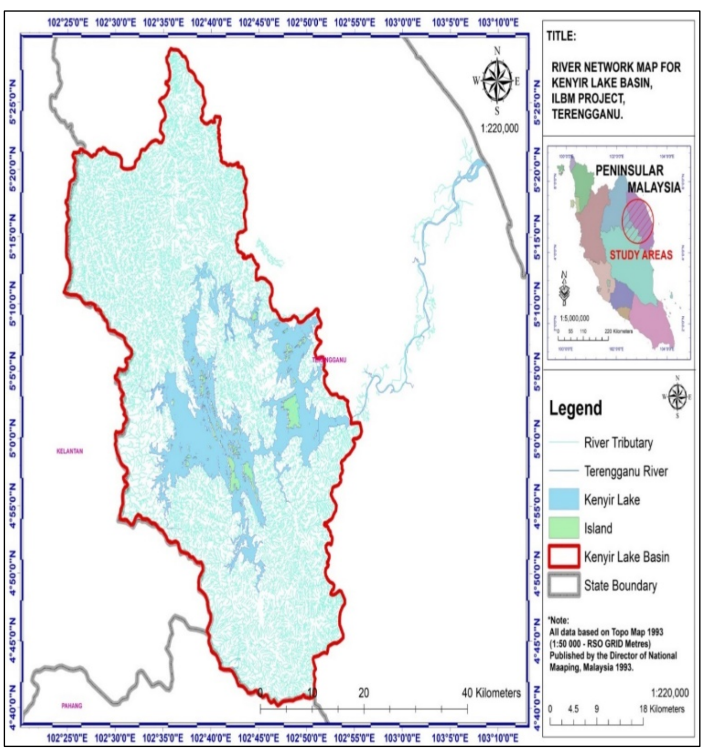
T(year)	Kelantan River (m^3/s)	Pahang River (m^3/s)	Linggi River (m^3/s)	Padas River (m^3/s)	Sadong River ($m^{3/}s$)
2	132.07	162.67	4.13	35.99	12.06
5	79.94	100.87	1.98	16.70	5.27
10	57.17	74.43	1.34	10.82	3.71
20	41.32	56.30	1.01	7.69	3.03
.25	37.25	51.69	0.94	7.03	2.90
50	26.97	40.16	0.79	5.59	2.66
100	19.46	31.85	0.70	4.78	2.55

Materials and Methods

Figure 2 shows the main river network and tributaries that flow into Kenyir Lake. This water is dammed by the Kenyir Hydropower Dam and is then channeled downstream into the Terengganu River in Kuala Terengganu, eventually flowing into the South China Sea. The main water sources contributing to Kenyir Lake consist of the main rivers in the Terengganu River basin and several rivers along the Kenyir Lake basin. Geomorphological and hydrological changes resulting from natural and anthropogenic factors occurring throughout the Kenyir Lake basin, in terms of land use and vegetation cover, explain the complex interactions that can be assessed in the basin. The construction of the Kenyir Dam was intended to control the large amount of water in the Terengganu River; the hydroelectric project in Kenyir Lake has involved a vast area, and its construction provides various benefits. Flood mitigation structures are part of disaster management initiatives, namely prevention, mitigation, and adaptation. Therefore, the primary function of flood mitigation is a mitigation measure that can prevent flooding in a particular location. These walls serve to prevent river surges from flooding areas at risk of flooding. This increases the river system's capacity and the river's ability to accommodate high rainfall intensity.

The hydroelectric project in Hulu Terengganu has created a three-stage lake system, namely the Tembat Dam (operational in March 2016), which is drained into the Puah Dam and then into the Kenyir Dam before flowing into the Terengganu River [22–23]. This lake functions as a natural sponge, slowing the flow of water that reaches the downstream part of the river before it is discharged into the sea. This naturally reduces the impact of floods on the human and biophysical environment in the downstream part of the river, especially in the districts of Kuala Terengganu and Kuala Nerus. The main direction of water flow is important to assess and determine the direction in which pollutants in the water will be channeled and moved. This is to determine the sampling locations for monitoring, management action plans, and mitigation planning to be carried out later. Figure 2 also shows the main direction of water flow in Kenyir Lake based on the lake elevation model that has been conducted. Water movement in Kenyir Lake flows in three main directions.

Firstly, water flows from the northwest to the southeast, originating from the Petuang River, Tembat River, and Terengganu Mati River, flowing through the development areas of Pengkalan Gawi and Pulau Poh and continuing to the southeast until the dam at *node 35*. Second, water flows from the west to the east, originating from the Ketiar River, Besar River, Lepar River, and Lawit River, flowing towards the east and converging with the flow from the south of the lake at *node 30*, and continuing towards the east until the dam area. Third, water flows from the south of the lake, originating from the Cenana River, Bewah River, Perepek River, Cicir River, Terenggan River, and Cacing River, flowing towards the north and converging with the flow from the west at *node 30*, and continuing towards the east until the dam area. There are also two main tributary sources in Kenyir Lake, namely the Petang River and Lasir River, which flow from the southeast, converging with the flow from the west at *node 34* and *node 25*, and continuing towards the east until the dam area at *node 35*



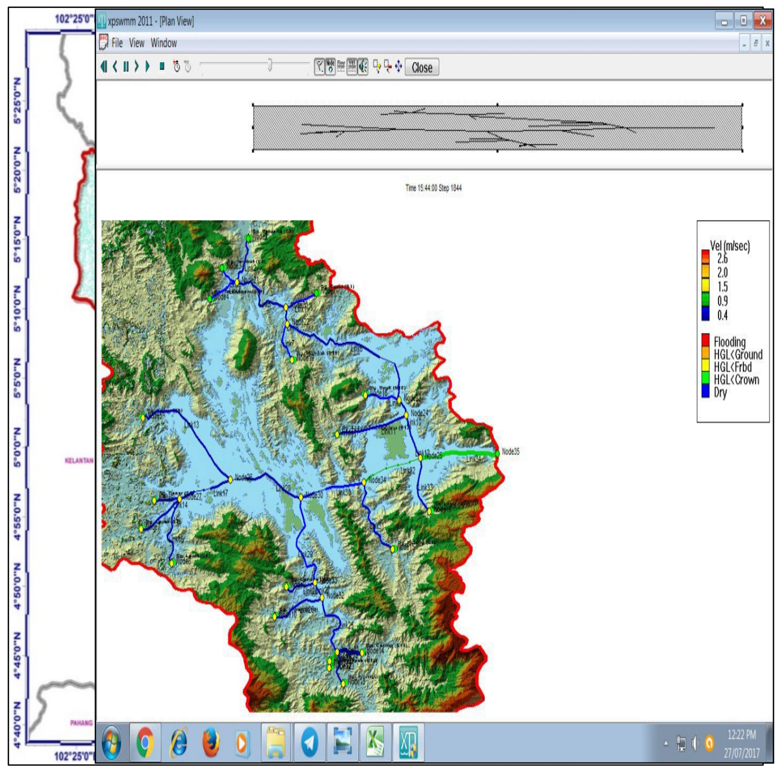


Figure 2. The map of the river network and water flow direction simulation in the Kenyir Lake basin is adapted from the Integrated Lake Basin Management (ILBM) Development Plan (2018) [24].

This study selected two rivers, namely the Terengganu River as the outlet river and the Petuang River as the inlet river to Kenyir Lake, located in the southeastern part of Terengganu within the latitude range (5°01'57.3"N to 5°14'14.9"N) and longitude range (102°55'37.6"E to 102°39'37.4"E), as sampling locations to identify the optimal environmental flow (refer to Table 2, Figure 3(a) and Figure 3(b)). To facilitate the analysis of the optimal environmental flow, these two study areas were divided into three sub-sampling stations: Terengganu River I, Terengganu River II, Terengganu River III, Petuang River I, Petuang River II, and Petuang River III. The diversity of data from the selection of these study locations is expected to yield more extensive and accurate research findings, representing the determination of optimal environmental flow values in Peninsular Malaysia. The sampling stations were selected based on high accuracy in Mean Sea Level (MSL) elevation data. A Differential Global Positioning System (DGPS) was used in this study, where the collected data were directly verified with the data system of the Department of Survey and Mapping Malaysia (JUPEM) for correction and data accuracy.

Table 2. Location of sampling stations in the inlet (Petuang River) and outlet (Terengganu River) reaches of the Kenyir Lake basin, Malaysia

Sampling Stations	River	Longitude	Latitude
Station 1	Terengganu River I	102°55'37.6" E	5° 01'57.3" N
Station 2	Terengganu River II	102°56'12.051" E	5° 03'04.559" N
Station 3	Terengganu River III	102°56'28.354" E	5° 04'00.363" N
Station 4	Petuang River I	102°39'36.0" E	5° 15'21.1" N
Station 5	Petuang River II	102°39'43.8" E	5° 15'11.7" N
Station 6	Petuang R III	102°39'37.4" E	5° 14'14.9" N

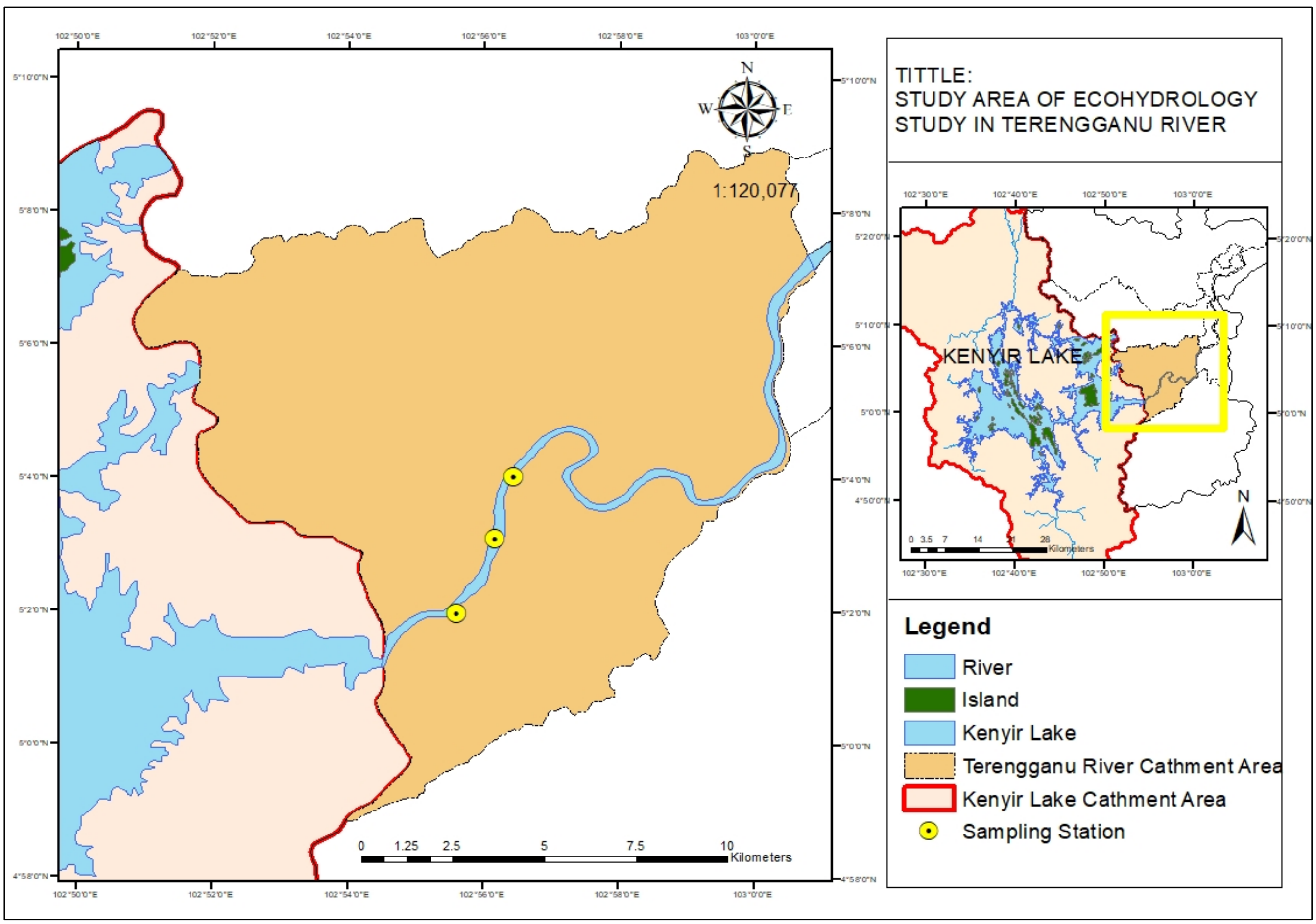


Figure 3(a). The map of the sampling stations in the oulet (Terengganu River) reach of the Kenyir Lake basin, Malaysia

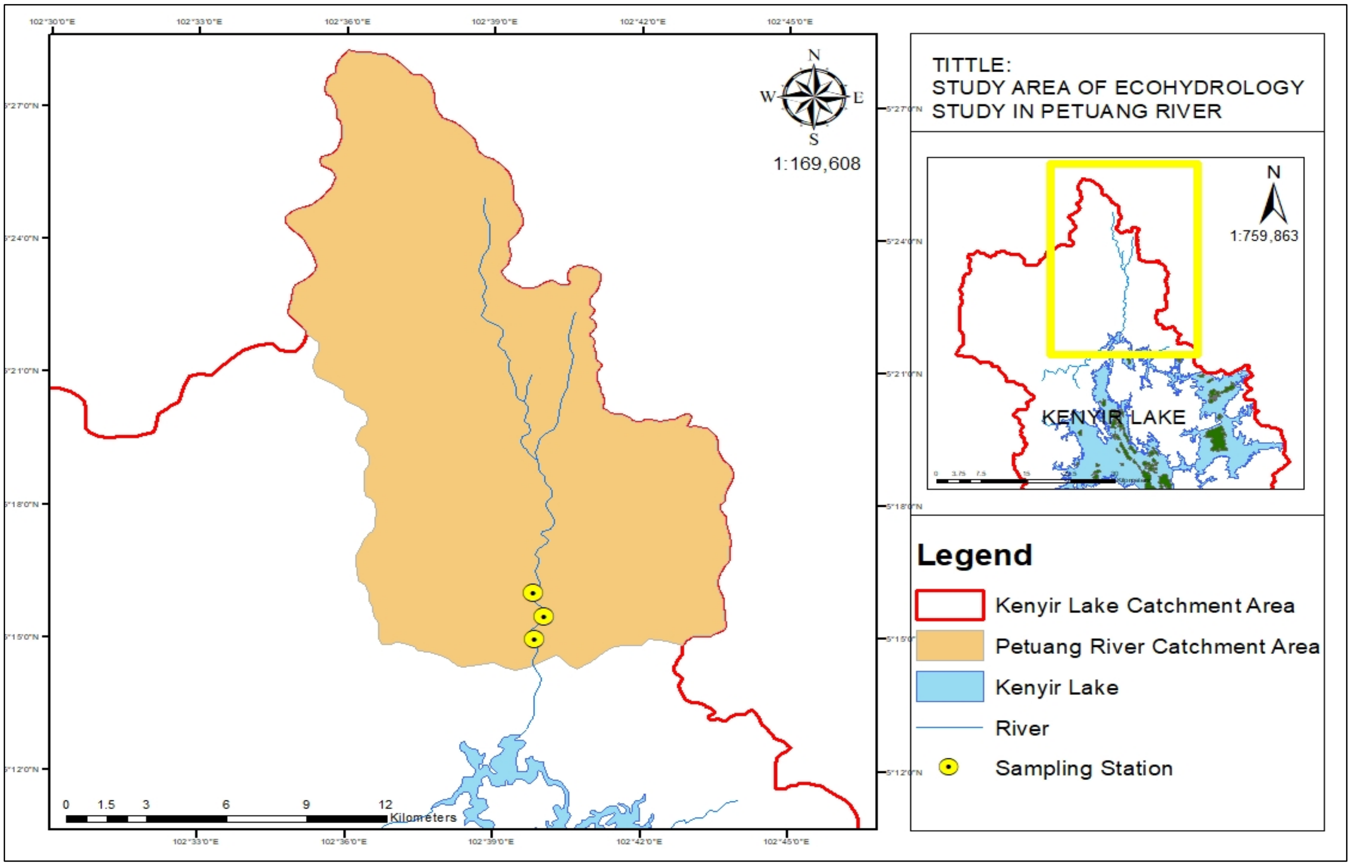


Figure 3(b). The map of the sub-sampling stations in the inulet (Petuang River) reach of the Kenyir Lake basin, Malaysia

Figure 4 illustrates the basic components of hydrological, hydrodynamic, and ecological characteristics identified by ecohydrological indicators and Environmental Flow Assessment (EFA) in the inlet and outlet reaches of the Kenyir Lake basin. A computer-based modelling analysis will integrate all these components to estimate environmental flow conditions within the study area. Hydrological data collection includes river flow measurements such as river width, water depth, and water velocity, along with secondary flow data spanning over 20 years obtained from two nearby observation stations, and 48-hour water level data. Cross-sectional measurements of the river channel were taken at three sub-sampling stations for each of the two study rivers. Water level observations during a 48-hour in the normal seasons were also collected from the Terengganu River and Petuang River. The selection of station locations was based on straight sections of the river with minimal obstructions, allowing for the collection of accurate and representative cross-sectional data [25–26]. The ecological component of this study uses fish as biological indicators, considering the minimum environmental flow requirements needed to ensure that these biotic components can thrive optimally. The limiting factor for the sustainability of fish species in the study area is based on the assumption that fish habitat preference is entirely dependent on the available habitat capacity, as determined by the flow regime of the study rivers [27–28]. The assumption is that the sustainability of indicator fish species in an environment suitable for their species serves as a threshold for assessing the sustainability of other fish species. A total of n = 150 fish were sampled across both seasons in the Terengganu and Petuang Rivers, with three replicates per sampling event and an associated error margin of ±5%, thereby ensuring methodological rigor and transparency in the data collection process. The choice of indicator fish species was based on selecting the largest fish species with the highest average standard weight and standard length, under the assumption that if this species can thrive in an optimal river flow regime, smaller fish species are more likely to thrive in the same habitat. Indicators used in the ecological component of this study include measurements of individual fish sample physiographic characteristics, Length-Weight Relationship (LWR) analysis, and analysis of selected water quality parameters. The ecological component is crucial for identifying the environmental flow values, which are essential for proposing an environmental flow index to promote the sustainability of indicator fish species and to support effective restoration and rehabilitation management in the Kenyir Lake basin.

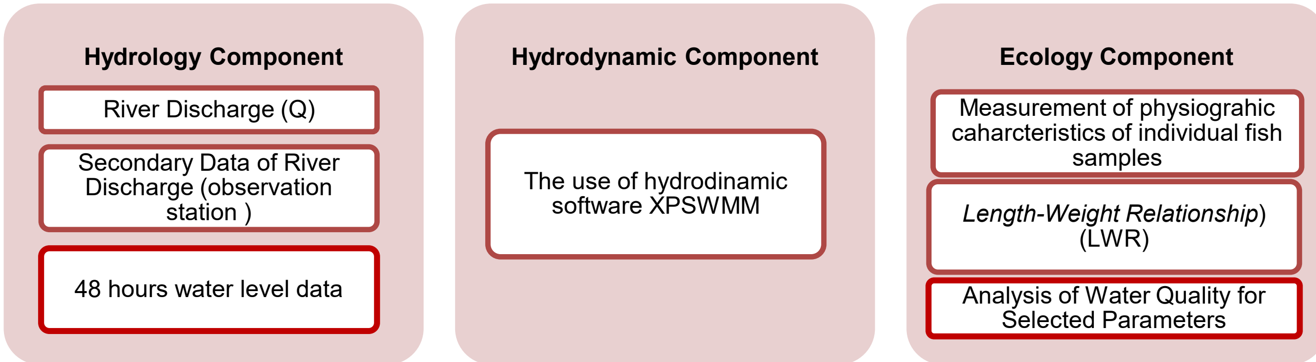


Figure 4. Basic components of hydrological, hydrodynamic, and ecological characteristics

Assessment of river environmental flow is divided into three main categories: analysis of flow regime records, the hydrological-hydrodynamic approach, and physical habitat analysis. Based on hydrological characteristics measured at each sampling station along the study rivers, hydrodynamic modeling using the XPSWMM model was configured to simulate hydrodynamic flow in the Kenyir Lake basin using both hydrologic (rainfall-runoff) and hydraulic (flow routing) modules. Input parameters included land use, rainfall, evaporation, and channel cross-sections. Model geometry was constructed using GIS-derived topography and bathymetry. The XPSWMM software was applied to predict suitable flow levels to provide the required habitat suitability for the identified indicator fish species [12, 29]. This study excludes other factors affecting the suitability of environmental flow levels for the sustainability of native indicator fish species. The study assumes that the presence of indicator fish species (representing the entire fish population in the study area) reflects both direct and indirect responses to environmental flow levels. Some basic principles for estimating environmental flow in this study, including environmental flow for both rivers, were collected and recorded in the field over two study seasons. Local information was used in the 7Q20 analysis for these rivers. Comparisons with river flows of equivalent basin size were conducted to reduce estimation errors. Second, the extent of use and selection of methods for estimating environmental flow depend on experience and expertise. In this study, a combination of hydrological index methods and modeling software enabled the estimation of ecological flow in the study area with an error of less than 20% compared to actual conditions. This error was mitigated through additional considerations, including expert opinions, field observations, and comparisons with other rivers. Based on the XPSWMM modeling, a sensitivity analysis was carried out by adjusting key hydraulic parameters, particularly Manning's roughness coefficient, within the range of 0.03 to 0.07. The analysis revealed that even slight variations in this parameter resulted in significant changes in simulated discharge outputs, highlighting the model's sensitivity and the critical importance of accurate calibration for reliable environmental flow assessment in Kenyir Lake basin. Third, the response of indicator fish species is based on the principle of habitat adaptation in river channels, assuming that flow factors at a given time (water depth, flow magnitude, and critical flow levels in certain seasons) are key determinants affecting the sustainability of indicator fish species in the study rivers. This includes the minimum fish movement requirements for feeding, migration, breeding, and protection within the proposed environmental flow levels [16, 27, 30].

Additionally, the growth response of indicator fish species is identified based on physiographic characteristics and significant relationships with natural factor parameters. Fourth, selected water quality parameters are also considered as contributing factors that may affect the sustainability of fish species, with the primary assumption being that the presence of these pollutants will influence the sustainability levels of fish species. The LWR analysis showed a strong positive correlation, indicating that the weight of the sampled fish increases proportionally with length. This suggests healthy growth conditions and can support ecosystem health assessments under varying environmental flow scenarios. The high coefficient of determination in the LWR reflects consistent growth patterns, indicating that the current flow regime supports stable aquatic habitat conditions in the Kenyir Lake ecosystem. The robust LWR correlation provides a reliable baseline for monitoring bio-indicators of environmental change and can serve as a useful metric in future ecological flow management strategies. This finding reinforces the ecological relevance of maintaining suitable environmental flow regimes for sustaining biodiversity in Kenyir Lake. Furthermore, the strong correlation observed in both the LWR and the validation of simulated discharge against observed data supports the reliability of the XPSWMM model for environmental flow assessment, while reinforcing the ecological importance of maintaining suitable flow regimes to sustain biodiversity in Kenyir Lake. The reported error margin (< 20%) specifically refers to simulated streamflow parameters (discharge) and is quantified using the Percent Bias (PBIAS) metric. Model fit was also evaluated using Nash–Sutcliffe Efficiency (NSE) and R^2, following established hydrological validation protocols. Under these guidelines, PBIAS ≤ ±25% and NSE ≥ 0.50 are considered satisfactory. Our model achieved PBIAS < 20% and NSE > 0.50, which places it squarely within accepted thresholds. Figure 5 illustrates the conceptual framework for modeling environmental flow values, which utilizes a combination of hydrological, hydrodynamic, and ecological modeling techniques to identify patterns of environmental flow.

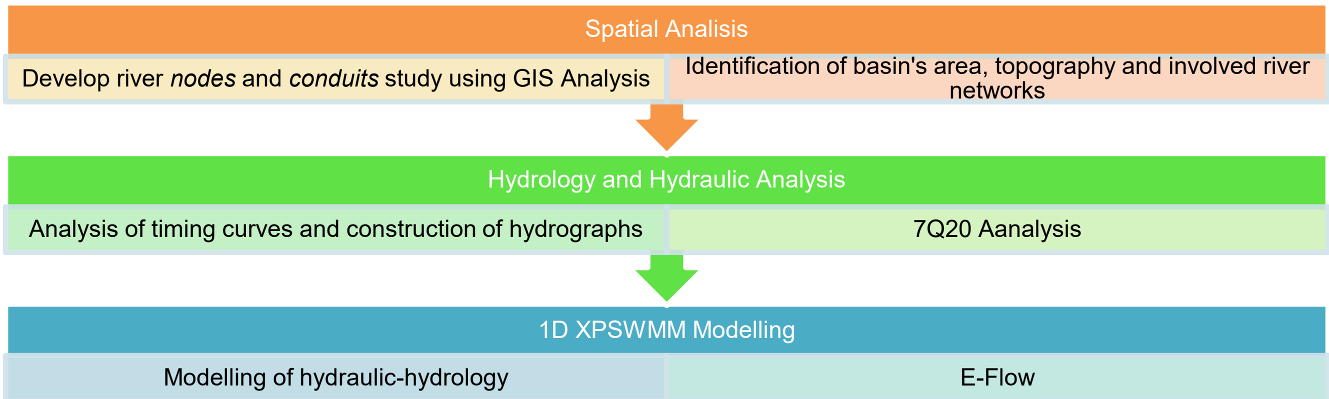


Figure 5. The framework of ecohydrological indicators and Environmental Flow Assessment (EFA) in the inlet and outlet reaches study of the Kenyir Lake basin, Malaysia

Results and Discussion

In addition, to identify the estimated distribution of discharge frequency data for the dry season as the main input for modeling the lowest discharge scenario, the 7Q20 analysis is used to propose an optimal environmental discharge index. Thus, the estimate for the frequency and magnitude of the lowest discharge in this study is based on the 7-day consecutive lowest discharge analysis based on available discharge data, which are from Kampung Tanggol Station (Station 5130432) representing the input for the Terengganu River, and Menerong Station (Station 4930401) representing the input for the Petuang River (refer Table 3). Table 4(a) and Table 4(b) show the 7Q20 analysis using secondary data collected over 20 years at Kampung Tanggol station. It was found that, on average, there is a probability of occurrence once in every 25 years, where the 7-day lowest discharge value (7Q) reaches 18.82 m³/s for the Terengganu River. Based on the average daily discharge pattern for the Terengganu River, this discharge level tends to occur around June each year. The average discharge values for each 7-day consecutive lowest event are arranged by level, as shown in Table 5(a) for data from the Petuang River. The recorded average value is -0.7999, and the standard deviation is 0.4378 for the Petuang River. On average, the probability of occurrence is once every 2.33 years, where the 7-day lowest discharge (7Q) will reach a value of 0.027 m³/s (refer to Table 5(b)). Failure of river drainage, particularly in the upstream basin, to maintain the optimal depth required for aquatic species' sustainability results in many of these species becoming invasive and affecting growth activities, especially during the dry season.

Table 3. The lowest 7-day consecutive values recorded over 20 years at Kampung Tanggol Station (Terengganu River) and Menerong Station (Petuang River)

Kampung Tanggol Station			Stesen Menerong Station		
Date/Time		Q (m^3/s)	Date/Time		Q (m^3/s)
21/6/2004 0:00	22/6/2004 0:00	67.5	8/8/2014 0:00	9/8/2014 0:00	0.098
22/6/2004 0:00	23/6/2004 0:00	45.7	9/8/2014 0:00	10/8/2014 0:00	0.104
23/6/2004 0:00	24/6/2004 0:00	42.8	10/8/2014 0:00	11/8/2014 0:00	0.077
24/6/2004 0:00	25/6/2004 0:00	31.1	11/8/2014 0:00	12/8/2014 0:00	0.072
25/6/2004 0:00	26/6/2004 0:00	28.3	12/8/2014 0:00	13/8/2014 0:00	0.095
26/6/2004 0:00	27/6/2004 0:00	26.9	13/8/2014 0:00	14/8/2014 0:00	0.661
27/6/2004 0:00	28/6/2004 0:00	98.7	14/8/2014 0:00	15/8/2014 0:00	0.709

Table 4(a). Seven-day lowest average discharge values over 20 years at Kampung Tanggol Station

Q (m^3/s)	Level	Probability Plot	log Q
67.5	1	0.13	1.8293
45.7	2	0.25	1.6599
42.8	3	0.38	1.6314
31.1	4	0.5	1.4928
28.3	5	0.63	1.4518
26.9	6	0.75	1.4298
98.7	7	0.88	1.9943
		Average, $\overline{Y}$	1.6413
		Standard deviation, S_y	0.2094

Table 4(b). Estimated 7-day lowest discharge values over 20 years at Kampung Tanggol Station

T (year)	z	Y	Q7 (m^3/s)
2	0	1.6413	43.78
2.33	-0.25	1.5883	38.75
5	-0.84	1.4650	29.17
10	-1.28	1.3729	23.6
25	-1.75	1.2746	18.82
50	-2.05	1.2112	16.26
100	-2.33	1.1541	14.26

Table 5(a). Seven-day lowest average discharge values over 20 years at Menerong Station

Q (m^3/s)	Tahap	Plot Kebarangkalian	log Q
0.098	1	0.13	-1.0088
0.104	2	0.25	-0.9829
0.077	3	0.38	-1.1135
0.072	4	0.5	-1.1427
0.095	5	0.63	-1.0223
0.661	6	0.75	-0.1798
0.709	7	0.88	-0.1494
		Purata, $\overline{Y}$	-0.7999
		sisihan piawai, S_y	0.4378

Table 5(b): Estimated 7-day lowest discharge values over 20 years at Menerong Station

T (year)	z	Y	Q7 (m^3/s)
2	0	-0.7999	0.159
2.33	-0.25	-0.9107	0.123
5	-0.84	-1.1684	0.068
10	-1.28	-1.3610	0.044
25	-1.75	-1.5665	0.027
50	-2.05	-1.6991	0.019
100	-2.33	-1.8185	0.015

Table 6(a), Table 6(b), Table 6(c), and Table 6(d) show the LWR analysis for the three fish species sampled during the dry season. Table 7(a), Table 7(b), Table 7(c), Table 7(d), and Table 7(e) present the LWR analysis for the same three fish species sampled during the normal season. Based on the LWR analysis for the three indicator species, it was found that two indicator fish species, the Toman (*Channa micropeltes*) and the Sebarau (*Hampala macrolepidota*), exhibit good isometric growth characteristics (recording ideal *b* values between 2.5 and 3.5) during the normal season in the Terengganu River, with *b* values of 2.943 (Toman) and 3.207 (Sebarau), respectively. In contrast, the Belida (*Chitala lopis*) species showed less ideal growth between length and weight parameters, with a *b* value of 2.371 (< 3). This is possibly due to slight environmental stress factors, such as physical conditions and predation, causing an imbalance in these parameters.

Additionally, the Sebarau and Belida species showed good isometric growth characteristics during the normal season in the Petuang River, with *b* values of 2.975 (Sebarau) and 3.098 (Belida), respectively. During the dry season, only two indicator fish species, Sebarau and Belida, were successfully sampled in both rivers. Analysis of these two indicator species showed good isometric growth characteristics with *b* values of 3.029 (Sebarau) and 2.965 (Belida) in the Terengganu River. In the Petuang River during the dry season, isometric values were less ideal between length and weight parameters (recording ideal *b* values below 2.5), with values of 2.201 (Sebarau) and 2.222 (Belida). Both indicator species in the Petuang River showed less balanced growth between length and weight parameters due to ecosystem disturbances caused by environmental stressors. The successful sampling in the Petuang River did not exceed 10 samples, because shallow water levels resulted in an inadequate wet perimeter area in the river's cross-section to provide a suitable habitat for the development of various fish species.

The wet perimeter is closely related to river discharge and allows for an estimate of the minimum environmental discharge necessary for the sustainability of biotic components. LWR analysis found that the Belida species can grow better during the dry season compared to the normal season, with a b value of 2.965 in the Terengganu River. This may be due to natural predation factors, where larger predator fish such as the Toman, during the normal season, exert physical pressure on the fish species, thereby naturally controlling their population. During the dry season, no Toman were successfully caught in either river, allowing the Belida species to grow better in both rivers, as this species tends to inhabit deeper river habitats, approximately 50 cm from the riverbed.

The length-weight regression results recorded R^2 coefficients of 0.881 ± 0.793 and 0.882 ± 0.621 for the Terengganu River during the dry and normal seasons, respectively, and 0.629 ± 0.577 and 0.882 ± 0.778 for the Petuang River during the dry and normal seasons, respectively. These recorded regression values generally show that weight increases around 62%–88% in the Terengganu River and 57%–88% in the Petuang River, based on length increases. The LWR obtained shows varied growth patterns, including isometric, positive allometric, and negative allometric growth, with the relationship classified as moderately strong, around 90% ± 50% [30-31]. This study also indicates that all three native fish species are in good condition, as the mean condition factor values are greater than 1 ($K > 1$). The average *K* values for the dry season in both study rivers were slightly lower compared to the normal season, indicating spawning and recovery conditions for the fish. The condition factor calculations in this study describe the general health of fish populations from specific habitats. These findings can be used to estimate the status of fishery resources by fish biologists and fishery resource managers in Malaysia [30–33].

Table 6(a). Length-weight relationship (LWR) of Sebarau (*Hampala macrolepidata*) in Terengganu River during the dry season

Model	Analysis of LWR of Sebarau (*Hampala macrolepidata*)
R^2	0.793
Coefficient a	1.764×10^{-5}
Coefficient b	3.029 (> 3)
Condition Factor (K)	2.056

Table 6(b). Length-weight relationship (LWR) of Belida (*Chitala lopis*) in the Terengganu River during the dry season

Model	Analysis of LWR of Belida (*Chitala lopis*)
R^2	0.881
Coefficient a	1.269 x 10-5
Coefficient b	2.965 (≈ 3)
Condition Factor (K)	1.095

Table 6(c). Length-weight relationship (LWR) of Sebarau (*Hampala macrolepidota*) in the Petuang River during the dry season.

Model	Analysis of LWR of Sebarau (*Hampala macrolepidata*)
R^2	0.629
Coefficient a	1.151 x 10-3
Coefficient b	2.200 (< 3)
Condition Factor (K)	2.301

Table 6(d). Length-Weight Relationship (LWR) of Belida (*Chitala lopis*) in the Petuang River during the dry season

Model	Analysis of Length-Weight REL Belida (*Chitala lopis*)
R^2	0.577
Coefficient a	4.689 x 10-^{4}
Coefficient b	2.222 (< 3)
Condition Factor (K)	0.965

Table 7(a). Length-Weight Relationship (LWR) of Toman (*Channa micropeltes*) in theTerengganu River during the normal season

Model	Analysis of Length-Weight REL Toman (*Channa macrophytes*)
R^2	0.899
Coefficient a	1.917 x 10-5
Coefficient b	2.943 (≈ 3)
Condition Factor (K)	1.409

Table 7(b). Length-Weight Relationship (LWR) of Sebarau (*Hampala macrolepidota*) in Terengganu River during the normal season

Model	Analysis of Length-Weight REL Sebarau (*Hampala macrolepidata*)
R^2	0.7646
Coefficient a	8.7177 x 10-6
Coefficient b	3.2067 (> 3)
Condition Factor (K)	2.509

Table 7(c). Length-Weight Relationship (LWR) of Belida (*Chitala lopis*) in Terengganu River during the normal season

Model	Analysis of Length-Weight REL Belida (*Chitala lopis*)
R^2	0.6217
Coefficient a	2.5811 x 10-54
Coefficient b	2.3713 (<3)
Condition Factor (K)	1.118

Table 7(d). Length-Weight Relationship (LWR) of Sebarau (*Hampala macrolepidota*) in Petuang River during the normal season

Model	Analysis of Length-Weight REL Sebarau (*Hampala macrolepidata*)
R^2	0.882
Coefficient a	2.566 x 10-5
Coefficient b	2.976 (≈ 3)
Condition Factor (K)	2.326

Table 7(e). Length-Weight Relationship (LWR) of Belida (*Chitala lopis*) in Petuang River during normal season

Model	Analysis of Length-Weight REL Belida (*Chitala lopis*)
R^2	0.778
Coefficient a	3.820 x 10-5
Coefficient b	3.098 (> 3)
Condition Factor (K)	6.253

Figure 6 shows a dynamic display illustration of Link ST1, Link ST2, and Link ST3. The maximum depth that each station can reach during the normal season ranges between 3.74 and 4.94 m, according to the Terengganu River's typical discharge simulation findings. The upstream station ST1 recorded the lowest depth (3.74 m) and the lowest discharge value (184.196 m^3/s), with a maximum flow velocity of about 1.91 m/s. In contrast to other stations, the midstream stations (ST2 and ST3) showed denser flow conditions than the upstream stations. It was observed that the river flow velocity increases the discharge rate at each link conduit segment. This indicates that the flow velocity is directly proportional to the river discharge rate in these sections. The river's discharge rate in particular areas is closely related to the flow velocity. This occured because the flow slowed down as it moved downstream before entering the

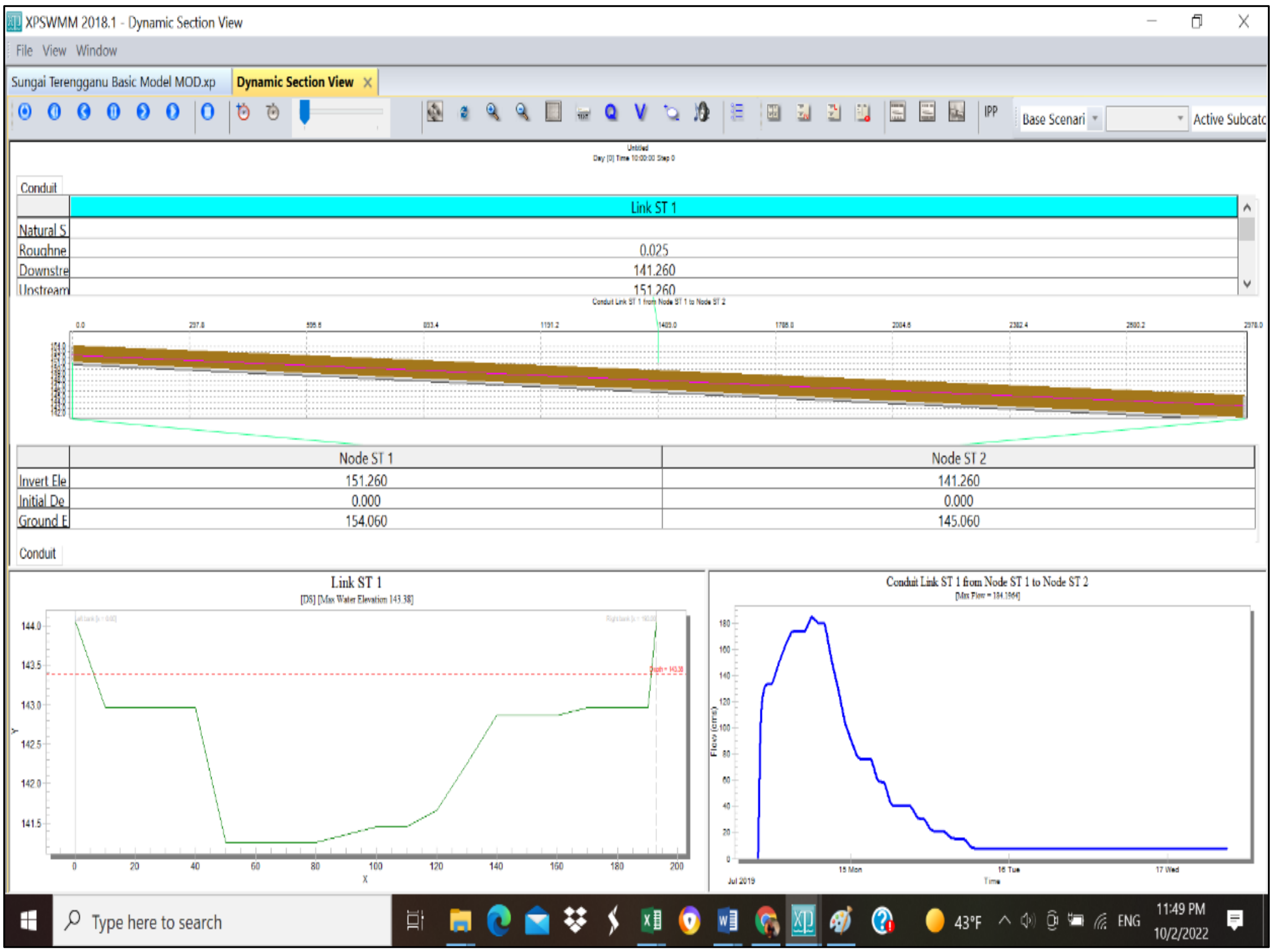
Terengganu River basin due to dam development in the area. These structures act as barriers to the water flow, which is regulated by the spillway at a rate of 1.43 m/s during the normal season to maintain a water depth of no less than 1.0 m. The results of the LWR analysis conducted for the three indicator fish species in this study showed healthy fish development in the physical river environment with an average depth of 2.8 ± 1.1 m, a current velocity of 0.060 ± 0.011 m/s, and a river discharge of 18.741 ± 12.588 m³/s during the normal season in the Terengganu River. A low discharge scenario was conducted to determine critical levels to ensure the minimum tolerable discharge level that the river drainage system must provide to avoid the failure of these species to thrive.

With a maximum flow velocity of 0.79 m/s, the upstream station ST1 recorded the lowest discharge value of 14.26 m³/s and the shallowest depth of 3.64 m compared to other stations. This simulation indicates that the maximum depth that each station can reach during the dry season ranges from 3.64 m to 3.94 m, suggesting that river flow velocity may be affected by the discharge rate in each conduit segment. Although the midstream and downstream stations (ST2 and ST3) have greater depths, the flow rate in these areas correlates strongly with the river discharge rate. This is due to the presence of a dam that periodically releases water during the dry season, causing the flow to slow as it approaches the downstream section relative to the upstream. The structure acts as a flow barrier, regulated by a spillway operating at a rate of 0.54 m/s during the dry season to maintain a minimum water depth at no less than 1.0 m (refer to Figure 7). It can be concluded that the maximum depth of 3.94 m with a discharge rate of 42.78 m³/s downstream can only support small to medium-sized fish species, unlikethe normal season. With a maximum discharge rate of 42.78 m³/s (simulation) and 8.52 m³/s (observation) during the dry season, the Terengganu River exhibited a lower flow rate than during the regular season. Based on the number and abundance of fish species successfully captured during this period, only small to medium-sized fish species (Kawan, Patung, Tengalan, Sebarau, and Belida) were recorded, with maximum weights and lengths of 92.5 g and 16.03 cm, respectively.This indicates that the discharge rate during the dry season is insufficient to support the survival of one of the study's key indicator species, the Toman. In this study, only the low-flow scenario was simulated for the Terengganu River, as the discharge during the normal season was already sufficient to support the survival and good condition of the three indicator fish specie. The imbalance in environmental discharge conditions observed in the low-flow simulation highlights potentialimpacts on the river ecosystem and could indirectly affect the socio-economy systems that depend on it [34–35].

Figure 8 shows a dynamic display illustration for Link SP1, Link SP2, and Link SP3. It was found that the rate of discharge in each conduit's connection section depends on the river flow velocity, with the upstream and downstream stations (SP2 and SP3) having greater depths (more than 0.5 m). However, in some cases, the river discharge rate is not always proportional to the flow rate. Since the riverbed elevation for SP2 and SP3 is lower compared to that of SP1, the lower sections of the river receive more water than the agricultural section can manage. At the end of the simulation, the downstream (SP4) station recorded a maximum discharge rate of 0.91 m³/s, with a depth of about 0.9 m from the riverbed. At this depth, small and medium-sized fish species can survive in the drainage environment, but in reduced numbers. This is because the outflow from the upstream drainage in the lake basin area, which proceeds toward the lakeside outlet near the dam structure, causes the flow to accelerate as it approaches the downstream section. The dynamic display of Link SP1, Link SP2, and Link SP3 during the Petuang River's lowest flow scenario is also illustrated in Figure 8. The simulation results show that each station can reach a maximum depth of 0.1 to 0.4 m during the dry season. The upstream station, SP1, recorded the shallowest depth at 0.1 m while having highest discharge rate of 0.1063 m³/s compared to the other stations, with a peak flow velocity of 0.56 m/s.

In each conduit link section, it was discovered that the discharge rate is influenced by the river flow velocity, with the middle and downstream stations (SP2 and SP3) having a deeper depth (above 0.5 m). It was observed that the flow velocity declines as the river progresses downstream, with the highest flow velocity at the final station (SP4) reaching just 0.04 m/s. This demonstrates that the highest depth recorded in the downstream part of the river results in a larger wetted perimeter.

Figure 9 illustrates the dynamic display for Link SP1, Link SP2, and Link SP3 during the simulation of the lowest discharge at the Petuang River. Based on the simulation results, the maximum depth achievable at each station during the dry season ranges from 0.1 to 0.4 m, with the upstream station SP1 recording the lowest depth (0.1 m) and the highest discharge value at 0.1063 m³/s, with a maximum flow velocity of 0.56 m/s compared to the other stations. It was found that river flow velocity influences the discharge rate at each section of the conduit link. Even though the midstream stations (SP2 and SP3) have greater depths, the river discharge rate in these sections does not correspond proportionally to the flow rate, particularly downstream, due to external factors such as human activities and climatic influences. Flow velocity decreases downstream, with the maximum flow velocity at the final station (SP4) being only 0.04 m/s. This demonstrates that the highest recorded depth in the downstream section results in a larger wetted perimeter. However, the water level does not exceed the overflow level of the dam structure at the river mouth, causing the flow velocity to be very slow. contradicts to the original purpose of constructing the structure, which is to prevent the water level from dropping below a depth of 1.0 m. After the simulation, the downstream section recorded a peak discharge of 0.886 m³/s and a maximum depth of 0.40 m. At this depth, it was found that only small-sized fish could be sustained, as most adult or larger fish species would not be able to survive in such anenvironment [36, 37]. Based on low and normal simulations for both rivers, discharge plays a crucial role in maintaining the balance of the river ecosystem by shaping channel conditions that support the biotic components within the system. River discharge also has a significant impact on the development of aquatic fauna, affecting both species diversity and abundance in the river habitat. The ability of key species, such as the Toman, to survive highlights the sensitivity of fish to changes in discharge, which is essential for the survival of other native fish species [38, 39].



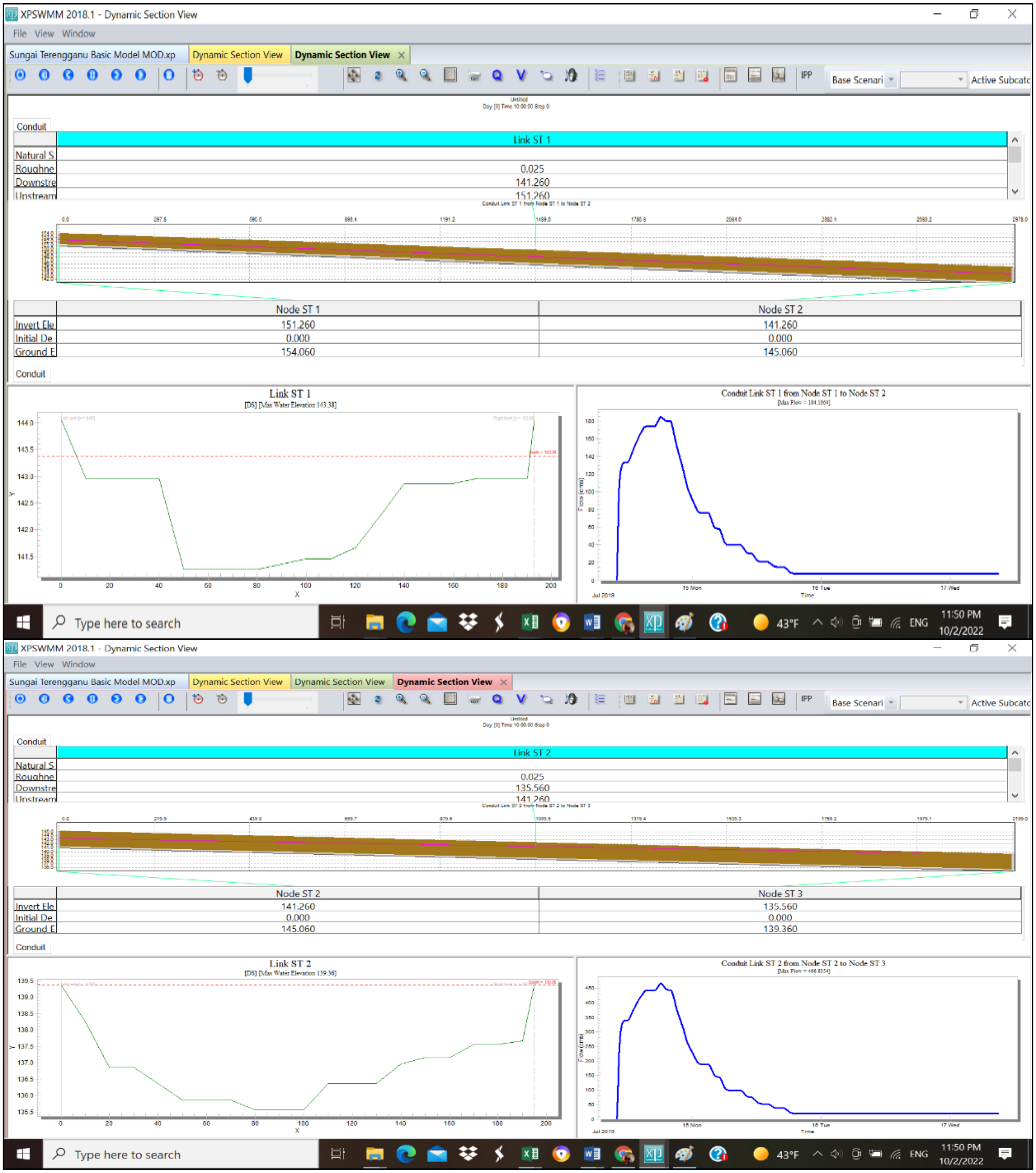


Figure 6. Dynamic simulation of normal discharge for Link ST1, ST2, and ST3

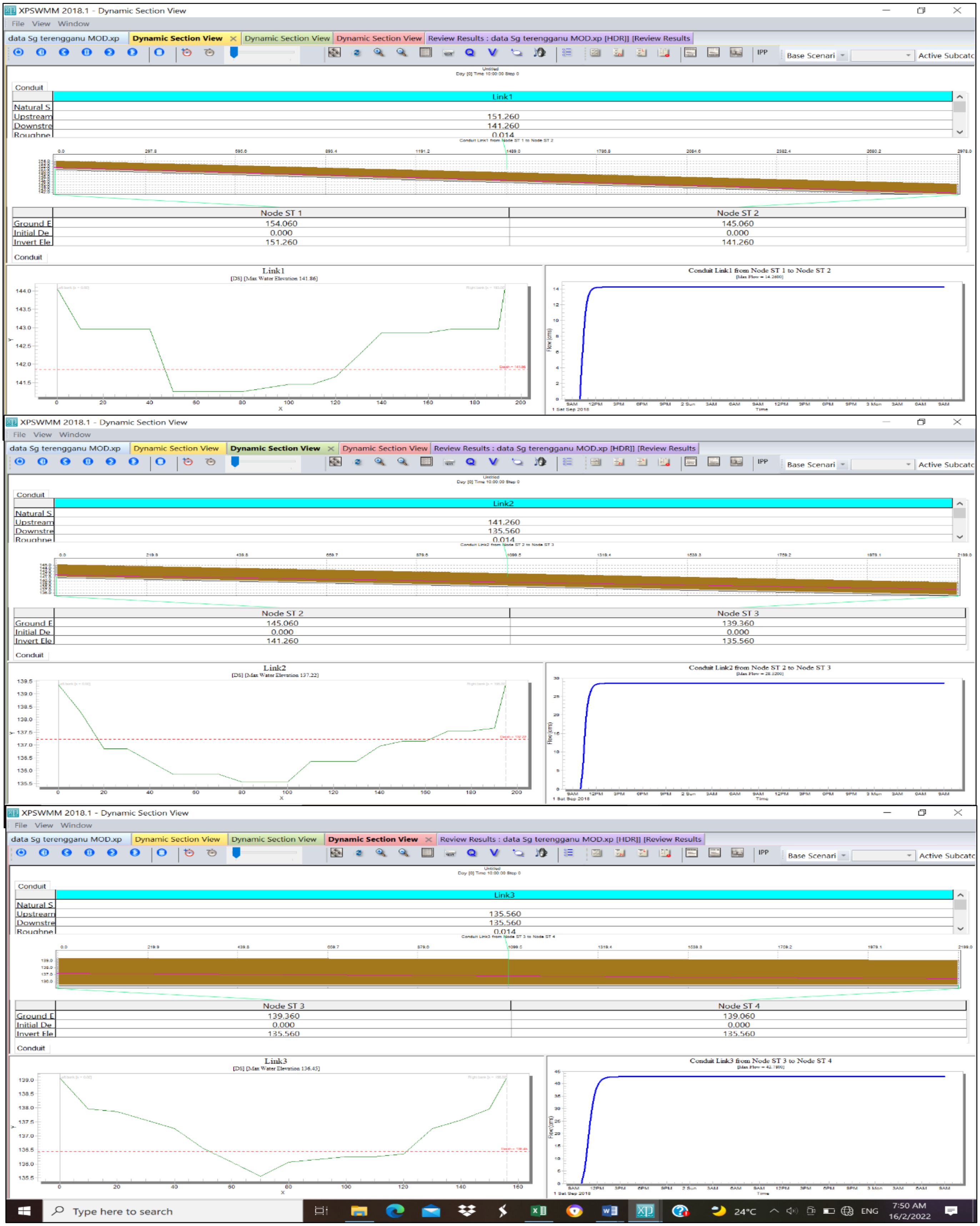


Figure 7. Dynamic simulation of low flow for Link ST1, ST2, and ST3

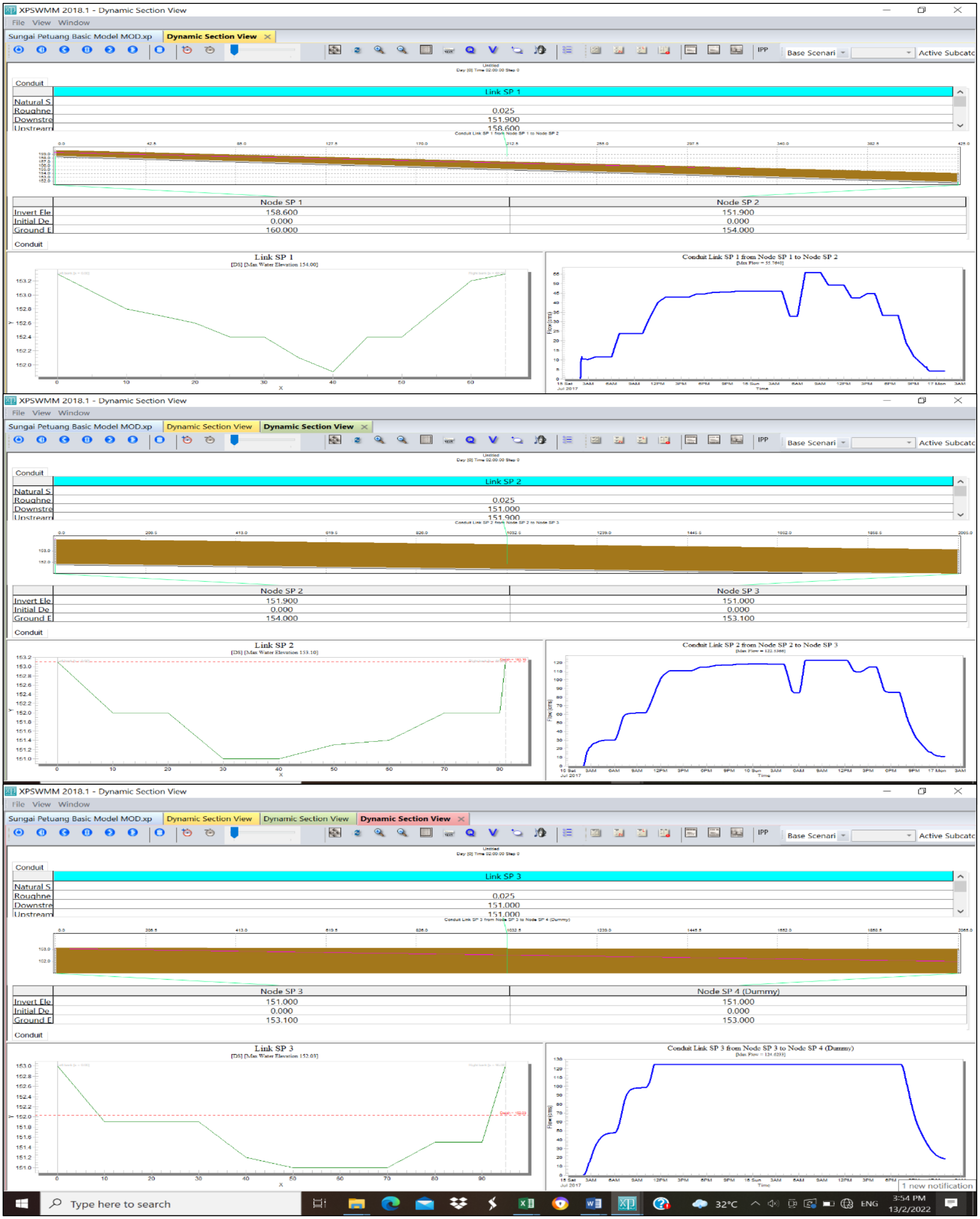


Figure 8. Dynamic simulation of normal flow for Link SP1, SP2, and SP3

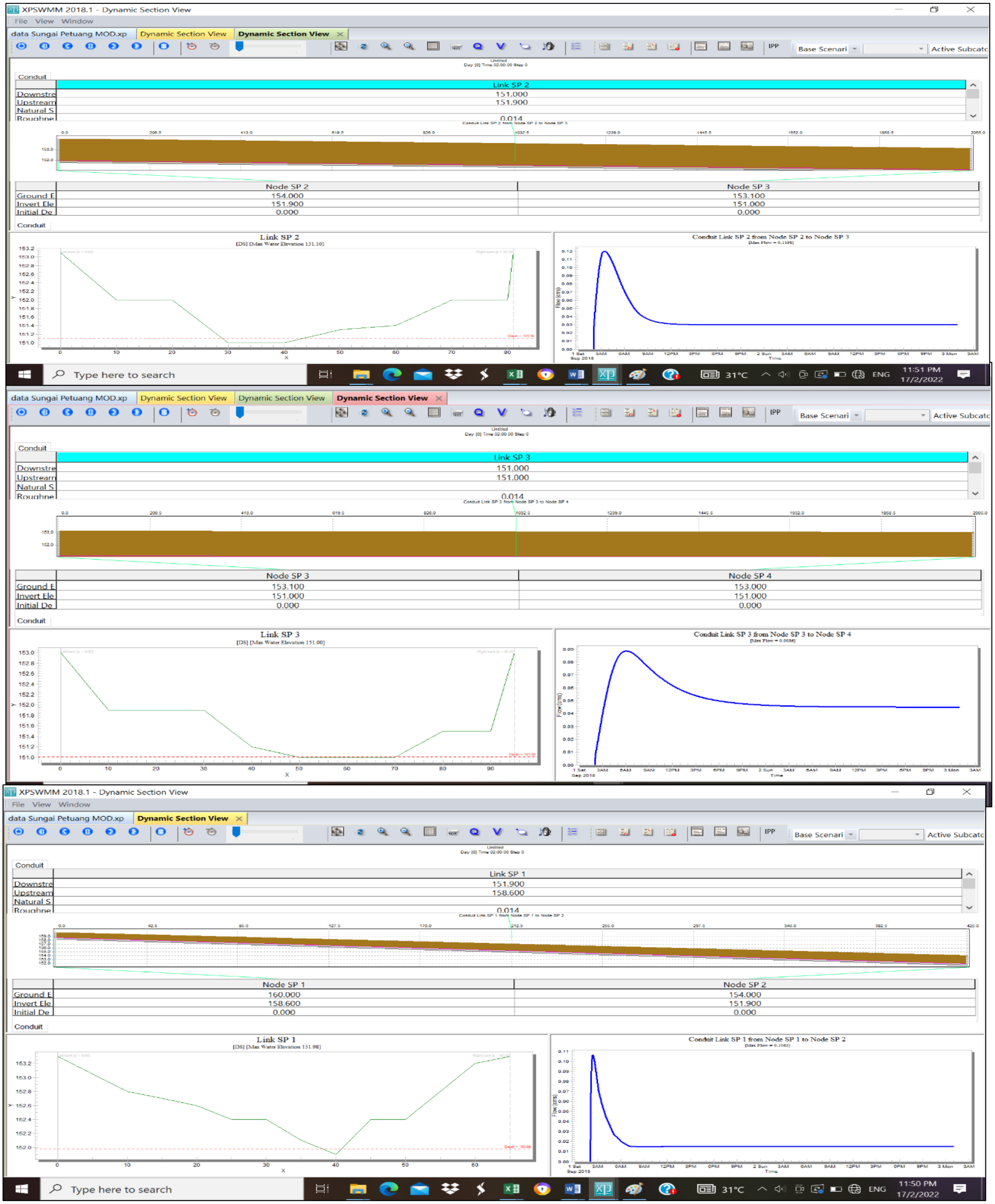


Figure 9. Dynamic simulation of low flow for Link SP1, SP2, and SP3

Conclusions

Based on the analysis of hydraulic, hydrological, and ecological components, the distribution and abundance of native fish were found to be higher in the Terengganu River during the normal season, whereas only a few native fish species were recorded in the Petuang River during the same period. In the dry season, both the Terengganu and Petuang Rivers experienced a noticeable decline in the number and diversity of fish species, with only two native species, Sebarau and Belida, found in the Petuang River. The selection of three indicator species which are Toman, Sebarau, and Belida was based on the isometric growth patterns across different discharge conditions. Throughout the year, both rivers appear capableof supporting the survival of at least two native fish species, based on the physical habitat conditions suitable for these indicator species. The findings of this study, including the the proposed environmental flow index for river restoration and rehabilitation, are intended to serveas an initial reference for more comprehensive management planning. It is hoped that this research on Environmental Flow (E-Flow) determination can serve as a guide for balancing and sustaining resources in the Kenyir Lake basin. While the study focuses on Kenyir Lake system, the insights gained from modeling environmental flows using XPSWMM software offer valuable guidance for ecohydrological management in tropical reservoir basins. This approach can support adaptive water governance and ecosystem resilience in similar environments, thus providing meaningful contributions to the broader field of ecohydrology. Although the modelling framework successfully estimated environmental flows, uncertainties remain due to variability in input data, limitations in model structure, and assumptions regarding ecological responses. Acknowledging these uncertainties is crucial for transparent interpretation and serves as a foundation for improving future hydrological and ecological modeling efforts.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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