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RESERVOIR SEDIMENTATION MANAGEMENT: A SUSTAINABLE DEVELOPMENT CHALLENGE IN THE KENYIR LAKE BASIN, MALAYSIA

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Abstract

Reservoir sedimentation poses a significant challenge to the sustainable development of water resources, with profound implications for ecosystem health and water management. These lead to cause changes and challenges for rivers, such as floods, river erosion, sedimentation processes, and anthropogenic interference, which contribute to problems for humans and specifically for river basin ecosystems. This research examined the issue of sedimentation, a critical water body for the region's hydrology and socio-economic activities and proposed a multi-faceted management strategy that integrates sediment control measures, regular monitoring, and community involvement to enhance the sustainability of reservoir operations and safeguards the ecological integrity of the Kenyir Lake Basin. Through a combination of field surveys and sedimentation problem analysis, we assessed the current state of sediment accumulation and its impact on reservoir capacity, water quality, and downstream ecosystems. There are several aspects of processes such as erosion, sedimentation and the overflow of the river that have been found. The sedimentation problem in the Kenyir Lake Basin is caused not only by the flow rate of water but the land use activities also contribute to the increasing sediment levela. The implementation of recommendations should be carried out more specifically for reservoir sedimentation problems to avoid and minimise various other problems.

Keywords: Reservoir sedimentation; Kenyir Lake Basin; sedimentation problem; reservoir operation; velocity flow

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INTRODUCTION

Reservoirs are vital for water resource management, supporting a range of activities including water supply, irrigation, hydropower generation, and recreation. However, sedimentation in reservoirs poses a significant challenge, threatening their long-term sustainability and efficiency. Sediment accumulation reduces storage capacity, impacts water quality, affects aquatic habitats, and increases maintenance costs, ultimately reducing the lifespan of reservoir infrastructure. These issues are prominent in tropical regions, where high rainfall and steep topography accelerate erosion and sediment transport (Lee et al., 2018; Hogeboom et al., 2018; Fulazzaky et al., 2023). Kenyir Lake Basin in Malaysia exemplifies these challenges. As the largest man-made lake in Southeast Asia, Kenyir Lake is crucial for the region's hydrology and socio-economic activities, including water supply, flood control, hydropower generation, fisheries, and tourism. However, sedimentation is jeopardizing the sustainability of these services. The sedimentation problem in Kenyir Lake is driven by multiple factors such as land use changes, deforestation, agricultural activities, and natural erosion processes. Additionally, climate change and extreme weather events exacerbate these issues by altering precipitation patterns and increasing the frequency of heavy rainfall which leads to higher rates of soil erosion and sediment transport. The main objective of this research is to examine the issues of sedimentation in Kenyir Lake Basin and to propose a multi-faceted management strategy to address them. Uncontrolled river management can cause the water level raise, allowing it to be tapped and directed into the intake channel. The drainage system is built up as a network of rivers with settling basins positioned between 250 to 300 metres apart to maintain the high standards of the river water. To prevent basic and high sediment transport, particularly the sand fraction into the irrigation network, the concept of creating sedimentary pockets is a supplementary component of the main building. In addition, if the effectiveness of the sediment pockets declines, some buildings may not be able to be cleaned up for optimal work, which could lead to fewer incorrect operation plans and field maintenance (Uca et al., 2018; Wahab et al., 2019). It was also discovered that in certain instances, the building's poor design concepts made them difficult to operate and required expensive upkeep. By addressing these objectives, the study seeks to enhance the sustainability of reservoir operations and safeguard the ecological integrity of Kenyir Lake Basin. The proposed multi-faceted management strategy involves implementing sediment control measures to reduce sediment influx, establishing regular monitoring programs to track sedimentation trends, and engaging the local community in sediment management efforts. These comprehensive approaches aim to provide a framework for managing sedimentation challenges in tropical reservoir systems and contribute to a broader understanding of reservoir sedimentation issues.

LITERATURE REVIEW

Sedimentation is a process whereby deposition of the soil, gravel and sand is transported by the river flow and eventually settles as mud and reshapes the riverbed geometry. This process will leave a noticeable effect on the change in the geometry of the river, especially the downstream, where the velocity is low. After a few years of this process, the formation of the land following the sedimentation process will become clearer from the aerial view (Kamarudin et al., 2019). Sedimentation is a deposition event or process that occurs in several abiotic components that exist in the environment such as soil and sand. This sedimentation process is caused by several factors such as water flow or wind gusts which can move small particles from the soil or sand to other places until they are deposited and form the new land. The sedimentation process can occur in various places such as on soils, at the sea or in river ecosystems. These degrading materials are residual materials from weathering or erosion which last for a long time so that they are easily transported. The geological sedimentation process is the accumulation of sediments at a normal rate. This refers to the deposition process that occurs within the limits allowed, remaining or within the natural balance of the the degradation process. The rate of sedimentation process or total transport rate and reservoir life expectancy are very important for a sustainable ecosystem. The river flow and discharge are important in relation to the sedimentation production level and sediment movement (Kamarudin et al., 2017; Wahab et al., 2019). The accelerated sedimentation process is a sedimentation process that occurs in a relatively shorter time. This process is different from the geological sedimentation process (Chang & Liao, 2016). The accelerated sedimentation process has a detrimental effect, causing harm or damage, and disrupting the natural balance of the environment (Ismail et al., 2023). Besides that, the accelerated sedimentation process creates magnetic particles which enhance the sensitivity through the concentration process. The rapid immunological reaction on the walls by the magnetic field leads to a higher sedimentation rate. The sedimentation process is the direct result of erosion and sediment deposition from other aquatic areas or land-based areas. Based on previous hydrological studies, the sedimentation process can be detrimental and degrade the river ecosystem (Rendana al., 2017; Hossain et al., 2019). According to Ismail & Amin (2020) and Wahab et al. (2019), the natural physical processes such as deposition, transportation and erosion always will continue regardless of whether they are influenced by human activities or anthropogenic and natural factors along the river basin. According to Gasim et al. (2013), morphological or river planform changes (physical changes over a large area) in large river basin systems can also be major factors contributing to changes in natural sediment erosion and consequently, sediment production in the river basin (Lee et al., 2018; Hogeboom et al., 2018; Fulazzaky et al., 2023).

STUDY AREA AND RESEARCH METHODOLOGY

Study Area

Using a global positioning system (GPS), the latitude and longitude coordinates for every sampling point were recorded during the fieldwork. The massive development that has been carried out has had a significant impact on the environment. The development of the areas, including buildings, parking spaces, and roads, has led to the loss of the land's ability to absorb rainfall. Poor ability to absorb rainfall contributed to the surface runoff. The surface runoff became faster and the river faced difficulties in controlling the flow of water entering it. Table 1 and Figure 1 display the sampling locations along the Terengganu River Basin, which includes the districts of Kuala Terengganu, Kuala Nerus and Hulu Terengganu, representing areas from the upstream to the downstream. The Kenyir Dam controls the water capacity in the Terengganu River, and the hydroelectric project in Kenyir Lake involves a large area and provides various benefits. Water discharge activities from the Kenyir Dam affects the flow of lake water, making it less dynamic and triggering disruptions in the sedimentation process as well as the equilibrium of environmental flow assessment. These hydro resources create a socio-economic overflow effect and serve as flood mitigation, especially in Terengganu. This study included 19 sampling stations during dry season and 21 sampling stations during wet season which are Sungai Siput (ST1), Sungai Petuang (ST2), Sungai Tembat (ST3), Sungai Terengganu (ST4), Sungai Ketiar (ST5), Sungai Besar (ST6), Sungai Lepar (ST7), Sungai Lawit (ST8), Sungai Cenan (ST9), Sungai Bewah (ST10), Sungai Cicir (ST11), Sungai Perepek (ST12), Sungai Terenggan (ST13), Sungai Cacing (ST14), Sungai Pertang (ST15), Sungai Lasir (ST16), Sungai Leban Terengganu (ST17), Sungai Sauk (ST18), Sungai Mandak (ST19), Sungai Kenyir (ST20) and Sungai Berangan (ST21).

Table 1: The sampling station in Kenyir Lake Basin, Terengganu, Malaysia

Station	Longitude	Latitude	Station	Longitude	Latitude
ST 1	102° 42'42.602"E	05°11'01.064"N	ST 11	102°44'30.707"E	4° 47'42.302"N
ST 2	102°39'49.705"E	5° 17'42.360"N	ST 12	102°44'31.9"E	4° 47'16.9"N
ST 3	102°38'19.879"E	5° 12'57.393"N	ST 13	102°45'00.244"E	4° 46'28.235"N
ST 4	102°37'46.486"E	5° 11'24.258"N	ST 14	102°42'32.595"E	4° 48'17.089"N
ST 5	102°33'17.735"E	5° 03'30.462"N	ST 15	102°48'00.5"E	4° 55'26.2"N
ST 6	102° 34'15.044"E	04°58'03.613"N	ST 16	102°50'22.510"E	4°57'54.633"N
ST 7	102° 33'09.379"E	04°56'16.506"N	ST 17	102°45'03.621"E	5° 02'21.528"N
ST 8	102°35'13.374"E	4° 54'38.067"N	ST 18	102° 46'42.443"E	05°04'58.079"N
ST 9	102° 42'04.9"E	04°52'32.0"N	ST 19	102° 20'6.25"E	05°07'34.463"N
ST 10	102°41'24.427"E	4° 50'36.340"N	ST 20	102°54'5.18"E	05° 0'40.01"N
			ST 21	102°54'40.34"E	05° 1'2.36"N

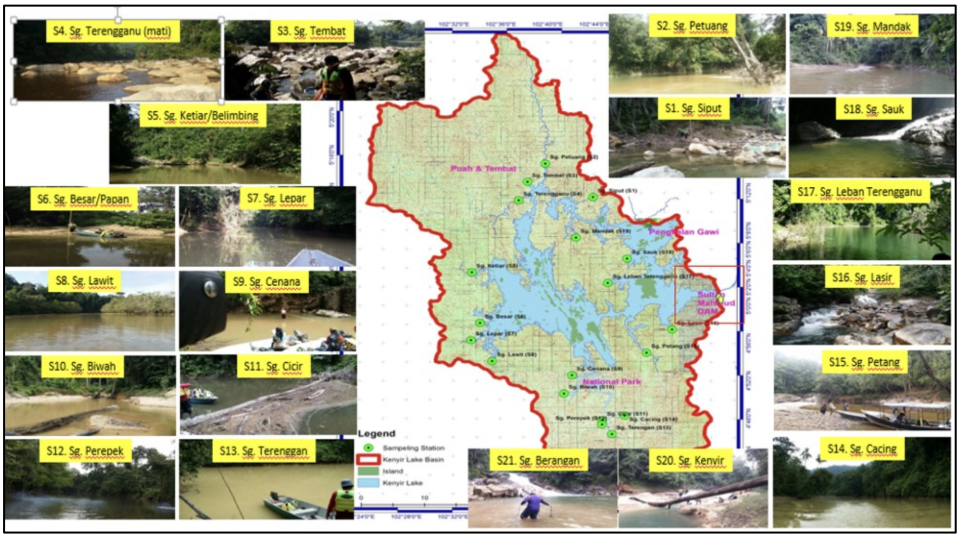


Figure 1: The Ilustration of Sampling Station in Kenyir Lake Basin, Terengganu, Malaysia

Research Methodology

Sedimentation is a critical environmental issue affecting water bodies worldwide, and the Kenyir Lake Basin in Hulu Terengganu, Malaysia, is no exception. Effective management of sedimentation problems requires a comprehensive understanding of various hydrological and sediment-related parameters. Table 2 shows the basic indicators used to measure the level of sedimentation in the Kenyir Lake Basin, providing essential data for environmental monitoring and management strategies. Monitoring these indicators provides valuable insights into the dynamics of sedimentation in the Kenyir Lake Basin. The indicators outlined in Figure 2 are essential tools for understanding and managing sedimentation problems in the Kenyir Lake Basin.

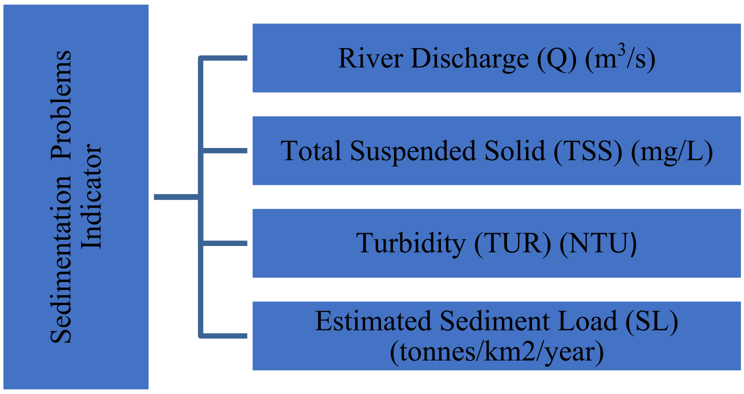
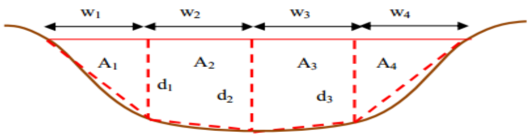
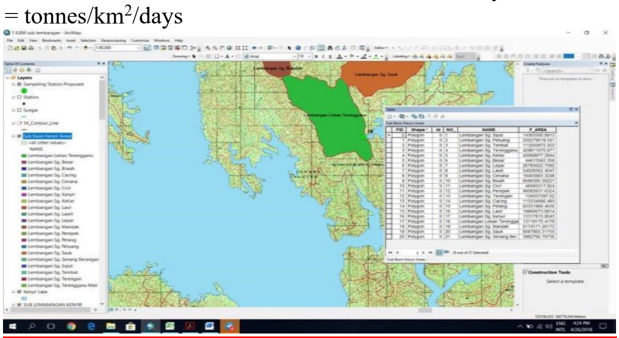


Figure 2: The Basic Indicators in Measuring the Level of Sedimentation in Kenyir Lake Basin, Hulu Terengganu, Malaysia

Table 2: The sediment problems indicator applied in this research and scientific used in measurement for each indicator

Sedimentation Problems Indicator	Scientific Method
River Discharge (Q) (m^3/s)	The discharge value (Q) is the product of velocity and cross-section area (A). The cross section area is derived from the product of depth (d) and width (w), the cross-section area is trapezium or triangular shaped and the value is half the product which is due to imprecision of the current meter, variability of the river flow velocity over the cross section and uncertainty in the estimation of the cross section geometry (**Figure 3(a)**).  **Figure 3(a)**: The Theory of Discharge Measurement By River Cross-Section
Total Suspended Solid (TSS) (mg/L)	The United States Environmental Protection Agency (USEPA) and the American Public Health Association (APHA) provide standard procedures for sample processing and preservation, which were followed in all cases. Using the gravimetric method, the laboratory evaluation was conducted in accordance with the standard analytical process to measure the precise values of TSS (Wahab et al., 2019).
Sediment Load (SL) (tonnes/km^3/year)	The calculation of annual sediment load production (MS) is based on the discharge value (Q) (m^3/s), TSS value (mg/L) and area of the sampling basin (km^2). The analysed data will be used to determine the changes in the concentration of suspended sediment and its relationship with hydrological and geomorphological factors and other variables. **Equation 1** shows the formula used in the measurement of MS (tonneskm^2/year). **Figure 3(b)** shows the Fundamentals of the Georeferencing of the ArcGIS method to determine the area of each sub-catchment (area sampling basin) (Kamarudin et al., 2020). **Equation 1** Annual sediment load production (MS) = (Q x TSS)/ Area of sampling basin

Sedimentation Problems Indicator	Scientific Method
	= (L/day x tonnes/day)/ km^2 = tonnes/km^2/365 days = tonnes/km^2/days  **Figure 3(b)**: Fundamental of Georeferencing of ArcGIS to Determine the Area of Each Sub Catchments in Kenyir Lake Basin, Hulu Terengganu, Malaysia
Turbidity (TUR)	The measuring tool used to identify the TUR values is the HACH 2100Q portable turbidimeter. This tool is equipped with a copper carrying case so that it can be easily carried to the field (Wahab et al., 2019).
Total Dissolve Solid (TDS)	To measure Total Dissolved Solids (TDS) using a TDS meter, the meter is firstly clean and calibrated. A water sample was collected in a clean container, and the TDS meter was turned on. The probe was then immersed into the sample, ensuring it was fully submerged to the indicated level. The reading is allowed to stabilise, which may take a few seconds, and then displayed TDS value, typically in parts per million (ppm) or milligrams per litre (mg/L), was recorded. Finally, the probe was cleaned with distilled water, the meter was turned off and stored appropriately.

ANALYSIS AND DISCUSSION

River Discharge

The observed value (Q) at Sungai Petuang (Station 2) showed the highest value at 10.48 m^3/sec and the lowest value (Q) at Sungai Bewah was at 0.07 m^3/sec during the dry season. During the wet season, the maximum value of discharge was recorded at 28.436 m^3/sec and the minimum is at 0.809 m^3/sec **(Figure 4)**. This is a normal reading for a river, where the observed value (Q) or water velocity in the elevated upstream is higher than the downstream. In flat areas, excess water flows out from Kenyir Lake into Sungai Terengganu and the difference in depth and width of the river significantly influences the flow of the river. The processes of erosion, transport, and sedimentation occur along the river to the estuary to influence deposition. The speed of water flows is the main factor, affects the capacity of the sediment transportation and movement. The processes of deposition of sediment indeed depends on the river discharge and the speed of the river flow. The theory of hydrology describes that when the discharge value is high and the water velocity is low, the amount of sediment load deposited in the downstream area is higher. The action involves the normal process of erosion, transport, and sedimentation along the river. Rivers are important sources of water for humans and other organisms as they are essential for sustaining life. The sedimentary content and quality of water influence the condition of the river. The frequency and intensity of rainfall influence the water level flow and the rates of the erosion process (Wahab et al., 2019).

JPS River Index (JRI)

JRI is based on the flow (discharge), turbidity, TSS, and TDS parameters, with the main focus on monitoring the physical changes in polluted rivers as a result of land use development, logging, tourism, and the opening of agricultural land along the Lake Kenyir Basin. Based on the results obtained (refer to **Figure 5**), it is evident that increased velocity and volume of water would also increase the rate of erosion, leading to increased production of TSS, water turbidity and eventually the river becoming shallower. This harms the benthic ecosystem, and flora and fauna in the area surrounding the river and lowers the water quality. The advantage of using JRI which takes into account the area of the river basin catchment area at the station location when the flow is high, medium and low makes JRI suitable for monitoring the quality of river water in rural areas because the classification of river water index JRI is more oriented towards the physical shape of the river and not to the quality of life in the river water (JPS, 2012; Hasan et al., 2015; Shafii et al., 2018; Wahab et al., 2019).

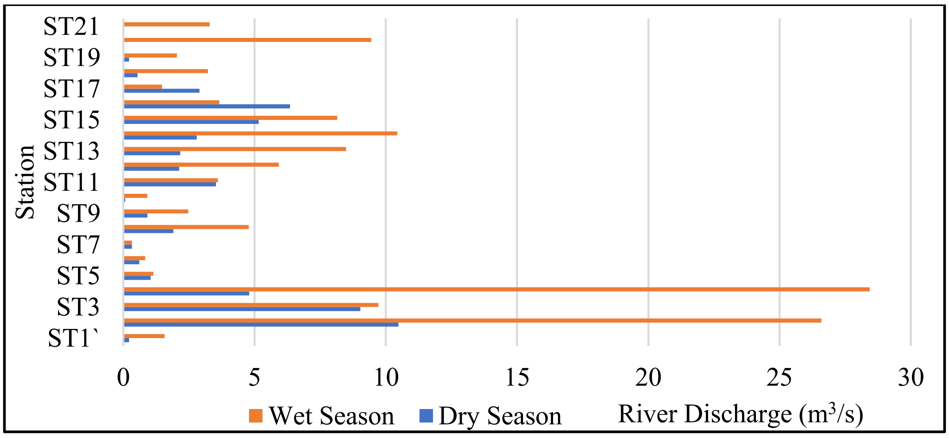


Figure 4: The Estimated of River Discharge (Q) at Kenyir Lake Basin, Hulu Terengganu, Terengganu During Dry Season and Wet Season

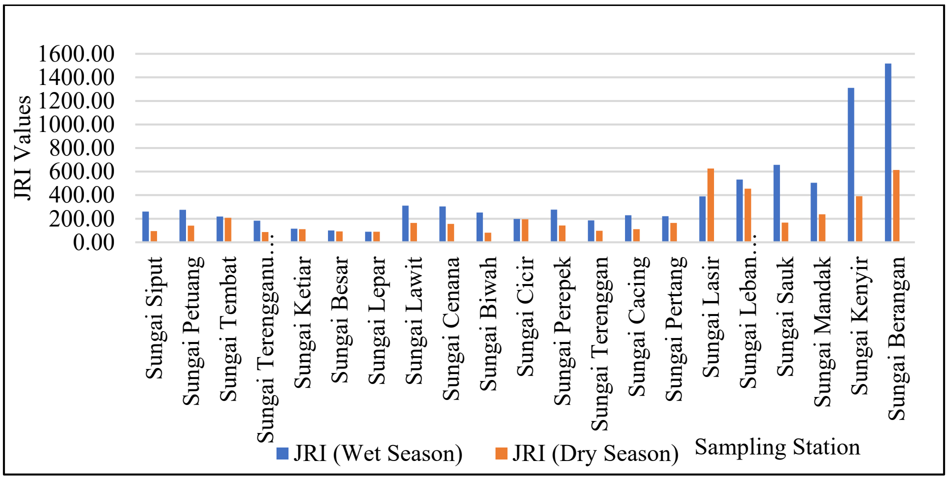


Figure 5: The JPS River Index (JRI) at Kenyir Lake Basin, Hulu Terengganu, Terengganu During Dry Season and Wet Season

Table 3(a) and **Table 3(b)** show the leave-one method or analysis of the importance of inputs to determine hydrological parameters that significantly affect water quality status using JRI. Sediment mobilisation processes in a semi-arid tropical river system state that river water flow has been proven to influence the flow pattern peaks in the wet season compared to the dry season. The low flow rate recorded in the sub-basin that has a small basin area is proven in this study through linear analysis with the highest percentage contribution value for the Specific Flow parameter compared to other parameters which are 99.97% (wet season), 94.19% (dry season) and 99.95% (normal season). The tendency of the Specific Flow condition depends on the rapid water velocity and the river receives a high intensity of rain during the wet season. In general, high water speed and volume result in a tendency to increase the erosion rate and water speed is the main factor that affects the Specific Flow trend (Toriman et al. 2015). In addition, TSS is one of the most important parameters that affect the production of sediment load each year. The concentration of TSS is higher in the wet season compared to the dry and normal seasons because the erosion process is more active and facilitates the deposition of suspended solids. This theory also describes that water flow during the wet season has more energy to transport TSS in larger amounts than during slow water flow (Wahab et al., 2019).

Table 3(a): Important variables in the linear relationship between water quality parameters and JPS River Index (JRI) in Kenyir Lake Basin in the wet season

R-Square Reference = 0.9989			
Leave Variable	**R-Square Leave Variable**	**R-Square Difference**	**Percent Contribution**
Specific Flow(SF)	0.0606	0.9383	99.97
Total Suspended Solid (TSS)	0.9988	1E-04	0.01
Turbidity (TUR)	0.9988	1E-04	0.01
Total Dissolve Solid (TDS)	0.9988	1E-04	0.01
TOTAL	**3.057**	**0.9386**	**100.00**

Table 3(b): Important variables in the linear relationship between water quality parameters and JPS River Index (JRI) in Kenyir Lake Basin in the dry season

R-Square Reference = 0.9891			
Leave Variable	**R-Square Leave Variable**	**R-Square Difference**	**Percent Contribution**
Specific Flow(SF)	0.0512	0.9379	94.19
Total Suspended Solid (TSS)	0.9601	0.029	2.91
Turbidity (TUR)	0.9703	0.0188	1.89
Total Dissolve Solid (TDS)	0.979	0.0101	1.01
TOTAL	**2.9606**	**0.9958**	**100.00**

Estimated Sediment Load (SL) Production

The highest value of MS during the wet season was recorded at 348968.41 $kg/km^2/year$ in the Sungai Kenyir Sub Basin and the lowest value of MS during the wet season in the Sungai Lepar Sub Basin was 6993.35 $kg/km^2/year$. In addition, the highest MS value in the dry season was recorded in the Terengganu Leban River Sub-Basin which was 36249.93 $kg/km^2/year$ and the lowest value in the Siput Sungai Sub-Basin was 581.96 $kg/km^2/year$ (refer to **Figure 6(a)** and **Figure 6(b)**). The value of MS production in the dry season was relatively high in some sub-basins compared to the wet, possibly due to the geographical position of most of the sub-sub-basins in the Kenyir Lake Basin, especially the sub-basins in the upper part located near the forest area near the border of the National Park. During the wet season, the rapid flow of water facilitates the absorption of foreign substances by trees, resulting in clearer water and fewer suspended particles flowing into the river compared to the dry season. This is also the main reason why MS production is higher during the dry season compared to the wet season throughout the research. Sediment load rates were found to be relatively high at the beginning of the wet season because observations were made after rainfall, when the accumulated river flow provided sufficient energy to transport sediment in large quantities, especially in the river basin with an area of only 13,318 km^2.

The comparison of the sediment load value for the Sungai Kenyir Sub-Basin area with other rivers that have similar basin areas is very high. For example, the sediment load value for the Siput River Sub-Basin with a basin area of 14,306 km² recorded a sediment load concentration of 55409.54 kg/km^2/year during the wet season and 581.96 kg/km^2/year during the dry season. On the other hand, the Kenyir River Sub-Basin recorded a sediment load value 10 times higher with a basin area of only 13,318 km². This shows that the amount of sediment production in this basin area is high compared to the selected river sub-basins that have been studied in the Lake Kenyir Basin. It was found that the sub-basin in the downstream part is more vulnerable to soil erosion due to the construction carried out near the banks of the river, causing soil erosion to easily occur when it rains. The estimated value of Sediment Load (SL) in the lower and middle parts of Tasik Kenyir Basin is higher than the upper part. This study proves that sediment production is the result of geomorphological factors, hydrology, the development of anthropogenic factors and climate change that occur in the Kenyir Lake Basin. It shows a clear relationship whereby the wider the basin, the higher the annual sediment load that can be produced, based on hydrological theory. However, most studies in Malaysia cannot be fully applied without considering the external environmental factors surrounding the basin and the uncertain impacts of climate change in recent years. Taken together, changes in the activity within the entire river basin will impact sediment production in the river (Aweng et al., 2016; Saad et al., 2023).

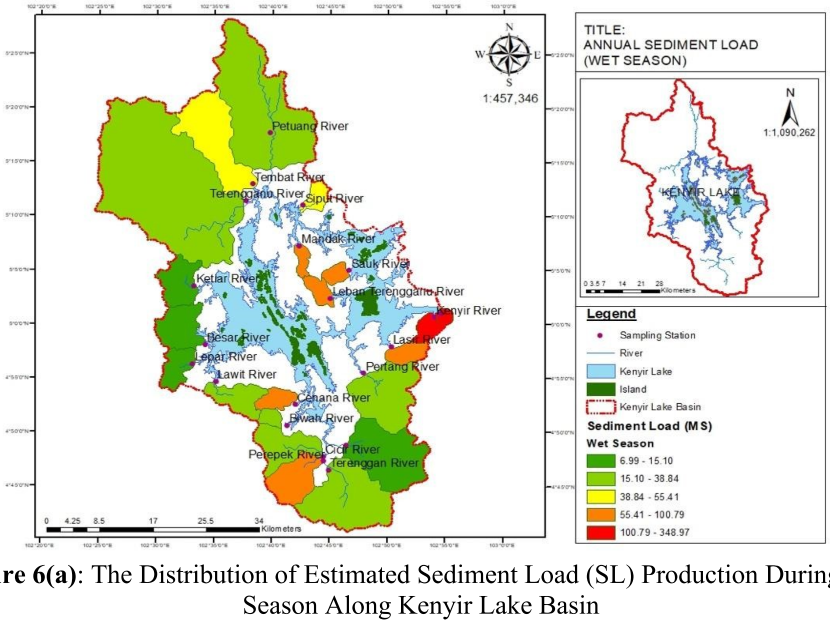


Figure 6(a): The Distribution of Estimated Sediment Load (SL) Production During Wet Season Along Kenyir Lake Basin

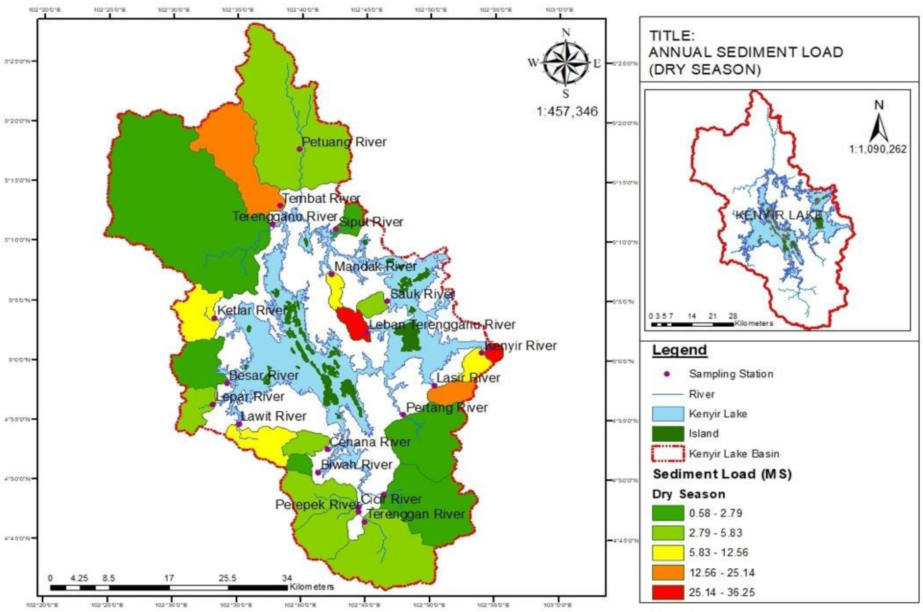


Figure 6(b): The Distribution of Estimated Sediment Load (SL) Production During Dry Season Along Kenyir Lake Basin

Reservoir Sedimentation Mitigation Management

The land use changes around the Kenyir Lake Basin, such as agriculture, tourism, domestic development, animal husbandry and cage fishing, have resulted in the creation of certain areas suffering from deteriorating water quality and critical sedimentation along the basin. Through the "Regional Local Plan (RTD) Kuala Terengganu 2008-2020", several environmental management methods have been implemented, including aspects of environmental quality control, biological diversity protection and the management of environmentally sensitive areas (*Kawasan Sensitif Alam Sekitar*) (KSAS), to achieve progress in the environmental management development by 2020. **Figure 7** shows a structured approach to manage reservoir sedimentation mitigation in the Kenyir Lake Basin, highlighting three primary strategies. The first strategy, land use management along the Kenyir Lake Basin, involves the implementation of sustainable land-use practices to minimise soil erosion and reduce sediment influx into the reservoir. The second strategy to address bank erosion along the Kenyir Lake Basin, focuses on controlling erosion of the reservoir's banks through various erosion control measures, thereby preventing sediment from degrading water quality and reservoir capacity. The third strategy involves mitigation management based on the concept of Integrated Water Resources Management

(IWRM) in the Kenyir Lake Basin, utilising comprehensive and coordinated water resource management practices. This strategy integrates various sectors and stakeholders to develop and implement effective solutions for managing and mitigating sedimentation in the reservoir, ensuring long-term sustainability (Wahab et al., 2023).

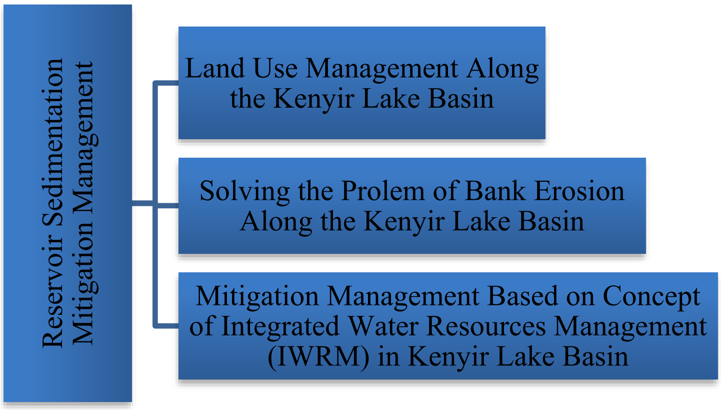


Figure 7: The Ilustration of reservoir sedimentation mitigation management in Kenyir Lake Basin

CONCLUSION

The management of reservoir sedimentation in the Kenyir Lake Basin presents a complex yet critical challenge for sustainable development in Malaysia. This study highlights the multifaceted nature of sedimentation issues, including environmental, social, and economic dimensions. Effective sedimentation management is essential not only to preserve the reservoir's capacity and prolong its lifespan to protect the surrounding ecosystems and support the livelihoods of local communities. Community involvement is paramount in ensuring the success of sedimentation management initiatives. Engaging local stakeholders in decision-making processes and promoting awareness about sustainable practices can foster a sense of responsibility towards the lake's health. Moreover, interdisciplinary collaboration among government agencies, research institutions, and non-governmental organisations is crucial to developing and implementing comprehensive sediment management plans. The findings from the Kenyir Lake Basin can serve as a valuable reference for other reservoir systems facing similar challenges. Future research should focus on long-term monitoring and evaluation of sediment management practices to adapt and refine strategies as needed. By prioritising sustainable sedimentation management to the broader goals of environmental sustainability and socio-economic development in Malaysia.

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