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River Health Index: A Review on Current Assessment Practice in Malaysia Towards a Holistic Evaluation of River Health

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Abstract: Assessing the health of river systems is a crucial endeavour that requires a multifaceted approach. This paper explores the key components of river health evaluation, integrating physical, chemical, biological, and socioeconomic indicators. Fluvial geomorphology provides valuable insights into the river's dynamic characteristics, while ecological indicators, such as fish and macroinvertebrates, serve as sensitive markers of environmental change. Sociological factors, including stakeholder involvement and land use patterns, further highlight the complex interactions between human communities and river ecosystems. To develop a comprehensive River Health Index (RHI), the study proposes the use of Multi-Criteria Decision Analysis (MCDA) and the Analytic Hierarchy Process (AHP) to prioritize and weigh the relative importance of diverse indicators. This structured approach ensures a balanced and context-specific assessment, reflecting the unique needs and challenges of the river system. Stakeholder engagement emerges as a vital component, fostering local knowledge integration and promoting adaptive management practices. By adopting this holistic framework, river managers and policymakers can make informed decisions that safeguard the long-term sustainability and resilience of these vital natural resources.

Keywords: River health assessment, River health index, Fluvial geomorphology, Ecological indicators, Socioeconomic factors, Multi-Criteria Decision Analysis (MCDA) - Analytic Hierarchy Process (AHP)

1. Introduction

River water quality is a critical issue in Malaysia, where the country's rapid urbanisation and industrialisation have led to increased pollution and degradation of water resources [1]. Studies have shown that Malaysian rivers are facing significant pollution challenges, including high levels of biochemical oxygen demand (BOD), chemical oxygen demand (COD), and suspended solids (SS) [2]. In addition, the country's rivers are also affected by point and non-point sources of pollution, such as industrial and agricultural activities, domestic wastewater, and stormwater runoff [3]. Water quality in river can be characterized through the assessment of a range of physical habitat, chemical, and biological parameters [4]. These characteristics provide an information about the health of the river ecosystem, its suitability for human use, and its ability to support aquatic life.

The concept of river health index has gained increasing attention in recent years as a way to assess the status and trends of river ecosystems and guide management decisions. In Malaysia, the current assessment of river water quality is based on the National Water Quality Standard for Malaysia (NWQS) and the Water Quality Index (WQI) by Department of Environment (DOE) Malaysia. DOE and the Department of Irrigation and Drainage (DID) are among Malaysia's technical agencies responsible for river monitoring. The DOE has applied a standard manual to monitor the quality and status of rivers in Malaysia. The Environmental Quality Monitoring Program (EQMP) is a government initiative to consolidate and strengthen environmental quality monitoring, involving data

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collection of river water quality throughout Malaysia. The existing methodology used for river water quality classification and monitoring in Malaysia is quite extensive. There are two primary methods employed to classify the river water quality monitored which are the Water Quality Index (WQI), which in turn is rooted on the Interim National Water Quality Standards (INWQS), a set of standards derived based on beneficial uses of water [5]. The current practice of river monitoring in Malaysia relies heavily on the WQI, which consists of physicochemical parameters, is based on six parameters: dissolved oxygen concentration (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammoniacal nitrogen (AN), suspended solids (SS), and pH. The WQI formula and calculation are as follows:

$$\boldsymbol{WQI} = (0.22 * \mathrm{SIDO}) + (0.19 * \mathrm{SIBOD}) + (0.16 * \mathrm{SICOD}) + (0.15 * \mathrm{SIAN}) + (0.16 * \mathrm{SISS}) + (0.12 * \mathrm{SIpH}) \quad (1)$$

where each SI represents a subindex for the corresponding parameter.

2. The Water Quality Index (WQI)

The WQI, as shown in Equation 1, ascribes quality value to an aggregate set of measured parameters. It consists of sub-index values such as dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammoniacal nitrogen (NH_3-N), total suspended solids (TSS) and pH. Each sub-index is assigned a weightage where, this approach transforms the water quality data into a single numerical value to represent the overall water quality with a score between 0 and 100 [6]. Table 1 and 2 shows the DOE WQI Classification and DOE Water Quality Classification Based on the WQI. Meanwhile, Table 3 depicts the water classification and its uses.

Table 1 – DOE water quality index (WQI) classification

Parameter	Unit	Class				
		I	II	III	IV	V
Ammoniacal Nitrogen	mg/l	<0.1	0.1-0.3	0.3-0.9	0.9-2.7	>2.7
Biochemical Oxygen Demand	mg/l	<1	1-3	3-6	6-12	>12
Chemical Oxygen Demand	mg/l	<10	10-25	25-50	50-100	>100
Dissolved Oxygen	mg/l	>7	5-7	3-5	1-3	<1
pH	-	>7	6-7	5-6	<5	>5
Total Suspended Solid	mg/l	<25	25-50	150	300	>300
Water Quality Index (WQI)		<92.7	76.5-92.7	51.9-76.5	31.0-51.9	<31.0

On the application of WQI to evaluate river water quality, Naubi et al. [7] showed that WQI of the Skudai River ranging from 94 to 53, which denotes degradation of water quality at the river. Water quality in the upstream sections of the Skudai and its tributaries was better compared to the downstream river sections and tributaries. There was significant increase in most of the important water quality parameters (BOD, COD, NH_3-N, and others) at the downstream of the river, which indicates that the increasing contribution from the nearby pollutants deteriorate the water quality of river.

Table 2 – DOE water quality classification based on water quality index

Parameter	Index Range		
	Clean	Slightly Polluted	Polluted
Biochemical Oxygen Demand (BOD)	91-100	80-90	0-79
Ammoniacal Nitrogen (NH_3-N)	92-100	71-91	0-70
Suspended Solid (SS)	76-100	70-75	0-69
Water Quality Index (WQI)	81-100	60-80	0-59

Table 3 – Water classes and uses

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

Another study by Al-Badaii et al. [8] was carried out to determine the Semenyih River water quality based on the WQI and NWQS. The results indicated that temperature, pH, conductivity, TDS, SO4, and TH were classified as Class I, while DO, turbidity, and BOD were categorized under Class II, and NH3-N, TSS, COD, and OG were categorized as Class III based on NWQS, Malaysia. While physicochemical parameters as applied in the WQI and NWQS have traditionally been used as indicators of river health, their limitations in capturing the complexity of river ecosystems have become increasingly apparent. This reliance on solely physicochemical parameters presents several challenges, hindering a comprehensive understanding of river health and potentially leading to inadequate management decisions. The WQI and NWQS are limited in their ability to capture the complexity of river ecosystems, neglecting biological, ecological and possible sociological/socioeconomics aspects of river health.

3. River Health Evaluation

River health evaluation is a more comprehensive approach that considers water quality and the ecological and biological integrity of the river ecosystem [9]. While water quality assessment focuses on the physical and chemical characteristics of the water, river health evaluation considers the overall health of the river ecosystem, including the presence and abundance of aquatic species, habitat diversity, and ecosystem processes [10].

In Malaysia, river health evaluation is still in its infancy, and most studies have focused on water quality assessment using the WQI [11] However, recent studies have highlighted the need for a more holistic approach to river health evaluation, incorporating biological and ecological indicators [1]. Several issues have been identified in river health evaluation in Malaysia. One of the main challenges is the lack of standardization in river health assessment methods, leading to inconsistencies in data collection and analysis [3]. Another issue is the limited availability of biological and ecological data, making it difficult to develop a comprehensive understanding of river health [11].

In addition, the current practice of river health monitoring in Malaysia is fragmented, with multiple agencies involved, leading to inconsistencies in data collection and analysis. Furthermore, the lack of public awareness and education on river health issues has hindered efforts to improve river health in Malaysia [1].

4. River Health Indicators

River ecosystems are vital to the natural environment, providing essential services such as water supply, flood control, nutrient cycling, and recreational opportunities. However, increasing anthropogenic pressures, such as urbanization, industrialization, and agricultural activities, have led to the deterioration of river health in many regions around the world. To address this issue, researchers have developed various methods for assessing river health, including the use of physicochemical, ecological, and socioeconomic/sociological indicators [12]. The concept of "river health" was first proposed in 1996 by Scrimgeour and Wicklum [13], and since then, it has gained significant attention in the scientific [12]. River health assessment is a comprehensive approach that considers the quality and function of natural water ecosystems, as well as their social and economic impacts.

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By integrating these diverse indicators, the river health index can offer a comprehensive assessment of the river's condition, enabling informed decision-making and targeted interventions to effectively manage and conserve the river ecosystem [14].

4.1 Physicochemical Indicator

Physicochemical indicators are measurable physical and chemical parameters used to assess the quality and characteristics of rivers. The major physicochemical parameters which are the dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammoniacal nitrogen (NH_3-N), total suspended solids (TSS) and pH, formed the WQI.

The importance of physicochemical indicators lies in their ability to fundamentally determine the type of water body and habitat [15]. One of the key physicochemical indicators is DO, which is critical for the survival and proliferation of aquatic organisms. The levels of dissolved oxygen can be influenced by various factors, such as temperature, water flow, and the presence of organic matter and pollutants [16]. Therefore, monitoring and maintaining appropriate levels of dissolved oxygen is essential for ensuring the overall health and sustainability of aquatic ecosystems. A study by Abd. Wahab et al., [17] showed that the range of DO is in the range of 2.11 mg/L – 8.07 mg/L for 29 sampling stations at Terengganu River Basin.

Additionally, BOD provides a measure of the amount of oxygen required by microorganisms to break down organic matter present in a water body [18]. This parameter is particularly important in evaluating the overall health and pollution levels in river. The biochemical oxygen demand is closely linked to the concentration of dissolved oxygen in the water. When organic waste materials are introduced into a water body, microorganisms begin to decompose them, a process that consumes dissolved oxygen [19]. As the organic matter is broken down, the demand for oxygen increases, leading to a decrease in the overall dissolved oxygen levels [18]. BOD concentration at Klang River and Juru River were recorded 7.33 to 11.28mg/L and 10.47 to 11.57mg/L respectively, this BOD classified as class III. BOD concentration is higher at both of the rivers mainly due to the influx of organic material stemming from domestic waste and rubbish [20].

Meanwhile COD measures the amount of oxygen required to chemically oxidize organic and inorganic pollutants in the water. This parameter is widely used to assess the degree of pollution in water. High COD values indicate a high concentration of oxidizable pollutants, which can be harmful to aquatic life and human health [21]. COD concentration at Klang River recorded between 22.74-32.5mg/l were classified as class I to IIB, while COD concentration at Juru River indicates the range between 37.95-38.18mg/l in class IIB [20].

Ammonia (NH_3) is a key parameter in assessing the water quality of rivers. Its presence and concentration can significantly impact aquatic ecosystems and human health [22]. A high amount of ammonia enters the aquatic environment via anthropogenic activities such as agricultural runoff and municipal effluent discharges and can lead to severe and even irreversible effects on aquatic ecosystems (Lin et al., 2019). NH3 concentration at Klang River recorded between 2.00-4.97mg/l which are classified as class III to V whereby it exceeds the standard level of NH_3 (0.9mg/L). Meanwhile, Juru River recorded NH3 in the range of 3.63-4.76mg/L (Class V). The increasing of NH_3 values is generally due to the decomposition process such as the waste from human and animal's faces, agricultural, fertilizers, domestic sewage and industry [20].

Total Suspended Solids (TSS) refers to the particles suspended in water that are not dissolved. These particles include a wide range of materials such as silt, decaying plant and animal matter, industrial wastes, and sewage. According to Abd. Wahab et al. [17] showed that the range of TSS is 0.4 mg/L – 128.2 mg/L in 29 sampling stations at Terengganu River Basin.

pH is a scale used to specify the acidity or basicity (alkalinity) of an aqueous solution. The optimum pH for river water is around 7.4. Extremes in pH can make a river inhospitable to life, while low pH is especially harmful to immature fish and insects. According to Zin et al. [20], pH index ranges at Klang River is between 6.91-7.25 and classified as class IIA-IIB. The level of pH still under controlled and it is not exceeding the standard level (pH 5). While. the pH level at Juru River showed as good level of alkalinity which recorded between 6.82-6.96 compared to Klang River.

4.2 Hydrological and hydraulics characteristics of river

A river's hydrological and hydraulic characteristics are crucial factors that determine the behaviour, flow, and overall dynamics of a water body. Hydrologic factors, such as runoff and groundwater, are closely linked to the operation of the hydrologic cycle and the specific conditions within the drainage basin. The knowledge of hydrology is a critical ingredient in decision-making processes where water resources are involved [24]. River basins, which encompass the drainage area of a river and its tributaries, play an essential role in managing and utilizing water resources. The location, direction, and other properties of river flow within a basin provide valuable insights into the availability and distribution of water (River Basins of Imo State for Sustainable Water Resources Management, 2014).

One primary water cycle component is streamflow, which encompasses water movement in rivers, channels, and seas. The main effect on streamflow is rainfall runoff in the watershed [25]. Water's roles are distributed and interact hierarchically in the landscape, and for the bulk of the drainage network, the duration of water availability represents the primary determinant of ecological processes [26].

Flood-associated disturbances and hydrologic exchange emerge as essential drivers of local dynamics only for the largest catchments with the most permanent flow regimes. Predicting how river ecosystems may respond to future environmental pressures will require a clear understanding of how changes in the spatial extent and relative overlap of these different roles of water shape ecological patterns [26]. Streamflow is a primary component of the water cycle and a critical hydrological factor required for water resources management and the operation of water resources. The main driver of streamflow is rainfall runoff within the watershed. However, the limited understanding of the critical factors that can influence hydrological processes often restricts the applicability of rainfall-runoff models [25].

Additionally, the duration of water availability can be the primary determinant of ecological processes in the bulk of the drainage network. At the same time, for the largest catchments, flood-associated disturbances and hydrologic exchange emerge as essential drivers of local dynamics [26]. Predicting how river ecosystems may respond to future environmental pressures will require a clear understanding of how changes in the spatial extent and relative overlap of these different roles of water shape ecological patterns [26]. The complex interactions between the controlling parameters often lead to critical issues like accelerated overland flow generation, soil erosion and sedimentation, landslides, and river flash floods (Sarkar et al., 2015). Experimental investigations have been conducted under diverse physical and hydrogeologic conditions to develop a physical understanding of the runoff generation processes [27].

Rapid population growth, urbanisation, drastic changes in land use, and growing industrialisation threaten water resources with increasing demand [28]. These factors directly or indirectly affect rainfall and streamflow patterns, emphasising the importance of estimating streamflow with available rainfall to manage water resources effectively [28].

Moreover, human factors can also significantly impact the hydrology and sedimentation of a river, both directly through engineering projects such as channelisation, dredging, and dam construction and indirectly through changes in floodplain land use that can lead to increased erosion during flood events [29]. With a comprehensive understanding of the impact of human activities on stream flow and sediment load in hydrological systems, the capacity to sustainably manage riverine ecosystems would be protected [30].

4.3 Geomorphology of river

Geomorphology, the scientific study of landforms and landscapes formed by natural processes on the Earth's surface, includes a crucial branch known as fluvial geomorphology. This field specifically focuses on the study of landforms shaped by flowing water, such as rivers and streams. Fluvial geomorphology is a powerful tool that empowers us to understand and manage river systems. The shape and dynamics of a river are intricately linked to its water and sediment regimes, which are in turn influenced by the watershed characteristics and human activities [31].

Analysing river basins' morphometric parameters, such as their area, shape, and stream network configuration, provides valuable insights into the hydrological behaviour and processes occurring within the basin. These parameters affect the time of concentration of water flow, which influences the river system's peak discharge and flood characteristics [32]. Understanding the principles of fluvial geomorphology and its application in river management is not just important, it's essential for sustainable development and water resource utilization. Fluvial geomorphology has a critical role to play in addressing regional and local-scale challenges, as it can inform decision-making and help mitigate the impacts of anthropogenic activities on riverine environments [33]. This knowledge enlightens us and equips us with the necessary tools to make informed decisions.

Over the past century, the focus of fluvial geomorphology has shifted from global-scale analyses to a greater emphasis on regional and local-scale problem-solving [33]. This transition has enabled fluvial geomorphologists to provide more targeted and practical insights to stakeholders, such as river managers, engineers, and policymakers, supporting them in their decision-making processes. Understanding the geomorphological timescales, data, and procedures involved in fluvial geomorphology in river management is essential to effectively applying the discipline [34]. By integrating this knowledge with an understanding of the water and sediment regimes, stakeholders can make informed decisions that balance the needs of human communities and the natural environment. Ultimately, integrating fluvial geomorphology into river management and engineering practices can lead to more sustainable and resilient river systems, which are crucial for the well-being of human societies and the natural world.

In summary, fluvial geomorphology provides a comprehensive framework for understanding the evolution and behaviour of river systems, which is essential for sustainable river management and the development of structures along watercourses.

4.4 Ecological Indicators

In recent years, researchers have recognized the importance of incorporating ecological indicators, such as fish species and macroinvertebrates, into assessing river health [35][36][37][38][39][40]. Fish and macroinvertebrates are

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sensitive to environmental changes and can provide valuable insights into the overall ecological condition of a river system [41]. Fish species and macroinvertebrates offer a more holistic approach to assessing river health, reflecting the cumulative impacts of various environmental stressors over time [42]. The presence and diversity of these organisms can serve as bioindicators, reflecting the overall health of the aquatic ecosystem, including the water quality, habitat, and trophic interactions.

Various studies have been conducted in Malaysia to assess the health of rivers using ecological indicators, mainly fish and macroinvertebrates. These studies have highlighted the importance of integrating these biological components into the overall river health assessment, as they can provide a more holistic understanding of the ecosystem's functioning. For instance, a study on the Ulu Bendul River in Negeri Sembilan, Malaysia, assessed the determinant factors for macroinvertebrate assemblages in a recreational river [43]. In a different study, Azrina et al. [44] investigated the effects of human activities on the macroinvertebrate communities and water quality in the Langat River. This study compares four pristine upstream stations with four downstream stations affected by anthropogenic activities.

Similarly, a study on the Beranang River in Selangor, Malaysia, evaluated the fish community structure and its relationship with environmental variables. The researchers found that water quality parameters, such as dissolved oxygen and pH, strongly influenced the fish community and habitat characteristics, such as substrate type and riparian vegetation [45]. Diverse fish communities generally indicate a healthy and well-functioning ecosystem, while a decline in fish diversity and abundance can signal ecological degradation. Studies have shown that the diversity and composition of fish communities are influenced by factors such as pollution, habitat fragmentation, and changes in land use [46]. For example, a study on the Langat River highlighted the decline in fish species diversity due to increased urbanization and industrial activities in the river basin [47]. The presence of sensitive fish species can indicate high water quality, while the dominance of tolerant species may suggest pollution or habitat degradation [48]. For instance, the study to evaluates the environmental factors affecting fish assemblages in the upper Sungai Pelus, Kuala Kangsar, Perak, Malaysia had found that water conductivity, river width, COD, and water velocity significantly influenced fish assemblages, and Neolissochilus hexagonolepis was the only species listed as nearly threatened, with the highest number of individuals recorded [49].

Using macroinvertebrates and fish in biomonitoring programs has become increasingly common, as these organisms offer complementary information about the overall health of river ecosystems. While macroinvertebrates can provide insights into localized, short-term changes, fish communities reflect the integration of conditions over a broader spatial and temporal scale. Furthermore, combining these two bioindicators can provide a more comprehensive assessment of the complex, interrelated factors that contribute to river health, such as water quality, habitat structure, and the balance of trophic levels.

4.5 Socioeconomics/ Sociological Indicators

In addition to the physicochemical and ecological aspects of river health, socioeconomic or sociological indicators are also important in evaluating the overall well-being of river systems [50]. These indicators can include factors such as the river's recreational and cultural value, its role in supporting local livelihoods, and the impact of river management policies on human communities [51]. Sociological indicators are crucial for understanding the multifaceted human dimensions of river health, as they consider the complex interplay of social, cultural, and economic factors between human communities and river systems. These indicators provide valuable insights into various aspects, including stakeholder involvement, land use patterns, community engagement, economic dependence, and cultural significance. These elements collectively play a vital role in shaping the overall health, resilience, and sustainability of river ecosystems, making sociological indicators indispensable for comprehensive river management and conservation efforts.

4.6 Stakeholder Involvement

Active participation of diverse stakeholders is crucial for inclusive and sustainable river management. These stakeholders include local communities, governmental agencies, non-governmental organizations, and businesses, each bringing unique interests and perspectives. Effective involvement of stakeholders ensures that these varied interests are represented in management decisions, promoting cooperative and adaptive governance. Indicators of stakeholder involvement include the frequency and attendance of stakeholder meetings, the extent of stakeholder influence on management decisions, and the availability and effectiveness of awareness and education programs. Research by Vollmer et al. [52] underscores the importance of stakeholder participation in integrated water resources management, emphasizing that inclusive governance leads to more adaptive and resilient water management systems. Similarly, Bezerra et al. [53] highlight that inclusive stakeholder participation fosters adaptability and resilience in water management systems.

4.7 Land use

Land use patterns have a significant impact on the overall health and ecological integrity of river systems. Understanding this relationship is crucial for developing effective strategies to protect and manage these valuable natural resources [54]. Urbanization and the expansion of human activities, such as agriculture and mining, can have detrimental effects on river ecosystems [54][55]. These activities often disrupt the continuity of rivers, altering key factors like flow velocity, nutrient load, sediment deposition, and water [56]. Such changes can directly or indirectly impact the survival of aquatic organisms, water quality, and the overall health of the river ecosystem [56]. Another previous research stated that inappropriate land use activities lead to the deterioration of water quality [57].

The connection between land use and surface water quality is well-documented [54]. Increased urbanization and agricultural development can lead to higher levels of conventional water pollution, such as nutrients and sediments, as well as toxic pollutants from transportation and mining activities [55]. These pollutants can degrade water quality, impacting aquatic life, recreational use, and the overall ecological functioning of the river. Concurrently, changes in land use can also affect the hydrology of river systems, leading to alterations in stream flow, flooding patterns, and groundwater recharge [58]. Effective integrated planning and management approaches that consider both land and water resources within a watershed framework are crucial for addressing these complex interactions and ensuring the long-term sustainability of river systems [58].

Past research has shown that the specific impacts of land use on river health can vary depending on the intensity and distribution of different land use types [59]. For example, the

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expansion of urban and agricultural areas may lead to increased nutrient and sediment loads, while the loss of natural vegetation, such as forests, can reduce the buffering capacity of the landscape and exacerbate water quality issues. By understanding these relationships, policymakers and resource managers can develop targeted strategies to mitigate the negative effects of land use changes and promote the overall health and resilience of river ecosystems.

5. Integrating the river health indicators for an evaluation framework

In the process of developing a River Health Index (RHI) in Malaysia, several international applications have been referred to, which can help in the process of determining the index and sub-index for the development of RHI in Malaysia. In China, the river health assessment for the Dagujia River in China was based on the WQI methodology. This approach involves grading various indicators such as Water Temperature Variation (WTV), Dissolved Oxygen (DO) Index, Oxygen Consumption Organic Pollutants (OCP), and Heavy Metals Pollutants. The study identified five health status levels: ideal, healthy, sub-healthy, unhealthy, and morbid, with corresponding scores and colours (blue for ideal, green for healthy, etc.). The findings of river health index, as shown in Figure 1, highlighted that the DO index was optimal for aquatic life, scoring a full 100, while heavy metal pollutants also scored zero, indicating no contamination. However, high WTV resulted in poor health status, with 66.3% of the assessed river sections falling into the morbid category. This emphasizes that temperature variation is a crucial factor affecting river health in the Dagujia River [60].

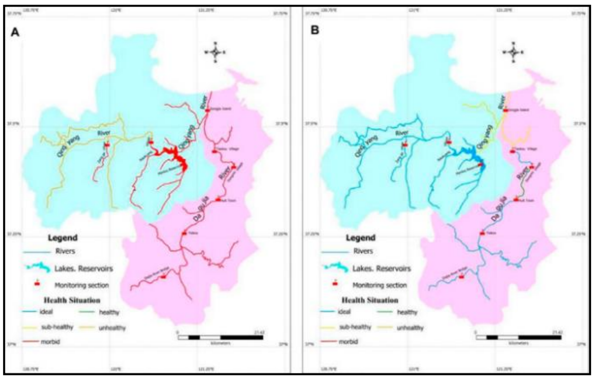

Fig. 1 – Health assessment results of the Dagujia River, showing results including water temperature variation and excluding heavy metal pollutants [60]

Another study by Luo et al. [61] developed an RHI based on harmony theory, integrating human activities into the assessment. The RHI considers both the Human Service Demand Index (HSDI) and the River Ecosystem Integrity Index (REII). The assessment categorized river health into five grades, ranging from health (0.8-1.0) to morbidity (0-0.2). The RHI evaluation for China's ten first-grade water resource zones in 2019 revealed that the southeastern rivers and the Taihu Lake scored the highest at a medium-high level, while the Liaohe and Haihe rivers scored lower, indicating medium-low happiness levels.

Meanwhile, in Thailand, researchers from the Asian Institute of Technology (AIT) developed a framework for river health assessment. This framework, as shown in Figure 2, outlined in a manual, focuses on various dimensions of river health, including biological, physical habitat, water quality, and socio-economic factors. The River Health Index (RHI) in Thailand is a numeric value ranging from 1 to 5, representing different health levels. Indicators are used to quantify these dimensions, ensuring a comprehensive evaluation of river health. For example, the biological dimension considers the well-being of aquatic life, while the physical habitat dimension assesses flow stability and erosion control [62].

The framework also includes variables such as the concentration of dissolved oxygen and biochemical oxygen demand to measure the self-cleansing property of rivers. Socio-economic indicators evaluate ecosystem services for human activities and investment in river protection. This holistic approach ensures that all aspects of river health are addressed, from ecological conditions to human impacts. The implementation of this framework aims to provide a clear and systematic method for assessing and improving river health in Thailand [62].

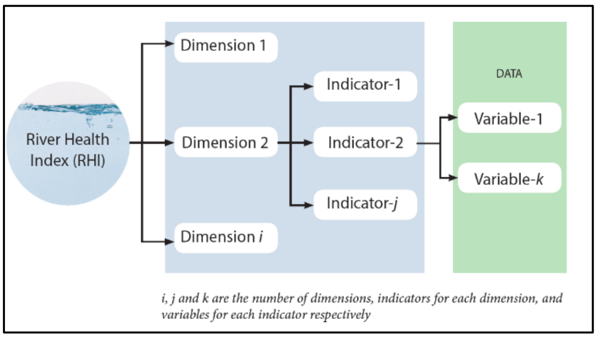

Fig. 2 – Schematic of the basin-scale river health assessment framework [62].

To construct an effective River Health Index (RHI), it is crucial to integrate diverse parameters that offer a comprehensive assessment of the river ecosystem. The methodology involves incorporating biological, physical, chemical, and sociological indicators, each contributing unique insights into river health.

First, physical indicators examine the river's geomorphological characteristics, including water flow patterns, sediment dynamics, and the integrity of the riparian zone can be the suitable sub-index. Parameters like streamflow and sediment transport are essential for understanding the river's dynamics and its ability to support diverse aquatic life. Natural flow regimes and stable riverbanks usually denote a healthy environment, while altered patterns and significant sediment deposition often indicate human impacts.

Next, chemical indicators such as nutrient levels, total coliform, and salinity are vital for evaluating water quality and identifying pollution sources needs to be also be included. Elevated nutrient levels can lead to eutrophication and algal blooms, while high total coliform counts indicate fecal contamination. These chemical parameters ensure a thorough understanding of factors influencing river health.

Then, biological indicators such as fish species and macroinvertebrates are highly sensitive to environmental changes can also be the perfect indicator for the RHI. Their diversity and abundance reflect the ecological condition of the river, where sensitive species indicate good water quality, and pollution-tolerant species signal degradation. These indicators help assess the cumulative impacts of environmental stressors over time.

Sociological indicators that focus on human activities, including land use patterns and stakeholder engagement can also be incorporated in the RHI as the attributes. By evaluating these indicators, researchers can identify primary pollution sources and habitat degradation, guiding targeted management strategies. Involving local communities and stakeholders ensures diverse perspectives are considered, enhancing the relevance and effectiveness of river health management practices.

To integrate these parameters effectively, the Multi-Criteria Decision Analysis (MCDA) using the Analytic Hierarchy Process (AHP) is suggested. This method helps priorities and weigh the importance of different indicators, providing a structured approach to derive a composite River Health Index (RHI). MCDA systematically addresses complex decision-making problems involving multiple criteria by organizing the decision problem into objectives, criteria, and alternatives. By aggregating the scores of various indicators, the overall RHI can be calculated, providing a single, actionable metric for decision-makers. This holistic assessment tool facilitates the identification of priority areas for intervention and monitoring of long-term trends in river health. Integrating expert judgments and systematically evaluating multiple criteria ensures a balanced and comprehensive river health assessment.

AHP, a widely used MCDA method, simplifies complex decision-making through pairwise comparisons and expert judgment. The process involves constructing a hierarchy of criteria and sub-criteria, comparing them in pairs to establish relative importance, and calculating priority scales. The priority scale ranges from 1 (equal importance) to 9 (extreme importance). For instance, a scale of 1 indicates equal importance, while a scale of 9 denotes extreme importance.

Table 4 – The scale of relative importance in AHP

The scale of relative importance	
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very strong to extreme importance
9	Extreme importance

The AHP method can be applied to evaluate various sub-indices, including physical, chemical, biological, and sociological/socioeconomics factors, to develop the River Health Index (RHI). Table 5 provides an example of evaluation process for these sub-indices through pairwise comparisons method.

Table 5 illustrates the physical sub-index is compared to the chemical, biological, and sociological sub-indices, and the relative importance is rated. For instance, the physical sub-index is considered to have stronger importance (rated 5) compared to the chemical sub-index. From this understanding, the MCDA-AHP method can contribute to the creation of a comprehensive and context-specific index that supports informed decision-making for river management. Each sub-index might need to be further elaborated by a second-tier parameters, which may be refered to as attributes. These attributes for each sub-index should also be evaluated using the same method to assign specific weights. The selection of these attributes must involve stakeholders, as their importance is significantly influenced by the river's function, such as, food security, flood mitigation etc.

Table 5 – Pairwise comparison example for RHI evaluation by using MCDA-AHP method

Sub-index	Physical	Chemical	Biological	Sociological
Physical	1	5	4	7
Chemical	0.2	1	0.5	0.3
Biological	0.25	2	1	3
Sociological	0.14	0.33	0.33	1

Table 5 illustrates the physical sub-index is compared to the chemical, biological, and sociological sub-indices, and the relative importance is rated. For instance, the physical sub-index is considered to have stronger importance (rated 5) compared to the chemical sub-index. From this understanding, the MCDA-AHP method can contribute to the creation of a comprehensive and context-specific index that supports informed decision-making for river management. Each sub-index might need to be further elaborated by a second-tier parameters, which may be refered to as attributes. These attributes for each sub-index should also be evaluated using the same method to assign specific weights. The selection of these attributes must involve stakeholders, as their importance is significantly influenced by the river's function, such as, food security, flood mitigation etc.

6. River Health Index (RHI) Development in Malaysia

The development of RHI in Malaysia was undertaken through a comprehensive feasibility study, using Sungai Muda Basin (Kedah–Pulau Pinang) and Sungai Kurau Basin (Kerian, Perak) as initial case studies. The selection of these two basins was considered based on their critical roles for domestic water supply, agricultural irrigation, and national food security. as compare to other river basin, which were for domestic water supply, agricultural irrigation, and national food security. These importance making both river basins highly relevant for evaluating the applicability of a holistic river health assessment framework in Malaysia.

6.1 RHI Framework and Methodological Approach

The RHI framework was developed using a Multi-Criteria Decision Analysis (MCDA) approach, specifically the Analytical Hierarchy Process (AHP), to determine the relative importance of river health components and their associated attributes. Four main sub-indices form the core structure of the RHI:

a) Chemical Sub-Index (30%), incorporating WQI, nutrients, faecal coliform, salinity, and supporting water quality parameters;

b) Physical Sub-Index (27%), including river flow characteristics, sediment transport, river reserve condition, turbidity, colour, and odour;

c) Biological Sub-Index (25%), assessed using benthic macroinvertebrates (BMWP) and fish indices; and

d) Sociological Sub-Index (18%), represented by land use patterns and stakeholder engagement.

These attributes and related weightages are based on the feedback from relevant technical agencies, which then will put a score standardised, and aggregated based on its assigned weight.

$$RHI\ (\%) = W_C A_C + W_P A_P + W_B A_B + W_S A_S$$

Where

W_C = Weightage of Chemical;

W_P = Weightage of Physical sub-index,

W_B =Weightage of Biological sub-index,

W_S =Weightage of Sociological sub-index,

A_C =Normalised score of Chemical attributes

A_P = Normalised score of Physical attributes

A_B = Normalised score of Biological attributes

A_S = Normalised score of Sociological attributes

The RHI value then was expressed as a percentage, and the value were then being referred to a health category as Table 6 below

Table 6 – Classification of RHI

RHI (%)	Category	Description
75-100	A	Very healthy
50-74	B	Moderately healthy
25-49	C	Poor
0-24	D	Very Poor

This structured approach allows for consistent spatial and temporal comparison of river health conditions across different river reaches and seasons.

6.2 Application and Results in the Sungai Muda and Kerian River Basins

The application of RHI in the Sungai Muda and Sungai Kurau basins revealed a clear upstream–downstream gradient in river health status (Figure 3 and Figure 4). In general, upstream sections of both rivers recorded RHI values within Category A (Very Healthy), reflecting relatively intact ecosystems, better water quality, higher biological diversity, and minimal anthropogenic disturbance. Moving downstream, RHI values declined to Category B (Moderately Healthy), particularly in areas influenced by intensive agriculture, settlements, small-scale industries, and land use modification. In the Sungai Muda Basin, seasonal variability was evident, with slightly higher RHI values observed during the wet season compared to the dry season, likely due to dilution effects and changes in flow regime.

In contrast, Sungai Kurau exhibited less pronounced seasonal variation, reflecting differences in basin characteristics and dominant land use activities. Biological assessments supported these findings, where upstream reaches exhibited more diverse and pollution-sensitive macroinvertebrate and fish communities, while downstream sections were dominated by more tolerant species.

Additionally, stakeholder engagement outcomes highlighted key pressures affecting river health in both basins, including agricultural runoff, domestic wastewater discharge, river reserve encroachment, and land clearing activities.

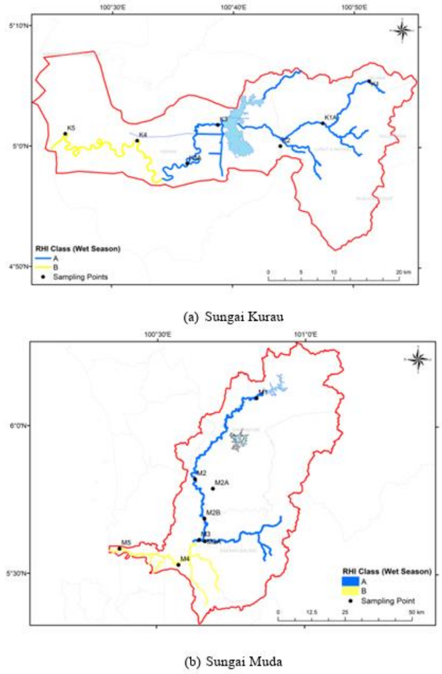

Fig. 3 - RHI value for Sungai Kurau Basin dan Sungai Muda Basin during the wet period

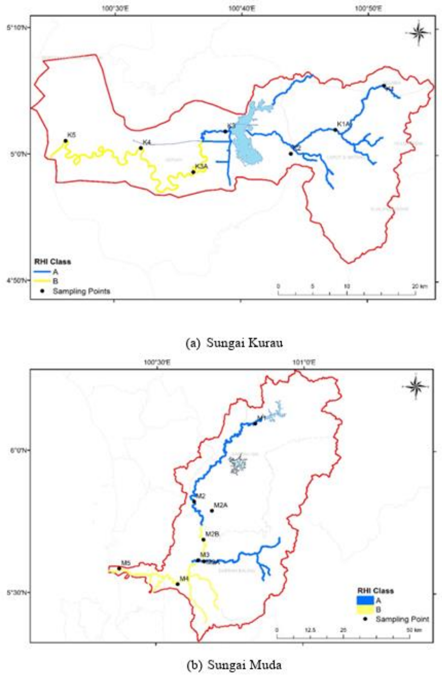

Fig. 4 - RHI value for Sungai Kurau Basin dan Sungai Muda Basin during the dry period

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6.3 Implications for River Basin Management

Overall, the findings of this study demonstrate that the River Health Index (RHI) provides a more comprehensive representation of river condition than conventional water quality indices alone. The integration of biological, chemical, physical, and sociological dimensions, RHI enhances the ability of river managers to identify priority issues, evaluate management effectiveness, and support evidence-based decision-making. The successful application of RHI in the Sungai Muda and Kerian basins indicates its strong potential to be adopted as a supporting assessment tool for sustainable river basin management in Malaysia.

7. Conclusion

Assessing river health requires a comprehensive approach that considers physical, chemical, biological, and socioeconomic factors. Fluvial geomorphology provides a fundamental understanding of the river's physical characteristics and dynamics, shaping its flow patterns, sediment transport, and overall landscape. This knowledge is crucial for understanding the river's natural processes and how human activities might disrupt them.

Ecological indicators, such as fish and macroinvertebrates, act as sensitive sentinels of environmental change. Their presence, diversity, and abundance reflect the overall health of the river ecosystem, indicating water quality, habitat integrity, and the balance of trophic levels. These biological indicators provide a valuable complement to physical and chemical assessments, offering a more holistic perspective on the river's well-being.

Sociology/socioeconomic indicators, encompassing stakeholder involvement, land use patterns, and the cultural and economic values associated with the river, are equally vital. These factors highlight the complex interplay between human communities and river systems, emphasizing the need for inclusive and sustainable management practices.

Integrating these diverse indicators into a comprehensive River Health Index (RHI) framework allows for a robust and nuanced evaluation of river health. By employing multi-criteria decision analysis (MCDA) methods, such as the Analytic Hierarchy Process (AHP), one can prioritize and weigh the relative importance of different indicators, ensuring a balanced and context-specific assessment.

The development and implementation of an RHI require active stakeholder engagement, incorporating local knowledge and expertise to ensure the index reflects the specific needs and challenges of the river. This collaborative approach fosters acceptance and support for the index, promoting adaptive management and ensuring its ongoing relevance and effectiveness.

Some examples of how your references should be listed are given at the end of this template in the 'References' section, which will allow you to assemble your reference list according to the correct format and font size.

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