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ASSESSMENT OF WATER QUALITY AND HEAVY METAL CONTAMINATION (ALUMINUM, IRON, COPPER, CADMIUM, LEAD, AND ZINC) IN TERENGGANU, SETIU AND BESUT RIVERS, MALAYSIA

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Graphical abstract

Abstract

Rivers in Malaysia, including the Terengganu, Setiu, and Besut Rivers, serve as vital water sources for domestic, agricultural and aquaculture use. However, their quality has deteriorated due to pollutants such as heavy metals, excessive nutrients, and organic waste, primarily from industrial discharge, agricultural runoff, batik dye effluents and untreated sewage. Hence, this study assessed key indicators of water quality, including temperature, pH, dissolved oxygen (DO), chemical and biological oxygen demand (COD) and (BOD), total suspended solids (TSS), and ammoniacal nitrogen (NH3-N), along with heavy metal content, during wet and dry seasons. Water quality was analysed using the APHA 2017 method, and heavy metal concentrations were measured using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). The Water Quality Index (WQI) classified the rivers as Class III, indicating the need for extensive water treatment. These rivers support economically significant fish species that are tolerant of moderate pollution and are suitable for livestock consumption. Heavy metal concentrations followed the hierarchy of Fe>Cu>Al>Zn>Cd>Pb in the Terengganu River, Fe>Cu>Al>Cd>Zn>Pb in Setiu River, and Al>Fe>Cu>Cd>Pb>Zn in Besut River. The highest recorded concentrations were Fe in the Terengganu and Setiu Rivers (0.92 and 1.30 ppm, respectively), while Al (0.44 ppm) was highest in the Besut River. These findings suggest that pollution sources originated from industrial discharge, batik manufacturing, agricultural runoff, untreated sewage, and transportation activities near the rivers. This study indicated that Terengganu needs better wastewater treatment, stricter enforcement of industrial discharge regulations and more public awareness programs to protect its water quality.

Keywords: Besut, Heavy metal, River, Setiu, Water quality

Abstrak

Sungai-sungai di Malaysia, termasuk Sungai Terengganu, Setiu, dan Besut, merupakan sumber air penting untuk kegunaan domestik, pertanian dan akuakultur. Walau bagaimanapun, kualitinya semakin merosot akibat pencemaran seperti logam berat, nutrien berlebihan dan sisa organik, yang berpunca terutamanya daripada pelepasan industri, larian air pertanian, efluen celupan batik dan kumbahan yang tidak dirawat. Oleh itu, kajian ini menilai penunjuk utama kualiti air seperti suhu, pH, oksigen terlarut (DO), permintaan oksigen kimia dan biologi (COD dan BOD), jumlah pepejal terampai (TSS), dan nitrogen amonia (NH3-N), bersama kandungan logam berat, semasa musim hujan dan kemarau. Kualiti air dianalisis menggunakan kaedah APHA 2017, dan kepekatan logam berat diukur menggunakan Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES). Indeks Kualiti Air (WQI) mengklasifikasikan sungai-sungai ini sebagai Kelas III, yang memerlukan rawatan air secara meluas. Sungai-sungai ini menyokong spesies ikan yang bernilai ekonomi, yang toleran terhadap pencemaran sederhana dan sesuai untuk kegunaan ternakan. Kepekatan logam berat menunjukkan susunan Fe>Cu>Al>Zn>Cd>Pb di Sungai Terengganu, Fe>Cu>Al>Cd>Zn>Pb di Sungai Setiu, dan Al>Fe>Cu>Cd>Pb>Zn di Sungai Besut. Kepekatan tertinggi dicatatkan ialah Fe di Sungai Terengganu dan Setiu (masing-masing 0.92 dan 1.30 ppm), manakala Al (0.44 ppm) adalah tertinggi di Sungai Besut. Penemuan ini mencadangkan bahawa sumber pencemaran berasal daripada pelepasan industri, pembuatan batik, larian air pertanian, kumbahan tidak dirawat dan aktiviti pengangkutan berhampiran sungai. Kajian ini menunjukkan bahawa Terengganu memerlukan rawatan kumbahan yang lebih baik, penguatkuasaan yang lebih tegas terhadap pelepasan industri dan program kesedaran awam yang lebih meluas bagi melindungi kualiti air.

Kata kunci: Besut, logam berat, sungai, Setiu, kualiti air

1.0 INTRODUCTION

Rivers serve as vital water sources and play a crucial role in environmental sustainability. A nation's ability to balance development with ecological conservation reflects its commitment to sustainable progress. Beyond supporting human needs, rivers sustain aquatic ecosystems, provide renewable energy, regulate drainage, and serve as habitats for diverse flora and fauna [1,2,3]. Although 71% of the Earth's surface is covered by water, rivers account for only 0.006% of the total water supply, making their preservation essential for maintaining clean water resources.

In Malaysia, rivers supply approximately 97% of the nation's water [4]. Population expansion, urbanization, and economic growth have led to an increasing water demand, placing greater pressure on river systems [5,6]. Initially, rivers are in a pristine state, but they gradually accumulate pollutants from two main sources: point and non-point sources. Non-point sources originate from dispersed activities such as small and medium-sized enterprises (SMEs), household waste, and agricultural runoff, which flow into the drainage systems and consequently pollute rivers [7]. In contrast, point source pollution comes from industrial facilities that discharge scheduled waste. In addition to chemical and physical contamination, which alter water colour and taste, suspended materials further degrade water quality [8]. Prolonged exposure to polluted water poses significant health risks to communities relying on rivers for daily activities. The number of contaminated rivers in Malaysia was increasing by 2020, with 51 out of 477 monitored rivers by the Department of Environment (DOE) Malaysia classified as polluted and 168 were slightly polluted, making them unfit for human consumption [8].

In Peninsular Malaysia, the highly populated and tourist-driven state of Terengganu is well known for fish crackers and Batik industries. These industries potentially contribute to river pollution by discharging waste, particularly in Besut, Setiu, and Terengganu Rivers. Batik production generates wastewater containing dyes, heavy metals, and suspended solids, which many small-scale operators fail to treat before release [9]. This industrial sewage significantly pollutes river ecosystems, exacerbating environmental risks.

Furthermore, heavy metal pollution is a critical concern due to its persistence in aquatic environments. Heavy metals are elements with high atomic weight and density (>5 g/cm³) and are toxic even at low concentrations [10]. Heavy metals mainly enter the environment through industrial waste and contaminated food and beverages. This contamination is particularly harmful due to the toxin's ability to biomagnify within biological systems, posing significant risks to human health and ecosystems [8]. Exposure to waterborne pathogens, including bacteria *Vibrio cholerae*, and *Salmonella Typhi* can lead to cholera disease and typhoid fever, while prolonged exposure to heavy metals like lead or cadmium has been linked to neurological, renal, and developmental issues [8].

Land development, industrial activities, and agriculture in the middle to lower reaches of the Terengganu River have increased the amount of heavy metal contamination [11, 12]. Agricultural runoff in Besut and sand mining activity along the Setiu River [13] contribute to contamination. The runoff may carry soluble and particulate forms of Fe, washing off into adjacent waterways during rainfall events. Sand mining, which extracts large volumes of sand from riverbeds and banks, can release trapped heavy metals from the benthic layer into the water column, increasing the existing metals from the industrial and waste effluents and agricultural runoff [14]. While Besut lacks major industries, it plays a critical role in wastewater dilution and irrigation [15].

Unlike organic contaminants, heavy metals are non-biodegradable and accumulate in aquatic organisms and sediments. Pollutant accumulation in aquatic biota through the food chain leads to reproductive and physiological disorders, damaging organs, disrupting endocrine system and reducing fecundity, hence, altering the species biodiversity composition by selectively eliminating sensitive taxa while proliferating tolerant species. The reduction in certain species diversity might collapse the complex ecological interactions, weakening ecosystem resilience and function [16,17].

In light of the health and environmental risks associated with heavy metal contamination, continuous regulation and monitoring are essential to preserving river ecosystems and mitigating pollution. Therefore, this study aimed to assess water quality (temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), ammoniacal nitrogen (NH_3-N), and heavy metal contamination (Al, Cd, Cu, Zn, Fe, and Pb) in the Terengganu, Setiu, and Besut Rivers, providing necessary data for sustainable management of water resources.

2.0 MATERIALS AND METHODS

Study Area

The present study took place in the Terengganu, Setiu, and Besut Rivers, with three stations per river. The rivers have been selected as study sites as they support urban, industrial, agricultural, aquaculture, residential areas and tourism activities. These anthropogenic pressures potentially contribute to metal pollution, thereby necessitating monitoring activities to mitigate associated human and ecosystem health risks. In addition, the rivers are varied in length, catchment area and hydrological characteristics, which might influence the water quality and heavy metal levels. The sampling was conducted seasonally in November 2023 (wet season) and May 2024 (dry season).

Terengganu River

The Terengganu River, situated in the centre of Terengganu State, extends 64.4 km from Kenyir Lake to the South China Sea, covering a catchment area of 4,560 km² [18]. The river crosses the Hulu Terengganu, Kuala Terengganu, and Setiu districts, receiving inflows from the Telemung, Berang, Tersat, and Nerus Rivers. The total catchment area of 5,000 km² supports various socio-economic activities, including industry, aquaculture, agriculture and urban development [12]. This study focused on major metropolitan areas, including Seberang Takir and Kuala Terengganu, which are key tourist destinations with direct access to the city centre. Three sampling stations were selected along the Terengganu River, as shown in Table 1 and Figure 1.

Table 1 Sampling Station of Terengganu Rivers

Rivers	Station 1	Station 2	Station 3
Terengganu	5°21'05.0"N 103°07'49.8"E	5°20'16.2"N 103°08'06.7"E	5°20'44.7"N 103°08'08.1"E
Besut	5°44'15.3"N 102°29'48.2"E	5°48'12.5"N 102°34'08.5"E	5°49'40.2"N 102°33'23.0"E
Setiu	5°36'14.1"N 102°48'55.3"E	5°35'23.9"N 102°46'56.7"E	5°31'14.2"N 102°44'38.5"E

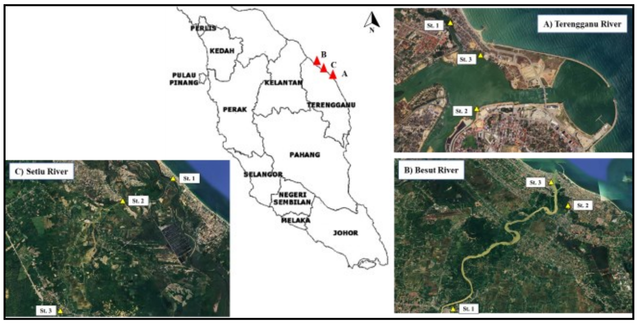


Figure 1 Map of sampling sites. The centre panel shows the location of the Peninsular Malaysia. The right panel depicts the Terengganu and Besut rivers, while the left panel illustrates the Setiu river. Yellow triangles indicate sampling stations, and red triangles represent main rivers

Setiu River

The Setiu River, located in the Setiu district on the east coast of Peninsular Malaysia, is a crucial aquatic system with a watershed covering approximately 188 km² and extending 52 km in length [19]. The district shares its northern boundary with Besut, its southern border with Kuala Nerus, and its western edge with Hulu Terengganu. Hydrologically, the Setiu River serves as a primary freshwater source for agricultural and domestic use, providing essential irrigation for crop farming. It also helps in diluting wastewater and supports the fishing and aquaculture industries, which are vital to the livelihoods of local communities [13]. Furthermore, as the river is hydrologically connected to the Setiu Wetlands, it receives freshwater inflows from the southeast before discharging into the wetland ecosystem. Three stations were selected along the Setiu River (Table 1 and Figure 1), near the residences where fishing and agriculture (vegetable and fruit cultivation) are prominent. Additionally, these sites are closely linked to developments driven by tourism, highlighting the river's importance in regional ecotourism.

Besut River

The Besut River, situated in northern Terengganu, originates in the non-coastal areas and flows eastward into the South China Sea, where it discharges. The river has a 953 km² catchment area, with its lower reaches covered by a predominantly swampy and flat landscape. The Besut River serves as the main drainage system for the eastern region of Kuala Besut, receiving inflows from several tributaries, including the Pelagat, Angga, Peda, Jertih, Tenang, La, and Keriuk rivers [15]. While the river basin lacks significant industrial activities, the towns of Jertih, Kampung Raja, and Kuala Besut are located along its lower and middle reaches, where population density is relatively high. Three stations were selected (Table 1 and Figure1) near a fishing boat port and a fish cracker sausage (keropok lekor) processing facility. During the site survey, researchers observed oil spills from boats and detected foul odours from the river, indicating possible pollution sources.

Field Sampling and Laboratory Analysis

For each sampling event, triplicate water quality indicators- including temperature, pH, and dissolved oxygen (DO) were assessed from the riverbank by lowering a YSI Handheld Multiparameter Probe into the river. Water samples for biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), ammoniacal nitrogen (NH_3-N), and heavy metals (Al, Cd, Cu, Zn, Fe, and Pb) were collected and brought back to the laboratory for further analysis and processing. The heavy metal contents were assessed through Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). The quality control included procedural analytical blanks and standard reference materials (SRM 1643f). Table 2 provides an overview of the water quality parameters examined and the methods used.

Table 2 Analysis of water quality parameters and method used

Water quality parameter	Unit	Method
Temperature	℃	In situ measurement, YSI Handheld Multiparameter Probe
pH		
Dissolved oxygen (DO)	mg/l	
Chemical oxygen demand (COD)	mg/l	APHA (2017). Method 5220D (Closed reflux, Colorimetric). Measured using HACHDR 2800 Colorimeter at 620 nm
Biochemical oxygen demand (BOD)	mg/l	APHA (2017). Method 5210B (5-days incubation at 20℃). Final reading measured using YSI Probe
Total suspended solid (TSS)	mg/l	APHA (2017), Method 2540D (Turbidity estimation using a photometer, calibrated with gravimetric validation
Ammoniacal Nitrogen (NH_3-N)	mg/l	Salicylate Method (USEPA Method 10023). Measured using HACH DR2800 Colorimeter at 655 nm)

APHA= American Public Health Association
USEPA= United States Environmental Protection Agency

Statistical Analysis

A two-way analysis of variance (ANOVA) was conducted to assess the effect of river locations (Terengganu, Setiu, and Besut rivers) and seasonal variations (monsoon and non-monsoon) on water quality parameters and heavy metal concentrations. This statistical approach allowed for the evaluation of the main effects of each parameter and their potential interactions on water quality variations. The two-way ANOVA was used to assess significant differences in key physicochemical parameters and heavy metal concentrations (where applicable) due to spatial variability among the rivers and seasonal changes. All data analyses were carried out using the Statistical Package for the Social Sciences (SPSS, version 26, IBM). Before applying ANOVA, tests for normality and homogeneity of variances were carried out to determine whether the data met parametric assumptions, using a 95% significance level. The Tukey post-hoc test was conducted when significant differences were found to identify specific differences between groups. Multiple linear regression (MLR) analyses were conducted using SPSS to study the relationship between six heavy metals (Fe, Cd, Al, Cu, Zn, and Pb) with water quality parameters (temperature, pH, DO, BOD, COD, TSS and NH_3-N).

Water Quality Index (WQI)

The Water Quality Index (WQI) is a mathematical formula that integrates multiple water quality parameters into a single value for assessing water quality [20]. In Malaysia, the classification of river water quality and determination of its suitability for various uses or necessary treatment levels are based on the National Water Quality Standards (NWQS; Table 3).

Table 3 National Water Quality Standards for Malaysia-NWQS 2021

		Class				
Parameters	**Unit**	**I**	**IIA/IIB**	**III**	**IV**	**V**
pH		6.5–8.5	6–9	6–9	5–9	–
DO	mg/L	> 77	5–7	3–5	1–3	< 1
BOD_5	mg/L	< 1	1–3	3–6	6–12	> 12
COD	mg/L	< 10	10–25	25–50	50–100	> 100
SS	mg/L	< 25	25–50	50–150	150–300	> 300
AN	mg/L	< 0.1	0.1–0.3	0.3–0.9	0.9–2.7	> 2.7
Mn	mg/L	Natural level or absent	0.1	0.1	0.2	Level above IV
NO_2 (nitrite)	mg/L	Natural level or absent	0.4	0.4	–	Level above IV
NO_3 (nitrate)	mg/L	Natural level or absent	5	–	7	Level above IV
P	mg/L	Natural level or absent	0.1	0.2	–	Level above IV
WQI		**> 92.7**	**76.5–92.7**	**51.9–76.5**	**31.0–51.9**	**< 31.0**

Class I (preservation of natural environment. Water supply I—Minimum no treatment needed. Fishery I—Supports sensitive aquatic species). Class IIA (Water supply II—Requires standard treatment. Fishery II—Habitat for sensitive aquatic species). Class IIB (Recreational use with body contact permitted). Class III (Water supply III—Extensive treatment required. Fishery III—Common of economic value and tolerant species; livestock drinking). Class IV (Agricultural irrigation). Class V (none of the above).

The Water Quality Index (WQI) was derived based on six key parameters: dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), ammoniacal nitrogen (NH_3-N), pH, and total suspended solids (TSS), applying the following formula:

$$WQI = (0.22 \times SDO) + (0.19 \times SBOD) + (0.16 \times SCOD) + (0.15 \times SNH3\text{-}N) + (0.16 \times STSS) + (0.12 \times SpH)$$

Where:
SDO, SBOD, SCOD, SAN, STSS, and SpH represent the sub-index values for each parameter obtained using standard WQI sub-index equations (Table 4).

Table 4 Equations for determination of parameter's sub-index [20]

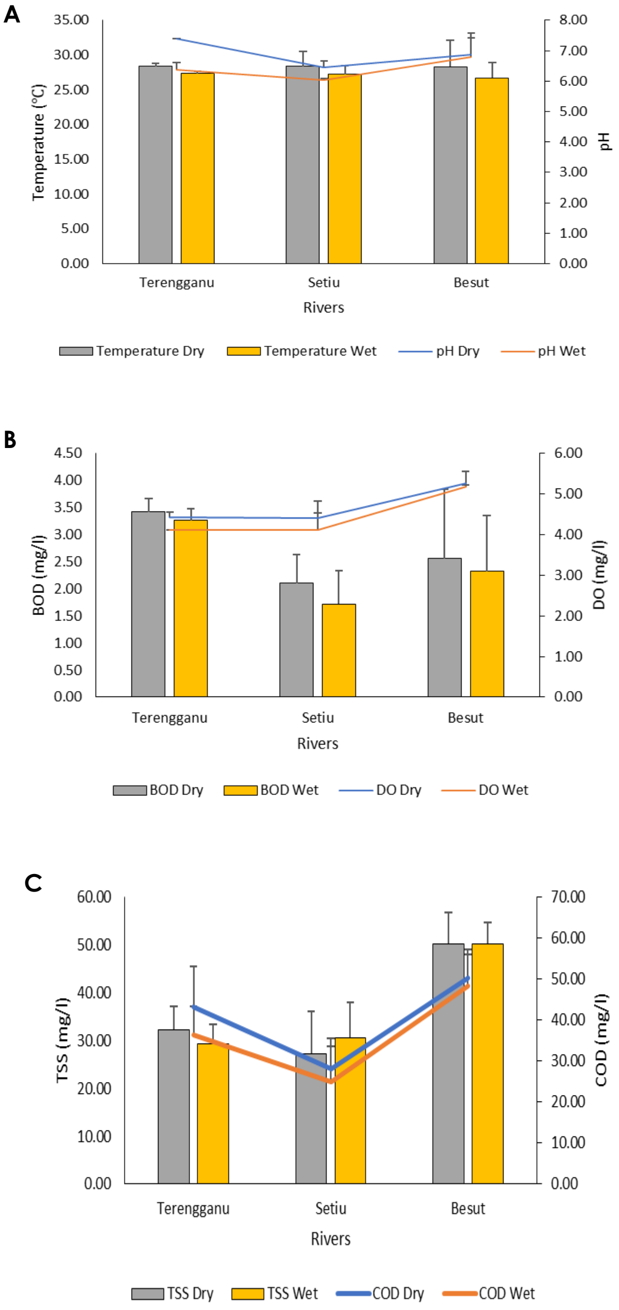
1	**Sub-index DO (ml/L)**	
	$x \le 8\%$	SIDO = 0
	$x \ge 92\%$	SIDO = 100
	$8\% < x < 92\%$	SIDO = $-0.395 + 0.030 \times^{2} - 0.00020 \times^{3}$
2	**Sub-index BOD (ml/L)**	
	$x \le 5$	SIBOD = $100.4 - 4.23x$
	$x > 5$	SIBOD = $108e^{-0.055x} - 0.1$
3	**Sub-index COD (ml/L)**	
	$x \le 20$	SICOD = $-1.33x + 99.1$
	$x > 20$	SICOD = $103e^{-0.0157x} - 0.04x$
4	**Sub-index NH_3-N (ml/L)**	
	$x \le 0.3$	SIAN = $100.5 - 105x$
	$0.3 < x < 4$	SIAN = $94e^{-0.573x} - 5\ \lvert x-2 \rvert$
	$x > 4$	SIAN = 0
5	**Sub-index TSS (ml/L)**	
	$x \le 100$	SITSS = $97.5e^{-0.00676x} + 0.05x$
	$100 < x < 1000$	SITSS = $71e^{-0.0016x} - 0.015x$
	$x > 1000$	SITSS = 0
6	**Sub-index pH**	
	$x < 5.5$	SIpH = $17.2 - 17.2x + 5.02 \times^{2}$
	$5.5 \le x < 7$	SIpH = $-242 + 95.5x - 6.67 \times^{2}$
	$7 \le x < 8.75$	SIpH = $-181 + 82.4x - 6.05 \times^{2}$
	$x \ge 8.75$	SIpH = $536 - 77.0x + 2.76 \times^{2}$

Note: X is the concentration in mg/L for all parameters except pH

3.0 RESULTS AND DISCUSSION

Figure 2 displays the present study's water quality findings. The WQI incorporates six essential factors: pH, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS), and ammonia-nitrogen (NH_3-N), excluding temperature as a factor. Temperature, however, is still an important element of river water quality, as it directly affects dissolved oxygen solubility, species distribution, and aquatic metabolism, making it a basic component of ecosystem productivity [21]. Temperature readings from the Terengganu, Setiu, and Besut rivers (Figure 2A) revealed no statistically significant differences among seasons and rivers ($p = 0.211$ and 0.955, respectively). However, seasonal variations were detected, with higher temperatures recorded during the dry season (28.40 ± 0.458 °C–28.33 ± 3.761°C) and lower temperatures during the wet season (26.73 ± 2.194 °C–27.33 ± 0.289°C). These values fall within the normal range based on the NWQS for Malaysia, which specifies an optimal river temperature of 22°C to 27°C. The temperature of the Besut river in the present study is lower (26.73 °C ± 2.194; wet season and 28.33 °C ± 3.761; dry season) in comparison to [22] in Besut river estuary (30.19 ± 0.61 ˚C).

The observed seasonal temperature variations can be credited to meteorological and hydrological factors [23]. Higher temperatures during the dry season may result from prolonged sun exposure and reduced water volume. In contrast, increased surface runoff and precipitation during the wet season cause cooler water, leading to a decrease in temperature [24]. Temperature variations can have significant impacts on ecology, affecting dissolved oxygen availability, metabolic rates, and overall biodiversity in freshwater ecosystems.



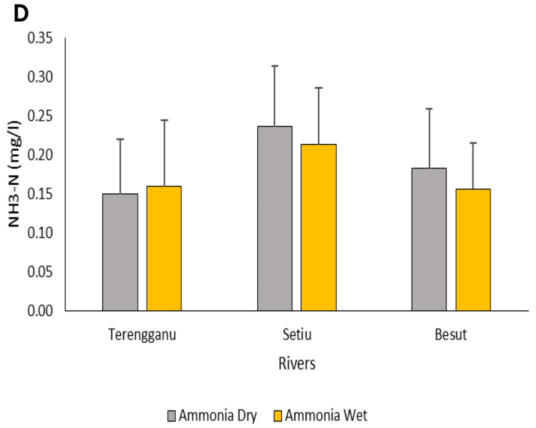


Figure 2 Seasonal variation of water parameters in Terengganu, Setiu and Besut rivers

In relation to pH variations, results revealed significant seasonal and station differences (p= 0.021 and 0.036, respectively). The pH values in Setiu River (6.03 ± 0.058; wet & 6.46 ± 0.213; dry seasons) were lower in comparison with [25] (6.9–8.6) in Setiu Wetlands. In Besut River, the pH values also revealed the same pattern, which are lower (6.79 ± 0.642; wet season and 6.87 ± 0.709) than reported in [22] (7.80 ±0.87) in Besut River estuary. Seasonally, higher pH values (6.46 ± 0.213–7.39 ± 0.015) were recorded during the dry season across all three rivers (Figure 2A). These findings align with [26], which reported pH levels ranging from 5.80 to 6.89 during wet seasons and increasing to 5.57 to 7.15 during dry seasons. The decrease in pH water during the wet season can be attributed to rainfall, which is slightly acidic due to dissolved carbon dioxide forming carbonic acid, which dilutes river water [27]. Additionally, external water sources from increased surface runoff further reduce pH levels. Runoff from industrial activities, agricultural land, and developed areas may contribute acidic pollutants, further reducing pH during the wet season. The pH variations critically impact the ecology, with the optimal pH range between 6.5 and 8.5 for most aquatic organisms [28]. Significant fluctuations in PH can cause physiological stress, impacting reproductive success, metabolic processes, and overall ecosystem stability and productivity. Notably, the pH levels recorded during the wet season, specifically in the Setiu River (6.03 ± 0.058), approach the lower threshold of the optimal range for most aquatic organisms, posing potential risks to aquatic life. These seasonal variations emphasize the necessity for targeted water quality management strategies to mitigate pH fluctuations and protect the sustainability and health of riverine ecosystems.

BOD levels varied across the three rivers, with higher values recorded during the dry season (2.10 ± 0.529 mg/L to 3.42 ± 0.241 mg/L) compared to the wet season (1.72 ± 0.625 mg/L to 3.27 ± 0.208 mg/L; Figure 2B). However, statistical analysis showed no significant seasonal and station differences in BOD levels (p= 0.681 and 0.172, respectively). The BOD in Setiu River was higher (1.72 ± 0.625 to 2.10 ± 0.529 mg/L) in comparison with [25] in Setiu Wetlands, which are in the range of 0.22 to 1.33 mg/L. Among the studied rivers, the Terengganu River exhibited the highest BOD levels in both the dry (3.42 ± 0.241 mg/L) and wet seasons (3.27 ± 0.208 mg/L), categorizing it as Class III under the NWQS 2021. This classification indicates moderate pollution, requiring extensive treatment before use for livestock. Class III waters support only a limited range of aquatic biota due to high pollutant loads. The higher BOD levels in the Terengganu River are likely the result of inadequately processed sewage and discharges from nearby industrial and agricultural activities. Notably, batik production significantly increases BOD levels, as industrial pollutants containing organic compounds require higher oxygen consumption for microbial breakdown [9]. Consequently, this leads to reduced dissolved oxygen (DO) levels, negatively impacting aquatic ecosystems. Conversely, the Setiu River recorded lower BOD levels (1.72 ± 0.625 mg/L to 2.10 ± 0.529 mg/L), categorising it as Class II. This finding suggests relatively better water quality than Class III, potentially attributed to more sustainable agricultural practices in the region. Effective land management strategies and minimum industrial influence may help reduce organic matter and nutrient runoff into the river, thereby preserving good lower BOD levels.

Dissolved oxygen (DO) readings were lower during the wet season (4.11 ± 0.010 mg/L to 5.17 ± 0.045 mg/L) compared to the dry season (4.41 ± 0.411 mg/L to 5.26 ± 0.291 mg/L) (Figure 2B). However, statistical analysis showed no significant seasonal variation (p= 0.096), suggesting that pollutant influences remain relatively constant across the studied rivers. These findings align with those of [29] and [25], which reported within range of DO concentrations (4.19–5.04 mg/L) in the Setiu river and Setiu Wetlands (2.21–6.52 mg/l), respectively. The DO levels in Besut River (5.26 ± 0.291 mg/l; dry season and 5.17 ± 0.045 mg/l), however, are lower than reported in [22] (8.11 ± 0.55 mg/l). The DO levels are influenced by temperature, as higher temperatures reduce oxygen solubility in water [30]. Additionally, higher DO levels can be detected in fast-flowing water bodies due to increased oxygen mixing with the atmosphere.

In contrast, lower DO levels are detected in stagnant or slow-moving water due to decreased oxygen mixing. The DO levels classify Terengganu, Besut, and Setiu rivers as Class III (3–5 mg/L), indicating moderate pollution. The closeness of these rivers to their mouths likely contributes to lower DO levels due to increases in organic matter and pollution loads, reduced turbulence, eutrophication, and anthropogenic influences transported by the rivers [31,32]. In the Terengganu River, industrial waste, particularly discharges from batik production, along with tourism activities and urban development, are primary contributors to reduced DO levels. Similarly, the Setiu River experiences pollution from fishing activities, agricultural runoff, and domestic waste from restaurants, markets, and hospitals, worsening the depletion of DO concentrations. These findings are consistent with those of [18], which identified domestic waste as a primary factor in DO depletion in the Setiu River. In the Besut River, low DO levels are linked to transportation-related pollution, such as oil spills from boats and industrial activities, including fish cracker manufacturing.

Despite significant spatial variations in TSS levels across the three rivers (p= 0.0001), no statistically significant seasonal differences were observed (p= 0.970). Spatially, the Besut River displayed significantly higher TSS values (50.33 ± 4.509 mg/l) relative to the Setiu (27.33 ± 8.373 mg/l) and Terengganu Rivers (29.33 ± 4.041 mg/l; Figure 2C), possibly because of nearby anthropogenic activities nearby. The higher TSS levels in Besut River during both seasons can be attributed to a major flood event in 2022, which caused severe bed and riverbank erosion, leading to significant vegetation and soil loss [33]. This flooding event also increased sediment transport and debris load downstream, subsequently modifying the river's depth and morphology [34]. In addition, the higher TSS levels in both Besut and Terengganu Rivers are likely attributed to seafood processing industries and aquaculture, which release particulate and organic waste [29]. The TSS levels in Setiu river in the present study are far higher (up to 50 mg/L) in comparison to [25] (0.31–4.11 mg/L). Based on TSS concentrations, the Setiu and Terengganu Rivers were categorized as Class II, while the Besut River fell into Class III.

Furthermore, [35] reported that TSS levels in the downstream and midstream sections of the Terengganu River Basin were to be higher than those upstream, varying between Class II and Class III. In contrast, the TSS levels in the Jareth River reached 179.3 mg/L in 2017, placing it as Class IV. Excessively high or low TSS levels can negatively affect irrigated crops, decrease the efficiency of wastewater treatment systems, and compromise overall water quality [36]. Higher TSS values can significantly reduce light penetration within the water column, hence limiting photosynthetic activity in aquatic plants. This, in turn, affects the distribution and growth of submerged vegetation, ultimately degrading aquatic ecosystems.

Spatially, COD levels in Besut and Terengganu Rivers were significantly different from those in the Setiu River (Figure 2C). A significant spatial difference (p= 0.001) was found (p= 0.001); however, no significant seasonal variation was found (p= 0.297). Across all studied rivers, COD concentrations surpassed the NWQS permissible limits. The Terengganu and Setiu Rivers were categorized as Class III (moderately polluted). At the same time, the Besut River was categorized as Class IV (poor quality), making it unsuitable for direct contact or human consumption but still acceptable for irrigation activity. A comparison with previous studies suggests a decline in water quality over time. [37] reported a COD concentration of 23.87 mg/L in the Terengganu

River, which was previously categorized as Class II. This reclassification of Class III suggests increased organic pollution, likely caused by urban development near the Terengganu River and intensive industrial activities such as batik production. Seasonally, higher COD levels during the dry season in three rivers are linked with enhanced biological activity, elevated temperatures, and increased organic matter decomposition [38,39]. In the Terengganu River, higher COD levels during the dry season (43.33 ± 9.866 mg/L) are likely caused by batik industry effluents, which release considerable organic pollutants, including chemicals, dyes, and residual solvents. Slower flow rates and reduced water volume during the dry season likely worsen pollutant accumulation, leading to increased COD concentrations [40]. Conversely, COD levels were slightly lower during the wet season (36.33 ± 7.095 mg/L), possibly attributed to decreased industrial discharge resulting from stricter regulatory constraints or reduced manufacturing activities. Additionally, the increased river flow during the wet season improves dilution, effectively decreasing contaminants and COD concentrations.

Seasonal variations in NH_3-N levels across the three rivers did not reveal a significant trend (Figure 2D). Statistical analysis confirmed no significant seasonal influence on NH_3-N concentrations (p= 0.709 and 0.265). Despite the lack of significant seasonal variation, the observed NH_3-N levels likely due to a complex interaction of anthropogenic activities, including agricultural runoff, industrial discharge, and domestic waste. The NH_3-N levels in Besut River (0.18 ± 0.076 mg/l and 0.16 ± 0.059 mg/l) are lower than reported in [22] (0.0077–0.088 mg/l). Higher NH_3-N levels recorded during the dry season (0.15 ± 0.070 mg/l to 0.24 ± 0.078 mg/l) may be due to reduced dilution capacity, as slower river flow results in a higher concentration of pollutants, including ammonia [40]. Conversely, larger water volume during the wet season facilitates pollutant dispersion and dilution, thereby lowering NH_3-N concentrations. NWQS 2021 has categorized the NH_3-N levels as Class II, indicating that ammonia concentrations remained within tolerable limits for selected water use at the time. Class II water quality is generally suitable for aquatic ecosystems, fisheries, and recreational activities, highlighting that ammonia levels do not significantly harm human health or aquatic life under current conditions. NH_3-N is widely known as an indicator of pollution sources primarily linked to anthropogenic activities [41], with its presence strongly related to agricultural activity. The NWQS 2021 sets border limits for various water quality parameters and regulatory guidelines, safeguarding pollution control and sustainable water resource management in Malaysia.

The concentration of heavy metals in the study areas follows distinct trends: Fe > Cu > Al > Zn > Cd > Pb in Terengganu River, Fe > Cu > Al > Cd > Zn > Pb in Setiu River, and Al > Fe > Cu > Cd > Pb > Zn in Besut River, with Fe exhibited the most significant spatial disparity. As shown in Figure 3, iron (Fe) recorded the highest concentration in both Terengganu (0.92 ppm) and Setiu Rivers (1.30 ppm), suggesting statistically significant differences across all sites. Al was the highest in the Besut River (0.44 ppm), with very minimal differences across the three rivers, suggesting no statistically significant differences. Among the three rivers, Setiu River displays the highest heavy metal levels, particularly Fe, potentially due to anthropogenic influences such as boating activities around the small jetty in Setiu Wetlands and industrial discharge [42]. The motorized boats combust fossil fuel for propulsion, releasing trace metals into the river through exhaust emissions and fuel leakage.

Additionally, the Setiu River basin may contain iron-rich minerals, leading to a higher discharge of Fe into the river system [43]. Agricultural runoff, potentially carrying pesticides and fertilizers from poorly managed agricultural plots with minimal buffer zones or erosion control measures, could further contribute to elevated soluble and particulate Fe levels. Terengganu River exhibits a similar heavy metal pattern to Setiu River, suggesting common pollution sources. In contrast, the Besut River consistently shows lower metal concentrations, suggesting minimal agricultural and industrial impacts. Notably, Al and Fe are recognized as primary elements in soil, water, and sediment, frequently existing in higher concentrations compared to other metals [44,45].

The measured Fe levels in the Setiu River (1.30 mg/l) surpass the recommended standard of NWQS (Class I-IIB: 1.0 mg/l), which are designated for conservation, sensitive fisheries and recreational contact, suggesting potential adverse effects and risks to aquatic biodiversity and urgent management action. In contrast, while the Fe levels in the Terengganu River (0.92 mg/l) remain within acceptable limits for sensitive water (Class I–IIB), it is approaching the upper limit. This proximity raises concerns over ecological safety and necessitates precautionary monitoring, especially during peak agricultural and industrial periods.

Multiple linear regression (MLR) analyses revealed that temperature exhibits a consistently strong and negative relationship with all six heavy metals, suggesting a systemic influence of thermal conditions on metal behavior in freshwater systems (Table 5). Lower temperatures may enhance the solubility or suspended availability of certain metal ions. Conversely, higher temperatures may transform metals into particulate forms or bind them to sediments, lowering the dissolved concentrations [46]. Biochemical Oxygen Demand (BOD) emerged as a recurring positive predictor for Cd, Cu, Zn, Pb, and Al, indicating that organic pollution, such as from sewage, industrial discharge, or decaying biomass, may facilitate metal mobilization. Organic matter can interact with metals by increasing their solubility and bioavailability, releasing them through metal-laden compounds [47]. pH and COD were statistically significant only for Fe, highlighting its distinct geochemical behavior among the metals studied. Fe is highly sensitive to pH, with lower pH enhancing the solubility of Fe, while higher pH promotes precipitation of Fe [48]. These findings support the use of physicochemical indicators to model and predict heavy metal behavior in Terengganu riverine systems, which is valuable for targeted water quality management and early detection of contamination trends.

Table 5 Multiple linear regression (MLR) coefficients of significant water quality parameters on heavy metal concentrations (Cd, Cu, Zn, Fe, Pb, Al)

	Coefficients					
Predictor	**Cd**	**Cu**	**Zn**	**Fe**	**Pb**	**Al**
Temperature	-0.042 ***	-0.076 ***	-0.078 ***	-0.144 ***	-0.053 ***	-0.014 **
BOD	+0.043 *	+0.076 *	+0.081 *		+0.053 *	+0.021 **
pH				+0.451 **		
COD				-0.033 *		

*** = $p < 0.01$ (highly significant)

** = $p < 0.05$ (moderately significant)

* = $p < 0.10$ (marginally significant)

The non-biodegradable nature of heavy metals in the environment can accumulate and magnify in sediments and aquatic biota over time [49]. The bioaccumulation and biomagnification of heavy metals in aquatic organisms lead to various physiological, biochemical, and behavioral disruptions. Aquatic organisms exposed to high concentrations of heavy metals experience alteration in the gill and liver histopathology, impaired reproduction, disrupted enzymatic activity, and suppressed immune function [50]. The Cd and Hg, for example, are known to damage kidney and gill tissues, while Pb affects neurological development in fish larvae. Moreover, chronic and prolonged exposure to heavy metals can cause a reduction in biodiversity, alterations in species composition, and ecosystem instability. These effects threaten aquatic life and pose a significant human health risk through the consumption of contaminated seafood.

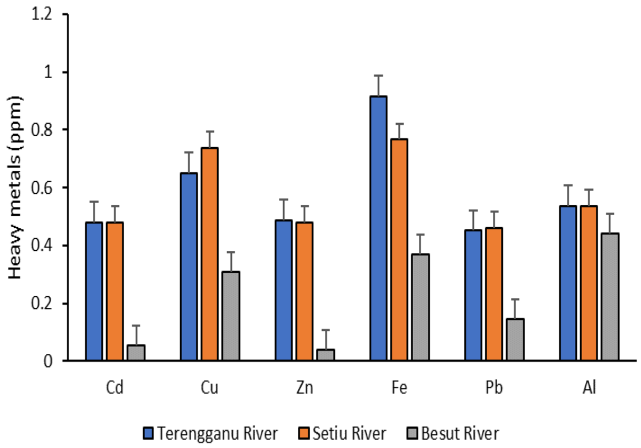


Figure 3 Heavy metal concentrations in Terengganu, Setiu and Besut rivers

Water Quality Index (WQI)

The NWQS uses the WQI to assess pollution levels, including key parameters such as DO, COD, BOD, NH3-N, TSS, and pH. In this study, the Setiu River recorded the lowest SDO (Table 6), indicating poor water quality, likely due to industrial effluents and high organic matter content. The SBOD values ranged between 85.92 and 93.14, categorising the rivers as slightly polluted, which aligns with NWQS standards, where values below 79 are considered polluted. The overall WQI values for Setiu, Terengganu, and Besut river ranged from 71.95 to 75.85, putting them within Class III, indicating moderate pollution largely caused by significant anthropogenic activities near their estuaries [43]. Previous studies reported variations in water quality classifications, with the Terengganu River previously classified as Class II and the Setiu River once categorised as Class I. Higher levels of SAN, SCOD, and STSS further indicate pollution sources such as industrial discharges, fertilizer runoff, and land erosion [20,35]. The lower WQI observed in Besut river is primarily related to insufficient sewage treatment, whereas the Terengganu River is more impacted by livestock farming and industrial chemical discharges. Despite Setiu river displaying a relatively higher WQI, it remains within Class III, highlighting the urgent need for pollution control measures and improved waste management to enhance water quality.

Table 6 Sub-indexes (S) of six water quality parameters and WQI for different water sampling stations and seasons

Rivers	Season	SDO	SBOD	SCOD	SAN	STSS	SpH	WQI	Class
Terengganu	Dry	54.45	85.92	50.43	84.75	79.98	97.53	73.60	III
	Wet	49.22	86.58	56.77	83.7	81.43	99.32	73.43	III
Setiu	Dry	54.47	91.52	64.99	75.3	82.42	96.59	75.85	III
	Wet	49.04	93.14	68.56	78.45	80.78	94.33	75.10	III
Besut	Dry	69.59	86.74	34.23	81.60	65.83	99.28	71.95	III
	Wet	68.06	87.78	36.00	83.70	64.97	99.12	72.24	III

4.0 CONCLUSION

The findings of this study indicate that the physico-chemical parameters vary across the Terengganu, Setiu, and Besut Rivers. According to NWQS, the water quality parameters of these rivers fall within Class II and Class III categories. Notably, water quality during the dry season shows higher pollution levels compared to the wet season. The WQI values categorize all three rivers in Class III, indicating moderate pollution levels that require extensive water treatment to ensure safe usage. The heavy metal concentrations follow distinct trends: Fe > Cu > Al > Zn > Cd > Pb in the Terengganu River, Fe > Cu > Al > Cd > Zn > Pb in the Setiu River, and Al > Fe > Cu > Cd > Pb > Zn in the Besut River. The elevated Fe and Al levels in these rivers are primarily attributed to batik production, agricultural runoff, industrial activities, untreated sewage discharge, and transportation-related pollution. In comparison to NWQS guidelines, the Cd, Cu, and Al concentrations surpassed the allowable limits, while Zn, Fe, and Pb remain within the acceptable range.

These results highlight the urgency for continuous, river-specific monitoring by governmental environmental agencies such as the DOE and local water authorities (Lembaga Sumber Air Terengganu (LAUT), and Jabatan Pengaliran dan Saliran (JPS)), research institutions and community stakeholders to track pollution dynamics over time. Targeted mitigation strategies for controlling pollution include identifying point and non-point sources, enhancing buffer zones, and adopting green remediation technologies, led by the DOE, in collaboration with local municipal councils, river basin management authorities, and supported by academicians. The adoption of eco-friendly industrial practices can significantly reduce pollutant discharge at the source. Regulatory enforcement must be strengthened by the DOE and local environmental health units, including imposing fines on polluters and periodic audits of industrial discharge. Public education campaigns and active community engagement, led by non-governmental organizations (NGOs), are essential to increase the conservation efforts, mitigating pollution and ensuring long-term water quality. Collectively, this study provides a baseline for environmental authorities and contributes to national water resource policy, in parallel to the objectives of Malaysian Science, Technology, Innovation & Economy (MySTIE) and Sustainable Development Goal (SDG) 6 - Clean Water and Sanitation. If proactive measures are not taken by all parties, the pollution levels in these river systems are presumed to worsen, driven by expanding anthropogenic activities.

In general, increases in heavy metal concentrations and deteriorating water quality could jeopardize the ecosystem in the long term, losing biodiversity, bioaccumulating toxins in aquatic food chains, and declining ecosystem services that local communities depend on (e.g, for fisheries, tourism, and daily water use). Without the enforcement and catchment-level planning, the rivers could shift from moderately polluted (Class III) to severely degraded (Class IV or worse), necessitating costly remediation and posing risks to public health. Therefore, this study highlights the current pollution status and serves as an early warning for escalating environmental risks if immediate and coordinated interventions are not pursued.

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Conflicts of Interest

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

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