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Original Research Article

Beneficial Use Based Water Quality Targets and Concentration Improvement Needs in Setiu River, Terengganu, Malaysia

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Abstract

This study evaluated water quality in the Setiu River, Terengganu, Malaysia by integrating beneficial use classification, Water Quality Target (WQT) setting and impairment analysis. 25 sampling points were assessed during wet and dry seasons using key WQI and NWQS parameters: dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS) and ammoniacal nitrogen (AN). Based on land use and dominant water uses, downstream reaches (P1–P11) were assigned to Class III, middle-stream reaches to Class III (P12–P15) and Class II (P16–P18), and upstream reaches to Class I (P19–P25). Upstream water quality was generally better, while deterioration was more evident downstream and at selected middle stream stations. Target deviations were mainly associated with DO, AN and COD. AN required 9 % to 29 % reduction, while DO improvement requirements ranged from 12 % to 100 % across the impaired sampling stations. Overall, this study provides a practical framework for translating river monitoring data into beneficial WQT.

Keywords: Beneficial uses; national water quality standards; river monitoring; Setiu River; water quality index; water quality target.

1. Introduction

Water quality assessment is an essential approach to understand the current conditions, identifying trends, and determining the key factors influencing the quality of water resource, enabling effective collection of water samples from different locations and sources, including rivers, lakes, groundwater, and treated drinking water supplies. These samples are then analysed in laboratories or through field testing to measure various parameters that indicate water quality. The collected data from water quality assessments are analysed and compared to established water quality standards and guidelines, which vary depending on the intended use of the water. These standards define acceptable

levels of contaminants and provide benchmarks for assessing water quality target (WQT). Deviations from the standards can indicate pollution or contamination issues and the need for further investigation and action. In Malaysia, the quality of a river can be identified by conducting a water quality assessment with the classification according to the Water Quality Index (WQI) and National Water Quality Standards (NWQS) established by the Department of Environment Malaysia (DOE). The WQI includes six parameters: pH, dissolved oxygen, biochemical oxygen demand (BOD), chemical oxygen demand (COD), total suspended solids (TSS) and ammonia nitrogen to assess the water quality. While, NWQS outlines the minimum requirements for freshwater in terms of microbiological, physical, chemical, and radioactive components before it qualifies as a source of potable water (DOE, 2021).

Internationally, water quality management frameworks commonly link the intended or designated uses of a water body with numerical or narrative water-quality criteria. Under the U.S. Water Quality Standards framework, designated uses such as aquatic-life protection, recreation, public water supply and agricultural use are associated with criteria intended to protect those uses (USEPA, 2024). The Total Maximum Daily Load (TMDL) framework extends this concept by determining the pollutant reduction necessary for impaired waters to attain applicable water quality standards, while considering pollutant sources, differences between the two sampled dates and uncertainty (USEPA, 1991; National Research Council, 2001; Wang et al., 2025). Similarly, the Australian and New Zealand water-quality framework establishes water-quality objectives according to identified community values and recommends the use of appropriate guideline values to protect those values (ANZG, 2018). The European Water Framework Directive also adopts a river basin based approach in which management objectives are established to protect or restore ecological and chemical status (European Commission, 2000). Collectively, these international approaches demonstrate that water-quality targets should be linked to the intended function and environmental value of individual water bodies rather than relying solely on an overall water quality index.

The prevailing challenges in Malaysia regarding water supply primarily revolve around river pollution and water quality. There is a growing awareness among both the general public and government agencies about the necessity of effective watershed management to preserve the ecosystems, particularly in river basins experiencing land use change, agricultural activities and climate driven rainfall variability. Therefore, regular assessment of river water quality is essential to support evidence based decision making, pollution control and the establishment of appropriate water quality targets. Setiu River is located in Setiu District, Terengganu, Malaysia, an area well known for its ecological, economic, and tourism importance. The Setiu River Basin is closely connected to the Setiu Wetlands, one of the largest wetland systems on the east coast of Peninsular Malaysia. The area supports diverse ecosystems, including mangroves, seagrass beds, turtle landing areas, terrapin habitats, aquaculture zones, and fisheries-related activities. Several parts of the Setiu River Basin have also been classified as Environmentally Sensitive Areas, indicating their vulnerability to natural and anthropogenic disturbances. Because of this ecological sensitivity, maintaining good river water quality is important not only for water resource sustainability but also for biodiversity conservation, local livelihoods, aquaculture productivity, and environmental planning.

Previous studies have assessed water quality in the Setiu River Basin and nearby lagoon or wetland systems. Earlier assessments generally indicated that the Setiu River was within clean or Class II status reporting an overall mean WQI value of 84.0 for the Setiu River Basin (Zaideen et al., 2017). Zainol et al., (2021) and Poh et al., (2018) researched had focused on the Setiu lagoon while DID (2021) not covered the overall Setiu river. Latif and Suratman (2015) focused on the nutrient distribution into the river while others are reported the river status in the form of thesis (Jessie (2008); Deraman (2005); Zulfadhli (2002)). However, many of the available studies are either based on older datasets, selected river stretches, lagoon environments, nutrient distribution, ecological indicators or specific sub catchments rather than a comprehensive beneficial use based assessment of the river system. Recent studies further support the need for updated assessment in the Setiu River Basin. Bakar et al. (2025) analysed rainfall

variability and water quality parameters in Setiu River using data from 2018 to 2022 and showed that rainfall patterns influence key WQI parameters such as DO, BOD, COD, suspended solids, pH, and ammonia nitrogen. This finding strengthens the need to consider seasonal variation, particularly wet and dry season differences, when interpreting Setiu River water quality. Meanwhile, Yusri & Yaakub (2022) reported that water degradation in the Setiu River Basin has potential implications for local communities who depend on river water use, highlighting the importance of linking water quality assessment with human and environmental related. Furthermore, research in the wider Setiu aquatic environment also shows that environmental pressure remains relevant. Kasan et al. (2023) assessed water quality parameters and nutrient levels in Nyatuh River, Setiu, in relation to freshwater prawn population, showing the importance of water quality for aquatic habitat and local ecological resources. In addition, Maulana et al. (2025) reported microplastic contamination in mangrove sediments of Setiu Wetlands, with 2292 microplastic particles/kg dry sediment, indicating emerging pollutant concerns in this sensitive wetland system. These recent findings suggest that although earlier studies generally classified Setiu River as clean or moderately affected, continuous assessment remains necessary due to differences between the two sampled dates, local development, aquaculture activities and emerging contaminants.

Over the period from 2001 to 2021, the average WQI was derived from the collective contributions of researchers such as Deraman (2002), Zulfadhli (2005), Jessie (2008), Mohd Zaideen et al. (2017) and Department of Irrigation and Drainage (2021) as shown in Figure 1. The existing data suggests an overall clean status except in the year 2005 it is categorized as slightly polluted, but to fully comprehend the implications of this status and guide effective environmental management, further research into water quality impairment and reach specific quality targets is essential. Basically, despite this comprehensive overview, there exists a notable gap in the research concerning the reach specific water quality targets and parameter specific impairment in the Setiu River system amid the dynamic developments at the state and district levels.

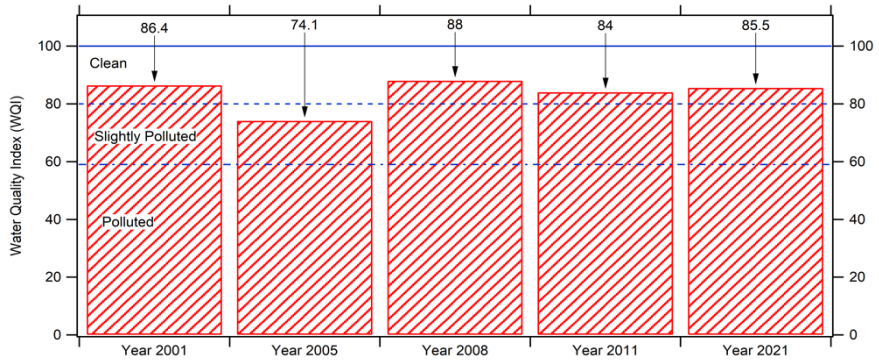


Figure 1. Trend of WQI at Setiu River from 2001 until 2021

Furthermore, a section of the Setiu River has been designated as an Environmentally Sensitive Area (ESA), signifying its heightened vulnerability to environmental changes induced by natural processes or human activities. The sensitivity of an ESA is determined by three key characteristics: the risk of catastrophic events, its role in supporting life, and its heritage value (PLAN MALAYSIA, 2021). These ESAs are categorized into three ranks: Rank 1, Rank 2, and Rank 3 with Rank 1 indicate the most sensitive areas. Within the Setiu River Basin, notable areas classified under ESA Rank 1 include the Setiu Wetland, the turtle landing site, the eroded shorelines, the central forest, the seagrass, and the terrapin habitat. Preserving these ESAs is crucial for establishing a spatial framework that guides planning at regional, state, and local levels. The ESA Rank 1 designation applies to specific environmentally sensitive areas within the Setiu River Basin and does not necessarily encompass the entire main-stem downstream reach. Therefore, the environmental sensitivity and dominant beneficial use associated with individual

river reaches were considered separately when establishing the WQT. Understanding the intricacies of these factors is pivotal for a more nuanced assessment of the water quality in the Setiu River.

The existing data suggests an overall clean status, but to fully comprehend the implications of this status and guide effective environmental management, further research into water quality targets and parameter specific improvement requirements is essential. Such insights will not only contribute to the refinement of water quality models but also play a crucial role in sustaining water resources in the face of ongoing development. Despite the availability of previous water quality studies, limited research has focused on establishing Water Quality Targets for the Setiu River based on beneficial uses under the NWQS framework. Water Quality Targets are important because they provide measurable benchmarks for identifying impairment, supporting pollution control, guiding river basin planning, and protecting beneficial uses such as aquatic life, water supply, recreation, and ecosystem conservation. Therefore, a WQT based assessment using 2023 field data remains relevant as a post pandemic baseline for understanding the current management needs of the Setiu River Basin. The 2023 dataset is particularly useful because it can update earlier river assessments and provide a recent basis for comparing seasonal water quality behaviour between wet and dry periods. Accordingly, this study aims to: (i) characterize water quality at 25 stations along the Setiu River during one wet-season and one dry-season sampling campaign; (ii) identify dominant beneficial uses and establish reach specific Water Quality Targets based on the NWQS framework; (iii) determine parameter specific water quality impairment by comparing observed concentrations with the assigned WQT and (iv) estimate the concentration reduction or DO improvement required at impaired stations and screen potential pollution sources.

2. Methods

Figure 2 outlining the steps to achieve the research objectives. The process of determining impairment involves acquiring desktop analysis to determine the beneficial uses and water quality target. Then, field measurements and lab analysis of water quality data were acquired for a comprehensive analysis. The subsequent subtopics elaborate on the methods employed to obtain these data and highlight the associated laboratory procedures for acquiring the necessary datasets.

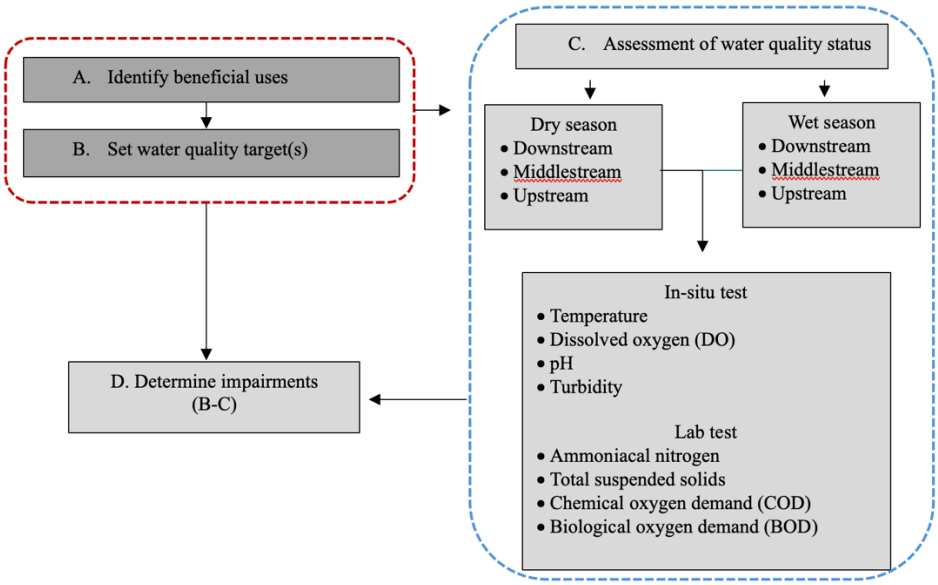
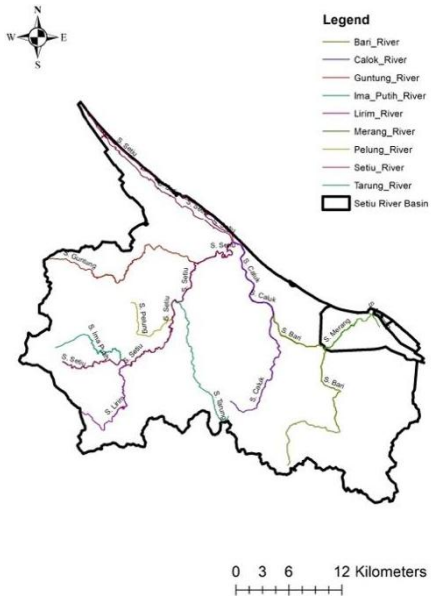


Figure 2. Research methodology chart for the study

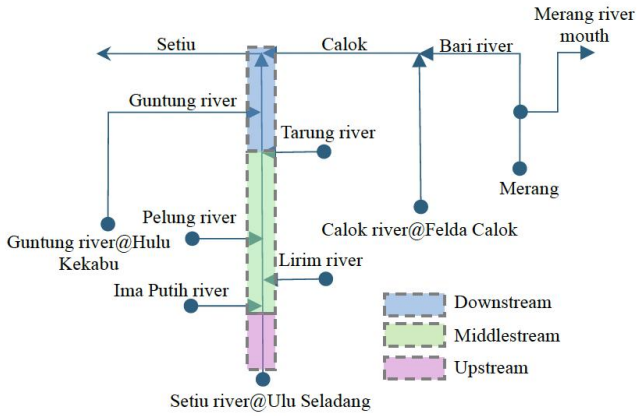
2.1 Study Area

The selection of the study area was determined by considering both accessibility and its relevance to the overall research outcomes. The Setiu river and its tributaries were shown and depicted in schematic

view in Figure 3. The main drainage outlet is Setiu river mouth and Merang river mouth as a minor drainage outlet. Setiu river river can be grouped into two: 1) The headwater originated from Ulu Seladang; and 2) The headwater originated from Felda Chalok and Hulu Merang. There are five (5) major feeder rivers that flow into the Setiu River from the south-west, notably Guntung river (25 km), Ima Putih river (4.2 km), Pelong river (18 km), Lirim river (15.8 km) and Tarung river (18.6 km). Bari river (23.1 km) enters Chalok river from the south-west, eventually feeding into Setiu river in Kampung Penarik.



(a)



(b)

Figure 3. Setiu river basin (a) drainage network; (b) schematic diagram

There are 25 sampling points were selected for the downstream (Point 1-11), middle stream (Point 12-18), and upstream (Point 19-25) sections of the Setiu river. These figures collectively illustrate that all sampling locations were concentrated along the main Setiu River, primarily on the western side of the basin. Notably, the Calok River, Bari River, and Marang River were excluded from sampling during the study period. The specific coordinates for sampling locations are shown in Table 2. Based on the 3 partitioning segment (Downstream, middlestream and upstream), two sampling campaigns were conducted, on 18 January 2023 and 28 March 2023, representing wet-season and dry-season conditions, respectively. Each hydrological period was represented by a single sampling event, therefore, comparisons between the two campaigns are descriptive and are not interpreted as replicated estimates of differences between the two sampled dates.

Table 2. Coordinates for all sampling locations

Sampling Points	Latitudes	Longitudes	Notes
Downstream			
Point 1	N 05°36'24"	E 102°48'25"	Confluence between Calok river and Setiu River
Point 2	N 05°36'12"	E 102°48'17"	
Point 3	N 05°35'60"	E 102°48'07"	
Point 4	N 05°35'52"	E 102°48'11"	
Point 5	N 05°35'43"	E 102°48'05"	
Point 6	N 05°35'58"	E 102°47'52"	
Point 7	N 05°35'24"	E 102°47'02"	Nyatuh Jetty@Setiu River
Point 8	N 05°35'08"	E 102°46'25"	
Point 9	N 05°56'07"	E 102°46'15"	
Point 10	N 05°35'06"	E 102°46'06"	Guntung river
Point 11	N 05°34'33"	E 102°45'54"	
Middlestream			
Point 12	N 05°34'8.12"	E 102°45'49.82"	
Point 13	N 05°34'25.28"	E 102°45'24.87"	
Point 14	N 05°33'14.80"	E 102°44'57.39"	
Point 15	N 05°32'53.47"	E 102°44'46.85"	
Point 16	N 05°31'46.32"	E 102°44'47.38"	Ibu Bekalan Setiu River
Point 17	N 05°31'21.05"	E 102°44'41.50"	Bandar Permaisuri
Point 18	N 05°29'3.46"	E 102°42'30.86"	
Upstream			
Point 19	N 05°28'34.3"	E 102°38'57.2"	Ulu Seladang
Point 20	N 05°28'30.3"	E 102°38'50.8"	Ulu Seladang
Point 21	N 05°28'26.9"	E 102°38'45.0"	Ulu Seladang
Point 22	N 05°28'27.3"	E 102°38'38.3"	Ulu Seladang
Point 23	N 05°28'28.6"	E 102°38'32.4"	Ulu Seladang
Point 24	N 05°28'32.3"	E 102°38'28.7"	Ulu Seladang
Point 25	N 05°28'37.2"	E 102°38'25.0"	Ulu Seladang

Comprising six key parameters: ammoniacal nitrogen; biochemical oxygen demand; chemical oxygen demand; dissolved oxygen; pH, and total suspended solids as shown in Table 3&4. These standards offer a swift and straightforward approach to assessing water quality. WQI provides a concise, single-value indicator, expressed as a percentage, allowing for a quick determination of water quality status. On the other hand, the NWQS consists of standards aligned with the beneficial uses of water as shown in Table 5. Maintaining water quality in the environment involves managing a dynamic system. It is crucial to implement occasional monitoring requirements, regulate effluents, and establish water quality standards to sustainably manage water resources, addressing both point and non-point pollution sources. DOE employs the WQI and adheres to the NWQS to systematically monitor and assess the status of river water quality affected by pollution.

Table 3. Department of Environment (DOE) Water Quality index

Parameter	Unit	Class				
		I	II	III	IV	V
AN	mg/l	< 0.1	0.1 - 0.3	0.3 - 0.9	0.9 - 2.7	> 2.7
BOD	mg/l	< 1	1 - 3	3 - 6	6 - 12	> 12

Parameter	Unit	Class				
		I	II	III	IV	V
COD	mg/l	< 10	10 - 25	25 - 50	50 - 100	> 100
DO	mg/l	> 7	5 - 7	3 - 5	1 - 3	< 1
pH	-	> 7	6 - 7	5 - 6	< 5	> 5
TSS	mg/l	< 25	25 - 50	50 - 150	150 - 300	> 300
WQI	-	> 92.7	76.5 - 92.7	51.9 - 76.5	31.0 - 51.9	< 31.0

Table 4. DOE Water Quality classification based on Water Quality index

Sub Index & Water Quality Index	Index Range for river		
	Clean	Slightly polluted	Polluted
BOD	91 – 100	80 – 90	0 – 79
NH_3-N	92 – 100	71 – 91	0 – 70
SS	76 – 100	70 – 75	0 – 69
WQI	81 – 100	60 – 80	0 – 59

Note: DOE river status categories are based on the overall WQI and selected subindices and are distinct from the five WQI classes in Table 3 (DOE, 2021).

Table 5. National Water Quality Standards for Malaysia

Parameter	Unit	Class					
		I	IIA	IIB	III	IV	V
Ammoniacal Nitrogen	mg/l	0.1	0.3	0.3	0.9	2.7	> 2.7
Biochemical Oxygen Demand	mg/l	1	3	3	6	12	> 12
Chemical Oxygen Demand	mg/l	10	25	25	50	100	> 100
Dissolved Oxygen	mg/l	7	5 - 7	5 - 7	3 - 5	< 3	< 1
pH	-	6.5 - 8.5	6 - 9	6 - 9	5 - 9	5 - 9	-
Colour	TCU	15	150	150	-	-	-
Electrical Conductivity*	µS/cm	1000	1000	-	-	6000	-
Floatable	-	N	N	N	-	-	-
Odour	-	N	N	N	-	-	-
Salinity	%	0.5	1	-	-	2	-
Taste	-	N	N	N	-	-	-
Total Dissolved Solid	mg/l	500	1000	-	-	4000	-
Total Suspended Solid	mg/l	25	50	50	150	300	300
Temperature	°C	-	Normal + 2 °C	-	Normal + 2 °C	-	-
Turbidity	NTU	5	50	50	-	-	-
Faecal Coliform**	count/ 100ml	10	100	400	5000 (20000)a	5000 (20000)a	-
Total Coliform	count/ 100ml	100	5000	5000	50000	50000	> 50000

Note: The pH values above are the official NWQS class-specific acceptable ranges and are used for WQT compliance; these are not the DOE-WQI pH subindex categories. Source: DOE, National Water Quality Standards for Malaysia (DOE, 2021).

The land used information obtained from PLAN Malaysia was used as a resource to determine the beneficial uses of water quality for the study areas. and use information within the study area was extracted using satellite imagery technique. This global land use/land cover (LULC) map is crafted from ESA Sentinel-2 imagery at a 10m resolution. Each annual iteration is created through Impact

Observatory's deep learning AI land classification model, which has been trained using billions of human-labeled image pixels sourced from the National Geographic Society. The generation of these global maps involves applying the model to the Sentinel-2 Level-2A image collection on Microsoft's Planetary Computer, encompassing the processing of over 400,000 Earth observations per year (ESRI, 2022).

Usually, a river basin encompasses diverse water users along various stretches, necessitating consideration for each impaired river stretch in the impairment determination. To determine WQT, a technical approach involves utilizing land use data obtained from PLAN Malaysia to assess the various types of land usage within a watershed or relevant geographical area. The next step is to align this data with the beneficial uses designated by the NWQS. This alignment process is crucial as it helps in identifying the specific water quality requirements based on the designated uses of the water body, such as recreation, drinking, or agriculture. After establishing the relationship between land use and beneficial uses, WQT are set according to the permissible concentration levels of pollutants stipulated by the NWQS. These targets are tailored to ensure that the water body meets the necessary standards to support its designated beneficial uses, effectively guiding the implementation of management practices and regulatory measures to protect and improve water quality.

The Malaysian DOE-WQI was calculated using six parameter-specific subindices, where WQI = 0.22(SIDO) + 0.19(SIBOD) + 0.16(SICOD) + 0.15(SIAN) + 0.16(SISS) + 0.12(SIpH). The index ranges from 0 to 100. The following are the complete DOE best-fit subindex equations (DOE, 2021):

SIDO: 0 if $x \le 8$; $-0.395 + 0.030x^2 - 0.00020x^3$ if $8 < x < 92$; 100 if $x \ge 92$.

Here x = DO percentage saturation (not DO in mg/L).

SIBOD: $100.4 - 4.23x$ if $x \le 5$; $108\exp(-0.055x) - 0.1x$ if $x > 5$.

SICOD: $99.1 - 1.33x$ if $x \le 20$; $103\exp(-0.0157x) - 0.04x$ if $x > 20$.

SIAN: $100.5 - 105x$ if $x \le 0.3$; $94\exp(-0.573x) - 5|x - 2|$ if $0.3 < x < 4$; 0 if $x \ge 4$.

SISS: $97.5\exp(-0.00676x) + 0.05x$ if $x \le 100$; $71\exp(-0.0016x) - 0.015x$ if $100 < x < 1000$; 0 if $x \ge 1000$.

SIpH: $17.2 - 17.2x + 5.02x^2$ if $x < 5.5$; $-242 + 95.5x - 6.67x^2$ if $5.5 \le x < 7$; $-181 + 82.4x - 6.05x^2$ if $7 \le x < 8.75$; $536 - 77.0x + 2.76x^2$ if $x \ge 8.75$.

For BOD, COD, AN and SS, x is concentration (mg/L); for pH, x is pH. For SIDO, x is dissolved oxygen (% saturation), not mg/L. The SISS coefficient –0.0016 is taken from the DOE 2025 NWQS/WQI booklet. Recalculate station WQI values from the raw dataset before final submission.

The WQI classes (Table 3) are used for overall water quality categorisation, while NWQS limits (Table 5) define the parameter-specific WQT and impairment thresholds. In particular, compliance with pH targets must use the NWQS acceptable range for the assigned class

2.2 Assessment of Water Quality Status

During the water quality assessment of the Setiu River, field measurements were conducted for parameters such as pH, turbidity (expressed in Nephelometric Turbidity Units, NTU), dissolved oxygen (DO), and temperature. For onsite quantification of heavy metals including manganese (Mn), aluminium (Al), iron (Fe), and nickel (Ni), an in-situ heavy metal analysis was performed using Lovibond Photometer MD600. Sample collection at designated checkpoints involved the systematic retrieval of three 1-liter bottles per checkpoint. The Van Dorn water sampler was employed to collect water samples directly from the river, ensuring the reliability of the data obtained. Field measurements for pH, temperature, and DO were recorded using a multiparameter probe (EUTECH), while turbidity levels were determined with a turbidity meter (EUTECH). In the laboratory, water samples underwent detailed analysis for ammonia as nitrogen (NH_3-N), total suspended solids (TSS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD). The spectrophotometer model DR2800 was utilized for these analyses. For the COD tests, a Hach DRB200 thermal reactor was used to heat the samples pre-mixed with reagents within the vials, ensuring precise quantification of COD afterwards using HACH Method 8000.

2.3 Water Quality Impairment and Improvement Requirement Analysis

Water quality impairment was assessed by comparing the observed concentration of each parameter with the corresponding threshold of the assigned Water Quality Target (WQT). For AN, BOD, COD and TSS, a station was classified as impaired when the observed concentration exceeded the applicable WQT threshold. The percentage concentration reduction required to achieve the target was calculated as:

Reduction required (%) = $[(C_o-C_t)/C_o] \times 100$

Where C_o is the measured parameter concentration and C_t is the concentration threshold corresponding to assigned WQT.

For DO, where higher concentration indicates better water quality, a station was classified as impaired when the observed DO concentration was below the assigned target. The required improvement was calculated as:

DO improvement required (%) = $[(DO_t-DO_o)/DO_o] \times 100$

These calculations represent parameter specific concentration reduction or improvement requirements rather than absolute pollutants mass loads because rover discharge was not measured during the sampling.

3. Result and Discussion

3.1 Water Quality Index (WQI)

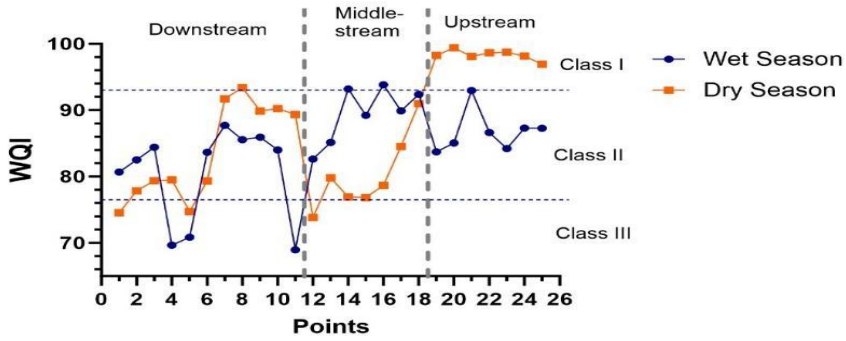
WQI was calculated using the DOE-WQI equation and this index is categorized into three ranges: clean (81-100), slightly polluted (60-80), and polluted (0-59). These ranges can be further classified into five classes, as depicted in Figure 4(a). The WQI values along the Setiu River showed a clear longitudinal pattern, with better water quality generally observed in the upstream reach and gradual deterioration towards the middle and downstream reaches. Notably, the upstream section recorded a clean water status, with WQI readings surpassing 81. As depicted in Figure 4(b), examining the water quality class at upstream, a majority of sampling points during the wet season exhibited class II, indicating a clean status. However, this classification is influenced by lower DO levels, which contribute to reduced WQI readings. Although the upstream area is generally associated with forested and less disturbed land use, some reduction in WQI was observed due to lower dissolved oxygen (DO) values at selected stations. This suggests that even protected upstream reaches may experience short-term water quality fluctuation, particularly during periods of low flow, organic matter accumulation or reduced reaeration capacity. This spatial pattern is consistent with earlier Setiu River studies, where Zaideen et al. (2017) reported Class II conditions with a mean WQI of 84, while Yusri and Yaakub (2022) reported WQI values of 71-82 and an overall mean WQI of 77, indicating slightly polluted conditions at selected locations.

Progressing downstream, the downstream section showed lower WQI values, with the minimum value reaching approximately 68. This value falls within Class III and indicates slightly polluted status. The decline in WQI towards the downstream reach may be associated with cumulative pollutant inputs from surrounding land use activities, agricultural areas, settlements and local point sources. Although the overall downstream water quality was not classified as polluted, the shift from clean to slightly polluted status indicates increasing pressure along the river continuum. The WQI results therefore suggest that Setiu River remains generally within acceptable water quality conditions, but selected downstream and middle stream areas require closer monitoring. This is particularly important because WQI provides an overall water quality status but may not fully reflect whether the river meets specific beneficial used based targets. Similar seasonal and anthropogenic effects have been reported by Bakar et al. (2025), who showed that rainfall variability influenced all WQI parameters in the Setiu River using 2018-2022 monitoring data. More importantly, WQI alone may underrepresent management needs because a river reach can remain within clean or slightly polluted status while still failing to meet stricter water quality targets assigned for specific beneficial uses. This justifies the subsequent WQT and

impairment analysis conducted in this study. Therefore, further interpretation using NWQS based Water Quality Targets is necessary to identify parameter specific impairment.

Class V	Class IV	Class III	Class II	Class I
0 - 31	31 – 51.9	51.9 – 76.5	76.5 – 92.7	92.7 - 100
0 - 59		60 - 80	81 - 100	
Polluted		Slightly Polluted	Clean	

(a)



(b)

Figure 4. WQI (a) along the longitudinal profile of Setiu River and; b) range and associated class\

3.2 Beneficial Uses and Water Quality Target

The determination of Water Quality Targets (WQT) was based on the dominant beneficial uses and land use characteristics within the Setiu River Basin. Usually, a river basin encompasses diverse water users along various stretches, necessitating consideration for each impaired assessment. There are nine classification of LULC as shown in Figure 5 such as water body, forest, flooded vegetation, crops, built area, bare ground, snow/ice, clouds and rangeland. Within the Setiu river catchment, the primary beneficiaries of water are identified as irrigation schemes, forest reserves and potable water supply. Additional beneficial uses encompass fisheries, crops, and recreational activities. These land use characteristics influence the expected water quality requirement for different river reaches. In contrast to WQI, which provides a single integrated water quality score, WQT links the observed condition to the intended river function and therefore provides a more management-oriented interpretation.

The primary source of irrigation water for the Setiu Irrigation Scheme is the Setiu River. On the left bank, drainage water is redirected to Sg. Guntung, which subsequently joins Sg. Setiu near the scheme's downstream end. At Setiu district, there are two main water treatment plants (WTPs) that supply treated water to the domestic users in the district. From those two WTPs, one of them abstract water from Setiu river (DID, 2011). Ensuring the water quality remains within the target Class II is essential upstream from the water intake, as it plays a critical role in preserving the quality of abstracted water before the treatment process. Three Forest Reserves are located in this river basin namely Hulu Setiu Forest reserve to the west, Hulu Besut Forest reserve and Gunung Tebu forest reserve to the north west of the river basin. These forest reserves fall within the ESA. To visualize the WQT, the rivers within the basin was marked in accordance to the WQT as shown in Figure 6. Based on the prominent beneficial use of water, Setiu river can be grouped into three main WQT; rivers within forest reserve area and forested land cover are designated as WQT class I (green); rivers upstream from water intake for WTP are designated as class IIA/B (blue); and rivers within crops and agricultural area are designated as class III (red).

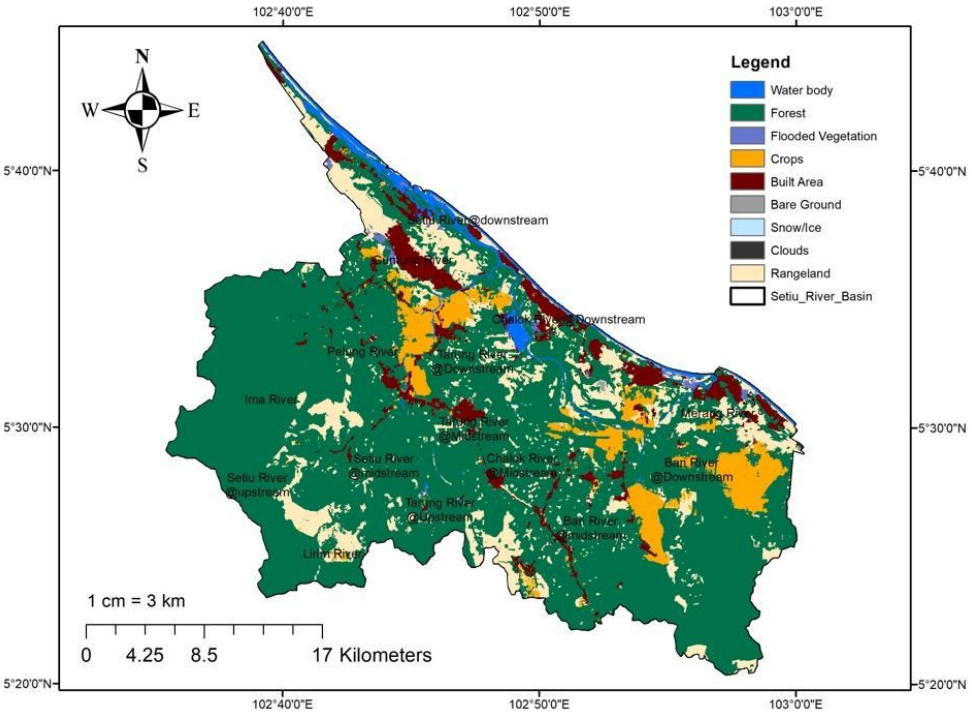


Figure 5. LULC at Setiu River Basin extracted from Sentinel dataset

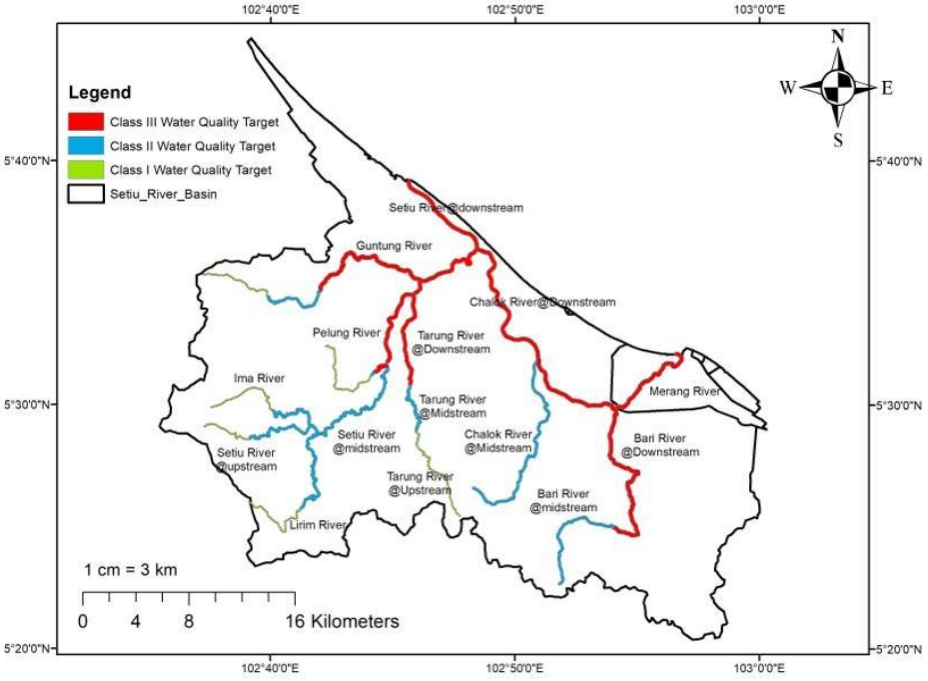


Figure 6. Water Quality target for Setiu River

The upstream section, represented by P19 to P25, was assigned to Class I due to its association with forested areas, protected catchments and ESA. Class I represents a stricter target and reflects the need to maintain high water quality in less disturbed river reaches. These upstream areas function as important water source zones and ecological support areas within the Setiu River Basin. The downstream section is mainly influenced by agricultural and settlement-related activities; therefore, the WQT for

sampling points P1–P11 was set as Class III. Although ESA Rank 1 areas occur within the wider Setiu River Basin, the downstream sampling reaches P1–P11 assessed in this study were assigned according to their immediate dominant beneficial uses and surrounding land-use characteristics. These reaches are predominantly influenced by agricultural and settlement-related activities and were therefore assigned a Class III WQT. The ESA designation and reach-specific WQT were treated separately to avoid assuming that the ESA classification applies uniformly across the entire downstream river section. This target is considered suitable for agricultural water use and general river functions in areas affected by land development. The middle stream section showed mixed beneficial uses. Sampling points P12–P15 were assigned to Class III due to the influence of agricultural activities, while P16–P18 were assigned to Class II because of their relevance to water abstraction and domestic water supply protection. This distinction is important because river reaches located upstream of water intake points should maintain better water quality to reduce treatment burden and protect public water supply. Overall, the WQT classification demonstrates that different river segments require different management targets according to their beneficial uses. This approach is more useful than relying only on WQI because it links water quality assessment directly to river function, land use and management priority as justified in Table 6.

Table 6. Justification for proposed beneficial-use water quality targets.

Stations / reach	Dominant beneficial use	Supporting evidence	Assigned WQT and justification
P19–P25, upstream	Aquatic habitat / catchment conservation	Ulu Seladang; forested headwaters, forest reserves and mapped environmentally sensitive areas	Class I: protective management target appropriate to relatively undisturbed headwaters; proposed target, not an official designation
P16–P18, middle reach	Water abstraction / treated domestic supply	Proximity to Ibu Bekalan Setiu River and Bandar Permaisuri; water-treatment intake context described in the study	Class II: protective raw-water target; use Class IIA concentration criteria for water-supply abstraction
P12–P15, middle reach	Mixed agriculture and local river uses	Cropland and irrigation-related land use identified in mapped LULC	Class III: study-defined mixed-use management target, not an assertion that Class III is Malaysia's designated irrigation class
P1–P11, downstream	Mixed settlements, agricultural activity and river use	Developed and cropped areas, Setiu/Guntung tributary and settlements; ESA features exist elsewhere in wider basin	Class III: study-defined mixed-use target; Class IV is the NWQS irrigation-use category, so agriculture alone does not establish Class III

3.3 Water Quality Impairment

Water quality impairment was assessed by comparing the observed pollutant load with the target load based on the assigned WQT for each river reach. Parameters such AN, BOD, COD and TSS represent pollutant related indicators, where higher concentrations indicate deterioration of water quality. In contrast, DO is a positive water quality indicator, where lower values indicate reduced oxygen availability and potential ecological stress. Monitoring these water quality indicators provides valuable insights into the overall ecological health of the river. To better understand the impairment analysis, the following threshold plot was shown in Figure 7 while spatial distribution of impairment is shown in Figure 8(a-j).

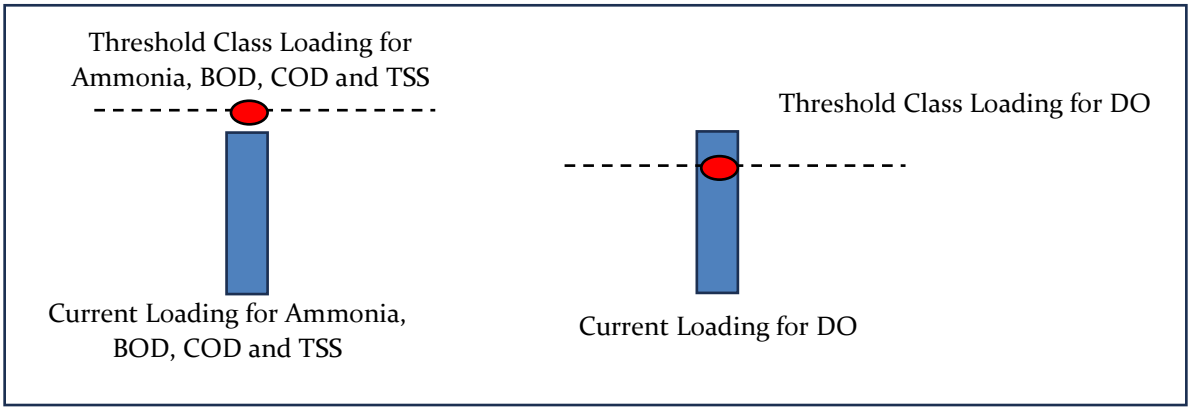
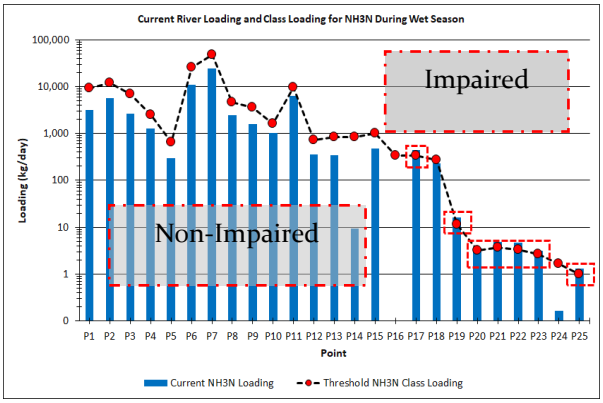
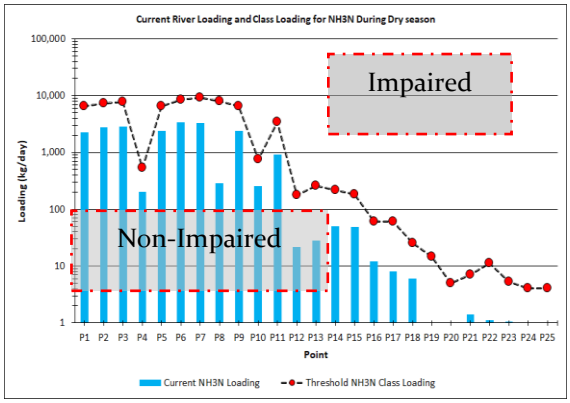


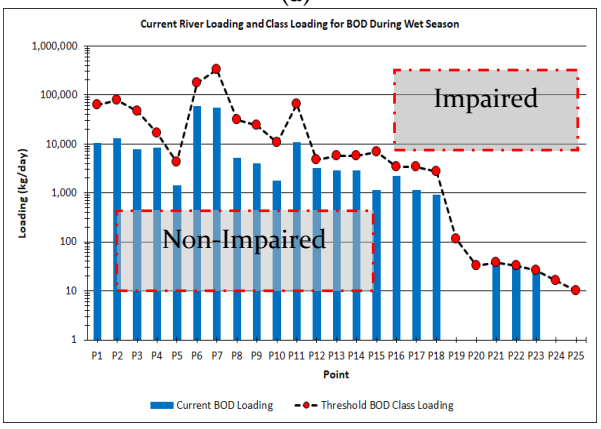
Figure 7 Non-impaired Plot for Observed Water Quality Parameters



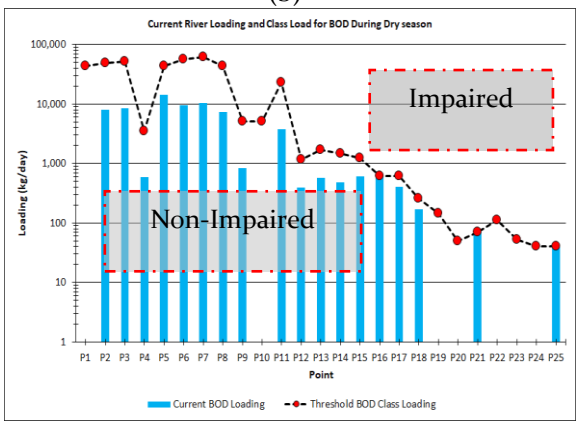
(a)



(b)



(c)



(d)



Figure 8. Spatial distribution of impairment of Setiu River for (a) NH_3N during wet season; (b) NH_3N during dry season; (c) BOD during wet season; (d) BOD during dry season; (e) COD during wet season; (f) COD during dry season; (g) DO during wet season; and (h) DO during dry season; (i) TSS during wet season; and (j) TSS during dry season.

The impairment analysis showed that most sampling locations were not impaired for BOD (Figure 8 (c, d) and TSS (Figure 8 (i, j). This indicates that organic pollution represented by BOD and sediment related pollution represented by TSS were generally within the assigned water quality targets during the study period. Therefore, BOD and TSS were not the main limiting parameters in achieving the WQT for Setiu River.

In contrast, impairment was mainly observed for AN, DO and COD. During the wet season, AN impairment (Figure 8 (a, b) was most evident in the upstream section, where 6 out of 7 stations were impaired, representing 85.71% of the upstream sampling points (Table 7(a)). DO impairment (Figure 8 (g, h) was also recorded at all upstream stations during the wet season, representing 100% impairment for this parameter. This finding suggests that the stricter Class I target assigned to the upstream reach makes the section more sensitive to deviation, especially for DO and AN.

The simultaneous occurrence of elevated AN and reduced DO may indicate oxygen demand associated with nitrogen transformation and organic matter decomposition. Ammoniacal nitrogen can originate from natural organic matter, agricultural runoff, animal waste, domestic discharge or other nitrogen-rich inputs. During nitrification, ammonia is converted to nitrite and nitrate by microorganisms, and this process consumes dissolved oxygen. Therefore, elevated AN may contribute indirectly to lower DO levels, especially when river flow is limited or reaeration is insufficient. This interpretation is consistent with Bakar et al. (2025), who reported that rainfall variability influenced key water quality parameters in the Setiu River and that oxygen-related parameters varied between wet and dry conditions.

At the downstream reach (Table 7(b), impairment was less widespread but was still observed for selected parameters. DO impairment occurred at selected downstream stations, possibly due to water stagnation and reduced mixing. No COD impairment was observed at the downstream stations during the wet-season sampling event. In contrast, COD impairment occurred at selected downstream stations during the dry-season sampling event, indicating difference between these two sampling events in COD relative to the assigned Class III WQT, as illustrated in Figure 8. This may reflect the influence of organic matter, oxidizable substances, saline intrusion or local discharge from surrounding activities. Since COD represents the amount of oxygen required to chemically oxidize organic and inorganic substances, elevated COD values may indicate the presence of decaying organic matter, wastewater input or runoff related pollutants (Long et al., 2021; Samio et al, 2002). During the dry season, lower discharge may reduce dilution and oxygen replenishment, allowing DO depletion to occur at selected middle stream and downstream stations even when pollutant concentrations are not extremely high. Previous Setiu related studies have also reported seasonal influence on water quality and nutrient behaviour, including phosphorus variability in the Sungai Setiu Basin (Hee et al., 2018), monsoon related lagoon water quality changes (Zainol et al., 2021), and rainfall effects on Setiu River WQI parameters (Bakar et al., 2025).

The dry-season sampling event showed fewer impairment cases compared with the wet season. However, DO impairment was still observed in selected middle stream and downstream stations (Table 7 (b, c). This suggests that low flow conditions during the dry season may reduce dilution and oxygen replenishment, allowing oxygen depletion to occur even when pollutant concentrations are not extremely high. The concentration reduction analysis further supports the parameter specific nature of water quality impairment in Setiu River. BOD and TSS did not require concentration reduction, indicating that these parameters were generally within the target limits. In contrast, AN required approximately 9–29% reduction at impaired locations. DO improvement requirements ranged from 12–83%, during the wet season sampling and from 32% to 100% during the dry-season sampling event. Across both sampling time, the overall DO improvement requirement ranged from 12% to 100%, indicating a substantial spatial variation in the magnitude of improvement required to achieve the assigned WQT. This suggest that DO was the most critical parameter requiring management attention. COD reduction was also required at selected downstream locations, particularly where the observed concentration exceeded the Class III target.

Table 7. Percent of impaired station during wet season at (a) upstream; (b)Downstream; and (c) middlestream

(a)

Parameters	No. of Impairment at Main Stem Level *7 stations	Total Impairment %
AN	6	85.71
BOD	0	0
COD	0	0
DO	7	100
TSS	0	0

Parameters	No. of Impairment at Main Stem Level *7 stations	Total Impairment %
Total Impairment	**13**	**37.14***

(b)

Parameters	No. of Impairment at Main Stem Level *11 stations	Total Impairment %
AN	0	0
BOD	0	0
COD	0	0
DO	1	9.09
TSS	0	0
Total Impairment	**1**	**1.82***

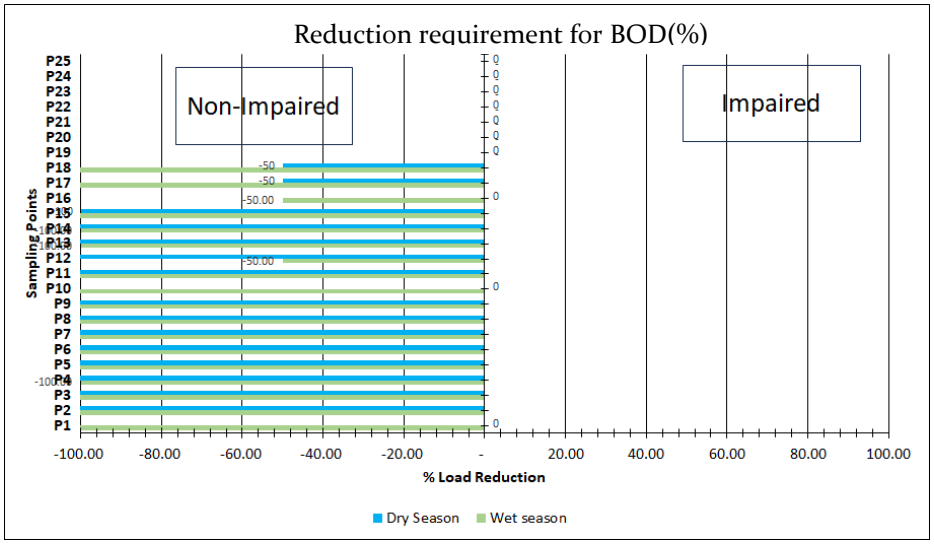
(c)

Parameters	No. of Impairment at Main Stem Level *7 stations	Total Impairment %
AN	1.00	14.29
BOD	0.00	0.00
COD	0.00	0.00
DO	0.00	0.00
TSS	0.00	0.00
Total Impairment	**1.00**	**2.86***

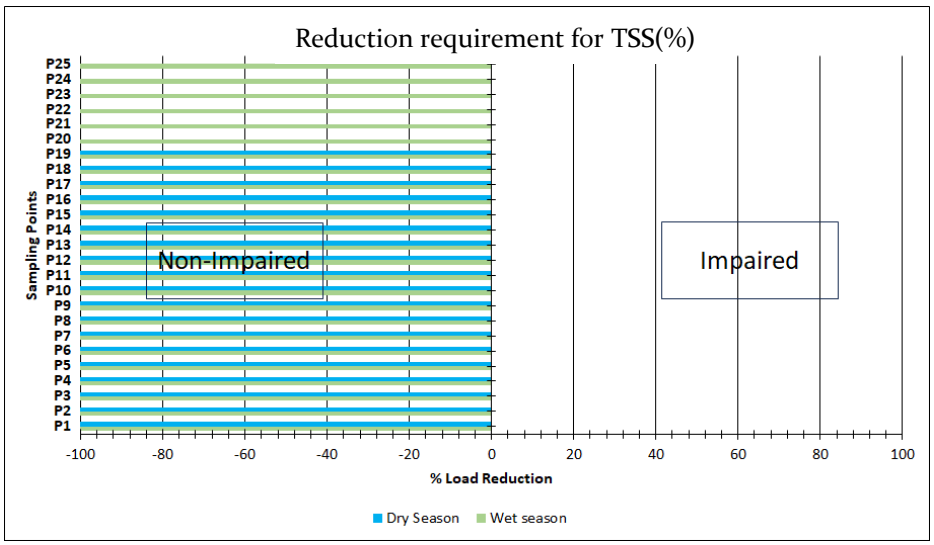
** Parameter-specific impairment (%) = 100 × impaired stations / stations in the reach. Total impairment (%) = 100 × number of impaired parameter–station combinations / (number of stations × five assessed parameters). Upstream: 13/(7×5) = 37.14%; downstream: 1/(11×5) = 1.82%; middle: 1/(7×5) = 2.86%. These totals refer to the wet-season sampling snapshot only.*

Based on the pollution source screening, non-point source pollution was mainly associated with crop and agricultural areas distributed in the middle stream section, upstream of Bari River and eastern parts of Merang River. Agricultural areas may contribute nutrients, sediments, fertilizers and other runoff-related pollutants into nearby water bodies, particularly during rainfall events. Point-source inventory further showed that eateries and restaurants were the dominant potential contributors, with 71 identified sources. Other point sources included workshops with 35 sources, settlements with 34 sources, markets with 13 sources, aquaculture and livestock activities with 10 sources, and industrial activities with 7 sources. This distribution indicates that local commercial and settlement related activities may play an important role in pollutant input to the Setiu River Basin. Overall, the impairment results indicate that the Setiu River is not broadly polluted across all parameters, but selected reaches fail to meet their beneficial used based targets for AN, DO and COD. This highlights the importance of targeted management rather than general river wide intervention. Priority should be given to improving DO conditions, controlling nitrogen related inputs, reducing COD sources at downstream stations and strengthening management of local point sources such as eateries, restaurants, workshops and settlement related discharges.

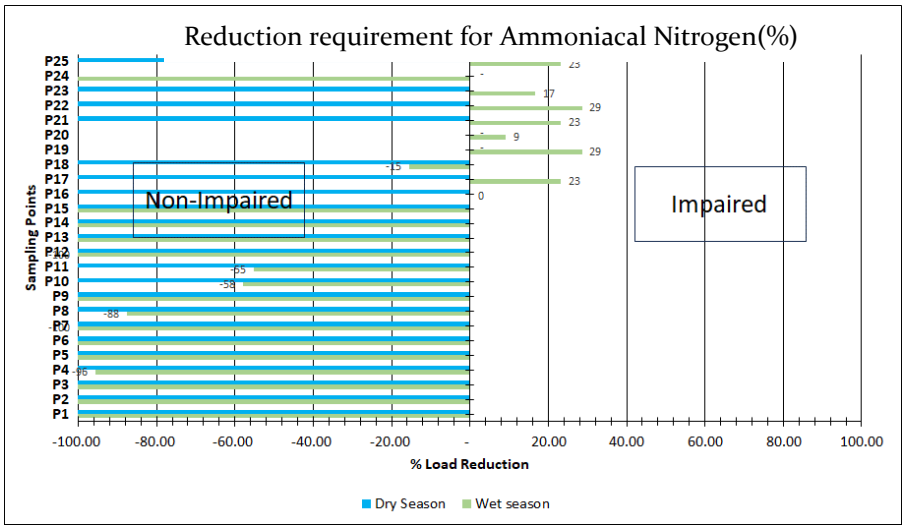
Pollution source screening provides further support for the impairment findings. Crop areas were mainly distributed around the middle-stream section, upstream of Bari River and eastern parts of Merang River, indicating potential agricultural non-point source contributions. Agricultural runoff is commonly associated with nutrients, sediment, pesticides, organic residues and other pollutants that can enter waterways during rainfall events (USEPA, 2024). In addition, previous work in Setiu Wetland Lagoon linked nutrient variability to upstream land clearing, aquaculture discharge, oil palm expansion and lagoon inlet changes (Poh et al., 2018), supporting the role of land-use change and human activity in influencing water quality. Although this study did not quantify individual source loads, the spatial overlap between agricultural areas and nutrient-related impairment indicates the need for runoff control, riparian buffer protection and improved agricultural drainage management. Owing to the deterioration of water quality below the specified target levels, a critical imperative emerges for load reduction measures to be implemented, ensuring the restoration of water quality to the desired benchmarks. Notably, TSS and BOD parameters exhibit a contrasting scenario, with Figure 9 (a,b) indicating that these parameters necessitate no load reduction interventions. Because selected parameters exceeded the assigned WQT, load reduction and oxygen recovery requirements were estimated to identify management priorities. This step is important because it translates water quality deviation into parameter-specific intervention needs. BOD and TSS showed no load reduction requirement, indicating that these parameters were generally within the WQT limits during the sampling period. Therefore, the main management concern was not broad sediment or biodegradable organic pollution, but selected nitrogen-related, oxygen-balance and COD-related impairment. AN and COD, on the other hand, fall within the specified range of load reduction, calling for measures to achieve reductions of less than 30% and between 40-60%, respectively as depicted in Figure 9 (c, d). The load reduction requirements for DO present a more diverse spectrum, varying between 12-100% for the majority of impaired points for both seasons, as illustrated in Figure 9 (e). These disparities highlight the nuanced and site-specific nature of the challenges posed by DO levels, reinforcing the need for targeted interventions to address the distinct requirements of each point of concern. Based on satellite imagery (2022), the distribution of crop area is shown in Figure 10. The crop area is always associated with agriculture land use which induced sediment, nutrients, pesticides, and chemicals into water body. Inferring this figure, the crop area mostly scattered at midstream of Setiu river, upstream of Bari River and East of Merang river. Point source pollution refers to the discharge of pollutants from clearly identifiable and localized sources into the environment, such as rivers, lakes, or the air. These sources are typically associated with industrial facilities, sewage treatment plants, or specific discharge points like pipes and outfalls. Unlike non-point source pollution, which arises from diffuse and widespread activities, point source pollution is easier to trace and regulate. Based on IRBM Report (2021), the point source pollution for all area was divided into six (6) main types: Industry/sewage treatment plant, aquaculture/livestock, car wash/workshop/petrol station, eatery, market and settlement/chalet/resort as shown in percentage values in Figure 11.


Reduction requirement for BOD(%)
Non-Impaired
Impaired
Sampling Points
% Load Reduction
Dry Season
Wet season

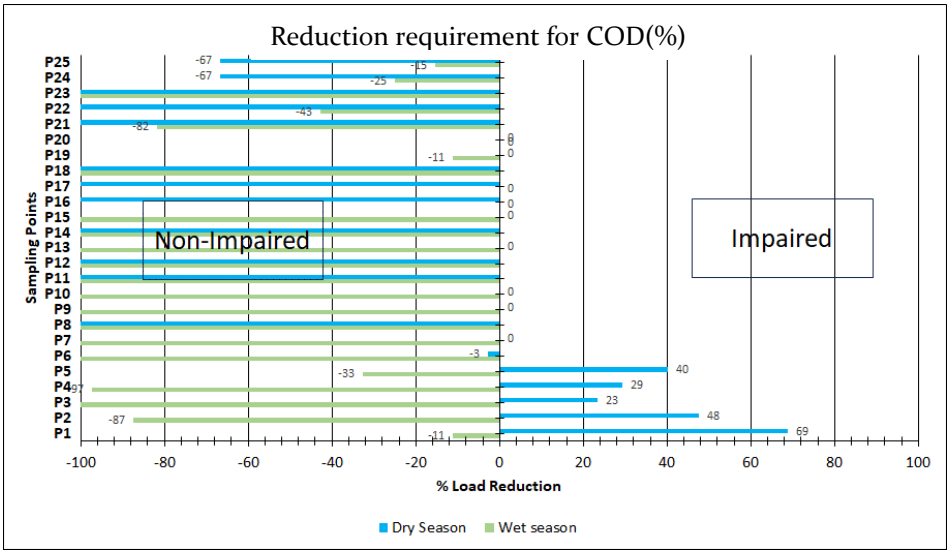
(a)


Reduction requirement for TSS(%)
Non-Impaired
Impaired
Sampling Points
% Load Reduction
Dry Season
Wet season

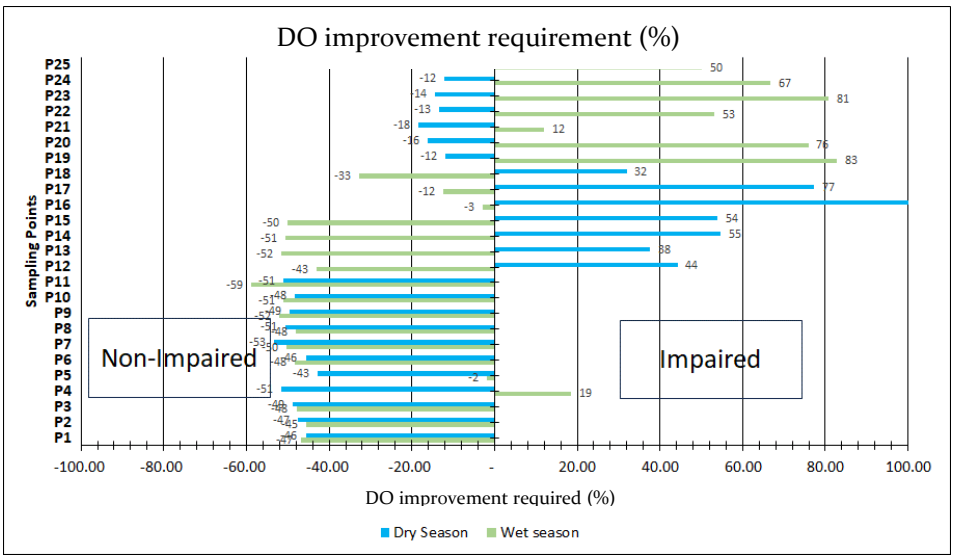
(b)


Reduction requirement for Ammoniacal Nitrogen(%)
Non-Impaired
Impaired
Sampling Points
% Load Reduction
Dry Season
Wet season

(c)



(d)



(e)

Figure 9. Parameter specific reduction requirement for (a) BOD; (b) TSS; (c) AN; (d) COD, and DO improvement requirements for (e) DO in the Setiu River

Examining the cumulative impact of point sources across the four subbasins, it becomes evident that eatery and restaurant activities are the predominant contributors to point source pollution, accounting for a significant 71 numbers. Following closely are workshops at 35 numbers, settlements at 34 numbers, markets at 13 numbers, aquaculture/livestock at 10 numbers, and industry at 7 numbers. Eateries and restaurants may contribute sullage, food residues, grease, organic matter and nutrient-rich wastewater if drainage and waste management are inadequate. These inputs are relevant to COD and oxygen balance issues because organic and oxidisable materials can increase oxygen demand in receiving waters. Workshops may contribute oil, grease and other chemical residues, while settlements may contribute domestic wastewater or greywater. Therefore, downstream COD impairment and selected DO deficits should be interpreted together with the spatial distribution of these local point sources. This breakdown emphasizes the need for targeted intervention strategies and management practices,

particularly in areas where the concentration of point sources is higher, to address and mitigate the impact of diverse pollutants on the local water bodies.

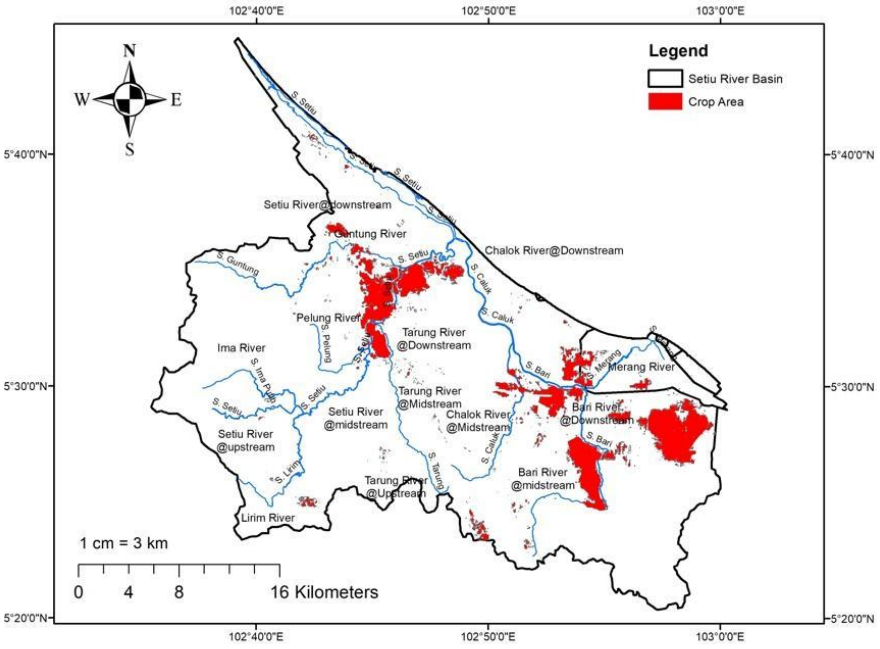


Figure 10. Distribution of crop area identified as potential non-point pollution source areas at Setiu River Basin

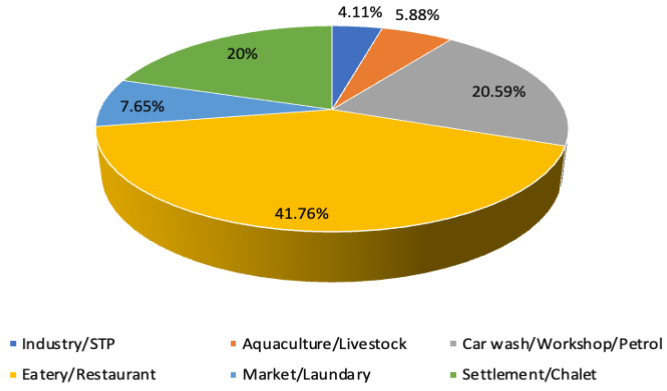


Figure 11. Percentage distribution of point source pollutions

Overall, the findings demonstrate that WQI alone may underestimate management needs because several river reaches remained generally clean or slightly polluted, yet failed to meet specific beneficial used based targets for AN, DO and COD. Therefore, combining WQI, NWQS based WQT and load reduction analysis provides a more practical basis for identifying priority parameters and targeted river management actions. For the Setiu River Basin, management should focus on improving DO conditions, controlling nitrogen related inputs, reducing COD sources at selected downstream stations and strengthening control of local point sources such as eateries, restaurants, workshops and settlement-related discharges. This WQI WQT load reduction framework is therefore useful for translating routine river monitoring data into targeted river basin management actions.

4. Study Limitations and Future Perspective

This reach-specific WQT assessment is a preliminary management-screening tool. Only one wet-season and one dry-season sampling event were undertaken, so the data represent two seasonal snapshots rather than replicates suitable for inference about seasonality or long-term trends. Flow/discharge data and source-specific concentrations were not collected, preventing calculation of mass loads, mass-load reductions or source attribution. Future work should include replicated sampling, discharge measurements and an independently verifiable station-level dataset.

5. Conclusions

The present study evaluated the Setiu River by integrating three key components: water quality status, water quality impairment, and potential pollution source identification during wet and dry seasons. Water quality was assessed using selected parameters, namely TSS, BOD, COD, DO and AN, based on the WQI and NWQS frameworks. The WQT were established according to the beneficial uses derived from land use characteristics within the basin. The downstream reach was assigned to Class III for P1–P11 due to agricultural activities, while the middle-stream reach was assigned to Class III for P12–P15 and Class II for P16–P18 due to the combined influence of agricultural use and water abstraction. The upstream reach was assigned to Class I for P19–P25 because of its association with protected and forested areas. The results showed that deviations from the assigned WQT were mainly associated with DO, AN and COD. In the upstream reach, DO and AN deviated from the Class I target during the wet season, indicating that even protected areas may experience water quality stress under certain seasonal conditions. In the middle stream reach, DO deviation was observed during the dry season, while in the downstream reach, DO deviation occurred during the dry season and COD impairment was not observed during the wet season sampling time but occurred at selected stations during the dry season sampling time. These findings suggest that impairment in the Setiu River is parameter specific and varies according to river segment and season. During the wet season, higher AN concentrations were generally accompanied by lower DO levels. This relationship may be linked to the decomposition of organic matter and nitrogen transformation processes. Therefore, elevated AN can increase oxygen demand and contribute to DO depletion, particularly when oxygen replenishment is limited. The impairment analysis indicated that AN required a load reduction of approximately 9–29% at affected locations, while DO improvement requirements ranged from 12–100% across the two sampling time. Overall, the results show that the Setiu River is not broadly impaired across all parameters, but selected reaches require targeted management, especially for nitrogen related inputs, DO recovery and COD control. Source screening further indicated that eateries and restaurants were the dominant potential point-source contributors in the Setiu River Basin. Therefore, future management should prioritize improved control of commercial wastewater discharge, agricultural runoff, and local point-source activities to support the achievement of beneficial used based WQT.

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Ethics Statement

This study did not involve human participants, human data, or animal testing. Ethical approval and informed consent were therefore not required. The research was based solely on environmental water samples collected from the Setiu River, Terengganu, Malaysia, for water quality assessment and impairment analysis.

CRediT Author Statement

Mohd Sofiyan Sulaiman: Supervision, writing, original draft, methodology. **Nazaitulshila Rasit:** Supervision, writing, original draft, visualization, editing. **Goay Teoh Shu Yee:** Data collection, writing. **Muhammad Nazarul Azreel Ab Azih:** Data collection; writing. **Muhammad Hakim Che Harun:** Supervision, conceptualization, review. **Wan Rafizah Wan Abdullah @ Abd. Rahman:** Supervision, review. **Muhammad Amir Samsudin:** Data collection; writing. **Muhamad Ikmal Zulkefli:** Data collection; writing. **Aiman Asyraf Abd Aziz:** Data collection, writing. **Daria Mathew:** Review, funding acquisition. **Chik Maslinda Omar:** Review, funding acquisition.

References

ANZG 2018. Australian and New Zealand Guidelines for Fresh and Marine Water Quality. Australian and New Zealand Governments and Australian state and territory governments, Canberra, Australia.

Bakar, S.N.A., Jafrei, F.F. and Yanfang, S. 2025. Impacts of rainfall variability on water quality parameters in the Setiu River, Malaysia. Frontiers in Water and Environment 6 (1), 13–31.

Department of Environment (DOE) 2021. Environmental Quality Report 2021. Department of Environment Malaysia, Kuala Lumpur.

Department of Irrigation and Drainage 2021. Penyediaan Pelan Pengurusan Lembangan Sungai Bersepadu (IRBM) Sungai Setiu, Terengganu (Vol. III: Management Plan). Department of Irrigation and Drainage, Kuala Lumpur.

ESRI 2022. Sentinel-2 10m land use/land cover time series. https://www.arcgis.com/home/item.html?id=cfcb7609de5f478eb7666240902d4d3d (accessed 15 May 2024).

Hee, Y.Y., Suratman, S., Mohd Tahir, N. and Jickells, T. 2018. Seasonal variability and fractionation of p-based nutrients in Setiu River Basin, Terengganu, Malaysia. Sains Malays. 47, 883–891.

Jessie, J.B. 2008. Water quality assesment of Setiu River Basin, Terengganu (Master's thesis). Universiti Malaysia Terengganu, Terengganu, Malaysia.

Kasan, N.A., Ikhwanuddin, M., Manan, H., Zakaria, N.S., Kamaruzzan, A.S., Rahim, A.I.A. and Ishak, A.N. 2023. Assessment on water quality parameter and nutrients level of Nyatuh River in relations with macrobrachium rosenbergii prawn populations. Tropical Life Sciences Research 34 (1), 51–66.

Latif, M.T. and Suratman, S. 2015. Reassessment of nutrient status in Setiu Wetland, Terengganu, Malaysia. Asian Journal of Chemistry 27, 239–242.

Long, J., Cui, Y., Wang, R., Chen, Y., Zhao, N., Wang, C., Wang, Z. and Li, Y. 2021. Combined effects of high salinity and ammonia-N exposure on the energy metabolism, immune response, oxidative resistance and ammonia metabolism of the Pacific white shrimp Litopenaeus vannamei. Aquaculture Reports 20, 100648.

Maulana, N.S.M., Zulkifli, M.S., Khalid, A.A., Shahrudin, R., Anuar, S.T., Jaafar, M. and Ariffin, E.H. 2025. Revealing microplastic contamination in mangrove sediments from Setiu Wetlands, Malaysia. Indonesian Journal of Chemistry 25 (2), 520.

National Research Council 2001. Assessing the TMDL Approach to Water Quality Management. National Academies Press, Washington, DC.

PLAN MALAYSIA 2021. Rancangan fizikal negara keempat. Jabatan Perancangan Bandar Dan Desa, Kementerian Perumahan dan Kerajaan Tempatan, Kuala Lumpur.

Poh, S.C., Ng, N.C.W., Suratman, S., Mathew, D. and Mohd Tahir, N. 2018. Nutrient availability in the Setiu Wetland Lagoon, Malaysia: trends, possible causes and environmental impacts. Environmental Monitoring and Assessment 191 (1), 3.

Tonning, B., Parry, K. and Boschen, C. 2019. Integrating aquatic designated use protection and restoration strategies using an ecosystem goods and services framework. Integrated Environmental Assessment and Management 15 (5), 808–818.

USEPA 1994. Water Quality Standards Handbook, 2nd ed. Office of Water, United States Environmental

Protection Agency, Washington, DC.

Wang, H., et al. 2025. Enhancing pollution management in watersheds: A critical review of total maximum daily load (TMDL) implementation. Environmental Research 264, 120394.