INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 17 No. 9 (2025) 366-381
https://publisher.uthm.edu.my/ojs/index.php/ijie

IJIE

Turbidity Trends in 20 Water Treatment Plants Across Sabah, Malaysia: Implications for Sustainable Water Resource Management

Janice Lynn Ayog[1]*, Min Fui Tom Ngui[1,2], Marieanne Christie Leong[3,4]

[1] *Faculty of Engineering,*
Universiti Malaysia Sabah, Jln UMS, 88400, Kota Kinabalu, Sabah, MALAYSIA
[2] *Eramaju Synergy Sdn. Bhd.*
Lot 23, 2nd Floor Lido Plaza, Jln Nosoob, 88300, Kota Kinabalu, Sabah, MALAYSIA
[3] *Faculty of Earth Science,*
Universiti Malaysia Kelantan, 17600, Jeli, Kelantan, MALAYSIA
[4] *Institute for Artificial Intelligence & Big Data,*
Universiti Malaysia Kelantan, 16100 Kota Bharu, Kelantan, MALAYSIA

*Corresponding Author: jay@ums.edu.my
DOI: https://doi.org/10.30880/ijie.2025.17.09.025

Article Info

Received: 20 May 2025
Accepted: 17 August 2025
Available online: 31 December 2025

Keywords

Water treatment plant, turbidity, land-use change, raw water, water supply, catchment management

Abstract

Water Treatment Plants (WTPs) play a vital role in ensuring safe drinking water by removing contaminants, with turbidity serving as a key indicator of raw water quality. However, turbidity levels in raw water sources are increasingly influenced by extreme weather events and anthropogenic activities, presenting challenges for effective water treatment. This study aims to assess turbidity trends and identify contributing factors in WTPs across Sabah, Malaysia, to support more sustainable water management practices. Turbidity data from the WTPs, spanning 1 to 8 years, were analysed, supplemented by time-lapse satellite imagery to assess upstream catchment conditions wherever possible. Data were categorised into four administrative divisions - West Coast, Kudat, Interior, and Tawau divisions - and examined for temporal and spatial variations. The analysis revealed frequent turbidity spikes, particularly in the Tawau and Interior divisions, with some WTPs, such as Kalabakan and Beaufort I & II, recording levels exceeding 1000 Nephelometric Turbidity Units (NTU), which is the operational shutdown threshold used by WTPs to prevent treatment failure and equipment damage. Kalabakan recorded a peak turbidity of 2,264 NTU, while Beaufort I and II reached 2,528 NTU, more than twice the downtime threshold. These elevated levels were closely linked to extensive land clearing and agricultural activities. The study underscores the importance of integrated water resource management, including erosion control, reforestation, and stricter land-use regulations. To improve operational resilience, real-time turbidity monitoring and predictive modelling are recommended to enhance WTP resilience and ensure a sustainable water supply in tropical regions amidst intensifying environmental pressures.

1. Introduction

Water Treatment Plants (WTPs) are essential in protecting public health by ensuring the consistent delivery of safe drinking water. They effectively remove a wide range of contaminants through advanced processes such as coagulation, sedimentation, and sand filtration, which can eliminate suspended particles from raw water sources. These treatment methods also significantly reduce the presence of harmful microorganisms. For example, WTPs can remove up to 99% of mycobacteria, which are highly resistant to conventional disinfection methods [1]. This capacity is crucial in reducing the prevalence of waterborne diseases [2]. These facilities have been critical in mitigating severe health risks associated with significant exposure to bacteria, nutrients, heavy metals and more recently, emerging organic contaminants e.g., pesticides and industrial additives, in surface water sources [3].

Turbidity, measured in Nephelometric Turbidity Units (NTU), reflects the presence of suspended particles such as sediment, organic matter, and microorganisms [1]. While not directly harmful, turbidity often correlates with pathogenic microorganisms and serves as a key indicator of raw water quality [4]. Elevated levels during extreme weather can overwhelm treatment performance, reducing water availability and increasing health risks [1], [5]. These disruptions have been linked to outbreaks of gastrointestinal illness [6] – [9]. Turbidity also increases chlorine demand and can reduce disinfection effectiveness [1]. In visibly cloudy water (typically above 4 NTU), public trust declines, and users may turn to unsafe sources [10]. Thus, turbidity is both a public health and operational concern in WTPs.

High turbidity also imposes significant operational and economic burdens on WTPs. WTPs are frequently forced to shut down following heavy rainfall, as elevated turbidity overwhelms the treatment processes, increasing the risk of untreated or poorly treated water entering the distribution system [1]. Furthermore, sporadic spikes in turbidity can allow enteric pathogens to bypass treatment barriers, whilst suboptimal filtration after filter backwashing further compromises water safety by introducing pathogens into the distribution system. Higher coagulant dosing is required during periods of extreme turbidity, driving up operational costs. Rapid turbidity fluctuations necessitate adaptive management strategies, such as adjusting treatment processes, managing abstraction depths, and even avoiding affected water sources [4]. Failure to meet turbidity targets not only signals potential pathogen presence but also increases the risk of biofilm detachment in the distribution system, further degrading water quality [4].

Turbidity in water systems is heavily influenced by natural processes and environmental events. Seasonal variations, such as increased rainfall during rainy or typhoon seasons, contribute significantly to surface runoff, which mobilizes sediments and other particulate matter into water bodies [1], [11], [12]. Transient turbidity events caused by heavy rainfall and spring snowmelt further increase sediment loads, even affecting treated water quality [13]. Extreme weather events like floods and droughts also play a critical role [14]. Natural disturbances such as wildfires can exacerbate turbidity, with burned watersheds showing turbidity increases of up to 200%, and peaks during stormflows reaching as high as 1,311 NTU [15]. Furthermore, watersheds with steep slopes or sedimentary rock formations, like limestone, naturally experience higher sediment transfer rates, further contributing to elevated turbidity levels [14].

Human activities significantly intensify turbidity in water systems by altering natural landscapes and introducing pollutants. Urbanisation increases impervious surfaces, leading to greater surface runoff and sediment transport. Urban watersheds consistently exhibit total suspended solids (TSS) concentrations up to 300% higher than forested areas, with sediment and nutrient loads sometimes five times greater [14]. Agricultural practices contribute to turbidity through runoff containing fertilisers, pesticides, and loose soil, which elevate sediment loads and nutrient levels. Deforestation accelerates soil erosion, resulting in sediment yields 20-50% higher in deforested watersheds compared to intact forests [14]. Additionally, salvage logging after wildfires exacerbates turbidity, with logged watersheds exhibiting TSS levels over 19 times higher than reference watersheds and peak turbidity levels reaching 1,179 NTU during stormflows [15]. Point sources like wastewater discharges also contribute to turbidity by releasing organic matter and pathogens directly into water bodies [1]. These anthropogenic factors not only increase turbidity but also complicate water treatment processes, highlighting the need for effective land-use management and pollution control to maintain water quality.

Sabah, a Malaysian state in Borneo, offers a compelling case for studying turbidity challenges in water systems. Its diverse natural landscapes and complex river networks are highly vulnerable to both natural and anthropogenic pressures, often resulting in raw water quality deterioration and supply disruptions. Heavy rainfall during monsoon seasons and extreme weather events, including typhoons from the nearby Philippines, frequently cause sudden spikes in turbidity [16], complicating water treatment operations. Projected increases in rainfall intensity [17] – [18], which will exacerbate water supply challenges, particularly in rural areas [19]. Meanwhile, rapid urbanisation, expanding oil palm plantations, and widespread land clearing continue to increase sediment loads in many catchments [20] – [22], placing additional strain on WTPs. Despite growing concerns, there is a lack of studies in Sabah that quantify turbidity trends in relation to upstream land-use change and operational impacts at WTPs. This study addresses this gap by analysing turbidity data from 20 WTPs managed by Sabah State Water Department (JANS) with the highest recorded downtimes. The findings aim to inform more effective water resource management in Sabah, particularly in shaping land-use regulation, catchment protection strategies, and climate-resilient water supply planning.

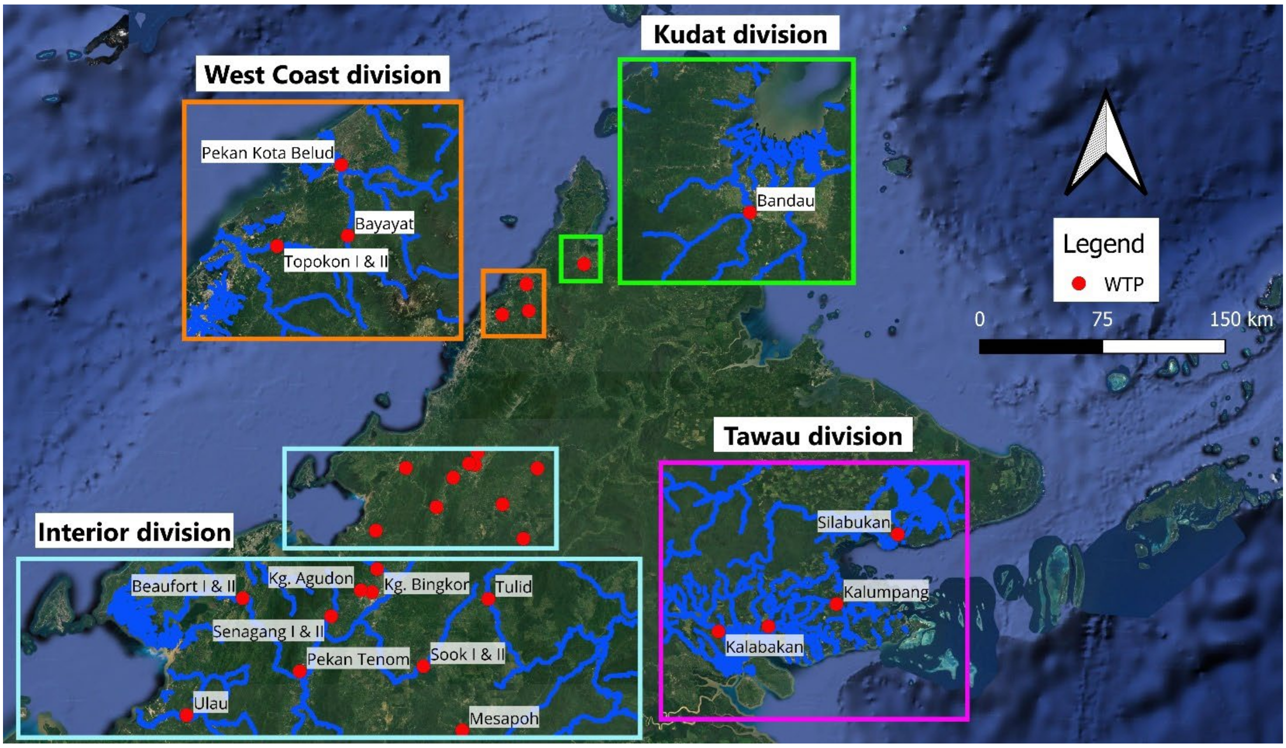

Fig. 1 *Location of 20 WTPs in Sabah, Malaysia. The WTPs in the West Coast division is enclosed by an orange border, in the Kudat division a green border, in the Interior division a cyan border and in the Tawau division a magenta border. The zoomed-in insets of the West Coast, Kudat and Interior divisions are provided to enhance visibility*

2. Methodology

This study analyses turbidity data measured at the raw water intakes of 20 WTPs managed by the Sabah State Water Department (JANS). The temporal coverage of the turbidity datasets varies between WTPs, with Kg Mesapoh having the longest dataset, spanning from 2014 to 2022, and Kalabakan and Merotai having the shortest, covering 2021 to 2022. To streamline the analysis, the WTPs are categorised into four administrative divisions: West Coast, Kudat, Interior, and Tawau, as shown in Fig. 1 and Table 1. Table 1 also includes information on the design capacities in million litre per day (MLD), number of reported downtimes between January 2020 and December 2022, and number of turbidity data for each WTP in this study.

Turbidity data were obtained directly from the Sabah State Water Department (JANS) as part of routine in-situ measurements conducted at raw water intakes. Although detailed specifications of the measurement instruments were not provided, the data were collected in accordance with JANS's regulatory monitoring protocols and reported in standard nephelometric turbidity units (NTU). While minor variations in instrumentation or measurement frequency may exist between WTPs, the dataset is considered reliable for the purpose of this study, given its source from official regulatory records.

Land-use changes were identified through visual comparison of satellite images in Google Earth Pro from two time periods: prior to January 2020 and between January 2020-December 2022, based on the best available imagery for each location within those periods. The analysis focused on visible indicators such as exposed soil surfaces, expansion of plantation grid patterns, and signs of terraced land clearing in upstream catchment areas. These images were manually selected to maximise visibility and minimise cloud cover. Only high-resolution imagery was used to ensure accurate interpretation. Automated classification techniques were not employed, as the primary objective was to provide qualitative support to the turbidity trends observed at each WTP.

Table 1 *Summary of the reported downtimes and details of the turbidity data for all WTPs in the study*

No.	WTP	Design capacity (MLD)	No. of reported downtimes with turbidity ≥ 1,000 NTU (January 2020 – December 2022)	No. of turbidity data obtained from JANS
		West Coast division		
1	Kg. Topokon I	3	42	36
2	Kg. Topokon II	6	40	32
3	Pekan Kota Belud	22	46	63
4	Bayayat	15	79	58
		Kudat division		
5	Bandau	30	79	19
		Interior division		
6	Beaufort I	30	44	79
7	Beaufort II	30	60	78
8	Kg. Ulau	15	53	71
9	Kg. Agudon	8	41	38
10	Kg. Bingkor	20	45	54
11	Kg. Keningau	5	75	48
12	Tulid	8	131	31
13	Sook I & II	3.5	209	42
14	Senagang I & II	12	97	51
15	Pekan Tenom	4.5	46	28
16	Mesapoh	8	129	67
		Tawau division		
17	Kalumpang	12.5	108	28
18	Kalabakan	2	97	27
19	Kg. Silabukan	4	36	36
20	Merotai	5	193	29

The turbidity data are visualised through two distinct types of plots. The first plot illustrates the time histories of turbidity data measured by JANS, recorded at each WTP intake. A horizontal threshold line at 1000 NTU is superimposed on these plots, representing the operational limit beyond which the WTP must temporarily shut down to prevent complications in the water treatment processes and equipment damages [23]. The second plot provides a smoothed representation of the turbidity data using a 5-period moving average, calculated as in Eqn. (1):

$$T_{MA,t} = \frac{1}{5}\sum_{i=t-2}^{t+2} T_i \tag{1}$$

Here, $T_{MA,t}$ denotes the moving average of the turbidity data at t time, and T_i represents the measured turbidity at time i. This approach reduces short-term variability, allowing the identification of broader trends in the data. To examine long-term trends, a linear trendline is fitted to the moving average using first-order polynomial regression. The trendline equation is given by Eqn. (2):

$$T_{trend,t} = a + bt \tag{2}$$

where $T_{trend,t}$ is the predicted turbidity at time t, a is the intercept, and b is the slope of the trendline. The parameters a and b are estimated using the least time square method, which minimises the sum of squared residuals between the measured and predicted turbidity (Eqn. (3)):

$$min \sum_{t} \left(T_{MA,t} - T_{trend,t}\right)^2 \tag{3}$$

In addition to the trendline, the plots include a horizontal threshold at 50 NTU, corresponding to the Class II standard outlined in the National Water Quality Standards for Malaysia (NWQSM). This threshold delineates the turbidity levels suitable for conventional treatment under Class IIA, which is deemed appropriate for potable water supply [24].

To complement the quantitative analysis of turbidity trends, a qualitative assessment of upstream catchment conditions is conducted using time-lapsed satellite imagery from Google Earth Pro, whenever high resolution images are available. This involves comparing historical and recent satellite images of the catchment areas feeding into each WTP. Particular attention is paid to identifying land use changes such as land clearing due deforestation, agricultural expansion, urbanisation, and other anthropogenic activities that may contribute to increased sedimentation and, consequently, higher turbidity levels in the raw water sources.

3. Results and Discussions

This section presents the analysis of turbidity data collected from 20 WTPs across four divisions in Sabah: West Coast, Kudat, Interior, and Tawau. The discussion highlights spatial and temporal variations in turbidity levels, including their relationship with upstream land-use changes. By analysing the turbidity data in detail, this study not only identifies the immediate factors contributing to elevated turbidity levels but also emphasises the broader implications for water resource management, including the need for adaptive strategies to ensure sustainable WTP operations.

3.1 West Coast division

In this study, the WTP located in the West Coast division serves several areas, including Kg Topokon I, Kg Topokon II, Pekan Kota Belud, and Bayayat. Kg Topokon I and Kg Topokon II are situated in the Tuaran district and abstract raw water from Sg. Topokon, an upstream tributary of Sg. Tuaran. Meanwhile, Pekan Kota Belud and Bayayat, located in the Kota Belud district, rely on different water sources: Bayayat abstracts from Sg. Kadamaian, whilst Pekan Kota Belud, located downstream of Bayayat, receives water from both Sg. Kadamaian and Sg. Wariu.

The turbidity time series for these four water intakes, spanning from 3 to 5 years (Fig. 2), indicates that turbidity levels have consistently remained below the 1000 NTU threshold. This observation suggests minimal or no shudown at the WTPs during this period, as high turbidity levels often trigger operational downtimes to prevent damage to treatment systems and ensure compliance with water quality standards. However, whilst these results may seem reassuring, they should be interpreted with caution. Several limitations may affect the reliability of these observations, including gaps in data, potential underreporting during extreme weather events, and the absence of continuous turbidity monitoring, particularly during long periods of COVID-19 movement restrictions.

A closer look at the moving averages of turbidity levels (Fig. 3) provides additional insights into the longer-term trends. For Pekan Kota Belud and Bayayat, the turbidity levels have remained within the Class II range, indicating that the raw water quality from Sg. Kadamaian and Sg. Wariu is generally good and suitable for treatment with conventional methods. This stability suggests that, despite some variability, these water sources are less impacted by significant upstream disturbances or land-use changes during the study period.

In contrast, the turbidity levels at Kg Topokon I and Kg Topokon II exhibit a clear increasing trend, particularly from 2021 onwards. This trend points to a gradual deterioration of raw water quality, raising concerns about the sustainability of Sg. Topokon as a reliable water source. The rising turbidity levels are particularly concerning as they indicate increased sediment loads, which can lead to higher treatment costs and potential strain on the WTP's capacity to meet water demand.

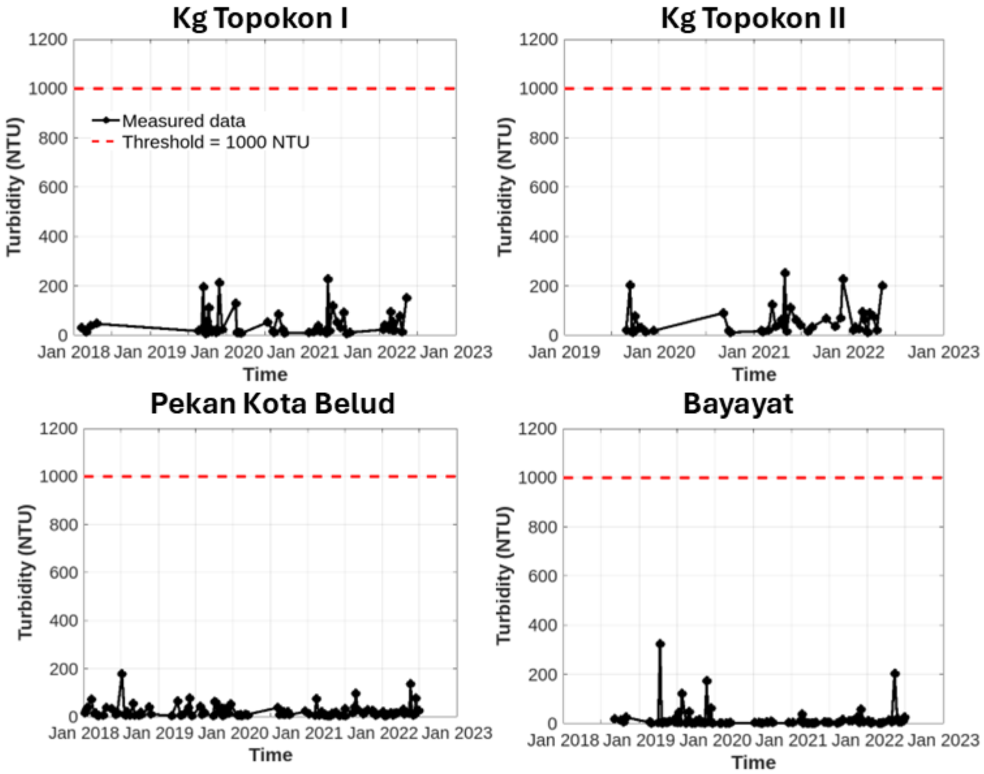

Fig. 2 *Time histories of the turbidity data at the plants in the West Coast division, along with the threshold for water treatment plant closures (i.e. 1000 NTU)*

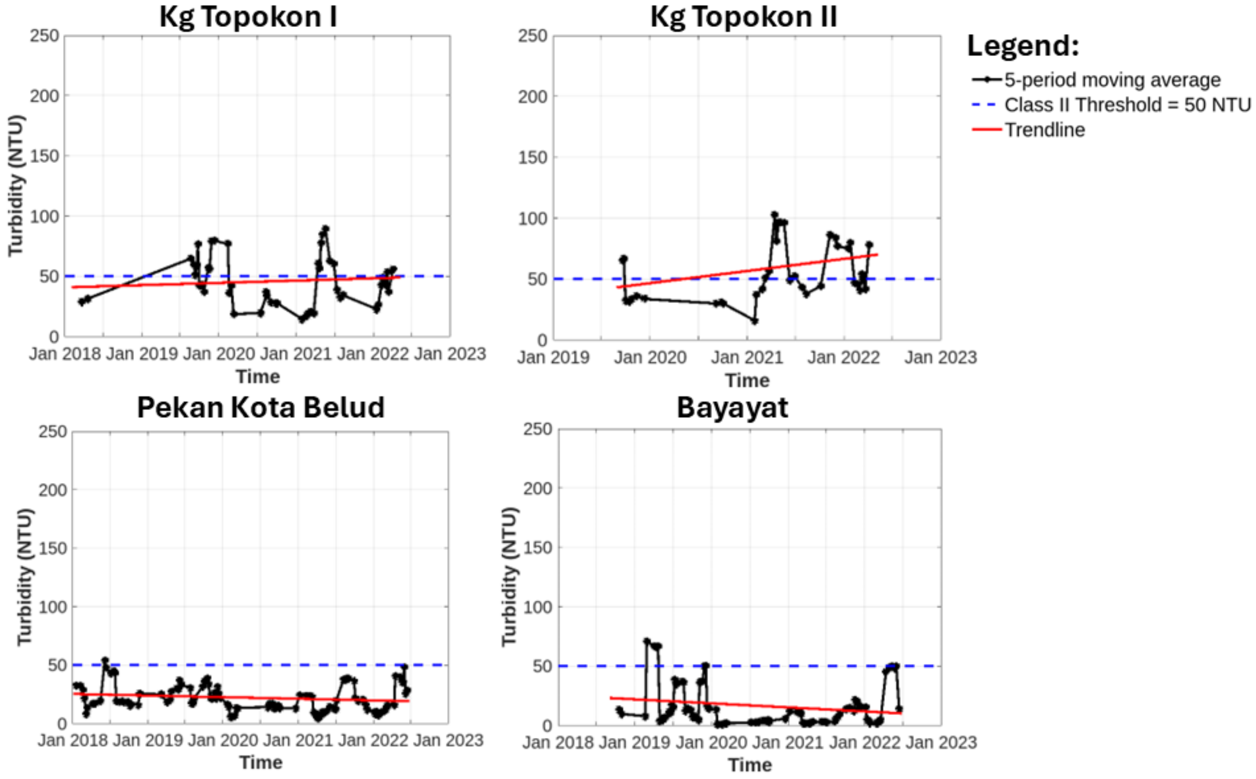

Fig. 3 *5-period moving average of turbidity data time histories and the projected trendlines at the plants in the West Coast division, along with the threshold for Class II of the DOE's NWQSM (i.e. 50 NTU)*

The deterioration in water quality at Kg Topokon I and Kg Topokon II appears to be closely linked to significant land-use changes in the upstream catchment area (Fig. 4). One notable factor is the large-scale terraced-cut land clearing observed near Kg. Toboh Baru, located approximately 12 km upstream of the WTP. Based on time-lapse Google satellite imagery (Fig. 5), the cleared land area in this region has increased roughly fourfold between 2019 and 2021. Such extensive land clearing is likely to expose large areas of soil to erosion, particularly during heavy rainfall, resulting in increased sediment loads in the river system.

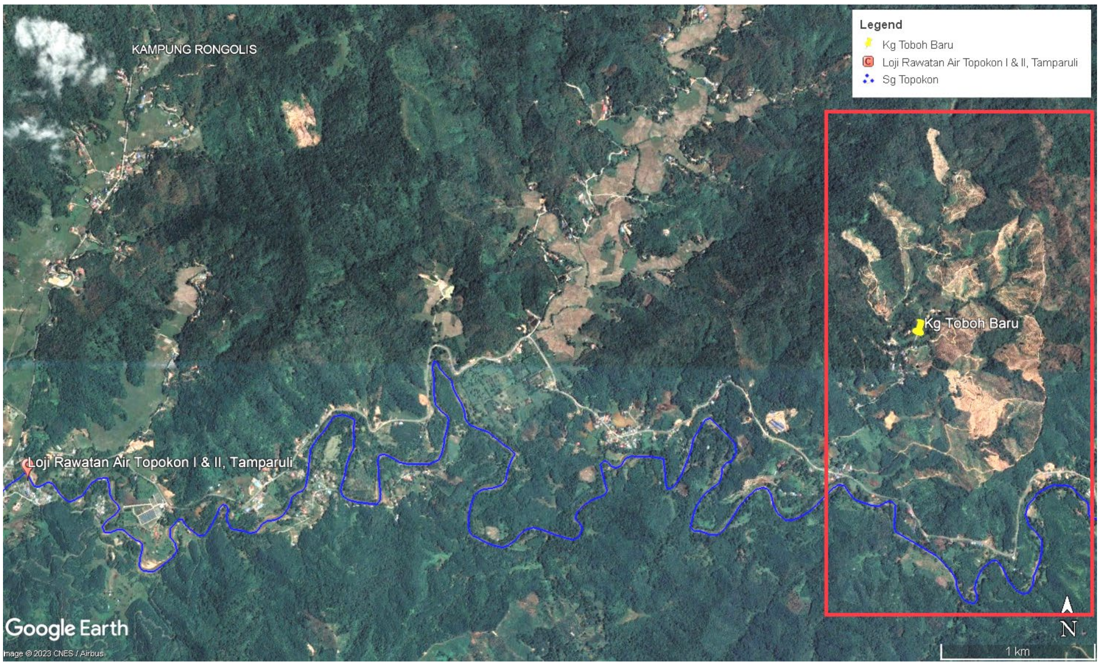

Fig. 4 *Sg Topokon upper catchment, showing the location of the Topokon I & II WTP and Kg Toboh Baru. The red box shows the location of the cleared land surrounding Kg. Toboh Baru. (Source: Google Earth)*

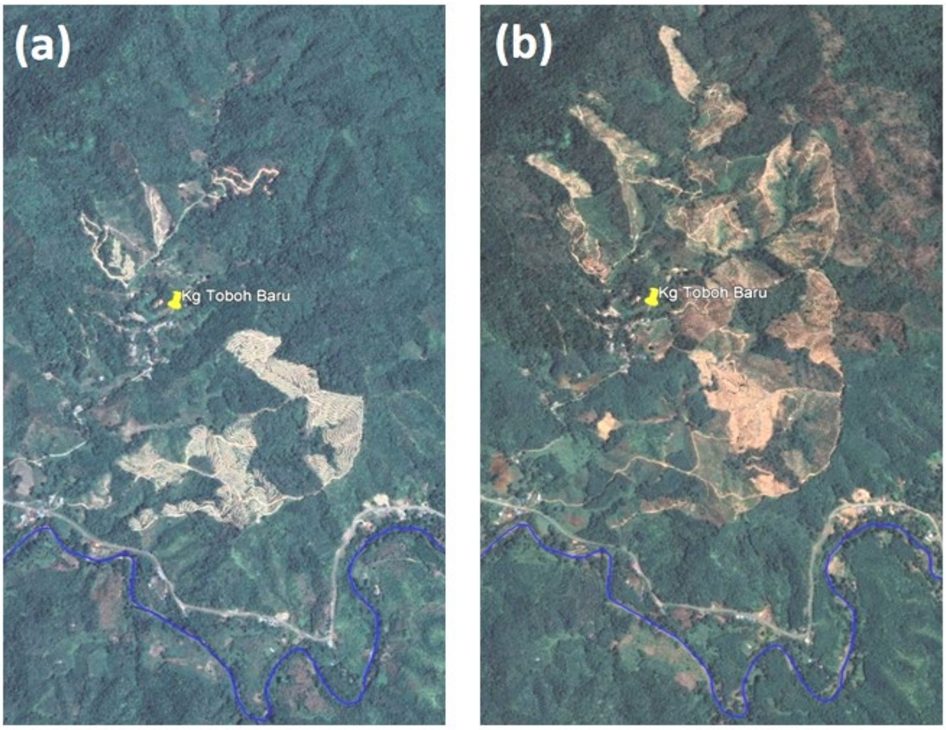

Fig. 5 *The zoomed-in images within the red box in fig. 4 showing the extent of cleared land surrounding Kg Toboh Baru in (a) 28th February 2019; and (b) 9th March 2021. (Source: Google Earth)*

3.2 Kudat Division

Bandau is the only WTP in this study located within the Kudat division, specifically in Kota Marudu. It abstracts raw water from Sg. Bandau, a critical water source for the region. Turbidity levels recorded at the intake from 2020 to 2022 have remained below the 1000 NTU threshold and within the Class II range (Fig. 6), with a peak turbidity of 142 NTU. This suggests that the water quality is generally within acceptable limits for conventional treatment processes, ensuring consistent WTP operations during this period. However, a closer examination of the project trendline (Fig. 6, right panel) reveals a slight upward trend in turbidity levels. Whilst the observed values still fall within the Class II range, the increasing trend signals a gradual deterioration in raw water quality. This subtle but notable change could have implications for the long-term sustainability of the WTP, as even marginal increases in turbidity may elevate treatment costs and operational complexity over time.

The observed deterioration can be linked to changes in land use upstream of the WTP. Time-lapsed satellite imagery highlights a significant terraced land clearing of approximately 0.5 km^2 near Kg. Lampada, located about 6 km upstream of the WTP (Fig. 7). In the 2020 satellite imagery (Fig. 7(a)), this area shows clear signs of disturbance, in contrast to the relatively undisturbed landscape seen in 2019 (Fig. 7(b)). Such land-clearing activities are known to increase soil erosion, particularly during rainfall events, contributing to higher sediment loads in the river system.

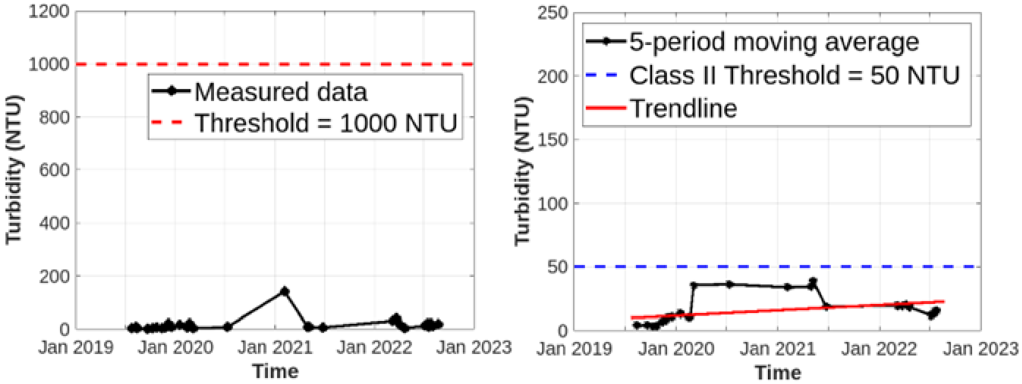

Fig. 6 *Time histories of turbidity data at the Bandau plant along with the threshold for water treatment plant closures (i.e. 1000 NTU) (left panel); the 5-period moving average of turbidity data time histories and the projected trendline, along with the threshold for Class II of the DOE's NWQSM (i.e. 50 NTU) at the Bandau plant.*

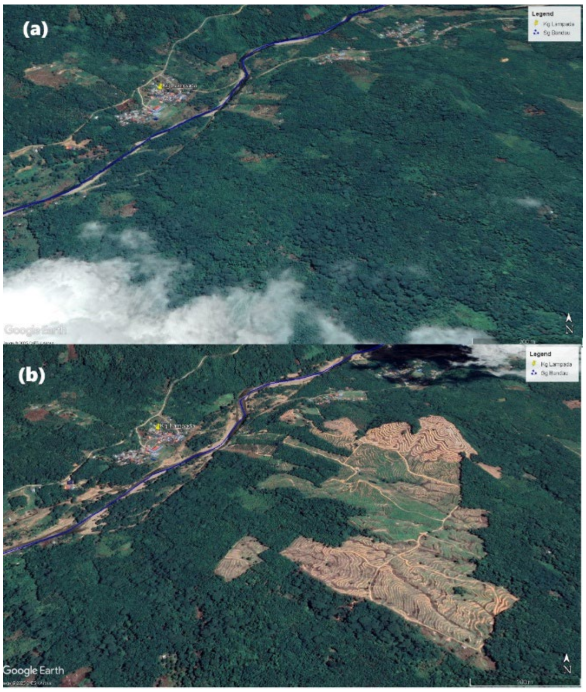

Fig. 7 *The extent of cleared land surrounding Kg Lampada in (a) 17th August 2019 and (b) 6th July 2020. (Source: Google Earth)*

3.3 Interior Division

The Interior division contains the highest number of WTPs in this study, comprising 11 out of the 20 WTPs analysed. These include Beaufort I, Beaufort II, Kg Ulau, Kg Agudon, Kg Bingkor, Kg Keningau, Tulid, Sook I & II, Senagang I & II, Pekan Tenom, and Kg Mesapoh. Of these, eight WTPs are situated in five tributaries of the Pegalan-Padas River system: Kg Agudon, Kg Bingkor, and Kg Keningau abstract raw water from Sg. Pampang, Sg. Baiayo, and Sg. Liawan, respectively, in the Keningau district. Sook I & II abstract raw water from Sg. Sook in the Sook district, whilst Senagang I & II rely on Sg. Senagang in the Tenom district. These five river tributaries (i.e. Sg. Pampang, Sg. Baiayo, Sg. Liawan, Sg. Sook and Sg. Senagang) converge into Sg. Pegalan, which subsequently meets Sg. Padas near Pekan Tenom. Sg. Padas then flows downstream through Beaufort, at which Beaufort I and II WTPs abstract water before the river ultimately drains into the South China Sea. Three WTPs in this division that are not located along the Pegalan-Padas River system - Kg Ulau, Tulid, and Kg Mesapoh - abstract raw water from Sg. Mengalong in the Sipitang district, Sg. Labou in the Keningau district, and Sg. Tondulu in the Nabawan district, respectively.

Fig. 8 illustrates the turbidity time histories at the water intakes of each WTP. Given the large variation in peak turbidity values across WTPs, two different y-axis scales were used to improve clarity: for WTPs with peak turbidity exceeding 1000 NTU, the y-axis maximum was set at 3000 NTU, whereas for WTPs with peak turbidity below 1000 NTU, the y-axis maximum was set at 1200 NTU. This approach ensures that both extreme events and subtle variations are clearly visible without compressing lower-value trends. Kg Agudon, Kg Bingkor, and Kg Keningau consistently exhibit turbidity levels below 200 NTU, well within acceptable limits and far below the operational downtime threshold of 1000 NTU. Similarly, both Sook I & II and Senagang I & II maintain turbidity levels below the threshold, although their maximum turbidity levels are significantly higher, reaching 757 NTU and 569 NTU, respectively. However, at the confluence of Sg. Pegalan and Sg. Padas, Pekan Tenom displays substantially higher turbidity levels, with a peak value of 2,264 NTU, far exceeding the downtime threshold. This elevated turbidity is expected, given the combined contributions of sediment-laden flows from both upstream tributaries of Sg. Pegalan and the southern upstream catchment of Sg. Padas. Consequently, Beaufort I and II WTPs, being located further downstream, experience the highest turbidity levels recorded in this study, with a peak value of 2,528 NTU. In contrast, Kg Ulau and Tulid exhibit turbidity levels consistently below the 1000 NTU threshold, indicating stabler water quality conditions. Kg. Mesapoh shows generally acceptable turbidity levels, with only one turbidity record exceeding the downtime threshold.

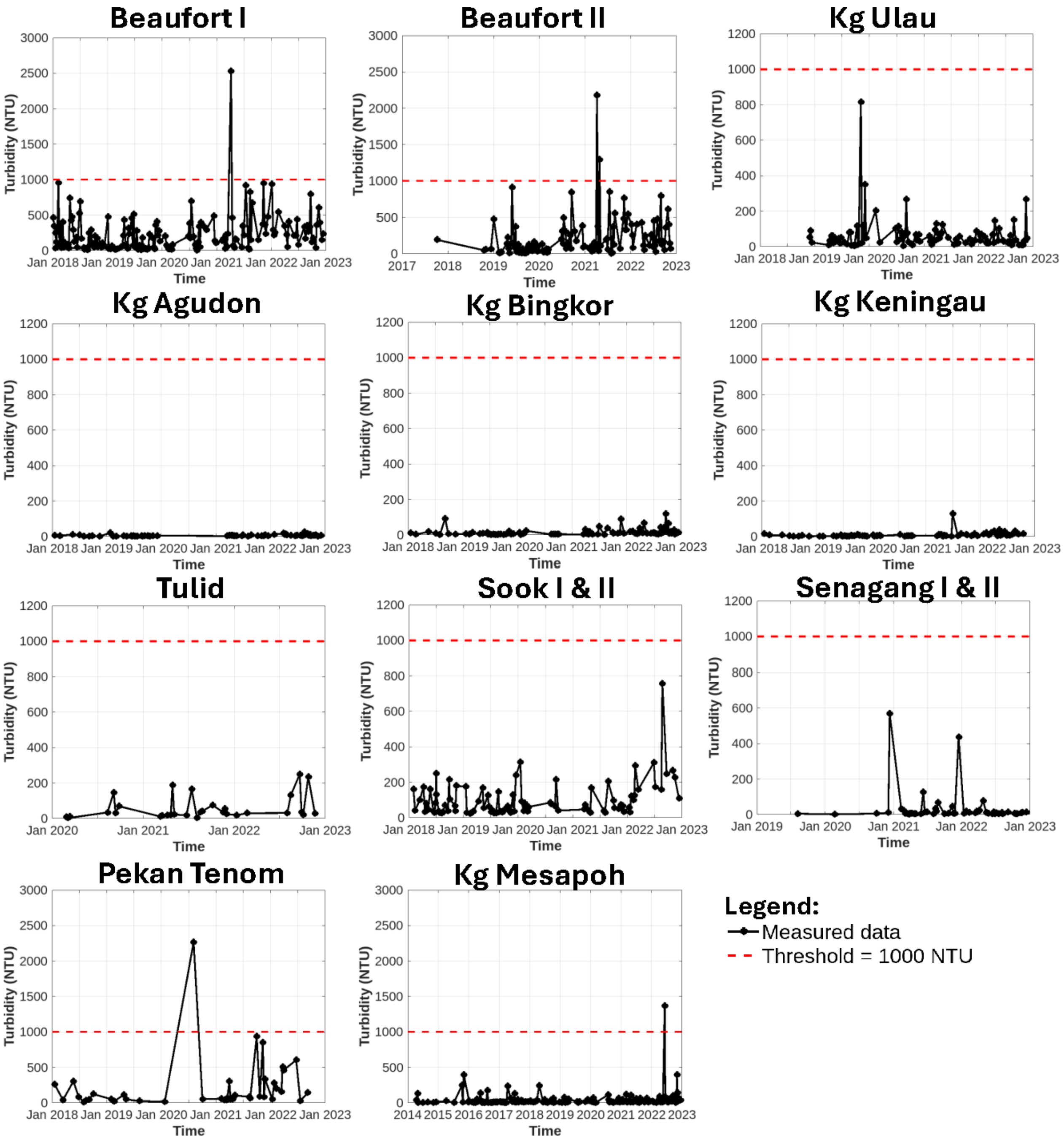

Fig. 8 *Time histories of turbidity data at the water treatment plants in Interior division, along with the threshold for water treatment plant closures (i.e. 1000 NTU)*

The time histories of the 5-period moving averages in Fig. 9 indicate that turbidity levels in Kg. Agudon, Kg. Bingkor, and Kg. Keningau remain within the acceptable range for Class II water quality. Similarly, most turbidity levels in Senagang fall within the Class II range. However, the turbidity levels in Sook frequently exceed this range. Notably, the moving average plot for Sook shows a significant upward trend, particularly in early 2022, suggesting a marked deterioration in raw water quality during this period. This increase in turbidity at Sook may plausibly be attributed to intensified land-clearing activities in the upper catchment. Such activities often lead to higher sediment loads, which in turn elevate turbidity levels. Further downstream, turbidity levels at Pekan Tenom and Beaufort I & II consistently exceed the Class II threshold. This trend is likely driven by the compounded effect of poor water quality from both Sg. Pegalan and the upstream sections of Sg. Padas. Satellite imagery and land-use data indicate significant land clearings in these areas, potentially for cultivation or afforestation, which may have contributed to the elevated sediment loads.

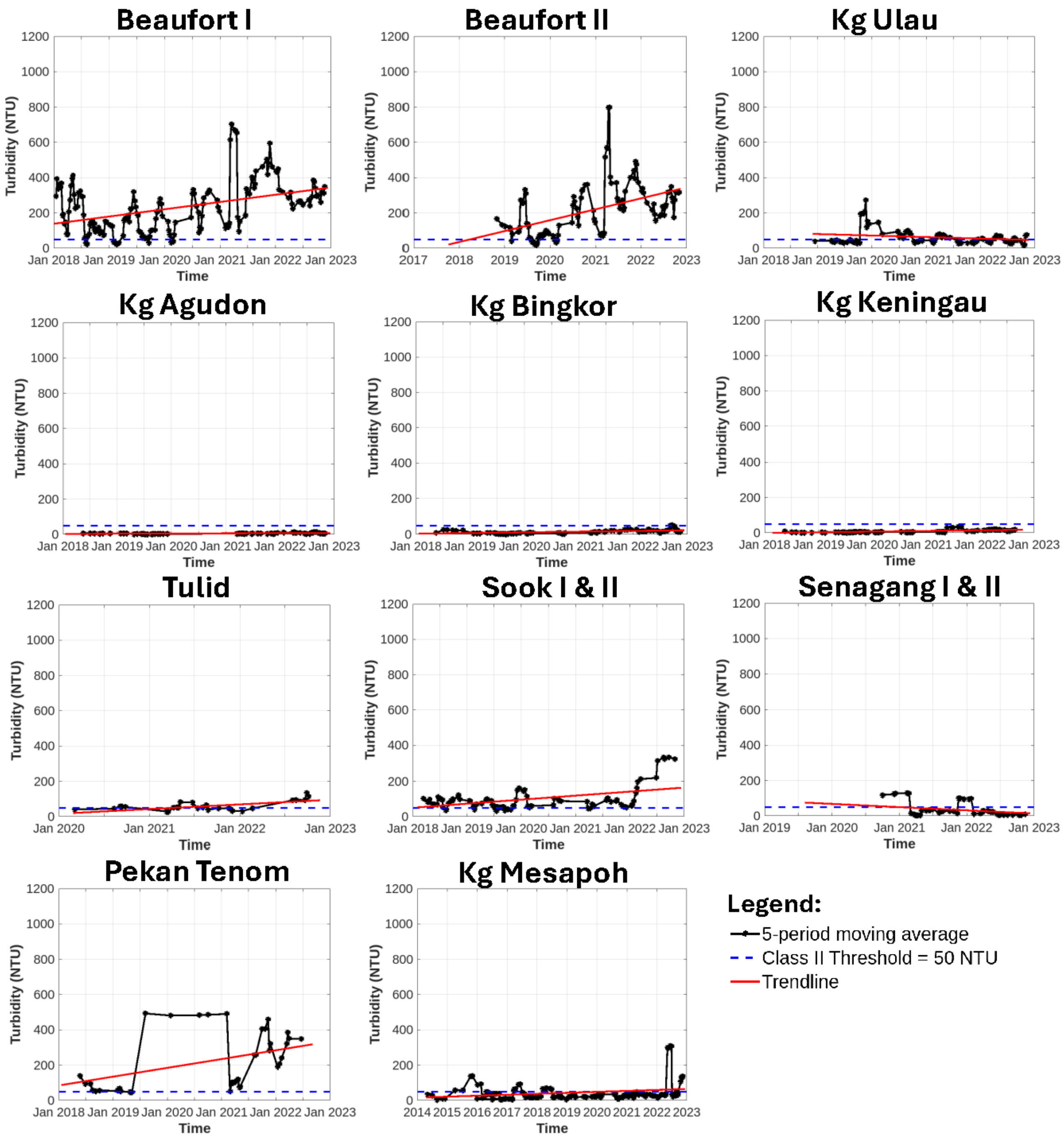

Fig. 9 *5-period moving average of turbidity data time histories and the projected trendlines at the water treatment plants in the Interior division, along with the threshold for Class II of the DOE's NWQSM (i.e. 50 NTU)*

In contrast, whilst the turbidity levels in both Kg Ulau and Tulid generally hover around the Class II threshold, their trends differ. Kg Ulau exhibits a slight decrease in turbidity since 2020, whereas Tulid shows a gradual increase. This divergence could be linked to land-use changes, similar to those observed in Sook, as the upper catchments of these WTPs are geographically close and likely share similar land-use characteristics. Lastly, Kg Mesapoh shows an increasing trend in turbidity levels, with notable peaks in mid- and late-2022. This pattern is also likely associated with land-clearing activities, potentially for afforestation, in the upper catchment.

3.4 Tawau Division

There are four WTPs located in the Tawau division examined in this study: Kalumpang, Kalabakan, Kg Silabukan, and Merotai, situated in the Semporna, Kalabakan, Lahad Datu, and Tawau districts, respectively. Each WTP abstracts raw water from different river systems: Sg. Kalumpang (Kalumpang WTP), Sg. Kalabakan (Kalabakan WTP), Sg. Matamba (Kg Silabukan WTP), and Sg. Merotai (Merotai WTP). The time histories of turbidity levels at these water intakes, as depicted in Fig. 10, reveal that three out of the four WTPs recorded turbidity measurements exceeding the 1000 NTU threshold, which is often associated with operational downtime. Among these, Kalabakan WTP exhibited the highest recorded turbidity level, peaking at approximately 3,495 NTU. This extreme value suggests significant sediment load, potentially linked to upstream land-use activities such as logging or agriculture, which warrant further investigation. Kg Silabukan WTP, whilst not recording the highest single turbidity value, experienced the most frequent exceedances of the 1000 NTU threshold. This indicates persistent challenges in maintaining raw water quality, likely due to recurring sedimentation events or consistent sources of contamination in the catchment area of Sg. Matamba. Although Kalumpang WTP did not record turbidity levels exceeding 1000 NTU, its maximum turbidity level reached 726 NTU, which is still relatively high.

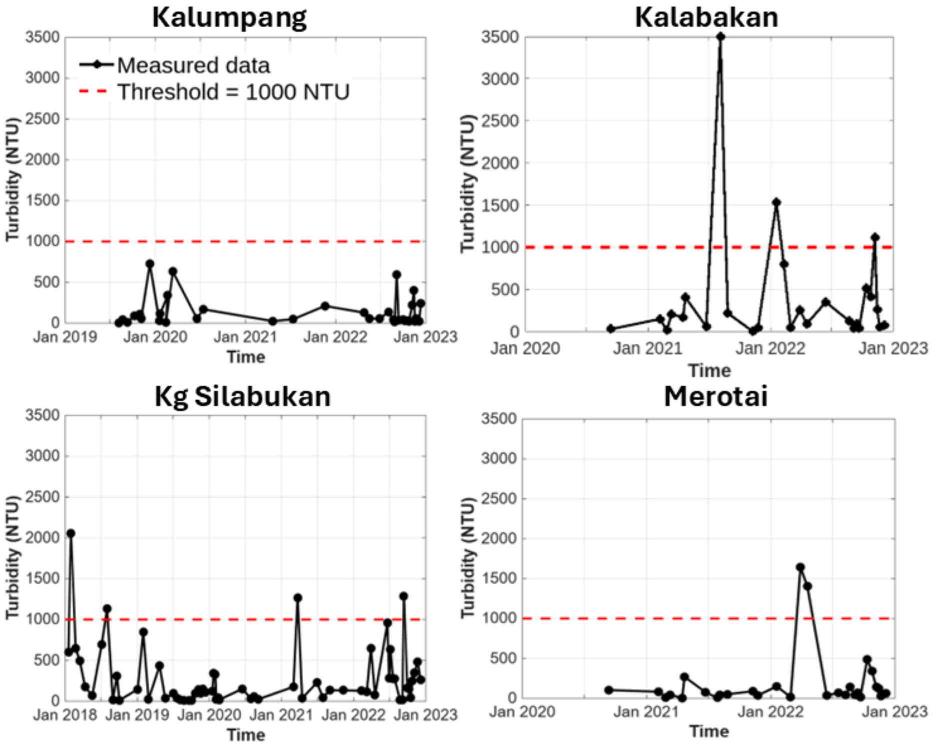

Fig. 10 *Time histories of turbidity data at the water treatment plants in the Tawau division, along with the threshold for water treatment plant closures (i.e. 1000 NTU)*

The high levels of turbidity at the 4 WTP intakes has led to poor quality of the raw water sources. This finding is in line with the time histories plot of the 5-period moving averages (Fig. 11), in which most of the turbidity levels are beyond of the Class II range. Upon the inspection of the satellite images, it is apparent that the upstream areas of the 4 WTP have undergone massive change of land use over time. In particular, a vast size of the upstream areas has been cleared and transformed into oil palm plantations and mills. Thus, it could be deduced that the discharges of oil palm effluents may be a possible contributor to the deterioration of the raw water quality in the 4 WTPs, in addition to exposed land surface with erodible sediments due to land clearings for oil palm plantations. These elevated turbidity levels suggest that, whilst operational thresholds were not breached, the water quality remains a concern, potentially leading to increased treatment costs and operational strain.

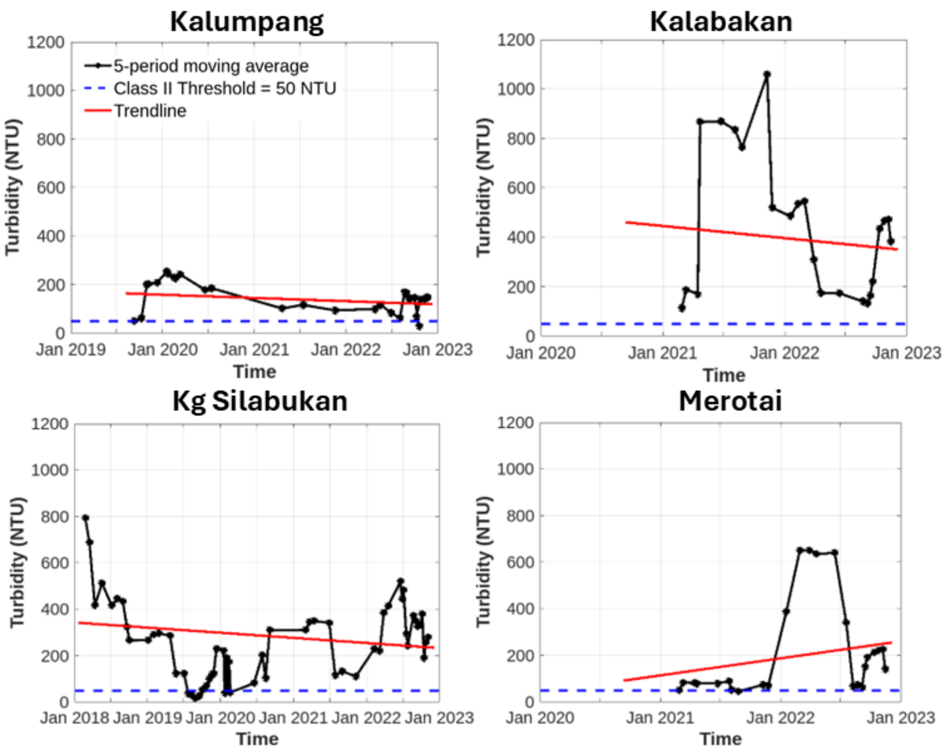

Fig. 11 *5-period moving average of turbidity data time histories and the projected trendline at the water treatment plants in the Tawau division, along with the threshold for Class II of the DOE's NWQSM (i.e. 50 NTU)*

3.5 Spatial Variation in Mean Turbidity by Division

To assess spatial differences in raw water quality, the mean turbidity at each water treatment plant (WTP) was calculated over the available monitoring period and grouped according to the four administrative divisions: West Coast, Kudat, Interior, and Tawau. Fig. 12 presents the distribution of mean turbidity values for all 20 WTPs. Substantial variability is evident both between and within divisions. In the Interior division, mean turbidity ranged from as low as 5.7 NTU at Agudon to as high as 392.1 NTU at Kalabakan. Similarly, in the Tawau division, Merotai and Silabukan recorded high means of 194.9 NTU and 285.9 NTU, respectively, while other plants recorded lower values. The West Coast division generally exhibited lower mean turbidity levels, with Bayayat at 16.5 NTU and Pekan Kota Belud at 22.2 NTU, although Topokon II recorded 58.9 NTU. Kudat division's sole WTP in this study, Bandau, recorded 15.8 NTU. These variations reflect the influence of local catchment characteristics, land-use patterns, and hydrological conditions on raw water quality [20] – [22]. The observed spatial patterns also suggest that turbidity challenges are not confined to specific regions but can vary widely even within the same division.

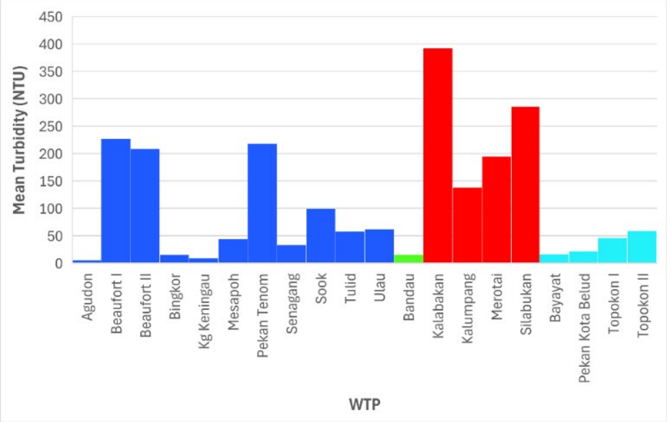

Fig. 12 *Mean turbidity at 20 water treatment plants (WTPs) in Sabah, grouped by administrative divisions – Interior (blue bar), Kudat (green bar), Tawau (red bar) and West Coast (cyan bar). The histograms illustrate the distribution of mean turbidity within each division, highlighting both inter- and intra-divisional variability*

3.6 Synthesis of Turbidity Trends Across Divisions: Drivers, Impacts, and Management Implications

The findings from the four divisions (i.e. West Coast, Kudat, Interior, and Tawau) highlight both shared and unique turbidity challenges faced by the WTPs. This synthesis explores the overarching drivers of turbidity, their operational and environmental impacts, and the implications for sustainable water resource management.

3.6.1 Key Drivers of Turbidity

Across all divisions, land-use changes have emerged as a critical factor influencing turbidity levels. Activities such as afforestation, agricultural expansion, and terraced land clearing have led to increased sediment loads in rivers. In the West Coast division, Kg Topokon I and II saw a marked rise in turbidity from 2021 onwards, corresponding to extensive land clearing near Kg. Toboh Baru. Similarly, in the Tawau division, Kalabakan WTP recorded peak turbidity levels of 3,495 NTU, likely driven by logging and agricultural practices in its catchment. Kg Silabukan also experienced frequent exceedances of the 1000 NTU threshold, reflecting ongoing sedimentation issues. In the Kudat division, although Bandau WTP's turbidity levels remained below 1000 NTU, a gradual upward trend hints at emerging risks. The Interior division presents a mixed picture: whilst some WTPs, like Kg Ulau, show improving trends, others such as Beaufort I & II face persistent high turbidity due to the compounded effects of sediment-laden inflows from multiple upstream sources. The impact of river confluences on turbidity is particularly evident in the Interior division. Pekan Tenom, located at the confluence of Sg. Pegalan and Sg. Padas, recorded some of the highest turbidity levels in the study, exceeding 2,000 NTU. This compounded effect of sediment transport is even more pronounced at the Beaufort WTPs, where turbidity levels peaked at 2,528 NTU. These observations underscore the cumulative impact of sedimentation within interconnected river systems, posing significant challenges for downstream WTP operations.

There is an important consideration regarding the dataset that should be noted. The sampled turbidity data may not fully reflect periods of WTP downtimes caused by turbidity levels exceeding 1000 NTU. The number of turbidity measurements ≥ 1000 NTU between January 2020 and December 2022 analysed in this study is significantly lower than the reported downtimes due to high turbidity (Table 1). Moreover, in more than half of the WTPs, the total number of sampled data points is less than the reported downtime events (Table 1). This discrepancy suggests that extreme turbidity events may have been underrepresented, potentially leading to an incomplete assessment of their frequency and severity. This highlights the need for continuous and automated turbidity monitoring systems to ensure comprehensive data coverage.

3.6.2 Operational and Environmental Implications

The variability in turbidity levels across divisions presents significant operational challenges. WTPs such as Kalabakan and Pekan Tenom frequently exceeded the 1000 NTU threshold, necessitating shutdowns and increasing the risk of supply disruptions. Even where turbidity levels remained below 1000 NTU, as in Kalumpang and Kg Ulau, sustained high levels place additional strain on treatment processes, increasing costs and reducing efficiency. Additionally, the environmental impact of elevated turbidity contributes to increased sedimentation, which can alter river geomorphology, degrade aquatic habitats, and impact downstream ecosystems. With climate change driving more extreme and unpredictable weather patterns, both increased and decreased rainfall can exacerbate these issues [17], [18]. Intense rainfall can lead to greater runoff and sediment influx, further destabilising riverbanks and degrading water quality, whilst reduced rainfall may lower river flow, concentrating pollutants and turbidity in remaining water sources [20], [21]. These shifts underscore the need for proactive interventions to mitigate the dual threats posed by changing weather patterns and their compounded effects (i.e., sediment influx) into river systems.

3.6.3 Recommendations for Sustainable Water Resources Management

The findings emphasise the importance of integrated, division-specific strategies for sustainable water management. Key recommendations include:

- Erosion Control and Reforestation: Implementing erosion control measures and reforestation in critical areas, particularly upstream of high-risk WTPs, can significantly reduce sediment loads.
- Land-Use Regulation and Monitoring: Strengthening land-use regulations and leveraging satellite imagery for regular monitoring will help mitigate the impacts of deforestation and agricultural expansion.
- Legislative and Regulatory Review: Many WTPs were built long ago and are difficult to adapt to modern needs. With rivers vital for water supply yet burdened by pollutant discharges, a review of regulations is needed to ensure fair use, stronger protection, and long-term sustainability through collaboration with stakeholders such as government agencies, local communities, and industries.

- Community Engagement: Encouraging sustainable land-use practices through community involvement is vital to balance development with environmental conservation.
- Inter-Divisional Coordination: Collaboration across administrative boundaries is crucial, particularly in managing interconnected river systems. Joint watershed management initiatives can enhance the resilience of water resources.

4. Conclusions

This study demonstrates how land-use changes have affected turbidity levels at 20 water treatment plants (WTPs) across Sabah, highlighting a critical but underexplored risk to water supply reliability. Elevated turbidity poses significant operational challenges, including frequent shutdowns and increased treatment costs. The findings contribute to improved understanding of turbidity management in WTPs and support evidence-based decision-making for water resource planning. The study emphasises the need for stricter land-use regulations, erosion control strategies, and collaborative watershed management to ensure long-term sustainability of water supply systems. In particular, engaging local communities and integrating land-use monitoring into catchment management could help mitigate turbidity-related disruptions. Future research should focus on real-time turbidity monitoring, early warning systems, and predictive tools to enhance WTP resilience under changing land-use and climate conditions.

Acknowledgement

The authors would like to thank Sabah State Water Department for sharing the turbidity data, and to Ir. Pet Royston from Eramaju Synergy Sdn. Bhd. for facilitating the acquisition of the data.

Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Janice Lynn Ayog, Min Fui Tom Ngui;* ***data collection:*** *Janice Lynn Ayog;* ***analysis and interpretation of results:*** *Janice Lynn Ayog;* ***draft manuscript preparation:*** *Janice Lynn Ayog, Min Fui Tom Ngui, Marieanne Christie Leong. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] World Health Organization. (2022) Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda, 4th edition, https://iris.who.int/bitstream/handle/10665/352532/9789240045064-eng.pdf?sequence=1

[2] Tzanakakis, V. A., Paranychianakis, N. V. & Angelakis, A. N. (2020) Water Supply and Water Scarcity, *Water*, *12(9)*, 2347, https://doi.org/10.3390/w12092347

[3] Mukhopadhyay, A., Duttagupta, S. & Mukherjee, A. (2022) Emerging organic contaminants in global community drinking water sources and supply: A review of occurrence, processes and remediation, *Journal of Environmental Chemical Engineering*, *10(3)*, 107560, https://doi.org/10.1016/j.jece.2022.107560

[4] World Health Organization. (2017) Water quality and health-review of turbidity: information for regulators and water suppliers, https://www.who.int/publications/i/item/WHO-FWC-WSH-17.01

[5] Stevenson, M. & Bravo, C. (2019) Advanced turbidity prediction for operational water supply planning, *Decision Support Systems*, *119*, 72-84, https://doi.org/10.1016/j.dss.2019.02.009

[6] Hrudey, S. E., & Hrudey, E. J. (2004) Safe drinking water. IWA publishing.

[7] Stirling, R., Aramini, J., Ellis, A., Lim, G., Meyers, R., Fleury, M. & Werker, D. (2001) Waterborne cryptosporidiosis outbreak, North Battleford, Saskatchewan, Spring 2001.

[8] Arias, C., Sala, M. R., Domínguez, A., Bartolomé, R., Benavente, A., Veciana, P., Pedrol, A. & Hoyo, G. (2006) Waterborne epidemic outbreak of Shigella sonnei gastroenteritis in Santa Maria de Palautordera, Catalonia, Spain, *Epidemiology & Infection*, *134(3)*, 598-604, https://doi.org/10.1017/S0950268805005121

[9] Hrudey, S. E. & Hrudey, E. J. (2019) Common themes contributing to recent drinking water disease outbreaks in affluent nations, *Water supply*, *19(6)*, 1767-1777, https://doi.org/10.2166/ws.2019.051

[10] World Health Organization (2024) Guidelines for drinking-water quality: small water supplies, https://iris.who.int/bitstream/handle/10665/375822/9789240088740-eng.pdf?sequence=1

[11] Dorner, S. M., Anderson, W. B., Gaulin, T., Candon, H. L., Slawson, R. M., Payment, P. & Huck, P. M. (2007) Pathogen and indicator variability in a heavily impacted watershed, *Journal of Water and Health*, *5(2)*, 241-257, doi: 10.2166/wh.2007.010

[12] Göransson, G., Larson, M. & Bendz, D. (2013) Variation in turbidity with precipitation and flow in a regulated river system – river Göta Älv, SW Sweden, *Hydrology and Earth System Sciences*, *17*, 2529–2542, https://doi.org/10.5194/hess-17-2529-2013

[13] Gauthier, V., Barbeau, B., Tremblay, G., Millette, R. & Bernier, A.-M. (2003) Impact of raw water turbidity fluctuations on drinking water quality in a distribution system, *Journal of Environmental Engineering & Science*, *2*, 281-291, https://doi.org/10.1139/s03-026

[14] Mishra, A., Alnahit, A., & Campbell, B. (2021). Impact of land uses, drought, flood, wildfire, and cascading events on water quality and microbial communities: A review and analysis, *Journal of Hydrology*, *596*, 125707, https://doi.org/10.1016/j.jhydrol.2020.125707

[15] Emelko, M. B., Silins, U., Bladon, K. D. & Stone, M. (2011) Implications of land disturbance on drinking water treatability in a changing climate: Demonstrating the need for "source water supply and protection" strategies, *Water Research*, *45(2)*, 461-472, https://doi.org/10.1016/j.watres.2010.08.051

[16] Nainar, A., Bidin, K., Walsh, R. P. D., Ewers, R. M. & Reynolds, G. (2017) Effects of different land-use on suspended sediment dynamics in Sabah (Malaysian Borneo) – a view at the event and annual timescales, *Hydrological Research Letters*, *11(1)*, 79 – 84, https://doi.org/10.3178/hrl.11.79

[17] Chuah, S. L., Ayog, J. L. & Bolong, N. (2017) Application of Linear Moments and Uncertainty Analysis to Extreme Rainfall Events in Sabah, *MATEC Web of Conferences*, *103*, 04014, https://doi.org/10.1051/matecconf/20171030

[18] Leong, M. C., Ngui, M. F. T. & Ayog, J. L. (2024) Assessment on future rainfall variability for adaptive water resource management in Sabah, *BIO Web of Conferences*, 131, 05012, https://doi.org/10.1051/bioconf/202413105012

[19] Sarbatly, R., Abd Lahin, F., & Chiam, C., -K. (2020) The outlook of rural water supply in developing country: review on Sabah, Malaysia, *Borneo Science*, *41(1)*, 19 – 43, https://doi.org/10.51200/bsj.v41i1.4442

[20] Camara, M., Jamil, N. R., & Abdullah, A. F. (2019) Impact of land uses on water quality in Malaysia: a review, *Ecological Processes*, *8(10)*, https://doi.org/10.1186/s13717-019-0164-x

[21] Payus, C., Lim, A. H. & Farrah Adn., F. A. (2020) Satellite imagery system in water resources management: impacts from the land use and land cover change, *Asian Journal of Scientific Research*, *13*, 197-204, https://doi.org/10.3923/ajsr.2020.197.204

[22] Wong, S. R., Chars, B., Jainih, L., Fikri, A. H., Harun, S. & Moh, P. Y. (2018) Comparative assessment of Moyog river watershed and Malaysia water quality index, *ASM Science Journal*, *11(2)*, 29-35

[23] Loi, J. X., Chua, A. S. M., Rabuni, M. F., Tan, C. K., Lai, S. H., Takemura, Y. & Syutsubo, K. (2022) Water quality assessment and pollution threat to safe water supply for three river basins in Malaysia, *Science of The Total Environment*, *832*, 155067, https://doi.org/10.1016/j.scitotenv.2022.155067

[24] Department of Environment Malaysia (2020) Environmental Quality Report. https://www.doe.gov.my/en/national-river-water-quality-standards-and-river-water-quality-index/