Stormwater Quality Dynamics in a Recovering Forest of the Upper Rasau Catchment in Ayer Hitam Forest Reserve

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ABSTRACT

Monitoring catchment water quality is crucial for maintaining safe water resources and supporting effective conservation and management strategies. This study evaluates stormwater quality in the Upper Rasau Catchment, located within the Ayer Hitam Forest Reserve (AHFR) in Klang Valley, Malaysia, under both baseflow and stormflow conditions. Key water quality parameters, including dissolved oxygen (DO), turbidity, total suspended solids (TSS), salinity, total dissolved solids (TDS), electrical conductivity (EC), pH, and temperature, were measured across 189 samples collected during 11 storm events between September 20, 2023, and February 24, 2024. The findings reveal that river responses were influenced by rainfall intensity, with most discharges occurring approximately 30 minutes after rainfall, highlighting the Ayer Hitam Forest Reserve's ability to regulate water storage and flow. Descriptive analyses and classification based on the National Water Quality Standards (NWQS) indicated that Upper Rasau's water quality typically falls under Class I, even during storm events, although pH levels dropped to Class III/IV during two storm events. Pearson's correlation and simple linear regression analyses showed significant relationships between discharge and water quality parameters, and pollution load calculations estimated the total dissolved solids (TDS) and total suspended solids (TSS) produced during each storm event. Overall, the study suggests a significant improvement in the water quality of Upper Rasau, reflecting over 60 years of ecological recovery.

Keywords: Ayer Hitam Forest Reserve, catchment hydrology, ecological recovery, stormwater quality, pollution loading

INTRODUCTION

Monitoring and managing catchment water quality is crucial for identifying specific pollutants, their sources, and their chemical nature (Sinay, 2021). Water pollution arises from various factors such as deforestation, improper disposal of domestic and agricultural waste, pesticide use, and technological waste mismanagement (Ukaogo et al., 2020). Logging and deforestation, in particular, can significantly affect water quality by increasing sediment yield (Walker et al., 2019). Changes in land cover have been linked to heightened flood risk, particularly during small and moderate storm events (Hurtado-Pidal et al., 2022). Stormwater pollution is a growing concern, and accurately estimating pollutants in stormwater is essential for creating effective water quality management plans. For example, Caja et al. (2018) highlighted that significant land-use changes can increase river and stream discharge, leading to floods, while logging activities, such as winching, contribute substantially to soil disturbance (Latterini et al., 2023). In Malaysia, extensive logging in Terengganu and Kelantan has negatively impacted local flora and fauna, especially during major floods (Besi et al., 2019). Research shows that flooding during the rainy season also degrades water quality, with several sub-catchments in Kelantan exhibiting water quality levels as low as Class V (Maulud et al., 2021).

Logging and post-logging activities disrupt hydrological functions, reducing canopy cover and compacting soil, which leads to increased runoff and greater sedimentation in water bodies (Kasran & Nik, 1994; Bakar et al., 2023). This exacerbates erosion and sedimentation, negatively affecting aquatic ecosystems (Saberi et al., 1999). Changes in forest canopy structure due to logging also affect water interception and its availability for groundwater recharge and streamflow (Jesudhas et al., 2022).

Stormwater, the excess runoff generated during precipitation events, is shaped by several factors, including rainfall intensity, duration, land composition, slope, impermeable surfaces, and the catchment's ability to absorb water (Saifur et al., 2021). Under normal conditions, stormwater infiltrates into the ground, recharging groundwater. However, delayed infiltration due to soil types and land slope can cause excess runoff (Lowe et al., 2020). As runoff moves over land, it collects sediments, pollutants, and debris. There is considerable variability and uncertainty in stormwater quality during storm events, with runoff discharge largely determined by rainfall, runoff volume, and catchment characteristics (Memon et al., 2017).

Factors such as rainfall intensity, runoff volume, and time since the last rain event significantly affect stormwater quality. Liu et al. (2013) found that both rainfall duration and intensity impact stormwater quality, with many studies noting that the initial 40% of runoff carries the highest proportion of pollutants (Amanullah et al., 2020). Li et al. (2015) further highlighted that pollutant wash-off during rainstorms is highly variable, both temporally and spatially.

Runoff processes are influenced by soil type, vegetation cover, land slope, and land use (Azinoor, 2020). Urbanization, which increases impermeable surfaces, accelerates runoff, while forested areas mitigate it (Garcia-Prats et al., 2016). Intense, short-duration storms contribute to higher surface runoff and increased flood risk, with rainfall intensity and duration being key contributors to runoff pollutant concentrations (Perera et al., 2021).

Stormwater quality is driven by three main processes: runoff routing, pollutant build-up, and pollutant wash-off. Runoff routing involves converting excess rainfall into runoff, influenced by catchment characteristics (Sitanggang et al., 2010). Pollutant build-up occurs during dry periods, while pollutant wash-off happens when accumulated pollutants are transported into water bodies by stormwater runoff (Brodie, 2017). Forestry operations, particularly logging, contribute to non-point source pollution by increasing soil erosion and sediment runoff, with storm events further exacerbating water quality issues (Hou et al., 2022; Perera et al., 2021).

Given these challenges, continuous water quality monitoring is essential. Understanding a catchment's water-holding capacity during storm events is equally important. Based on previous research on post-logging effects, this study aims to address key questions, including: Do storm events affect water quality and discharge? What are the characteristics of stormwater quality? How do rivers respond during storm events? Thus, this research evaluates the hydrological functions related to stormwater quality, contributing to future management planning. The objectives are to characterize stormwater quality in the Upper Rasau Catchment, Ayer Hitam Forest Reserve; analyze relationships between water quality parameters; and assess the effects of discharge on stormwater quality.

The significance of this research lies in its potential to guide future management strategies for water catchments, ensuring the sustainable use of natural resources. This study is particularly valuable given the scarcity of research on stormwater quality in natural catchments. It aims to explore stormwater quality characteristics and impacts, motivated by the need to understand how storm events affect water quality and pollution in forested catchments. By monitoring stormwater quality and pollutant loading, the study contributes to the protection and management of water resources, biodiversity, and ecological health in forest reserves. Additionally, this research provides localized insights into pollutant mobilization during storm events in the Upper Rasau Catchment, contributing to the growing body of knowledge on hydrological processes in tropical forest ecosystems. A key innovation of this study is its focus on real-time water quality monitoring during storm events, offering a nuanced understanding of how rainfall patterns directly affect pollution levels. Unlike many studies that focus on normal flow conditions, this research emphasizes the variability and complexity introduced by storm events.

METHODOLOGY

Study site description

This study was conducted in the Ayer Hitam Forest Reserve (AHFR), a lowland dipterocarp forest situated in the Klang Valley, Selangor, Malaysia as shown in Figure 1. Surrounded by residential areas, AHFR was designated as a forest reserve in 1906, originally covering 4,270.7 hectares. However, due to land use changes over time, its area has been reduced to 1,248 hectares since the 1980s. This isolated secondary lowland forest was subjected to logging activities between 1936 and 1954, with the last recorded operations taking place in 1954. These logging activities had a significant impact on the forest ecosystem, disturbing soil structure, degrading wildlife habitats, and reducing biodiversity, particularly among the local flora and fauna. Additionally, these activities have influenced the forest's hydrological functions, especially in the water catchment areas, which play a critical role in maintaining water quality (Moreno et al., 2023).

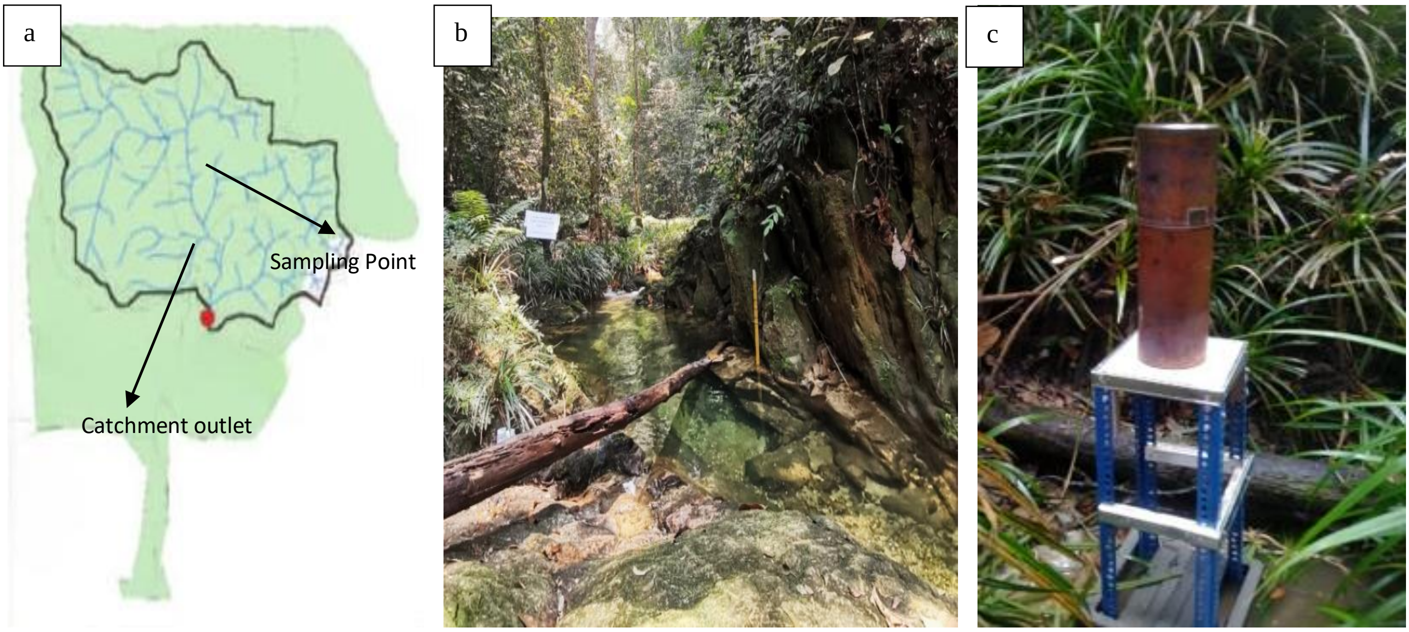


Figure 1: (a) Upper Rasau Catchment (Nurhidayu et al., 2022), (b) Sampling point, and (c) Rainfall station

Research Framework and Sampling Design

A manual rain gauge (Figure 1 (c)), was used to catch the rainfall to represent the rainfall for the catchment area. The rainfall was measured for every storm event to obtain the storm size with the starts and ends time to determine the rainfall intensity. The water discharge was estimated based on average time-area method where the velocity was measured using SEBA velocity current meter. The velocity was measured at 0.6 meters from the water surface. The water current velocity readings were taken three points which are left, centre, and right sections of the stream. Conversion from water level to discharge were made based on the rating curve of Upper Rasau catchment which were established using the relationship between water level stage (h) and discharge(Q) through continuous or periodic stage measurements (Nurhidayu et al., 2022).

The sampling point was at Upper Rasau, as it contributes to local water supply and ecosystem services, making it crucial to monitor the water quality for pollution levels that could affect downstream users and ecosystems. The water sample was grabbed every 4 hourly basis which are 9 am, 1 pm, and 5 pm during baseflow conditions and every 30 minutes during storm conditions. The sample measured in-situ (at the sampling point location) such as Dissolved Oxygen (DO), turbidity, salinity, Total Dissolved Solids (TDS), Electrical Conductivity (EC), the potential of hydrogen (pH), and temperature, while ex-situ (at the laboratory) such as Total Suspended Solids (TSS). The parameters used for sample analysis of stormwater quality were ex-situ and in-situ parameters (Table 1).

Table 1: Selected in-situ and ex-situ water quality parameters and equipment used

Parameter	Equipment	Model	Accuracy
In-situ			
Dissolved Oxygen (DO)	DO Meter	YSI52 DO Meter	±1.5%
pH	pH Meter	YSI60 pH Meter	±0.02
Turbidity	Turbidity Meter	HACH 2100P	±0.01 NTU
Total Dissolved Solids (TDS)	EC Meter	EC 300 Meter	±2%
Temperature	Thermometer	(Model Not Specified)	(Accuracy Not Specified)
Salinity	Salinity Meter	(Model Not Specified)	(Accuracy Not Specified)
Electrical Conductivity (EC)	EC Meter	EC 300 Meter	±2%
River Width	Distance Tape	(Not Specified)	±1 to 50 m
River Velocity	SEBA Velocity Meter	(Not Specified)	±0.01 s
River Depth	Staff Gauge	(Not Specified)	±1 to 50 m
Ex-situ			
Total Suspended Solids (TSS)	Gravimetric Method	Temp.-controlled oven / analytical balance / vacuum pump / filter paper	±5 mg/L

RESULTS AND DISCUSSION

Rainfall

The rainfall data during the sampling period from 20 September 2023 until 24 February 2024 is displayed in Figure 2. Storm events are classified into three classes based on the storm size which are light for rainfall less than 10mm (6 events, 57 samples), moderate for rainfall 10mm-20mm (2 events, 36 samples), heavy for rainfall more than 20mm (3 events, 38 samples). The highest rainfall recorded was 89.6mm/hr (20/9/2023) and the lowest rainfall was 1.59mm/hr (3/10/2023). The antecedent precipitation and storm event duration of each storm event was simplified in Table 2. The highest intensity recorded was event 1 with a rainfall intensity of 89.60mm/hr and the lowest was event 7 with a rainfall intensity of 1.59. The longest rainfall duration was event 10 with 3 hours 30 minutes while the shortest rainfall duration was event 7 and 11 with 30 minutes rainfall duration. The longest was Event 3 with 15 hours and the shortest storm event duration was event 11 with only 1 hour. The highest discharge peak recorded was 0.92 m³ /s which are event 1 and event 3 while the lowest discharge recorded was 0.03 m³ /s which are event 6 and 7.

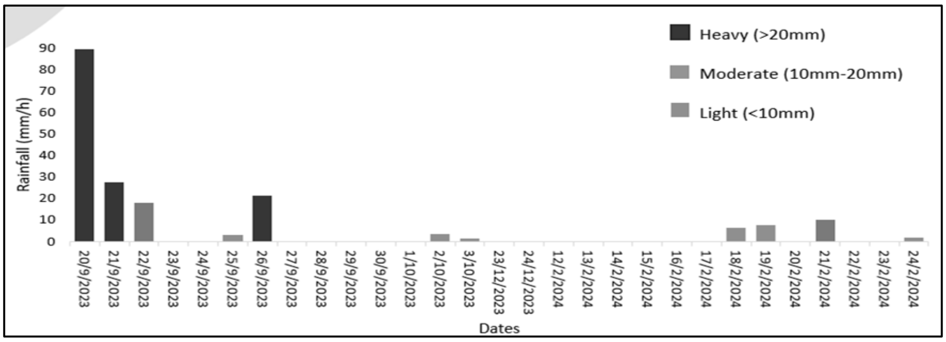


Figure 2: Rainfall data from 20 September 2023 until 24 February 2024

Table 2: Storm events monitored at Upper Rasau catchment

Storm Event/Date	Antecedent Precipitation (days)	Rainfall Intensity (mm/hr)	Rainfall Duration (hr)	Storm Event Duration (hr)	Discharge Peak (Q Peak)
1 (20/9/2023)	1	89.6	2 hr	3 hr 30 m	0.92
2 (21/9/2023)	1	27.6	1 hr 30 m	6 hr	0.32
3 (22/9/2023)	1	18	2 hr	15 hr	0.92
4 (25/9/2023)	3	3.18	1 hr 30 m	5 hr	0.12
5 (26/9/2023)	1	21.6	1 hr 20 m	8 hr 20 m	0.27
6 (2/10/2023)	1	3.4	1 hr	2 hr 40 m	0.03
7 (3/10/2023)	1	1.59	30 m	3 hr	0.03
8 (18/2/2024)	9	6.46	1 hr	2 hr	0.27
9 (19/2/2024)	1	7.7	1 hr 30 m	6 hr 30 m	0.29
10 (21/2/2024)	2	10.1	3 hr 30 m	12 hr	0.56
11 (24/2/2024)	3	2	30 m	1 hr	0.31

Descriptive Statistics of Overall Water Quality of Upper Rasau Catchment

The results of water quality parameters such as pH, temperature, electrical conductivity (EC), salinity, total dissolved solids (TDS), dissolved oxygen (DO), turbidity, total suspended solids (TSS), and water discharge, measured from a total of 189 samples, are summarized in Table 3. These parameters were classified based on the National Water Quality Standard of Malaysia (NWQS) (DOE, 2021). Most of the parameters, including temperature, EC, salinity, TDS, DO, turbidity, and TSS, fall under Class I, indicating excellent water quality. However, the average pH falls into Class V, suggesting a more acidic water environment. The pH levels are influenced by several factors, notably the acidity of the soil. Forest soils in Malaysia tend to be acidic, with pH values typically ranging from 4.5 to 5. This acidic soil condition is likely a contributing factor to the lower pH values observed in the water in forested environments (Karyati et al., 2014).

Salinity refers to the concentration of dissolved salts in water or the presence of salts on land surfaces, soil, or rocks. While salinity can occur naturally, it can also be affected by human activities such as irrigation, dryland farming, and urban development. In natural freshwater catchments, salinity levels are typically low, often around 0 ppt. Since salinity strongly influences conductivity, higher EC values generally indicate higher salinity levels (EPA, 2012). When comparing the results to a previous study by Nurhidayu et al. (2022), no significant changes in water quality classification were observed after three years, suggesting stability in the water quality of the catchment area.

Table 3: Descriptive statistics of the water quality and discharge recorded at Upper Rasau, AHFR (9 Sept 2023 – 24 Feb 2024)

Parameter	Min	Max	Mean	Water Quality Class	Std. Error	Std. Dev (±)	Variance (Var)
Temperature (°C)	24.2	27.9	25.61	I	0.04	0.64	0.4
EC (µs/m)	21.7	49	32.72	I	0.51	7.04	49.51
Salinity (ppt)	0	0	0	I	0	0	0
TDS (mg/L^{-1})	14.4	30.3	21.24	I	0.31	4.22	17.8
DO (mg/L)	6.77	8.42	7.78	I	0.03	0.39	0.15
Turbidity (NTU)	0.7	12.6	2.59	I	0.17	2.3	5.27
pH	4.28	7.52	4.72	V	0.03	0.39	0.15
TSS (mg/L^{-1})	0.5	37.5	6.39	I	0.47	6.41	41.09
Discharge (m^3/s)	0.02	0.92	0.301	-	0.016	0.22	0.05

Relationship between Water Quality Parameters

The relationship between the parameters was analyzed using Pearson's correlation. The correlation significant level was tested at p=Value of 0.01 and p-Value of 0.001 as shown in Table 4. As shown in Table 7, the temperature shows a weak negative relationship with discharge ($r = -0.229$, $p<0.01$) which means the temperature tends to decrease when the discharge increases. River discharge usually has a negative relationship with temperature (Cherinet et al., 2019). On the other hand, the temperature has a weak negative relationship with pH ($r = - 0.163$, $p<0.05$). This means the increase in temperature will decrease the pH level. This is due to the higher the temperatures, water dissociates more into hydrogen ions (H+) and hydroxide ions (OH-). This increases the concentration of hydrogen ions, leading to a lower pH (Saalidong et al., 2022). Aquatic organisms, including fish and microorganisms, have specific temperature ranges for optimal metabolic activity, reproduction, and survival. Rapid temperature changes can stress or harm aquatic life. Additionally, temperature affects chemical reactions, nutrient cycling, and the physical properties of water. Warm water can enhance the growth of harmful bacteria and algae, leading to water quality issues (Lazim et al., 2020). Besides, the low pH (acidic) also can harm aquatic life, corrode infrastructure, and reduce biodiversity. Acidic conditions can result from pollution, industrial discharge, or acid rain, impacting water quality. On the other hand, high pH (basic) levels can also affect aquatic ecosystems, potentially causing stress to organisms unable to adapt to alkaline conditions. Maintaining a balanced pH is crucial for healthy aquatic environments, as extreme pH levels can disrupt ecological balance and harm aquatic life.

DO has a strong negative relationship with temperature with $r =-0.894$, $p<0.01$ meaning that, DO tends to decrease as the temperature increases. The correlation between temperature and DO indicates that as the water warms up in the catchment, the ability of the water to hold dissolved oxygen decreases substantially. Dissolved

Oxygen (DO) measures oxygen dissolved in water, vital for aquatic life. Low DO levels cause stress, suffocation, or death in aquatic organisms like fish due to oxygen deprivation. It alters ecosystem balance, impacting species differently and disrupting the food chain. Pollution, excessive organic matter, high temperatures, or altered water flow can deplete DO. High DO levels usually benefit aquatic organisms, fostering healthier ecosystems. However, excessive DO, often linked to abundant plant growth, can fluctuate and harm aquatic life, upsetting the ecosystem balance (Yu et al.,2012). The high temperature led to a decrease in the solubility of oxygen in the stream, this has important implications for aquatic life, as lower DO levels can stress or harm organisms that rely on sufficient oxygen in the water. (Tan et al., 2022). EC has a strong positive correlation with discharge ($r=0.718$, $p<0.01$) and TDS ($r =0.980$, $p<0.01$) which means the EC increases along with the discharge and TDS. This correlation between EC and discharge is influenced by the conductive mobility of the ions present in the water usually have a high correlation with EC in the natural catchment (Thirumalini & Joseph, 2009).

TDS shows a weak negative relationship with pH ($r= -0.619$, $p<0.01$) and has a strong relationship with EC ($r= 0.980$). Meaning that the EC will increase along with the increases of TDS, in contrast with pH. EC, salinity, and TDS are related to each other due to the same indicators where the TDS is the amounts of dissolved solids such as minerals, salt, and ions in the water which contain the small particles that are measured as EC and salinity. Electrical Conductivity (EC) measures water's ability to conduct electricity, indicative of dissolved ions. It is a basic characteristic that establishes a material's ability to transfer electricity. The flow of charged particles within the material, such as ions or electrons, is what causes this conductivity. Low EC levels suggest fewer dissolved ions, affecting nutrient availability for aquatic life and agricultural productivity. High EC indicates increased dissolved ion concentrations, potentially indicating pollution, excessive salts, or minerals. The correlation between EC and TDS is influenced by the conductive mobility of the ions present in the water and TDS usually have a high correlation with EC in natural catchment (Thirumalini & Joseph, 2009). In contrast with pH, the higher the dissolved ions such as hydroxide and hydrogen ions may decrease the pH level.

pH has a weak negative correlation with DO ($r = -0.233$), TSS ($r = -0.166$) at $p<0.01$, and turbidity ($r = -0.126$, $p<0.05$). This means, that when TDS, DO, turbidity, and TSS increase, the pH tends to decrease. Rainfall and surface runoff bring all the dissolved solids and ions into the river which contributes to the increases of EC, DO, turbidity, and TSS, which decreases the pH level in the catchment. Pearson's correlation coefficient of 0.465 between turbidity and TSS is relatively weak, similar to pH ($r= -0.126$, $p<0.05$) but still significant. This means that there is a positive relationship between the two variables which TSS tends to increase as the turbidity increases. This is because turbidity is primarily caused by the presence of suspended particles, which are the same particles that contribute to TSS (Rugner et al., 2013). Low TSS levels are beneficial, as they maintain water clarity and support aquatic life by reducing light blockage. Conversely, high TSS can degrade water quality, cloud water, reduce oxygen levels, and disrupt aquatic ecosystems. It is widely acknowledged that suspended solids (SS) serve as a crucial indicator of declining water quality (Bilotta and Brazier, 2008). Also, most importantly, Total suspended solids (TSS) also act as a means for gathering, moving, and holding other pollutants, including harmful substances like heavy metals and hydrocarbons. Therefore, TSS can be considered a surrogate indicator of stormwater quality.

Table 4: Correlation between the water quality parameters

Variable	Q	Temperature (°C)	EC (µs/m)	Salinity (ppt)	TDS (mg/L^{-1})	DO (mg/L)	Turbidity (NTU)	pH	TSS (mg/L^{-1})
Q	1	-0.229**	0.718**	-	0.753**	0.300**	0.391**	-0.527**	0.282**
Temperature (°C)	-0.229**	1	0.085	-	0.014	-0.894**	-0.286	-0.163*	-0.005
EC (µs/m)	0.718**	0.085	1	-	0.980**	-0.031	-0.037	-0.577**	0.094

Salinity (ppt)	-	-	-	-	-	-	-	-	-
TDS (mg/L⁻¹)	0.753**	0.014	0.980**	-	1	0.045	0.02	-0.619**	0.122
DO (mg/L)	0.300**	-0.894**	-0.031	-	0.045	1	0.035	-0.233**	0.045
Turbidity (NTU)	0.391**	-0.286	-0.037	-	0.02	0.035	1	-0.126*	0.465**
pH	-0.527**	-0.163*	-0.577**	-	-0.619**	-0.233**	-0.126*	1	-0.166*
TSS (mg/L⁻¹)	0.282**	-0.005	0.094	-	0.122	0.045	0.465**	-0.166*	1

Notes: ** Significant at 0.01 level * Significant at 0.05 level

Stormwater quality characteristics

The stormwater quality characteristics of the Upper Rasau, including TSS, TDS, temperature, DO, pH, EC, and turbidity, are summarized in Table 5. In general, storm events with higher rainfall intensity tend to record the highest maximum values for these parameters, while lower-intensity events show lower values.

The highest TSS was 30.5 mg/L, recorded during event 1, which had a rainfall intensity of 89.6 mm/hr. In contrast, the lowest TSS was 1 mg/L, observed during event 4 with a rainfall intensity of 3.18 mm/hr. For TDS, the highest value of 30.3 mg/L was recorded during event 3 (rainfall intensity: 18 mm/hr), while the lowest value, 1 mg/L, was again recorded at event 4 with 3.18 mm/hr. The highest temperature recorded was 27.9°C during event 1 (rainfall intensity: 89.6 mm/hr), while the lowest temperature was 25.2°C. Dissolved oxygen (DO) levels peaked at 8.42 mg/L, observed during both event 2 (rainfall intensity: 27.6 mm/hr) and event 5 (21.6 mm/hr). The lowest DO level was 7.62 mg/L, recorded during event 6 (3.4 mm/hr). The pH values ranged from a high of 5.16 during event 7 (1.59 mm/hr) to a low of 4.54 during event 3 (18 mm/hr). For electrical conductivity (EC), the highest value was 47.5 µs/m, recorded at event 4 (7.5 mm/hr), while the lowest EC was 23.4 µs/m, observed at event 7 (1.59 mm/hr). Lastly, turbidity reached a maximum of 12.6 NTU during event 5 (21.6 mm/hr), with the lowest turbidity recorded at event 8 (6.46 mm/hr) at 1.06 NTU.

Table 5: Stormwater quality parameters at Upper Rasau catchment

Storm Event/Date	Rainfall Intensity (mm/hr)	Maximum						
		TSS (mg/L)	TDS (mg/L)	Temp (°c)	DO (mg/L)	pH	EC (µs/m)	Turbidity (NTU)
1 (20/9/2023)	89.6	30.5	22.7	27.9	8.29	4.57	35.2	10.7
2 (21/9/2023)	27.6	20.5	25.4	25.7	8.42	4.59	39	9.17
3 (22/9/2023)	18	21	30.3	25.9	8.4	4.54	47.5	10.3
4 (25/9/2023)	3.18	1	17.4	25.8	8.07	4.87	26.8	2.35
5 (26/9/2023)	21.6	6.5	17.1	25.2	8.42	4.93	25	12.6
6 (2/10/2023)	3.4	7.4	15.1	26.2	7.62	5.11	23.6	2.72
7 (3/10/2023)	1.59	7.5	14.9	26.4	7.92	5.16	23.4	3.42

8 (18/2/2024)	6.46	5	22.5	26.6	7.87	4.63	35.4	1.06
9 (19/2/2024)	7.7	5.5	22.9	26.2	7.98	4.65	35.9	1.49
10(21/2/2024)	10.1	8.5	27.1	26.7	7.82	4.67	42.3	1.49
11(24/2/2024)	2	10.5	23.7	26.4	7.74	4.76	37.4	1.28

Hydrograph and pollutograph during storm event

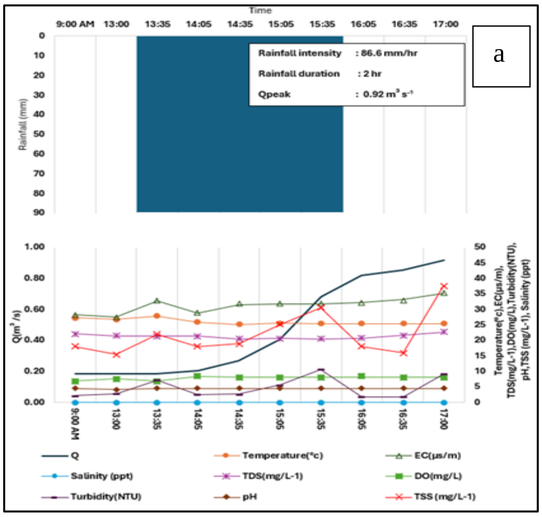
Each of the storm events is plotted using a pollutograph and hydrograph to see the different changes in concentrations during the storm event as shown in Figure 3 (a) to (k). Out of 4 from 11 storm events show the delay increases of discharge which increase after 30 minutes of rainfall (events 1, 2, 5, 8 and 11), only 3 events show that the discharge increases after 1 hour of rainfall (event 4 (3.18mm), event 7 (1.59mm), and event 6 (3.4mm) as shown at Figure 3. The water takes time to infiltrate into the soil before producing the run-off and delays the increase of discharge (Danacova et al., 2017). The rainfall intensity, duration of the rainfall, and antecedent precipitation might be the factors that contribute to the changes in discharge. The discharge increase after 1 hour might be due to the low rain intensity that only occurs locally at the sampling point and might be due to antecedent precipitation. There is the antecedent condition on event 4 which is 3 days with no event. This might cause the water contained in the soil are decrease which requires time to fill up during the storm event. The increases after 30 minutes of the event might be due to high rain that occurs distributed within the catchment outlet and might be influenced by the antecedent condition which experienced the rain 1 day before which might cause the water in the soil to increase which led to the rapid increase of surface runoff.

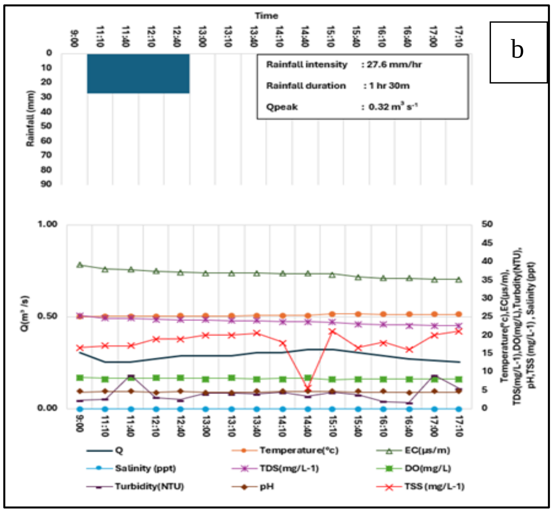
Only five events (2, 5, 6, 4, and 7) with peak discharges (Q_P) were recorded during sampling, and only event 6 (3.40mm) was recorded as a complete storm event (rising limb, peak, and falling limb). Event 2 (27.6mm) reached the Q_P 4 hours after the rainfall started and event 5 (21.6mm) reached Q_P after 3 hours of rainfall, these might be due to the water from far tributaries being slow to reach the sampling point due to the long distances, which is the far tributaries in the catchment outlet (almost 2.4 km) from the sampling point. Event 4 (3.18mm) 2 hours 30 minutes after rainfall started, which might be due to the antecedent conditions with no event for 3 days. While event 7 (1.59mm) and event 6 (3.4mm) reach the Q_P after 1 hour 30 minutes of rainfall. This might be due to several factors such as the precipitation locations which means, the precipitation occurs at different locations at the catchment outlet before the sampling point which led to the delayed $Q_{P.}$

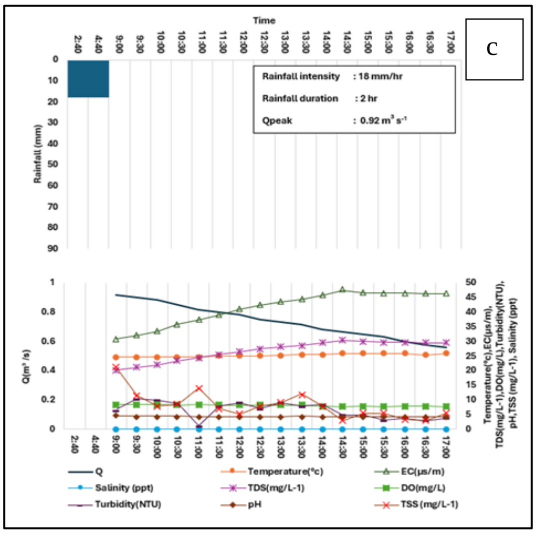
Event 9 (7.7mm), 10 (10.10mm) and 3 (18mm) recorded a falling limb during sampling. Event 3 is steeper compared to events 10 and 9 which means. These might be due to the antecedent conditions of event 3 which means, there are rainfall occurs a day before event 3 which might cause the soil to be fully saturated and there will be no infiltration, leading to increased surface runoff and a steeper falling limb. Similar to event 9 (7.7mm), event 9 is less steep might be due to the size of the rainfall which is lighter than event 3. In contrast, event 10 shows the most less steep which means the discharge decreased slower than other falling limb events which might be the factors of the antecedent conditions where the last precipitation was 2 days before the event, meaning that, the water in the soil is decreasing and required time to filled up and leading to the slower decrease of discharge.

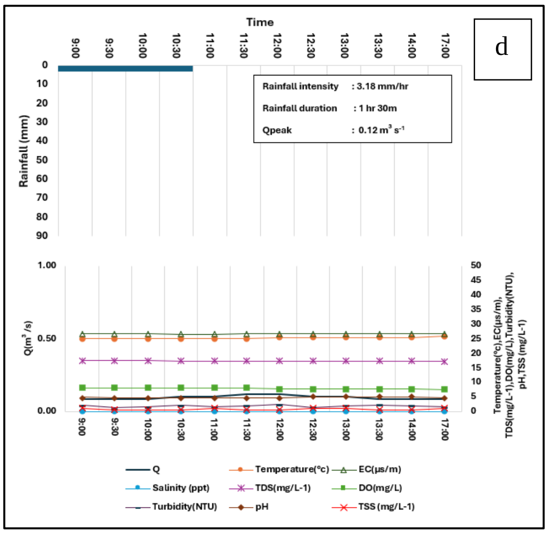
The changes of water quality influenced by discharge

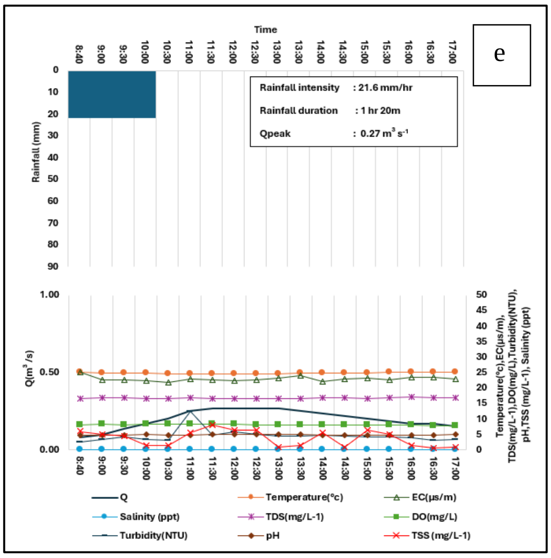
The concentrations in event 1 show that the EC, TSS, and turbidity increased slightly after the rain started, this might be due to the rain occurring at the upstream first before at the sampling point which caused the sediment increases. TSS concentration along with the discharge after 30 minutes of rainfall. Event 1 and 2 shows a slight decrease when the discharge increases possibly due to the suspended sediment from the upstream flushed out along with discharge. And the slight increase shows that the suspended sediment might be from near the sampling point. The turbidity trends seem to go along with the TSS the increases in turbidity might be due to the increases in TSS at the sampling point. Event 5 (21.6mm) shows that the TSS tends to decrease when the discharge increases which might be due to the dilution of the TSS concentrations.

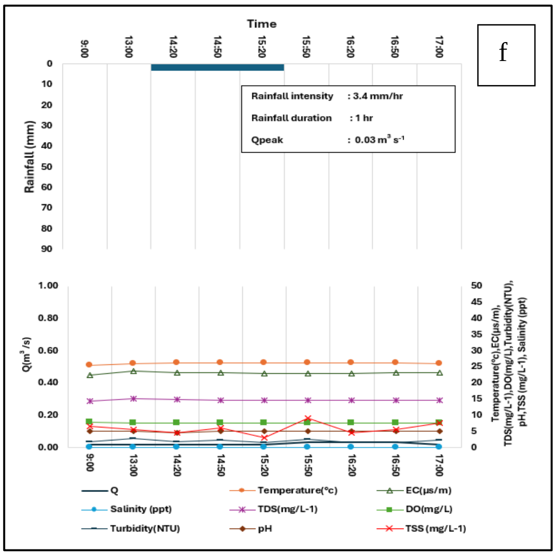

a
Time
9:00 AM 13:00 13:35 14:05 14:35 15:05 15:35 16:05 16:35 17:00
Rainfall (mm)
Rainfall intensity : 86.6 mm/hr
Rainfall duration : 2 hr
Qpeak : 0.92 m³ s⁻¹
Q(m³ /s)
Temperature(°c),EC(µs/m), TDS(mg/L-1),DO(mg/L),Turbidity(NTU), pH,TSS (mg/L-1), Salinity (ppt)
Q
Temperature(°c)
EC(µs/m)
Salinity (ppt)
TDS(mg/L-1)
DO(mg/L)
Turbidity(NTU)
pH
TSS (mg/L-1)


b
Time
9:00 11:10 11:40 12:10 12:40 13:00 13:10 13:40 14:10 14:40 15:10 15:40 16:10 16:40 17:00 17:10
Rainfall (mm)
Rainfall intensity : 27.6 mm/hr
Rainfall duration : 1 hr 30m
Qpeak : 0.32 m³ s⁻¹
Q(m³ /s)
Temperature(°c),EC(µs/m), TDS(mg/L-1),DO(mg/L),Turbidity(NTU), pH,TSS (mg/L-1) , Salinity (ppt)
Q
Temperature(°c)
EC(µs/m)
Salinity (ppt)
TDS(mg/L-1)
DO(mg/L)
Turbidity(NTU)
pH
TSS (mg/L-1)


c
Time
2:40 4:40 9:00 9:30 10:00 10:30 11:00 11:30 12:00 12:30 13:00 13:30 14:00 14:30 15:00 15:30 16:00 16:30 17:00
Rainfall (mm)
Rainfall intensity : 18 mm/hr
Rainfall duration : 2 hr
Qpeak : 0.92 m³ s⁻¹
Q(m³ /s)
Temperature(°c),EC(µs/m), TDS(mg/L-1),DO(mg/L),Turbidity(NTU), pH,TSS (mg/L-1), Salinity (ppt)
Q
Temperature(°c)
EC(µs/m)
Salinity (ppt)
TDS(mg/L-1)
DO(mg/L)
Turbidity(NTU)
pH
TSS (mg/L-1)


d
Time
9:00 9:30 10:00 10:30 11:00 11:30 12:00 12:30 13:00 13:30 14:00 17:00
Rainfall (mm)
Rainfall intensity : 3.18 mm/hr
Rainfall duration : 1 hr 30m
Qpeak : 0.12 m³ s⁻¹
Q(m³ /s)
Temperature(°c),EC(µs/m), TDS(mg/L-1),DO(mg/L),Turbidity(NTU), pH,TSS (mg/L-1)
Q
Temperature(°c)
EC(µs/m)
Salinity (ppt)
TDS(mg/L-1)
DO(mg/L)
Turbidity(NTU)
pH
TSS (mg/L-1)


e
Time
8:40 9:00 9:30 10:00 10:30 11:00 11:30 12:00 12:30 13:00 13:30 14:00 14:30 15:00 15:30 16:00 16:30 17:00
Rainfall (mm)
Rainfall intensity : 21.6 mm/hr
Rainfall duration : 1 hr 20m
Qpeak : 0.27 m³ s⁻¹
Q(m³ /s)
Temperature(°c),EC(µs/m), TDS(mg/L-1),DO(mg/L),Turbidity(NTU), pH,TSS (mg/L-1), Salinity (ppt)
Q
Temperature(°c)
EC(µs/m)
Salinity (ppt)
TDS(mg/L-1)
DO(mg/L)
Turbidity(NTU)
pH
TSS (mg/L-1)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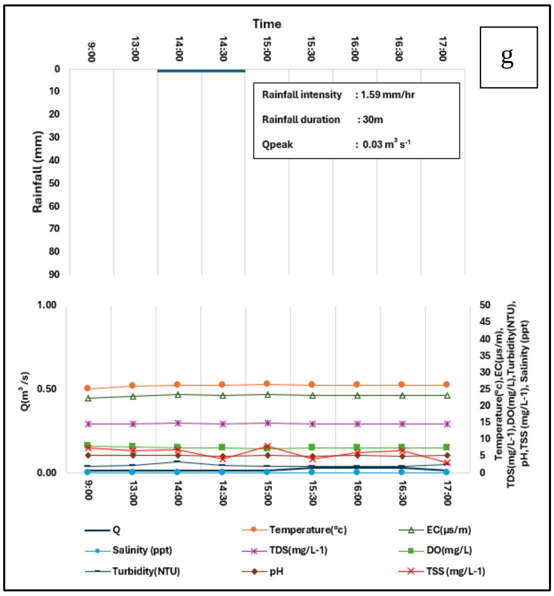
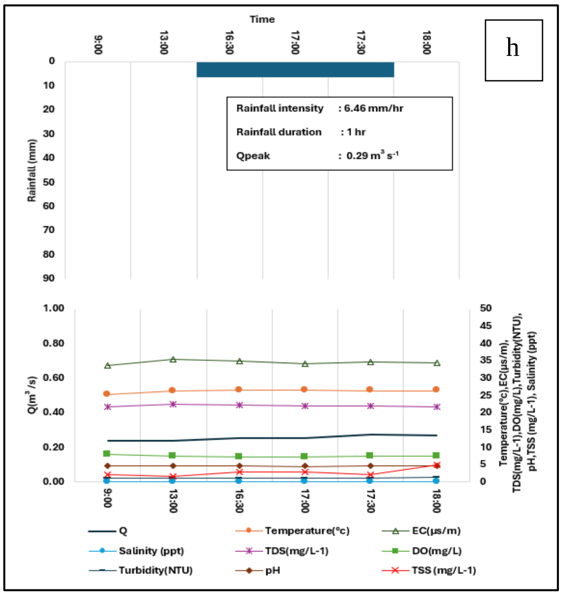
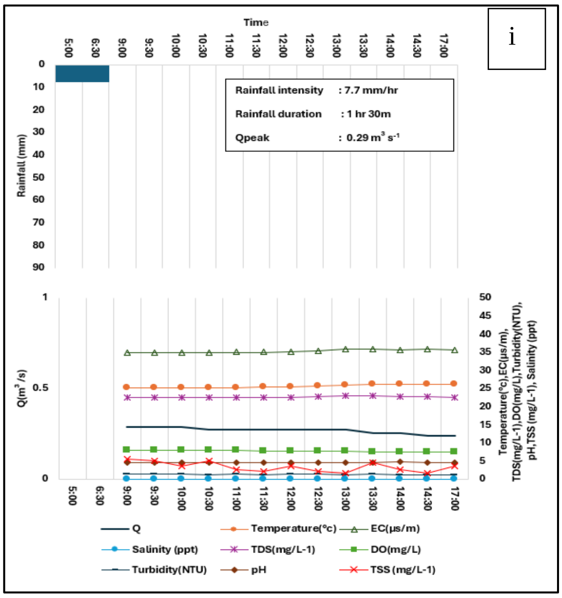
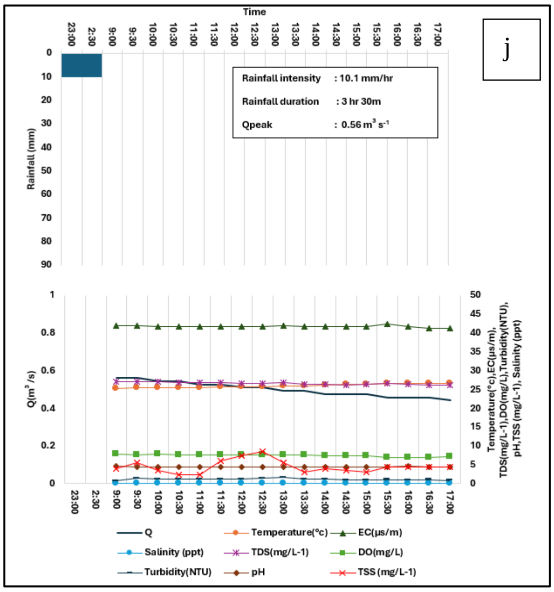
Time
9:00 13:00 14:20 14:50 15:20 15:50 16:20 16:50 17:00
Rainfall (mm)
Rainfall intensity : 3.4 mm/hr
Rainfall duration : 1 hr
Qpeak : 0.03 m³ s⁻¹
Q(m³ /s)
Temperature(°c),EC(µs/m), TDS(mg/L-1),DO(mg/L),Turbidity(NTU), pH,TSS (mg/L-1), Salinity (ppt)
Q
Temperature(°c)
EC(µs/m)
Salinity (ppt)
TDS(mg/L-1)
DO(mg/L)
Turbidity(NTU)
pH
TSS (mg/L-1)


g
Time
9:00 13:00 14:00 14:30 15:00 15:30 16:00 16:30 17:00
Rainfall (mm)
Rainfall intensity : 1.59 mm/hr
Rainfall duration : 30m
Qpeak : 0.03 m³ s⁻¹
Q(m³/s)
Temperature(°c),EC(µs/m), TDS(mg/L-1),DO(mg/L),Turbidity(NTU), pH,TSS (mg/L-1), Salinity (ppt)
Q
Temperature(°c)
EC(µs/m)
Salinity (ppt)
TDS(mg/L-1)
DO(mg/L)
Turbidity(NTU)
pH
TSS (mg/L-1)


h
Time
9:00 13:00 16:30 17:00 17:30 18:00
Rainfall (mm)
Rainfall intensity : 6.46 mm/hr
Rainfall duration : 1 hr
Qpeak : 0.29 m³ s⁻¹
Q(m³/s)
Temperature(°c),EC(µs/m), TDS(mg/L-1),DO(mg/L),Turbidity(NTU), pH,TSS (mg/L-1), Salinity (ppt)
Q
Temperature(°c)
EC(µs/m)
Salinity (ppt)
TDS(mg/L-1)
DO(mg/L)
Turbidity(NTU)
pH
TSS (mg/L-1)


i
Time
5:00 6:30 9:00 9:30 10:00 10:30 11:00 11:30 12:00 12:30 13:00 13:30 14:00 14:30 17:00
Rainfall (mm)
Rainfall intensity : 7.7 mm/hr
Rainfall duration : 1 hr 30m
Qpeak : 0.29 m³ s⁻¹
Q(m³/s)
Temperature(°c),EC(µs/m), TDS(mg/L-1),DO(mg/L),Turbidity(NTU), pH,TSS (mg/L-1), Salinity (ppt)
Q
Temperature(°c)
EC(µs/m)
Salinity (ppt)
TDS(mg/L-1)
DO(mg/L)
Turbidity(NTU)
pH
TSS (mg/L-1)


j
Time
23:00 2:30 9:00 9:30 10:00 10:30 11:00 11:30 12:00 12:30 13:00 13:30 14:00 14:30 15:00 15:30 16:00 16:30 17:00
Rainfall (mm)
Rainfall intensity : 10.1 mm/hr
Rainfall duration : 3 hr 30m
Qpeak : 0.56 m³ s⁻¹
Q(m³/s)
Temperature(°c),EC(µs/m), TDS(mg/L-1),DO(mg/L),Turbidity(NTU), pH,TSS (mg/L-1), Salinity (ppt)
Q
Temperature(°c)
EC(µs/m)
Salinity (ppt)
TDS(mg/L-1)
DO(mg/L)
Turbidity(NTU)
pH
TSS (mg/L-1)

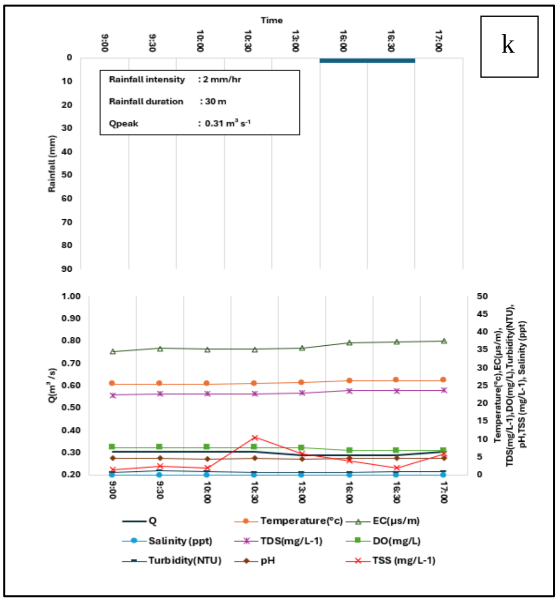

k
Time
9:00 9:30 10:00 10:30 13:00 16:00 16:30 17:00
Rainfall (mm)
Rainfall intensity : 2 mm/hr
Rainfall duration : 30 m
Qpeak : 0.31 m³ s⁻¹
Q(m³/s)
Temperature(°c),EC(µs/m), TDS(mg/L-1),DO(mg/L),Turbidity(NTU), pH,TSS (mg/L-1), Salinity (ppt)
Q
Temperature(°c)
EC(µs/m)
Salinity (ppt)
TDS(mg/L-1)
DO(mg/L)
Turbidity(NTU)
pH
TSS (mg/L-1)

Figure 3: Pollutographs and hydrographs during storm events : (a) Storm event 1 (89.6mm/hr), (b) Storm event 2 (27.60mm/hr), (c) Storm event 3 (18mm/hr), (d) Storm event 4 (3.18mm/hr), (e) Storm event 5 (21.6mm/hr), (f) Storm event 6 (3.40mm/hr), (g) Storm event (1.59mm/hr), (h) Storm event 8 (6.46mm/hr), (i) Storm event 9 (7.7mm/hr), (j) Storm event 10 (10.1mm/hr) and (k) Storm event 11(2mm/hr)

Stormwater quality classifications

The water quality class for each event was determined based on NWQS (DOE, 2021) classified in Table 6. Temperature, EC, Salinity, TDS, DO, Turbidity, and TSS fell into class I except for pH. Most of the events show the pH class that fell into Class V except for events 6 and 7 with class III / V. This might be due to the low rainfall intensity that gives less effect on pH. The high intensity might lead to decreases in pH levels. The study also found that higher rainfall intensity contributes to lower pH levels (Nova et al., 2019)

During storm event, most of water quality fell in class I (except for pH), meaning that, the water quality remains in class I even during the storm event conditions. pH levels during storm events 7 and 6 show that the WQ class for pH falls into Class III to IV. The study by Nurhidayu et al. (2022) shows that the mean pH class during the storm flow was in Class V which means lower than events 6 and 7. This might be due to the acidic rain, several studies show that one of the reasons why the water is acidic could be due to the acidic rain (Zhang et al., 2023). Urbanization and industrialization may cause air pollution (Tan et al., 2022), and interestingly, AHFR is surrounded by industrial areas that may lead to acid rain which leads to the decrease of Ph level in the stream.

The salinity falls into class I as shown in Table 6. Salinity refers to the concentration of dissolved salts in water. It significantly impacts water quality, particularly in aquatic ecosystems. Natural sources, such as seawater intrusion, evaporation, or geological factors, and human activities like irrigation or industrial processes, can alter salinity levels. High salinity can stress freshwater organisms adapted to lower salt concentrations and affect their growth, reproduction, and survival (Arif, 2018). It also influences the density and buoyancy of water, affecting ocean currents and ecosystem dynamics. Salinity variations in estuaries can impact biodiversity and habitats, as some species are more sensitive to salt changes than others.

Table 6: Stormwater quality and the classification based on NWQS (DOE, 2021) in bracket by storm event

Storm Event	Temp (°C)	EC (µs/m)	Salinity (ppt)	TDS (mg/L^{-1})	DO (mg/L)	Turbidity (NTU)	pH	TSS (mg/L^{-1})	Classifications
1	25.98 (I)	31.33 (I)	0 (I)	21.28 (I)	7.89 (I)	4.67 (I)	4.67 (V)	21.95 (I)	Temperature (I), pH (V), Others (I)
2	25.36 (I)	36.67 (I)	0 (I)	23.72 (I)	8.14 (I)	4.1 (I)	4.5 (V)	17.81 (I)	Temperature (I), pH (V), Others (I)
3	25.28 (I)	41.5 (I)	0 (I)	26.81 (I)	8.09 (I)	6.45 (I)	4.38 (V)	8.12 (I)	Temperature (I), pH (V), Others (I)
4	25.24 (I)	26.73 (I)	0 (I)	17.31 (I)	7.83 (I)	1.81 (I)	4.75 (V)	0.71 (I)	Temperature (I), pH (V), Others (I)
5	24.85 (I)	22.94 (I)	0 (I)	16.76 (I)	8.15 (I)	4.55 (I)	4.89 (V)	3.8 (I)	Temperature (I), pH (V), Others (I)

6	26.02 (I)	23.06 (I)	0 (I)	14.69 (I)	7.57 (I)	1.95 (I)	5.02 (III/IV)	5.78 (I)	Temperature (I), pH (III/IV), Others (I)
7	26.12 (I)	23.06 (I)	0 (I)	14.71 (I)	7.48 (I)	2.24 (I)	5.11 (III/IV)	5.83 (I)	Temperature (I), pH (III/IV), Others (I)
8	26.22 (I)	34.52 (I)	0 (I)	22 (I)	7.45 (I)	1.07 (I)	4.61 (V)	2.75 (I)	Temperature (I), pH (V), Others (I)
9	25.58 (I)	35.29 (I)	0 (I)	22.68 (I)	7.73 (I)	1.22 (I)	4.63 (V)	3.27 (I)	Temperature (I), pH (V), Others (I)
10	25.97 (I)	41.72 (I)	0 (I)	26.64 (I)	7.47 (I)	1.21 (I)	4.55 (V)	4.53 (I)	Temperature (I), pH (V), Others (I)
11	25.88 (I)	35.94 (I)	0 (I)	23.01 (I)	7.34 (I)	0.93 (I)	4.73 (V)	4.31 (I)	Temperature (I), pH (V), Others (I)

The Effects of Discharge on Stormwater Quality

The result of simple linear regression shows that the discharge has significant effects on water quality variables and the significance at a p-value of <0.001 and TSS at a p-value of 0.006 (Table 7). The increases in discharge may bring the amount of sediment that gives an impact on variables value as shown in Table 8. The studies by Malik et al. (2022) on stormwater stream water quality, show that storm events often result in increases in discharge runoff, leading to more erosion and sediment transport, thus increasing turbidity, TSS, TDS, DO, and EC levels and decreasing the temperature and pH level. The increases in discharge may bring the amount of sediment that has an impact on variable value (Saito et al., 2023). Discharge affects the turbidity of the stream which significantly shows the difference during the storm event as shown in Figure 4.

Table 7: Regression of stormwater quality and discharge

WQ Variable	R^2	F-Value	P-Value
TDS (mg/L-1)	0.516	137.433	<0.001
TSS (mg/L-1)	0.092	13.095	0.006
pH	0.536	149.315	<0.001
EC (µs/m)	0.479	118.561	<0.001
Temperature (°c)	0.030	4.981	<0.001
DO (mg/L-1)	0.084	11.905	<0.001
Turbidity (NTU)	0.185	29.242	<0.001
Salinity (ppt)	0.0	0.0	

Figure 4: Upper Rasau sampling point during (a) baseflow and (b) stormflow conditions

Pollution Loadings

The results indicate low Total Suspended Solids (TSS) and Total Dissolved Solids (TDS) across all storm events. Among the events, the lowest TSS loadings were observed in events 4, 6, and 7, each recording 0.001 kg, while the lowest TDS was in event 7 with 0.003 kg. One possible factor influencing the pollution levels could be the antecedent conditions. As shown in Table 8, the highest pollution loading, 0.33 kg during event 3, coincided with 3 consecutive days of precipitation, which likely contributed to elevated pollution levels. Rainfall triggers soil erosion, releasing sediments into water bodies and thereby increasing TSS and TDS concentrations (Gadhia et al., 2013). Additionally, rainfall intensity may play a role, as lower intensity rainfall tends to have a reduced impact on soil erosion, leading to lower pollution loadings (Saito et al., 2023).

Table 8: Total Pollution Loadings of TDS and TSS at Upper Rasau Catchment

Storm event	Antecedent precipitation (days)	Rainfall intensity (mm/hr)	TDS (kg)	TSS (kg)
1	1	89.6	0.10	0.11
2	1	27.6	0.11	0.08
3	1	18	0.33	0.11
4	3	3.18	0.2	0.001
5	1	21.6	0.06	0.01
6	1	3.4	0.004	0.001
7	1	1.59	0.003	0.001
8	9	6.46	0.03	0.004
9	1	7.7	0.08	0.011
10	2	10.1	0.23	0.04
11	3	2	0.055	0.01

CONCLUSION

This study focused on stormwater quality to understand how storm events affect the physico-chemical parameters of river systems. The results demonstrated that rivers respond differently to varying rainfall intensities, with most events showing a delayed increase in discharge approximately 30 minutes after the onset of rainfall. This delayed response indicates that the Ayer Hitam Forest Reserve (AHFR) functions effectively as a natural water storage system, slowing down runoff processes. The findings revealed significant relationships between stormwater quality parameters, with variables such as pH, total dissolved solids (TDS), electrical conductivity (EC), temperature, dissolved oxygen (DO), turbidity, and total suspended solids (TSS) being notably influenced by changes in discharge. Most of these parameters remained within Class I of the National Water Quality Standards (NWQS), even during storm events. However, pH levels consistently fell into Class V and fluctuated between Class III and V during these events. A previous study by Foong (2011) also reported that the water quality in the Upper Rasau River was classified as Class II, primarily due to lower pH levels. Overall, the Upper Rasau catchment maintains high water quality, except for pH. The water quality status in this catchment could serve as a useful indicator of the forest's health, showing improvement after 60 years of recovery. However, the absence of continuous data monitoring presents a critical limitation, particularly for hydrological studies that depend on long-term rainfall-runoff data. The findings of this study can contribute valuable insights for future management and planning of water catchments, ensuring the sustainable use of natural resources in the region. Additionally, studying storm events and their impact on water quality and ecosystems is crucial for understanding how these processes influence pollution loading and for developing sustainable water resource management strategies to protect ecosystems.

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