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# River Sedimentation Due to Tin Mining Activities in Bangka Island

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**ABSTRACT** Sedimentation in rivers is a major issue of environmental damage in the Kepulauan Bangka Belitung Province. In the last two decades, since tin mining was carried out by the community, massive sedimentation has occurred in the river. The purpose of the study is to investigate the characteristics of sediment materials and the effects of illegal tin mining on river sedimentation on Bangka Island. Sediment characteristics can be seen from the distribution of grain size and specific gravity of the bed sediment material and the concentration of suspended sediments seen from their position along the river. Sediment grain size is classified according to the American Geophysical Union. A total of 45 sediment samples spread across 12 rivers in the district capital area on Bangka Island were collected at the end of the rainy season in 2023, and 4 more samples were added in the dry season of 2023 in the Muntok River. The MPM formula was applied to estimate bedload transport and statistical methods were used to estimate suspended sediment rates. Additionally, the sedimentation rates are estimated based on dependable continuous flow with a probability exceeding 50% (Q50%). The study's findings indicate that Illegal tin mining in Bangka Island has a major impact on river sedimentation. The particle size distribution of bed material sediments does not align with what is typically found in nature, which often exhibits coarser particles upstream and finer downstream. Similarly, in areas downstream of tin mining operations, the concentration of suspended particles increases significantly, up to 12 times higher than natural conditions.

**KEYWORDS** Sediment; bed load; suspended load; Tin Mining; Bangka Island



## 1 INTRODUCTION

### 1.1 Background

Flood disaster mitigation, erosion management, and sedimentation control are important measures for addressing natural disasters and preserving the environment in Bangka Belitung Islands Province. Almost all cities on the Bangka and Belitung Islands are prone to flooding. In 2016, major floods hit Bangka Island, submerging the entire district city. A year later, major floods hit Belitung Island, with the worst incident in Belitung Timur Regency.

Apart from heavy rainfall and simultaneous sea tides, flooding in multiple areas of Bangka Island is largely caused by decreased river capacity due to sedimentation. The problem of erosion and sedimentation in the Bangka Belitung Islands is more dominantly caused by illegal tin mining activities, both on land and at sea. Illegal tin mining on land using the open-cast method has led to accelerated erosion due to the activities detrimental impact on the topsoil. Excavation at the mining site causes the land cover to open and alters the contour lines compared to the surrounding area. Overburden and topsoil from the excavation are stacked up around the mining site, where it can be degraded by rainwater runoff. In the previous study, Hambali and Wahyuni (2021) found that when land with vegetation cover was converted into a mining area, land erosion was significantly increased at that site. This increase can reach more than 150%. Mining waste has a negative impact on downstream areas and can even reach the sea (Sukarman et al., 2020).

Deforestation and changes in land use in the upper reaches of many tropical rivers led to changes in flow regimes and an influx of sediment into river channels (Hurni, 1999; Nyssen et al., 2004). River flow transfers sediment grains from the erosion process, resulting in deposition in the river channel. Sediment particles carried by the river's flow to the sea will generate sedimentation at the river mouth, which can obstruct river water flowing to the sea. When the discharge is high, the river's lower cross-sectional capacity may cause flooding.

Sediment handling in rivers with sediment control structures necessitates an understanding of sediment properties. The characteristics of sediments in rivers that traverse urban areas on Bangka Island are investigated in this work. Understanding the properties of the sediment in the river allows for the development of appropriate handling solutions. The goal of this study is to investigate the effects of illegal tin mining on river sedimentation on Bangka Island, as well as the properties of sediment materials.

### 1.2 Tin Mining in Bangka Island

Bangka Belitung is known as the largest tin producer in Indonesia. Tin mining in Bangka Belitung has been going on for more than 300 years (Ulya et al., 2024). Until the 1990s, tin mining by PT. Timah Tbk is running quite intensively while still paying attention to aspects of post-mining environmental improvement. However, since the issuance of Regional Regulation No. 6 of 2001 concerning General Mining Management, unconventional tin mining activities have been very widespread among the community.

The tin mining industry in Kepulauan Bangka Belitung Province has created numerous job and business opportunities for communities, improving regional accessibility, education, and public health. Nurtjahya et al. (2017) stated that tin mining activities in Kepulauan Bangka Belitung not only improve the welfare of the communities but also reduce social conflicts among them. However, mining activities, both on land and offshore, as well as the processing and supporting facilities, can have negative impacts on the environment (Sutono et al., 2020). Typically, the conventional mining process involves digging or dredging the soil to a certain depth and then washing it until the tin ore is extracted. Sukarman et al. (2020) reported that the majority of ex-tin mining land in seven districts/cities in Kepulauan Bangka Belitung Province has suffered severe damage, leading to a decline in the soil's physical, chemical, and biological properties.

Conventional tin mining causes significant harm to the natural aspects of land. The mining activities typically lead to topsoil damage due to excavation and disruption of land cover. With the loss of the topsoil, its water-holding capacity decreases, leading to low nutrient levels and hindering plant growth and productivity (Hamid et al., 2017). According to (Pirwanda and Pirngadie, 2015), the impact of illegal tin mining activities has led to a 9.62% change in the land use designation outlined in the Belitung Regency Spatial Plan, resulting in significant environmental damage.

Figure 1 depicts an illegal tin mining activity in Bangka Regency. Land mining activities with environmental impact involve four stages: topsoil stripping, material disposal, dam construction (voids), and tailings leaching and disposal (Sukarman et al., 2020). To create the dam (voids), the material used is obtained from overburden produced during mining activities. The ore is then extracted from the sedimentary layer rich in tin

Figure 1 Illegal tin mining activity at Sungailiat District, Bangka Regency

ore using mechanical tools. Water is sprayed to separate the excavated ore. The ore is then collected in a holding pond and transferred to a washing facility, such as a jig, using a pump. The waste material from the washing process (leaching) will be directed to a settling pond or may flow directly into the nearby water body.

Sukarman et al. (2020) revealed that ex-tin mining areas show anthropogenic changes that affect the landscape and soil types. Soil types in unmined land are Dystric Alluvial, Gleic Alluvial, Sulfic Alluvial, and Dystric Cambisol, while ex-mine soils are Gleic Alluvial, Sulfidic Alluvial, Gleic Regosol, Arenic Regosol, Quartzic Regosol, and Dystric Regosol. In the previous study, Hamid et al. (2017) reported that separating sandy tailings from clay changes soil texture and density in ex-mining land, which typically has a sandy loam to sandy clay texture.

### 1.3 Rivers in the City area on Bangka Island

Bangka Island is a major island in the Kepulauan Bangka Belitung Province, consisting of one city and four districts. Several important rivers flow through each Regency City, including the Baturusa River, Selindung River, Rangkui River, Pedindang River, Berok River, Cauyan River, Muntok River, Daeng River, Air Kolong Baru River, Air Anyut River, Jelitik River, and Rawabangun River. A Map of Bangka Island, showing the location of each river, is illustrated in Figure 2 and Table 1.

In Pangkalpinang City, the Rangkui River and the Pedindang River cross through, while the Selindung River runs alongside the city. Both the Rangkui and Selindung rivers feed into the Baturusa River, which is the longest river on Bangka Island, measuring 34.08 km long. Except for the Pedindang River, the rivers in Pangkalpinang City have a gentle slope of less than 8%. The city of Koba, the capital of Bangka Tengah Regency, is traversed by the Berok and Cauyan rivers. The Berok River stretches for 20.48 km with an aver-

Table 1. Main River Characteristics in the City area on Bangka Island (Bangka Belitung River Basin Development Agency, 2023)

| ID | River Name | City/Regency | Basin Area (km$^2$) | Length (km) | Slope (%) | | | Potential Sediment Yield (tons year$^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| | | | | | Max | Mean | Min | |
| BT00 | Baturusa | Pangkalpinang | 609.74 | 34.08 | 73.62 | 6.11 | 0.00 | 229,636.65 |
| SL00 | Selindung | Pangkalpinang | 83.85 | 18.42 | 34.19 | 5.54 | 0.00 | 8,115.31 |
| RK00 | Rangkui | Pangkalpinang | 129.53 | 17.18 | 73.62 | 7.97 | 0.00 | 51,756.58 |
| PD00 | Pedindang | Pangkalpinang | 40.50 | 10.94 | 73.62 | 13.79 | 0.00 | 195,923.43 |
| AB00 | Berok | Bangka Tengah | 148.34 | 20.48 | 96.43 | 7.13 | 0.00 | 162,680.82 |
| MT00 | Muntok | Bangka Barat | 19.58 | 8.84 | 73.38 | 11.21 | 0.00 | 15,564.32 |
| KB00 | Air Kolong Baru | Bangka | 64.99 | 11.82 | 67.77 | 5.63 | 0.00 | 31,078.49 |
| RB00 | Rawabangun | Bangka Selatan | 4.56 | 4.00 | 43.13 | 4.54 | 0.00 | 1,015.75 |

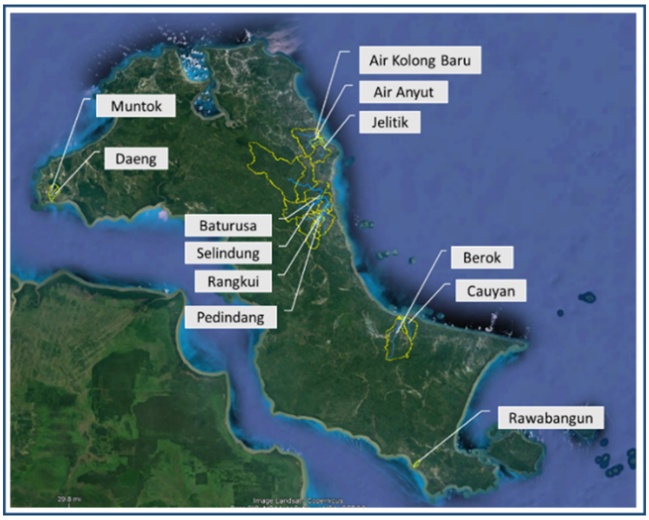


Figure 2 Map of rivers in the city area on Bangka Island

age slope of 7.13%. The Cauyan River is a tributary of the Berok River. In the Muntok City district of Bangka Barat, the primary river is the Muntok River. While not very long, the Muntok River has steep upper sections near Menumbing Hill.

Sungailiat City in Bangka Regency is the only city without a river running through its center. However, the Air Kolong Baru River and the Jelitik River, which are major rivers on the outskirts of the city, serve as important transportation routes for fishing boats. The Air Kolong Baru River is quite long, although it has a steep slope of approximately 5.6%. In South Bangka, particularly in the City of Tobolai, the Rawabangun River is a significant waterway, functioning as the primary drainage channel. It is about 4 km long with a mean gradient of 4.54%.

Most of the rivers on Bangka Island are contaminated by sediment from land erosion, primarily due to tin mining activities. According to Bangka Belitung River Basin Development Agency (2023), the potential rate of soil erosion in Bangka Island is relatively high, ranging from 60–180 tons/ha/year. Some of the sub-basins are categorized as experiencing very heavy erosion, including the upstream part of Pedindang sub-basin in Pangkalpinang City, the downstream part of the Cauyan sub-basin in Bangka Tengah Regency, the downstream part of the Air Anyut and Jelitik sub-basins in Bangka Regency, and the downstream part of the Rawabangun sub-basins in South Bangka Regency. It's noteworthy that Bangka Barat is the only regency on Bangka Island that is recorded as having no areas with very heavy erosion potential. Furthermore, Bangka Belitung River Basin Development Agency (2023) estimated that the potential sediment yield at the downstream control point of the river is up to 229,636.65 tons year$^{-1}$ on the Baturusa River (Table 1).

## 1.4 Sediment Properties and Sedimentation Rate Prediction

The process of sedimentation in river channels is quite complicated. It begins with rainfall, which generates kinetic energy and initiates the erosion process (Asdak, 2004). Naturally, as the soil is lost due to the flow, it gets deposited in areas of the river channel where the flow rate decreases or stops. This depositing of soil is known as the sedimentation process. River sediment transport involves two types: suspended load and bed load. Suspended load refers to small particles (mainly silt-and clay-sized) of low settling velocity, held in suspension by upward currents in turbulent flow (Williams, 2012). Bed load primarily consists of sediment transport for coarse materials (saltation) or fine material on plane beds (saltation at low shear stresses and sheet flow at high shear stresses) (Camenen and Larson, 2005). Coarse sediments such as gravel and sand can be seen as the foundational material of most riverbeds, shaping the channel bed, bars, and often banks. The fine-grained sediment, composed of silt and clay, is significant for shaping certain riverine features like vertically accreted floodplains and estuarine mud flats. Additionally, it serves as a crucial factor contributing to turbidity and carries contaminants that are adsorbed onto clay particles (Kondolf et al., 2014).

Sediment properties are essential for understanding sedimentation processes, including grain size and distribution, specific gravity, shape, and fall velocity

Table 2. Grain size classification according to AGU (modified after Garde and Raju, 1985).

| Grain Diameter Range (mm) | Grade Name |
|---|---|
| 0.0002 – 0.0005 | Very Fine Clay |
| 0.0005 – 0.001 | Fine Clay |
| 0.001 – 0.002 | Medium Clay |
| 0.002 – 0.004 | Coarse Clay |
| 0.004 – 0.008 | Very Fine Silt |
| 0.008 – 0.016 | Fine Silt |
| 0.016 – 0.032 | Medium Silt |
| 0.032 – 0.0625 | Coarse Silt |
| 0.0625 – 0.125 | Very Fine Sand |
| 0.125 – 0.25 | Fine Sand |
| 0.25 – 0.5 | Medium Sand |
| 0.5 – 1.0 | Coarse Sand |
| 1 – 2 | Very Coarse Sand |
| 2 – 4 | Very Fine Gravel |
| 4 – 8 | Fine Gravel |
| 8 – 16 | Medium Gravel |
| 16 – 32 | Coarse Gravel |
| 32 – 64 | Very Coarse Gravel |
| 64 – 128 | Small Cobbles |
| 128 – 256 | Large Cobbles |
| 256 – 512 | Small Boulders |
| 512 – 1024 | Medium Boulders |
| 1024 – 2048 | Large Boulders |
| 2048 – 4096 | Very Large Boulders |

(Ghani et al., 2013). A sediment deposit comprises a variety of sediment grain sizes from different sources, collectively known as the population (Besperi, 2011). At numerous sites, the sediment composition of the river in the longitudinal and transverse directions changes in different gradation variations, which might be fine sand, coarse sand, gravel, or rock. This demonstrates that sediment movement is affected by gradation, which includes differences in particle form, size, density, and roundness (Junaidi, 2012; Hambali and Apriyanti, 2016). Grain size is a sediment property that can be measured in practical terms. Some hydraulic experts use the grain size classification according to the American Geophysical Union (AGU), as shown in Table 2.

Many formulas for bed load transport have been developed by experts based on laboratory experiments. These different formulas can yield significantly different results (Ikhsan et al., 2019). The initial formulas proposed to estimate bed load transport were primarily based on the concept that the sediment transport rate can be linked to the bottom shear stress (Meyer-Peter and Muller, 1948), and these formulas (MPM) were applicable for steady, uni-directional flow (Camenen and Larson, 2005). MPM formula can be used for well-graded sediments, and the resulting flow conditions are no longer limited to just the basic plane shape. Sediment particles used in the MPM formula range from 0.4 to 29 mm with a specific gravity of 1.25 to 4.0 (Purnomo et al., 2015).

The basic MPM formula for bed load sediment transport is written as follows:

$$\left(\frac{k_r}{k'_r}\right)^{3/2}\gamma RS = 0.047(\gamma s-\gamma)d_{50} + 0.25\left(\frac{\gamma}{g}\right)^{1/3}\left(\frac{\gamma_s-\gamma}{\gamma s}\right)q_b^{2/3} \quad (1)$$

where $q_b$ is the unit sediment transport rate, $k_r$ is the roughness coefficient, $k'_r$ is the roughness coefficient based on the grains, $\gamma$ is the unit weight of water, $\gamma s$ is the unit weight of sediment, $g$ is the acceleration of gravity, $d_{50}$is the median particle diameter, $R$ is the hydraulic radius, and $S$ is the energy gradient.

Several methods have been developed to estimate suspended loads, including measurement. Fuladipanah and Mak Vandi (2013) used the USBR Equation to calculate the mean annual sediment load in the Dez River, Iran. Three scenarios were evaluated: using the average value of sediment discharge, using the probabilistic classification of river flow data, and using the separation of wet and dry months. Apart from using USBR, (Makenanizadeh, 2012; Sadeghian et al., 2014) also employed the FAO method to estimate sediment loads in dams. The equations utilized in USBR are derived from the exponential regression relationship between suspended load and flow discharge, which are directly measured in large quantities (Fuladipanah and Mak Vandi, 2013). This method is quite challenging because it requires measuring these two parameters over an extended period. Sadeghian et al. (2014) suggested an alternative statistical method for determining suspended load $(Q_s)$: multiply the flow discharge $(Q_d)$ by sediment concentration $(C)$.

$$Q_s = 0.0864\ Q_d\ C \quad (2)$$

Where $Q_s$ is suspended load (tons day$^{-1}$), $C$ is average concentrations of suspended load (mg liter$^{-1}$) and $Q_d$ is daily discharge (m$^3$ s$^{-1}$). Because each transport mechanism is unique, the basic formula for bed load and suspended load cannot reflect the entire sedimentation rate. As a result, the total sediment rate $(T)$ can be calculated using the following equation:

$$T = Q_b + Q_s \quad (3)$$

Where $Q_b$ is bedload, dan $Q_s$ is suspended load.

## 2 METHODS

This study was carried out through field studies, laboratory tests, and analysis. In addition to collecting sediment samples, field investigations were required to ascertain the geometry of rivers, including flow depth and width. The necessary values of sediment particle properties, such as grain size, specific gravity, and volume weight, were obtained by laboratory tests. The results of field observations and laboratory tests were used as the basis for sedimentation rate calculations.

In the first period, near the end of the rainy season in February 2023, we collected 45 sediment samples spread across 12 rivers in the district capital area on Bangka Island. The distribution of the number of sample points in each river is presented in Table 3. During the dry season (August 2023), we conducted field observations and collected sediment samples at four locations along the Muntok and Daeng Rivers. The four sites are downstream of Cuilong Weir (MT-SS1), upstream of the Muntok River (MT-SS2 and MT-SS3), and upstream of the Daeng River (MT-SS4). In the upstream areas of the Muntok River and Daeng River, there are active mining activities on the riverbanks.

Bed material sampling was carried out using the Ekman grab while suspended load sampling is carried out using a suspended sediment sampler. To evaluate the sediment transport rate, instantaneous flow velocity measurements were also carried out. Flow velocity measurements were carried out on cross-sections of the river using the average depth method using a current meter.

To estimate sedimentation rates, river discharge data from the entire year are required. In fact, river flows carry a wide range of discharges and sediment loads. Variations in river flow make it difficult to determine the appropriate discharge. Sembiring et al. (2014) employs dominant discharge, which includes a discharge approach where the probability 50%. Determining the dominant discharge also necessitates obtaining continuous discharge data from the river throughout the year. Unfortunately, no continuous discharge measurements are available for rivers on Bangka Island (including the rivers under investigation). On the other hand, the observed instantaneous flow does not reflect flow conditions throughout the year.

Based on these conditions, an alternative approach was used to obtain continuous discharge values through the Mock rainfall-runoff model. The Mock rainfall-runoff model is a river flow calculation technique from rainfall, evapotranspiration, and watershed characteristics to estimate water availability, if there is a minimum observed flow data or no observed flow data (Mock, 1973). The data needed as the main input into this model are rainfall data, climate data (temperature, wind speed, humidity, and solar radiation), and observed flow (if any). Observed flow data is needed to assess the accuracy of the calculated flow by the model. If observed discharge data is not available, then an iteration approach must be carried out by considering the ratio of runoff ($R$) to annual rainfall ($P$). According to Van der Weert (1994), for P < 1.800 mm year$^{-1}$ and for P > 1.800 mm year$^{-1}$, the relationship are given by Equation 4 and 5, respectively:

Table 3. Sediment sampling points

| City/Regency | River/Kolong | ID | Number of Points |
|---|---|---|---|
| Pangkalpinang | Baturusa | BT | 3 |
| | Rangkui | RK | 7 |
| | Pedindang | PD | 6 |
| | Selindung | SL | 3 |
| Bangka Tengah | Berok | BR | 5 |
| | Cauyan | CY | 3 |
| Bangka Barat | Muntok | MT | 5 |
| | Daeng | DE | 1 |
| Bangka | Kolong Air Baru | KB | 3 |
| | Air Anyut | AA | 1 |
| | Jelitik | JL | 2 |
| Bangka Selatan | Rawabangun | RB | 6 |
| TOTAL | | | 45 |

$$R = 155(\frac{P}{1000})^{2.5}) \quad (4)$$

$$R = 0.94P - 1018 \quad (5)$$

## 3 RESULTS

### 3.1 Characteristics of Bed Material

Particle size distribution and specific gravity are two ways that sediment properties are characterized using the findings of laboratory tests. For the purposes of calculating bed sediment transport rates, various particle sizes are considered. Figure 3 shows the grain size distribution of riverbed material in Pangkalpinang City (Baturusa River, Selindung River, Rangkui River, and Pedindang River).

The bed material sediment size ($d_{50}$) of the rivers in Pangkalpinang City ranges from 0.21 to 4.75 mm, with an average of 1.19 mm. The specific gravity of the bed materials is approximately 2.45 on average. According to Table 2, the sediment grains size of rivers in Pangkalpinang city are classified as very fine sand to fine gravel (see Table 4). As illustrated in Figure 3 and Table 4, there is no distinct distribution pattern of sediment grains between the upstream and downstream of the river. The varied size of $d_{50}$ upstream and downstream can be attributed to the gently sloping riverbed, branching with tributaries, and mining activities that occur along the river.

The bed material sediment size ($d_{50}$) of the rivers in Bangka Tengah Regency varies between 0.23 and 4.75 mm, with an average of 1.78 mm (Table 5). Figure 3 shows the grain size distribution of riverbed material in Bangka Tengah Regency (Berok River and Cauyan River). The grain size distribution in BR-S3 and CY-S0 shows striking differences. In BR-S3, the sediment is dominated by fine sand with a weight of up to 72%, while in CY-S0, the sediment is dominated by fine

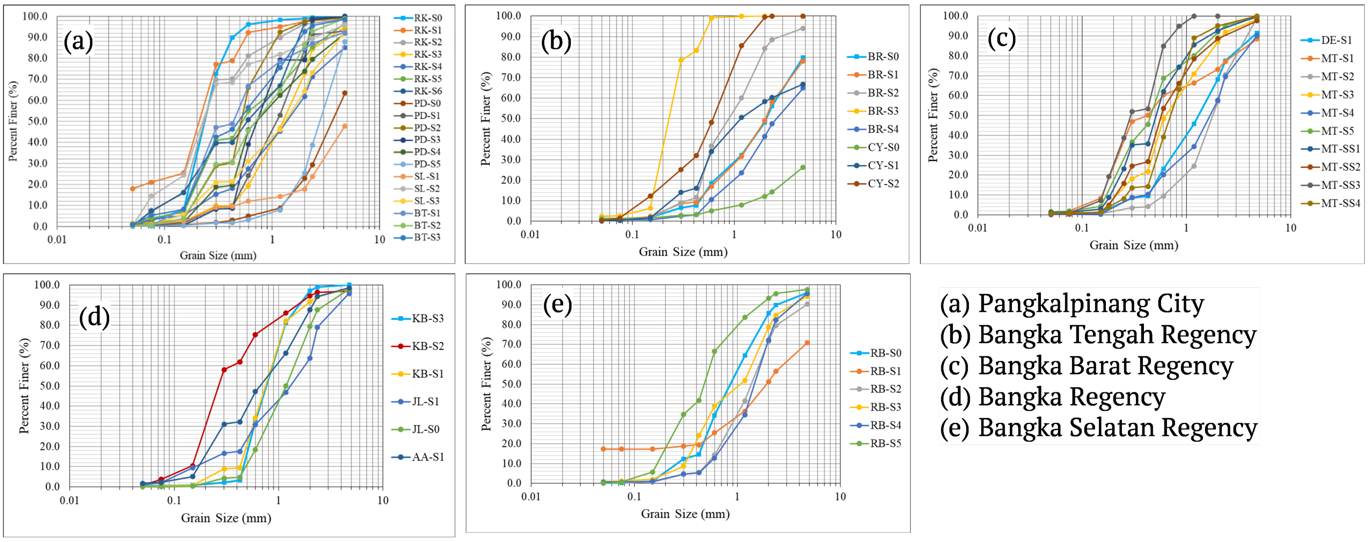


Figure 3 Grain size distribution of riverbed material

Table 4. Bed material properties for rivers in Pangkalpinang City

| Sample | Dominant Materials | Weight (%) | ($d_{50}$) (mm) | Specific gravity |
|---|---|---|---|---|
| RK-S0 | Fine sand | 64.86 | 0.24 | 2.53 |
| RK-S1 | Fine sand | 51.80 | 0.21 | 2.41 |
| RK-S2 | Fine sand | 54.04 | 0.23 | 2.39 |
| RK-S3 | Coarse sand; | 54.04 | 1.25 | 2.40 |
| | Very coarse sand | 26.02 | | |
| RK-S4 | Coarse sand; | 17.98 | 1.36 | 2.49 |
| | Very coarse sand | 16.48 | | |
| RK-S5 | Fine sand | 34.14 | 0.53 | 2.49 |
| RK-S6 | Very coarse sand; | 29.70; | 0.59 | 2.43 |
| | Fine sand | 23.40 | | |
| PD-S0 | Fine gravel; | 36.50; | 3.6 | 2.39 |
| | Very fine gravel | 40.62 | | |
| PD-S1 | Coarse sand; | 31.06; | 1.09 | 2.58 |
| | Very coarse sand | 28.80 | | |
| PD-S2 | Medium sand | 37.20 | 0.51 | 2.49 |
| PD-S3 | Coarse sand; | 40.08; | 0.71 | 2.39 |
| | Medium sand | 30.88 | | |
| PD-S4 | Medium sand | 27.22 | 0.71 | 2.37 |
| PD-S5 | Very fine gravel | 62.44 | 2.77 | 2.52 |
| SL-S1 | Fine gravel; | 52.26 | 4.75 | 2.42 |
| | Very fine gravel | | | |
| SL-S2 | Fine sand | 43.45 | 0.23 | 2.41 |
| SL-S3 | Very fine gravel | 28.38 | 1.32 | 2.56 |
| BT-S1 | Fine sand | 38.76 | 0.44 | 2.40 |
| BT-S2 | Fine sand; | 25.96; | 0.71 | 2.41 |
| | Very coarse sand | 21.52 | | |
| BT-S3 | Fine sand | 34.28 | 0.48 | 2.55 |

gravel which reaches 73%. Unde and Dhakal (2009) revealed that despite common geological sources, tributary streams are distinguished by larger and more spherical material than the tabular material of the mainstream.

In Bangka Barat (Muntok River and Daeng River), we collected and analyzed six samples in the rainy season and 4 in the dry season at different points. There is

Table 5. Bed material properties for rivers in Bangka Tengah Regency

| Sample | Dominant Materials | Weight (%) | ($d_{50}$) (mm) | Specific gravity |
|---|---|---|---|---|
| BR-S0 | Very fine gravel | 31.58 | 2.05 | 2.43 |
| BR-S1 | Very fine gravel | 28.98 | 2.03 | 2.55 |
| BR-S2 | Medium sand | 27.60 | 0.89 | 2.39 |
| BR-S3 | Fine sand | 72.06 | 0.225 | 2.44 |
| BR-S4 | Fine gravel | 35.00 | 2.55 | 2.42 |
| CY-S0 | Fine gravel | 73.66 | 4.75 | 2.37 |
| CY-S1 | Fine gravel | 33.14 | 1.15 | 2.42 |
| CY-S2 | Coarse sand | 37.32 | 0.62 | 2.55 |

no obvious difference in the grain size distribution between the seasons. In general, the sediment material is mostly medium sand. The $d_{50}$ value ranges from 0.29 to 1.77 mm, with an average specific gravity of 2.43 (see Figure 3 and Table 6). On the Muntok River, there are several illegal tin mining locations operating, including upstream (between points MT-SS2 and MT-SS3), and in the middle stream between points MT-S2, MT-S3, and MT-S4. Those activities contribute a lot to a finer grain size.

In Bangka Regency, the Jelitik riverbed has a coarser grain size, with an average $d_{50}$ of 1.24 mm, distinguishing it from other rivers. Tin mining activities take place both upstream and downstream. Upstream mining is carried out onshore with an open pit system, and downstream mining is done offshore with suction vessels. Mining activities are also taking place along the Kolong Air Baru River, primarily in the downstream sections near the estuary. The average specific gravity of sediment in Bangka Regency is 2.43, which is the same as that of river sediments in Bangka Barat. Grain size distributions of river bedload sediment in Bangka Regency are shown in Figure3, while the sediment properties are

Table 6. Bed material properties for rivers in Bangka Barat Regency

| Sample | Dominant Materials | Weight (%) | ($d_{50}$) (mm) | Specific gravity |
|---|---|---|---|---|
| DE-S1 | Very fine gravel; | 23.54; | 1.29 | 2.42 |
| | Very coarse sand; | 22.22; | | |
| | Coarse sand | 22.72 | | |
| MT-S1 | Fine sand | 38.64 | 0.40 | 2.42 |
| MT-S2 | Very coarse sand | 32.52 | 1.77 | 2.41 |
| MT-S3 | Medium sand | 26.42 | 0.63 | 2.52 |
| MT-S4 | Very fine sand | 32.52 | 1.67 | 2.38 |
| MT-S5 | Medium sand; | 31.96; | 0.45 | 2.43 |
| | Fine sand | 32.36 | | |
| MT-SS1 | Medium sand | 39.02 | 0.51 | 2.48 |
| MT-SS2 | Medium sand | 37.55 | 0.57 | 2.49 |
| MT-SS3 | Medium sand | 46.18 | 0.29 | 2.30 |
| MT-SS4 | Coarse sand | 49.78 | 0.70 | 2.49 |

Table 7. Bed material properties for rivers in Bangka Regency

| Sample | Dominant Materials | Weight (%) | ($d_{50}$) (mm) | Specific gravity |
|---|---|---|---|---|
| KB-S1 | Coarse sand | 47.92 | 0.74 | 2.40 |
| KB-S2 | Fine sand | 47.56 | 0.27 | 2.43 |
| KB-S3 | Coarse sand | 49.04 | 0.76 | 2.52 |
| AA-S1 | Fine sand | 25.96 | 0.66 | 2.42 |
| JL-S0 | Coarse sand; | 31.52; | 1.17 | 2.42 |
| | Very coarse sand | 29.62 | | |
| JL-S1 | Very fine gravel | 32.04 | 1.30 | 2.37 |

Table 8. Bed material properties for rivers in Bangka Selatan Regency

| Sample | Dominant Materials | Weight (%) | ($d_{50}$) (mm) | Specific gravity |
|---|---|---|---|---|
| RB-S0 | Coarse sand | 30.30 | 0.85 | 2.35 |
| RB-S1 | Fine gravel | 29.17 | 1.90 | 2.53 |
| RB-S2 | Coarse sand; | 27.36; | 1.37 | 2.43 |
| | Very coarse sand | 29.88 | | |
| RB-S3 | Medium sand | 30.56 | 1.05 | 2.57 |
| RB-S4 | Very coarse sand | 37.74 | 1.45 | 2.39 |
| RB-S5 | Fine sand; | 29.00; | 0.47 | 2.39 |
| | Medium sand | 31.80 | | |

shown in Table 7.

Figure 3 shows the grain size distribution of riverbed material in Bangka Selatan Regency. In Bangka Selatan, only the RB-S1 station in the Rawabangun River shows uneven grain size distribution. At this location, there are more grains with a larger size. Table 8 shows that the average $d_{50}$ size is relatively large, at 1.18 mm, and has a specific gravity of 2.44.

## 3.2 Characteristics of Suspended Load

Figure 4 depicts the concentration of suspended load at all sampling points on Bangka Island. This also represents the situation during the wet season. The suspended sediment concentration diagram in the dry season is separated. The suspended sediment content varied at each sample point, even in one river. The values ranged from 4.14 to 1,978 mg l$^{-1}$. The lowest concentration was in RB-S0, whereas the highest was in MT-S1. Although concentrations appear to be higher upstream, several locations show anomalies. This is due to the impact of tin mining operations. Tin mining onshore using an open pit system discharges large amounts of

Table 9. Dependable flow ($Q50\%$) for each representative location

| Regency/City | Points | Area (km$^2$) | Q (m$^3$ s$^{-1}$) |
|---|---|---|---|
| Pangkalpinang | BT_S1 | 342.32 | 10.13 |
| | BT_S2 | 377.78 | 11.18 |
| | BT_S3 | 396.41 | 11.73 |
| | SL_S1 | 61.86 | 1.83 |
| | SL_S2 | 68.41 | 2.03 |
| | SL_S3 | 82.32 | 2.44 |
| | PD_S0 | 26.12 | 0.77 |
| | PD_S1 | 28.65 | 0.85 |
| | PD_S2 | 36.15 | 1.07 |
| | PD_S3 | 38.22 | 1.13 |
| | PD_S4 | 40.11 | 1.19 |
| | PD_S5 | 42.50 | 1.26 |
| | RK_S0 | 29.18 | 0.86 |
| | RK_S1 | 34.91 | 1.03 |
| | RK_S2 | 37.45 | 1.11 |
| | RK_S3 | 43.67 | 1.29 |
| | RK_S4 | 87.89 | 2.60 |
| | RK_S5 | 88.83 | 2.63 |
| | RK_S6 | 123.00 | 3.64 |
| Bangka Tengah | BR_S0 | 101.19 | 2.99 |
| | BR_S1 | 104.11 | 3.08 |
| | BR_S2 | 106.79 | 3.16 |
| | BR_S3 | 108.85 | 3.22 |
| | BR_S4 | 146.48 | 4.33 |
| | CY_S0 | 28.18 | 0.83 |
| | CY_S1 | 36.81 | 1.09 |
| | CY_S2 | 37.21 | 1.10 |
| Bangka Barat | DE_S1 | 6.39 | 0.19 |
| | MT_S1 | 8.59 | 0.25 |
| | MT_S2 | 16.61 | 0.49 |
| | MT_S3 | 17.17 | 0.51 |
| | MT_S4 | 17.66 | 0.52 |
| | MT_S5 | 18.12 | 0.54 |
| Bangka | KB_S1 | 58.03 | 1.72 |
| | KB_S2 | 64.99 | 1.92 |
| | KB_S3 | 74.93 | 2.22 |
| | JL_S0 | 38.95 | 1.15 |
| | JL_S1 | 40.26 | 1.19 |
| | AA_S1 | 6.82 | 0.20 |
| Bangka Selatan | RB_S0 | 1.46 | 0.04 |
| | RB_S1 | 2.25 | 0.07 |
| | RB_S2 | 0.41 | 0.01 |
| | RB_S3 | 0.17 | 0.01 |
| | RB_S4 | 3.26 | 0.10 |
| | RB_S5 | 3.55 | 0.11 |

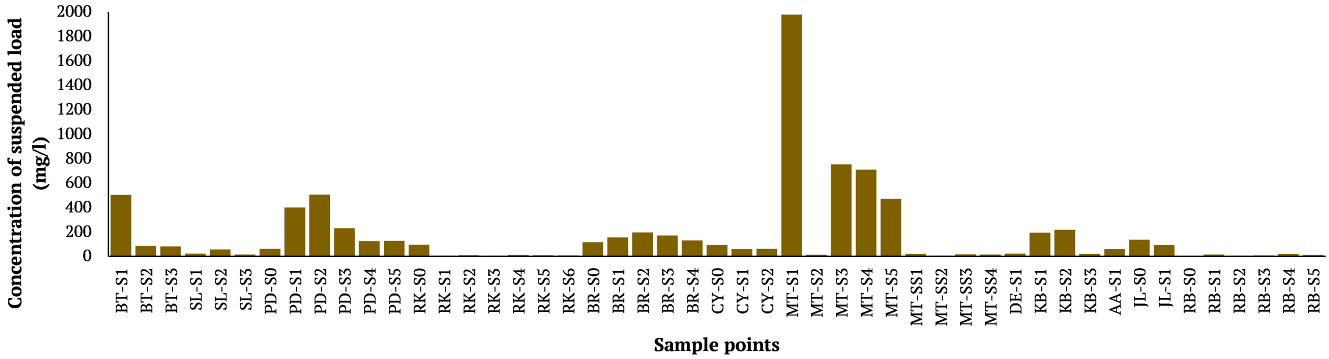


Figure 4 Concentration of suspended sediment in rivers on Bangka Island

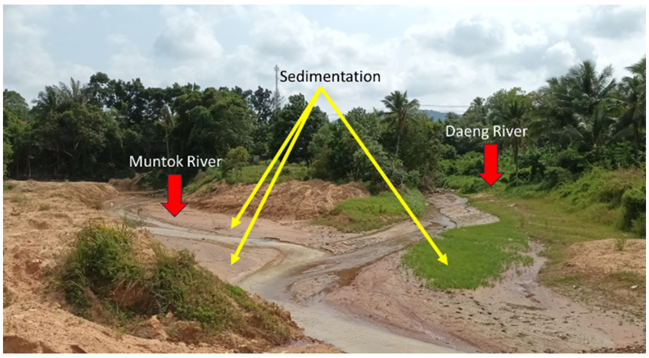


Figure 5 The situation of the Muntok River and Daeng River Confluence in the dry season

water containing very fine clay into rivers.

In Pangkalpinang City, sediment concentrations are fairly high in the Pedindang River, which has many tin mining operations in the upstream area. A similar situation also happened to rivers in Bangka Tengah Regency and Bangka Regency. When there are tin mining activities, the concentration of suspended sediment will be high, such as in the Berok River, Air Kolong Baru River and Jelitik River.

At the MT-S1 (Muntok River, Bangka Barat), the sediment concentration is very high. This is because the MT-S1 point is the confluence of the upstream Muntok River and the Daeng River, where, in both parts, there are illegal tin mining operations. At MT-S2, sediment concentration drops dramatically because the weir at the upstream site discourages sediment from flowing downstream. The weir decreases flow velocity, causing a large amount of sediment to accumulate in the weir's upstream section. Sediment concentrations increased again from locations MT-S3 to MT-S5. This resulted from the existence of areas exploited for illegal tin mining between MT-S2 and MT-S3 as well as between MT-S3 and MT-S4. Figure 5 depicts the situation at the confluence of the Daeng and Muntok rivers during the dry season of 2023. It is obvious that sedimentation in the river body was severe. The river's capacity is significantly reduced from its native state.

## 3.3 Sedimentation Rate

Since the lack of recorded flow data, the dominant flow cannot be determined. Hence, the sedimentation rate is estimated by the continuous flow computed from the Mock rainfall-runoff model. We used the dependable flow at 50% exceedance probability ($Q50\%$), based on the flow rate that equaled or exceeded 50% of the time monthly from 2002 to 2021. Because there is no measured flow data for model validation, the model parameter values are determined according to the flow-rainfall ratio as recommended by (Van der Weert, 1994). We applied continuous flow estimates to a standard area (100 km$^2$) and adjusted the final values for each of the sub-basins of Bangka Island based on their respective areas. The average annual rainfall for the last 20 years is 2,258.30 mm. Thus, the annual runoff is estimated at 1104.8 mm (48.92%). Table 9 is a recapitulation of the results of calculating the dependable flow $Q50\%$ for each representative location.

Figure 6 shows the results of estimated sedimentation rates in all investigated rivers. According to an analysis of river sediment transport rates in Pangkalpinang City, the BT-S1 had the highest sediment transport rate (169,337.67 tons year$^{-1}$). Furthermore, this site serves as the estuary for all Pangkalpinang City's rivers. The watershed's enormous area contributes to a high discharge of suspended sediment. The estimated sediment flow rates into the Kacang Pedang retention pond (RK-S2) were the lowest, at 397.73 tons year$^{-1}$. The Perumnas check dam, which accommodates a portion of the debris and reduces the flow velocity from upstream, is evidence of this.

In Bangka Tengah Regency, BR-S4 is considered as the location with the highest sedimentation rate, namely 67,249.36 tons year$^{-1}$. Bed load is projected to have the most significant contribution to sedimentation at the location. The average sedimentation rates in the Muntok River and Daeng River are 19,519.03 tons year$^{-1}$

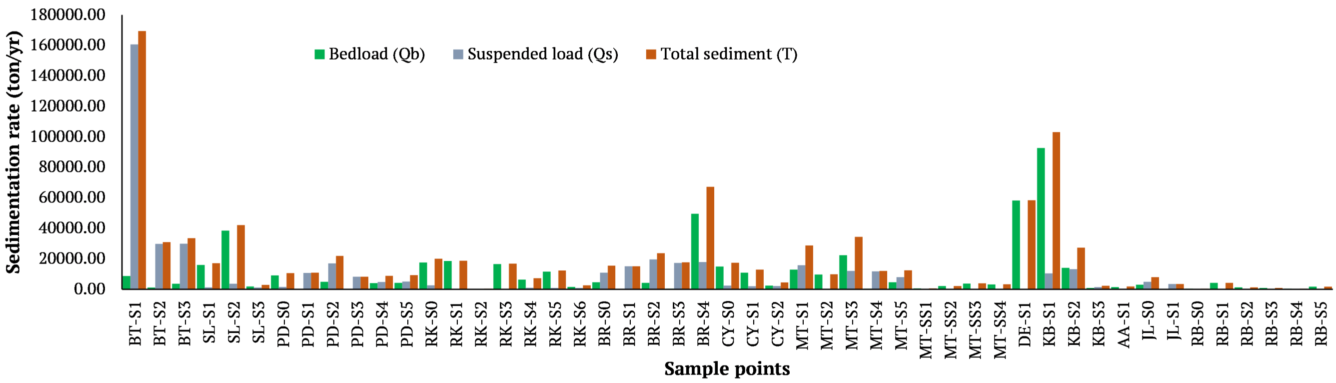


Figure 6 Sedimentation rate in all investigated rivers

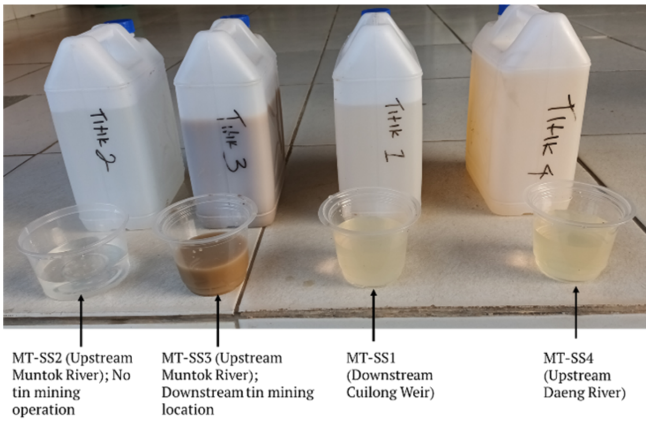


Figure 7 Water samples in the Muntok and Daeng Rivers in the dry season

and 58,403.98 tons year$^{-1}$, respectively. KB-S1 has the highest sedimentation rate in Bangka Regency and the largest source is from bedload sediment. There are a lot of open land or mining areas upstream. Based on an analysis of the sedimentation rate in Bangka Regency, it is known that the location with the highest sedimentation rate is RB-S1 (4,191.70 tons year$^{-1}$). This figure is notably lower than the average sedimentation rate compared to the other locations of the five regencies. Overall, all sample locations in Bangka Selatan had low estimated sedimentation rates.

## 4 DISCUSSION

In almost all rivers on Bangka Island, the contribution of bed load and suspended load is almost equal to the sedimentation rate. Many factors, including stream discharge, river slope, and bed sediment characteristics, influence the sedimentation rate estimated using the MPM equation. The grain size distribution of bed material sediments does not follow an identical pattern of natural rivers. Coarser sediment grains typically settled further upstream and eventually became finer as they moved downstream. For example, consider the Rangkui and Pedindang rivers in Pangkalpinang City. More fine particles were discovered in the Rangkui River's upper reaches (RK-S0, RK-S1, and RK-S2). This is due to an abundance of sediment control structures and retention ponds downstream from the sampling stations. In the middle stream (downstream of the retention pond), coarse and very coarse sands predominate. At RK-S6, which is downstream of the Rangkui River, the dominant material is a combination of very coarse and fine sand. This control station also got sediment transport from the Pedindang River. The Pedindang River has sediment particles with most of the coarse size along the river. This is because of the massive tin mining in the upstream and middle streams of the river, in addition to the rather steep slope of the river. The considerable concentration of suspended load is another effect of illegal tin mining operations in the Pedindang River.

In Bangka Tengah, large grain sizes are typically observed in river confluence zones or near tin mining operations. Along the Rawabangun River (Bangka Selatan Regency) is a highly populated area, so there is no evident justification for the sediment grain size distribution pattern.

The Muntok River in Bangka Barat is the river with the highest concentration of suspended sediment on Bangka Island. Strong evidence has been found of the impact of tin mining on sedimentation in the Muntok River. Observations and analysis results show that there has been very high turbidity in the river flow downstream of mining operations during the dry season. During the dry season, the impact of tin mining on the concentration of suspended sediment in the Muntok River is more evident since the flow rate is low while the sediment concentration is high. Figure 7 shows photos of water samples taken at four points along the Muntok and Daeng Rivers in the dry season, from upstream to middle stream. MT-SS2 is located closest to the furthest upstream point of the Muntok River. At this station, as well as further upstream, there are no tin mining operations, so the water's color is exceptionally clear. Tin mining takes place between MT-SS2 and MT-SS3 and was in progress at the time the water samples were collected. The unusually muddy color of the water indicates that tin mining activities lead to a high concentration of suspended material in the river. After passing through the Cuilong weir (MT-SS1), the watercolor becomes lighter than before. This is a result of sediment being captured upstream of the weir.

Normally, in the dry season, the concentration of suspended sediment is very low. Based on analysis, it was found that the impact of mining caused sediment concentrations to be 12 times higher than natural conditions. The river sedimentation rate in Bangka Barat is remarkable, given that the river's dimensions are not as vast as those in Pangkalpinang City (such as the Baturusa River and the Selindung River), yet the sedimentation rate is considerably high.

## 5 CONCLUSION

The effects of tin mining, particularly around river systems, are evident in the characteristics of bed sediment and suspended load concentrations. The grain size distribution of bed sediments deviates from natural patterns, where coarser particles are typically found upstream and finer particles downstream. Further, in sections of the river previously affected by tin mining, the flow tends to carry high concentrations of silt and clay. This study revealed that the effects of illegal tin mining led to increases in sediment concentrations up to 12 times higher than the natural condition. This study provided additional contributions to previous research regarding the negative impacts of onshore tin mining on water and land quality. However, the sediment observations in this study were limited to the dry season. To gain a more comprehensive understanding, future research should include observations across different rivers and seasons.

## DISCLAIMER

The authors declare no conflict of interest.

## ACKNOWLEDGMENTS

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