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Assessing Flow, Sediment, and Salinity Patterns in Tidal-Affected Meandering Rivers: Insights from Kali Wonokromo

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Abstract*—This study investigates the interplay between tidal influences and river meandering dynamics in the Wonokromo River, focusing on the alterations in flow patterns, sediment transport, and salinity levels. The research was driven by the need to understand how tidal phases and river meandering affect the geomorphological and ecological characteristics of tidal-affected meandering rivers. Field measurements were conducted across three strategic river cross-sections, employing instruments such as a TH-02 series current meter for flow velocity and a DH-48 type sampler for suspended sediment collection. Salinity was gauged using a Constant WT61 salinometer. Results indicated significant variability in flow velocity, suspended sediment concentration (SSC), and salinity across different river sections and tidal conditions. Notably, river bends showed pronounced asymmetries in flow velocity and SSC, intensified by tidal influences, with higher salinity observed closer to the estuary. The study found that mangrove vegetation along the riverbanks is crucial in stabilizing these parameters, mitigating typical erosion and deposition processes in other meandering rivers. These findings suggest that tidal phases significantly modulate river dynamics, further influenced by local geomorphological features such as bends and vegetation. For future research, exploring the long-term impacts of these dynamics on riverine ecosystems and the potential implications for river management practices, particularly in the context of climate change and human interventions is recommended. This research contributes to the broader understanding of estuarine and coastal river systems, offering insights into sustainable management and conservation strategies.

***Keywords*— Tidal influence; River Meandering; ecological management; Kali Wonokromo.**

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I. Introduction

The study of river meandering dynamics holds significance not only for geomorphological research but also finds practical applications in fields such as civil engineering and environmental management, making it an area of great interest and importance [1], [2], [3]. Tides are another significant factor influencing river meandering, with their rhythmic ebb and flow [4] caused by gravitational forces from celestial bodies like the moon and sun. This phenomenon leads to changes in water levels within rivers, thereby impacting the flow velocity and consequently altering the meandering pattern of the river [5], [6], [7], [8]. By studying the interaction between tides and river meandering, valuable insights can be gained into the dynamics of these natural systems. This enables the development of effective strategies for managing and mitigating the impacts of meandering rivers.

Flow velocity plays a crucial role in the phenomenon of river meandering, as it significantly affects erosion and deposition processes along the riverbanks [9], [10], [11], [12]. Changes in flow velocity can lead to alterations in the shape and direction of meanders, making it a vital parameter to consider when analyzing river behavior [13], [14]. Suspended sediment transport and salinity also have a significant influence on affecting tidal currents. They can alter the density and viscosity of water, ultimately impacting the direction and strength of the tidal flow [15], [16], [17]. Understanding how suspended sediment transport and salinity affect tides is vital for comprehending the broader implications of tidal interactions on river ecosystems and coastal environments.

The condition of the Wonokromo River, particularly at its downstream segment, presents an intriguing case study for examining mangrove vegetation's role in river meandering dynamics [18]. Dense mangrove forests along this part of the river have been observed to mitigate erosion and deposition processes significantly, a phenomenon uncommon in typical meandering river systems [19], [20]. This lack of significant erosion or deposition is attributed to the stabilizing effects of mangrove roots, which serve as a natural reinforcement for the riverbanks. Unlike the Fitzroy River studied by Lymburner [21], which experiences extensive sediment deposition influenced by tidal activities and seasonal variations, the Wonokromo River's mangroves provide a unique stabilizing effect that minimizes these dynamics. Similarly, it is observed in the Mekong River Delta that sediment transport is highly influenced by seasonal floods and tidal forces, which are less pronounced in the Wonokromo River due to the protective role of mangroves [22]. Mangroves, with their complex root systems, protect the banks from the direct impact of flowing water and trap sediments, contributing to the stability and shape of the river meander [19], [23]. This unique interaction between the river dynamics and the mangrove ecosystem underscores the importance of selecting the Wonokromo River as a focal site for our study [24]. It provides a compelling example of how natural vegetation can influence river morphology and flow patterns [25], [26], offering insights into sustainable river management practices that leverage the protective benefits of mangrove forests. The stability observed in the river's meandering pattern in the presence of mangroves highlights their critical role in coastal and riverine ecosystem dynamics, making the Wonokromo River an ideal location for assessing the interplay between flow, sediment, and salinity in tidal-affected meandering rivers.

Throughout the annals of riverine research, a considerable body of work has been dedicated to understanding the dynamics of river meandering, focusing on the morphological changes of river bends. Esteemed researchers such as [27], [28] have laid the groundwork by spatially analyzing the transformation of river bends. Other studies by [29], [30] have delved into laboratory simulations to study the evolution of channel bends under various discharge and flow velocity effects. Another study by [31] utilized digital terrain models for cross-sectional shape analysis and [32] explored water exchange dynamics. The cross-sectional review of river bends by [33], [34], alongside the studies by [35] on erosion and deposition dynamics have contributed significantly to our understanding.

A study by [7] conducted spatial analysis at bends influenced by tidal streams and [33] examined water and sediment fluxes in the Danube Delta’s meanders during floods further highlights the complexities of sediment storage and removal. Some other studies [36], [37], [38] conducted investigation into the impact of climate change on flow parameters in cross sections underscores the evolving nature of riverine studies. Despite these comprehensive analyses, the specific interplay between tidal influences and mangrove vegetation on erosion and deposition dynamics at river bends, particularly in the context of the Wonokromo River, remains underexplored, presenting a gap that this research seeks to fill. This inquiry stands at the frontier of riverine studies, extending state-of-the-art by integrating the unique environmental factors of the Wonokromo River into the broader discourse on river meandering and sediment dynamics.

This research aims to elucidate the complex interplay of flow phenomena in the bends of the Wonokromo River during varying tidal conditions, focusing on the sections proximal to the estuary and surrounded by mangrove forests and areas impacted by waste disposal. Contrary to everyday occurrences in river bend areas, where erosion and deposition are typically evident, these processes appear markedly subdued at the studied location, likely influenced by the protective presence of mangroves and other vegetative barriers.

To address this anomaly comprehensively, our approach involves a detailed investigation of key flow parameters, including flow velocity, sediment transport concentration, and salinity levels. By meticulously examining these parameters, this study aims to unravel the intricate relationships governing the dynamics within the river bend area. Through this analysis, we anticipate uncovering insights into how tidal fluctuations, coupled with the buffering effects of local vegetation, contribute to the observed stability and morphological peculiarities of the river, thereby providing a nuanced understanding of riverine dynamics in ecologically sensitive zones.

II. Materials and Methods

This section outlines the methodology employed in this study, including the planning and setup, field measurements, laboratory observations, and data analysis procedures. The overall process is depicted in the flowchart provided (Fig. 1).

A. Planning and Setup

Planning and preparation were conducted to ensure smooth data collection and analysis. This involved determining measurement locations and scheduling measurement times.

B. Field Measurement

Field measurements were conducted using a boat owned by local fishermen. Data collection in the river was divided into three cross sections labeled A, B, and C. Field measurements were scheduled for November 21 and 27, 2023. The measurement locations encompassed three cross-sections, as depicted in Fig. 2. The November 21 measurements progressed from section A to C, whereas those on November 27 proceeded from C back to A. These measurements aimed to elucidate the flow behavior from high tide to low tide in the morning at section A and from low tide back to high tide in the afternoon. Water level for the data collection period is presented in Fig. 3.a and 3.b. It was positioned in cross section B.

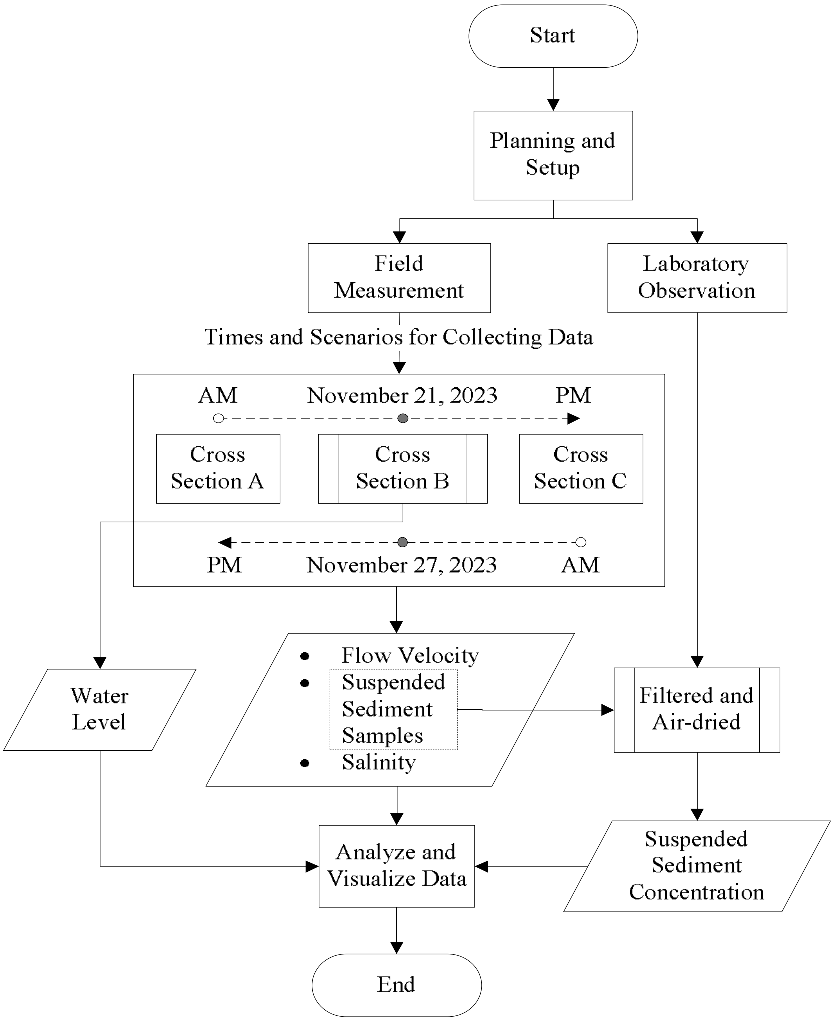

Fig. 1 Field and Laboratory Data Collection Process

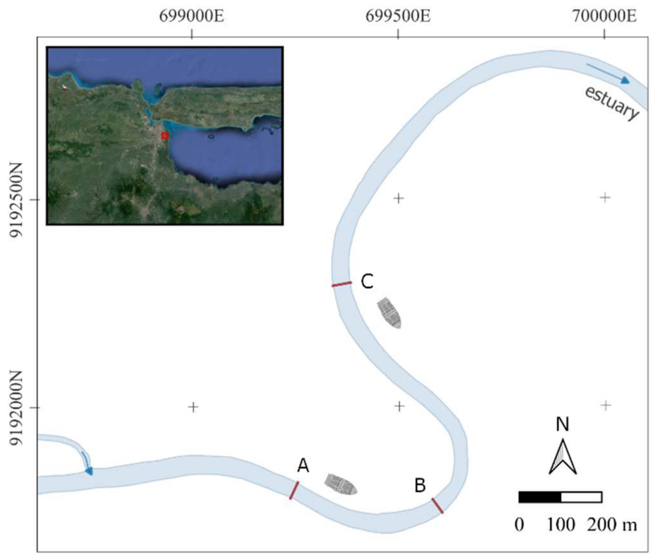

Fig. 2 Sampling locations in cross sections A, B, and C. Nov 21, 2023, sampling starts from A to C; Nov 27, 2023, sampling starts from C to A

Cross section A was positioned in a non-bend area. Meanwhile, cross sections B and C were located at river bends and used as comparators for physical flow parameters. At each cross-section, sampling was divided into five transects (Fig. 4), with each transect recording three water column parameters at depths of 0.2h, 0.6h, and 0.8h (where h represents the water depth), totaling 15 samples for each parameter at each cross-section.

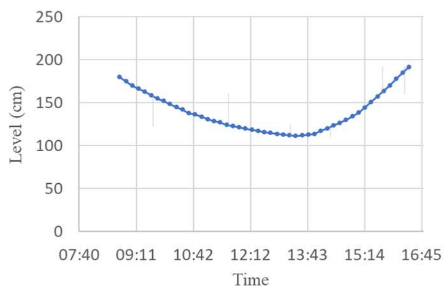

Fig. 3.a Water level data collection on November 21, 2023

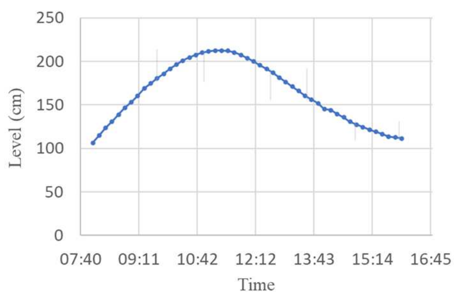

Fig. 3.b Water level data collection on November 27, 2023

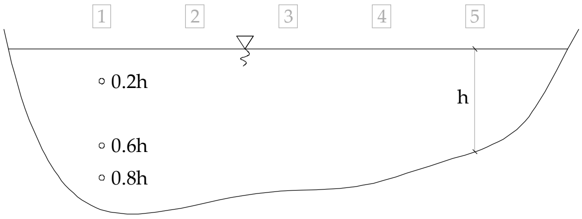

Fig. 4 Data collection points (0.2h, 0.6h, 0.8h) on five water-column in the river cross-sections

C. Data Collection

Data collection encompassed the measurement of several key parameters:

- Flow Velocity: Measured using a TH-02 series current meter by Tatonas. Flow velocity measurements were performed three times at each point and subsequently averaged.
- Suspended Sediment Samples: Collected using a DH-48 type sampler from the Hydraulic and Coastal Engineering Laboratory at ITS Surabaya, then placed into 600 ml bottles.
- Salinity: Salinity levels were gauged using a Constant WT61 salinometer.

D. Laboratory Observation

Suspended sediment samples collected in the field were brought to the Soil Mechanics Laboratory at the Civil Engineering Department of UNTAG Surabaya for detailed analysis. These samples were filtered using Whatman 42 filter paper and air-dried at room temperature for 24 hours to obtain data on suspended sediment concentration (SSC).

E. Data Analysis and Visualization

Collected data were analyzed to understand the river sections' flow characteristics and sediment transport dynamics. The analysis involved comparing data across different cross-sections and under varying tidal conditions. The acquired data were visualized in two dimensions using the Surfer tool, aiming to facilitate the analysis of the relationships between physical flow parameter phenomena.

III. Results and Discussion

The following results refer to cross-section figures of flow velocity (5 and 8), SSC (6 and 9), and salinity (7 and 10).

A. Velocity Distribution in Meandering River Sections

1) Temporal Variations of Flow Velocity: Observations on November 21, 2023: Section A: The velocity profiles displayed a gradual decrease from the center towards the banks, with a maximum velocity observed at the center of the channel. This section exhibited a symmetric distribution, indicative of a relatively straight flow path with lesser influence from river meandering. Section B and C: These sections showed a pronounced asymmetry in velocity distribution, with higher velocities shifting towards the river bend's outer bank. This shift suggests the development of secondary flows and increased momentum outside the bend due to the centripetal forces.

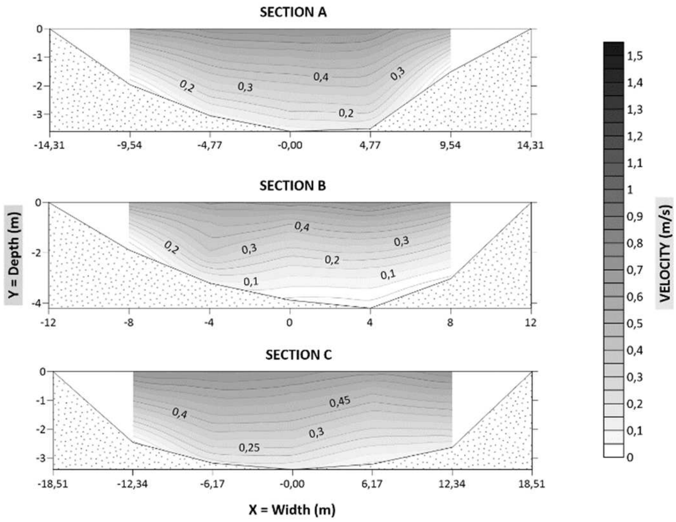

Fig. 5 The Velocity was observed from Sec. A to Sec. C

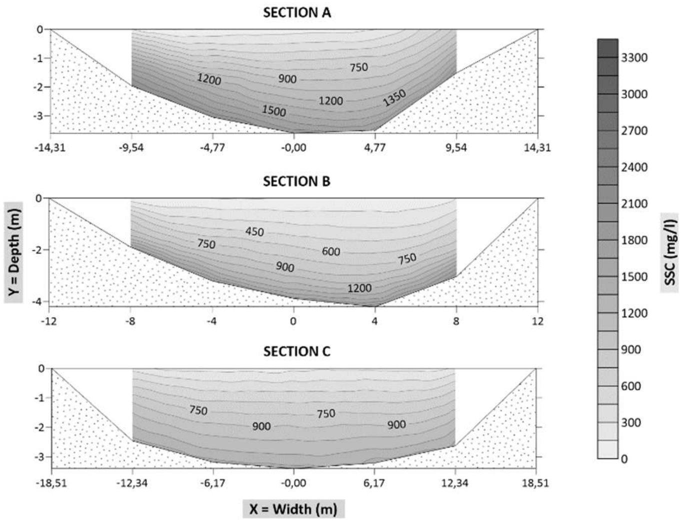

Fig. 6 The SSC was observed from Sec. A to Sec. C

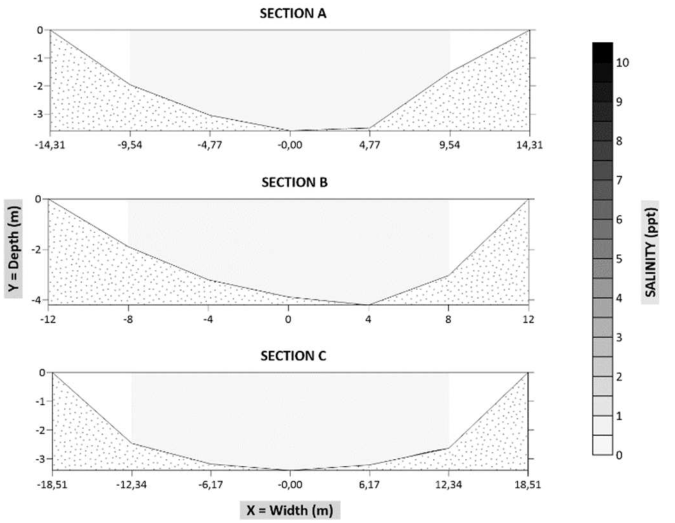

Fig. 7 The Salinity was observed from Sec. A to Sec. C

Observations on November 27, 2023: Section A: While maintaining a similar pattern to the previous observation, a slight shift in peak velocity towards one bank was noted, suggesting the initial effects of tidal influence at this upstream section. Section B and C: The asymmetry in velocity distribution became more pronounced compared to November 21, with the maximum velocities further skewed towards the outer bank. The enhanced tidal conditions accentuated the secondary flow patterns inherent in meandering sections.

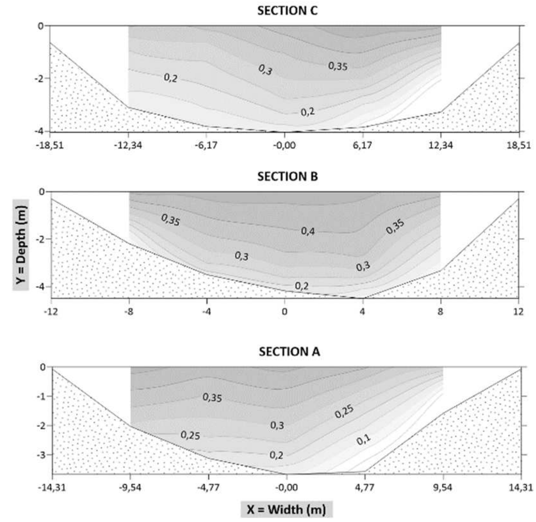

Fig. 8 The Velocity was observed from Sec. C to Sec. A

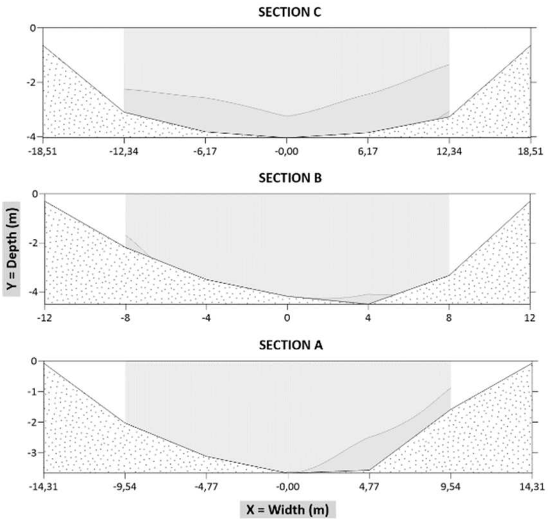

Fig. 9 The SSC was observed from Sec. C to Sec. A

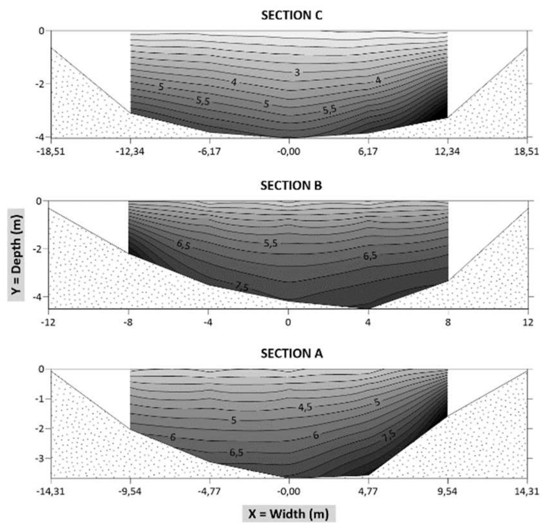

Fig. 10 The Salinity was observed from Sec. C to Sec. A

2) Impact of River Bends on Flow Velocity: The comparison between Sections A, B, and C demonstrated a clear impact of river meandering on velocity distribution. While Section A maintained a relatively uniform velocity profile, Sections B and C showed significant deviation from symmetry due to the influence of river bends. The influence of the river bend was more pronounced in Section C, the section immediately following the bend, indicating that the curvature of the riverbed had a substantial effect on flow behavior.

3) Influence of Tidal Phases on Flow Velocity: During the ebb tide conditions on November 21, velocities were generally lower, suggesting that the retreating water reduced the energy of the flow, particularly evident in Sections B and C. Conversely, during the onset of flood tide on November 27, there was an increase in flow velocities across all sections, with the most significant changes observed in the downstream sections B and C, highlighting the tidal amplification of flow dynamics in meandering river sections. Björn [34] investigated flow velocity variations across an estuary, noting significant variations in average velocity. This aligns with our findings of substantial flow velocity variations, especially around river bends, indicating complex interactions between river hydrodynamics and geomorphological processes. Focused on flow processes and sedimentation in the Danube Delta during episodic flooding, Tiron [33] observed intensified flow and sedimentation in human-made channels and confluence areas during flood conditions. Our study of river bends during tidal changes revealed similarly complex flow dynamics influenced by river morphology and tidal interactions.

B. Spatial and Temporal Distribution of Suspended Sediment Concentration (SSC)

1) Spatial Distribution of SSC: Observations on November 21, 2023: Section A: There was a noted increase in SSC towards the center of the river section, indicative of sediment uplift from the riverbed due to increased flow velocities at the core of the channel. Section B and C: An asymmetric distribution of SSC was observed, with heightened concentrations on the outer banks of the bends. This pattern suggests enhanced sediment entrainment due to the centrifugal forces acting on the flow at bends, leading to increased erosion on the outer banks and accumulation of sediments.

Observations on November 27, 2023: Section A: Similar to previous observations, a central peak in SSC was evident, with a moderate increase compared to the measurements taken on November 21, possibly due to the commencement of tidal inflow. Section B and C: A marked increase in SSC was observed, particularly on the outer bank of the bends. The tidal inflow appeared to augment sediment suspension and transport, particularly in these sections.

2) Impact of River Bends on SSC: A comparative analysis between Sections A (upstream straight section) and Sections B and C (downstream bend sections) revealed that bends significantly contribute to sediment dynamics within the river. The SSC was consistently higher in bend sections, affirming the role of river curvature in sediment suspension and distribution.

3) Influence of Tidal Phases on SSC: On November 21, during ebb tide conditions, lower SSC values were recorded, aligning with the expected decrease in flow energy and reduced capacity for sediment suspension. On November 27, correlating with the onset of flood tide, SSC values increased across all sections. The elevation was more pronounced in downstream sections, confirming the role of tidal forces in resuspending and redistributing sediments along the river course, especially after the river bends. Maulana [35] reported higher erosion and sediment transport rates at river bends, supported by measurements of lateral migration. Our observations confirm a strong correlation between SSC and flow velocity at bends, highlighting significant morphological changes at these locations. Björn [34] linked sediment concentration more with flow rate than flow velocity. In our study, flow velocity at bends was a crucial factor in sediment movement, explaining the discrepancies with Björn's observations in more stable estuarine conditions. Patriadi [36] noted that tidal conditions affect SSC distribution in river estuaries. Our sampling during tidal periods showed increased SSC during high tide, suggesting sediment input from the sea, contrasting with Tiron (2008), who focused on flow and sediment changes during episodic floods.

C. Variability of Salinity in a Tidal-Affected Meandering River

1) Spatial Variability of Salinity: Observations on November 21, 2023: Section A: Salinity levels showed a gradient consistent with distance from the estuary, with lower salinities upstream and increasing towards downstream sections. This gradient reflects the diminishing influence of saline water from the estuary moving upstream. Sections B and C: These sections, situated on river bends closer to the estuary, registered higher salinity levels. The salinity distribution in these bends indicated some degree of mixing and possible stratification, with a tendency of higher salinity towards the outer banks.

Observations on November 27, 2023: Section A: Salinity levels increased overall across the section, likely due to the advancing tidal waters bringing saline water further upstream. Sections B and C: Notably, salinity was higher compared to the measurements taken on November 21. The influence of the tide was evident, with salinity levels showing greater uniformity across the river width, suggesting increased mixing due to stronger tidal flows.

2) Impact of River Bends on Salinity: Comparison of salinity distribution between straight sections and bends revealed the tendency for river bends to enhance salinity gradients due to the complex hydrodynamics that promote differential mixing and solute transport along the curved pathways of the river.

3) Influence of Tidal Phases on Salinity: The salinity distribution during the ebb tide on November 21 indicated riverine water dominating the estuarine mixing zone, leading to a clear freshwater-saltwater interface. On November 27, during the flood tide, the intrusion of seawater into the river system was apparent, with a more pronounced homogenization of salinity across the river sections. The extent of tidal influence was particularly evident in downstream sections, showcasing the dynamics of saltwater penetration during different tidal phases. Patriadi [36] found a more homogeneous salinity distribution. In contrast, our study observed higher salinity near the surface and lower at the river bottom, possibly due to increased mixing between fresh and salt water at bends, whereas straighter river sections might exhibit more stable and less affected processes.

D. Factors Contributing to Differences in Findings

1) Sampling Location: Our samples were taken at river bends, which might experience different hydrodynamic interactions and greater influences on flow velocity compared to straighter sections or estuaries as studied by Björn [34], Tiron [33], and Patriadi [36].

2) Sampling Time: Our study conducted at estuary bends during critical tidal periods could influence flow velocity distribution due to water surface fluctuations. In contrast, Patriadi [36] sampled throughout the year, allowing observations of seasonal salinity fluctuations.

3) Tidal Conditions and Seasons: In Indonesia, the rainy and dry seasons significantly affect river discharge and sediment transport. Seasonal changes can substantially influence fluvial processes, including flow velocity and sedimentation, as observed in our study during tidal changes, showing increased salinity during high tide.

E. Implications

Our findings emphasize the importance of understanding river flow dynamics and tidal influences within the context of water resource management. The varied flow velocity distribution can have significant implications for material flux calculations, erosion and deposition predictions, and infrastructure planning and flood mitigation strategies. Additionally, the presence of mangroves along the riverbanks, as indicated by Kakati [19] and Yoshikai [23], plays a critical role in moderating flow velocity and SSC, as well as affecting salinity stratification, which promotes geomorphic stability and ecological health of riverine systems.

F. Limitations of the Study

This study presents several methodological and contextual limitations that are important to acknowledge:

1) Sampling Methodology: The methods used to measure Suspended Sediment Concentration (SSC) may not fully capture spatial or temporal variability, particularly during rapidly changing flow conditions or extreme events such as heavy rain or floods.

2) Data Representation: The data collected focused on tidal periods and may not reflect conditions outside these times, including seasonal influences and extreme weather events not covered during the sampling period.

3) Temporal Scale: The study was limited to a specific period, which might not include long-term SSC fluctuations influenced by climate change.

4) Geomorphological Influence: The local geomorphological complexity may affect the interpretation of data regarding erosion and sedimentation, which was not fully explained by the collected data.

IV. Conclusion

This study systematically investigated the flow dynamics, suspended sediment transport, and salinity distribution in the tidal-influenced bends of the Kali Wonokromo River. The findings revealed significant variability in flow velocity, suspended sediment concentration (SSC), and salinity across different river sections and tidal conditions. The presence of mangroves along the riverbanks plays a crucial role in stabilizing these parameters, mitigating typical erosion and deposition processes in other meandering rivers. The study demonstrated that tidal phases significantly modulate river dynamics, further influenced by local geomorphological features such as bends and vegetation. Key observations include: Asymmetries in flow velocity and SSC were pronounced at river bends, intensified by tidal influences; Salinity levels showed stratification influenced by tidal movements, with higher salinity observed closer to the estuary; Mangrove vegetation significantly contributes to the stability of the river's morphological and ecological characteristics. These insights underline the importance of preserving natural vegetation buffers like mangroves for sustainable river management and conservation practices. The research highlights the complex interplay between tidal dynamics and river morphology, offering valuable contributions to the understanding and managing tidal-affected meandering rivers.

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