South East Asian Marine Sciences Journal (SEAMAS)
Journal Homepage: https://journal.stedca.com/index.php/seamas

Analysis of Surface Currents during Flood and Ebb Tides Using the LSPIV Method in the Rokan River Estuary

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Article Info
Keyword:
LSPIV,
Rokan River Estuary,
Surface Current,
Tidal Current,
UAV

Received:
September 9, 2026
Accepted:
September 29, 2026
Published:
October 1, 2026

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Abstract

The Rokan River Estuary is a transitional zone with complex hydrodynamics shaped by the interaction of river discharge, tidal forces, and bed morphology, making reliable surface current data essential for coastal management and navigation safety. This study aimed to analyze the characteristics and velocity of surface currents during flood and ebb tide conditions in the Rokan River Estuary using the Large-Scale Particle Image Velocimetry (LSPIV) method based on UAV drone video imagery, and to evaluate its agreement with current meter measurements. The research was conducted in February 2025 through a quantitative descriptive-spatial field survey; video data were processed using pyOpenRiverCam and validated via linear regression, correlation coefficient (R), coefficient of determination (R^2), RMSE, and MAE. Results showed surface current velocities ranging from 0–2 m/s, flowing relatively uniformly toward the southwest–west during ebb tide following the river flow, while during flood tide the current became more variable toward the southeast–east due to seawater intrusion. Validation revealed a positive but weak relationship between LSPIV and current meter data, with better accuracy during the flood phase (R=0.362; R^2=0.131; RMSE=0.309) than the ebb phase (R=0.242; R^2=0.058; RMSE=0.407). The UAV-based LSPIV method proved to be a promising, efficient, and non-contact alternative for surface current measurement, supporting sustainable estuarine hydrodynamic studies.

1. INTRODUCTION

Surface current is the movement of water masses influenced by tides, river discharge, wind, and differences in the density of fresh and salt water (Khadami et al., 2022). These factors make river estuaries areas with highly variable current patterns, both temporally and spatially, and they play important roles in the physical, chemical, and biological processes of estuarine waters (Geyer & MacCready, 2014). Currents contribute to nutrient distribution that supports primary productivity, but they can also transport excess sediment that causes shallowing, alters salinity, and potentially carries pollutants into sensitive ecosystems such as mangroves and coral reefs.

The Rokan River Estuary is one of the major estuaries on the east coast of Sumatra and is directly connected to the Strait of Malacca, with high tidal dynamics and sedimentation rates (Metry et al., 2016). These conditions cause changes in estuary-bed morphology, shallowing, and abrasion that affect shipping activities, fisheries, and the lives of surrounding communities. The tidal-bore phenomenon (bono) identified in this estuary also demonstrates the high hydrodynamic energy of the area (Wisha et al., 2022). Therefore, understanding the pattern and

velocity of surface currents during flood and ebb tides is an important basis for coastal management and environmental-impact mitigation.

Current measurements in estuarine areas are generally conducted in situ using a current meter or Acoustic Doppler Current Profiler (ADCP). Although accurate, these methods have limited spatial coverage and require substantial operational costs and time. The use of an Unmanned Aerial Vehicle (UAV) through the Large-Scale Particle Image Velocimetry (LSPIV) approach is a promising alternative because it can analyze the movement patterns of the water surface from video imagery to obtain flow-velocity vectors in a non-contact, rapid, and accurate manner (Tauro et al., 2015). Although tidal dynamics in the Rokan River Estuary have been widely studied in terms of morphology and sedimentation, studies specifically analyzing surface-current patterns and velocities during flood and ebb tides using the LSPIV method remain limited. This study aimed to (1) measure and analyze surface-current velocity using the LSPIV method, (2) analyze the characteristics of surface currents during flood and ebb conditions in the Rokan River Estuary, and (3) evaluate the level of agreement between LSPIV measurements and current-meter measurements.

2. RESEARCH METHODS

Time and Place

The study was conducted in February 2025 around Pedamaran 1 Bridge, Rokan River Estuary, Rokan Hilir Regency, Riau Province, using a field-survey method with a quantitative descriptive-spatial approach. The research location and distribution of observation stations are shown in Figure 1.



Figure 1. Map of the research location in the Rokan River Estuary, Rokan Hilir Regency, Riau (SD: drone station; SC: current-meter station)

Procedures

Drone video recording was conducted at a 90° angle with a flight altitude of 40-60 m for approximately 5 minutes under two conditions, namely the ebb phase and flood phase (Liu et al., 2021). Current-meter measurements were conducted in situ at the same location and time as the LSPIV recording so that the hydrodynamic conditions were relatively uniform. Bathymetric data were obtained through sounding at 30-m intervals along each survey line.

LSPIV Data Processing

The video data were processed through image orthorectification using Ground Control Points (GCPs) based on photogrammetric principles to correct spatial distortion (Muste et al., 2008), followed by grayscaling and cross-correlation analysis to identify particle movement on the water surface. The entire process was performed using the open-source Python-based pyOpenRiverCam library, which uses OpenPIV for flow-velocity analysis and OpenCV for image reprojection, producing spatial vectors of surface-current direction and velocity.

Data Analysis

The agreement between LSPIV and current-meter measurements was evaluated using linear regression analysis ($y = ax + b$), the Pearson correlation coefficient (R), the coefficient of determination (R^2), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE). An R value

approaching 1 indicates a strong positive relationship, whereas smaller RMSE and MAE values indicate that the LSPIV measurements are closer to the current-meter measurements.

3. RESULTS AND DISCUSSION

General Conditions and Bathymetry of the Research Location

Bathymetric mapping results (Figure 2) showed variations in water depth ranging from 0.5 to more than 7 m. The middle part of the river channel was dominated by greater depths (2-6 m), indicating the presence of a main channel as the dominant pathway for water-mass movement, while the margins tended to be shallower (0.5-2 m). This pattern indicates a main channel that functions as a pathway for estuarine water masses entering and leaving the estuary (He et al., 2023), as well as an indication of active sedimentation processes caused by interactions among river discharge, tidal currents, and suspended-sediment distribution (Metry et al., 2016).

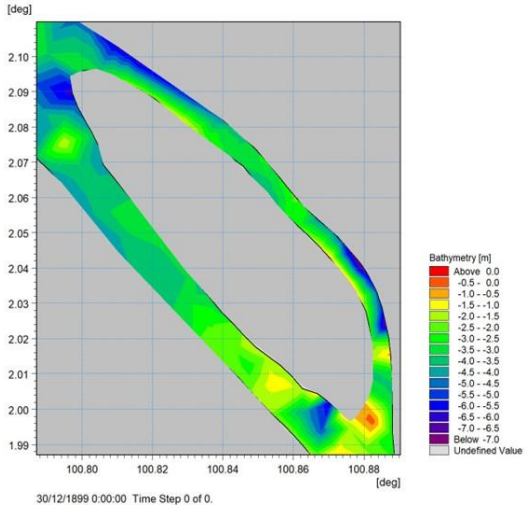


Figure 2. Bathymetric map of the research area

Tidal Conditions at the Research Location

Based on the tidal chart from observations at the BIG station during the period from January 2025 to January 2026 (Figure 3), water-surface elevation at the research location fluctuated from -3.2 m to 3.2 m, with a pattern of two high tides and two low tides per day (mixed tide prevailing semidiurnal). Variations in amplitude between spring and neap tides indicate that the hydrodynamics of the Rokan River Estuary are strongly influenced by the gravitational pull of the moon and sun, consistent with the finding that tidal currents are a major controlling factor of water-mass circulation in estuaries (Li et al., 2023).

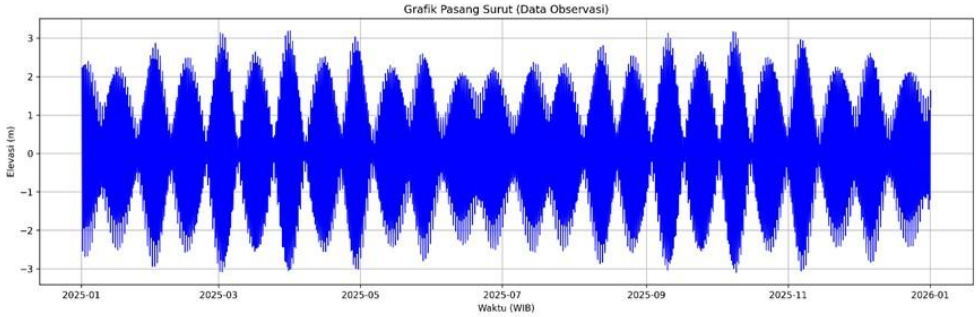
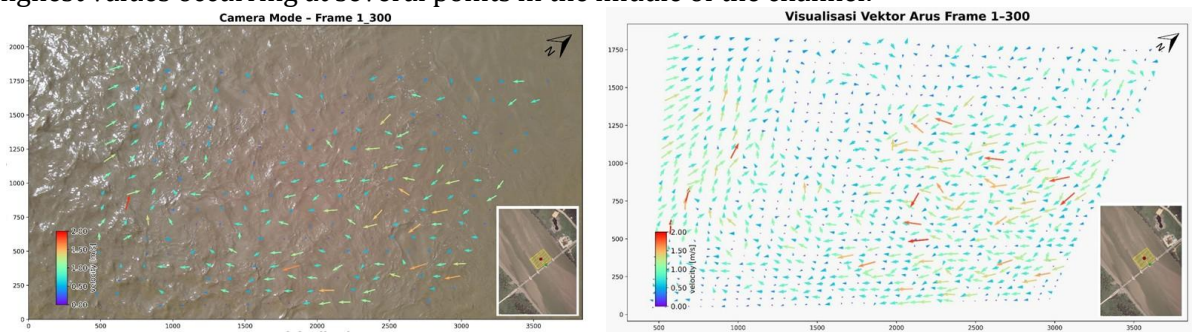


Figure 3. Tidal chart of the Rokan River Estuary (Source: BIG)

Surface-Current Characteristics During Flood and Ebb Tides

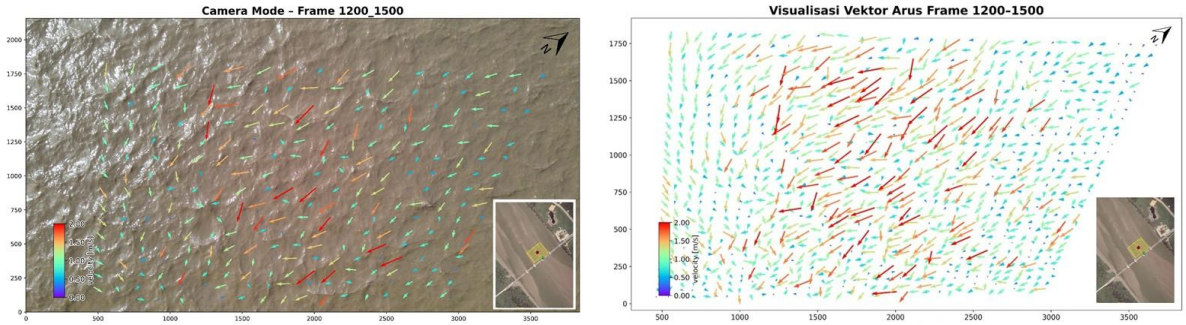
LSPIV image-processing results during the ebb phase (Figure 4) and flood phase (Figure 5) show the spatial distribution of surface-current vectors, each displayed with the original image background (a) and without the background (b) to clarify the velocity-vector pattern. During the ebb phase, surface currents moved predominantly downstream toward the sea, with the highest

velocities (1.5-2.0 m/s) concentrated in the middle of the channel, representing the main flow path, while the margins showed lower velocities due to bottom friction and bank morphology. During the flood phase, the current-vector directions appeared more variable, with some reversing because seawater entered the estuary, with velocities ranging from 0- 2 m/s and the highest values occurring at several points in the middle of the channel.



(a) with image background (b) Without background

Figure 4. LSPIV analysis of surface-current vectors and velocities during the ebb phase



(a) with image background (b) Without background

Figure 5. LSPIV analysis of surface-current vectors and velocities during the flood phase

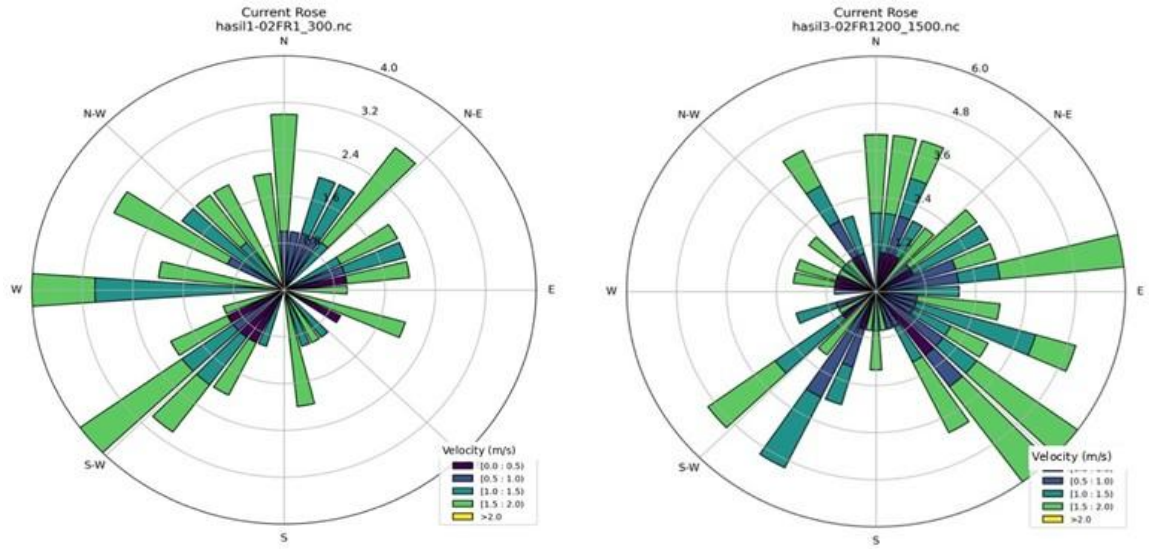


Figure 6. Current rose during the ebb phase (left) and flood phase (right)

In many estuaries, ebb currents tend to be stronger and last longer than flood currents, resulting in higher sediment-transport rates during ebb tide and a tendency for sediment to move out of the estuary/seaward (Wang et al., 2019; Teng et al., 2022). Meanwhile, local changes in current direction during the flood phase indicate the formation of turbulence and small eddies caused by interactions between currents and changes in bottom depth, a condition commonly observed in estuaries with strong tidal dynamics (Bo et al., 2024; Xie et al., 2022).

Validation of LSPIV Against Current Meter

This pattern is further supported by the current-rose diagram (Figure 6). Under ebb conditions, surface currents showed a dominant direction from southwest to west, with the highest occurrence frequency in the 1.0-2.0 m/s velocity class, consistent with the river-flow pattern toward the sea. In contrast, under flood conditions, the current pattern was more complex because of seawater intrusion, with a dominant direction from southeast to east and an average velocity of 0.95-1.0 m/s. This difference in pattern confirms the presence of a mixed flow pattern resulting from interactions among tidal forcing, river discharge, and bottom morphology (Pénicaud et al., 2025).

The ebb phase produced the regression equation Y = 0.496x + 0.233, with R = 0.242 and R^2 = 0.058. The scatter plot for the ebb phase (Figure 7) showed a positive relationship between LSPIV and current-meter measurements; however, the points were still relatively dispersed and did not consistently follow the line of agreement (1:1 line). The flood phase produced the regression equation Y = 0.209x + 0.716, with R = 0.362 and R^2 = 0.131, with RMSE and MAE values (0.309 and 0.254) lower than those for the ebb phase (0.407 and 0.306). The scatter plot for the flood phase (Figure 8) showed points relatively closer to the regression line than those in the ebb phase, so overall, the flood phase showed better agreement between the LSPIV and current-meter measurements.

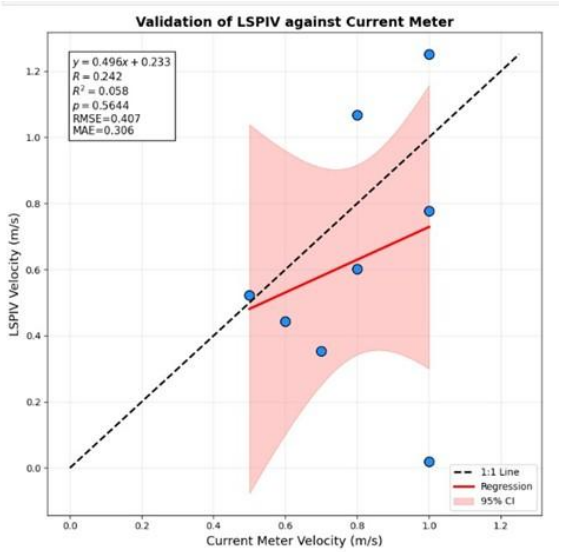


Figure 7. Validation of LSPIV against the current meter during the ebb phase

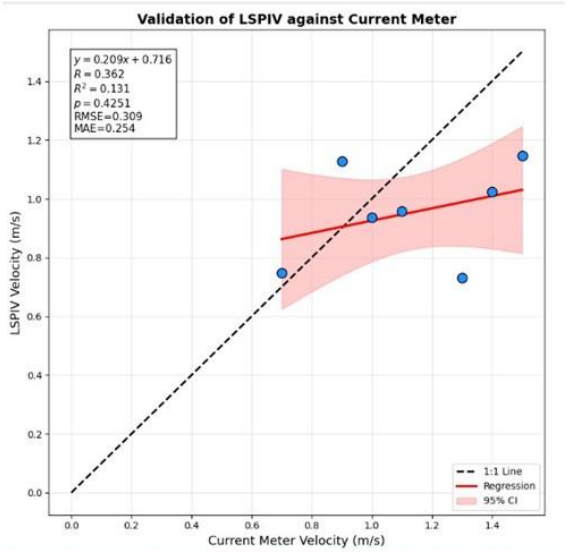


Figure 8. Validation of LSPIV against the current meter during the flood phase

The relatively weak positive relationship in both phases is thought to be influenced by differences in the operating principles of the two methods: LSPIV measures velocity optically based on the displacement of patterns at the water surface, whereas the current meter measures velocity at a specific point within the water column, so the resulting values are not always identical, especially in estuaries with strong vertical velocity distributions and water-mass mixing. Nevertheless, the relatively low error levels indicate that LSPIV has potential as a rapid, efficient, and non-contact method for measuring surface currents, consistent with the advantages of LSPIV reported in previous studies (Tauro et al., 2015; Liu et al., 2021).

4. CONCLUSIONS

Surface-current velocities in the Rokan River Estuary ranged from 0.5 - 2.0 m/s, were relatively more stable during ebb tide, and were more variable during flood tide because of interactions between river flow and ocean tides. The current pattern showed clear differences between the two conditions: it was predominantly downstream, following river flow during ebb tide, and showed directional variability caused by seawater intrusion upstream during flood tide.

The LSPIV method was able to estimate surface-current velocity with relatively low error, with better accuracy during the flood phase than during the ebb phase, indicating its potential as an alternative method for rapid, efficient, and non-contact measurement of surface currents to support sustainable estuarine hydrodynamic studies

AUTHOR CONTRIBUTIONS

AR: Conceptualization, Methodology, Investigation, Data Curation, Writing – Original Draft; M: Formal Analysis, Visualization, Data Curation Writing – Review & Editing; YIS: Supervision, Writing – Original Draft, Writing – Review & Editing.

SOURCES OF FUNDING

There is no funding

CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

AI DECLARATION

I technology (Chat GPT) was used in some instances to check language on an early draft and to format references. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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