

Article

Estimating Vessel Speed Through Water from Sparse Publicly Available Data Using AIS Trajectories and Tidal Current Reconstruction

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Abstract

Understanding vessel energy demand requires knowledge of vessel motion relative to the surrounding water, rather than motion relative to the Earth's surface. However, direct measurements of speed through water (STW) are rarely accessible beyond individual vessels, as they rely on onboard instrumentation and are not publicly available. As a result, studies of vessel energy consumption and zero-emission transition pathways in inland waterway transport (IWT) often rely on Automatic Identification System (AIS) data, which provides speed over ground (SOG) but does not account for environmental current effects. The objective of this study is to develop an inferential method to estimate STW using sparse publicly available data. The proposed method combines AIS-derived vessel trajectories with a modelled environmental current field derived from tidal elevation data to resolve the component of the current acting along the vessel's direction of travel. Vessel motion is reconstructed from AIS position data, and the along-track current component is obtained through vector projection onto the vessel trajectory. Combining this with observed SOG enables estimation of STW without onboard measurements. The method is evaluated using representative vessel case studies on the tidal River Thames, where estimated STW is compared with independent Doppler-based measurements. A detailed validation is presented for one representative vessel, with additional validation undertaken across multiple vessel types operating under different conditions. Across the validation cases, the methodology shows strong agreement with measured STW, demonstrating that STW can be estimated with acceptable accuracy using widely available data. This establishes the physical foundation required for subsequent propulsion power and energy-demand assessment in data-constrained environments.



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1. Introduction

Inland waterway transport (IWT) is increasingly being considered as part of broader strategies to reduce emissions within the transport sector [1,2]. Achieving this transition requires a clearer understanding of the energy demand associated with vessel operations along inland waterways (IWW). Estimating propulsion power requires knowledge of vessel

speed relative to the surrounding water rather than its motion relative to the Earth's surface. This quantity, referred to as speed through water (STW), determines the hydrodynamic resistance experienced by the vessel and therefore the propulsion power required to sustain motion. Publicly available vessel movement datasets are typically derived from Automatic Identification System (AIS) observations, which record vessel position and speed over ground (SOG) [3]. Because SOG reflects both vessel propulsion and environmental currents, it does not directly represent the hydrodynamic conditions experienced by the vessel, limiting its direct use in studies that estimate vessel energy demand.

This study presents a method for estimating vessel STW using sparse publicly available AIS position data combined with environmental current data. By separating vessel motion from environmental flow effects, the method enables estimation of vessel motion relative to the surrounding water using publicly available data sources across IWW systems. The approach is demonstrated using a case study on the tidal River Thames and further evaluated across additional representative vessel types using independent Doppler-derived STW measurements.

1.1. Operational Vessel Monitoring

Modern vessels generate large volumes of operational data through onboard navigation and monitoring systems. These systems typically record vessel position, heading, speed, engine performance and a range of other operational parameters that support safe navigation, vessel management and performance analysis [4]. One of the most widely available sources of vessel movement information is AIS, which provides time-stamped position reports transmitted by vessels at regular intervals along with other vessel data. From these position records, it is possible to reconstruct vessel trajectories and derive motion characteristics such as SOG and direction of travel. AIS data has therefore become a widely used resource for analysing vessel movements and operational behaviour across maritime domains [5].

The speed reported by AIS represents SOG, which reflects the combined effect of vessel propulsion and environmental forces such as tidal currents. STW is typically measured onboard using dedicated instrumentation such as Doppler speed logs or electromagnetic sensors that determine vessel velocity relative to the surrounding water [3,6].

The availability of such measurements varies considerably across vessel classes. Large ocean-going and deep-sea vessels are commonly equipped with integrated navigation systems that continuously record STW alongside other operational parameters. These systems often feed into voyage data recorders or vessel performance monitoring platforms used by operators [6]. In contrast, inland waterway vessels (IWW) are typically smaller, older and more operationally diverse, and the installation of advanced onboard monitoring systems is far less consistent. Many vessels operating on urban and IWW do not routinely capture or archive detailed vessel operational data, even where basic navigation instruments are present [7].

Even where STW measurements exist onboard a vessel, access to this data is typically restricted to the vessel operator and it is not available through public data sources [8]. Researchers analysing vessel performance, fuel consumption, or energy demand must therefore rely on publicly available datasets such as AIS, and in the absence of STW measurements, these analyses often depend on simplified assumptions or published studies based on limited or vessel-specific datasets [9,10]. In many cases, SOG is used as a direct proxy for vessel STW, implicitly assuming negligible current interaction [10,11]. In other cases, approximate corrections are applied using average current values or broad upstream-downstream classifications rather than time-resolved current fields [3]. These approaches introduce uncertainty into estimates of vessel performance, fuel consumption and energy

demand, particularly where analyses rely on AIS-derived speed information without explicitly accounting for environmental current effects [12].

1.2. Why Speed Through Water Matters

As a vessel moves through water, it must overcome frictional resistance along the hull, wave-making resistance, and other hydrodynamic effects arising from the interaction between the hull and the surrounding flow field [13]. These forces depend on the vessel's velocity relative to the water and therefore determine the propulsion effort required to sustain motion [3,14–16].

Propulsion systems must generate sufficient thrust to overcome this hydrodynamic resistance [15]. The power required to propel a vessel therefore depends on the relationship between hull resistance and STW [16]. For most displacement vessels operating within their normal speed range, the propulsion power requirement increases rapidly as vessel speed increases. This relationship is often approximated by a cubic dependence between vessel speed and required propulsion power, meaning that relatively small changes in STW can produce significant changes in power demand [17–19].

Environmental currents modify the relationship between observed vessel motion and propulsion effort. When currents are present, the vessel's ground-referenced motion reflects both propulsion and environmental flow, meaning that similar SOG values may correspond to different hydrodynamic loading conditions depending on current alignment [18,19].

This distinction is particularly important in tidal and river environments, where current velocities may represent a substantial fraction of the vessel's operating speed. In such conditions, SOG alone does not provide a reliable indication of the propulsion effort required to move the vessel [20]. Two voyages that exhibit similar SOG may correspond to significantly different hydrodynamic conditions depending on whether the vessel is travelling with or against the prevailing current [3]. Understanding propulsion energy demand therefore requires separating vessel motion from environmental current effects.

1.3. Limitations of Current Approaches

Several approaches have been developed to analyse vessel performance and propulsion demand using operational data [4,13,17,18]. These datasets allow vessel performance to be analysed directly, but they are typically obtained from individual vessels and are therefore not widely accessible [21]. In addition, such datasets may contain measurement uncertainties, missing records, or anomalies arising from sensor limitations, data transmission issues, or operational variability, which can affect the reliability and completeness of the analysis [10].

Where onboard measurements are unavailable, alternative approaches often rely on simplified assumptions regarding vessel motion [3]. AIS-derived vessel speeds are frequently used directly within performance analyses or corrected using broad average current estimates rather than time-resolved environmental data. While such assumptions may be acceptable in open sea conditions where currents are relatively weak, they become increasingly unrealistic in tidal waterways and river systems where current velocities may represent a substantial fraction of vessel operating speed [22]. Under these conditions, small differences between SOG and estimated or measured STW can lead to significant errors in estimated propulsion energy demand [5].

Other approaches attempt to account for environmental effects using hydrodynamic modelling or resistance prediction methods. These techniques typically require detailed vessel characteristics such as hull form, displacement, propeller geometry and propulsion system configuration, alongside hydrodynamic models that require scale model tank testing. Such information is rarely available for large numbers of vessels, particularly

within IWW fleets where vessel designs and operating conditions vary widely [23–25]. As a result, there remains a gap between the widespread availability of AIS vessel movement data and the ability to infer the hydrodynamic conditions experienced by a vessel during operation. In particular, a reproducible method for estimating vessel STW using sparse publicly available data remains limited. Addressing this gap is necessary for improving the analysis of vessel performance, propulsion energy demand and operational behaviour in data-constrained environments.

1.4. Research Objective

The objective of this study is to develop a method for estimating STW using sparse publicly available data. The study combines AIS-derived vessel motion with environmental current data to estimate the STW consistent with the observed trajectory. The method is evaluated against independent onboard measurements to determine whether it provides a practical representation of vessel hydrodynamic operating conditions in data-constrained environments.

The remainder of this paper is structured as follows. Section 2 presents the theoretical background underlying the relationship between vessel motion and environmental current. Section 3 describes the methodology used to estimate vessel STW from AIS trajectory data and environmental current information. Section 4 introduces the case study, including the study area, vessel dataset, and environmental current data, together with the validation approach. Section 5 presents the reconstruction and validation results. Section 6 discusses the limitations of the method and its applicability to IWW systems, and Section 7 concludes the paper.

2. Theoretical Background

Understanding how vessel motion and environmental currents interact is necessary to separate SOG from the hydrodynamic conditions experienced by the vessel. The following sub-sections, therefore, outline the fundamental velocity relationships governing vessel motion in a moving water mass and describe how the alignment of environmental currents with the vessel trajectory determines the difference between SOG and STW.

2.1. Vessel Velocity Components

The motion of a vessel operating in a moving water mass can be described using three velocity components:

- a. The velocity of the vessel relative to the Earth's surface.
- b. The velocity of the vessel relative to the surrounding water.
- c. The velocity of the environmental current.

These quantities are related through vector addition, where the SOG results from the combined effect of vessel motion through the water and movement of the surrounding water mass. This relationship can be expressed as:

$$\vec{V}_g = \vec{V}_w + \vec{V}_c \quad (1)$$

where $\vec{V}_g$ represents the vessel velocity relative to the ground, $\vec{V}_w$ represents the vessel velocity relative to the water, and $\vec{V}_c$ represents the environmental current velocity.

This relationship provides the physical basis for resolving vessel motion in environments where environmental currents influence the observed SOG.

2.2. Environmental Current Effects

Environmental currents influence vessel motion according to their directional alignment with the vessel's trajectory. Only the component of the current acting in the direction of vessel travel, positively or negatively, contributes to the difference between SOG and estimated or measured STW [26,27].

This component can be determined through the vector projection of the current velocity onto the vessel's direction of travel. The resulting along-track current component represents the portion of the current that assists or opposes vessel motion, as illustrated in Figure 1.

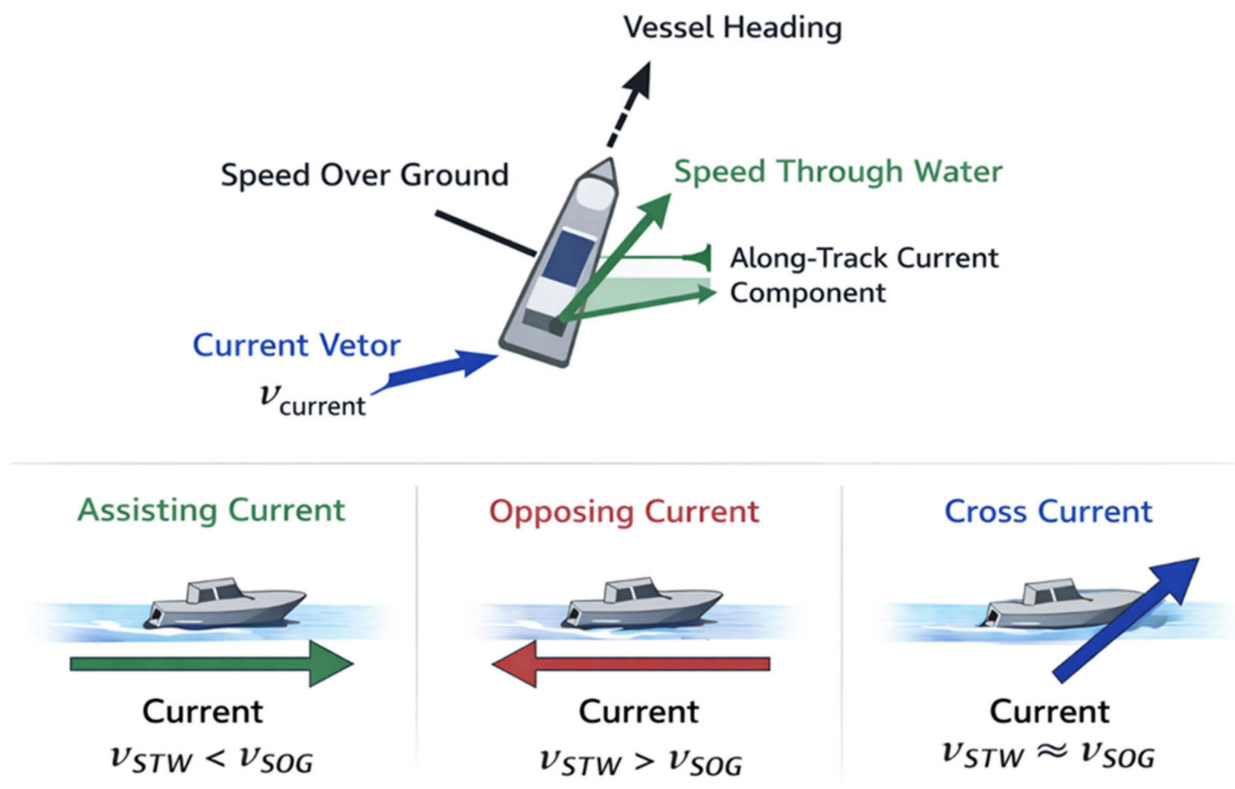


Figure 1. Vector representation of vessel motion showing the relationship between SOG, the environmental current vector, and the inferred STW. The along-track component of the current determines whether the vessel operates under assisting, opposing, or cross-current conditions.

This relationship forms the basis of the STW estimation methodology described in Section 3.

3. Methodology

Vessel STW is estimated using publicly available vessel movement data combined with environmental current information. AIS-derived vessel trajectories are reconstructed geometrically from position and time data, while environmental current conditions are derived from tidal elevation datasets using a proxy modelling approach. These independently derived components are then combined to resolve the component of the current acting along the vessel's direction of travel, allowing the corresponding STW to be estimated; see Figure 2.

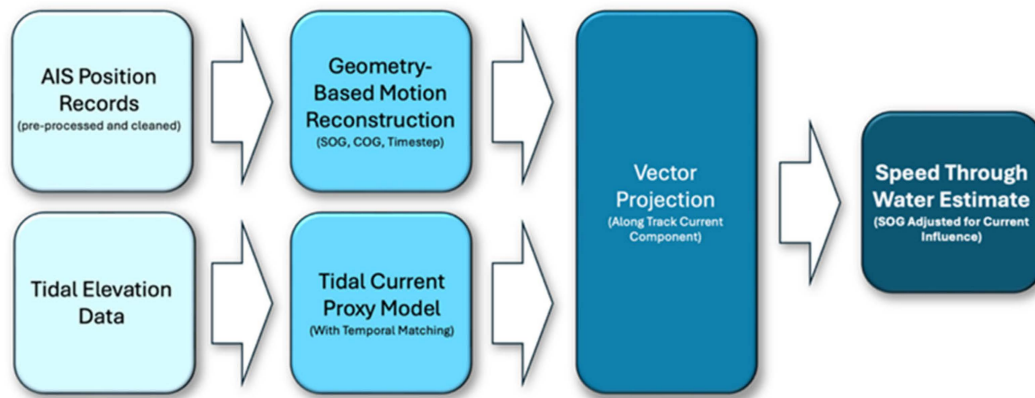


Figure 2. Methodological framework for estimating vessel STW from AIS trajectory data and tidal information.

3.1. AIS Trajectory Reconstruction

AIS position reports provide time-stamped geographic coordinates describing vessel movement over time. Each message may also include additional fields such as reported SOG, Course Over Ground (COG), and vessel heading; however, the reliability and completeness of these motion-related values can vary depending on the transmission source and the subsequent data processing performed by AIS providers.

In this study, vessel motion is reconstructed using only the timestamp and geographic coordinates contained within the AIS observations. For each pair of successive observations, the elapsed time is calculated as:

$$\Delta t_i = t_i - t_{i-1} \quad (2)$$

where t_i and t_{i-1} are the timestamps of successive AIS observations in seconds.

The geographical displacement between the two positions is calculated using the Haversine relationship:

$$d_i = 2R \arcsin \left(\sqrt{\sin^2 \left(\frac{\Delta \phi_i}{2} \right) + \cos(\phi_{i-1}) \cos(\phi_i) \sin^2 \left(\frac{\Delta \lambda_i}{2} \right)} \right) \quad (3)$$

where R is the Earth's radius, ϕ is latitude in radians, λ is longitude in radians, and $\Delta \phi_i$ and $\Delta \lambda_i$ are the differences in latitude and longitude between successive observations.

Geometry-derived SOG is then calculated as:

$$V_{\text{SOG},i} = \frac{d_i}{\Delta t_i} \quad (4)$$

where d_i is in meters and t_i is in seconds, with the result converted to knots. This provides the ground-referenced vessel speed between successive AIS observations directly from the recorded trajectory.

The direction of travel between successive positions is calculated as the initial bearing:

$$\theta_i = \text{atan2}(\sin(\Delta \lambda_i) \cos(\phi_i), \cos(\phi_{i-1}) \sin(\phi_i) - \sin(\phi_{i-1}) \cos(\phi_i) \cos(\Delta \lambda_i)) \quad (5)$$

The resulting bearing is normalised to the range 0° to 360° and used as the geometry-derived vessel direction of travel. COG was derived geometrically from successive AIS positions, and the COG values reported within AIS messages were not used.

The use of geometry-derived motion quantities avoids dependence on AIS-reported SOG and COG values, which may be subject to smoothing, interpolation, or inconsistencies across observations. For the analysed voyages, geometry-derived SOG showed closer

agreement with reconstructed vessel trajectory than AIS-reported SOG, which exhibited occasional discontinuities and smoothing artefacts.

The resulting time-ordered sequence of vessel positions and derived motion characteristics forms the basis for the STW estimation method described in the following subsections.

3.2. Data Pre-Processing

AIS position data may contain blank records, duplicate observations, irregular time intervals, and occasional positional anomalies that do not represent physically plausible vessel movement. Before motion reconstruction, blank records are removed and duplicate observations are identified as records containing an identical timestamp, identical geographic coordinates, or both.

The remaining AIS records are sorted into chronological order.

Successive observations are reviewed for trajectory consistency within the navigable corridor. Observations that imply physically implausible vessel speeds or positions are flagged. Positions outside the corridor are corrected by projecting them towards the nearest valid location bounded by the river centreline and corresponding river-edge geometry. Observations that remain physically inconsistent with the surrounding trajectory are excluded from the analysis. These procedures produce a clean, time-ordered sequence of AIS positions for the geometric reconstruction described in Section 3.1.

3.3. Tidal Current Modelling and Integration

Environmental current conditions are derived from tidal elevation data rather than direct current measurements. Tidal datasets provide time-stamped records of water level together with associated high- and low-water events at defined locations along the river corridor. These datasets are used to construct a continuous, time-resolved representation of current velocity by modelling the tidal cycle between successive tidal extrema.

Tidal elevation between successive high and low water events is reconstructed using a half-cosine interpolation applied independently to each tidal interval:

$$h(t) = h_{min} + \frac{h_{max} - h_{min}}{2} \left[1 - \cos\left(\pi \frac{t - t_0}{T}\right) \right] \quad (6)$$

where $h(t)$ is the reconstructed tidal elevation at time t , h_{min} and h_{max} are the tidal elevations at successive tidal extrema, t_0 is the start of the tidal interval, and T is the duration between successive high and low water events. This formulation ensures a smooth transition between slack-water conditions at the extrema and the mid-tide peak in the rate of change of water level, providing a continuous, phase-resolved representation of the tidal cycle.

The reconstructed tidal phase is then used to generate a normalised current velocity profile for each interval. A sinusoidal function represents the increase from slack water at the tidal extrema to peak flood or ebb flow mid-interval, with differing durations of flood and ebb naturally producing tidal asymmetry. The normalised profile is subsequently scaled using representative maximum current velocities for each river reach, together with adjustments for spring and neap tidal range.

The representative maximum velocities used for each river reach were selected from published guidance and literature values for the tidal Thames and were not calibrated against the validation dataset used in this study [27,28].

Verification of current velocity presents a significantly greater challenge than comparison of tidal elevation. While tidal height observations are routinely recorded and publicly available, suitable continuous current velocity measurements covering the study area were not available. Consequently, the reconstructed environmental current field represents a physically informed proxy derived from tidal elevation data and representative current

velocities reported in the literature, rather than a fully validated hydrodynamic model. Current behaviour within the tidal Thames is influenced by numerous interacting factors, including tidal phase, river geometry, channel constriction, local bathymetry, freshwater discharge, meteorological conditions, and tidal asymmetry. This means identical water levels can be associated with substantially different current velocities, depending upon whether the tide is flooding or ebbing.

To assess the behaviour of the tidal interpolation independently of the vessel validation cases, the reconstructed tidal elevation profile was compared with recorded tidal elevation observations at Chelsea on 3 January 2026 [28,29]. This date and location were selected because a suitable continuous observed tidal elevation series was available for comparison. The dataset was used only to assess the interpolation procedure and was not used as the environmental input for the vessel voyages analysed in Sections 4 and 5. For each vessel voyage, the tidal reconstruction was generated using tidal information corresponding to the actual voyage date, time and river reach. The purpose of the Chelsea comparison is to evaluate how well the sinusoidal interpolation reconstructs the continuous tidal elevation profile between successive high- and low-water events, where only tidal extrema are available [29]. As shown in Figure 3, the reconstructed profile captures the overall timing of tidal extrema and tidal range. Differences remain during the intermediate stages of the tidal cycle, reflecting the simplification inherent in representing tidal elevation using a half-cosine interpolation. The comparison, therefore, demonstrates that the interpolation provides a practical approximation of tidal elevation suitable for deriving the proxy current field rather than validating the environmental current field itself.

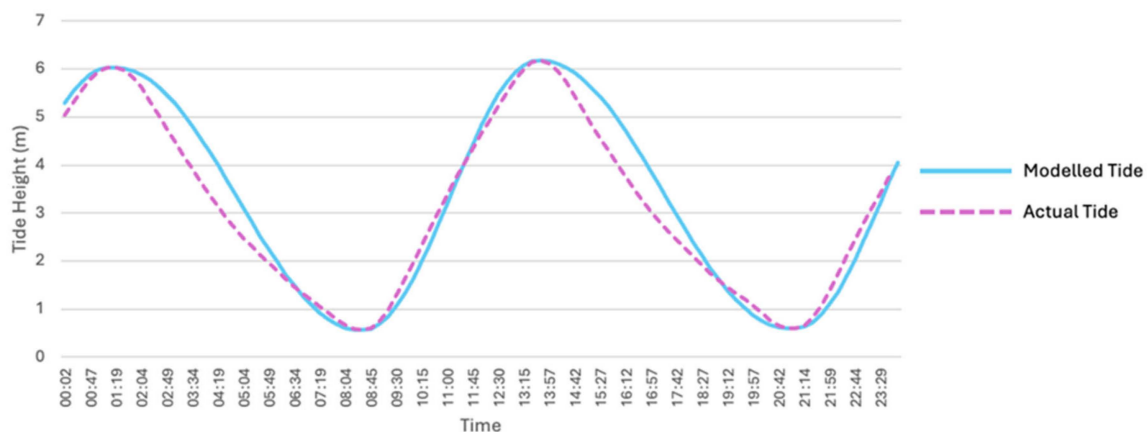


Figure 3. Illustrative comparison between sinusoidally reconstructed tidal elevation and recorded tidal observations at Chelsea on 3 January 2026. The comparison assesses the behaviour of the interpolation procedure using an available continuous tidal elevation series and is independent of the vessel validation voyages [27–31].

For the same illustrative Chelsea case, the derived current velocity profile was compared with representative velocity ranges reported in the literature and operational guidance for the central Thames tidal reach [31,32]. Published sources indicate that current velocities between Chelsea and London Bridge typically reduce to near-slack conditions at tidal extrema and increase to approximately 2.5–4.5 knots during peak flood and ebb periods, with higher velocities occurring during spring tides [32]. Given that the tidal range observed on 3 January 2026 exceeded 5 m, peak velocities towards the upper end of this range would be expected.

Figure 4 compares the derived current velocity profile with the literature-derived velocity envelope range. The derived current profile remains within the expected operational range throughout the tidal cycle and reproduces the characteristic behaviour of tidal flow,

including slack water conditions at high and low tide and peak velocities occurring during mid-tide periods. This comparison indicates that the reconstructed current field provides a physically realistic representation of the environmental conditions suitable for integration with AIS-derived vessel trajectories. It should be emphasised that this comparison represents an assessment of physical plausibility against published operational ranges rather than a direct validation against measured current velocity observations.

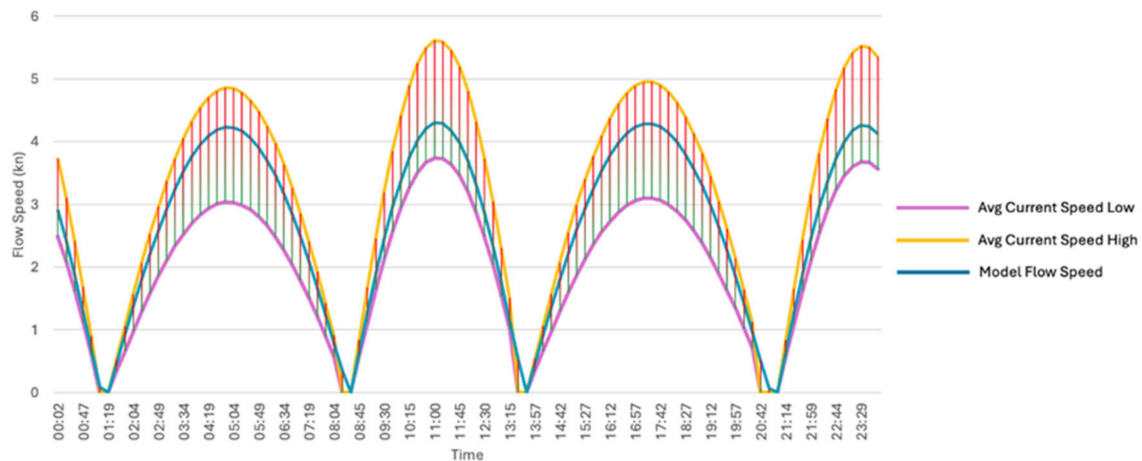


Figure 4. Illustrative plausibility comparison of the derived current velocity at Chelsea on 3 January 2026, against representative flow velocity ranges reported in published literature and operational guidance for the central Thames tidal reach. This comparison is independent of the vessel validation voyages against measured current velocity [29–31].

The derived current field is subsequently assigned to each AIS observation by identifying the nearest reference along the river corridor. Current magnitude and direction are then temporally interpolated between adjacent time steps to estimate the environmental current vector at the exact AIS timestamp. This produces a continuous, time-resolved estimate of the environmental current vector experienced by the vessel throughout the reconstructed trajectory.

3.4. Vector-Based Speed Through Water Estimation

Once vessel motion and environmental current vectors are defined for each timestep, the interaction between these quantities can be resolved using vector projection. Using the velocity relationship described in Section 2, the component of the environmental current aligned with the vessel trajectory is resolved and used to adjust the observed SOG.

The along-track current component is therefore determined by projecting the current velocity vector onto the vessel's direction of travel such that:

$$V_{current,along} = V_{current} \cos \theta \quad (7)$$

where $V_{current}$ is the magnitude of the tidal current, and θ is the angular difference between the vessel's direction of travel and the current direction.

This projection isolates the portion of the environmental current that assists or opposes the vessel's motion. The estimated STW is then obtained by removing the resolved along-track current component from the derived SOG:

$$V_{STW} = V_{SOG} - V_{current,along} \quad (8)$$

where V_{STW} is the estimated vessel speed through water, V_{SOG} is the geometry-derived speed over ground, and $V_{current,along}$ is the resolved current component acting parallel to

the vessel trajectory. Positive along-track current values represent assisting currents, while negative values represent opposing currents.

The resulting value represents the vessel speed relative to the surrounding water after removing the contribution of the environmental current from the observed ground-referenced speed. The estimated STW is subsequently used throughout the validation and analysis presented in the following sections.

3.5. Direction and Signal Smoothing

Following the geometric reconstruction of vessel motion and reconstruction of the environmental current field, smoothing is applied to stabilise the direction and alignment signals used in the STW calculation. Small variations in AIS position and timestamp resolution can introduce short-duration fluctuations in the geometry-derived direction of travel, particularly at low vessel speeds. These fluctuations can propagate into the current projection step and produce unrealistic variation in the estimated along-track current component [5,33]. With AIS observations typically recorded at intervals of approximately 25–35 s, this represents an effective smoothing period of approximately two to three minutes. The smoothed direction is then used to calculate the relative alignment between vessel motion and current direction before resolving the along-track current component. This procedure suppresses short-duration position fluctuations while preserving sustained changes in direction associated with genuine vessel manoeuvres and river geometry.

The principal preprocessing and smoothing procedures used within the STW estimation framework are summarised in Table 1.

Table 1. Summary of AIS preprocessing and directional smoothing procedures used in the STW estimation method.

Processing Stage	Implemented Method	Parameter or Treatment
AIS motion inputs	Geographic position and timestamp only	AIS-reported SOG and COG were not used
Record ordering	Chronological ordering	Ascending timestamp order
Duplicate handling	Removal of repeated observations	Identical timestamp, identical coordinates (8 decimals), or both
Trajectory consistency	Review of successive vessel positions	Physically inconsistent movements were corrected or excluded
River-corridor treatment	Comparison with defined navigable corridor	Positions outside the corridor were moved to the nearest physically plausible location within the defined river geometry
Vessel direction	Geometric bearing derived from the AIS position sequence	Calculated independently of AIS-reported COG
Direction smoothing	Rolling moving average	Five-observations window
Approximate smoothing duration	Determined by AIS reporting interval	Approximately 125–175 s, based on typical intervals of 25–35 s

Table 1. *Cont.*

Processing Stage	Implemented Method	Parameter or Treatment
Current alignment	Comparison of smoothed vessel direction with current direction	Applied before resolving the along-track current component
Low speed treatment	Same smoothing procedure retained during low-speed operation	No separate speed threshold should be reported unless confirmed from the implementation

3.6. Methodological Workflow Summary

The methodology described consists of a sequence of processing steps that transform AIS observations into an estimate of STW. The complete workflow is summarised in Figure 5.

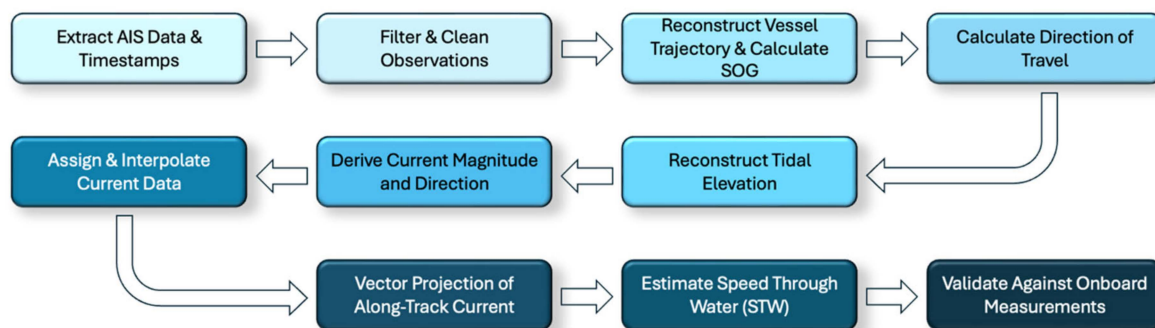


Figure 5. Methodological workflow summarising the sequential process used to estimate vessel STW from AIS observations and reconstructed environmental conditions.

4. Case Study

4.1. Study Area

The case study was conducted on a section of the River Thames in London, United Kingdom. The analysed route extends between Bermondsey in central London and Belvedere in the lower Thames (see Figure 6). This stretch of river forms part of one of the busiest navigational corridors within the Thames waterway and supports a wide range of vessel operations, including passenger services, freight transport, and service vessels.

The tidal Thames provides a suitable environment for evaluating the estimation method because vessel motion within this reach is strongly influenced by environmental currents. Tidal flow reverses direction approximately every six hours, producing alternating flood and ebb currents. Current magnitude also varies significantly throughout the tidal cycle, typically increasing during mid-tide periods and reducing near slack water. As a result, vessels operating along the route may encounter both favourable and opposing currents during normal operations.

Navigation conditions within this reach of the Thames are also shaped by the physical and operational constraints of the river environment. The river channel is relatively narrow in several sections and includes numerous piers, bends, variations in channel geometry, and areas of concentrated vessel traffic. These features create a complex operational environment in which vessels adjust their behaviour in response to these constraints.

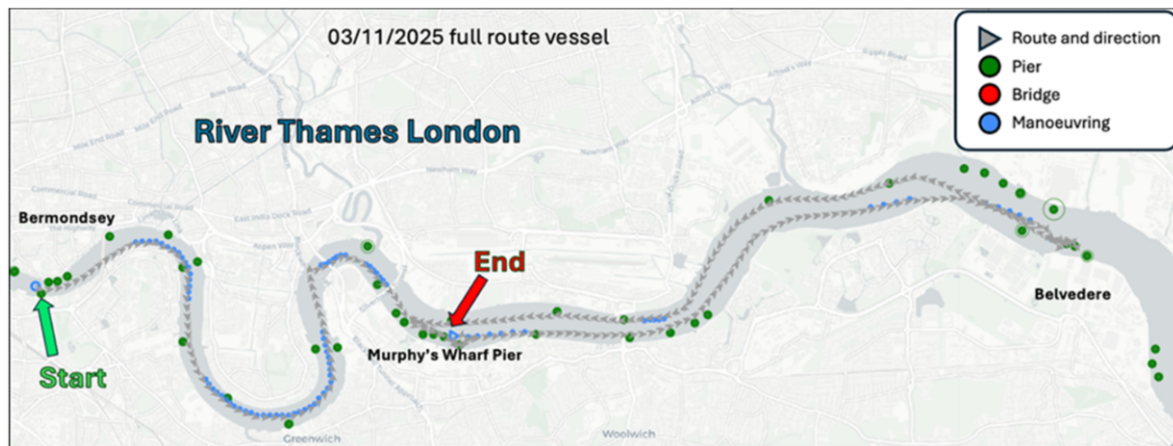


Figure 6. Study area showing the section of the River Thames analysed in this study and the AIS-derived vessel trajectory between Bermondsey (Start) and Belvedere, with Murphy's Wharf pier being the end of the trip.

The study area used for the analysis is illustrated in Figure 6, which shows the analysed section of the Thames together with the reconstructed vessel trajectory derived from AIS observations.

4.2. Vessel Dataset

The detailed case study is based on a single IWV operating within the section of the River Thames described in Section 4.1. The identity of the vessel has been anonymised. AIS observations were collected as timestamped geographic coordinates, providing a time-resolved record of the vessel's movement along the river corridor. The data collection approach used in this study records vessel positions at intervals typically between 25 and 35 s, producing a relatively high-resolution trajectory of the vessel's movement along the river.

The portion of the voyage analysed in this study begins when AIS observations are first recorded near Bermondsey. The vessel subsequently travels downriver to Murphy's Wharf Pier, where operational activity takes place. The vessel then continues further downriver to Belvedere before returning upriver and completing the analysed segment near Murphy's Wharf Pier, South Greenwich, where the AIS record used in this study ends. The resulting trajectory, therefore, includes both upstream and downstream movement relative to the tidal current, as well as periods of variable vessel speed and manoeuvring behaviour. These conditions provide a suitable operational profile for evaluating the relationship between ground-referenced motion and the estimated STW.

4.3. Environmental Current Data

To apply the STW estimation framework described in Section 3, including the vector-based relationship between vessel motion and environmental current, the current conditions encountered along the analysed route must be represented. For each validation voyage, the environmental current field was reconstructed using tidal information corresponding to the same date, time and river reach as the associated AIS trajectory and Doppler STW measurements.

Each AIS observation along the trajectory is associated with a corresponding current vector derived from this dataset. The spatial location of the AIS point is first matched to the nearest current reference location within the river corridor. The AIS timestamp is then used to determine the corresponding point within the current time series. Current magnitude and direction are subsequently interpolated between the surrounding time points to estimate the current conditions at the exact AIS observation time.

The process assigns a time-resolved current vector to each AIS observation, allowing the environmental flow field encountered by the vessel to be represented along the trajectory. Because AIS observations in the dataset are recorded at intervals, the resulting current assignment provides a relatively high temporal resolution representation of the tidal conditions experienced during the voyage.

The tidal current conditions encountered by the vessel along the analysed trajectory are illustrated in Figure 7, where the vessel track is coloured according to the interpolated current magnitude assigned to each AIS observation, while directional indication arrows show the corresponding flow direction. Together, this data provides a spatially and temporally resolved representation of the environmental flow experienced by the vessel throughout the analysed voyage and illustrates the variability in current strength and direction along the route.

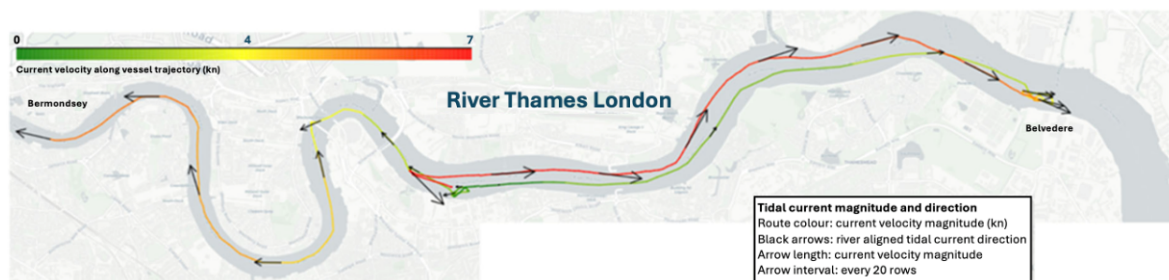


Figure 7. Vessel trajectory for the analysed voyage on the River Thames between Bermondsey and Belvedere. The trajectory is coloured according to the interpolated current magnitude assigned to each AIS observation following spatial matching and temporal alignment of the derived current field. The black arrows indicate the direction of tidal flow, while the trajectory colouring represents the interpolated current velocity magnitude.

4.4. Integration of Vessel Motion and Environmental Current

To estimate STW, geometry-derived SOG is combined with the environmental current conditions described in Section 4.3. The environmental current field provides a time-resolved representation of the water-mass velocity encountered by the vessel along the trajectory. As a first-order representation, the dominant current direction is assumed to follow the local orientation of the river centreline at each vessel position. This allows the current to be expressed as a velocity vector aligned with the navigable channel while avoiding the need for a fully resolved hydrodynamic model of the river. The approach does not resolve local cross-channel currents around bends, piers, channel constrictions or bathymetric features. These effects are therefore outside the present model boundary.

The interaction between vessel motion and environmental current is evaluated using the vector projection approach described in Section 3.4. The relative alignment between the vessel's direction of travel and the current direction determines whether the current contributes to or opposes the observed SOG, allowing the effective vessel velocity relative to the surrounding water to be obtained for each observation along the trajectory.

4.5. Validation Approach

To evaluate the accuracy of the proposed STW reconstruction method, STW estimates are compared with independent measurements obtained from onboard Doppler instrumentation. For the detailed case study, the Doppler dataset provides time-resolved STW measurements for the same vessel and voyage, enabling direct comparison between measured and estimated vessel behaviour throughout the analysed voyage. The same validation procedure is subsequently applied to the additional representative vessel datasets presented in Section 5.5.

AIS-derived vessel positions and timestamps are aligned with the corresponding Doppler measurements to produce a time-resolved comparison dataset. Observations with missing or unreliable Doppler values are excluded from the analysis. Model performance is assessed using standard statistical metrics, including mean bias, mean absolute error (MAE), root mean square error (RMSE), and correlation coefficient. These metrics quantify both systematic and random deviations between reconstructed and measured STW. Uncertainty in the reconstruction arises primarily from AIS positional resolution, temporal sampling intervals, and the representation of environmental current conditions. To assess the sensitivity of the reconstructed STW to current uncertainty, a dynamic uncertainty envelope is applied based on variation in the estimated along-track current component, as described in Section 5.

Validation performance is assessed using both graphical and statistical measures. Time-series comparison is used to evaluate the ability of the estimated STW to reproduce the temporal behaviour of the measured data, while the statistical metrics described above are used to quantify overall agreement. Agreement between estimated and measured STW is further assessed using Bland–Altman analysis [34], which provides an assessment of bias and limits of agreement across the vessel operating range.

The validation undertaken in this study applies to the final estimated STW output rather than to each environmental input independently. The environmental current field is an intermediate component within the estimation process and was not separately validated against the continuous measured current data or a two-dimensional hydrodynamic model. Instead, the combined methodology is evaluated by comparing its resulting STW estimates with independent onboard Doppler measurements across the analysed vessel cases.

5. Results

5.1. Raw SOG Behaviour

The geometry-derived SOG obtained from the AIS trajectory provides a direct representation of the vessel's ground-referenced motion during the analysed voyage.

The observed SOG varies throughout the voyage in response to navigational and operational conditions. Periods of relatively steady speed correspond to sections where the vessel is transiting along the river channel, while variations occur where the vessel adjusts its operation in response to traffic conditions, river geometry, or operational activity at intermediate locations. As shown in Figure 8, the SOG profile exhibits a combination of steady transit segments and periods of variable speeds, reflecting the changing operational conditions encountered along the route.

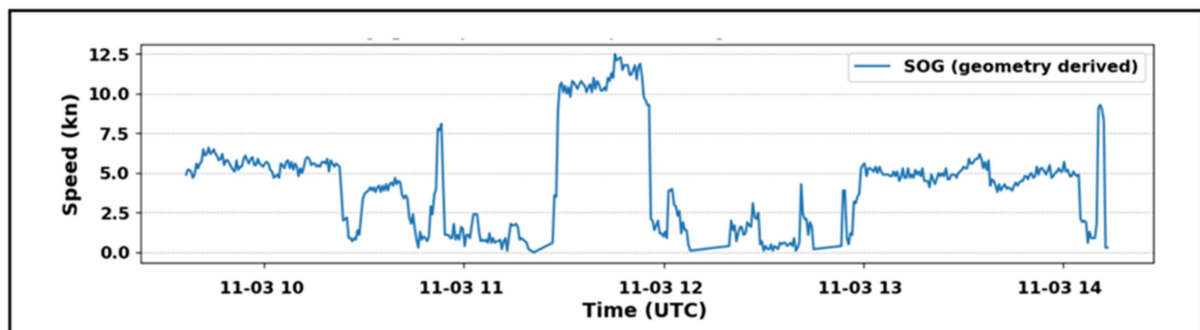


Figure 8. Geometry-derived SOG profile showing vessel ground-referenced speed variation over the analysed voyage.

The resulting SOG profile captures the overall operational structure of the voyage, including downstream and upstream transits, together with periods of reduced or vari-

able speed. This ground-referenced behaviour provides the baseline against which the reconstructed STW profile presented in Section 5.2 can be interpreted.

5.2. Estimated Speed Through Water Profile

The application of the method described in Section 4 produces a time-resolved profile of estimated STW along the analysed voyage. This estimation can be compared directly with the observed SOG to examine how environmental current conditions influence the vessel's effective motion through the water.

Figure 9 illustrates the vessel behaviour for the analysed voyage. The upper panel compares the geometry-derived SOG with the estimated STW. Differences between the two profiles occur where tidal currents either assist or oppose the vessel's motion along the river corridor.

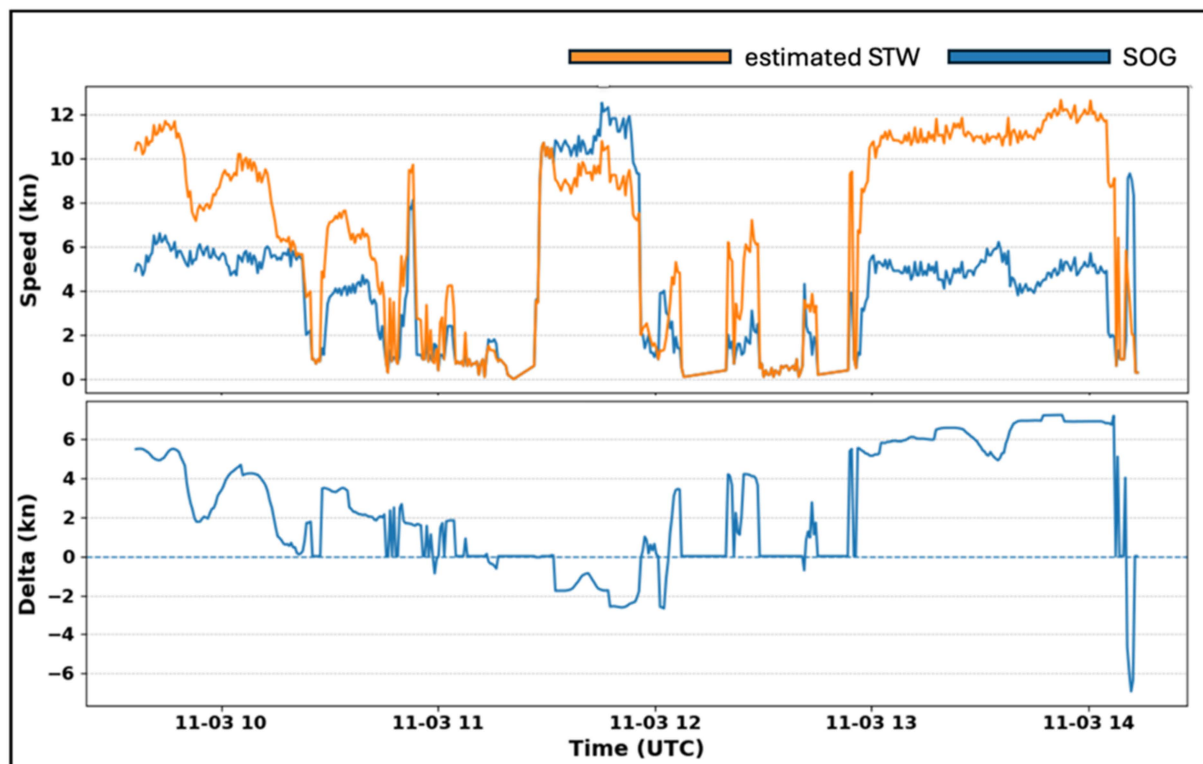


Figure 9. Comparison between geometry-derived SOG and inferred STW along the analysed voyage. The (**upper panel**) shows the observed SOG and the estimated STW time series. The (**lower panel**) shows the difference between these quantities (STW – SOG).

Periods where estimated STW exceeds SOG correspond to conditions where the vessel is travelling against the prevailing current, while periods where estimated STW is lower than SOG indicate that the vessel is moving with a favourable current.

The lower panel of Figure 9 shows the difference between these two quantities (estimated STW – SOG), which represents the magnitude and direction of the current influence acting along the vessel trajectory. Positive values indicate sections of the voyage where the vessel is operating against an opposing current, requiring a higher through-water velocity to maintain the observed SOG, while negative values indicate sections where the tidal flow contributes to the vessel's motion, reducing the required through-water velocity.

The distinction between SOG and STW has important implications for vessel energy demand. Periods where STW exceeds SOG indicate that the vessel must generate additional propulsion power to overcome opposing currents, whereas periods where STW is lower than SOG reflect conditions where tidal flow contributes to vessel motion. Although

propulsion power is not evaluated directly within this study, the observed difference between SOG and STW demonstrates that environmental current effects have the potential to influence vessel energy demand over a duty cycle. The ability to reconstruct STW from publicly available data, therefore, provides an important foundation for future analyses of vessel energy demand and decarbonisation pathways.

5.3. Sensitivity to Current Variation

The estimated STW depends on the environmental current field used to represent the tidal conditions encountered along the analysed route. Although the current dataset provides a time-resolved estimate of tidal flow within the river corridor, some uncertainty is inevitably associated with the interpolation of current magnitude between reference locations and time points. Evaluating the sensitivity of the estimated STW to these uncertainties provides an indication of the robustness of the method when applied to sparse environmental datasets.

Figure 10 illustrates the sensitivity of the estimated STW profile to variation in the estimated along-track current component.

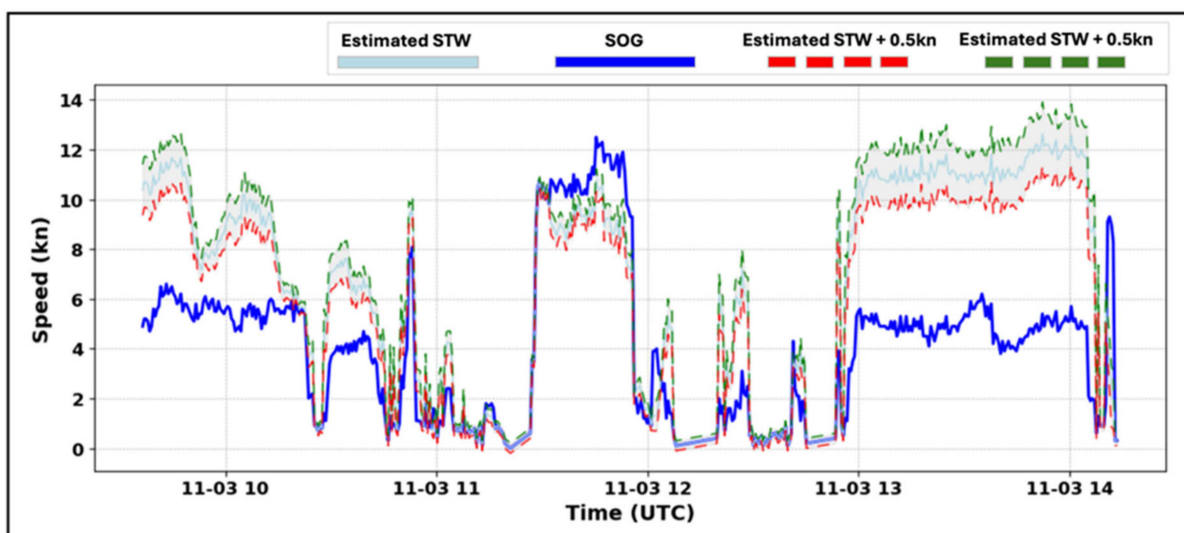


Figure 10. Sensitivity envelope for estimated vessel STW resulting from uncertainty in the estimated along-track tidal current, shown relative to the observed SOG.

The blue line shows the observed SOG, while the light blue line represents the estimated STW obtained using the baseline current dataset. The dashed green and red curves define the upper and lower sensitivity bounds, producing a dynamic envelope around the estimated STW profile.

Rather than assuming a constant variation in the current estimate, the sensitivity envelope is defined as a function of current magnitude. The envelope combines a baseline current variation of 0.2 knots with an additional proportional term of 15% of the along-track current component, such that:

$$\Delta V = 0.2 + 0.15|V_{\text{current}}| \quad (9)$$

where V_{current} represents the resolved along-track current component.

The baseline variation of 0.2 knots is based on observed variability in the reconstructed current field during model development, reflecting fluctuations introduced by spatial interpolation between reference locations and the temporal resolution of the tidal data. The additional proportional term accounts for the greater variation expected under stronger

tidal currents, where spatial gradients and temporal variability in tidal flow become more pronounced.

This formulation is not intended to represent a calibrated error model, but rather to provide a physically informed range of plausible current conditions. The purpose is to assess the robustness of the estimated STW to reasonable variations in the environmental current input, rather than to quantify the exact uncertainty of the current field. It therefore represents a practical robustness assessment of how the estimated STW responds to plausible variations in the reconstructed environmental current field, rather than a formal uncertainty model or error propagation analysis.

The resulting envelope represents a range of estimated STW values for the analysed voyage. Across much of the trajectory, the estimated STW remains relatively stable despite variation in the reconstructed current field, indicating that the inferred vessel behaviour is not dominated by moderate changes in the environmental input. Larger divergence between SOG and estimated STW occurs in sections of the route where tidal currents exert a stronger influence on vessel motion, highlighting locations where accurate representation of current conditions becomes more important for estimating vessel performance.

5.4. Comparison Against Vessel Speed Through Water

To evaluate the accuracy of the results, the estimated STW series was compared with independent measured STW data obtained from onboard Doppler instrumentation for the same voyage. This comparison provides an empirical assessment of how closely the estimation methodology reproduces the vessel's motion relative to the surrounding water.

Figure 11 compares the estimated STW time series with the onboard Doppler STW measurement data. The two profiles show close agreement throughout the voyage, with the estimation capturing both the magnitude and temporal variation of the measured values. The correspondence between the two series is maintained across the full operational range of the vessel, including both high-speed transit segments and lower-speed manoeuvring periods.

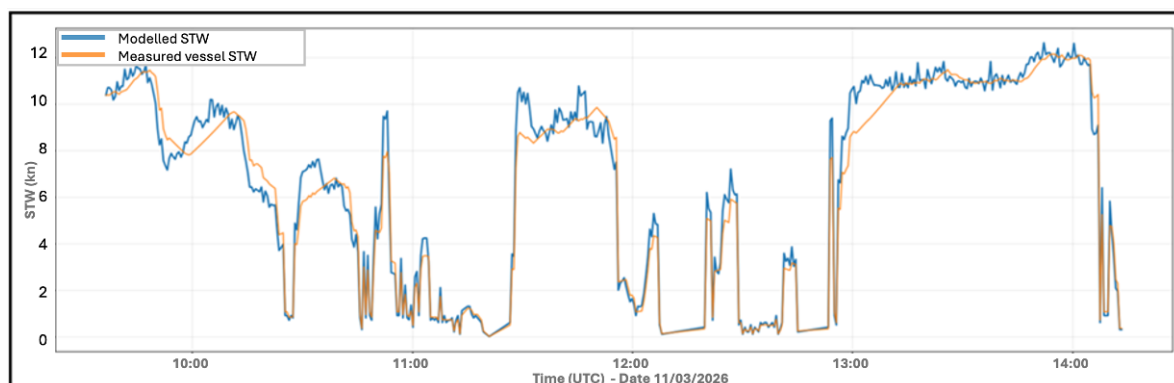


Figure 11. Comparison between model-estimated STW and onboard Doppler measurement data over the analysed voyage.

Figure 12 shows the difference between the estimated STW and onboard Doppler-measured STW throughout the analysed voyage. The error fluctuates throughout the operational segment, with no evidence of sustained drift over time, indicating that the estimate remains stable across the duration of the voyage. In absolute terms for this specific vessel, the deviation is typically within approximately ± 0.5 kn, with peak differences approaching approximately 1.8 kn. When expressed as a percentage of the maximum observed STW, these deviations correspond to peak values of -16.33% and $+13.23\%$, reflecting the normalisation applied rather than a change in underlying model behaviour.

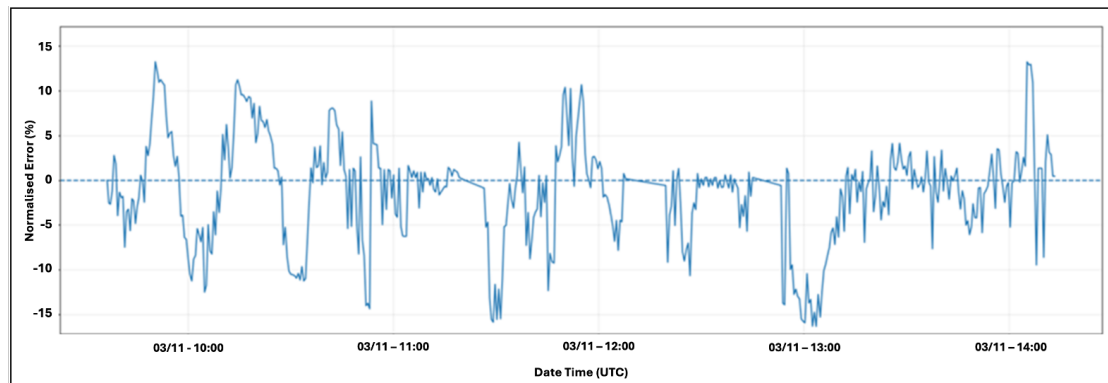


Figure 12. Time-resolved STW estimation error normalised against the maximum observed Doppler-derived STW for the analysed voyage.

The variation in error is not strongly correlated with vessel speed, and deviations occur across the full operational range. Periods of more stable error are generally associated with sustained operating conditions, where vessel speed and heading remain relatively constant, while increased variability occurs during transitions between operating states. Despite this variability, the error remains bounded and does not accumulate over time, indicating that the estimation method maintains consistent performance throughout the analysed trajectory.

Agreement between estimated and measured STW values is further examined using the Bland–Altman analysis shown in Figure 13 [34].

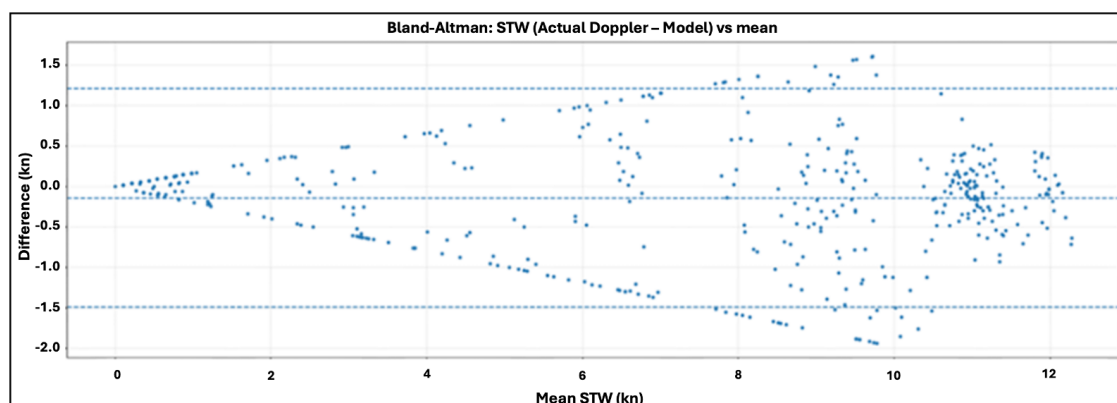


Figure 13. Bland–Altman comparison between Doppler-derived and model-estimated STW values, showing the difference between the two data sets as a function of their mean. The dashed lines indicate the limits of agreement.

Approximately 92.06% of observations lie within the limits of agreement, with no strong systematic trend observed across the vessel’s operating range. Examination of the observations lying outside the limits of agreement did not identify any consistent association with manoeuvring, low-speed operation, or periods of high tidal current. Instead, these observations occurred across a range of operating conditions, suggesting that the larger deviations are more likely to arise from the combined influence of multiple factors, including local environmental variability and the inherent limitations of reconstructing STW from sparse publicly available data. Overall, the results indicate that the estimation maintains consistent accuracy across the analysed operating range.

Because the tidal current direction changes throughout the analysed voyage (see Figure 6), the vessel experiences both assisting and opposing flow conditions. Figure 14 examines the error in the STW estimate as a function of the along-track current component

encountered by the vessel. Positive values correspond to favourable current acting in the direction of vessel travel, while negative values represent opposing current conditions.

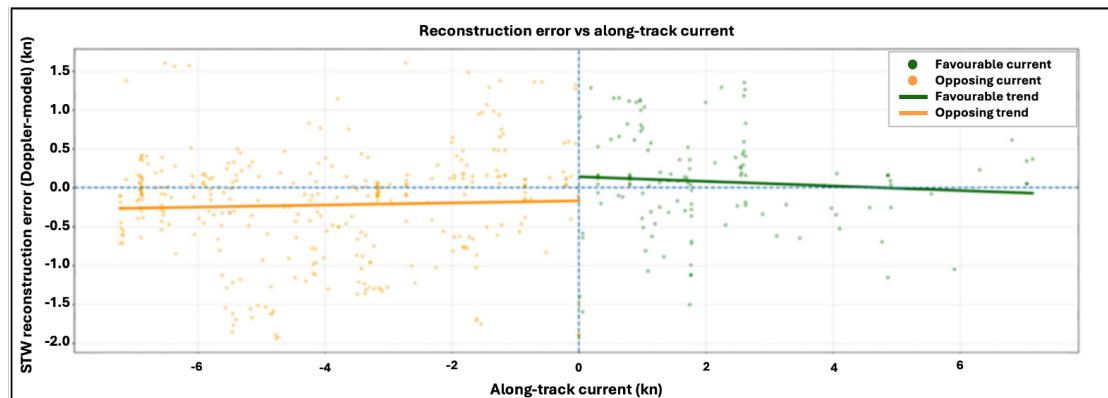


Figure 14. STW error plotted against the along-track tidal current component, illustrating model behaviour under favourable and opposing flow conditions.

The distribution of STW errors remains centred close to zero across both current regimes. Separate linear trend lines fitted to the favourable and opposing current observations show only a weak dependence of the error on current magnitude. These trend lines are included as visual guides to illustrate the overall direction of the relationship and are not intended to represent a formal statistical significance test. The results indicate that the estimated STW method performs consistently under both assisting and opposing tidal flow conditions, with no strong directional bias evident in the error behaviour. This is consistent with the Bland-Altman analysis, which showed that the observations lying outside the limits of agreement did not exhibit any consistent association with manoeuvring, low-speed operation, or periods of high tidal current.

Across 466 observations, the validation produced a mean error (bias) of -0.38% and a mean absolute error of 9.86% , with the mean estimated STW of 5.16 knots. The root mean square error is 0.70 knots, with a correlation coefficient of 0.985 between estimated and measured STW.

5.5. Validation Across Additional Vessel Types

Although the detailed validation presented above focuses on a single representative vessel and voyage, additional validation was undertaken using representative vessel datasets to examine whether the proposed methodology performs consistently across different vessel types and operating conditions within the tidal Thames (Figures 15–18). These cases comprise four representative vessel types operating within the Chelsea–North Woolwich reach on three separate dates and across different stages of the tidal cycle. Their temporal and tidal context is summarised in Table 2.

Table 2. Summary validation statistics for the four representative vessel types shown in Figures 15–18, operating within the tidal River Thames under different operating and tidal conditions.

Vessel	Vessel Type	Samples	Mean Bias (%)	MAE (%)	RMSE (kn)	Correlation Coefficient (r)
1	Workboat	418	-3.66	10.29	0.984	0.962
2	Fast Ferry	681	-1.51	8.67	1.141	0.994
3	Tug	661	-1.96	9.55	0.874	0.982
4	Sightseeing	368	-0.57	7.82	0.629	0.991

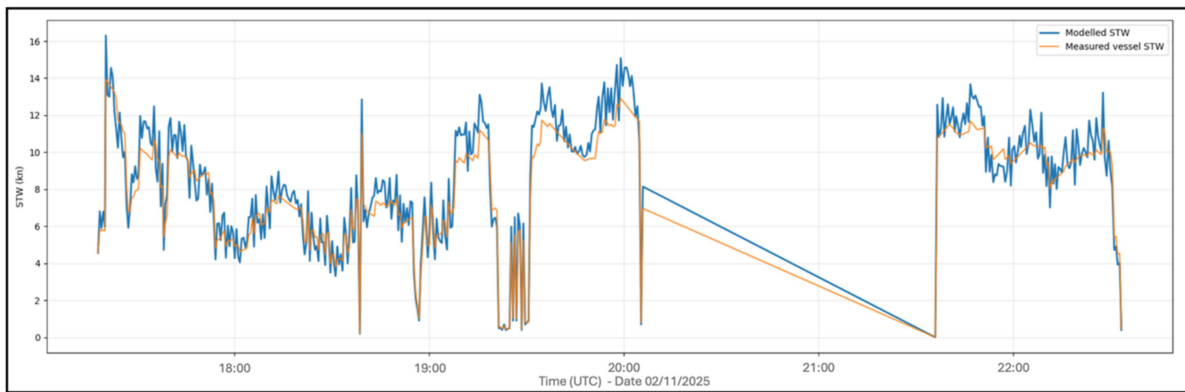


Figure 15. Comparison of estimated STW and onboard measured data for a workboat operating on the tidal River Thames under varying tidal conditions.

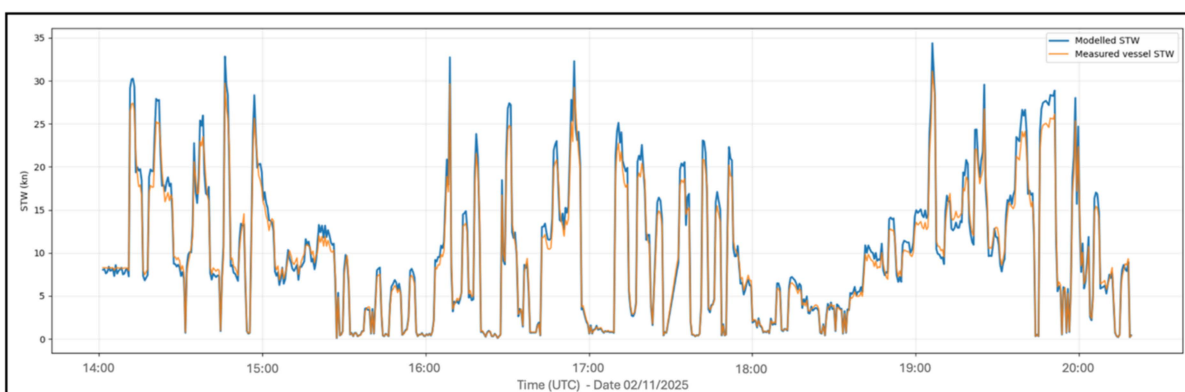


Figure 16. Comparison of estimated STW and onboard measured data for a fast ferry operating on the tidal River Thames under varying tidal conditions.

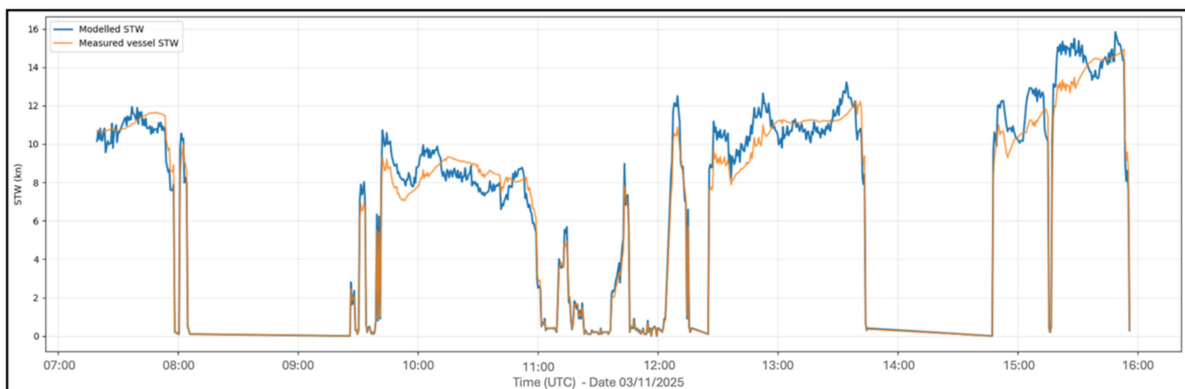


Figure 17. Comparison of estimated STW and onboard measured data for a pushing tug operating on the tidal River Thames under varying tidal conditions.

Table 3 shows that the four validation cases cover three separate dates, different river reaches and multiple stages of the tidal cycle. The Workboat voyage began during the late flood, passed through high-water slack and continued into the early ebb. The Fast Ferry voyage covered the flood phase, high-water slack and the beginning of the ebb. The Tug voyage began around high-water slack, continued through the main ebb phase and low water, and extended into the initial flood. The Sightseeing voyage began around the low-water transition and continued through the developing flood phase. Across these cases, tidal ranges varied from approximately 3.9 to 5.3 m. The validation, therefore, covers multiple vessel types, dates, river reaches and tidal phases under relatively energetic

spring-period conditions. However, a separate neap-tide case was not available, and the results should therefore be interpreted as evidence of repeatability within the tidal Thames rather than comprehensive validation across the full spring–neap cycle.

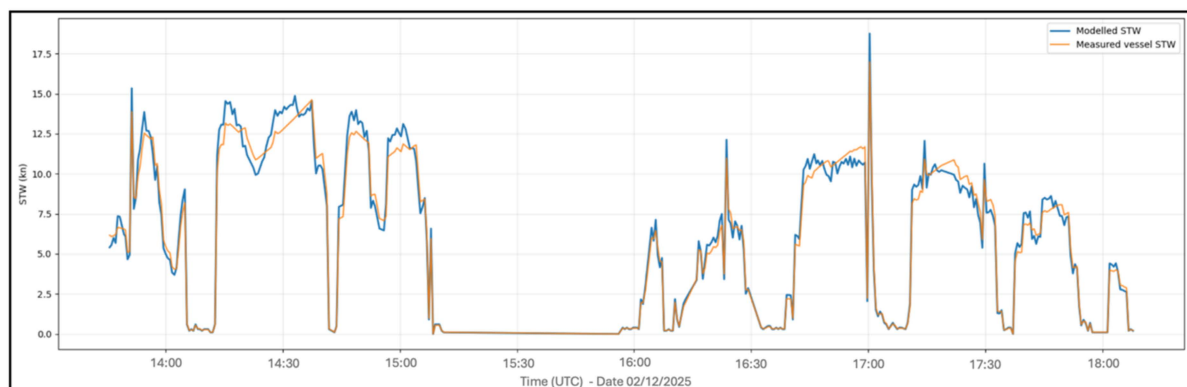


Figure 18. Comparison of estimated STW and onboard measured data for a sightseeing vessel operating on the tidal River Thames under varying tidal conditions.

Table 3. Temporal and tidal context for the four representative validation cases shown in Figures 15–18. Tidal ranges indicate the approximate variation across each river reach, based on successive high- and low-water levels at the relevant upstream and downstream reference locations. All cases occurred during high-range spring-period tidal conditions.

Vessel	Date	Time Band (App)	River Reach	Tidal Range (m)	Tidal Class
1	2 November 2025	17:30–22:45	Richmond–London Bridge	3.9–5.0	High-range, Spring
2	2 November 2025	14:00–20:30	Chelsea–North Woolwich	4.8–5.0	High-range, Spring
3	3 November 2025	07:30–16:00	Richmond–Tilbury	4.0–4.8	High-range, Spring
4	2 December 2025	13:30–18:30	Chelsea–London Bridge	5.1–5.3	High-range, Spring

The additional validation cases demonstrate that the proposed methodology maintains good agreement with measured STW across multiple representative vessel types. Although differences in vessel characteristics, operating profiles and tidal conditions introduce some variation in statistical performance, the results remain consistent with those observed for the detailed case study. This provides additional confidence that the methodology is repeatable across a range of representative operating conditions within the tidal Thames, while recognising that wider validation across additional waterways and vessel classes remains an area for future work.

6. Discussion

The results presented in Section 5 demonstrate that vessel STW can be estimated with strong agreement to measured values using sparse AIS position data combined with environmental current information across multiple representative vessel types operating within the tidal River Thames. While these results demonstrate the practical feasibility of the approach, it is important to consider its limitations and the contexts in which the method can be applied reliably. This section, therefore, discusses the principal sources of uncertainty in the estimation process, the applicability of the method to IWW environments, and the broader implications for analysing vessel energy demand and operational behaviour.

6.1. Accuracy Limitations

The estimation of STW from AIS-derived SOG involves several sources of uncertainty. The most significant contributors arise from the temporal resolution of AIS position updates, the representation of environmental current conditions, and the assumptions required to interpret vessel motion between successive observations.

AIS messages typically provide position updates at intervals ranging from a few seconds to several minutes, depending on vessel class, operational state and the characteristics of the AIS provider. When reconstructing vessel motion from these observations, the resulting geometry-derived SOG represents an average ground-referenced velocity between successive observations rather than an instantaneous measurement. Consequently, rapid manoeuvring, acceleration, and deceleration occurring within a single AIS interval cannot always be resolved. In addition, positional accuracy and the AIS sampling interval influence the reconstructed vessel trajectory and, consequently, the estimated STW. A formal sensitivity analysis examining the effects of AIS sampling interval, positional accuracy, and trajectory reconstruction was beyond the scope of the present study but represents an important area for future research. These factors contribute to the short-duration discrepancies observed in the time-resolved error behaviour shown in Figure 9.

A further source of uncertainty arises from the environmental current field used to represent tidal flow conditions along the analysed route. The reconstructed current field is a physically informed proxy derived from tidal elevation data and representative current velocities reported in the literature, rather than a directly measured or fully validated hydrodynamic model. Current direction is represented using the local river centreline, and the model does not resolve local cross-channel flow, shallow water or bathymetric effects, bank interactions, turbulence around bends and fixed infrastructure, vessel-to-vessel interaction, or wind-induced leeways. These factors may contribute to local differences between estimated and measured STW, particularly during manoeuvring or where environmental conditions vary over short distances. The analysis presented in Figure 10 demonstrates that the estimated STW remains relatively well constrained under plausible variations in the reconstructed current field. Future work should compare reconstructed environmental inputs with continuous current measurements or suitable two-dimensional hydrodynamic model outputs when such datasets become available.

It is also important to recognise that the Doppler-derived STW measurements used for validation are themselves subject to measurement uncertainty. Doppler speed logs measure the vessel's motion relative to the surrounding water mass using acoustic signals reflected from suspended particles in the water column. Variations in water turbidity, vessel motion, and acoustic scattering conditions can therefore introduce small fluctuations in the measured values. As a result, the observed differences between estimated and measured STW reflect the combined uncertainty of both the estimation process and the reference measurement.

Taken together, these factors indicate that the STW error observed in Section 5 reflects the combined uncertainties associated with AIS-derived motion estimation, environmental current representation, and reference measurement accuracy rather than a purely methodological limitation of the framework.

6.2. Applicability to Inland Waterways

The approach presented in this study has been developed with a particular focus on IWT and environments, where vessel operations frequently occur within tidal rivers, canals, and confined waterways where environmental currents exert a significant influence on vessel motion. In such environments, the distinction between SOG and STW becomes particularly important for understanding vessel performance and energy consumption.

Tidal currents can substantially assist or oppose vessel motion depending on the direction of travel and the stage of the tidal cycle. As illustrated in Figure 9, these effects can produce considerable differences between observed SOG and estimated STW during a single voyage. Without separating these effects, it is difficult to interpret the true propulsion energy demand experienced by the vessel.

This approach provides a practical means of estimating vessel motion relative to the surrounding water using datasets that are widely available across IWW systems. Basic AIS position data is routinely collected for navigational monitoring and traffic management, while environmental current information is available through tidal predictions or observational datasets. By combining these information sources, the method enables estimation of vessel STW even where direct onboard measurements are unavailable.

Although the validation presented in this study is confined to representative vessel types operating within the tidal River Thames, the methodology demonstrated repeatable performance across multiple vessel classes and operating conditions. The underlying framework is therefore not limited to a single vessel type or operational profile. Application to other IWW requires only that an estimate of the environmental current acting along the vessel trajectory can be obtained. For tidal waterways, this may be derived from tidal prediction data, while non-tidal rivers and canals would require representative flow information appropriate to the local hydrodynamic conditions. Wider validation across additional waterways remains an area for future research.

The underlying estimation framework remains unchanged across these environments because it relies on resolving vessel motion relative to the surrounding water rather than any specific hydrodynamic setting. The principal adaptation is therefore the source used to characterise the environmental flow field. In non-tidal rivers, representative river discharge or flow measurements would provide the corresponding environmental input. In canal systems, where flow velocities are generally lower and may be influenced by lock operations or controlled water management, appropriate operational flow information would be required where such effects are significant. In each case, the methodology assumes that a representative estimate of the along-track environmental flow acting on the vessel can be obtained. Once this information is available, the remaining stages of the framework are unchanged.

The use of AIS trajectory data combined with derived current information, therefore, provides a practical foundation for analysing vessel operations across IWW systems at scale. In particular, separating vessel motion from environmental current effects enables a more realistic interpretation of the hydrodynamic conditions experienced by vessels during real-world voyages, providing the physical basis for subsequent propulsion power and energy demand estimation.

6.3. Implications for Energy Demand Estimation and Infrastructure Planning

Separating vessel motion from environmental current effects has important implications beyond the direct analysis of vessel movement. While propulsion energy estimation provides an important motivation for this work, developing and validating an energy-demand model is beyond the scope of the present study. Instead, the objective has been to demonstrate that vessel STW can be estimated reliably from sparse publicly available data. Because hydrodynamic resistance depends on vessel speed relative to the surrounding water rather than SOG, the estimated STW provides the physical input required for subsequent propulsion power, energy, fuel, and emissions calculations.

Propulsion energy demand depends on the hydrodynamic conditions experienced by the vessel during operation. When significant environmental currents are present, analyses based solely on AIS-derived SOG may misrepresent the propulsion effort required

to complete a voyage. By separating the effects of vessel motion and environmental flow, the framework presented in this study provides a means of estimating vessel operating conditions that are more closely aligned with the physical processes governing propulsion energy demand.

This capability becomes particularly important in the context of the transition toward zero-emission IWT. Many existing IWW operate using high energy density fuels such as diesel and have been designed around the storage and operational characteristics of these fuels. In retrofit scenarios, which are expected to dominate the early phases of decarbonisation in IWT, vessels may not be able to carry equivalent amounts of alternative energy carriers such as batteries, hydrogen, or other lower energy density fuels without significant changes to vessel configuration or operational practices [35].

As a consequence, future zero-emission vessel operations may require more frequent energy replenishment along operating routes. Understanding when, where, and how much energy vessels require therefore becomes a critical component of planning the energy infrastructure needed to support the transition to alternative propulsion systems. However, obtaining detailed operational data directly from vessel operators is often difficult due to commercial sensitivities and the limited availability of onboard performance measurements.

The approach presented in this study provides a practical pathway to overcome this limitation. Because AIS trajectory data and derived current information are widely available across many IWW, the method enables retrospective analysis of vessel operations using existing datasets. By estimating vessel STW along historical trajectories, it becomes possible to estimate the propulsion energy demand associated with real operational voyages without requiring direct access to vessel instrumentation data.

These reconstructed operating profiles may then be combined with vessel-specific power or resistance models to estimate the energy demand associated with historical vessel movements. In turn, this information can support the development of regional energy demand profiles for IWT systems. Such profiles could provide a foundation for evaluating how alternative energy carriers might be deployed across IWW and for identifying locations where energy provision infrastructure may be required to support future zero-emission vessel operations.

This study establishes the physical basis required for subsequent propulsion power and energy-demand estimation using publicly available operational datasets. Wider validation across additional waterways and operational environments would further strengthen the general applicability of the methodology.

7. Conclusions

This paper has presented a method to estimate STW from sparse AIS position data combined with derived current information. The approach enables estimation of vessel motion relative to the surrounding water using datasets that are widely available across IWW systems, addressing the challenge that direct onboard measurements of STW are rarely accessible for research or operational analysis.

Validation against independently measured Doppler-derived STW demonstrated strong agreement between estimated and measured vessel behaviour across multiple representative vessel types operating within the tidal River Thames. While detailed validation was presented for a single representative vessel, additional validation across workboat, fast ferry, tug and sightseeing vessel operations demonstrated similarly strong agreement. The environmental current field used within the methodology represents a physically informed proxy derived from tidal information and published representative current velocities rather than a directly validated hydrodynamic model. Nevertheless, the close agreement between estimated and measured STW demonstrates that the reconstructed current field is suffi-

ciently representative for STW estimation across the analysed vessel cases within the study area, despite the simplified representation of local environmental conditions.

The ability to estimate vessel motion relative to the surrounding water has important implications for the analysis of IWW operations. In environments where tidal or river currents exert a significant influence on vessel motion, analyses based solely on SOG may misrepresent the propulsion conditions experienced by vessels. Separating vessel motion from environmental flow effects, therefore, enables a more realistic interpretation of operational behaviour and propulsion demand.

More broadly, the framework provides a practical pathway for analysing vessel operations using publicly available datasets. The methodology established in this study provides the physical basis required to estimate vessel motion relative to the surrounding water. When combined with vessel power or resistance models, the estimated STW provides the physical input required for subsequent propulsion power and energy demand estimation from historical vessel movements. Such analysis may contribute to improved understanding of energy demand patterns within IWT systems and support the development of infrastructure required to enable the transition toward zero-emission vessel operations.

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Abbreviations

The following abbreviations are used in this manuscript:

AIS	Automatic Identification System
COG	Course Over Ground
IWT	Inland Waterway Transport (Transportation)
IWW	Inland Waterway Vessel
IWW	Inland Waterway
MAE	Mean Absolute Error
PLA	Port of London Authority
RMSE	Root Mean Square Error
SOG	Speed over Ground
STW	Speed through Water

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