A practical framework to assess the hydrodynamic impact of ship waves on river banks

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Abstract
The temporal alteration of the hydrodynamic regime in rivers due to navigation has significant effects on riverine ecosystems. Most of the key mechanisms and interactions between hydrodynamic and ecological variables have already been revealed; however, the quantitative evaluation of biotic and abiotic variables still stands a challenge. This paper aims to present a thorough, spatiotemporal framework, involving field and computational tools, for the assessment of wave hydrodynamics in the littoral zone of rivers, where its ecological relevance is the most significant. The temporal variation of significant wave heights is derived from high-frequency pressure measurements, offering a well-comparable statistical evaluation of individual wave events considering the duration of different wave intensities. Acoustic Doppler velocimetry (ADV) is used for the assessment of near-bank velocities, from which the secondary wave-related components have been filtered offering relevant validation data for numerical modelling. The small footprint of the ADVs is extended with up-to-date computational fluid dynamics modelling. Wave spectra derived from the pressure measurements are used as boundary conditions for phase-resolved irregular wave modelling with the level set method based numerical model REEF3D. The properly validated model offers the assessment of the most relevant hydrodynamic variables (e.g., velocity or turbulent kinetic energy) in a spatially extended manner, from which the hydrodynamic footprint of the wave events can be interpreted in a statistical fashion. The implementation of the proposed framework is illustrated through a case study at a Hungarian section of the Danube River.

KEYWORDS
ADV, CFD, field measurements, navigation, ship waves, wave modelling

1 INTRODUCTION

Though inland navigation is usually considered the most sustainable and eco-friendly mode of transportation due to relatively low fuel consumption, thus CO₂ emissions (Lambert, 2010), its potential negative effects are not to be neglected. The available knowledge concerning these effects is increasing and provides research topics for a wide range of scientific disciplines. Direct contact with ship hulls and/or propellers may cause mechanical damage to aquatic animals (Bulté, Carriere, & Blouin-Demers, 2010), whereas oil and fuel discharges
have unfavourable effect on water quality (Jackivicz & Kuzmins, 1973). Canals built for navigational purposes often remove biogeographical boundaries, which can lead to the degradation of biodiversity through the spreading of non-native, invasive species (Sala, Chapin, Armesto, et al., 2000). River trainings performed in order to ensure the required widths and depths in navigational routes usually entail significant alterations in river morphology, whereas locks, in absence of fish ladders, are unsurmountable obstacles for migratory fish species. Navigation also affects many biotic and abiotic variables through the temporal alteration of the local hydraulic regime, that is, generation of ship-induced waves and currents. A thorough review on the effects of ship-induced waves on aquatic ecosystems was given by Gabel, Lorenz, and Stoll (2017), who have summarized the effects of ship-induced waves on the structure, function, and services of aquatic ecosystems.

In contrast with relatively slowly developing wind-induced wave events in lakes or even rivers, ship waves can increase current velocities by an order of magnitude within seconds (Rapalgia, Zaggia, Palm, Lorenzetti, & Vafeidis, 2004). These increased velocities, especially in the close proximity of the river bed, may have serious effects on the aquatic ecosystem at multiple hierarchical levels (Gabel, Lorenz, & Stoll, 2017). Furthermore, passing ships usually result in the notable drawdown of the water level, entailing considerable habitat losses as the shoreline runs dry (Liedermann, Tritthart, & Gmeiner, 2014), for which riverine (except for estuarine) communities are not adapted.

As ship waves reach the shallower areas, the related hydrodynamic stresses affect the near-bed boundary layer more and more, and bed shear stress increases gradually, leading to the resuspension of fine sediments. The rates of these stresses are strongly correlated with wave characteristics such as the wave height and wave length, which are not only functions of ship-related parameters (e.g., travelling speed, distance from shore, draught, and shape) but also highly influenced by the local morphological characteristics of the main channel and the littoral zone as well. The connection between the near-bed turbulent stresses and the rate of sediment mobilization can be connected through sediment characteristics (grain size and cohesion), which, considering the previous findings, makes the whole phenomenon even more complex and site specific. In the case of rivers, the suspended sediment concentration only jumps for a short time period, that is, in the order of minutes, after a passing vessel (in contrast with particle settling times of hours) as the background current of the river sweeps these suspended plumes downstream (Bauer, Lorang, & Sher- man, 2002), which can significantly contribute to the annual sediment yield of rivers.

Wave-induced turbidity also affects fish, especially visually oriented species (Utne-Palm, 2004). Moderate level of turbidity is beneficial for predators as the contrast between water and prey is better compared with clear water conditions, whereas on the contrary, high levels of turbidity can decrease foraging effectiveness (Kucera-Hirzinger et al., 2009).

Increased near-bed currents can detach benthic invertebrates from the substrate: Significant correlation has been found between the ratio of dislodged macroinvertebrates and wave-related bed shear stress (Gabel, Garcia, Schnauder, & Push, 2012). In addition, it has been pointed out that habitats with increased complexity provide better shelters against such stresses (Gabel et al., 2008).

Vessel-generated waves affect fish through different mechanisms in different life stages. The most direct and usually lethal situation occurs in the close proximity of the shore, where fish can get stranded due to wave load (Pearson & Skalski, 2010). The effect amplifies during night-time, when many fishes move to predation-sheltered areas for resting (Gaudin, 2001). Due to the quick drawdown of the water level, which is a navigational characteristic, fish eggs and larvae in the littoral zone can get dewatered, which can also lead to mortality (Holland, 1986). Similarly to benthic invertebrates, fish egg ribbons can also get detached from the substrate, eventually resulting in mortality as eggs get stranded or swept away by currents (Clady & Hutchinson, 1975). Kuzera-Hirzinger et al. (2009) highlighted that flow velocities increasing the maximum swimming capabilities of fish are problematic as fish can get displaced from their preferred habitats and washed downstream by river currents, which coincides with the findings of Schludermann et al. (2014) as the drift of larval fish increases with increasing wave heights. Consequently, swimming speeds exceeding the maximal wave-induced flow velocities are required to permanently live in navigational waters (Wolter & Aringhaus, 2003), which emphasizes the relevance of bays and tributaries (Arlinghaus, Engelhardt, Sukhodolov, & Wolter, 2002) as fish are able to detect hydrodynamic gradients, hence can relocate to calmer areas during wave events (Stoll & Beeck, 2012). These effects can further upscale to population and community level as well (Gabel, Lorenz, & Stoll, 2017).

Previous studies already have dealt with the hydrodynamic effects of ship-induced waves in the littoral zone of the Danube; moreover, quantitative relationships between biotic and abiotic features were assessed as well. Krouzecky, Fenton, Huber, and Klasz (2013) conducted high-frequency water level measurements in the area of the Donau-Auen National Park in Austria and highlighted the main characteristics of the most typical vessel types in the Danube (e.g., push tug with barges, passenger cruise boat, and fast passenger catamaran). Ecohydraulic investigations conducted by Liedermann et al. (2009) estimated the drift rate of fish larvae by exposing drift nets in the close proximity of the shore to collect specimens being swept into the current. Near-bank, shallow water habitats with inhomogeneous morphology and woody debris were found to provide safer conditions compared with more exposed areas with gravel bed, where drifting due to ship waves is more likely (Liedermann, Tritthart, & Gmeiner, 2014). The effects of different hydrologic conditions were also investigated, which is a sound first step towards a durability-based evaluation methodology. Results highlighted the importance of considerations regarding ship-induced waves in river restoration projects. Synchronized hydrodynamic (current, wave height, and wave frequency), fish drift, and abundance measurements were found to be suitable and necessary to assess correlations between biotic and abiotic features (Schludermann et al., 2014). Such integrated approaches play a key role in revealing these ecohydraulic interconnections in a quantitative
manner, ultimately leading to the development of a comprehensive methodology, which can truly support river engineering and restoration measures.

In addition to experimental studies, many have investigated the hydrodynamic aspects of vessel movement by means of up-to-date computational methods. David, Roeber, Goseberg, and Shlurmann (2017) validated a depth-averaged, phase-resolving Boussinesq-type model for the efficient numerical reproduction of wave events in the port of Hamburg. Ji, Ouahsine, Smaoui, and Sergent (2012) investigated the waves generated by passing convoys in a restricted waterway and reported that both primary and secondary wave patterns can be properly reproduced via Reynolds-averaged Navier–Stokes modelling; hence, the relationships between wave patterns and ship-related geometric and kinematic variables (e.g., width, draught, shape, and speed) can be assessed in such an effective way. Bellafiore et al. (2018) presented and validated an efficient, hybrid modelling methodology for the numerical simulation of vessel-generated waves in shallow water conditions. The model chain consisted of a detailed 3D CFD (computational fluid dynamics) solver calculating the hydrodynamics in the close proximity of the ship hull, and a shallow water model, responsible for the simulation of the horizontal propagation of the arising pressure perturbations.

Considering the above-mentioned biotic–abiotic interactions, it is clear that ship-induced waves have great significance regarding the quality of aquatic ecosystems; many biotic features are tightly connected to hydrodynamics. Although these connections are usually based on simpler hydraulic variables (e.g., maximal flow velocity or bed shear stress), it is noted that navigation results in both spatially and temporally complex hydrodynamic features, hence the characterization of the effects of ship waves, require a spatiotemporal approach. This study does not aim to investigate the kinematics of wave generation by ships, but to reveal the hydrodynamics characteristics of these waves in the littoral zone of the river Danube. A complex framework is presented for the assessment of ship waves by means of field measurements, data processing, and computational modelling. These tools offer high-resolution analysis of the resulting pressure and velocity conditions of these transient wave events. Field measurement data can be exploited to characterize the temporal variability of such wave trains, ultimately resulting in a statistical evaluation of wave characteristics. Computational models built up and verified based on adequate field data not only offer spatially extended analysis of the measured hydrodynamic conditions but can also be used for the analysis of different hydrological or morphological (i.e., river training) conditions as well.

Ship-induced wave trains can usually be decomposed into two major components on the frequency scale: primary waves of long periods and large wave lengths, superimposed onto secondary waves of short periods, and small wave lengths (Figure 1). Former can be realized as the slow back and forth motion of the shoreline. Although the direct hydrodynamic impact of these components is rather mild, their relevance from the ecological point of view is clear, as they entail temporal habitat losses (Liedermann, Tritthart, & Gmeiner, 2014) due to nearshore areas running dry as a function of the bank slope.

Secondary waves, on the other hand, have much shorter periods, whereas height-wise is usually in the same order of magnitude as the primary ones. Consequently, these waves carry much higher hydrodynamic energy; high velocities, erosion potential, and turbulence (especially in the surf zone, where wave breaking occurs) are typical. This study deals with the hydrodynamic characteristics of secondary waves exclusively and the relevant field and computational methodologies in particular.

2 | METHODS OF THE PROPOSED FRAMEWORK

In this section, a brief theoretical overview is given on the background of the applied measurement processing and modelling techniques. The analysis of measured pressure and velocity time series is presented, to show how they can contribute to the characterization of secondary waves. Pressure time series are used to reconstruct the movement of the free surface, which is further analysed with a transient, discrete Fourier transform-based methodology. In addition to offering a well-comparable footprint of the different ships, the measured pressure time series also provide boundary conditions for numerical modelling. An open-source, phase-resolving CFD model (REEF3D) is used to generate irregular waves based on measured spectra. After the separation of secondary wave-related velocities, the acoustic Doppler velocimetry (ADV) data are used for model verification purposes. With a verified computational model in hand, it is permissible to extrapolate wave hydrodynamics spatially. On Figure 2, a schematic figure of a
river bank is presented to give a spatial overview on the most important elements of the proposed methodology. Based on the findings of this study, the following recommendations are made:

- At least one pressure sensor is to be deployed in order to gather information about wave characteristics. The sensor should be fixed as close to the surface as possible (while being submerged at all times), so that the effect of the exponential pressure attenuation is minimal. The sensor should have a sampling frequency of min. 8 Hz, so that all relevant fluctuations can be captured and to provide enough data for a transient Fourier analysis. A pressure sensor is to be deployed farthest from the bank compared with other devices, so it can be used to derive boundary conditions for numerical modelling.

- Velocity probes are to be used in the near bank region, to assess the direct hydrodynamic impact of ship waves. The probes should operate at a sampling frequency so that wave-related velocity fluctuations as well as turbulence can be captured (min. 8-16 Hz). Probes sampling the bed boundary layer can be used to evaluate bed shear stress as well (Fleit et al., 2016). In addition to the direct information, velocity measurements provide good verification data for numerical modelling.

- The bank section of interest is to be evaluated from the morphological aspect as well. Such measurements (surveying and depth measurements) not only support the proper interpretation of the wave-related measurements but also provide bathymetry for the numerical model. Additional substrate sampling can be relevant from the ecological point of view and can offer roughness information for CFD modelling as well.

The flowchart presented in Figure 3 illustrates the main steps of data processing and numerical modelling, as well as the links between them. In the following subsections, the individual elements of this framework will be presented in detail.

2.1 Pressure analysis

High-frequency pressure measurements can be exploited for the estimation of local free surface excursions, from which relevant wave parameters can be derived. The exponential attenuation of pressure fluctuations with depth is to be taken into account through the compensation of the amplitude of each Fourier component (derived with fast Fourier transform [FFT]) of the wave train with a frequency-dependent factor according to linear wave theory (see, e.g., Homoródi, Józsa, Krámer, Ciraolo, & Nasell, 2012). The free surface excursion time series are then reconstructed from the compensated Fourier components with inverse FFT. On the basis of these time series, one can derive the so-called wave spectrum, mathematically describing the distribution of wave energy with wave frequency \( S(f) \). In contrast with marine and lacustrine conditions, where it is a common practice to characterize longer time periods (hours, days) with a stationary wave spectrum, ship-induced wave trains usually change their characteristics under much smaller time scales (minutes, seconds). In order to capture this time-dependent nature of wave characteristics on the frequency domain, wave spectra are derived with 10-s windows starting at every round second of the time series, hence with overlap between the consecutive intervals, resulting in a transient spectrogram \((S(f,t))\). It is noted that the choice of this calculation window is arbitrary, and its proper size also depends on the sampling frequency. Assuming that the wave heights follow a Rayleigh distribution, the moments \( m \) of the individual spectra can be exploited to derive bulk wave parameters such as the significant wave height \( H_s = H_{\text{rms}} = 4 m_0^{1/2} \). Wave height, for example, can be associated with the rate of larval drift (Schludermann et al., 2014). Figure 4 presents an example to this where the low frequency \((f < 0.15 \text{ Hz})\), primary wave components have already been removed via a low-pass filter.

The relevance of such transient analysis is underlined on the bottom part of Figure 4, where the original surface excursion time series already suggests varying characteristics over time. This nature of the wave train becomes more easily understood on the spectrogram and the calculated \( H_{\text{rms}} \) time series, which corresponds well to the upper envelope of free surface excursions. The duration of waves with different heights is also observed, short-term extremes are evaluable through the spectral analysis. As a comparison, significant wave height has been calculated using a single spectrum for the whole wave event, which gave approximately \( H_{\text{rms}} = 0.05 \text{ m} \), which clearly hides the presence of short-term extremes of approximately 0.14 m.

2.2 Velocity analysis

High-frequency acoustic velocity time series unavoidably contain erroneous values, that is, spikes, which are to be eliminated before
any further analysis. Despiking is performed with the phase-space thresholding (PST) method introduced by Goring and Nikora (2002); erroneous data are then replaced using quadratic interpolation. In case of shorter, 1-day-long field campaigns, the background current of the river can be considered constant; hence its effect can be eliminated through removing the mean values of all three velocity components. The resulting, that is, navigation-related, velocity time series can be further divided in the frequency domain to high-frequency secondary waves with periods of a few seconds and low frequency primary waves with periods of minutes. In terms of velocities, also, only the former is considered here. The separation is implemented by applying a high-pass ($f_{\text{cut-off}} = 0.15$ Hz) filter on the time series. Principal component analysis is then used to determine the principal direction of waves.
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(1967), and the time step is chosen at

\[ \frac{\partial u_i}{\partial t} = 0, \tag{1} \]

\[ \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \nu + \nu_l \right) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) + g_i, \tag{2} \]

where \( u \) is the velocity averaged over time \( t \), \( p \) is the fluid density, \( \nu \) is the pressure, \( \nu_l \) is the kinematic viscosity, \( \nu_l \) is the eddy viscosity coming from the Boussinesq-approximation, and \( g \) is the acceleration due to gravity. Indexes \( i \) and \( j \) refer to Cartesian components of vector variables, and terms containing \( j \) are implicitly summed over \( j = 1, \ldots, 3 \). The advective term is approximated with the weighted essentially non-oscillatory scheme (Liu, Osher, & Chan, 1994), whereas time marching is achieved with a third-order total variation diminishing Runge–Kutta scheme (Gottlieb and Shu., 1998). The governing equations are closed with a two-equation \( k-\omega \) turbulence model (Wilcox, 1994). The pressure term is solved with the projection method (Chorin, 1968), and the resulting Poisson equation is solved with a geometric multigrid preconditioned BiCGStab solver (Ashby and Flagout, 1996) provided by the high-performance solver library HYPRE (Flagout et al., 2006). Adaptive time stepping is implemented based on the Courant–Friedrich–Lewy (CFL) condition (Courant, Friedrichs, & Lewy, 1967), and the time step is chosen at every iteration so that \( \text{CFL} = 0.1 \) to suppress numerical diffusion and dispersion to tolerable levels in this class of simulations (Bihs, Kamath, Chella, Aggarwal, & Arntsen, 2016). Efficient parallelization is achieved via message passing interface and domain decomposition.

As one of the main features of wave propagation and breaking is a complex free surface that is multivalued in \( z \), a multiphase modelling approach is to be employed. REEF3D uses the level set method (Sussman, Smereka, & Osher, 1994) to capture the free surface between the phases. The location of the free surface is represented by the zero level set of a smooth signed distance function \( \phi(x,t) \). This level set function gives the closest distance to the interface \( \Gamma \), and the phases are distinguished by the sign. The level set function can be written as

\[ \phi(x,t) = \begin{cases} > 0, & \text{if } x \in \text{phase 1} \\ = 0, & \text{if } x \in \Gamma \\ < 0, & \text{if } x \in \text{phase 2} \end{cases} \tag{3} \]

The interface moves with the external velocity field \( u \); that is, a convection equation is to be solved for the level set function as well:

\[ \frac{\partial \phi}{\partial t} + u_i \frac{\partial \phi}{\partial x_i} = 0. \tag{4} \]

As the interface moves, the level set function loses its signed distance property; therefore, in order to maintain this property and ensure mass conservation, the level set function is reinitialized at each time step (Peng, Merriman, Osher, Zhao, & Kang, 1999).

Waves are generated in the first section of the computational domain with the so-called relaxation method, which uses a relaxation function to introduce the analytical values for velocities, pressure, and free surface based on the given wave parameters smoothly into the numerical wave tank (Bihs, Kamath, Chella, Aggarwal, & Arntsen, 2016). The relaxation method was also found effective in absorbing waves reflected from the inside of the domain (Miquel, Kamath, Chella, Archetti, & Bihs, 2018). The end of this initial flattened wave generation zone is the location of the pressure sensor; hence, the properties of the generated wave events can be adjusted to the measurements. Measured (calculated) free surface excursion time series are decomposed with FFT, from which an irregular wave train is reconstructed at the inlet boundary through super-positioning the individual wave components based on their amplitude, angular frequency, and phase angle according to linear wave theory:

\[ \eta_{l=0} = \sum_{i=1}^{N} A_i \cos(\epsilon_i - \omega_i t). \tag{5} \]

\[ u_{l=0} = \sum_{i=1}^{N} A_i \omega_i \frac{\cosh(k_i(z + d))}{\sinh(k_i d)} \cos(\epsilon_i - \omega_i t), \tag{6} \]

\[ w_{l=0} = \sum_{i=1}^{N} A_i \omega_i \frac{\sinh(k_i(z + d))}{\sinh(k_i d)} \sin(\epsilon_i - \omega_i t), \tag{7} \]

where \( A_i \) is the amplitude, \( k_i \) is the wave number, \( \omega_i \) is the angular...
frequency, \( d \) is the total water depth, \( z \) is the signed distance of the point of interest from the mean free surface, and \( \epsilon_i \) is the phase of each \( u_i = 1, ..., N \) wave component.

With respect to the findings of the pressure analysis, not whole wave events, but shorter, stationary periods are to be assessed with the numerical model, whose wave composition can be well characterized with a single spectrum. The calculated spectrum is divided into an arbitrary number (\( N \)) of sections (equidistant along the frequency axis), and then the position of the free surface, the horizontal and vertical velocity components, are calculated according to linear wave theory (Equations 5–7), where the phase of the individual components \( \epsilon_i \) are random generated numbers \( \epsilon_i [0, 2\pi] \). Although this method does not offer the direct reproduction of measured wave trains, it provides a statistically representative sample. The verification of the model is then conducted through comparing single-point measured (ADV) and simulated velocity energy spectra. For more details on irregular wave generation in REEF3D, see, for example, Aggarwal, Chella, Kamath, and Bihs (2016).

### 3 | RESULTS

In this chapter, results obtained by the proposed framework are presented for a case study based on data obtained during a 1-day field measurement campaign.

#### 3.1 | Study site, field campaign

The study site is located in a free-flowing reach of river Danube in the area of Horány (river kilometre 1668). The measurements were conducted at the right bank of the channel, which is the bank of the 31-km-long Szentendrei Island, dividing the Danube into two branches. Two-thirds of the total discharge flows in this (left) branch, with an annual mean of approx. 1,300 m\(^3\) s\(^{-1}\); hence, it is the main fairway. In order to provide the necessary water depth for navigation, groins have been built. The closest pair is located approximately 1 km upstream the study site. The measurements were performed in the littoral zone (Figure 5), where the hydraulic and ecological impact of ship waves is believed to be the most significant.

The field campaign was held on 19 June 2017, during mean flow conditions (1,250 m\(^3\) s\(^{-1}\)). Pressure measurements were performed with the pressure gauge of an Acoustic Doppler Current Profiler (Nortek Aquadopp HR Profiler) at sampling frequency of 8 Hz. High-resolution three-dimensional single-point velocities were measured with two ADV devices at 16 Hz in different distances from the bank, also in different depths. The digital elevation model of the study site has been triangulated from vessel-mounted acoustic depth soundings and near-bank RTK-GPS surveying (Figure 5).

#### 3.2 | Field results

Analysing of the wave time series through a transient FFT-based methodology, the temporal evolution of wave events can be followed; moreover, the statistical, duration-based analysis of waves of different heights can be assessed as well. From the ecological aspect, different statistical properties may be relevant: the short-term extremes exceeding a critical value leading to fish stranding, for example, or the very presence and duration of any disturbance at all, entailed by navigation. The histogram of wave heights during wave events have been derived for different ships (Table 1, Figure 6). Because of the length of the wave event varies from ship to ship, relative frequencies are weighted with the total time duration. Sections of the time series, where \( H_{m0} \) exceeded 1.5 cm, were marked as navigation-related wave events, as lower disturbances are permanently present in the river, due to wind-induced waves, recreation and so forth.

In the present case, the three passenger vessels (Maxima I, Sofia, and Esmeralda) generated wave trains of similar length (~4–5 min) and with similar wave characteristics as well. Maximal wave heights are around 0.08–0.10 m, which are approximately an order of

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**FIGURE 5** Orthophoto of the study site, marked with the red box in the magnified right view. The close proximity of the bank is further magnified to present the horizontal position of the deployed instruments [Colour figure can be viewed at wileyonlinelibrary.com]
magnitude higher than wind-generated waves in the Danube during the measurements. These extreme wave heights only last for a few seconds (few wave periods), whereas the longest lasting ones are on the other end of the scale of 0.02–0.03 m. Although the wave height histogram for the cargo ship (Danimex 2) shows similar distribution to the previous ones, it is noted that the total length of the wave event is two to three times longer than those; moreover, maximal wave height also reaches 0.15 cm, which is 1.5 to two times larger than in case of the passenger vessels.

The presented statistical analysis of the wave events provides a clear, easily interpretable overview on the temporal distribution of waves of different heights. The analysis makes the description and characterization of ship-induced wave events less arbitrary; hence, the impact of different types of ships, or even individual vessels, becomes better comparable. An example of the presented velocity processing methodology is presented in Figure 7 for the Danimex 2 cargo ship, where the consecutive steps of the procedure are highlighted. The high amount of erroneous data underlines the necessity of despiking prior to further analysis, in spite of the fact that the sampling rate of the ADVs was not extremely high (16 Hz).

The despiked velocity data points clearly show the magnitude and direction of the background flow as a shift in the centre of the point cloud. On the other hand, the main direction of short waves is unidentifiable prior to the bandpass filtering. In the presented case, the background and the ship-generated velocity constituents are in the same order of magnitude in the sampled point. It is noted that although the background velocity has been shown to decrease gradually towards the bank, wave-related velocities show contradictory behaviour as they increase as reaching shallower and shallower areas (Fleit et al., 2016). Due to the strong spatial variability, it is clear that single-point velocimetry alone is not sufficient to analyse wave kinematics and its ecological effects in the littoral zone of rivers, spatially

| Vessel name | Travelling direction | Travelling speed, avg/max (km/h) | Length (m) | Width (m) | Drought (m) |
|-------------|----------------------|---------------------------------|------------|-----------|-------------|
| Maxima I    | Downstream           | 15.6/28.0                       | 127.5      | 11.4      | 1.7         |
| Sofia       | Downstream           | 15.4/29.6                       | 113.5      | 16.0      | 1.7         |
| Esmeralda   | Downstream           | 14.3/28.5                       | 90.0       | 11.2      | 1.4         |
| Danimex 2   | Upstream             | 12.2/23.7                       | 105.0      | 9.1       | 1.0–2.8     |

*FIGURE 6* Histogram of significant wave heights calculated for different ships [Colour figure can be viewed at wileyonlinelibrary.com]

*FIGURE 7* Consecutive steps of the velocity analysis and their effects on the measured horizontal velocity components. Note that the first figure from the left has different axis scales
extended procedures are to be employed. Nevertheless, the high-resolution 3D velocity time series gathered with ADVs offer quality control data for the profound validation of numerical models. This is explored in the next section.

### 3.3 | Numerical modelling

#### 3.3.1 | Numerical set-up

The computational domain is simplified to a two-dimensional vertical slice with the assumption that waves in the close proximity of the bank are already diffracted thus travel orthogonally to the shoreline. It is noted that a previous study has shown promising results with such an approach (Fleit et al., 2016, 2018). The geometry of the bank is generated based on single beam water depth soundings and GPS surveying in the shallower areas. The computational domain (Figure 8) is 20.00 m long × 2.0 m high × 1 cell wide; the grid is vertically refined in the proximity of the free surface, whereas horizontal refinement is applied in the area where wave run-up and breaking are expected ($dx_{\text{min}} = dz_{\text{min}} = 0.005$ m, $dx_{\text{max}} = dz_{\text{max}} = 0.010$ m). The initial flatbed wave generation zone is 5 m long. The computational mesh consists of approximately 470,000 active cells.

The sections analysed numerically in this paper are those of the wave event generated by the Danimex 2 cargo ship. It is noted that this arbitrarily selected wave train had the highest waves, thus the most intense wave breakings as well, hence was considered to be the most challenging from the numerical modelling point of view. An approx. 80-s-long part of this wave event has been deconstructed into two subsections of different wave intensities, both well characterizable with a single spectrum (Figure 9).

Based on the experimental spectra, irregular waves were generated from $N = 25$ Fourier components, and the simulations have been run for 150 s, to ensure the statistical stationarity of the resulting unsteady hydrodynamic conditions.

#### 3.3.2 | Numerical results

In order to ensure that the number of Fourier wave components were sufficient to reproduce the given wave spectra, a numerical wave gauge is located at the end of the wave generation zone, so that measured wave spectra (given as input) can be compared with the spectra generated by the numerical model (Figure 10). In order to give an impression on the investigated wave hydrodynamics, an instantaneous horizontal velocity distribution for Section 2 is presented in Figure 11. The minimal damping of the velocities with depth indicates depth-limited wave conditions.

The modelled wave spectra for the two sections show good agreement with the field data, indicating that spectra for these short wave train sections can be well reconstructed with the superposition of $N = 25$ regular wave components (top row in Figure 10). Having the correct inlet boundary conditions, the challenge still stands in reproducing wave propagation and shoaling in the shallower zones, as well as the reproduction wave breaking. Although the reproduction of breakers basically depends on the employed numerical methods (turbulence, free-surface tracking, etc.), the accurate

![FIGURE 8](https://example.com) Sketch of the computational domain with its most relevant dimensions (top); refined grid resolution ($dx = dz = 0.005$ m) in the close proximity of the shoreline (bottom). The location of the two ADV devices is marked P1 and P2. [Colour figure can be viewed at wileyonlinelibrary.com]

![FIGURE 9](https://example.com) Deconstruction of a wave event into smaller subsections, their representation in the time (left) and frequency (right) domain [Colour figure can be viewed at wileyonlinelibrary.com]
prediction of the hydrodynamic conditions in the shallow areas is also highly dependent on the abstractions adapted, that is in present case the simplification of the fluid flow problem to 2D, or the arbitrary (yet justified) selection of the bandpass frequency limits for filtering.

It is noted that the measured wave spectra do not include directional information; hence, waves that are possibly reflected from the bank cannot be separated in the spectra, consequently, neither from the boundary conditions of the CFD model, where unidirectional waves are generated. These reflections are, however, absorbed in the numerical simulations thanks to the application of the relaxation method at the inlet boundary. In terms of velocities on the other hand, both the field and the numerical values can potentially contain the effects of reflected waves and related currents. Measured and simulated velocity spectra are compared on the bottom row of Figure 10 as model verification. P1 and P2 are the locations of the ADV devices (see Figure 8). Reasonable agreement is observed, and the following observations can be made. The numerical model overestimates the total amount of kinetic energy at P1 with the same pattern: The peak frequency is lower in the CFD simulations, and the amount of energy in this frequency region ($f \approx 0.20$, ..., 0.25 Hz) is increased with approx. the same amount in both Sections 1 and 2. Slightly similar behaviour is observed at P2, where the peak frequencies are also notably lower; however, the model performs better in Section 1, where the total amount of energy is well approximated. In spite of these inaccuracies, the numerical model provides plausible results, especially if the simplifications and abstractions are also considered.

The verified numerical model provides a suitable tool to perform hydrodynamic assessment beyond the measured parameters, which is to evaluate the hydrodynamic characteristics of the whole modelled domain, even for different wave events. The governing equations solved within the numerical framework provide the spatial distribution of pressure, velocity vectors, turbulence related variables, and free surface profiles. In the following, the velocity magnitude ($|u|$) and turbulent kinetic energy ($k$) distributions will be presented as one of the most important features from the hydrodynamic point of view, which are the steering parameters from the morphodynamic aspect as well (sediment resuspension, bank erosion, etc.). Figure 12 presents the spatial distribution of time-averaged and maximal velocity magnitudes for the two selected sections. The general pattern observed between mean velocities are quite similar for the two cases: Velocities gradually increase towards the shallower areas, which is supported by wave theory and previous experimental findings as well (Fleit et al., 2016). However, in case of Section 1, the first two-thirds of the domain is dominated by values around 5 cm/s, whereas in the same areas, 10–15 cm/s values occur in Section 2. Near the shoreline, these relative differences decrease; velocities as high as 40 cm/s occur in both scenarios due to wave run-up.

Time-averaged values (often utilized in practical engineering applications) are, however, not necessarily the most relevant features from an ecological point of view. Short-term velocity extremes, for instance, can drift individuals to regions with flow conditions, which they cannot withstand, whereas bed shear stress temporarily increasing a critical value can detach macroinvertebrates or fish eggs from the river substrate—both potentially resulting in mortality. The comparison of
the maximal velocity values in the modelled domain is presented on the bottom part of Figure 12. The gradual increase of maximal velocities towards the bank is observed. Apart from the wave breaking zone, where velocities as high as 100–150 cm/s can occur in both cases, maximal values are around 10–25 and 20–50 cm/s for Sections 1 and 2, respectively.

In conclusion, time-averaged velocity magnitudes due to ship waves in the littoral zone may reach the same magnitude as the background flow of the river (in Section 2), which effectively doubles average flow velocities during the passage of ships. Maximal velocities, as temporary as they are, may still result in two to three times more intense currents in the littoral zone compared with time-averaged values. In the close proximity of the shoreline, where waves break and run up, velocities can reach as high as 1–2 m/s, which can mean an increase of more than one order of magnitude, considering that in these very shallow areas, standing water is expected in steady-state riverine conditions.

A similar evaluation is presented in Figure 13, where the intensity of turbulence is assessed through turbulent kinetic energy (k) distributions, as one of the state variables of the k-ω turbulence closure.

In case of turbulent kinetic energy, the differences between the two sections are more apparent: Both mean and maximal values at Section 2 show an approximately two orders of magnitude increase. On the contrary, compared with the range of k values within the domain, the differences between mean and maximal values for the separate sections are not that significant. The pattern of gradual increase of values towards the shallower areas, and eventually the breaking zone, is similar to what have been presented for the velocities. Values at the close proximity of the riverbed tend have be an order of magnitude higher compared with the rest of the water column, which is one of the most important drivers in the resuspension of fine sediments, or the erosion of even coarser bed material as well.

It is emphasized that the presented model result evaluation could be complemented with additional statistical methods, using other
hydrodynamic variables present in the governing equations or with further, post-derived variables (e.g., bed shear stress and vorticity).

### 4 DISCUSSION

An evaluation framework has been presented to assess the hydrodynamic effects of ship generated waves on the littoral zone of rivers, utilizing up-to-date field and computational methods. The time variability of wave events has been highlighted, and it has been shown that high temporal resolution pressure measurements can be exploited to characterize these changes. The proposed transient spectral analysis offers the statistical evaluation of the wave trains, with special focus on the duration of different wave heights, which is not only strongly related to the overall hydrodynamic impact of waves but also of major importance from an ecological point of view as well (Kuczera-Hirzinger et al., 2009). The methodology provides a quantitative footprint for ship-induced wave events, making the future analysis of the effects of different ship-related (speed, shape, and direction), morphological (bank slope, channel width, and bed material), or hydrological (discharge and water level) variables better interpretable.

The presented methodology is not yet considered complete. One of the most obvious directions for further development is the field and numerical investigation of bank erosion and sediment resuspension processes, as they are tightly connected to hydrodynamics and of great importance to the quality of riverine habitats (e.g., Schallenberg et al., 2004). Acoustic and/or optical backscatter sensors with proper calibration can provide quality-suspended sediment concentration time series of high temporal resolution in the field, contributing to a better understanding of sediment dynamics (e.g., Hofmann, Lorke, & Peeters, 2011; Houser, 2011). The combined implementation of current meters and optical backscatter sensor devices can be used to evaluate wave-induced bank erosion (Bauer, Lorang, & Sherman, 2002). The relevance of primary waves, and the initial drawdown of larger ships in particular, should also be considered in this matter (Rapalgia, Zaggia, Richlefs, Gelinas, & Bokuniewicz, 2011). Once these suspended sediment observations are available, a sediment transport model can be coupled to the hydrodynamic solver to provide an additional tool for the investigation of these hydromorphological processes (Ahmad, Bihs, Myrhaug, Kamath, & Arnsten, 2018).

ADVP measurements of high sampling frequency have been conducted in the littoral zone as well, in order to explore the flow conditions during vessel-generated wave events. In riverine conditions, the measured velocity time series can be further decomposed into velocities of different sources, such as the background current, primary and secondary ship waves, and turbulence. In this study, only the secondary wave-related velocity components have been analysed as the hydrodynamic; hence, the ecological impact of these is believed to be the most significant. The bandpass-filtered time series can then be used to determine the characteristic direction of waves through principal component analysis. Although such measurements can provide deep insights into wave-related velocities and turbulence characteristics (Homorödi et al., 2012), the information is restricted to single points (~1 cm²). The limited footprint of ADV has been overcome with CFD, after validation with the measured data.

In order to get a deeper insight into wave-related sediment dynamics in the littoral zone, more detailed information is required on the boundary layer hydrodynamics. CFD can provide solutions in any resolution; the numerical treatment of these boundaries, however, is still somewhat arbitrary. Acoustic Doppler velocity profilers (ADVP) on the other hand can provide highly detailed spatiotemporal information on velocities at vertical intervals of only a few centimetres, yielding a significant increase of information compared with single-point ADVs. ADVPs have already been successfully used for the investigation of breaking wave kinematics in the surf zone (Tomasicchio, 2006).

In addition to the usually expensive professional field measurement devices, there is a significantly increasing interest towards the development of various image-based techniques as well. Large-scale particle image velocimetry, for example, has been developed for fast and effective discharge estimation of floods, where conventional, intrusive equipment can no longer be used (see, e.g., Muste, Fujita, & Hauet, 2008). However, it has been reported that more complex, transient flow features can also be investigated with this method (Muste et al., 2014). Studies have shown that large-scale particle image velocimetry can also be used to quantify, for example, surface velocities in the proximity of breaking waves and the associated run-up, as the generated foam is an adequate tracer for the algorithm (e.g., Fleit et al., 2016; Fleit & Baranya, 2018).

The open-source level set method-based numerical solver REEF3D has been used to analyse wave hydrodynamics. A simplified 2D (vertical slice) model has been built based on the field measurements: Irregular waves have been generated at the inlet boundary based on the pressure measurements; measured velocity spectra have been used for validation. The measured wave spectra have been well reproduced from the superposition of N = 25 Fourier components, whereas a reasonable match was observed between field and numerical velocity spectra as well. Nevertheless, the authors believe that boundary conditions for the wave generation could be further improved to take account for the already emphasized transient nature of the wave events. This could be either done through directly reproducing the measured wave events with the so-called wave reconstruction method (see Aggarwal, Cs, Bihs, Myrhaug, & Chella, 2018) or through using spectrograms as inlet boundary conditions. The validated model offers a numerical wave tank providing the detailed spatial distribution of relevant hydrodynamic variables, such as the flow velocities or the turbulent kinetic energy. Thus, CFD allows us to study breaking waves (Chella, Bihs, Myrhaug, & Muskulus, 2016) whose high dynamic impact is mainly responsible for bank erosion and associated sediment resuspension and for which no conventional field measurement methods are applicable.

### 5 CONCLUSIONS

The effects of navigation, and ship-induced waves in particular, on the littoral zone of water bodies have already been realized by biologists
and ecologists; moreover, many effects and interconnections have been revealed through experimental investigations (see Gabel, Lorenz, & Stoll, 2017). Although the ultimate effects of the different hydrodynamic phenomena on the aquatic fauna have already been understood in the past decades (e.g., fish stranding due to waves and currents and detachment of benthic creatures due to increased shear stresses), the quantitative assessment of such variables have been barely investigated; hence, the proper linking of the relevant abiotic and biotic variables could not have been performed either. The need for such investigations, however, has been present for a long time; the scientific toolkit of the hydroscience community could not offer solutions for such small-scale, dynamic processes, especially not in field conditions.

Though the presented numerical modelling methodology provided reasonably accurate solutions in spite of the serious simplifications, it is emphasized that the potential in up-to-date CFD modelling has barely been harvested within the presented investigations. Expanding the computational domain towards the third dimension (i.e., along the banks) could point out the relevance of natural, three-dimensional bathymetry on wave shoaling. The six degrees of freedom (6DOF) algorithm implemented in the employed CFD model offers the numerical simulation of fluid–solid interactions (Bihs & Kamath, 2016), which in present case could mean the numerical simulation of these wave events along a whole river reach. It would not only offer the hydrodynamic characterization of ship waves in much larger spatial scales but also could provide an efficient, site-specific investigation tool to analyse the effects of various ship related (shape, draught, travelling speed, etc.) variables as well.

The combination of high-resolution field measurements with the proper data processing and state-of-the-art numerical simulations results in a comprehensive framework for the detailed assessment of ship waves. The temporal evolution of waves and the related flow and turbulent features can be revealed via field pressure and velocity probes. Taking the highly transient nature of ship waves into account, one can derive wave statistics for the wave events, which—considering the high correlation between wave heights and related hydrodynamic impacts (e.g., velocity or bed shear stress)—offer a well-comparable footprint for different ship passes. The proposed field methodology in a long-term monitoring fashion coupled with already available automatic identification systems used in inland navigation could result in a statistically significant sample, allowing to characterize the potential effects of different vessel-related parameters (size, shape, speed, etc.) in any flow regimes. In addition to the measured wave characteristics, the presented CFD-based methodology can be utilized to assess the relevant fine scale features in an adequately selected spatiotemporal resolution, offering an insight to hydrodynamics unattainable via field measurements. CFD is also considered a viable tool to predict the impacts of river training and restoration measures in a quantitative manner, as numerical simulations offer detailed hydrodynamics for conditions that cannot or have not been measured yet. The proposed hydrodynamic centred methodology supplemented with available and future ecological and ecohydraulic investigations could improve our understanding of the influence of fluvial navigation on water ecosystems and, as such, could, for example, scientifically support traffic regulations at reaches of intensive exposure to the negative effects of navigation. The authors believe that the applicability of the presented framework is not exclusive for rivers; after the necessary, reasonable adjustment of the methods, it could be potentially employed in lacustrine and coastal environments as well.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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CONFLICT OF INTEREST
The authors declare no conflict of interest.

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