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Review and rebuttal of the paper

A global review of vessel wave effects on land-water interfaces: collaborative baselining of issues, management strategies and future challenges

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Editor handling the paper: Olivier Bertrand

The reviewers remain anonymous.

Response to the reviewers

Detailed answers to the reviewers' comments are provided in this document.

Answers to the individual comments can be found below.

The convention is as follows:

- reviewer's comments
- *our responses to the comments*
- new text added to the manuscript
- ~~text removed from the manuscript~~

In addition to incorporating the reviewers' comments, literature published during the review or shortly before the initial submission was also included, making sure that the present manuscript is still up-to date with the latest advancements. Details on these amendments are given in Section 3 of this letter.

1 Reviewer B

The article examines ship-generated waves and their environmental impacts on waterways, as well as management practices in place to mitigate these effects. It discusses the importance of research on these waves, the challenges associated with their management, and analyse the existing solutions, whether short-term or long-term. The discussion includes case studies, recent measurement methods, and strategies adopted by different partenaires in the field. The workshop helped establish a baseline of current practices and highlighted gaps in data and understanding of the processes associated with vessel waves.

Comment 1:

1 Introduction:

The introduction effectively highlights the relevance and urgency of this bibliographic study. However, to further strengthen the motivation for this work, it is important to explicitly emphasize the impact of ship-induced waves on bank erosion.

Response: *Thank you for this advice. We added explicit mention of bank erosion to the introduction.*

Revision of the manuscript:

Trends, such as the continued increase in the dimensions and draft of seagoing ships (Prokopowicz and Berg-Andreassen, 2016) and proliferation of high-speed craft such as fast ferries (Soares and Santos, 2021) and recreational vessels (Carreño and Lloret, 2021) over the last decades has intensified the worldwide discussion on effects of ship-induced waves and currents that have been witnessed at land-water interfaces of sheltered, shallow and confined waterways. These impacts are most clearly demonstrated by readily observable effects, like the erosion and retreat of marginal areas such as (unprotected) banks, beaches and tidal flats which have been widely reported from many locations around the world (e.g., Almström et al., 2022; Bauer et al., 2002; Chakraborty et al., 2023; Dauphin, 2000; Duró et al., 2020; Davies, 2023; El Safty and Marsooli, 2020; Gourlay, 2011; Herbert et al., 2018; Houser, 2010; Mao and Chen, 2020; Meyers et al., 2021; Osborne et al., 2007; Parnell et al., 2007; Zaggia et al., 2017). Although some environmental impacts of vessel traffic have been known and first documented already decades, even centuries ago (Darrigol, 2003), it appears that in recent years a great number of (case) studies reporting on vessel wave effects from various geographies, in particular in relation to long-period waves from high-speed craft (e.g., Parnell and Kofoed-Hansen, 2001; Soomere, 2005, 2007; Parnell et al., 2007; Soomere et al., 2011) as well as large displacement vessels (e.g., Dauphin, 2000; Maynord, 2004; Rapaglia et al., 2011; Parnell et al., 2016; Zaggia et al., 2017; Dempwolff et al., 2022) and their effects on the surrounding environment have been published.

Comment 2:

2 Description of workshop methods, implementation and outcomes

The reviewer finds the methodology followed for this workshop excellent and has nothing to say about this section.

Response: *Thank you for your positive endorsement of this section.*

Comment 3:

2.2 Workshop outcomes

III: also the evolution of size of vessels.

Response: *This is an important point, which we have now included.*

Revision of the manuscript:

iii. A look ahead to future challenges facing waterways in relation to vessel-generated waves [...], concerning

- trends and developments in vessel size evolution and potentially intensifying waterway use,
- drivers and inhibitors of sustainable waterway use,

...

Comment 4:

3.2 Socio-economic aspects of vessel waves

In this section, the reviewer would have liked to see a discussion on intervention costs related to bank failures caused by the ship generated waves, which can cause accidents and are distinct from regular maintenance costs. Additionally, the impact on shipowners should be addressed, particularly the financial losses incurred due to the partial or total closure of waterways for intervention or maintenance work!

Response: *Thank you for highlighting this. We have added two examples showing the socio-economic ramifications of embankment erosion in waterways. We are not aware of any documented accidents due to bank failure or quantitative financial data on concrete losses to ship owners due to embankment erosion. However, we believe these examples clearly illustrate the cost-relevant interdependencies between ship-induced erosion and its associated socio-economic impacts.*

Revision of the manuscript:

The Kiel Canal serves as a pertinent example of the socio-economic cost of ship-induced erosion damage to a vital waterway. The Kiel Canal has experienced significant erosion to unprotected parts of the underwater embankment in a significant number of locations (WSV, 03.07.2023). To avert further damage and facilitate repair under traffic, a blanket speed restriction of 12 km/h was imposed in the summer of 2023, resulting in longer transit times (approx. 15%), higher pilotage costs and, at times, longer pre-transit waiting times due to a lack of pilots spending longer time in transit (NDR, 28.07.2023). These effects incur not only higher costs for ship owners but also for the economy as a whole; in response to the mentioned cost drivers, the German

Federal government has slashed the transit toll by half for three years (BMV, 5.4.2023) and is liable for the significant repair expenditure. The impact on freight shipping rates remains unclear, however a reduction of operational efficiency is typically associated with an increase in freight rates. Case in point, in the Cuyahoga River in Ohio, USA, a section of the waterway is at significant risk of embankment failure, which could lead to a prolonged closure of the waterway (Ewing, 10.01.2025). To prevent this, navigation in the affected area has been significantly restricted to allow for remedial works; this includes a "restricted navigation area" with a no-wake policy and 5 kn (9.3 km/h) speed restriction (Federal Register, 2024). These restrictions have raised concerns within the shipping industry, which reports substantial costs from transit constraints and supply chain disruptions, particularly for key heavy industries in the area.

Comment 5:

4.4.1 'Hard' engineered structures

The reviewer finds this sub section lacks sufficient detail, as many solutions have been proposed to protect shorelines from vessel-generated waves. The reviewer suggests to provide more in-depth descriptions of the various engineering solutions would improve the article. Furthermore, it would be beneficial to include some illustrations or figures, even though the current article is a review. Visual aids could enhance the reader's understanding of the proposed solutions and their effectiveness in real-world applications.

Response: *Thank you for bringing this to our attention. Given the substantial length of the manuscript and the need to maintain a balanced discussion of all mitigation measures, we have refrained from delving too deeply into the engineering options alone. However, we acknowledge that the section can benefit from illustrative descriptions, short comments on efficacy and three further photographs of different structural configurations (two further engineering solutions, one further bioengineered solution), which have now been included in Section 4.4.1.:*

Revision of the manuscript:

In more general terms, engineering solutions encompass the installation of physical barriers and structures to dissipate wave energy and/or stabilise the shoreline (Bain et al., 2022).To this end, ~~The most~~ widely applied solutions are groynes and revetments (Fig. 8), shore-parallel dams or berms (Fig. 9) and nearshore training walls (Fig. 10), often in combined configurations and in tandem with bioengineered defences. The mentioned structures are commonly constructed as rock structures, but can also include more complex composites (e.g. with sheet piling and concrete slabs, Fig. 9). Experience from German estuarine waterways demonstrates that engineered structures can be very effective in mitigating vessel wave effects in marginal areas but that often a combination of measures is required to fulfil the requirements for foreshore stabilisation (typically groynes, nearshore dams or bioengineered alternatives, see sec. 4.4.2) and embankment erosion control (typically rock revetments), as is illustrated in Figs. 8 to 12). This means, in the most basic sense, that it is necessary to consider ship-induced loads during structure design, especially in sheltered bodies of water where these present as the predominant loading.

Figure 8: Revetments and groyne system for embankment and foreshore stabilisation against ship waves at Pagensand in the Lower Elbe Estuary. Central groyne field without revetment. Source: Federal Waterways Engineering and Research Institute (BAW).

Figure 9: Nearshore composite berm for load reduction in combination with brushwood groynes for sediment retention at Harriersand in the Lower Weser Estuary, Germany. Source: Federal Waterways Engineering and Research Institute (BAW).

Comment 6:

5.5 Monitoring – Broadening the Data Base

In this section, the reviewer recommends incorporating satellite image exploitation as an additional valuable tool for monitoring vessel wave impacts. Satellite imagery can help track the evolution of erosion phenomena over time, providing a broader spatial view, especially in areas that are difficult to access. Additionally, it can aid in identifying shallow zones or high spots, where vessel-generated waves are amplified, leading to more severe impacts.

Response: *Thank you for this suggestion. We have now included this aspect. Additionally, we have included a further reference concerned with soil stresses under ship waves. This reference is not related to remote sensing, but related to the direct force measurement at embankments which is also discussed in this section:*

Actions taken:

Typically, monitoring entails point measurements of water level displacement and flow velocities. Recently, more advanced methods are being employed which allow vertically-resolved measurements (e.g. using surface-tracking ADCPs, Muscalus and Haas (2022, 2023)) and three-dimensional recording of vessel wave patterns using remote sensing techniques such as drone-mounted LiDAR or stereo photogrammetry methods (Jansch, 2023) (cf. Fig. 13). Spatially resolved monitoring data can shed light on the complex wave transformation processes and provide valuable validation data for numerical models. A high degree of relevance can be attached to the use of remote sensing applications for, e.g. ship wake detection (Higgins et al., 2022; Mazzeo et al., 2024), detailed photographic, topographical, and vegetation survey data (e.g., Tarolli, 2014; Dubayah et al., 2020; Kim et al., 2023) which is essential for understanding wave transformation effects in the nearshore area. Aerial and satellite imagery are well-suited to track the temporal evolution of spatial features such as erosional processes as exemplified by Duró et al. (2020) and Zaggia et al. (2017).

To quantify the erosive forces of vessel waves, force measurements have been employed to quantify vessel wave forces at the site of impact (e.g., Bain et al., 2023; Priestas et al., 2023). Similarly, Mordhorst et al. (2023) measured the vertical and temporal distribution of normal and shear stresses in estuarine soils with and without vegetation under ship wave attack. Both approaches provide deeper understanding of the wave-soil-interaction, vegetation effects and important wave parameters for embankment erosion potential.

Comment 7:

6 Conclusions

The conclusion is well-written and effectively summarizes the main points covered in the body of the article. It provides a clear synthesis of the discussions on ship-generated waves and their impacts, as well as the proposed management strategies. However, the reviewer would have appreciated further insight into the workshop's perspectives, if available. A discussion on future steps in terms of research, collaboration, or upcoming initiatives would be a valuable addition to provide a long-term vision of the impact of this work on the field of ship wave management.

Response: *Thank you for bringing this to our attention. We have included some concrete research collaborations, publications and data sharing initiatives that have emerged from the workshop. The workshop has been a catalyst for ongoing formal and informal exchanges between a multitude of parties.*

There also appears to be a viable path and a number of interested parties for the organisation of the next workshop, however not quite concrete enough for announcement yet.

Revision of the manuscript:

Addressing these gaps through collaborative and interdisciplinary efforts is essential for advancing sustainable waterway management. The workshop has already provided momentum to further research initiatives and collaborations between delegates, such as advanced statistical modelling of vessel wave dependencies in the Savannah River (Mares-Nasarre et al., 2024). The forming of, at least two, ongoing research collaborations, one which is focussing on improved ship wave prediction in various topographic settings using probabilistic methods, the other contributing to the understanding of resonant ship wave features in marginal areas can be attributed to fruitful exchanges at the workshop. Since a lack of openly available datasets was identified as a major concern (cf. sec. 2.2 and 5.5) , a first meaningful step towards increasing data availability was undertaken by workshop delegates in Seemann and Melling (2025). The authors believe this comprehensive, well-documented dataset will be instrumental in facilitating future ship wave research. To ensure a recurring forum for focussed discussion, the authors endeavour to facilitate the continuation of the 'ShipWave' workshop series to facilitate broader, multidisciplinary engagement with the topic from researchers and practitioners and foster exchanges with decision makers and regulators toward effective management of waterways.

Comment 8:

General review

The manuscript presents a relevant and well-documented analysis of ship-generated waves, along with a thorough discussion of the challenges and possible solutions. The article is well-structured, and the ideas are clearly communicated. The references are appropriate and help contextualize the results from the workshop. Illustrations and case study examples add a practical dimension to the theoretical discussion. However, the reading experience was somewhat challenging due to the citation style used in the article, which involves naming the authors directly rather than using numbered references. This citation method made it difficult to follow certain sections, particularly when multiple references were mentioned within the same context. The reviewer suggests that the editor consider this aspect and potentially switch to a more conventional citation format with numbered references, which would improve readability and ease of understanding for the audience. Despite this issue, the overall quality of the manuscript is very good.

Response: *Many thanks for your constructive review and positive outlook on the publication as a whole. We will seek guidance from the handling editor on the appropriate citation style to ensure consistency throughout the journal.*

2 Reviewer G

The document highlights the importance of managing the effects of ship-induced waves, particularly with the increasing size and draft of seagoing ships and the proliferation of high-speed craft and recreational vessels. An international workshop titled ”ShipWave2023” was held in Hamburg, Germany, to discuss these issues and promote interdisciplinary cooperation.

The publication compiles contributions from the workshop and contextualizes them within existing literature and case studies, focusing on management strategies and practices for vessel wave effects on land-water interfaces. It also presents future visions for these topics and summarizes the challenges and research needs ahead.

The publication aims to inform and raise awareness among stakeholders, offering guidance, encouraging further research, and fostering collaboration within the ’vessel wave community’. Management of vessel-generated waves requires a mix of short-term (e.g., speed limits) and long-term (e.g., improved vessel design, education) strategies.

While local interventions can manage hotspots, reducing wave generation at the source is preferable.

The authors aim to continue the ’ShipWave’ workshop series to promote engagement and effective management strategies.

I find the paper very interesting and it provides an excellent overview of the state of the art on the topic addressed.

The article fits perfectly within the theme of the journal.

Comment 1:

However, the author notes that there may be a bias in the article, as the participants are predominantly European, with no representation from countries on continents such as Asia and Africa. It would be useful to mention this bias in the conclusions to ensure greater transparency (first proposed modification).

Response: *This is a valid point. We have added the following sentence to the conclusion section of the manuscript.*

Revision of the manuscript:

As mentioned in section 2 the authors acknowledge that the presented findings reflect perspectives primarily shaped by European and other developed country contexts, which should be considered when generalising the findings more broadly. The authors encourage active workshop participation and input from delegates from developing and emerging economies to ensure more inclusive and representative discussions in the future.

Comment 2:

Additionally, it might be beneficial to include a glossary at the beginning of the article to improve readability. Terms such as WSV, BAW, UNCTAD, PIANC, MMC, BSH, BIMCO, TEU, MCCIP, AIS. . . while familiar to specialists, may require explanations for some readers (second proposed modification).

Response: *Thank you for this suggestion. We have included a list of acronyms at the end of the article (in keeping with formatting of previous publications).*

Revision of the manuscript:

AIS Automatic Identification System

BAW Bundesanstalt für Wasserbau / Federal Waterways Engineering and Research Institute

BIMCO	The Baltic and International Maritime Council
BRICS	Brazil, Russia, India, China, South Africa
BSH	Bundesamt für Schifffahrt und Hydrographie / Federal Maritime and Hydrographic Agency
CCNR	Central Commission for the Navigation of the Rhine IMF International Monetary Fund
MCCIP	Marine Climate Change Impacts Partnership
MMC	Malamocco-Marghera-Channel, Venice, Italy
OECD	Organization for Economic Co-operation and Development
PIANC	World Association for Waterborne Transport Infrastructure
TEU	Twenty-foot Equivalent Unit
UNCTAD	United Nations Conference on Trade and Development
ULCV	Ultra-large container vessel
USACE	United States Army Corps of Engineers
WSV	Wasserstrassen- und Schifffahrtsverwaltung / Federal Waterways and Shipping Administration

Comment 3:

I am not sure of the usefulness of Appendix A with the post-its or the writings that remain difficult to read (I'll let you see the benefit of leaving this appendix).

Response: *Thank you for this suggestion. We had initially included the photos as a documentation of the workshop methods and "raw" outcomes, however, on reflection, we see that the added value appears less than previously thought due to limited legibility. The appendix and references to the appendix in the methods section have been removed.*

Comment 4:

In summary, I think the article is good for publication with just few minor modifications.

Response: *We appreciate your positive view of the publication and your recommendation to publish.*

3 Additional bibliographical references added

The publication by Seemann and Melling (2025) was previously cited as 'accepted', it is now published and the reference was adjusted accordingly.

Publications by Krämer et al. (2025) and Muscalus et al. (2025) were added in section 3.1:

Krämer et al. (2025) reports on morphological bed form changes to the sea floor due to ship-induced currents. Similarly, the capacity for transport and redistribution of sediment through vessel-generated waves and currents with implications for tributaries has been documented for specific sites by Ravens and Thomas (2008); Houser (2011) and Muscalus et al. (2025).

A reference to Notteboom and Haralambides (2025) was added in section 4.3.1

Apart from the conscious redirection of vessel traffic, it is paramount to note that the significance of waterways can fluctuate inadvertently (Notteboom and Haralambides, 2025), and with it...

A reference to a recent study by Tong et al. (2025), examining the nearshore energy of long-period ship waves was added in section 3:

Although the contribution of ship-induced waves and currents to the overall load experienced by shorelines can vary throughout the year depending on hydrological and meteorological conditions, as well as the intensity of recreational boating (Maynord et al., 2008), studies using energy considerations indicate that in sheltered waters, the energy introduced by boat or ship traffic can be significant in terms of its overall contribution to energy input and, more specifically, in terms of the energy expenditure in the nearshore area (e.g., Parnell and Kofoed-Hansen, 2001; Soomere, 2005; Parnell et al., 2007; Maynord et al., 2008; Kelpšaite et al., 2009; Muscalus and Haas, 2022; Tong et al., 2025)

A reference to Wang and Cheng (2021) concerned with non-linear ship wave deformation in the nearshore area was added in Section 6. This had been missed in the initial submission:

ii. variety of vessel-generated wave forms (Bain et al., 2022), wave-following persistent oscillations and perturbations (Fenton et al., 2023) and trailing waves (Haas and Muscalus, 2023b,a) and their possible connection to resonant ~~effects~~ (Muscalus and Haas, 2020, 2022; Dempwolff et al., 2024) and non-linear effects in marginal areas (Wang and Cheng, 2021).