JOURNAL OF COASTAL AND HYDRAULIC STRUCTURES

Vol. 5, 2025, 49

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

Gregor Melling [1,*], Ingrid Holzwarth [1], León-Carlos Dempwolff [2], Christian Windt [2], Nils Goseberg [2,3]

Abstract

Waterborne vessels of all types generate waves as a result of their movement through and displacement of water. These surface disturbances spread toward the boundaries of waterways, where they interact with both natural and built environments, often with adverse effects. The magnitude and frequency of impacts related to vessel waves are becoming increasingly evident in estuarine and coastal waterways worldwide. As an outcome of an international workshop, drawing on the collective expertise of academics, practitioners, and policymakers from various disciplines, this overview synthesizes the current 'state of play' regarding the varied effects of vessel waves in sheltered water bodies, associated use conflicts, and potential mitigation strategies. These insights are presented within the context of existing literature and include references to illustrative case studies. While there is broad recognition of the need to manage the impact of vessel waves on both built and natural environments, challenges such as gaps in process understanding, regulatory limitations, political complacency, and economic realities of global seaborne trade can impede effective mitigation of vessel wave effects on land-water interfaces. With an anticipated increase in waterborne transportation and recreational boating on one hand and the need to reduce adverse effects of intense waterway use on the other, vessel waves are a prominent topic, underscoring the future requirements for improved process understanding, monitoring, data sharing and the importance of holistic management of vessel-related impacts in waterways.

Keywords:

vessel wave, ship waves, vessel wave impacts, wake, waterway management, infrastructure, environment

[1]Federal Waterways Engineering and Research Insitute (BAW), Germany
[2]Leichtweiß-Institute for Hydraulic Engineering and Water Resources, Technische Universität Braunschweig, Germany
[3]Coastal Research Center, Joint Research Facility of Leibniz University Hannover and Technische Universität Hannover, Germany
[*]gregor.melling@baw.de

Research article. **Submitted:** 20 December 2024. **Reviewed:** 24 June 2025. **Accepted** after double-anonymous review: 18 August 2025. **Published:** 14 October 2025.

DOI: 10.59490/jchs.2025.0049

Cite as: Melling, G.; Holzwarth, I.; Dempwolff, L.-C.; Windt, C.; Goseberg, N. (2025). A global review of vessel wave effects on land-water interfaces: collaborative baselining of issues, management strategies and future challenges, Journal of Coastal and Hydraulic Structures, 5, 49. 10.59490/jchs.2025.0049

ISSN: 2667-047X online

1 Introduction

Coastal, estuarine and riverine areas face the challenge of balancing the imperative to safeguard their environments while fostering economic prospects for an expanding population (Martínez et al., 2007). As an important economical element, ports are hubs of international trade and, thus, significant for global supply chain connectivity and socio-economic development (Santos et al., 2018; Munim and Schramm, 2018; Woo et al., 2018). Shipping and boating activities for transport, economic resource extraction and recreation are often historically deeply entrenched in these areas. Inadvertently, the intensive use of water bodies can cause a variety of unwanted effects, especially in naturally sheltered areas. Coastal water bodies are not only economically significant waterways but also serve as habitats for diverse flora and fauna, sources of drinking water, recreational and tourism assets, fisheries resources, and provide for industrial and agricultural uses; this recognition has increased awareness of the manifold detrimental effects that shipping and boating can have (Jägerbrand et al., 2019; Moldanová et al., 2022). Various air and water pollution issues, ambient and underwater noise (Jalkanen et al., 2022), physical damages (e.g., via fauna collisions or mooring) and proliferation of invasive or alien species typically feature prominently in this context (Mosisch and Arthington, 1998; Burgin and Hardiman, 2011; Byrnes and Dunn, 2020; Carreño and Lloret, 2021), but also the impact of ship-induced wave and current loads from recreational craft (e.g. Mosisch and Arthington, 1998; Burgin and Hardiman, 2011), high-speed craft (Soomere and Engelbrecht, 2005) and shipping (e.g., Gabel et al., 2017; Dempwolff et al., 2022) are gaining attention.

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*a*; 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.

Given the severity of the interactions between vessel-induced water motions and the land-water-interface, an international workshop titled ”ShipWave2023” was initiated, organized and held from 22[nd] to 24[th] March 2024, in Hamburg, Germany, with the authors of this work constituting the core group of the organizers. The motivation for this workshop stemmed from the authors' perceived intensifying urgency of this topic with the necessity for coordinated and cross-disciplinary examination and the apparent lack of formal venue of exchange and cooperation. While an increasing number of individuals are working on this topic, there is no coherent research network, dedicated conferences or organised forums of exchange to foster cross-pollination of ideas and experiences, which is desperately needed in the light of challenges ahead.

This publication attempts to compile the wide variety of contributions made during the workshop discussions and to contextualise them within the perspectives documented in literature and case studies, thus, it also constitutes a sweeping review of the current status quo relating to vessel wave effects on land-water interfaces, with a specific focus on their management strategies and practices. The format of the workshop is described in Section 2, followed by an elaboration on the outcomes from workshop discussions with respect to issues related to vessel waves (Sec. 3) and current and potential future management strategies (Sec. 4); future visions for these respective topics in terms of the expected future developments and challenges are given in Section 5. In closing, the authors offer a summary of their views on the 'state of play' with respect to problem descriptions, possible solutions and methods with a view to future challenges and research needs (Sec. 6).

2 Description of workshop methods, implementation and outcomes

The 1st International Workshop on Ship-induced Hydrodynamic Loads in Shallow Confined Coastal Waterways ('ShipWave 2023') was held in Hamburg, Germany, on the 22-24th March 2023. Workshop participants were invited primarily by personal invitation based on a review of publications; however, some participants joined via word-of-mouth recommendations. In total, approximately 45 delegates participated, mostly based in institutions (universities, consultancies, regulators) from continental Europe (Germany, Belgium, Netherlands, Italy, Estonia, France), but also from further afield such as the USA, Canada and Australia. Unfortunately, no delegates representing perspectives from BRICS economies attended; this also applies to emerging economies and developing countries. It is important to recognise that these perspectives might be lacking, and a certain degree of European bias cannot be ruled out. Notwithstanding this caveat, the authors believe that the broad ideas and discussions offered in this publication are not unique to the European context and are expected to be similarly applicable to other geographies. The aim of the workshop was to facilitate formal and informal exchange within the community, with the overarching assignment of baselining the current 'state of play' with regard to issues with vessel-induced waves across various geographies and, in particular, the way these are addressed. The aspired outcome was a unified view on the available knowledge and practices, while understanding similarities and differences.

2.1 Workshop methodology

The workshop was structured into conference-style presentations and interactive workshop sessions. It also contained a technical block for delegates to present relevant work in short presentations and Q&As as well as posters for free perusal and discussion. A mix of topics was presented at the technical sessions; abstracts can be found in Holzwarth et al. (2023). The workshop components consisted of moderated interactive sessions with break-out group discussions in the format of a 'world café' (Schiele et al., 2022) based on predetermined problem-oriented topical questions. The world café format is a structured conversational process designed to foster open and collaborative dialogue. Participants rotate between small groups to discuss a series of questions on a particular topic, with discussion points and key insights recorded and shared. The first world café focussed on region-specific experiences and issues associated with vessel-induced waves. In this, the scale and nature of issues as well as management and mitigation strategies were discussed while comparing and contrasting geographical commonalities and differences. The break-out groups were predetermined for maximum heterogeneity of origin, background and technical expertise to broaden perspectives and facilitate open exchange of ideas. The second world café was focussed on method-specific exchanges, the outcomes of which are not included in this publication. Discussion outcomes were documented interactively, enabling participants to annotate and visually represent ideas, enhancing collaborative engagement. These documents along with the recollections of the table moderators were then used in the knowledge mining process to aggregate, structure and compile the important findings and outcomes of the workshop. This is, in essence, what informs the contents of this publication.

2.2 Workshop outcomes

In the following, the authors endeavour, with the benefit of retrospect and extensive further research, to distill the accounts of delegates into a concise synthesis of the workshop outcomes. To ensure scientific rigour, these accounts are scrutinised and contextualized within the existing body of published knowledge. To achieve this, in a first knowledge mining step the documented outcomes of the group discussions were analyzed and aggregated in order to systematically organise and summarise the contributions under appropriate topical headers and subheaders. This excercise informs the structure of this publication in Sections 3, 4 and 5. In this process, relevant search strings were extracted to facilitate an in-depth exploration of available literature (scientific and grey) and case studies. These search terms include topical and technical terms related to the scientific background but were also used in combination with specific locations and geographies, to identify relevant case studies and uncover grey literature. The aim was to 'cast a wide net' as the reference to illustrative (case) studies is deemed imperative to provide further clarity, depth and insights from real-world practice. The main aspects cover:

i. A concise overview of reported issues related to the adverse impacts of vessel-generated waves on land-water interfaces (Sec. 3):

- environmental and ecological impacts,
- socio-economical conflicts of use, and
- infrastructural damages.

ii. A comprehensive compilation of current, as well as potential future management strategies and practices (Sec. 4) for the mitigation of vessel wave effects, classified into

- educational efforts,
- regulatory options,
- strategic decisionmaking,
- engineering solutions, and conversely
- non-mitigtaion with niche exploitation of vessel waves.

iii. A look ahead to future challenges facing waterways in relation to vessel-generated waves (Sec. 5), concerning

- trends and developments in vessel size evolution and potentially intensifying waterway use,
- drivers and inhibitors of sustainable waterway use,
- the influence of climate change-driven alterations of waterway characteristics, and ramifications for vessel loads and their spatial distribution,
- the importance of incorporating vessel wave mitigation in holistic waterway management plans, and
- the significance of monitoring and mutual open data sharing.

3 Vessel wave impacts

As vessels travel through water, they generate long-period and short-period wave components (e.g., Bhowmik, 1981; Oebius, 2000), which interact in different ways with waterway embankments (e.g., Maynord, 2004). Long-period waves (typically 60 s – 120 s wave period), including the bow wave, drawdown, and stern wave, are characteristic of displacement vessels, such as those used in commercial shipping within inland and tidal waterways. These waves, also referred to as the primary wave system, Bernoulli wave, or displacement wave, typically grow in magnitude with increased channel confinement and higher vessel speeds (cf. Fig. 1). The high significance of long-period vessel waves in shallow confined waterways – which was echoed in workshop discussions – led Dempwolff et al. (2022) to compile a comprehensive review of various issues related to waves from large displacement vessels. High-speed craft (e.g., ferries and small commercial vessels) can produce longer-period packets of diverging waves (10 s – 15 s wave period) (Kirkegaard et al., 1998; Parnell and Kofoed-Hansen, 2001; Soomere, 2005) and high-energy precursor solitons, when travelling at transcritical speed (Soomere, 2006; Osborne et al., 2007*a*), as well as secondary divergent wave packets (Kelvin wake, Reed and Milgram (2002); Sun et al. (2022)). While there are differences in the mode of generation, characteristics, propagation, transformation and range of influence of said low-frequency waves from displacement and high-speed vessels, their impacts in the nearshore area are often comparable. Recreational boating is associated with short-period (secondary) wave systems, which can also be harmful in sheltered environments (e.g., Mosisch and Arthington, 1998; Maynord et al., 2008; Herbert et al., 2018; Bilkovic et al., 2019; Safak et al., 2021), see Fig. 2. Vessel wave issues often arise in sheltered environments that are not naturally exposed to significant loads from wind waves or currents. These areas are thus not adapted for high wave loads and, in particular, are vulnerable to long-period wave loads (Macfarlane and Cox, 2004) due to the way these energetic low-frequency waves interact with and transmit energy to the bathymetry and shoreline (Gourlay, 2011; Osborne et al., 2007*a*). The complex highly nonlinear processes occurring during the interaction of these long-period waves with the topography (cf. Figs. 1, 7 and 12) have been partially described, including for solitons preceding fast-moving ships (Parnell and Kofoed-Hansen, 2001; Soomere, 2006, 2007; Soomere et al., 2011) as well as drawdown waves from displacement-type ships (Maynord, 2004; Rapaglia et al., 2011; Parnell et al., 2015, 2016; Wang and Cheng, 2021), however many questions still remain (cf. Sec. 5). 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). Even in cases where vessel waves contribute only a relatively small portion of the total wave energy, the long-period components of vessel waves can represent a disproportionately high share of the effective load on the shores in sheltered areas (e.g., Osborne et al., 2007*a*; Houser, 2010; Soomere et al., 2011). Vessel waves are thus universally acknowledged as important drivers of change in naturally low-energy environments that are associated with diverse deleterious effects at the land-water interfaces, as witnessed in the wide-ranging issues reported and discussed at the workshop.

3.1 Environmental aspects of vessel waves

A wider review of the impact of shipping and boating on various environmental aspects is given by Byrnes and Dunn (2020). Mosisch and Arthington (1998) and Burgin and Hardiman (2011) offer deeper insights into the detrimental impacts of recreational power boating, including the effects of boat wakes, on the physical, chemical and biological environment in non-tidal water bodies which demonstrates that, in principle, these impacts have been known for many years – Mosisch and Arthington had already concluded that due to the severity of impacts regulatory measures are required which restrict or prohibit outright the use of high-powered boats in vulnerable water bodies. An exhaustive review of environmental and ecological impacts on macrophyte vegetation and fauna such as invertebrates, fish and birds including their lifecycle, growth, abundance and behaviors is provided in Gabel (2012) and Gabel et al. (2017). Gabel et al. also offer their view on management of these issues, state however the need for research into the proposed solutions and their effects on ecology. Fenton et al. (2023) succinctly summarise the effects on ecology as stemming either from increases in fluid velocity and/or the rate, magnitude and duration of water level changes as experienced by the river bank. Xue et al. (2021) examined sedimentary cores from a shipping channel in China and show that ship activity mobilises fine-grained sediment, reducing its abundance in the cores (compared to pre-shipping era) and altering certain biogenic element ratios; these changes suggest that frequent ship disturbances reduced biological productivity in nearby waters. The capacity of ships to facilitate the mobilisation of sediment and increased turbidity has been widely documented for various ship types in tidal and non-tidal waterways alike for several decades (e.g., Renger and Bednarczyk, 1986; Velegrakis et al., 2007; Osborne et al., 2007*b*,*a*; Davis et al., 2009; Rapaglia et al., 2011; Gelinas et al., 2013; Göransson et al., 2014; Niehueser et al., 2016; Uliczka and Kondziella, 2016; Larson et al., 2017; Ulm et al., 2020; Mao and Chen, 2020; Wei et al., 2020; Fleit and Baranya, 2021; Chakraborty et al., 2023). 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). Sediment mobilisation potential is exacerbated in waterways with heavy ship traffic and closely timed ship passages due to the repeated wave resuspension events (e.g., Scarpa et al., 2019; El Safty and Marsooli, 2020) and owing to the reduced erosion threshold of previously mobilised sediments (Schoellhamer, 1996). The resulting potential for erosion of unprotected shorelines, mud flats and salt marshes as well as the morphological reshaping of beaches was widely reported at the workshop and has also been documented for various localities around the world for loads resulting from seagoing commercial ships (e.g., Dauphin, 2000; Houser, 2010; Zaggia et al., 2017; Scarpa et al., 2019; El Safty and Marsooli, 2020; Muscalus and Haas, 2022), for inland commercial shipping (ten Brinke et al., 2004; Duró et al., 2020; Stancu et al., 2024, e.g.,), high speed craft (e.g., Nanson et al., 1994; Parnell and Kofoed-Hansen, 2001; Soomere, 2005; Parnell et al., 2007; Velegrakis et al., 2007; Cote et al., 2013; Meyers et al., 2021) and for recreational boating (e.g., Bauer et al., 2002; Maynord et al., 2008; Fonseca and Malhotra, 2012; Bilkovic et al., 2019). Shoreline erosion can precipitate other deleterious effects such as, e.g., damage and potential loss of underwater and above water archaeological and historical sites (Murphy et al., 2006), and sites of local cultural significance (O'Halloran and Spennemann, 2002), or the reshaping of shallow water and intertidal habitats with ecohydraulic effects (Gabel, 2012; Gabel et al., 2017). Further, erosion is a major contributor to decreasing water quality via (re-)mobilisation of sediments, increased turbidity, as well as the release and dispersal of soil-bound pollutants and nutrients, all of which have a wide range of implications for flora and fauna (Murphy et al., 2006; Gabel, 2012; Gabel et al., 2017). Some morphodynamic effects of vessel waves such as gravel berm reshaping have proven irreversible even after the energy source is restrained due to the lack of naturally-occuring energy to reverse the morphological alterations, thus creating lasting legacy effects (e.g., Soomere et al., 2011).

Figure 1: Plunging breaker stern wave (part of the long-period wave system) in shallow embankment area generated by moderately-sized commercial vessel in the Weser Estuary, Germany. Source: Federal Waterways Engineering and Research Institute (BAW).

Figure 2: Interaction of short-period waves from recreational vessel with an embankment in an inland waterway. Source: Federal Waterways Engineering and Research Institute (BAW).

3.2 Socio-economic aspects of vessel waves

Conflicts of use arise from the multiple pressures faced by waterways as habitats, recreational areas and various economic uses such as shipping, tourism and fishing. The equitable use of water bodies by all stakeholders is a balance that is often skewed in favor of shipping (de Barros et al., 2022), a notion which was recognised and echoed by delegates. In this respect, aside from the previously discussed environmental degradation effects which can be detrimental to other uses and functions of the water body, vessel waves can directly affect the value of water bodies to society at large (cf. also Sec. 4). Apart from the obvious risk of collision, recreational use can be directly negatively impacted due to vessel-induced waves and currents; wave heights can be unsafe for beach users, or features such as strong undertow currents during the drawdown can pose grave danger to other waterway users. Risk to life, including fatality, for shoreline users has been documented by (de Jong et al., 2013) who also reconstructed the specific circumstances of the incident in a numerical model. A connection with passing ships is suggested as an aggravating factor for a number of drownings in the Elbe Estuary (e.g., Büll, 07.09.2023) and other cases exist where vessel waves are implicated in the endangerment of beach users (e.g., Summa, 12.07.2001; Gemeenschappelijk Nautisch Beheer Scheldegebied, 2011; Savannah Morning News, 07.02.2023). In general, the risk of ship-induced waves and currents to other recreational uses are accepted. In Germany, swimming in federal waterways is restricted near bridges, hydraulic structures (e.g., weirs, tidal gates, groynes, breakwaters, training walls, etc.) as well as port and shipping infrastructure (e.g., berths, quays, jetties, locks, buoys, etc.), near ships as well as anywhere with relevant prohibition signage (WSV, 2022, 2023). Local authorities either strongly advise against swimming in heavily shipped waterways such as the Elbe Estuary (hamburg.de, 22.01.2024) and the Rhine (e.g., Stadt Köln, 29.03.2023) or prohibit them outright, as for some sections of the tidal Elbe (Stadt Wedel, 22.01.2024) – with explicit reference to ship-induced waves and currents. Similarly, in the St. Lawrence Seaway swimming and other water sports activities are prohibited in all canals and channels as well as near canal and shipping infrastructure and their approaches (Great Lakes St. Lawrence Seaway System, 2023) and city ordinances prohibit entering the water near the Houston Shipping Channel off Galveston Island (Galveston Island Beach Patrol, 03.02.2024) due to treacherous ship-generated currents. Vessel waves can also pose a threat to other waterway users such as small pleasure craft, rowing boats and canoes by, e.g., the suction effect of the low-pressure depression of the drawdown which draws other vessels towards the ship or the danger of capsizing due to the divergent or transverse waves (Florio, 06.08.2018). Thus, safe recreational activities are often limited to the upper beach area, where illustrative warning signs highlight the dangers of vessel waves. 'Dry' land does not, however, entirely protect from vessel wave impacts as exemplified in Venice Lagoon where boating (with excessive speed) reportedly jeopardises the safety and perceived enjoyment of waterside culinary and leisure experiences (Giuffrida, 01.10.2024). Vessel waves can thus incur socio-economic cost to tourism and also property values, e.g., by loss of land area as a result of embankment erosion. Vessel waves can also interfere with other economic uses such as fishing or waterborne harvesting activities (e.g., seaweed, shellfish, crustaceans) (Haro et al., 2020).

Apart from the enjoyment value, the infrastructure of touristic and recreational waterway use can also be affected. The suction and surge currents of long-period waves (Kunz, 1977*a*) can damage vessels in waterway-adjacent marinas, especially if these are not moored appropriately. These are essentially the same processes which are recognised in passing ship effects on moored vessels that will be discussed in Sec. 3.3. The mentioned effects are some exemplary aspects of the clash of vessel wave effects with other economic and non-economic interests, especially recreational and tourism, reduction of property values along with other shipping-related (but non-wave) effects such as water and air pollution as well as noise. One topic of contention at the workshop was the question of liability for adverse effects and how to enforce it. Murphy et al. (2006) offer examples from the USA where legal responsibility for boat wake impacts (damages to property, personal injury) is assigned to the boat user, which in turn reportedly encourages low wake boating; it remains unclear if or how enforcement takes place in the recreational boating context. In the commercial shipping context the question of liability is, to the authors' knowledge, not settled, at least not in a practical sense, since it requires a willingness by waterway administrators to enforce and pursue offenders. Given the economic significance of major waterways, this can present as a conflict of interest. Further, there is a burden of proof which presumably requires evidence of the vessel wave and its associated impact to be documented in a legally incontestable manner. This is a technically challenging prospect, however is, in principle, feasible with tailored monitoring programs for damage hotspots (cf. Sec. 5.5). Thus, for the time being, it appears likely, that the damages created by shipping are, in effect, paid for by the taxpayer as part of the costs for upkeep of waterways and their infrastructure. 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.

3.3 Infrastructural considerations to vessel waves

Infrastructure damages due to vessel waves were not widely considered as a major concern in the workshop discussions. Similarly, relatively few publications exist on this topic, apart from the context of German estuarine waterways where there are reports of damage to revetments (Ohle and Zimmermann, 2001) (Fig. 3), rubble-mound structures (Melling et al., 2020, 2021) (Fig. 4) as well as hydraulic structures (Kunz, 1977*b*; Uliczka et al., 2008); further cases of vessel wave-induced structural damages are plentiful but often undocumented. Reports outside of the mentioned locality are linked to erosion of levee structures in the San Joaquin River Delta, California, USA (Bauer et al., 2002) and scour issues in the Burlington Channel, Canada (Taylor et al., 2007). Direct structural damage to the foundations and walls of historic buildings, canal walls and historic wooden pier structures by ship and boat waves is reported from Venice, Italy (Chiu et al., 2002). The perceived scarcity of documented cases of damage to the built environment in other locations may stem from a high number of unreported incidents, or civil structures in these areas are designed with inherently greater safety margins, making them more resilient to ship-induced loads. The latter, from anecdotal comparisons, appears to apply to rock structures (e.g., groynes, revetments) in German waterways as opposed to, e.g., waterways in the Netherlands.

One more common area of concern is damage to infrastructure through passing-ship effects on moored vessels. The influence of the long-period drawdown and its effects on moored ships at quays, jetties or marinas has been known for many years (e.g., Kunz, 1977*a*; Kurata and Oda, 1984; Flory, 2002; Cornetta and Knox, 2008; Tschirky et al., 2010; Delefortrie et al., 2012; Böttner and Kondziella, 2022) in particular lateral forces caused by the suction effect of the drawdown wave can lead to failure of mooring lines or mooring bollards. Drifting vessels

Figure 3: Displacement of rock armour from revetment due to long-period vessel wave action in the Lower Elbe Estuary, Germany. Source: G. Melling.

Figure 4: Rock groyne damage due to long-period vessel wave impact in the Lower Elbe Estuary, Germany. Source: Federal Waterways Engineering and Research Institute (BAW).

can cause further damage to other vessels (moored or under way), port, marina or transport infrastructure (e.g., National Transportation Safety Board, 12.11.2014; Buitendijk, 20.05.2019). In a similar vein, Heijboer (2024) reports that in the locks of the Western Scheldt, vessels are being displaced from open locks by currents generated by drawdown waves, which not only cause damage to lock structures but can also lead to vessel collisions within the locks.

4 Vessel wave management strategies

The workshop explored a wide range of management strategies for mitigating the effects of vessel waves, and further research uncovered numerous examples of practical implementations. Below, this work provides a comprehensive overview of these strategies, their efficacy and potential limitations. Mitigation generally focuses on either reducing wave generation at the source or reducing impacts in affected areas. As will be discussed, selecting appropriate measures —- or a combination of measures -— will depend on the specific challenges and boundary conditions at the respective location; however, there are some management options that are universally applicable and efficient.

4.1 Education and raising awareness

Educational initiatives offer accessible options for raising awareness among waterway users, both at the source and the receiving end of vessel waves. They do, however, require sustained, long-term efforts to effectively and lastingly 'convey the message'. Awareness raising with recreational boat users with respect to the impact of boat wakes and ways to minimise these appear established in the US and Canada (Murphy et al., 2006; National Boating Safety School, 2023). Conveyed mitigation measures include guidance to sustainable boating practices, prescription of 'no wake rules' in specific static (e.g., near shorelines or structures) or dynamic areas (e.g., near swimmers) or encouraging the use of low-wake hull types; these educational measures are deemed to be relatively successful tools to reduce adverse boating impacts especially when combined with penalties for non-adherence such as fines and damage liability (Murphy et al., 2006). Similarly, awareness raising for commercial ship captains and waterway pilots should also be considered. The German Federal Waterways Engineering and Research Institute (BAW) is engaging with the Elbe pilot association to educate about the impact of long-period vessel waves on the surrounding estuarine environment; after several years of engagement, perceived success is reported. Heijboer (2024) observes that the detrimental effects of passing ships in the locks of the Western Scheldt are significantly more severe in areas where pilots are unaware of the impact of their vessel waves, compared to locations that are perceived as vulnerable. In the latter, navigational practices have been adapted with reduced speeds and increased passing distances from the locks. The importance of training vessel operators is further emphasized by PIANC (2002) for operators of high-speed vessels, who should have an understanding

Figure 5: Warning sign illustrating the dangers of vessel waves at the Nieuwe Waterweg, the main access channel to the Port of Rotterdam, Netherlands. Source: G. Melling.

Figure 6: Sign warning of the risk of drowning due to vessel waves and associated currents at the Lower Elbe Estuary, fairway to the Port of Hamburg, Germany. Source: G. Melling.

of the physics of wave generation and the impact of navigational decisions on the resulting vessel wake; this knowledge is crucial for minimizing wave-related impacts through informed navigational practices (e.g., speed regimes, vessel trim, distance to shore).

It is imperative that other waterway users are fully aware of the risk posed by vessel waves. Signage indicating the dangers of swimming near shipping lanes are the most accessible and probably most widely practiced option, see Fig. 5 and 6. Other options include the deployment of lifeguards who, in addition to providing life-saving services, can play a key role in informing shoreline users and coordinating with traffic control to prepare beachgoers for the passage of large vessels, for instance, by advising people to exit the water (Gemeenschappelijk Nautisch Beheer Scheldegebied, 2011). Similarly, for Tybee Island on the Savannah River Bain et al. (2022) suggested an early-warning system which is described as a warning beacon with auditory alert for approaching vessels, potentially coupled to measurement devices that identify ship passages with potentially large wakes.

4.2 Regulatory measures

4.2.1 Optimised vessel design and selection

Optimised vessel design has long been recognized as a means to reduce the wavemaking resistance, the primary source of drag, of displacement vessels (e.g., Osawa and Osawa, 1995; Tsai, 2008; Bolbot and Papanikolaou, 2016) and high-speed craft (e.g., Stumbo et al., 1999; Cartwright et al., 2008; Radojcic, 2009; Wang and McOwan, 2000; Jasic, 2017; Soares and Santos, 2021). Low-wake vessel design is particularly important for commercial services that rely on speed for their economic viability (Stumbo et al., 1999; PIANC, 2002; Soares and Santos, 2021). Vessel hull design addresses primarily the issue of secondary waves; the long-period wave cannot be eliminated entirely through design, as it results from the vessel's water displacement (submerged cross-section) and the pressure disturbance caused by its motion. Most vessels are optimized for specific operating conditions (e.g., water depth, speed range) and tend to be less efficient when operating outside the design parameters (Donatini et al., 2019), as is the case, e.g., for sea-going vessels during approach channel navigation in shallow and confined waters. PIANC (2008) provides guidance on design options (such as hull, bow, and stern shapes, as well as propulsion systems) aimed at reducing wave and current loads for inland vessels. Due to the typical service life of vessels, improved designs are viewed as long-term strategies to reduce wave loading and, thus, selective licensing of specific low-wake vessel types can prove a long-term strategy to reducing future impact. Selective licensing restricts the type of vessel that can be operated in a specific waterway based on certain compliance criteria (cf. Sec. 4.2.2). Waves from high-speed vessels have been an issue in many locations globally (e.g., Canada, US, UK, Denmark, Australia, New Zealand) and has often resulted in selective licensing of lower-wake vessels and implementation of speed limits Stumbo et al. (1999); Murphy et al. (2006). Advancements such as hydrofoil technology have recently been touted as solutions to reduce boat and ferry wake impacts in sensitive areas such as Venice Lagoon (Reuters, 2021) and Rich passage, Seattle (Cote et al., 2013). Vessel design can also be used to address changing boundary conditions during vessel operation, e.g., increased frequency and duration of low water stages in inland waterways. Radojcic (2009) proposes optimised design parameters for barges and barge trains on the Danube, including reduced draft and weight to lower hydrodynamic resistance in shallow water. While acknowledging that these optimized designs incur a cost of reduced logistical and economic efficiency, making them less competitive with rail and road transport, lower-draft vessels have the advantage of being able to operate year-round. Similar recommendations have been compiled by CCNR (2021) for the Rhine, in response to increasing low water conditions. These adaptations to the shipping fleet, driven by climate change impacts, could present an opportunity to reduce vessel wave loads through regulations promoting low-wake vessel types. While secondary waves would be significantly reduced, primary waves would also decrease due to the lesser draft of these ships.

4.2.2 Speed regulation and vessel wake criteria

The beneficial effect of speed restrictions for all waterborne vessels on wave loading is proven and some best practice guidance already exists (e.g., Danish Maritime Authority, 1997, 1999; PIANC, 2002, 2008). For high-speed vessels the relationship between wave height/energy and vessel speed is non-linear in so far as waves generated in the trans-critical speed regime are higher than at either sub- or supercritical shallow-water Froude numbers ($Fr_{sw} = U/\sqrt{gh}$, where U is the vessel speed, g is the gravitational acceleration and h is the water depth) (Kirkegaard et al., 1998); sustainable navigational practices should, hence, avoid extended periods of cruising in the trans-critical speed regime during acceleration and deceleration. Reducing the rate of turn and vessel speed during course changes to avoid the focussing of wave energy on the inside of a turn is one of several navigational practices suggested by PIANC (2002). To this end, various incarnations of wake criteria for high-speed vessels exist. One of the earliest is a wake criterion by Danish Maritime Authority (1997) which limits the maximum permissible ratio of wave height to the square root of the wave period. This also finds application in Marlborough Sound, New Zealand (Marlborough District Council, 2002) and in slightly modified form also finds application in the operating area of the Washington State Ferries, USA (Cote et al., 2013). Stumbo et al. (1999) explains that the wake criteria for high-speed craft in Puget Sound were determined by a multidisciplinary study measuring erosion, habitat impact and wave characteristics and drawing inferences to the maximum permissible wave height of 0.28 m and maximum permissible wave energy. This can be translated into allowable vessel speed by knowing the characteristic (non-linear) relationship between vessel speed and energy density. This approach is suitable to inform for vessel selection and selective licensing, however it does not facilitate easy enforcement since the readily measurable vessel speed is not a fixed quantity. A similar approach for the licensing of vessels was implemented in the Gordon River, Tasmania (Bradbury, 2005), where long-standing erosion issues were addressed with a stringent wave height criterion for commercial cruise vessels and speed limits for recreational vessels. Owing to the increase in vessel lengths and the resulting longer wave periods, the regulators moved away from the simplistic wave height criterion to a version of the Danish Wash Rule modified for local conditions. Gourlay (2011) emphasizes that wave period is similarly important, as the interaction of long-period waves with shallow areas and embankments often results in increased current velocities, prolonged load duration, intensified vertical velocity components, and the formation of plunging breakers. This is compounded by the fact that natural environments are typically less adapted to withstand long-period wave loads, amplifying their impact. Macfarlane and Cox (2004) developed vessel wake criteria for the Noosa and Brisbane rivers in Australia based on an energy-based criterion and a period-based criterion, both of which account for long-period waves. The latter criterion is based on the vessel length at the water line, and suggested management options include a blanket speed limit that satisfies the two aforementioned criteria but is easier to enforce. Bilkovic et al. (2019) shows with the example of Chesapeake Bay that regulations are often not applied comprehensively but vary from state to state or even by local authority, and lists other localities with 'no-wake' speed limits such as Rhode Island, USA, and North Carolina, USA.

While relatively common for regulations on the travelling speed of high-speed or recreational vessels, there are also examples of such measures targeting commercial shipping. The efficacy of speed reductions in reducing ship-induced loads from commercial shipping is widely acknowledged and in numerous areas has been adopted into waterway regulations such as in the tidal Lower Elbe as the fairway to the port of Hamburg, Kiel Canal, Venice Lagoon and St. Lawrence Seaway – examples which will be discussed in the following. In Germany, from all major tidal waterways only the Lower Elbe has a speed restriction which applies to ships greater than 90 m in length and is increasingly restrictive, the more inland and the narrower the waterway, from 15 kn speed through water in the Outer estuary to 10 kn in the vicinity of the port (cf. Section 26(3) of BSH, 2023). Unpublished work by the Federal Waterways Engineering and Research Institute also suggests that the speed restriction for large vessels on the Lower Elbe estuary has resulted in a reduction of wave and current loads at the shoreline. Currently, in the Kiel Canal a blanket speed restriction of 12 km/h is in place for all vessel types (cf. Section 26(3) of BSH, 2023); prior to July 2023, smaller vessels were allowed to travel at a speed of 15 km/h, however due to the discovery of numerous damages to the unprotected underwater embankments this exception was retracted. In Venice Lagoon a local ordinance from 2002 imposes a blanket speed limit of 20 km/h in the Lagoon, 11 km/h in the historical centre and 5 km/h – 7 km/h in the Grand Canal and smaller canals (Chiu et al., 2002), however a lack of enforcement is being reported in news giving rise to novel ideas such as speed cameras for boats and ships (McKenna, 28.01.2024; Giuffrida, 01.10.2024). In the Malamocco-Marghera-Channel (MMC), recently speed restrictions have been adopted to combat excessive mud flat erosion (Zaggia et al., 2017); a 6 kn (11.1 km/h) limit in immediate port access area (Scarpa et al., 2019) and a speed restriction to 8 kn – 10 kn (14.8 km/h – 18.5 km/h) for commercial shipping in the approach channel (Pedroncini and Menegazzo, 2023, 2024). In some sections of the St. Lawrence River, Canada, where waves from commercial shipping were implicated as a major contributor to shoreline erosion (Dauphin, 2000; Gaskin et al., 2003; Davies, 2023), a voluntary speed limit of 10 kn (18.5 km/h) travelling upstream and 14 kn (25.9 km/h) travelling downstream (Ministère des Transports du Québec and Transports Canada, 2021) in particularly vulnerable areas of the river was introduced in 2000 and recently renewed (The St. Lawrence Seaway Management Corporation, 2022). As reported by Environment Canada (2010) this measure has proved successful in reducing erosion rates, owing also to the relatively high adherence rate of over 85%, however, the processes of shoreline erosion are complicated by the low erosion resistance of the clayey shoreline sediments to breaking waves and weathering phenomena, so that fluctuating water levels can give rise to renewed episodes of erosion at different levels of the embankment.

Speed restrictions are deemed effective low-cost solutions by delegates and backed up by an increasing number of real-world case studies. PIANC (2008) suggest speed limits could be the best option for mitigation in many cases, stresses however the need for effective enforcement and, prior to introducing such measures, an assessment of the costs incurred by imposing speed restrictions against those of engineering options. A certain minimum speed through water is required in order for safe navigation and maneuvering, there is however the potential for optimisation of blanket speed restrictions by more granular approaches. Exploring the advantages and disadvantages of speed restrictions based on ship dimensions, class or based on a meaningful parameter such as Froude-number as suggested by Saha et al. (2017). Blanket speed restrictions are, however, the simplest option in terms of enforcement; whether economic gains of more granular speed limit management outweigh the simplicity of the blanket restriction is to be considered by regulators. Speed limits could feature as part of the wider traffic management in waterways such as for ship scheduling, which determines the sequence of wait times, sailings and vessel speed and is used for better traffic fluidity and can lead to a more efficient exploitation of waterway capacity (Liang et al., 2019; Andersen et al., 2021; Tzortzis and Sakalis, 2021; Zhuang et al., 2024). This could be used to counteract the main downsides of speed restrictions which manifest in longer transit times and, thus, a lesser degree of utilisation of the waterway and an economic cost as well as a competitive disadvantage for port operators. This is the main reason that makes this very effective management option uniquely unpopular with regulators and port operators. For recreational boaters, speed limits can be perceived as a loss of enjoyment and welfare, as suggested by Zanatta and Rosato (2005). The use of decision support tools to determine where speed restrictions should be applied is outlined by, e.g., Glamore (2008); Fonseca and Malhotra (2012) and Almström et al. (2022), however, where available, the knowledge of local authorities and waterway regulators should be used to pinpoint vulnerable areas and let field experience inform decisions.

More widely, speed regulation is also being considered as a possible way of reducing emissions of global shipping (e.g., Corbett et al., 2009; Lindstad et al., 2011; CE Delft et al., 2012; Taskar and Andersen, 2020; Tillig et al., 2020) and air pollution (Heikkilä et al., 2024), which is adding a certain momentum for the increased adoption of 'slow steaming'. Speed restrictions, voluntary or mandatory, could thus offer multi-benefit solutions but must be weighed against the potentially increased economic and logistical cost. To date, experience shows that it is fairly universally not a very popular solution for port operators and waterway regulators, primarily because it is perceived as reducing competitiveness of the connected port due to increased passage duration and thus increased cost for shipowners. The shipping industry faces a large challenge to reduce its emissions

(UNCTAD, 2023) and 'slow steaming' is a viable option in the transition between old vessel fleet and new low-carbon fleet as many ships are too young to be retired and too old to be retrofitted, if the gains are not offset by a greater amount of ships required to cater for trade volumes.

4.2.3 Exclusion of vessels

Another option for the mitigation of negative vessel-induced effects is the complete exclusion of all or certain types of boats and ships from vulnerable areas, such as the cruise ship ban in parts of Venice, redirecting these via the MMC to a temporary terminal at the Marghera port (UNESCO World Heritage Centre, 2021), as well as a ban on touristic recreational boating on the Canale Grande (Florio, 31.07.2018). While serving to alleviate wave pressures in the exclusion zone, it can lead to increased pressure elsewhere, as is the case for the MMC. For this reason, exclusion of vessels should be considered as an option for areas that are not sufficiently served by a speed reduction. For small waterways and recreational boating, Mosisch and Arthington (1998) and Bilkovic et al. consider the possibility of banning motorised traffic outright or restricting vessels to a certain sustainable number per day; both options however appear unsuitable for commercial shipping in major waterways. Similar notions are found in PIANC (2008) who suggest limited licensing of vessels that satisfy certain dimensional or engine power criteria and cite the Canals of France and Great Britain as successful implementations of these policies. Depending on the impact to be alleviated, exclusions and restrictions can apply temporarily, seasonally or permanently and cover entire water bodies or only parts (such as specified distance to vulnerable area for instance). A more intricate version of this strategy could consider enforcing single-lane traffic and the prohibition of overtaking (PIANC, 2008) to keep vessels away from vulnerable lateral areas.

4.3 Strategic and administrative measures

Strategic decisions can relate to unilateral decisions on the (re-)location of port and waterway infrastructure, directing commercial shipping traffic to seaports as opposed to upstream ports, and could include multilateral strategic agreements on maximum vessel size. All the mentioned options have high-level implications and can, as such, have some unwanted consequences that should be considered.

4.3.1 Aspects of locating, routing and guiding traffic

In addition to regulation for specific waterways, a higher level, large scale management of the traffic structure on the strategic administrative level has the potential to reduce the number of waterways affected by vessel waves. This involves carefully planning the routes of high-speed vessels and strategically positioning port infrastructure to minimize long stretches where displacement vessels must navigate through narrow, confined channels. Redrawing routes for high-speed ferries can be an efficient mitigation strategy, allowing the distance to vulnerable areas to be increased and avoiding critical speed regimes and reducing wave focussing effects due to course changes (PIANC, 2002). Benassai et al. (2013) demonstrates that adjusting the high-speed ferry routes in Naples Bay can reduce vessel wave parameters, ensuring compliance with the established wake criteria. The concept of (re-)locating ports and associated infrastructure may initially seem impractical; however, relocation in general is increasingly being considered as a necessary adaptation to the impacts of climate change and associated natural hazards (e.g., Linnenluecke et al., 2011; Ellingwood and Lee, 2015; McNamara et al., 2018; Bier and King, 2024) and is also a potential option for port and waterway infrastructure (PIANC, 2020). Although vessel wave impacts are unlikely to feature as a primary factor when siting new port developments, they remain an important consideration of the impact assessment, amongst other environmental and operational factors. A related, and presently actionable, approach for regulators is to strategically redirect large vessel traffic from upstream ports toward coastal and seaports that lack shallow, confined approach channels and are naturally more exposed. Achieving this redirection, however, is likely to require some high-level incentives or regulatory measures, given the economic competition between ports and the complexity of factors that influence port selection. While upstream ports, which often require the passage of large vesssels through vulnerable estuarine waterways, are often limited by draft restrictions, they benefit from logistical advantages associated with proximity to hinterland distribution networks and the cost differential between waterborne and overland freight (Notteboom, 2016; Feng et al., 2024). Redirecting vessel traffic can jeopardize the economic viability of a port leading to potential job losses and diminished regional prosperity. Such measures would only be feasible if the resulting economic losses are offset by alternative sources of revenue or comparable benefits.

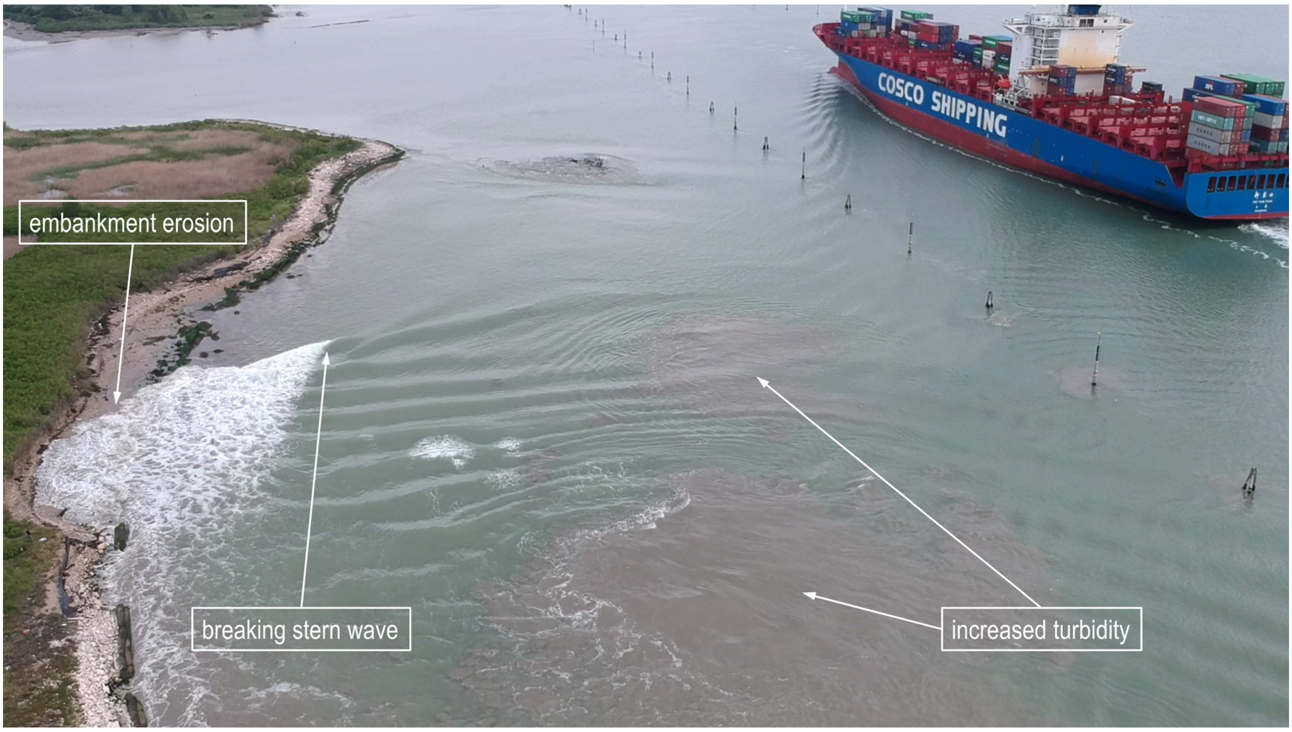

Figure 7: Long-period wave interaction with mud flat in Venice Lagoon. Breaking stern wave enhances embankment erosion; increased turbidity over mud flats are indicative of high sediment mobilisation. Source: L. Zaggia, CNR, Italy.

Redirecting ship traffic, however, can serve to merely shift concerns to another location rather than resolve them. For example, the ban on cruise ships in historic Venice, while beneficial to the city's historic sites, redirected traffic to the MMC and aggravated the existing mud flat erosion in Venice Lagoon. Large displacement vessels in the MMC generate, as a result of the bathymetric configuration, stark and long-lasting depression waves with high vertical velocity components and stronger near-bed flows with associated sediment mobilisation and transport potential (Parnell et al., 2016; Scarpa et al., 2019) (cf. Fig. 7). Unlike the smaller depression waves in the Lido and Giudecca channels, these stronger currents are detrimental to the integrity of mudflats and their habitat value (Zaggia et al., 2017; Scarpa et al., 2019) highlighting the need for a thorough assessment of possible unintended impacts is essential prior to implementing any redirection strategy.

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 the distribution of vessel wave loads to previously less affected areas. The Arctic Northeast Passage, touted as a potential future alternative route to the Suez Canal choke point (Haralambides, 2024), is one such example. The Suez Canal has been, and continues to be, vulnerable to shipping accidents (Wan et al., 2023), as well as political turmoil and piracy in the Red Sea region (Haralambides, 2024; UNCTAD, 2024) with severe ramifications for the globally integrated supply chain. The disintegration of the Arctic permafrost due to rising average temperatures (Fritz et al., 2017) could render this area uniquely vulnerable to exacerbated erosion of shallow-water areas, foreshores and banks by vessel-generated waves and currents (Korte et al., 2020).

4.3.2 Global or regional caps on vessel size

A notion discussed at the workshop was the trend toward ever-increasing ship sizes. Delegates considered whether this growth should be viewed as an inevitable 'law of nature' or if, either globally or regionally, upper limits on ship dimensions could be established. Global agreements would require high-level international cooperation between countries, ports and ship operators. There are 10 shipping companies, consolidated into three alliances, that make up 85% of global trade by volume (Alphaliner, 13.11.2024; Haralambides, 2024), which appears a manageable number of interested parties that must be brought to the negotiating table. Historically, commercial ship dimensions have been, in part, moderated by crucial navigational bottlenecks, in particular the

Panama Canal. This was superceded in the early 2000s by the arrival of the Post-Panmax vessels. Today's class of ULCVs (ultra-large container vessels, L: 400 m, B: 61.0 m – 61.5 m, T: 16.0 m – 16.5 m,) surpass the maximum ship dimensions for the Panama Canal, which in the newer locks accommodates the so-called Neopanamax of 366 m × 51 m × 15.2 m. Another vital route for global trade, the Suez Canal, has no restrictions on vessel length since there are no lockages required to traverse the canal. Considerable reserves in the serviceable beam and draft also exist with current limitations set at 77.4 m and 20.1 m draft; the permissible draft decreases with increasing beam, however, due to the trapezoidal channel geometry. All today's container ships can traverse the Suez Canal, draft limitations are only an issue for some of the tanker fleet (Suez Canal Authority, n.d.). Similar draft restrictions also apply in the heavily trafficked Malacca Strait, which, in sum, leads to the conclusion that the three most important trade route bottlenecks (Haralambides, 2024) could lead to persuasive physical limitations to vessel dimensions (Garrido Salsas et al., 2021). Further limits are imposed by existing port infrastructure (e.g., cranes, yard capacity) and efficiency of the associated logistics chain both of which require upgrades in order to cater for and efficiently service larger vessels (Prokopowicz and Berg-Andreassen, 2016; Garrido Salsas et al., 2021; Son and Cho, 2022); Haralambides (2017) calls this 'diseconomies of scale' with disproportionate increase in port-associated costs. There are, thus, some early indications that the maximum ship size may soon be reached, an increase in traffic density of ULCVs notwithstanding. Some authors believe that maximum ship dimensions, in terms of economic efficiency, have already been reached on some trade routes, as will be discussed in Sec. 5; this could provide an impetus for reaching consensus on a sustainable maximum ship size by all stakeholders. Imposing limits on vessel dimensions would require international mutually binding agreements by countries, port operators and the dominant shipping companies. It is difficult to envision that, given the intense economic competition between ports (Notteboom, 2016; Haralambides, 2024) and the current argumentative political climate, such an agreement could be forthcoming anytime soon.

4.4 Engineering measures

Implementing engineering solutions to mitigate vessel wave effects reflects a proactive approach to manage at the point of impact (cf. Secs. 4.4.1 and 4.4.2), acknowledging them as part of 'doing business' in waterways, but can also serve to reduce vessel loads at the source via adaptations of the shipping channel (cf. Sec. 4.4.3). The variety of structural solutions and maintenance strategies were widely discussed at the workshop. Typical 'hard' engineering options include armouring and fairway modifications. Recently, there has been a resurgence of nature-based solutions in coastal engineering in general (de Vriend et al., 2014; SAGE, 2015; Narayan et al., 2016; Pontee et al., 2016) and includes bioengineered defenses (Narayan et al., 2016; Perricone et al., 2023), beneficial use of dredged sediment (Burt, 1996; Baptist et al., 2019; USACE, 2023), large-scale renourishments (Stive et al., 2013) and allowing for more natural developments of coastal forelands and marginal areas (Gittman et al., 2015). The requirements for acceptable engineering solutions in the future are also discussed.

4.4.1 'Hard' engineered structures

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. While a body of literature exists which addresses the design of, predominantly rock, structures against (mostly short-period) vessel waves (e.g., Maynord, 1984; Verheij and Bogaerts, 1989; CIRIA/CUR/CETMEF, 2007; BAW, 2011; Schiereck, 2017), for some particular load cases associated with long-period wave-structure-interaction design guidance is scarce (Melling et al., 2021). Increased frequency and severity of damages and associated maintenance costs have driven efforts for improvements to design methods for rock revetments (Mittelbach et al., 2014; Kurdistani et al., 2019; Sorgatz et al., 2023; Huang et al., 2024), rock groynes (Dempwolff et al., 2023; Seemann et al., 2023) and efficiencies in maintenance guidance for vessel

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).

wave-related load cases (Sorgatz and Kayser, 2022; Mares-Nasarre et al., 2024, submitted). Bouwmeester et al. (1977) show that the design, construction and choice of material for both filter and armour layer can strongly influence the longevity of revetments to vessel waves. Some structures' survivability can be improved by the optimisation of geometrical shape based on an understanding of the wave-structure-interaction. This was shown for rock groynes under long-period vessel wave attack by Melling et al. (2020, 2021), where an innovative groyne geometry with a recessed root area has increased structure resilience. Existing structures may need to be reinforced with e.g. a larger rock grading for rock structures, additional grouting for increased coherence, or by means of rock alternatives such as interlocking artificial revetment/armour blocks, pattern placed revetments, concrete mattresses or gabions for increased stability through armour element weight and/or interlocking (e.g., Bouwmeester et al., 1977; Klein Breteler and Pilarczyk, 1998; Klein Breteler et al., 1999). It could also entail retrofitting existing structures with toe protection or energy dissipation structures such as detached rubble mound sills in the case of (natural or armoured) embankments or perforated caissons (Ju et al., 2023) and wave absorbing materials (PIANC, 2002) in the case of vertical walls.

Although there is a long-standing tradition of using hard engineering solutions, the workshop consensus was that, while such approaches may be effective in specific hotspots, their high construction and maintenance costs, along with potentially detrimental environmental (and visual) impacts, make them less desirable for large-scale implementation. Nature-based, bioengineered alternatives are preferred, and where feasible, even the naturalization of embankment areas should be considered as a sustainable option (PIANC, 2008).

4.4.2 Nature-based solutions

Growing awareness of biodiversity's role in ecosystem stability (Hooper et al., 2005), alongside concerns over ecological decline in coastal and estuarine environments (Barbier et al., 2011), is driving a shift in some regions towards nature-based solutions for managing these areas. This shift is further supported in certain geographies by environmental legislation, such as the EU Water Framework Directive. While definitions of nature-based solutions vary, the European Commission (n.d.*a*) defines them as approaches inspired by nature that enhance natural processes, offering cost-effective, resilient, and multi-benefit solutions with social, economic, and environmental advantages.

To date, the adoption of nature-based solutions to shoreline erosion can still be considered relatively sparse, although the proliferation appears to be increasing. The adoption of nature-based options can be hindered by lack of guidance (Borsje et al., 2011; Eisenmann and Fleischer, 2012), uncertainties about their efficacy (Morris et al., 2018), seasonality of plants or other design elements (Pfennings et al., 2024; Keimer et al., 2023, 2024) and cost-efficiency (Narayan et al., 2016) in comparison to conventionally engineered options. Nevertheless, experience from German inland (Söhngen et al., 2018) and estuarine waterways (BAW and BfG, 2022) has shown that bioengineered, predominantly deadwood, structures for beach and foreshore stabilisation can be employed in areas with intense commercial shipping and boating (Fig. 11), albeit, the location and type of structure must be considered carefully (Schreiber, 2023), especially for live defenses such as live willow staking (Fig. 10). Also, a penalty of starkly increased maintenance compared to hard engineered structures is reported by practitioners, as in the harsh loading conditions of German estuarine waterways a typical deadwood structure will last some 2-5 years. For 'living shorelines' with vegetation components exposed to vessel waves an energy dissipation structure is typically required in order to reduce wave loads to a sustainable magnitude for vegetation establishment and growth (cf. Fig 10, 11). Apart from off-bank structures (Almström et al., 2022), timber piling (de Roo and Troch, 2015; Thuy et al., 2017), bamboo fencing (Dao et al., 2018; Mai Van et al., 2021) or oyster reefs (Manis et al., 2015; Safak et al., 2020) have been investigated in relation to vessel wave loading. Almström et al. (2022) show that reed belts can be successfully established in a non-tidal coastal fairway with traffic by ocean-going vessels but with relatively moderate wave heights under the precondition of a rubble mound sill which reduces wave energy and inhibits the exposure of plant roots due to washout of soil. The vegetation serves to dissipate wave energy at higher water levels. No maintenance of these measures has been required since (Almström et al., 2023). However, the efficacy of wave dissipation as well as the height of the measure in relation to vessel wave attack is important as these factors can impact the survivability of vegetation (de Roo and Troch, 2015). In principle, the efficacy of deadwood bio-engineered defenses to reduce ship-induced loading is proven with a reasonable expectation of a reduction of secondary wave energy in the range of 20-70% (e.g., Ellis et al., 2002; Herbert et al., 2018; Everett et al., 2022) depending on structure porosity and freeboard in relation to tidal water levels. Similar attenuation performance is reported for various types of vegetation (Morris et al., 2018) and mangroves (Ismail et al., 2017; Tomiczek et al., 2022). The influence of these defenses on long-period wave components, however, is negligible due to their wave length (e.g., Everett et al., 2022). Gittman et al. (2016) compares the biodiversity and species abundance of armoured and natural shorelines and comes to the conclusion that while rubble-mound structures are not detrimental for certain fauna species and may even provide better protection to swimming biota, they do appear to negatively affect vegetation. Furthermore, the use of nature-based shoreline defense can actually enhance ecosystem services and are, thus, viewed favourably. Where space is available, and land ownership allows, naturalisation of banks can be possible, encouraging natural foreshore development, vegetation growth and increased structural diversity of marginal areas.

Some studies have suggested, that steeper beaches are beneficial in the reduction of vessel wave heights and wave runup (Gemeenschappelijk Nautisch Beheer Scheldegebied, 2011; Bain et al., 2022) and, thus, safer for beach users. This can be considered for some recreational beaches that are being replenished, and re-profiled on a regular basis. Small scale beach recharge evaluated by Almström et al. (2022) has proven successful to reduce erosion, but a very short lifespan was reported even under relatively moderate ship-induced loads. The beneficial use of dredged sediment for replenishment schemes should be considered. Thin layer placement of dredged sediment on marshes in the New Jersey Intracoastal Waterway was successful in mitigating shoreline erosion from wind and boat waves (Cagle et al., 2023).

4.4.3 Channel geometry modifications

In the case of large displacement vessels, modifying fairways, port access channels and canal cross-sections is considered a highly efficient measure to reduce bankside loads (PIANC, 2008). Enlarging the channel cross-section by deepening and/or widening, reduces blockage effects and serves to reduce the magnitude of the long-period wave components such as the drawdown – it does little, however, to reduce short-period secondary waves. While channel deepening and widening works are typically considered in order to increase permissible draft and thus catering for larger ships, e.g., to increase the economic exploitation of the waterway, there are also examples where this has been used as a direct measure to reduce vessel wave loads. In the so-called 'safeguarding program' ('Sicherungsprogramm') of the Kiel Canal in the 1960s a wider and deeper cross-sectional profile was constructed with the aim of reducing embankment erosion while also increasing the conveyance capacity of the waterway (Ramacher and Plate, 1969). Similarly, the cross-section of the Malamocco-Marghera access channel is being increased (in combination with a speed limit) to mitigate ship-induced erosion of the surrounding mud flats (Pedroncini and Menegazzo, 2024). Further, fairway realignments (Flory, 2002; PIANC, 2002; Bain et al., 2022) and, where feasible, fairway width reductions (PIANC, 2008) can create wider buffer zones for vulnerable areas and habitats by increasing the sailing distance of vessels. Channel modifications can constitute far-reaching interventions with severe implications for sensitive coastal, estuarine and riverine environments such as changes to hydrodynamic, sediment transport and morphodynamic regimes. Thus, stringent investigations of the environmental impact of these adaptations are required, although smaller scale optimisations (e.g., realignment

Figure 10: Combination of rubble mound training wall, brushwood fences and live willow staking for embankment erosion control at Hanskalbsand in the Lower Elbe Estuary, Germany. Source: Federal Waterways Engineering and Research Institute (BAW).

Figure 11: Brushwood berm and groynes are successfully employed to retain the beach and vegetation belt at Warflether Sand in the Lower Weser Estuary, Germany. Source: Federal Waterways Engineering and Research Institute (BAW).

Figure 12: Complex wave interaction effects of long-period vessel wave with shallow groyne field and armoured embankment at Juelssand in the Lower Elbe Estuary, Germany. Source: Federal Waterways Engineering and Research Institute (BAW).

of fairways without need for dredging) might be possible without physical changes to the waterway. In general, the scope for fairway optimisations is likely not universally available and can be limited, e.g., by the available width of the waterway cross-section or by natural (morpho-)dynamics.

4.5 Alternative measures

In cases where none of the previously discussed measures, either individually or in combination, prove applicable or effective for mitigating vessel waves at their source or within the area of impact, the resulting impacts may need to be accepted as unavoidable consequences of waterway use. In such instances, emphasis should shift toward compensatory strategies or possibly, in some cases, niche exploitation of vessel waves. Different innovative and unusual ways of exploiting vessel waves for socio-economic gain were suggested and discussed by delegates; in most cases the notions could be grounded in existing research or even real-world practice.

4.5.1 'Do nothing' policy paired with compensation

Compensation can offer a potential mitigation practice which allows shipping to continue while maintaining the overall habitat value of the estuary. This can involve the creation of habitat in more sheltered areas of the waterway, which act as nature and ecological reserves (PIANC, 2008). However, this would typically require space and ownership of land in suitable compensation areas; man-made habitats might not be fully in balance with the local hydro-morphodynamics which could result in require persistent maintenance to maintain a certain habitat in the long term.

4.5.2 Exploiting wave cancelling effects

Wave cancelling, as an idea mooted in DARPA (2020), was shown for ducks swimming in formation by (Yuan et al., 2021) and subsequently transferred to demonstrate the potential for wake destruction in secondary waves by ships travelling in a convoy Yuan (2022); Ellingsen (2022) and Liu et al. (2024). This approach likely represents only a partial solution, as it requires significant logistical planning to organize convoys, and navigating in a convoy can be challenging. Additionally, it only addresses secondary waves, offering no mitigation for larger commercial shipping vessels and the primary waves they generate. The applicability of wave cancelling in real-world boundary conditions, however, remains unproven. In a similar vein, Chen and Sharma (1997); Chen et al. (2003) have shown that for slender ships in a rectangular channel travelling at supercritical speed a favorable interference of the reflected bow wave and the stern wave can be achieved which causes a near-complete removal of wave resistance. However, the concept does not mitigate wave effects at the land-water interface, apart from elimination of trailing secondary waves.

4.5.3 Vessel waves as socio-economic resource

While the previously discussed concept of secondary wave cancelling focuses on reducing radiating waves at their source, the following ideas operate on the premise that vessel wave energy is both abundant and persistent. Rather than eliminating this energy, these approaches aim to redirect it or harness it for beneficial purposes.

In relation to ship-induced erosion, another idea was to attempt to trap sediments that are mobilised by ships and keep them in the beach area. It appears plausible that by means of artificial headlands or bioengineered defenses, such as groynes, training walls or brushwood fences (cf. BAW and BfG, 2022) beaches could profit from the erosion of the shorelines, however the processes and location-specific influences would need to be studied. In a similar vein, the potential for 'self-cleaning beaches' through the removal of fine sediments by vessel waves was discussed, a concept which relies on the mobilisation of fine sediments in marginal areas by vessel waves (cf. Sec 3.1) and transport via tidal currents. To the authors' best knowledge, these ideas have so far not been studied, the feasibility is not proven nor likely to be universally applicable. While attractive from the perspective of beach use, there could be conflicts of interests with aspects of fairway maintenance.

More exotic solutions, that may or may not be realistically plausible or realisable with current technology, include vessel wave energy harvesting in the nearshore area. Successful research is being carried out for energy harvesting of small waves such as from boats, and prototypes reportedly exist (US Department of Energy and Water Power Technologies Office, 2023). While little detailed information is available on this technology, converting the hydrokinetic energy of vessel waves into electrical power should be, in principle, possible with a range of existing technologies such as piezoelectric harvesters (Doaré and Michelin, 2011; Zhao et al., 2021) or 6DOF pendulums (Wickett et al., 2019), a variation of the concept introduced by Bernitsas et al. (2006). Both approaches allow random, chaotic vibrational movement to be converted into energy. Oscillating foils (Wu, 1972; Xiao and Zhu, 2014) might offer another option. While there appear to be some potential for this application, the development, implementation in practice and commercialisation are still very much in the early stages.

Some niche recreational use of vessel waves for surfing appears to exist. One activity in relation to recreational vessels is termed 'wakesurfing'; as opposed to the better known wakeboarding, the surfer rides the wave produced by high-powered recreational vessels without being pulled by it (Wikipedia, 2023). Similary, this activity is also catching on for the stern waves of large commercial shipping vessels (Taylor, 13.04.2020; Pierson, 02.06.2023), ferries (YouTube, 19.3.2024) and diverging waves of high-speed craft (YouTube, 5.7.2023). Surfable conditions are reportedly not generated just anywhere but require the correct water level, low wind conditions and a bathymetric feature such as a shoal or sandbank to generate desirable surfing waves which can be ridden for several hundreds of metres or more (Preci, 2004). Steep-faced and barreling vessel waves can be generated over channel-adjacent shallow areas (YouTube, 13.10.2021). Notwithstanding diverse safety concerns in heavily shipped waterways, this kind of recreational use of vessel waves is possible in suitable localities, although not likely to be encouraged by waterway administrators (cf. Sec. 3.2) and thus remains a niche waterway use which is unlikely to be exploited for socio-economic gains

5 Outlook

In light of evolving boundary conditions, including intensifying waterway usage, climatic and physical changes affecting the environment, future challenges in addressing vessel wave issues are explored and the need for adaptive and integrated management approaches is discussed.

5.1 Trends in future waterway utilisation

5.1.1 Commercial shipping

Although, currently, a significant amount of uncertainty can be attributed to any projection of economic and social development due to (geo-)political and socio-economic volatility as well as potentially contracting growth for the world's largest economies (IMF, 2023) with evidence of a slow-down of global trade (OECD, 2023), the development in shipping trends is difficult to predict. The order book for large vessels is very strong with a large volume to TEU to be delivered in the near future (BIMCO, 2024) and seaborne trade is expected to increase, albeit at a moderate pace (UNCTAD, 2023; BIMCO, 2024). Commercial shipping is recognised as one of the more energy, carbon and cost-efficient modes of transport and thus there is a strong imperative to increase the proportion of goods transported by sea and inland waterways. Particularly the latter has been predicted by many to be set to increase significantly globally (e.g., Sihn et al., 2015; Gabel et al., 2017; Aritua et al., 2020; de Barros et al., 2022) not least since it is often also supported by strategic political goals, e.g., in the European Union (European Commission, n.d.*b*) and China (Aritua et al., 2020), two of the geographies with the more developed and studied inland water transport systems (Calderón-Rivera et al., 2024).

While economies of scale have been gained with increasingly bigger vessels, this is outweighed by longer handling times in ports which grows (at least) proportionally with vessel container capacity which in turn leads to a need to make up for lost time by faster transit speed at increased fuel and emissions costs (Malchow, 2022). This leads Malchow to argue that the optimal economic ship size is essentially balanced by handling productivity and that for the North American/Pacific trade current ship sizes are near optimum, whereas for the Northern Europe and Far East trade the (currently) largest container vessels (24 000 TEU) are not the most economical option. This is a notion echoed by Haralambides (2017); Park and Suh (2019); Haralambides (2024) who argue that ship handling times and port infrastructure require a significant uplift for vessels in the 25 000 TEU – 30 000 TEU range. Reportedly, Jinhea New Port in Busan, Korea as well as Rotterdam World Gateway Port are considering infrastructure to accommodate a 30 000 TEU ship (Son and Cho, 2022; Haralambides, 2024), which is predicted to have the dimensions 428.1 m × 67.6 m and 17 m draft (Son and Cho, 2022). This is some 6 m wider than current largest ships with 0.5 m – 1.0 m of additional draft and equates roughly to an increase in submerged cross-section by over 15% with implications for blockage and long-period wave generation in estuarine waterways. Notwithstanding discussions on potential future ship dimensions, increasing ship traffic density as well as the increase in the share of large vessels is currently ongoing. Case in point, according to HANSA (2023) Hamburg Port experienced a 17.9% increase in Megamax-class vessels (400 m × 61.5 m × 16.5 m, 24 000 TEU) in 2023 compared to the previous year, and approx. 30% increase in ULCVs (L > 330 m, B > 48 m, > 24 000 TEU) and (Post-)Panamax-class vessels (L: 294 m − 366 m, B: 32 m − 49 m, T: 12 m − 15.2 m, 4500 TEU − 12 000 TEU). Thus, there is significant potential for ship-induced loads to increase in the future, even without upgrades to port infrastructure.

5.1.2 Recreational boating

The uptake of recreational outdoor activities in general can be expected to increase with changing weather patterns under climate change (Liu, 2022; O'Toole et al., 2019); this can also translate to increased popularity of boating activities, under scenarios where more leisure time and expendable income (Molitor, 2000; Burgin and Hardiman, 2011) are available and increased number of amenable days (longer summer season) for boating (Shaw and Loomis, 2008; Carreño and Lloret, 2021) and water sports in general (Willwerth et al., 2023). However, the marine leisure industry also faces challenges by increased weather extremes (e.g., storms, droughts) and changes to meteorological patterns (MCCIP, n.d.). A moderate increase in seasonal secondary wave loads from recreational boating in the future seems plausible.

5.2 Sustainable waterway use

While the former two sections describe trends that are commensurate with a higher degree of utilisation and with it the potential for increased magnitude and frequency of vessel loads, there is an antipole which is given by the public and political pressure to avoid further environmental degradation and setting areas aside for biodiversity (cf. Sec. 4.4.2). While the idea of 'port sustainability' is gaining traction in port business practice (e.g., Oh et al., 2018; Woo et al., 2018) the environmental concerns are primarily related to topics of waste management, water quality and energy consumption; the impact of vessel waves does hitherto not rate as a high priority in the eyes of port operators (Woo et al., 2018). Thus, it falls on waterway regulators to develop criteria and sustainable management practices and impose regulations backed up by enforcement practices. These considerations should be embedded into strategies for sustainable waterway development (Calderón-Rivera et al., 2024).

5.3 Holistic management strategies

It is important to recognize that vessel wave impacts are only one of many considerations in waterway operations. Waterway management decisions must address a range of factors and challenges, not solely the mitigation of vessel waves. Therefore, developing and implementing holistic and integrated management plans, with broad stakeholder engagement, appears to be an effective approach for sustainably managing waterways under multiple stressors.

A well documented example is the Sustainable Navigation Strategy for the St. Lawrence Seaway. It is embedded into the wider context of the St. Lawrence Action Plan which aims to reconcile environmental, social and economic concerns in this water body such as safeguarding biodiversity, water quality and fostering sustainable use (Environment Canada, 2011). The Sustainable Navigation Strategy aims to maintain the voluntary speed reduction (cf. Sec. 4.2.2), while also providing guidance for recreational boaters and improving the knowledge of the causal effects between shipping and erosion, essentially educational efforts. In the wider scheme, the strategy includes communication efforts for consensus building, integrated management solutions for dredging and sediments, as well as addressing environmental protection concerns from navigation (Ministère des Transports du Québec and Transports Canada, 2021).

5.4 Climate change effects

For inland waters the effects of more frequent and prolonged low water periods, such as witnessed on the river Rhine - one of the world's most frequented shipping channels - during the summers of 2018 and 2022, pose a threat to navigability. The effect on vessel-generated loads is most likely a decrease in wave loads due to reduced draft and speed which offset the effect of increased channel confinement. However, at low water vessel waves will impact on different elevations at the embankments than at regular river stages. With increasing likelihood of drought-related low waters in the future, this could act as a mid- to long-term driver to pursue strategic changes in the shipping fleet to make it sustainable in the future as discussed in Section 4.3. Vinke et al. (2022) have shown that during the low-water period in 2018 the shipping fleet dynamically changed with a strong preference for coupled barges, 'Rhine vessels' (L: 110 m – 135 m, B: 11.4 m, T: 3 m – 3.5 m) and shorter push-tow convoys at the expense of the previously favored six-barge push-tow convoys. Similar developments were reported for the Mississippi River for the low-water event of 2022/2023 with lighter barges, shallower draft and smaller push-tow convoys being favored (KCUR, 02.10.2023), despite efforts of the USACE to maintain required channel depths and widths with continuous dredging operations (USACE Mississippi Valley Division, 15.02.2024). The impact of such changes on ship-induced wave and current loads are not documented, however a reduction appears plausible. Reduced summer river discharge is particularly an issue for inland waterways, as in tidal waterways the missing discharge is compensated by increase in tidal volume. While seaports are not vulnerable to drought, there is important shipping infrastructure such as the Panama Canal which is vital for sea trade and ocean-going vessels but also prone to disruption due to drought due to water required for lockages and sufficient water levels in the freshwater Lake Gatún. The consequence of such low water periods are that the number of daily passages are reduced and/or only vessels with shallower draft can pass (Panama Canal Authority, 24.11.2023), while larger vessels are using the shipping routes of the pre-Panama Canal era. While these developments could lead to enduring changes to the structure of inland shipping fleets, it appears unlikely that seagoing vessel fleet will be influenced, despite the mentioned choke points; it could lead, however, to redirection of global ship traffic. Seaports that are less vulnerable to hydrologic and meteorologic extremes are likely to benefit.

Global warming effects can also potentially lead to a redistribution of ship traffic through prolonged or permanent opening of previously ice-covered water bodies. Vessel wave-related effects could be set to increase in the Arctic region if the predicted increases in ice-free periods in the Northeast Passage (cf. Sec 3.1) and plans for economic exploitation of these areas come to bear. While an increase in Arctic shipping is currently observed (Arctic Council, 2021), a review of studies on the future of trans-Arctic shipping reveals ambiguity regarding its long-term prospects (German Arctic Office, 2019), highlighting significant navigational, infrastructural and political uncertainties – an unambiguous prognosis is not feasible at this stage.

5.5 Monitoring – broadening the data base

Field measurements are a very important component in vessel wave management and research, which despite the possibilities in physical models and advances in advanced numerical methods still provides valuable information for process understanding, method development of management strategies. In the context of the latter, it provides a data basis for decision makers for the choice of management option and evaluation of the efficacy of such options post-introduction (PIANC, 2008). Bain et al. (2022), for example, use field measurements at Tybee Island at the mouth of the Savannah River, Georgia to develop recommendations to reduce the impact of vessel-generated waves on beach stability and recreational use, which include vessel speed restrictions, channel modifications, structural solutions and an active warning system which relies on real-time monitoring data. Monitoring can potentially also be used in the enforcement of liabilities for vessel wave-induced damages if individual vessel wave events can be linked to a negative outcomes (e.g., structural damages), and to determine the performance of structures, both of which are exemplified in Melling et al. (2021). On a more fundamental level, monitoring provides a basis for process understanding and method improvement. A key finding of the workshop was the notable scarcity of (openly available) data on vessel waves, which is viewed as a significant bottleneck for advancing process understanding, method development, and effective waterway management. There is considerable interest, e.g., in benchmark datasets that could support the validation of numerical models. Wherever possible, data should be made publicly available to benefit the wider research and management community. The benefits of monitoring, especially long-term (monthly to annual time series) or recurring multi-week campaigns are not promoted enough, they are however valuable to assess long-term impacts of vessel waves such as, e.g., shoreline erosion, sediment transport, turbidity, vegetation changes, ecological habitat alterations. Recognising the need for longer data series, extensive long-term monitoring of ship-induced loads at strategically chosen locations in the Lower Elbe Estuary is under way by means of multiple measurement campaigns of several weeks' duration (WSV, n.d.). Recent measurements can be used in conjunction with the historic database of vessel wave measurements in German estuarine waterways, compiled and documented in Seemann and Melling

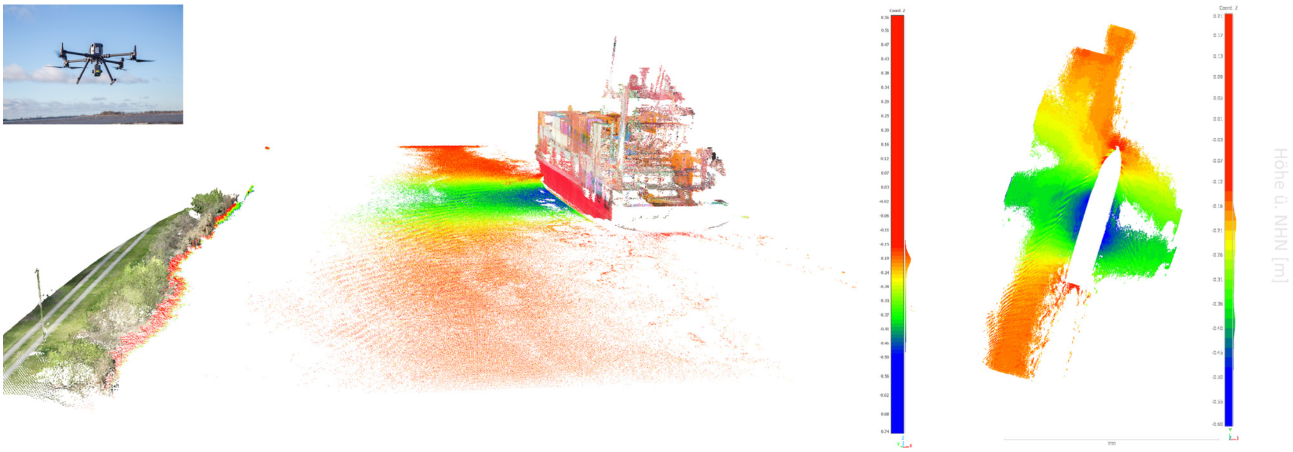

Figure 13: Example of vessel waves recorded with drone-mounted LiDAR scanner, resulting in instantaneous spatially-resolved water surface displacements around the vessel; both long-period primary wave system and short-period secondary wave systems are visible. Source: Federal Waterways Engineering and Research Institute (BAW).

(2025). The extended dataset allows the historical development of ship-induced loads in the Lower Elbe estuary to be evaluated; it also provides a unique database for the examination of causal relationships between ship parameters, nautical parameters and measured wave and current loads. The data can be used to inform, develop or revisit management strategies based on hard indisputable data.

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. It is essential that monitoring efforts encompass not only measurements of vessel-generated waves but also include bathymetric survey data, at a minimum within the measurement cross-section. Additionally, recorded wave events should be linked to AIS data to capture relevant nautical and vessel parameters, ensuring that the relationship between vessel passage and resulting wave is known.

6 Conclusions

The productive discussions during the workshop generated a wealth of reports and anecdotes regarding vessel wave-induced issues and management practices. The key points are successfully substantiated and effectively contextualized within existing research and real-world case studies, transforming oral accounts into verifiable descriptions of the global knowledge landscape regarding vessel waves and their management. This includes practical insights on implementation, effectiveness of various options, and potential challenges and pitfalls. The authors believe this baseline assessment is valuable in providing a comprehensive, bird's-eye view of the challenges facing waterways with respect to vessel waves and their intricate connections to other stressors, regulatory shortcomings, and economic pressures. The authors hope this publication informs and raises awareness among waterway stakeholders, offers actionable guidance, encourages further research, and fosters greater cohesion and collaboration within the 'vessel wave community'. 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.

The discussion of management options highlights that mitigating the effects of vessel-generated waves requires a combination of short-term measures (e.g., speed limits) and long-term strategies aimed at reducing waves at their source (e.g., improved vessel design and selection, education); the latter can be highly effective but require sustained and consistent efforts to realize their full potential. While hotspots can be managed through localized interventions at the point of impact, reducing wave generation at the source is preferable as it minimizes the reliance on costly engineering solutions at the land-water interface. Waterways are subject to multiple pressures in an ever-changing environment. Vessel-generated waves should not be addressed in isolation, but rather incorporated into a holistic waterway management framework that considers the wide range of adverse impacts from shipping and boating activities on waterways and stakeholders. While the discussed management practices offer proven benefits, the importance of integrating solutions that deliver multiple benefits, particularly in the context of multiple stressors, should be recognised. This calls for multidisciplinary, integrated approaches to waterway management that identify and implement strategies capable of addressing multiple challenges simultaneously. In terms of management, the challenges pertain to:

i. recognising the critical role economic realities play in influencing the distribution and severity of vessel wave impacts as it relates to global trade routes, competition within global trade (shipping companies, ports, waterways, countries), as well as commercial transportation (economic business case predicated on speed of service for high-speed vessels) and recreational boating (more disposable income and leisure time).

ii. recognising that mitigating vessel wave impacts is often constrained by the need to balance and, at times, overcome economic interests, both private and public. Addressing this issue could require re-incentivisation to align economic motivations with sustainable management goals.

iii. strengthening the case for vessel wave mitigation at the source (where effective and economic), as opposed to mitigating the symptoms at land-water interfaces.

iv. integrating vessel wave concerns into wider waterway management frameworks which can deliver multi-benefit synergistic effects (e.g., 'slow steaming') fostering sustainable use of waterways; more holistic waterway management strategies are required.

v. addressing existing knowledge gaps in process understanding (see below) to facilitate the development of more efficient management strategies.

vi. documenting the implementation and efficacy of management options (and combinations thereof) as it pertains to real-world case studies; these experiences should inform the development of best practice guidance for vessel wave management.

vii. promoting the use of monitoring as a critical tool to assess the need for, select, and evaluate the efficacy of management strategies. Encouraging data sharing is similarly important to facilitate research and investigation (Wilkinson et al., 2016).

The workshop highlighted a strong resonance within the community to promote consistent research on vessel waves and formalize exchanges among researchers, consultants, regulators, decision-makers, and other stakeholders. While some aspects of vessel waves, particularly those related to short-period wave components, are well understood, significant knowledge gaps remain in understanding the processes governing the interaction of long-period vessel waves with the surrounding environment. These gaps are particularly evident in aspects such as:

i. non-linearity (Lee et al., 1989; Soomere, 2007) and its impact on wave transformation processes in shallow water (Parnell et al., 2016; Scarpa et al., 2019; Bain et al., 2022) such as water surface deformation, vertical velocity and pressure distributions.

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, 2023*b*,*a*) and their possible connection to resonant (Muscalus and Haas, 2020, 2022; Dempwolff et al., 2024) and non-linear effects in marginal areas (Wang and Cheng, 2021).

iii. the intricate and multi-faceted interaction between (in particular long-period vessel waves) and embankment areas that are either natural, near-natural or protected by engineered or nature-based solutions.

iv. long-period wave generation at and non-linear interaction with topographic breaks (Grue, 2017, 2020) or channel geometry changes (Terziev, 2023).

v. superposition effects of multiple long-period waves, as exemplified by non-linear wave height amplification of solitons (Soomere and Engelbrecht, 2005; Soomere, 2006), with the possibility of abnormally high waves and their interaction with the natural and built environment (Soomere, 2010).

vi. importance of wave parameters for different problems (e.g., engineering issues vs. biological studies), and possible value of derived wave parameters such as those that integrate duration and magnitude (Fenton et al., 2023).

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. 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.

Acknowledgements

This workshop was part of the project "NumSiSSI" conducted in cooperation of the Federal Waterways Engineering and Research Institute with Technische Universität Braunschweig. This publication was made possible through the dedicated advocacy of the workshop delegates, namely (in alphabetical order): Rachel Bain, Hans Bihs, Markus Brühl, Cristian Brutto, Christina Carstensen, Mike Davies, Lara Dechant, Hisham Elsafti, Carolin Gesing, Georg Göbel, Kevin Haas, Jacek Jankowski, Hanne Jansch, Marko Kastens, Christian Kochanowski, Bernhard Kondziella, Santiago Lopez, Gregor Macfarlane, Patricia Mares-Nasarre, Dieter Meire, Sargol Memar, Héctor Montenegro, Oswaldo Morales-Nápoles, Alexandra Muscalus, Pablo Nieutin-Redon, Kevin Parnell, Raul Redondo, Julia Rothschink, Mohammad Saidee Hasan, Arne Seemann, Tarmo Soomere, Julia Sorgatz, Momchil Terziev, Gina Torres, Arne van der Hout, Charlotte van der Vorm, Jeroen Verwilligen, Luca Zaggia. The authors extend their gratitude for their invaluable contributions, which significantly enriched the workshop outcomes.

Funding

The workshop and subsequent investigation was funded by the Federal Waterways Engineering and Research Institute (BAW).

Author contributions (CRediT)

GM: Writing - original draft and editing, Investigation, Conceptualisation, Methodology, Project Administration; IH: Project administration, Funding acquisition, Manuscript draft review, Conceptualisation; CD:

Manuscript draft review and editing, Conceptualisation, Methodology; CW: Manuscript draft review and editing, Conceptualisation, Methodology; NG: Manuscript draft review and editing, Conceptualisation, Methodology

Use of AI

During the preparation of this work the authors used ChatGPT to generate suggestions to improve the structure and readability of a select number of individual sentences. After using this tool/service, the authors reviewed, edited, made the content their own and validated the outcome as needed, and take full responsibility for the content of the publication.

Data access statement

The data acquired in the study will be made available on request.

Declaration of interests

The authors report no conflict of interest.

Acronyms

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

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