Effects of morphological mitigation measures against ship-induced waves in freshwater ecosystems: A meta-analysis

Effets des mesures d'atténuation morphologique des vagues provoquées par les bateaux dans les écosystèmes d'eau douce : Une méta-analyse

Dittrich, Anna-Lisa[1,*]; Bilous, Olena[1]; Brauns, Mario[2]; Funk, Andrea[1]; Hein, Thomas[1]; Meulenbroek, Paul[1]; Bondar-Kunze, Elisabeth[1]

[1]Christian Doppler Laboratory for Meta Ecosystem Dynamics in Riverine Landscapes, Institute of Hydrobiology and Aquatic Ecosystem Management, BOKU University, Gregor Mendel Str. 33, 1180 Vienna, Austria
[2]Helmholtz-Zentrum für Umweltforschung GmbH - UFZ, 39114 Magdeburg, Germany
[*]Corresponding author: annalisa.dittrich@boku.ac.at

RÉSUMÉ

Les systèmes d'eau douce utilisés pour la navigation sont soumis à divers facteurs de stress. Outre les effets indirects, les navires exercent une force directe sur les zones littorales en augmentant la vitesse du courant et en créant des vagues. Ce phénomène affecte non seulement l'érosion et augmente la turbidité, mais touche également tous les groupes d'organismes et peut donc modifier les réseaux alimentaires. Pour protéger les écosystèmes aquatiques des vagues provoquées par les navires, des mesures d'atténuation morphologiques peuvent être mises en œuvre. Il s'agit notamment de mesures à l'intérieur des cours d'eau, telles que des îlots de bancs de gravier, ou de mesures sur le littoral, telles que des épis modifiés. À ce jour, il n'existe aucune vue d'ensemble des mesures existantes et de leur impact sur les écosystèmes d'eau douce et de transition. Dans cette méta-analyse, nous examinons et synthétisons les structures de protection contre les vagues existantes et leurs effets sur les processus hydrauliques tels que la hauteur des vagues, les processus abiotiques tels que l'érosion, et les organismes biotiques à différents niveaux trophiques avec des implications pour les réseaux alimentaires aquatiques.

ABSTRACT

Freshwater systems utilized for navigation are subject to various stressors. In addition to indirect effects such as river straightening or navigation channel dredging, ships exert a direct force on shoreline zones by increasing flow velocity and creating waves. This not only affects bank erosion and increases turbidity but also affects all groups of organisms and can alter entire food webs. To protect aquatic ecosystems from ship-induced waves, morphological mitigation measures can be implemented. These include in-stream structures such as gravel bar islands that act as breakwaters or shoreline measures such as modified groins that increase the shoreline complexity. To date, there is no comprehensive overview of the existing measures and their impacts on freshwater and transitional ecosystems. In this meta-analysis, we review and synthesize the existing wave protection structures and their effects on hydraulic processes such as wave height, abiotic processes such as erosion, and aquatic organisms at different trophic levels with implications for aquatic food webs.

KEYWORDS

Food webs, inland navigation, protection structures, shoreline zones, boat wakes

Navigation d’eau intérieure, réseaux trophiques, sillage des bateaux, structures de protection, zones littorales

EXTENDED ABSTRACT

1.1 Introduction

Freshwater systems have always played an essential role in human societies, and rivers were used early on as trade routes. Nowadays, inland navigation plays an essential role in transporting goods and for recreational purposes, with more than 500 000 river-km worldwide being altered for navigation in the last centuries (Revenga et al. 2000). Apart from its economic advantages and resource use efficiency compared to road and air freight (Worldbank 2024), shipping also causes adverse effects on ecosystems and exacerbates the decline in freshwater biodiversity (Sexton et al. 2024). These effects include, for instance, reduced habitat availability due to river straightening (Wolf et al. 2021), the spread of invasive species, discharges to the water, and direct physical forces like increased flow velocities and waves (Jägerbrand et al. 2019). Ship-induced waves hit shorelines that represent essential habitats with high biodiversity and affect the inhabiting organisms directly or by increased sediment suspension (Strayer and Findlay 2010). Measures to reduce the impact of these ship wakes can be taken by adapting ship hull construction, applying operational measures like speed-limit zones, or implementing morphological protection measures at shore zones (Gabel et al. 2017). The classic approach to protect shores from the eroding potential of waves is to implement shoreline hardening such as rip rap, which can have negative consequences for biota by reducing habitat complexity (Reid and Church 2015). Therefore, other measures have been developed that aim to ensure erosion protection and more heterogenous habitat conditions. These include river network measures, abiotic or biotic breakwaters, and an increased shoreline complexity (e.g., Preuß et al. 2023). While the effects of ships and ship-induced waves on freshwater ecosystems have started gaining scientific attention (e.g., Jeliazkov et al. 2024), the knowledge about the effects of morphological protection measures is still limited, and a comprehensive overview is missing to date. Therefore, we conducted a systematic literature review and meta-analysis to close this gap and provide an overview of mitigation measures and how they affect freshwater and transitional ecosystems. We look at hydraulic effects as wave height or flow velocity, abiotic effects as erosion, and biotic effects on aquatic organisms of all trophic levels.

1.2 Methods

The review was conducted by implementing a pre-defined search string in Web of Science, which yielded 497 results. No restrictions were applied in terms of peer review, language, or year of publication. The results were screened based on title and abstract, retaining only literature focused on waves in freshwater and transitional ecosystems, resulting in a selection of 68 studies. An additional 28 studies were identified via snowballing techniques. All records were downloaded, and the full text was screened. This led to a final number of 68 studies included in the review. These studies investigated 47 different morphological measures, as some were investigated in several articles. In a further step, response variables were extracted to calculate effect sizes for the meta-analysis. 121 variables could be identified, and the relevant parameters were extracted from the text, tables, and figures (plotdigitizer.com) or by contacting the authors. Effect sizes were calculated, and a random-effect model was applied using the “escalc” and “rma” function in the metafor package in RStudio 2024.09.0 (Viechtbauer 2010).

1.3 Preliminary results

The identified publications were conducted in 13 countries, mostly in Europe, followed by North America, with no studies published in Africa and Oceania. Most studies investigated an increased shoreline complexity, followed by biotic and abiotic breakwaters, and only a few studies published shoreline hardening or river network measures such as side-channel reconnection in direct relation with ship-induced waves. Rivers and canals were the predominant ecosystems, followed by lakes/reservoirs, tidally influenced rivers/estuaries, and artificial experiments in tanks or flumes. Overall, 40 studies directly measured hydraulic effects, with wave height being the dominant variable. Of the 26 studies investigating abiotic effects, almost 90% were focused on erosion; other variables, such as turbidity, were of minor importance. 35 publications investigated biotic effects, of which fish were the dominant organism group, followed by aquatic macrophytes and benthic invertebrates.

Random-effect models revealed reduced wave heights, wave forces and flow velocities with increased shoreline complexity and breakwaters, while shoreline hardening measures increased hydraulic forces. The erosion reduction was strongest with increased complexity, while breakwaters showed smaller effects on abiotic responses. Positive effects on aquatic organisms were found in decreasing order for biotic and abiotic breakwaters, increased complexity, and shoreline hardening (negative effects). The effectiveness of a mitigation measure was furthermore dependent on whether it was applied in a lake, river, or under more controlled conditions in a mesocosm. These results indicate that different measures should be implemented depending on which effects are prioritized and depending on the respective ecosystem.

LIST OF REFERENCES

1 Gabel, Friederike; Lorenz, Stefan; Stoll, Stefan (2017): Effects of ship-induced waves on aquatic ecosystems. In: The Science of the total environment 601-602.
2 Jägerbrand, Annika K.; Brutemark, Andreas; Barthel Svedén, Jennie; Gren, Ing-Marie (2019): A review on the environmental impacts of shipping on aquatic and nearshore ecosystems. In: The Science of the total environment 695.
3 Jeliazkov, Alienor; Martínez-Fernández, Vanesa; Altanov, Vassil Y.; Beisel, Jean-Nicolas; Buijse, Anthonie Dirk; Consuegra, Sofia et al. (2024): A global systematic map of knowledge of inland commercial navigation effects on freshwater ecosystems. In: Journal of environmental management 370.
4 Preuß, Julia; Fleit, Gábor; Baranya, Sándor (2023): CFD analysis of environmentally friendly wave mitigation measures in river waterways. In: River Research & Apps, Artikel rra.4112.
5 Reid, David; Church, Michael (2015): Geomorphic and Ecological Consequences of Riprap Placement in River Systems. In: J American Water Resour Assoc 51 (4).
6 Revenga, Carmen; Brunner, Jake; Henninger, Norbert; Kassem, Ken; Payne, Richard (2000): Pilot analysis of global ecosystems. Freshwater systems. Washington, DC: World Resources Institute (PAGE).
7 Sexton, Aaron N.; Beisel, Jean-Nicolas; Staentzel, Cybill; Wolter, Christian; Tales, Evelyne; Belliard, Jérôme et al. (2024): Inland navigation and land use interact to impact European freshwater biodiversity. In: Nature ecology & evolution 8 (6).
8 Strayer, David L.; Findlay, Stuart E. G. (2010): Ecology of freshwater shore zones. In: Aquat. Sci. 72 (2).
9 Wolf, Stefanie; Esser, Verena; Schüttrumpf, Holger; Lehmkuhl, Frank (2021): Influence of 200 years of water resource management on a typical central European river. Does industrialization straighten a river? In: Environ Sci Eur 33 (1).
10 Worldbank (2024): Moving from roads to rivers. Online at https://blogs.worldbank.org/en/transport/moving-from-roads-to-rivers--the-tremendous-potential-of-inland, accessed 28.10.2024.
11 Viechtbauer, Wolfgang (2010): Conducting Meta-Analyses in R with the metafor Package. In: J. Stat. Soft. 36 (3).