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Review

Effects of ship-induced waves on aquatic ecosystems

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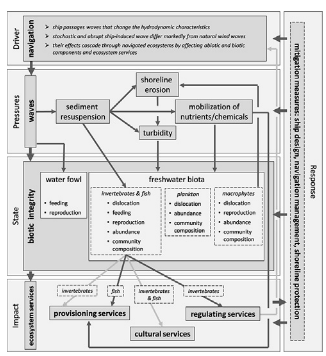
HIGHLIGHTS

- Effects of ship-induced waves are reviewed.
- Abiotic: increase of erosion, resuspension of sediments and chemicals and turbidity
- Biotic: effects on dislocation, growth, reproduction and diversity on all trophic levels
- Effects on ecosystem services and management options are discussed.

GRAPHICAL ABSTRACT



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ABSTRACT

Most larger water bodies worldwide are used for navigation, and the intensity of commercial and recreational navigation is expected to further increase. Navigation profoundly affects aquatic ecosystems. To facilitate navigation, rivers are trained and developed, and the direct effects of navigation include chemical and biological impacts (e.g., inputs of toxic substances and dispersal of non-native species, respectively). Furthermore, propagating ships create hydrodynamic alterations, often simply summarized as waves. Although ship-induced waves are recognized as influential stressors, knowledge on their effects is poorly synthesized. We present here a review on the effects of ship-induced waves on the structure, function and services of aquatic ecosystems based on more than 200 peer reviewed publications and technical reports. Ship-induced waves act at multiple organizational levels and different spatial and temporal scales. All the abiotic and biotic components of aquatic ecosystems are affected, from the sediment and nutrient budget to the planktonic, benthic and fish communities. We highlight how the effects of ship-induced waves cascade through ecosystems and how different effects interact and feed back into the ecosystem finally leading to altered ecosystem services and human health effects. Based on this synthesis of wave effects, we discuss strategies for mitigation. This may help to develop scientifically based and target-oriented management plans for navigational waters that optimize abiotic and biotic integrity and their ecosystem services and uses.

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Contents

1. Introduction

One of the oldest benefits for human societies living near inland waters is its use for navigation, both commercial and recreational. Today, more than 650,000 km of inland waterways are used for commercial and recreational navigation worldwide (Central Intelligence Agency, 2013). Inland navigation is globally distributed with the longest navigational waterway network in Asia (~370,000 km), followed by South America (~130,000 km), Africa (~53,000 km), Europe (~52,000 km) North America (~42,000 km) and Australia (2000 km) (Central Intelligence Agency, 2013). Both sectors of navigation were stable at a high level or slightly increased in recent years in the United States of America and Europe (US Army Corps of Engineers, 2015; Eurostat, 2016; Table 1), although the statistics of transport performance are subject to considerable annual fluctuation caused by e.g., the worldwide economic crisis in 2009 (US Army Corps of Engineers, 2015; Eurostat, 2016; Table 1).

Commercial and recreational navigation are expected to increase in the future. Navigation is commonly considered the most sustainable mode of transport in respect to fuel consumption, CO_2 - emissions and traffic safety (Lambert, 2010; Pauli, 2010; Radmilovic and Maras, 2011; Rohacs and Simongati, 2007). Similarly, recreational navigation is expected to further increase as people will have more leisure time (Molitor, 2000), and global warming may increase the number of days when boating is appealing and will attract more people to boating in cold to temperate areas in the world (Loomis and Crespi, 1999; Mendelsohn and Markowski, 1999; Shaw and Loomis, 2008). At present, more than 24 million recreational motor boats are registered in North America and more than 5.9 million boats (pers. com. European Boating Association) in the European Union. Apart from a persistent increase in the number of (recreational) boats, the size and horsepower of vessels have shown a steep increase in the past three decades (Asplund, 2003). Thus, navigation is an important and increasing socio-economic sector.

However, commercial and recreational navigation on inland waters also causes serious effects on aquatic ecosystems at multiple hierarchical levels. When natural rivers and lakes are used as waterways for navigation, their morphology becomes significantly altered as a result of anthropogenic river training commonly including a deepening and widening of the river channel and shoreline fortifications. Impoundments via locks hamper the passability for migratory species and turn free-flowing rivers into a series of stagnant water bodies. Other physical impacts emerge from anchored or moored vessels (Lenihan et al., 1990; Hastings et al., 1995; Ostendorp, 1999), from hull and propeller contact (Zieman, 1976; Bulte et al., 2010; Gutreuter et al., 2003; Killgore et al., 2001), or the generation of noise from propellers and motors (e.g., Graham and Cooke, 2008; Scholik and Yan, 2002; Wysocki et al., 2006).

Navigation is often accompanied by oil and fuel discharges (Jackivic and Kuzminsk, 1973), the release of polyaromatic hydrocarbons (Mastran et al., 1994), and the use of antifouling paints and biocides that affect a wide range of organisms (Juttner et al., 1995). The chemical effects of navigation have been reviewed by Liddle and Scorgie (1980), Mosisch and Arthington (1998), Burgin and Hardiman (2011), and Whitfield and Becker (2014). Some of these toxic substances have been shown to accumulate in the food web, are highly persistent in the environment and may lead to regime shifts in lakes (Sayer et al., 2006; for further details see review by Dafforn et al., 2011). For example Tributyltin (TBT), which was used in antifouling paints, which has been banned in 2008, can be still present in sediments (Dafforn et al., 2011; Hedge et al., 2009) and their substitutes are often also toxic and bioaccumulative (Mohr et al., 2009; Young et al., 1979; Turner et al., 1997).

Table 1
Transport performance (product of mass of transported goods [t] and transported distance [km]) of US American and European inland navigation.
(Source: US Army Corps of Engineers, 2015; Eurostat, 2016.)

Year	Transport performance USA (billion short tkm)	Transport performance Europe (billion tkm)
2005	1134.9	137.7
2006	1097.6	137.7
2007	1078.3	145.1
2008	1020.0	145.9
2009	919.4	131.7
2010	974.6	154.2
2011	972.5	140.8
2012	928.6	148.8
2013	908.8	151.6
2014	979.8	149.8