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Understanding the effects of resolving nautical bottlenecks on the Danube: a KPI-based conceptual framework

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Abstract

Background Shifting cargo from roads to eco-friendly inland waterway transport (IWT) is an important step towards reaching the decarbonization goals defined by the European Green Deal. The rehabilitation of nautical bottlenecks is essential to reach the fairway depth which is needed to allow a competitive transport on inland waterways.

Aim The goal of this paper is to (1) identify key performance indicators (KPI) associated with nautical bottlenecks caused by insufficient maintenance, (2) understand the effects of resolving nautical bottlenecks on the identified KPIs and (3) develop a conceptual framework.

Methods To develop the conceptual framework, we carried out a systematic literature review. We analysed the identified literature using qualitative content analysis and thus, derived relevant KPIs and their interdependencies.

Findings Ten KPIs were identified, which could be clustered as being either IWT-related, market-related or location-related. One example for an IWT-related KPI is the vessel draft, while market-related KPIs are e.g., referring to the KPI modal share and location-related KPIs to other KPIs such as *fairway depth*.

Contribution The conceptual framework visualizes the interdependencies between the KPIs and facilitates further research in this field, i.e., the development of a method for the evaluation of economic benefits of resolving nautical bottlenecks on inland waterways. A scientific method that allows the economic evaluation of resolving nautical bottlenecks it is essential to demonstrates the gain in quantitative net benefit if water levels are sufficient. A quantification of the net benefit serves as a motivator to intensify maintenance work on nautical bottlenecks and to facilitate decision-making regarding infrastructure projects.

Keywords Inland waterways, Nautical bottlenecks, Economic evaluation, Key performance indicators, Conceptual framework

1 Introduction and background

To tackle the effects of global warming and climate change, the European Green Deal was announced in 2019. It sets the goal of Europe to become the first climate-neutral continent by 2050 following the science-based targets for decarbonization [13]. The transport sector, including both, passenger and freight transport, represents a major area for decarbonization, since it produces around 25% of European greenhouse gas emissions [17]. The Sustainable and Smart Mobility Strategy was published by the end of 2020 to specify the exact goals

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and measures for the European transport sector. The overarching, highly challenging goal is to achieve a 90% reduction of greenhouse gas emissions from the transport sector by 2050 [13].

IWT has the potential to reduce the negative side effects caused by road transport, including external costs from emissions, noise and congestion [13]. Therefore, a modal shift to inland waterway transport (IWT) was defined by the European Commission as a measure to reduce emissions in the transport sector. In fact, IWT saves up to 70% of CO_2 per transported tonne kilometre compared to road transport [17]. Furthermore, IWT has the lowest external costs compared to road and rail, due to a very limited noise pollution and a virtually non-existent accident rate. For example, the Austrian river stretch of the Danube recorded 12 accidents in 2021, none with personal injuries [15, 51]. As with any other transport mode, IWT is characterized by sector-specific challenges: As the inland waterway network is limited in its density to the existing navigable rivers and canal network, IWT is generally part of multimodal transport chains. In fact, the pre-carriage and on-carriage is usually carried out by road, as the road network has a particularly high network density, which enables the collection and delivery of goods directly from the sender or to the recipient [7, 45].

Another challenge is represented by the maintenance of a consistent IWT infrastructure, since rivers are living systems which serve multiple uses such as recreation, leisure, energy production or IWT. Consistent infrastructure in the case of IWT means e.g., the need to maintain locks and bridges, minimum fairway width and depth. This work focuses on the provision of sufficient fairway depth to facilitate economic transport [23]. To enable efficient multimodal transport while strengthening inland navigation, a continuous and resilient infrastructure for the involved transport modes is required [6, 24]. This makes a minimum fairway width and depth an essential parameter for the economically viable use of inland waterways [23]. As a natural resource, inland waterways have uneven riverbeds, meaning that the fairway depth of the river can vary throughout the course of the river and throughout the year [5]. For smooth and economically viable inland waterway transport, it is essential to assure a minimum fairway depth throughout the year [19, 23].

The maintenance of minimum fairway parameters is particularly relevant for the Danube, as across its length of around 2850 km the river shows significant differences in its infrastructure, which makes it difficult to maintain these minimum fairway parameters. For the Danube, international agreements such as the agreement of the Commission du Danube (1988) recommend a minimum fairway depth of 2.5 m to ensure the continuous navigability of the river. River sections on the Danube with less than 2.5 m of fairway depth are called nautical bottlenecks [14]. Nautical bottlenecks occur because of nature due to the general water supply and meteorological conditions or be caused by insufficient maintenance [19]. This paper focuses on the latter reason. In 2020, a total of 17 bottlenecks were recorded on the Danube [14]. The reduction of nautical bottlenecks on the Danube was determined by the European Union through the Fairway Rehabilitation and Maintenance Master Plan. Despite dredging and rehabilitation works along the Danube, it has until now not been possible to remove these nautical bottlenecks entirely. The rehabilitation of bottlenecks is defined as the guarantee of a fairway depth of 2.5 m for 365 days a year. Fairway depth of 2.5 m ensures a smooth transport by inland vessel and generates several additional benefits, such as an increase of capacity, leading to a larger amount of goods being transported per vessel. The increase in capacity has a positive impact on the economic efficiency of the transports as well as the CO_2 emissions per transported tonne kilometre [23]. Navigating through low water levels increases the interaction between ship and waterway, the maximum speed being restricted by the available water depth, thus, the vessels' resistance increases. Therefore, the rehabilitation of bottlenecks contributes by increasing speed of a transport and by lowering the vessels' resistance [20]. To facilitate decision-making and encourage the maintenance of major nautical bottlenecks, it is necessary to quantify the performance improvements in IWT which resulting from the rehabilitation of nautical bottlenecks. By converting these performance gains into monetary benefits, we can gain a clearer understanding of the impact on investment decisions. This approach helps identify which infrastructure projects offer the greatest financial advantages. Therefore, evaluating the benefits of resolving nautical bottlenecks in quantitative terms serves as a foundation for making investment and project decisions [13, 31].

Due to the complexity of quantitative economic evaluations, the process is usually time-consuming and expensive. Since economic evaluations nevertheless play an important role in strategic planning, they are frequently applied to various fields, such as transport and infrastructure projects [12, 42, 47]. The process of quantitative economic evaluation has already been standardized in different approaches for various areas of application. Cost–benefit-analysis is one of the most commonly used [3], aggregating the costs and benefits of an investment project in monetary terms to show either a surplus or loss [32]. The difficulty lies in specifying the approach to specific use cases, as each use case has different indicators that ultimately determine the benefit [52].

Identifying these indicators (KPIs), which can be defined as figures which demonstrate the performance of a system, e.g. service level, and how to quantify them, is crucial for evaluating the economic benefits of a project. Identification of KPIs facilitates understanding the elements of the transport system that underlies nautical bottlenecks as well as the interdependencies between them. With the help of KPIs, the performance gains of resolving nautical bottlenecks can be measured, which are subsequently translated into quantified economic benefits [43]. However, such identification might be challenging, as currently there does not exist any framework of to enable the selection of appropriate KPIs for a project, and KPI measurement can vary in every specific investment project [52]. The higher the number of such indicators, the higher the complexity of the economic evaluation, as it is necessary to determine not only the quantification of these indicators but also their interdependencies [2, 29]. With this article we provide a foundation for developing the method for economic evaluation of resolving nautical bottlenecks by identifying (1) KPIs associated with nautical bottlenecks, (2) the interdependencies between them, and (3) the effects of resolving nautical bottlenecks on the KPIs. The KPIs are identified using a systematic literature review following the approach of Liberati et al. [30]. To understand the transport system that underlies nautical bottlenecks, we visualize the results in a conceptual framework focusing on the interdependencies of the identified KPIs.

Research in the field of IWT infrastructure is essential to support decision-makers responsible for maintenance which monetary benefits can actually be achieved through rehabilitation of nautical bottlenecks. To provide a starting point for developing a method for the economic evaluation of resolving nautical bottlenecks the goal of this paper is to (1) identify key performance indicators (KPI) associated with nautical bottlenecks caused by insufficient maintenance, (2) understand the effects of resolving nautical bottlenecks on the identified KPIs and (3) develop a conceptual framework using the results of a systematic literature review. The research questions guiding this paper are

> (RQ 1) Which KPIs can be used to understand the relationship between the rehabilitation of nautical bottlenecks and the economic benefits from it?
> (RQ 2) What is the interrelation between the identified KPIs?
> (RQ 3) How do the identified KPIs evolve as a result of bottleneck rehabilitation?

This article is structured as follows. Section two deals with the methodology used in creating the conceptual framework, including the methodology we followed for conducting the systematic literature review in December 2021. Section three presents the results and discussion, while section four concludes the paper, highlighting the research agenda and giving a final outlook following the approach of Gkiotsalitis and Cats [16] and Ertmer and Glazewski [11].

2 Methodology

Conceptual frameworks aim to illustrate phenomena, such as systems or processes, whilst at the same time explaining them. According to Meredith [34], conceptual induction applies when a system is described through the relationship of the system's elements. We applied the inductive approach to create the conceptual framework which supports the understanding of the identified KPIs and the effects of resolving nautical bottlenecks on them. Therefore, we conducted a systematic literature review (SLR) to analyse existing literature and systematically search for KPIs to include in the conceptual framework, following the approach of Onstein et al. [35]. The utilization of a systematic literature review serves as an appropriate approach to gather data, such as key performance indicators (KPIs), by utilizing existing literature [50]. This method enhances the value of the existing literature by producing outcomes, such as conceptual models derived from the findings or identifying research gaps [50].

This systematic literature review is based on the approach of Liberati et al. [30]. The review was carried out between December 2021 and January 2022 using five topic-relevant databases: Scopus, Emerald Collections, EBSCO Business Source Elite, IEEE and Google Scholar. To determine the relevant key words for the search strings, we followed the approach of Hamari and Keronen [18] and started an exploratory search of articles to reveal common terminology. In the databases, we firstly searched using wide terms, which were successively narrowed down by selecting several central keywords that appeared in salient studies. Finally, we used the search terms "inland waterway transport" OR "inland navigation" OR "IWT" AND "low water" OR "shallow water" OR "bottleneck*" to search the metadata of the databases. The exact search strings for the meta-analysis are stated in Table 1.

The search in the databases yielded a total of 99 results, which were systematically reduced by sorting out duplicates (7). The remaining publications (92) were analysed considering pre-defined inclusion and exclusion criteria. Articles not written in English (2) were excluded, as were articles published without peer review (5). In addition, publications which were not freely accessible as a full-text version were eliminated (3). We analysed the abstract of the remaining articles (82) and discarded publications

Table 1 Search strings per database

Database	Included metadata	Search strings
EBSCO Business Source Elite	Title, abstract, keywords	((TI “inland waterway transport” OR SU “inland waterway transport” OR AB “inland waterway transport”) OR (TI IWT OR SU IWT OR AB IWT) OR (TI “inland navigation” OR SU “inland navigation” OR AB “inland navigation”)) AND ((TI bottleneck* OR SU bottleneck* OR AB bottleneck*) OR (TI “low water” OR SU “low water” OR AB “low water”) OR (TI “shallow water” OR SU “shallow water” OR AB “shallow water”))
Emerald Collections	Title, abstract	((title:IWT OR title:“inland navigation” OR title:“inland waterway transport”) OR (abstract:IWT OR abstract:“inland navigation” OR abstract:“inland waterway transport”)) AND ((title:bottleneck* OR title:“low water” OR (title:“shallow water”) OR (abstract:bottleneck* OR abstract:“low water” OR abstract:“shallow water”))
Google Scholar	title, keywords	(((intitle:IWT OR keyword:IWT) OR (intitle:“inland navigation” OR keyword:“inland navigation”) OR (intitle:“inland waterway transport” OR keyword:“inland waterway transport”)) AND ((intitle:bottleneck* OR keyword:bottleneck*) OR (intitle:“low water” OR keyword:“low water”) OR (intitle:“shallow water” OR keyword:“shallow water”)))
IEEE	Title, abstract, keywords	(“All Metadata”: “inland navigation” OR IWT OR “inland waterway transport”) AND (“All Metadata”: bottleneck* OR “low water” OR “shallow water”)
Scopus	Title, abstract, keywords	TITLE-ABS-KEY (“inland navigation” OR IWT OR “inland waterway transport”) AND (bottleneck* OR “shallow water” OR “low water”)

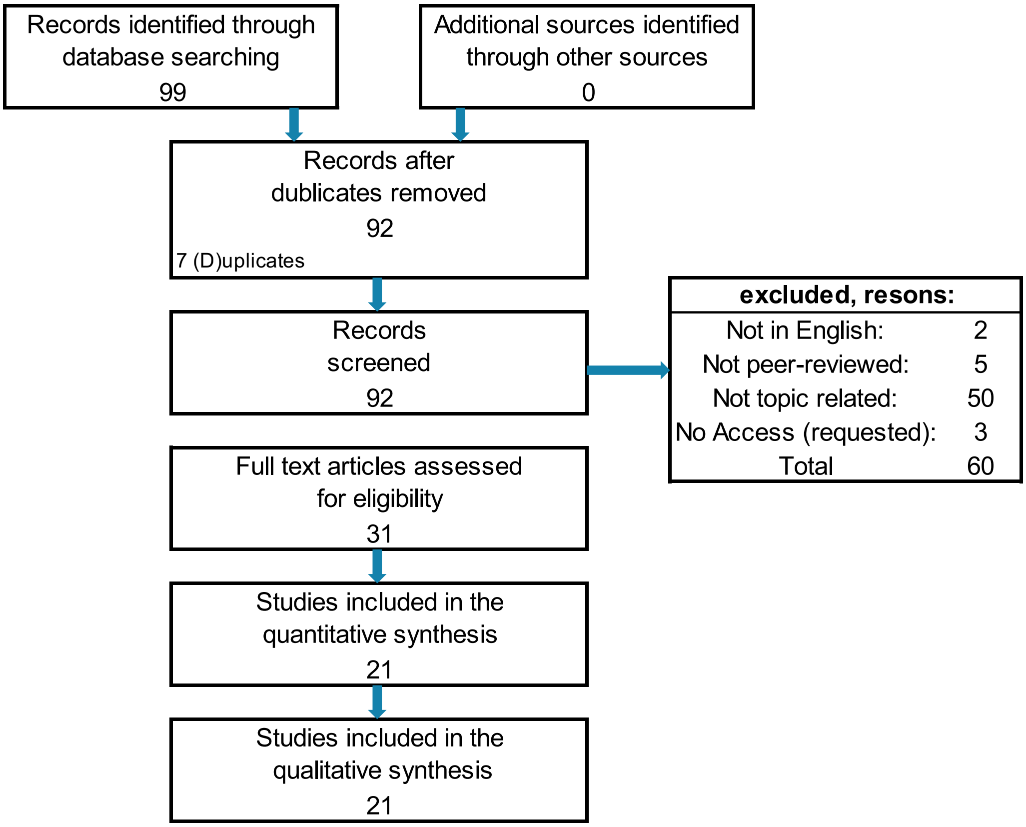

Fig. 1 Approach used for the systematic literature review according to PRISMA

where the topic did not fit our research questions (50). The remaining 32 articles were subjected to a full paper assessment. Among the 32 publications that we assessed entirely, 11 additional articles were excluded due to the content, which did not match our research questions. The literature review resulted in a total of 21 papers which tackle potential KPIs associated with nautical bottlenecks and are therefore further explored for this study.

Table 2 Categories for extracting relevant data used for the descriptive and thematic analysis

Type of analysis	Category	Information obtained
Descriptive	Publication date	Year of publication
	Journal	Name of journal
	Author	Authors name
	Title	Full title of paper
	Geographical distribution	Country/continent of origin, inland waterway researched
Thematic	KPIs related to nautical bottlenecks (and their rehabilitation)	Knowledge about different KPIs and how they are influenced by the rehabilitation of nautical bottlenecks

Figure 1 summarises the procedure of the literature review based on Liberati et al. [30].

The 21 topic-related articles were then qualitatively and quantitatively synthesized. In doing so, we conducted a descriptive and thematic analysis using the approach established by Tranfield et al. [46] and Raza et al. [37]. We decided to use several categories for extracting the data for the descriptive and thematic analysis, which is presented in Table 2.

The aim of the descriptive analysis was to extract data from the literature which is suitable and useful for describing and distinguishing the publications, e.g., the geographical distribution of the article, their authors, full title, or year of publication. In contrast, the thematic analysis serves to describe the article content-wise, i.e., by identifying the different KPIs and their behaviour regarding the rehabilitation of nautical bottlenecks. The next section presents the results and discussion of the descriptive and thematic analysis.

3 Results and discussion

For the descriptive analysis we analysed which literature contains which possible KPIs. We examined the frequency of occurrence of specific KPIs in the body of literature analysed. Furthermore, we analysed the geographical distribution of the articles, regarding the country or continent of origin and the specific inland waterway tackled. Within the thematic analysis, we identified KPIs related to nautical bottlenecks in different ways and emphasised the interdependencies between the KPIs and the nautical bottlenecks. The detailed results are presented in the following subsections.

Table 3 Journals or conference proceedings of publication and number of articles

Journals or conference proceedings of publication	Number of articles
Journals	
Transportation Research Part D: Transport and Environment	3
Case Studies on Transport Policy	2
European Journal of Transport and Infrastructure Research	2
Hydrology and Earth System Sciences	1
Research in Transportation Business and Management	1
Journal of Water and Climate Change	1
Operations Research/Computer Science Interfaces Series	1
Regional Environmental Change	1
Natural Hazards	1
Transport Problems	1
Climate Change Management	1
Transportation Research Part A: Policy and Practice	1
Journal of Transport Economics and Policy	1
Transportation Research Part E: Logistics and Transportation Review	1
Conference Proceedings	
Proceedings of the 4th International Symposium on Life-Cycle Civil Engineering, IALCCE 2014	2
2015 International Conference on Transportation Information and Safety (ICTIS)	1
Total	21

Table 4 Overview of the literature for each KPI

	Performance indicators	**Literature no. (references below)**																				
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**
IWT-related KPIs	Transport duration				x		x	x	x	x		x	x	x	x							
	Fuel consumption						x		x	x			x		x							
	Transport supply	x	x	x	x	x	x	x	x	x	x	x	x	x	x			x		x	x	
	Transport costs		x	x	x		x			x	x	x	x	x	x	x			x	x	x	
	Vessel draft	x		x	x	x	x	x			x	x			x		x					x
	Transport emissions						x		x	x			x		x							
Market-related KPIs	Transport demand			x						x		x		x								
	Modal share										x	x	x			x			x		x	
Location-related KPIs	Throughput (at specific geographic location)										x	x										
	Fairway depths	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

1. Li et al. [29] 2. Sys et al. [44] 3. van Hassel and Rashed [49] 4. Christodoulou et al. [9] 5. van Dorsser et al. [48] 6. Meißner et al. [33] 7. Du et al. [10] 8. Hekkenberg et al. [21] 9. Riquelme-Solar et al. [38] 10. Haselbauer et al. [19] 11. Hoffmann et al. [23] 12. Hekkenberg [20] 13. Jonkeren et al. [26] 14. Schweighofer [40] 15. Beuthe et al. [5] 16. Backalic et al. [1] 17. Scholten et al. [39] 18. Jonkeren et al. [25] 19. Koetse and Rietveld [28] 20. Jonkeren et al. [27] 21. Sheng et al. [41]

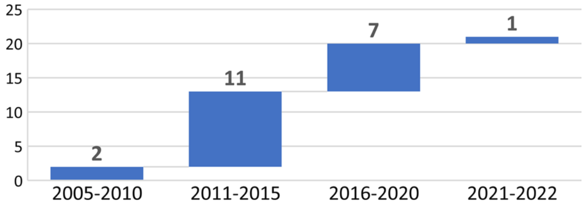

Fig. 2 Distribution of reviewed papers by year of publication

3.1 Descriptive analysis

As part of our descriptive analysis, we considered aspects previously defined as categories for the descriptive analysis. We began our analysis by extracting the journals and conference proceedings in which the articles were published. The detailed results, presented in Table 3 show that 18 out of 21 articles were published in journals, three out of 21 in conference proceedings. Articles published in "Transportation Research: Part D" are the most common, with three out of 21 articles, followed by "Case Studies on Transport Policies" and "European Journal of Transport and Infrastructure Research" with two publications each. All other journals published one article included in our literature review. Of the three articles in conference proceedings, two were published as proceedings of the IALCCE 2014 conference and one as proceedings of the ICTIS 2015 conference.

In the next step, we investigated the years of publication. The diagram in Fig. 2 shows that before 2010 only two articles were published. More than a half of the articles (eleven out of 21) were published between 2011 and 2015, and seven out of 21 articles between 2016 and 2020. In the last two years (2021–2022) only one article was published. The increased frequency of publications on low water and nautical bottlenecks since 2010 suggests that this research field has increasingly gained in relevance in the research community.

Subsequently, we observed that most of the identified literature deals with topics related to temporary bottlenecks, i.e., bottlenecks caused by a low water period, and few articles focus on permanent bottlenecks, i.e., river stretches with low water depth regardless of low water periods. As the effects of both are, to a high extent, similar, we included articles dealing with low water periods in the literature analysis. Furthermore, it is noteworthy that hardly any of the articles deal with the possible effects of nautical bottlenecks on different performance indicators in detail. Nevertheless, we succeeded in extracting several KPIs and subsequently clustered them, according to their focus, into (1) IWT-related, (2) market-related, and (3) location-related KPIs, resulting in three clusters containing a total of ten KPIs. The cluster containing IWT-related KPIs (1) comprises the most individual ones, i.e., vessel draft, transport supply, transport costs, transport duration, fuel consumption and transport emissions. We found two market-related KPIs (2), i.e., transport demand and modal share, and two location-related performance indicators (3), i.e., the throughput at a specific geographic location and the actual fairway depth.

Table 4 illustrates the identified clusters and the individual KPIs assigned to the clusters. Moreover, Table 4 provides an overview of the analysed literature for each identified KPI. This overview shows that most KPIs (six out of ten) as well as all of the literature (21 out of 21) can be assigned to the IWT-related KPIs. For location-related and market-related KPIs, two KPIs were identified for each. Market-related KPIs, i.e., *transport demand* and *modal share* are included in ten out of 21 publications. We also noted that all articles include more than one performance indicator, as each article refers to the fairway depth, which is indeed a major KPI when considering nautical bottlenecks. The KPI *transport supply* is discussed in 17 articles, making it the most frequently mentioned individual KPI besides *fairway depths*. The performance indicator *throughput at a specific geographic location* is mentioned in two articles only, making it the least frequently mentioned performance indicator.

Furthermore, we examined the geographical distribution of the identified literature in terms of region and inland waterways tackled. By far the most literature (18 out of 21) has its origin in Europe, followed by Asia with two out of 21 and North America with one out of 21 publications. No literature was found originating in Australia, Africa or South America. In the European publications, ten out of 18 publications investigate the Rhine, which correlates with its high economic importance due to the amounts of cargo transported on it.. Another five papers do not limit their research to the Rhine and include other rivers, such as the Danube or the Elbe. The remaining publications (three out of 18) tackle solely the Danube. Both Asian papers focus on the Yangtze, while the North American publication deals with the Mackenzie River in Canada. Table 5 visualises the publications' regions of origin and the inland waterways examined.

As the final step in the thematic analysis, we investigated which KPI clusters are examined regarding the region of origin and the specific inland waterways. We found that the articles about the Danube cover all three clusters, i.e., IWT-related (three out of seven), market-related (two out of seven) and location-related KPIs (two out of seven). At the same time, research about the Danube is the only research that takes the KPI *throughput at a specific geographic location* into account. In contrast to, e.g., the Rhine, the Danube has a large expansion area of about 2850 km. Several sections of the Danube show very different characteristics, be it

Table 5 Geographical distribution of the identified literature

Region	Investigated inland waterway	No. of publications	Sum
Europe	Danube	3	18
	Rhine	10	
	Danube and Rhine	4	
	Danube, Rhine, and Elbe	1	
North America	Mackenzie River	1	1
Asia	Yangtze	2	2
Australia	–		0
Africa	–		0
South America	–		0

in terms of waterway width or in terms of the riverbed [15]. Thus, the throughput at a specific geographic location of a nautical bottleneck may be more important than on other waterways. The research about the Rhinetackles all IWT-related KPIs, both market-related KPIs, and *fairway depths* as the only location-related KPI. Articles about the Rhine may emphasise market-related performance indicators as the utilisation rate of the Rhine is much higher than the utilisation rate of the Danube, and, thus, the effects of nautical bottlenecks on the inland waterway transport market and modal share may be more serious. Publications that examine more than one inland waterway (i.e., Danube/Rhine or Danube/Rhine/Elbe) and those in Asia (i.e., Yangtze) and North America (i.e., Mackenzie River) focus on IWT-related KPIs that are related to *fairway depth* within the articles. Table 6 shows the inland waterways and the KPI clusters addressed by the articles.

The next section presents the thematic analysis of the identified KPIs. Each section covers one cluster to provide a clear structure and readability. Section 3.2.4. summarises the main assumptions and illustrates the final conceptual framework.

3.2 Thematic analysis

Nautical bottlenecks limit continuous navigability and economically viable inland waterway transport. Moreover, they prevent shipping companies from providing reliable transport [38]. However, nautical bottlenecks have a major influence on different measures, i.e., KPIs. The effect of nautical bottlenecks on the KPI identified here and, thus, on the net benefit of resolving nautical bottlenecks was extracted from the body of literature and is described and discussed in the sections below.

3.2.1 Inland waterway IWT-related KPIs

"Fuel consumption" measured in litres per 100 km is a major KPI, as resolving nautical bottlenecks leads to fuel consumption decreases and, thus, monetary savings and an increase of the net benefit. Several researchers conclude that low water depths result in higher fuel consumption. Hekkenberg et al. [21] argues that low water depths require a significantly higher amount of power to reach a given speed, therefore resulting in a significant increase in fuel consumption. Hekkenberg [20] adds that, besides low fairway depths, limited fairway widths increase fuel consumption even further, as the vessel acts like a blockage that is moved through the river and that, therefore, even more fuel is needed to propel a vessel at a given speed. Meißner et al. [33] relate higher fuel consumption to higher transport costs. To save fuel, vessels have to sail at a lower speed [38], which influences sailing times and, thus, the total transport time of goods. Higher fuel consumption also leads to an increase in GHG emissions and, thus, in external costs [8, 17, 22, 36]. Transport-related GHG emissions have a substantial negative impact on the environment and must be reduced. A 90% reduction is a major goal of the European climate policy until 2050 [13]. *"Transport emissions"* is another relevant KPI related to nautical bottlenecks and is therefore included in our KPI framework.

The rehabilitation of nautical bottlenecks influences transport duration directly and may result in an economic benefit, thus we include *"transport duration"* measured in hours as a KPI. Low water depth restricts the speed of a vessel and leads to an increase in sailing times [38, 40]. According to Hekkenberg et al. [21] the maximum sailing speed of a conventional cargo vessel

Table 6 Investigated KPIs by inland waterways

Performance indicators	Region of origin and inland waterways					
	Europe				North America	Asia
	Danube	Rhine	Danube/Rhine	Danube/Rhine/ Elbe	Mackenzie River	Yangtze River
IWT-related	4	6	6	6	3	3
Market-related	2	2	1	–	–	–
Location-related	2	1	1	1	1	1

is determined by the actual water depth. A significant amount of power and fuel is needed to reach the maximum speed. Therefore, experienced captains hardly sail faster than 70% of the maximum speed, which leads to longer transport times. Haselbauer et al. [19] agree that captains usually lower the speed of the vessel at already known low water sections, i.e., nautical bottlenecks. Du et al. [10] add that traversing hazardous sections may take longer when the water depth is low. However, long waiting times can additionally contribute to an increase in overall transport duration [9, 26]. Increased transport costs are directly related to an increased transport duration [33], as longer transport time translates into less cargo being able to be transported overall, which leads to less transport supply and additional trips [9].

The KPI *"transport supply"* measured in tonnes consists of the actual loading capacity of vessels, the number of (additional) trips that could be carried out within a given timeframe, and the fleet composition, i.e., vessel's size in operation. Loading capacity is usually measured in tonnes and consists of a vessel's consumables and the payload [48]. Nautical bottlenecks influence the loading capacity of inland vessels [33] and the transport supply in the market itself [26]. Loading capacities are usually hardly affected above a critical water level. Below this, certain loading capacities decrease accordingly and imply restrictions for inland waterway vessels [27]. For the Mackenzie River, which was highlighted in the research of Du et al. [10], this critical water level is at 4.2 m. Riquelme-Solar et al. [38] indicate a similar value (i.e., 4.3 m) in their research. Above this value, inland vessels can be fully loaded on the Rhine, while they lose 85 tonnes of capacity per 10 cm loading draft. However, these values differ between vessels, as vessels can respond highly differently to changes in waterway conditions, despite carrying the same amount of cargo [21]. Thus, fleet composition plays an important role when it comes to transport supply. Li et al. [29] propose that carriers should focus on smaller ships, which fit better with the actual waterway parameters. Jonkeren et al. [26], Schweighofer [40] and Riquelme-Solar et al. [38] agree that lighter and wider vessels can provide up to 20% more loading capacity at low water depths and highlight that these vessels are performing less efficiently in normal water conditions. Christodoulou et al. [9] discuss the bearing capacities of ships related to different vessel size categories. A large vessel loses more capacity in low water conditions than a smaller vessel. However, larger ships imply lower capital cost per tonne of cargo and, therefore, have a major cost advantage over smaller ships in sufficient water conditions [20]. In practice, a significant trend towards larger vessels is observable [49]. Larger vessels lead to a greater dependency of the loading capacity on the water levels, leading to a greater influence of the water levels on the transport price [44]. Haselbauer et al. [19] agree that transport costs vary based on the fleet composition and therefore propose the calculation of transport costs for any investment strategy referring to fairway conditions on the basis of fleet composition. The vessels used on the Danube can be loaded on average with 55 to 60% of their initial capacity, whereas shallow water sections restrict the capacity further, dropping the loading capacity to only 40% [23]. As a result of the restricted capacity, additional trips frequently need to be carried out [9]. There are two main reasons why additional trips have to be carried out at low fairway levels. Christodoulou et al. [9] argue that low water depth leads to decreasing sailing speeds and, thus, decreases the overall transport supply and requires additional trips. Hekkenberg [20] agrees that the decreased speed (i.e. 70% of maximum speed) limits the number of trips a vessel can make and, thus, limits the amount of cargo a vessel can carry in a given amount of time. Another reason for additional trips is the reduced loading capacity per vessels due to low water depths [9, 33]. According to Meißner et al. [33] the situation regarding additional trips is accentuated particularly in periods of extreme or long-lasting low water. Then the vessel supply is limited compared to the transport demand, which leads to the need of shifting cargo to other transport modes.

The *vessel loading draft* measured in metres is directly related to fairway depths [10, 33], [1]. According to van Dorsser et al. [48] a vessel's loading draft correlates with the vessel's capacity, thus, if the loading draft increases, the capacity increases alike. Vessel draft is the underwater depth of a ship (Sheng et al.), which can vary depending on the weight loaded. In fact, the maximum draft of a vessel cannot be utilised up to a specific water level, leading to a limitation in transport supply [9]. According to Hoffmann et al. [23] and Haselbauer et al. [19], on the Danube a vessel loses between seven and 14 tonnes of capacity with each centimetre of decreased loading draft. In contrast, Riquelme-Solar et al. [38] state that the loading capacity decreases approximately 85 tonnes per 10 cm of lost loading draft. Schweighofer [40] provides an example: A large motor cargo vessel with a permitted draft of two meters is able to carry around 1200 tonnes, which represents only 40% of its maximum loading capacity. The larger the vessel and, related to that, the larger its maximum loading draft, the stronger the effect of low water levels on capacity [49]. As water levels vary on the course of the waterway [5], the most shallow river stretch on any given route will limit the maximum loading draft and, therefore, the maximum loading capacity [19].

Transport costs measured in monetary terms vary with a change in transport supply [28] and, thus, of water levels. Consequently, transport prices rise the same [38], often in a one-to-one relationship with the rise in transport costs [25]. In some specific cases, e.g., the tanker market, the increase of transport prices may lead to a decrease in demand for inland navigation services, as customers are rarely willing to pay increased prices [49]. In general, transport costs are higher for larger vessels in low water conditions than for smaller ones, as larger vessels lose more capacity than smaller vessels [33]. Haselbauer et al. [19] agree that transport costs largely depend on the fleet composition. Transport costs generally rise in low water conditions, not only due to a decrease in loading capacity, but also because of the increase in fuel consumption that occurs when a vessel sails on low water levels [20]. Jonkeren et al. [26] point out that stakeholders of the inland waterway sector can contribute to reducing the effects of low water depths, e.g., the increase in transport costs, by taking adequate adaption measures. According to Riquelme-Solar et al. [38], focusing on smaller vessels could be such an adaption measure,another would be to make already withdrawn barges operational again, which helps to maintain the total carrying capacity of the inland waterway despite low water levels [26]. Sys et al. [44] highlight a major difference between temporary low water periods and permanent nautical bottlenecks. While the rise in transport costs due to low water periods can be compensated for by charging a low water surcharge, low water surcharges are not used in the case of nautical bottlenecks. In the latter case, the increased costs have to be covered mainly by the shipping companies. Jonkeren et al. [26] found that freight prices on the Rhine can increase up to 75% per tonne in low water periods, which may affect the IWT market. Market-related KPIs constitute a separate cluster and are discussed in the section below.

3.2.2 Market-related KPIs

"Transport demand" measured in tonnes is a major KPI when analysing nautical bottlenecks. In Europe, the IWT market is characterised as strongly competitive, since there are many carriers on the market offering similar services at similar prices [27]. The loading capacity of vessels decreases due to low water levels, which, on the one hand reduces the effective transport supply in the IWT market, and, on the other hand is responsible for higher costs in IWT [26]. As the IWT market is strongly competitive, the increase in costs is directly transferred to the shippers, who have to cover higher freight prices, which in turn leads to a decrease in transport demand due to low water levels [49]. Insufficient fairway depth impedes both the demand and the supply of the IWT market. The growth of market shares in IWT depends on substantial improvements in the transport mode, e.g., regarding the higher availability of the waterway, which leads to an increased utilisation and lower costs of IWT. Both utilisation and transport demand rises if the fairway conditions and the water levels are satisfactory throughout the year [23], which is essential to ensure the competitiveness of IWT [19].

"Modal share," measured as the percentage of IWT compared to other transport modes is an essential key performance indicator (KPI), which allows for the quantification of competitiveness. Its value may change through the elimination of nautical bottlenecks. According to Hekkenberg [20], the interaction between vessel and waterway must be considered regarding the competitiveness of IWT, as the majority of an inland vessel's cost is influenced by the properties of the waterways. If the water level is high enough, the largest vessels incur the lowest costs per tonne transported regarding factors, such as personnel or capital costs. At low fairway depths, however, a large vessel loses the most loading capacity, which is a disadvantage for competitiveness. For navigation on low water levels, smaller vessels are more suitable and more economically viable. This leads to a dilemma, as vessel owners have to decide on a vessel size that is least disadvantageous to the competitiveness of IWT [38]. Higher prices in IWT may force shippers to transport their goods by road or rail, thus decreasing the modal share of inland navigation, while increasing the modal share of road and rail [25]. However, this effect is rather insignificant in the short run, with a modal shift rate to road and rail of less than 10% according to Jonkeren et al. [26]. Riquelme-Solar et al. [38] agree that the loss of transport demand due to modal shift may be limited, as the loading capacity of inland navigation is far higher than the loading capacity of road and rail. Furthermore, the nature and quantity of goods transported using IWT, e.g., bulk goods, impede a modal shift to other transport modes [5] and experienced shippers using IWT may have sufficient knowledge to plan in advance for low water periods, which occur seasonally, but not every year to the same degree [26]. Nevertheless, the cross-elasticity, i.e., the degree to which IWT can be substituted with another transport mode, is, according to Beuthe et al. [4], highly dependent on the goods transported. While for some goods the cross-elasticity is high, e.g., petroleum, for other product groups, e.g., fertilisers, it is low. Hoffmann et al. [23] state that inland navigation is not competitive, if the average loading capacity drops under 50%, which may be the case when water levels are low. Therefore, sufficient fairway parameters on the entire waterways are crucial to guarantee the competitiveness of inland navigation [19].

3.2.3 Location-related KPI

Throughput (at a specific geographic location) is included in our KPI framework and measured as tonnes passing a specific geographic location. Due to the linear structure of inland waterways, each bottleneck may limit the utilisation of the entire transport fleet. The throughput at a bottlenecks' location is therefore highly significant. The higher the throughput at a specific bottlenecks' location, the more utilisation is limited. If the throughput is high, the effect of resolving a nautical bottleneck is much higher than if the throughput at the bottleneck is low [23]. Another relevant aspect is that bottlenecks that are geographically close to each other generally influence each other. If several bottleneck locations are geographically close to each other, the rehabilitation of a single bottleneck is hardly sufficient to generate positive effects on the utilisation of the waterway. For this, the other surrounding bottlenecks must be removed, as the shallowest section limits the utilisation of the entire river stretch [19].

"Fairway depth" measured in metres is one of the most relevant KPIs with regard to nautical bottlenecks, as the actual fairway depth is decisive in determining the criticality of a bottleneck [23]. The smaller the fairway depth, the less a ship can be loaded. Thus, shallow fairway depth reduces loading capacity, which leads to lowered transport supply and negatively impacts economic viability [9, 19]. Therefore, to calculate the monetary benefits of resolving nautical bottlenecks, the fairway depth is an indispensable parameter, as all other KPIs are linked to it.

3.2.4 Main assumptions and conceptual framework

The thematic analysis proves that various KPIs are affected by nautical bottlenecks. Nautical bottlenecks have such a substantial impact on the net benefit of inland navigation that Meißner et al. [33] propose a monthly to seasonal forecast framework for water levels. To create the conceptual framework based on the KPIs identified above, we extracted the main assumptions from the thematic analysis. The main assumptions for each KPI are illustrated in Table 7, representing the foundation for developing the conceptual framework.

The assumptions for each KPI are interconnected and thus show interdependencies between them. Figure 3 illustrates the synthesis of these assumptions in a conceptual framework based on the identified KPIs, supporting

Table 7 Main assumptions for each identified KPI

KPI clusters	Individual KPI	Main assumptions
IWT-related KPIs	Transport duration	Low fairway depth reduces overall sailing speed and increases transport time
	Fuel consumption	Low fairway depth causes higher fuel consumption A higher fuel consumption is directly related to higher transport costs
	Transport supply	Low fairway levels reduce the loading capacity of vessels and simultaneously the transport supply in the market, which leads to higher transport costs Low fairway depths lead to increased sailing times, which results in lower loading capacity and leads to additional trips. Additional trips result in higher transport costs Loading capacity and transportation costs depend not only on fairway depth but also on vessel size
	Transport costs	Low fairway depth decreases loading capacity per vessel and the total capacity that can be carried on a waterway within a given timeframe and, thus, increases transport costs Low fairway depths increase fuel consumption, which contributes to the increase of transport costs Both capacity and fuel consumption depend on water levels and the vessel type in use
	Vessel draft	With low water depth, a vessel's actual loading draft decreases accordingly Vessel draft and capacity depend on the size of the vessel used. In general, the larger the vessel, the larger the maximum loading draft
	Transport emissions	Increased fuel consumption due to low fairway depth causes higher transport emissions
Market-related KPIs	Transport demand	The actual transport demand influences the net benefit generated by the rehabilitation of bottlenecks; if the transport demand shows a positive development, the net benefit of removing nautical bottlenecks is higher than if the market shows negative developments
	Modal share	In the short run, the effects of a modal shift to road and rail could be neglected, as they are insignificant In the long run, modal shift effects could be observed
Location-related KPIs	Throughput at bottleneck location	The higher the throughput at a bottleneck location, the higher the economic benefit of resolving this bottleneck The closer multiple bottlenecks are to each other, the less economic benefit can be achieved by resolving a single bottleneck
	Fairway depths	Fairway depth is essential to determining the criticality of a bottleneck's location Fairway depth is linked to all other KPIs

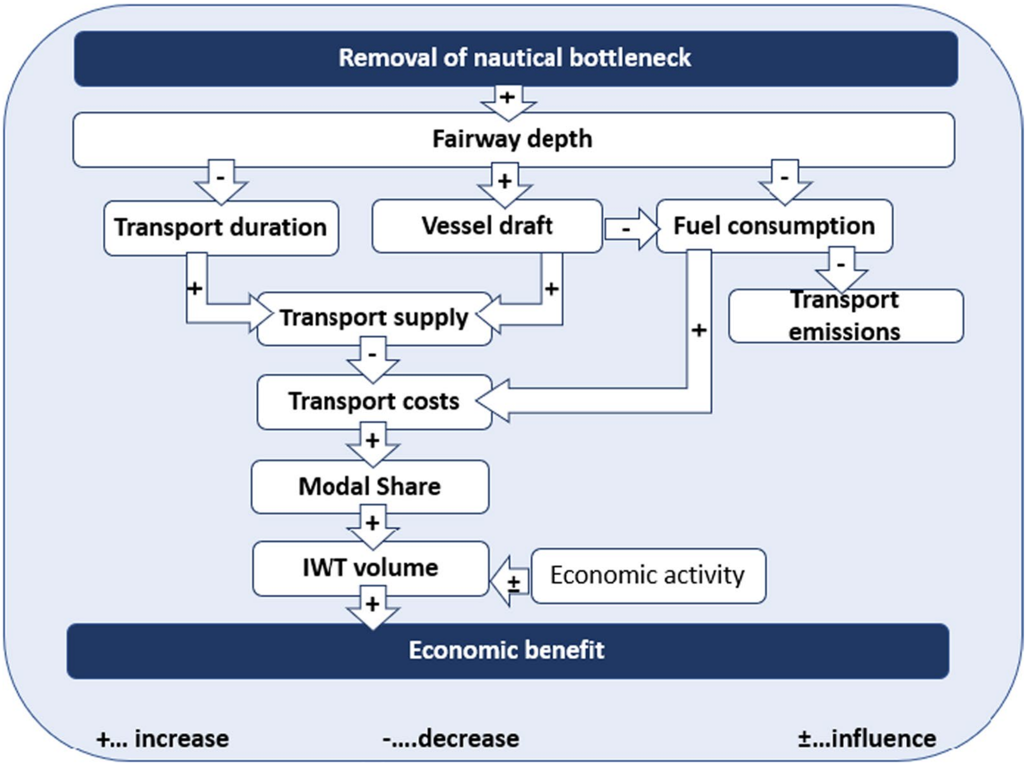

Fig. 3 Conceptual framework based on KPIs to understand the effects of removing nautical bottlenecks

the understanding of the effects of removing nautical bottlenecks and highlighting the interdependencies between the KPIs.

The main goal of resolving nautical bottlenecks is the increase of fairway depth. After successful maintenance or rehabilitation works, fairway depth should be at least at 2.5 m on the Danube. With an increased fairway depth, the vessel draft increases, thus the inland vessels are able to uptake heavier loads, which can be up to 85 tonnes more cargo for each 10 cm more draft. Also, the overall transport duration decreases, as inland vessels may navigate faster without a nautical bottleneck impeding their trip. The actual improvement in transport time depends on whether the river is free-flowing or regulated. These two measures (i.e., transport duration and vessel draft) are linked to an increased overall transport supply, as each inland vessel has an increased loading capacity and due to the lower transport duration, the total amount of possible trips with the available number of vessels increases. A higher transport supply, thus, leads to lower transport costs, as the vessel can be better utilised leading to a cost reduction per transported tonne. An adequate fairway depth results in decreased fuel costs, as inland vessels require a lower amount of engine power to reach a given speed if the fairway depth is sufficient. Less fuel costs contribute directly to lowering the overall transport costs. Lower transport costs may result in an increase of transport demand and, thus, of modal share. Lower transport costs for shipping companies allow to offer more attractive transport services for customers. An increased modal share will raise the overall IWT volume, i.e., the overall tonnes of cargo transported, on the inland waterway. An enhanced IWT volume, which is also influenced by the actual economic activity, contributes directly to the economic benefit, which is generated out of resolving nautical bottlenecks, as the increase in transported tonnes provides financial benefits for the inland navigation sector.

4 Research agenda and outlook

Nautical bottlenecks are river stretches that do not provide at least 2.5 m fairway depth throughout the year and thus hamper inland waterway transport. Resolving nautical bottlenecks on inland waterways is a crucial task, facilitating inland waterway transport by providing sufficient fairway depth. Sufficient fairway depth enables smooth and continuous transportation and contributes to the economic viability of transports using inland waterways. Quantification of the benefits yielded by resolving nautical bottlenecks is a difficult yet essential issue. It is difficult in as much as the IWT system is complex, comprising several KPIs that interact with one another and need to be considered holistically. It is an essential task in as much as quantification, on the one hand, motivates responsible parties to continue the rehabilitation of bottlenecks and, on the other hand, provides an important foundation for investment decisions.

The goal of this paper was to identify major KPIs associated with nautical bottlenecks and to determine the effects of resolving nautical bottlenecks on these KPIs. This knowledge was then to be synthesized within a conceptual framework based on the identified KPIs, aiming to create a robust understanding of the KPIs' interdependencies that can be used for further research in this field. Therefore, we conducted a systematic literature review, resulting in 99 initial hits. These were assessed with the help of predefined inclusion and exclusion criteria, yielding a total of 21 papers eligible for in-depth thematic and descriptive analysis. The results of the systematic literature were subsequently used to draw main assumptions and, finally, to create the conceptual framework.

We identified ten KPIs, which were clustered into (1) IWT-related KPIs, i.e., vessel draft, transport duration, fuel consumption, transport supply and transport emissions, (2) market-related KPIs, i.e., transport demand and modal share, and (3) location-related KPIs, i.e., throughput and fairway depths. Most of the literature originates from Europe, two publications are from Asia, and one from Northern America. The most-discussed inland waterway is the Rhine, emphasising its high value for the industry and transport sectors. Fairway depth is directly linked to nautical bottlenecks and is therefore a topic of each publication. Transport supply and transport costs are two further KPIs found in most of the literature, being interrelated with most of the other KPIs. The KPI modal share measures the increase of competitiveness in IWT, which may result from lower transport costs through resolving nautical bottlenecks. Throughput influences the benefits of resolving specific bottleneck locations, as the benefit is higher for high-throughput locations than low-throughput bottlenecks.

The research agenda in this field of quantitatively evaluating the benefits of resolving nautical bottlenecks is manifold. First, the identified KPIs need to be validated by experts and, if necessary, supplemented. Then, a procedure for measuring these KPIs needs to be established, followed by an integral methodology to measure the benefits of resolving nautical benefits. This integral approach has to be validated and tested, using real data. Therefore, data needs to be collected, processed and analysed.

A limitation of this article is that we used solely a systematic literature review to determine the KPIs. The findings should be validated by experts. Another limitation of this research is that we restricted our search to five relevant data bases, i.e., SCOPUS, Emerald Collections, EBSCO Business Elite, IEEE and Google Scholar; the search for relevant publications could, indeed, be expanded to other databases in this field. Furthermore, the list of identified KPIs through the systematic literature review may not be exhaustive, therefore as a next step activities, such as expert interviews should be carried out to supplement the list of relevant KPIs and the conceptual framework.

This research provides both theoretical and practical contributions. Besides providing an overview of the KPIs relevant to nautical bottlenecks, this paper supports the research community by laying the foundation for further research in this area. The conceptual framework can be further developed to create a method that leads to the economic evaluation of the rehabilitation of nautical bottlenecks. As research in the field of inland navigation is limited in comparison to other transport modes, this paper contributes to building a theoretical foundation in this field. Furthermore, the research can be relevant for stakeholders in IWT. For example, maintenance companies can benefit from this paper by becoming familiar with the economic gains which the rehabilitation of nautical bottlenecks deliver. Shipping operators receive an understanding of the complexity and the relevance of resolving nautical bottlenecks and how they can be addressed in the future.

Author contributions

Conceptualization, BB, EH, L-MP-E; methodology, BB; thematic and descriptive analysis, BB; writing—original draft preparation, BB; writing—review and editing, BB, EH, L-MP-E; project administration, BB and L-MP-E; funding acquisition, BB and L-MP-E; revision, BB.

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Competing interests

The authors declare that they have no competing interests.

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