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Preventing shipping accidents: Past, present, and future of waterway risk management with Baltic Sea focus

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ABSTRACT

Various national maritime authorities and international organizations show strong interest to implement risk management processes to decision making for shipping accident prevention in waterway areas. There is a recurring need for approaches, models, and tools for identifying, analysing, and evaluating risks of shipping accidents, and for strategies for preventively managing these in (inter-)organizational settings. This article presents a comprehensive review of academic work in this research area, aiming to identify patterns, trends, and gaps, serving as a guide for future research and development, with a particular focus on the Baltic Sea Region. To understand the links between research in the Baltic Sea area and the global community, a bibliometric analysis is performed, focusing on identifying dominant narratives and social networks in the research community. Articles from the Baltic Sea area are subsequently analysed more in-depth, addressing issues like the nature of the academic work done, the risk management processes involved, and the underlying accident theories. From the results, patterns in the historical evolution of the research domain are detected, and insights about current trends gained, which are used to identify future avenues for research.

1. Introduction

Waterways are important socio-economic zones for the nations around it. They are crucial means of transportation for goods and services and several people rely on them for their livelihood or commute, directly or indirectly (UNCTAD 2018). Thus, waterways are essential for ensuring continued prosperity and economic growth of countries around the region. However, transportation-related activities also involve high risks to human lives, environmental safety, and economic sustainability.

Accidents in waterways can have can have serious negative impacts to marine and coastal ecosystems (Wells 2017), to economic activities of neighbouring countries (Dolores et al. 2006), and can even lead to socio-cultural disruption (Miraglia 2002). This makes waterway transportation not only an essential aspect of global trade, but also a high-risk system. Further, illegal operational or accidental discharge of oil or other noxious liquid substances in the sea can similarly have serious negative ecological, economic and social consequences (Hassler 2011). With the advent of fast technological change in maritime industries, such as autonomous shipping becoming an increasingly realistic prospect, new risks continuously emerge (Jalonen et al. 2017). Improving society's ability to manage risks emerging from waterway transportation systems is therefore important. Due to the international nature of maritime shipping, national authorities need to ensure safety of navigation in their jurisdiction, pursue regional cooperation among littoral countries of a given body of water, and engage in international activities to ensure safe shipping. Worldwide, maritime industries and authorities are continuously involved in ensuring waterway safety. In academic environments, maritime risk management is an important area of research and development as well.

Prevention of accidents is a critical aspect of waterway management. One way to achieve this is to assess risk in waterways and sea areas and link it to preventive measures that enhance navigational safety. According to the Safety of Life at Sea (SOLAS) Convention, under regulation V/13, national authorities have an obligation to undertake to provide marine aids to navigation, and Vessel Traffic Services (VTS), “as the volume of traffic or the degree of risk justifies” (IALA 2016). Consequently, methods and tools for maritime waterway risk assessment and management have been developed, and guidelines for the use of specific tools have been adopted at the international level (IMO 2010). Furthermore, various research groups across the globe have contributed to developing approaches, frameworks, methods, and tools

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for prevention-oriented maritime waterway risk management, and the scientific literature is replete with models and empirical work to identify, analyse, and evaluate waterway risks.

Given the large and fast-expanding volume of research on maritime accident safety and risk, it is interesting and useful to obtain an overview and insights of the work in this field, not just for practitioners (end-users), but also for the academic community. Several review articles have been written on aspects of this research domain. Our work presents another angle to a specific part of the maritime accident literature, contributing to the discussion through identifying thematic and social patterns in the global research community, and by analysing selected fundamental aspects of preventive risk management. To clearly differentiate our work from existing reviews, we first briefly outline this related literature.

Hetherington et al. (2006) provides a review on human factors maritime safety, focusing on commonalities in accidents, human error, and interventions for improving safety. Pedersen (2010) reviews ship collision and grounding analysis procedures, focusing both on methods for the probability of accident occurrence, as well as the structural damages for accident scenarios. Li et al. (2012a,b) present an overview of maritime waterway quantitative risk assessment models, covering flow-based and simulation-based models for accident occurrence, as well as fault tree and mechanical engineering-based accident consequence models. They conclude that more focus is needed on human error quantification, and propose Bayesian simulation as a method for propagating model uncertainty. Ozbas (2013) describes the literature on safety risk analysis of maritime transportation, covering the concept of risk analysis and its introduction in the maritime domain, providing a high-level overview of qualitative and quantitative approaches to waterway risk analysis. Mazaheri et al. (2014) perform a literature review of ship grounding risk modelling. They first outline a scenario-based risk management framework, and then provide an overview of the ship grounding risk models, discussing their usability for risk management. They also classify the models in terms of the applied modelling tool, the data sources used, and their applicability for decision making through considering risk control options. Goerlandt and Montewka (2015b) analyse the literature on maritime transportation risk analysis with a focus on selected foundational issues in risk research, particularly the adopted definition of risk, the risk perspective used for measuring/describing risk, and the scientific approach underlying the analysis, i.e. the commitment to certain meta-theoretical notions of what the aims of risk analysis is, and how it should be conducted. Lim et al. (2018a,b) present a review of papers on maritime risk analysis, focusing on which models and computational algorithms are applied in different geographical areas, and on what safety or security concerns were addressed. Chen et al. (2019) perform a state-of-the-art review of the literature on probabilistic risk analysis of ship-ship collision. Luo and Shin (2019) review papers on maritime accidents, focusing on the disciplines involved, which causes are considered, and which research methods are used, along with insights in impacts of specific authors and global collaboration networks, as well as general publication trends in different journals and geographical areas.

The aims of the present review differ substantially from the existing reviews. A first issue concerns the selected scope of the research included in our review. Maritime transportation risk management covers a wide range of topics from the perspectives of different players in maritime transportation such as waterway's perspective and ship's perspectives. The current focus is on all aspects of the maritime transportation risk management process from the perspective of waterway, including risk identification, analysis, and evaluation. Risk management in maritime transportation may further be categorized as prevention or response-oriented. The focus of this article is on models, methods, and approaches for assessing safety, risk, reliability, or resilience of maritime transportation in waterway areas, aiming to support prevention-related risk management decisions about risks in sea areas, waterways, or harbour environments, in line with the mandate and needs of national maritime administrations as envisaged by the International Association of Aids to Navigation and Lighthouse Authorities (IALA 2013).

Second, this review applies a bibliometric analysis methodology, to obtain insights in the dominant narrative clusters in the global research area. Such clusters provide a high-level insight into how the academic community conceptualizes waterway risk management, and what approaches it predominantly relies on to inform risk management decisions. Bibliometric methods are also applied to map the scientific community as such, which provides insights in collaboration and knowledge exchange networks. The main aim of this is to understand how the research originating from the Baltic Sea Region connects to, and interacts with, the global research community.

Third, this review subsequently focuses on work originating from the Baltic Sea Region. This focus on the Baltic Sea Region is made to serve as a basis for communication and consultation with maritime stakeholders in this area for facilitating transfer of research results to end-user environments, and for funding agencies in this geographical area to understand future research development needs. The analysis of the work originating from the Baltic Sea Region focuses on a number of conceptual, process-related, and risk-theoretical issues about the prevention-oriented waterway risk management literature. Following issues are addressed: (i) the type of research contributions made (empirical, method development, method application), (ii) the aspects of the ISO risk management process covered (ISO 2018), (iii) the accident theories underlying the scientific contributions, (iv) the extent to which human and organizational factors are considered, (v) which modelling approaches are used in the literature, (vi) the extent to which uncertainty has been explicitly addressed, and (vii) the Technology Readiness Level (TRL) of the developed tools, as defined in EC (2016). Details about these research issues, in terms of why these aspects are important to systematically reflect on, and how these have been operationalized in the current review, are further elaborated in Section 5.

Finally, based on the insights from bibliometric and integrative review focusing on the Baltic Sea Region, current trends in the research domain, as well as future research directions are identified.

The remainder of this article is organized as follows. Section 2 provides details about the data collection process, i.e. what literature is considered in the scope of the current review, and how this literature is identified. Section 3 introduces the review methodology, outlining the bibliometric methods used to gain insights in the global literature. It also describes how the issues in focus in reviewing the literature originating from the Baltic Sea Region are operationalized. Section 4 then presents the results of the global bibliometric analyses, while Section 5 provides insights in specific topics within the research literature, contrasting the work originating from the Baltic Sea Region with work from other regions. Section 6 provides a concluding discussion on the findings, focusing on past and present trends and future research directions.

2. Review scope and data collection process

In performing literature reviews and bibliometric analyses, it is centrally important to utilise high-quality abstract and citation databases, and to apply a rigorous and traceable process for identifying relevant literature (Mingers and Leydesdorff 2015, Van Wee and Banister 2016).

For the current review, which focuses on models, methods, and approaches to support prevention-related risk management decisions of maritime transport in given sea areas, waterways, or harbour environments, the process for identifying the relevant literature is shown in Fig. 1. In stage 1, a search is performed based on combinations of keywords related to the theme in focus. By close reading of the title and abstract, relevant articles are retained in the initial global dataset. The search criteria in stage 1 are relatively restrictive, to avoid obtaining large numbers of irrelevant articles in the search results. In order to find additional relevant articles, in stage 2 the focus is on the key authors as

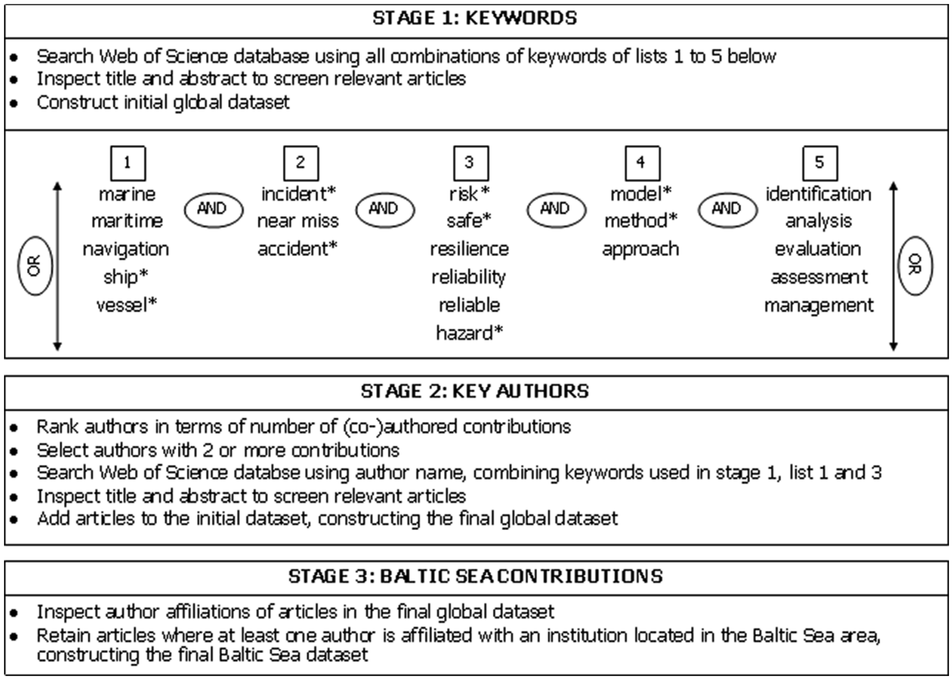

Fig. 1. Procedure for constructing dataset of relevant articles from the literature.

identified in stage 1. For authors with 2 of more (co-)authored articles in the initial dataset, an additional search is executed using selected keywords. Based on close reading of title and abstract of the resulting search results, additional articles are identified, resulting in the final global dataset. In stage 3, this final global dataset is used as a basis for constructing the Baltic Sea dataset, in which only articles in which at least one author is affiliated with an institution located in the Baltic Sea area, are retained. For the purposes of this work, the Baltic Sea area is defined as Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Poland, and Sweden, as intended in the BONUS programme (BONUS 2019). Articles from Russia are included as well, as long as the work focuses on maritime activities in the Baltic Sea basin.

The search is performed in May 2019, using the Web of Science abstract and citation database, which is one of the databases with highest data quality for bibliometric analyses (Mingers and Leydesdorff 2015). The final global dataset consists of 463 articles, of which the final Baltic Sea Region (BSR) dataset contains 206 articles.

3. Review methods

3.1. Bibliometric methods for global analysis

For obtaining insights in the global work on prevention-related maritime waterway risk management, a bibliometric approach is applied. Bibliometric analysis is a technique which can provide insights in a chosen domain of research, through analysing and visualizing data associated with the peer-reviewed literature in abstract and citation databases such as Scopus or Web of Science. Taking the scientific literature itself as a subject of analysis, various methodologies are applied to detect and visualize contributions and collaboration networks of authors or institutions, impacts of particular publications, clusters of publications, and knowledge networks across journals and academic disciplines. Text-mining and content analysis of words in titles, abstracts, and keywords are also applied to identify knowledge clusters and focus areas in the research domain (Qiu et al. 2017).

Various software exist for science mapping and visualization, see e.g. Kumar et al. (2015) for an overview. For the present purposes, bibliometric analyses are performed using VOSviewer, developed by van Eck and Waltman (2010), which implements the visualization of similarities mapping technique (van Eck and Waltman, 2007). This technique analyses similarities between articles in terms of co-authorship, co-occurrence of keywords, and co-citation of references in the reference lists of the analysed articles. The software can also generate term maps, which visualize the structure of a research domain by showing the relations between important terms in the field. Common terms in the titles and abstracts are automatically identified through text-mining techniques (van Eck et al. 2010). Due to its ease of use and its various capabilities, VOSviewer has been used in scientometric analyses of other safety and risk related research areas, including safety culture (van Nunen et al. 2018), construction safety (Jin et al. 2019), and health care resilience (Ellis et al. 2019), and for obtaining insights in the structure of safety science itself (Li and Hale 2016, Merigó et al. 2019).

3.2. Sorting methods for Baltic Sea Region

As mentioned earlier, the dataset for in-depth analyses consists of 463 articles. The articles were filtered using the country of affiliation of authors and sorted into two categories: ‘Baltic Sea Region’ (BSR) and ‘non-Baltic’ (NB). All articles having at least one author from the BSR were counted in the BSR group of articles. The summary of the review shows that the BSR has been responsible for approximately 44.5% of all scientific publications from 1971 to 2019 in waterway safety and risk assessment. Fig. 2 shows the global cumulative count of articles over the years.

Fig. 3 shows the publication outputs of the global and Baltic communities over the years. While the global research in waterway risk and safety has been active since 1970s, the Baltic efforts begin towards the early 1980s. A lot of the initial work in this field comes from Japan such as (Oshima and Fujii 1974). The research output in waterway risk assessment gained a momentum from the late 1990ies onwards and has become an active area of research since then. The Baltic region trends emulate the global trends, where the relative share of Baltic Sea contributions has increased over the years.

It can be observed that while the research output has seen a marked increase, with a first peak in 2009, there is relatively high fluctuation in the number of published articles. Since 2010, the Baltic Sea Region has become the primary area of activity in the research area.

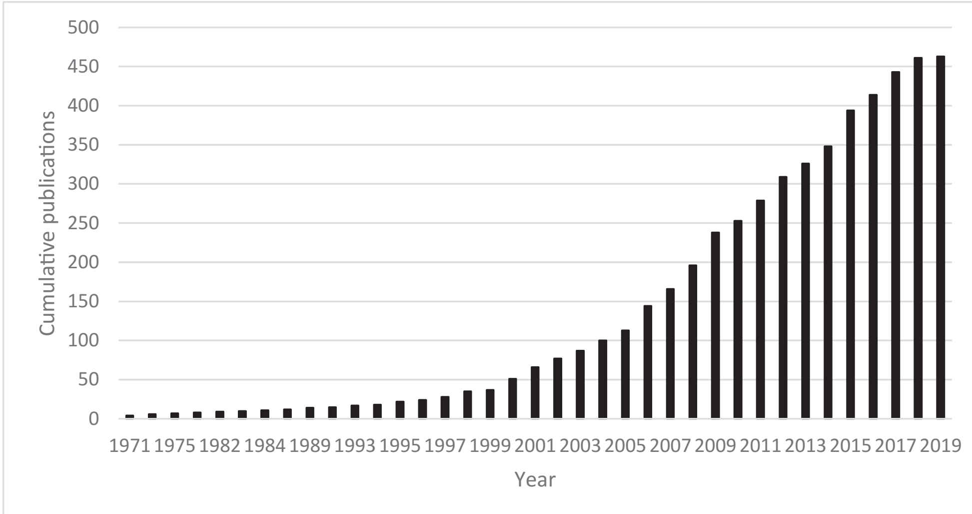

Fig. 2. Cumulative count of articles on prevention-oriented waterway risk management since 1971.

Table 1 summarizes the data from the three sets: complete dataset, BSR and NB. Although the BSR contributions begin to appear only in the 80s, the average for BSR and NB are quite close, indicating the rising contributions over the years.

Table 1
Summary statistics for number of publications.

	Total set	BSR	NB
Minimum	1	0	0
Maximum	46	31	26
Average	12.5	5.6	6.9
Median	10	2	6
Standard deviation	12.6	7.1	6.6

3.3. Review method for literature originating from the Baltic Sea Region

A key part of this work involved expeditiously reading through the 463 shortlisted articles, identifying salient features of each document, which are then collectively analysed. Although this section focuses on the BSR articles, all the 463 articles were reviewed. This allowed for comparative analysis between the BSR and NB trends. An integrative literature review (Torraco 2016) approach is used along with a close reading strategy (Kain 1998), to generate new perspectives and insights on the vast body of work in waterway risk management. Since multiple authors were involved in this process, a rubric has been developed for perusing the articles, to ensure consistency and reliability of the research process. An online form was created for this purpose, which was linked to a spreadsheet for ease of analysis. This form is shown in Appendix A.

In each article, the abstract, objectives, model description and conclusions are read to obtain factual information such as title, year of publication and author details, and to gather the information required to answer the review issues listed in the introduction. Subsequently, each of the research issues mentioned in the introduction, are analyzed and recorded.

First, focusing on review issue 1, the type of work reported in the article is identified. There are 5 categories of work chosen for the publications analyzed: whether the work presents an empirical analysis, proposes a new method, applies an existing method, tests/compares existing methods, or if something else is done (*other* category). The

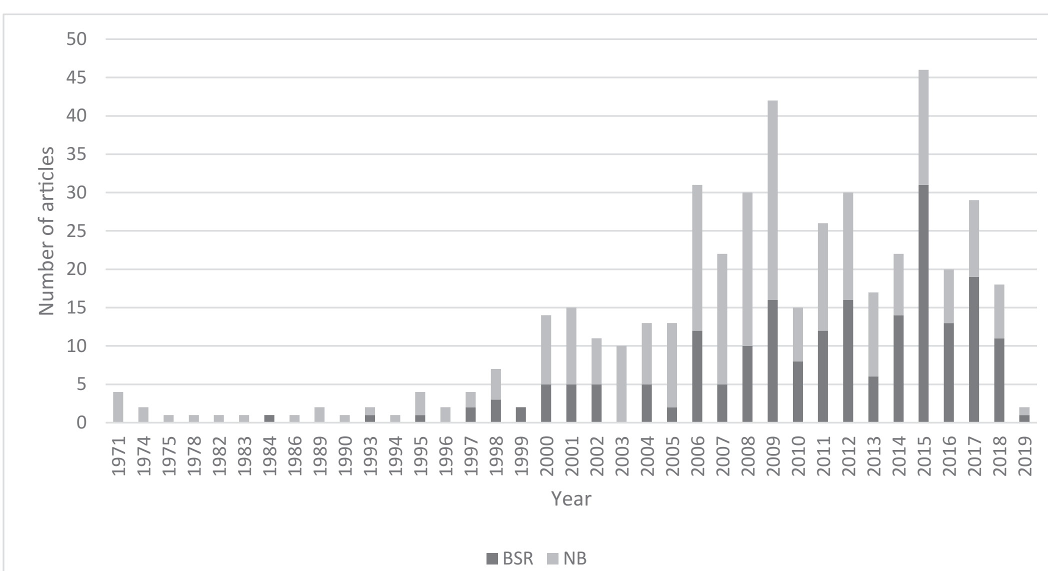

Fig. 3. Output of the prevention-oriented waterway risk management research domain, by year BSR: Baltic Sea Region, NB: Non-Baltic.

other category includes articles such as reviews, discussions on maritime risk management, and recommendations and navigational guidelines. This categorization is of interest as it provides insight into which forms of research the academic community mainly engages in.

Second, the article is inspected to determine which aspects of the risk assessment process have been addressed, in line with review issue 2. The ISO31000:2018 risk management standard (ISO 2018) is used as a benchmark for this classification, distinguishing risk identification, risk analysis, risk evaluation, and proposals for new risk management processes. The phases risk identification, risk analysis, and risk evaluation comprise the complete process of risk assessment. The ISO risk management standard further includes phases of 'communication and consultation' and 'monitoring and review' in the complete risk management process. Here, the focus is on the risk assessment process, and on proposals for how to implement risk management. This is of interest as it reflects the practical end-user needs for having models and tools available for assessing maritime risk, and how to use these in organizational processes.

To answer the third review research issue, the accident theory likely underlying the work is inferred. Based on (Qureshi 2007), following accident theories are distinguished: pyramid (Heinrich 1931), complex linear (Reason 1997), systems-theoretic accident model and processes (Leveson 2016), and functional resonance (Hollnagel 2012). This is significant from a scientific point of view, as it provides insight into how waterway safety is construed in the academic community and which theoretical commitments are made.

The model description is then scrutinized to ascertain whether human and organizational factors are included, answering the fourth review issue. This is significant, as earlier work has identified a need for continuous focus on these aspects, whereas in the maritime policy domain (Schröder-Hinrichs 2010), in maritime accident analyses (Schröder-Hinrichs et al. 2011), and in maritime risk models (Li et al. 2012a,b), human and organizational factors earlier been found to be insufficiently considered.

The fifth review issue pertains to modelling approaches used by researchers in works that present models for maritime safety and risk assessment. This is relevant from a methodological point of view, as different modeling approaches involve various simplifications, are not to the same extent capable to account for different types of evidence and uncertainties, and because there may be important differences in how easily end-users can interpret the model results.

Focusing on the sixth review issue, the articles proposing or applying modelling tools and techniques are inspected to gain understanding into if and how uncertainty has been addressed. The importance of considering uncertainty in risk assessment has been much emphasized in recent years (Flage et al. 2014, Goerlandt and Reniers 2016). In the analysis, a distinction is made between cases where uncertainty is not considered, where it is qualitatively considered, and where it is accounted for in a quantified manner, similarly as in Goerlandt and Montewka (2015b).

To investigate the seventh review issue, the Technology Readiness Level (TRL) of the articles presenting a model or a tool is assessed. This is a scale used e.g. in the Horizon 2020 program to assess the level of development of a certain technology, ranging from the lowest level TRL1, indicating that the basic principles of a technology are observed, to the highest level TRL9, indicating that the actual system is proven in an operational environment. For intermediate definitions, the reader is referred to (EC 2016).

Finally, the articles are inspected to note any limitations or future directions of work mentioned by the authors. This information is used as a guidance to formulate future research directions for the scientific community concerned with the maritime waterway risk application domain.

Two recorders were used to classify the articles into the categories. To ensure consistency of the findings between these, a procedure similar to the one presented in Rae et al. (2010) is applied. The papers were classified by the 1st and 3rd authors, covering approximately 50% of the articles each. As an initial training, 10 articles were randomly chosen and analysed by each of these authors separately, and subsequently discussed to gain a common understanding of the classification mechanisms. Afterwards, the reliability among the reviewers was checked by having each author check 20% of the segment of the articles initially analysed by the other author (i.e. 10% of the total). An additional check was performed by the 2nd author on these cross-analysed papers. For these samples, all reviewers achieved high reliability. The first author reviewed papers from 1971 to 2008 and the third author reviewed papers from 2009 to 2019.

4. Global waterway risk research: Bibliometric analysis

In the following, results of bibliometric analyses applied to the global dataset are shown. Three analyses are performed: two to obtain insight in the research area itself, and one to obtain insight in collaboration networks, investigating how the main Baltic Sea research groups link to one another and to the international research community.

4.1. Co-citation analysis for the global dataset

Fig. 4 shows a co-citation analysis of the global dataset. This analysis measures the relatedness of items in terms of how many times they are cited together, using the approach described in van Eck and Waltman (2007, 2010). Co-citation analyses provide insight in clusters of ideas, in the sense that articles which are cited together within the research domain are considered to form narrative patterns, which provide insights in dominant characteristics of the concepts and approaches on which the research focuses. The analysis shows the co-citation of articles which are cited 10 times or more. In the figure, the node size is indicative of the number of citations, whereas the number and size of the links indicates how strongly connected the articles are. A clustering algorithm groups articles using a color code, facilitating the interpretation.

Fig. 4 shows 5 clusters, where the blue, purple, green, and red are most strongly connected. The yellow cluster is less internally well connected, but contains some very influential articles.

The blue cluster contains highly-cited articles such as Kujala et al. (2009), Montewka et al. (2010), Pedersen (2010), Goerlandt and Kujala (2011), and Silveira et al. (2013), which focus on estimating the probability of collision and/or grounding accidents using traffic flow or traffic simulation, based on ideas related to the ship domain by Fujii et al. (1974), MacDuff (1974), and Goodwin (1975). Early implementations of such traffic flow-based methods (Friis-Hansen and Simonsen 2002, Otto et al. 2002), critical studies about the reliability of such methods (Goerlandt and Kujala 2014), and review articles (Li et al. 2012a,b, Goerlandt and Montewka 2015b) are included as well in this cluster. This blue cluster also includes other approaches using ship domains as a basis for analyzing the risk of ship collision, in which near miss events are detected in data from the Automatic Identification System (AIS), notably the work by Debnath and Chin (2010), Qu et al. (2011), and Weng et al. (2012). This cluster is dominated by contributions from the Baltic Sea area, and from Singapore.

The purple cluster mostly contains articles originating from the collaborations between research groups from the George Washington University (GWU), the Virginia Commonwealth University (VCU), and the Rensselaer Polytechnic Institute (RPI). It consists of several highly-cited articles such as Merrick et al. (2000), van Dorp et al. (2001), Merrick et al. (2002), Merrick et al. (2003), and Merrick and van Dorp (2006), which present system simulation methods for estimating the maritime accident risks, notably collision and grounding. These methods apply pairwise comparison methods in a Bayesian simulation approach to propagate parameter uncertainty in the model. This approach has been influential to similar later work by Uluşçu et al.

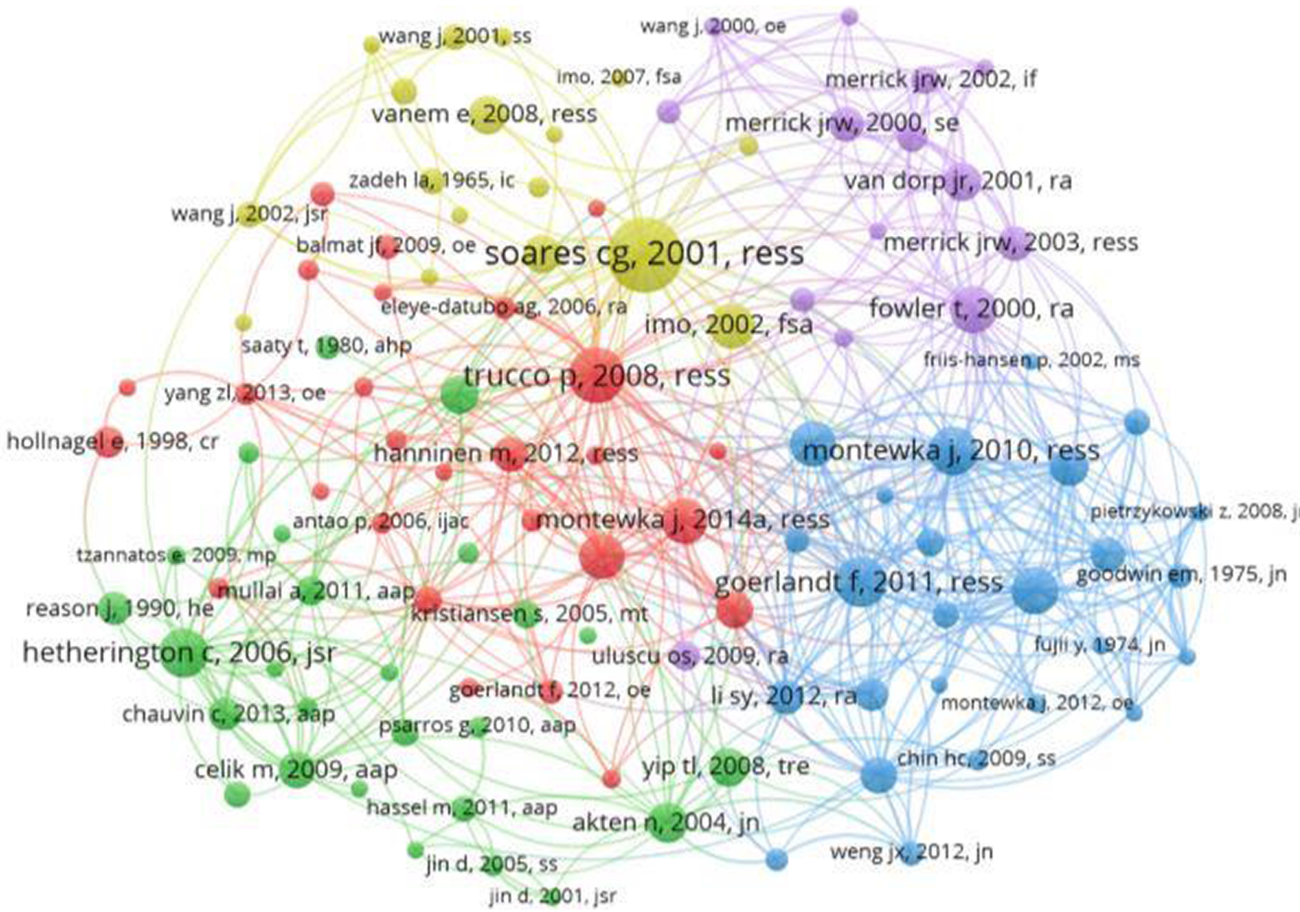

Fig. 4. Co-citation analysis of the global dataset, obtained using procedure of Fig. 1.

(2009). The cluster also contains the influential work by Fowler and Sørgård (2000), who present a traffic-flow based method for ship accident risk, more akin to work the blue cluster, but originating from the same time period as the work by the GMU-VCU-RPI groups, originally also addressing the risks in the Prince William Sound (Fowler et al. 1997).

The green cluster contains work related to accident data analysis and investigation, and human and organizational factors in a maritime risk assessment context. Most highly-cited work in this cluster performs statistical analysis of accident data of maritime activities. Akten (2004) presents an analysis of shipping casualties in the Bosphorus, Darbra and Casal (2004) of accidents in seaports, Jin and Thunberg (2005) of fishing activities in the northeast United States, and Yip (2008) of accidents in Hong Kong waters. This line of work makes simple statistical analysis or develops probability models, from which insights between accident occurrence and contextual factors are obtained. A theme linked to this line of work concerns the issue of underreporting of maritime accidents, investigated by Psarros et al. (2010) and Hassel et al. (2011). Another line of work focuses on accident investigation, where analytical techniques are applied to determine organizational factors and human errors involved in maritime accident occurrence. Celik and Cebi (2009) proposes a fuzzy analytical hierarchy approach with the Human Factors Analysis and Classification System (HFACS) to investigate shipping accidents, whereas Chauvin et al. (2013) apply the HFACS to collision accidents at sea. In another influential paper, Mullai and Paulsson (2011) apply grounded theory as a method for investigating accidents and identifying factors and clusters. Harrald et al. (1998) integrate a human error formalism into the system simulation methods originating from the GWU-VCU-RPI collaboration, and thus strongly links to the purple cluster. Finally, the review article by Hetherington et al. (2006), which focuses on the human element in shipping safety, is a very impactful article in this cluster.

The red cluster primarily includes Bayesian network (BN) approaches for maritime risk assessment. Eleye-Datubo et al. (2006) presents BNs and influence diagrams as decision support tools for maritime risk decision making. Trucco et al. (2008) develop a BN model for human and organizational factors in maritime transportation. Hänninen and Kujala (2012) develop a BN model for ship collision probability estimation. Zhang et al. (2013) apply BNs for estimating accident probability and consequences of vessel accidents in the Yangtze River. Akhtar and Utne (2014) develop a BN model for analyzing the effect of fatigue of grounding accident occurrence, based on analysis of accident investigation reports. Montewka et al. (2014) proposes a framework for maritime risk assessment using BNs, where the probabilities underlying the BN structure are derived from engineering and operations research models. Goerlandt and Montewka (2015a) introduces a two-stage risk analysis approach for maritime transportation systems, where an evidence uncertainty assessment accompanies a BN model in the first stage, the results of which are subsequently used in the second stage through an expert deliberation.

The yellow cluster is not strongly internally connected, but contains some very influential articles. Articles by Soares and Teixeira (2001) and Wang (2001, 2002) present a high-level overview of formal safety assessment and the risk assessment process, serving as early markers of the introduction of risk analysis methodology in the maritime application domain. These are linked to guidelines for formal safety assessment by the International Maritime Organisation (IMO 2002). This cluster also contains influential applications of the formal safety assessment for Liquified Natural Gas (LNG) operations (Vanem et al. 2008) and influence of pilotage on navigation risk (Hu et al. 2007).

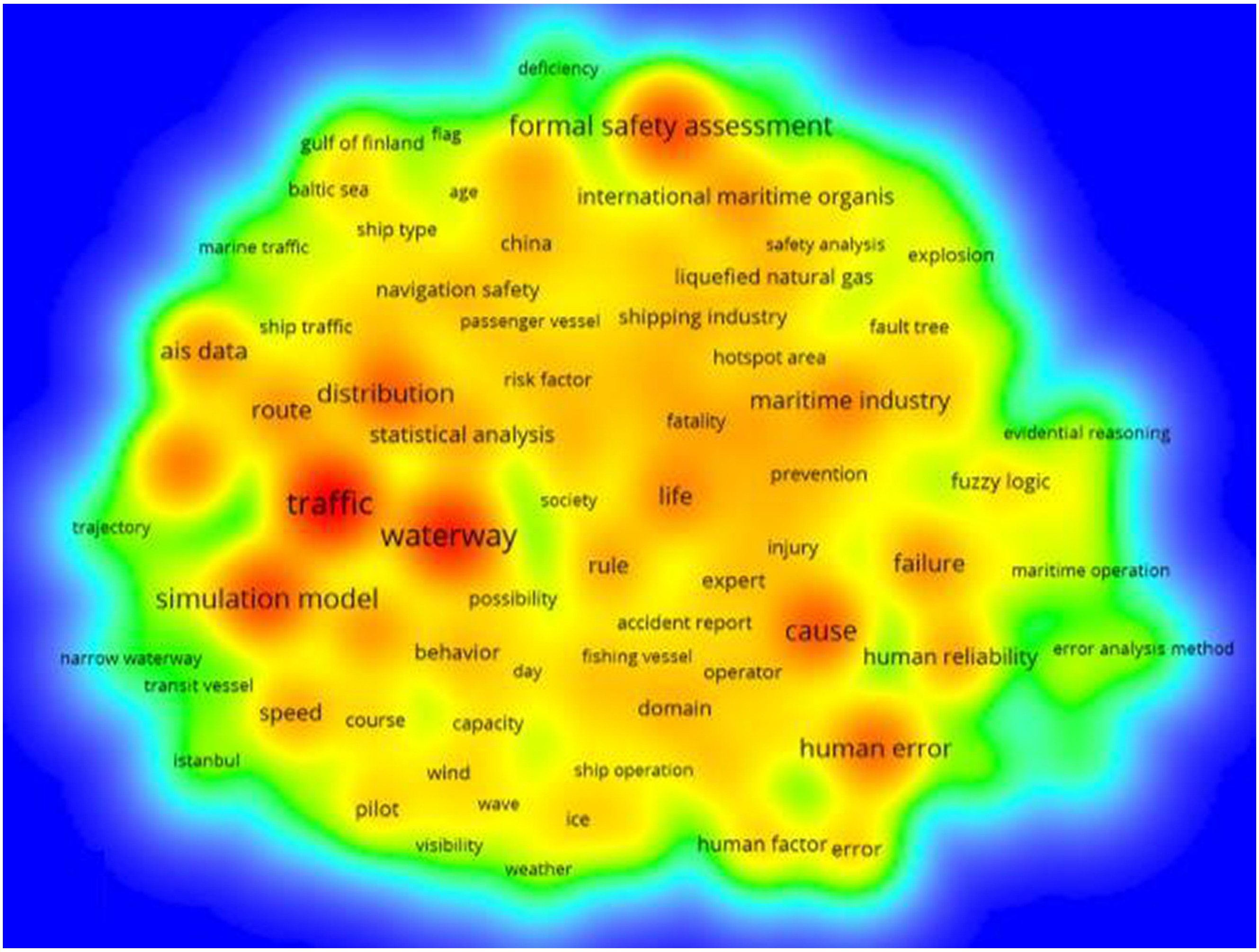

Fig. 5. Term map of global dataset, obtained using procedure of Fig. 1.

4.2. Term map analysis for the global dataset

Fig. 5 shows a term map of the global dataset. This analysis applies a text-mining approach described in van Eck et al. (2010) to the text data in the article dataset, from which related terms are clustered and a heat map generated. For this analysis, the text in the title and abstract of all 463 articles is utilized. Binary counting is applied (counting each term maximally once per article), and only terms which occur minimally 15 times are retained. Similar terms (e.g. FSA and formal safety assessment, LNG and liquefied natural gas) are merged, and non-informative or superfluous words such as risk analysis, risk assessment, or accident, are omitted. Finally, the map of Fig. 5 is created, giving a complementary view on the research area compared to Fig. 4.

A first clear cluster of centrally important terms includes 'traffic', 'waterway', 'AIS data', and 'simulation model', with associated terms including 'route', 'distribution', 'ship traffic', and 'trajectory'. This indicates a narrative cluster where AIS data is used to determine routes or trajectories in waterways, from which traffic is generated using a simulation model, accidents scenarios derived and their probability and/or consequences estimated. This corresponds well to the simulation and traffic flow modelling approaches prevalent in the purple and blue clusters as described in Section 4.1.

A second cluster of important terms includes 'formal safety assessment' and 'international maritime organisation', where associated terms like 'liquefied natural gas', 'passenger vessel', and 'navigation safety' indicate that the FSA process has been applied to these issues of concern. This can be associated with the yellow cluster of Section 4.1, but the term 'formal safety assessment' is also used in other clusters, notably the red cluster.

A third clearly delineated cluster includes key terms like 'human error', 'cause', 'failure', and 'human reliability', with associated terms such as 'human factor', 'operator', 'accident report', and 'error analysis method'. This cluster illustrates that the predominant narrative in the maritime risk management domain that accidents are caused (at least in part) by human errors, which is evident also from some of the analytical approaches involving HFACS and human error quantification approaches in the green and red clusters as described in Section 4.1.

Furthermore, there are several prevalent terms which are not as clearly clustered around key terms, but still indicate narrative patterns. For instance, the terms 'speed', 'course', 'pilot', 'wind', 'wave', 'ice', 'visibility' and 'weather' characterize a narrative focusing on factors involved in accident occurrence, covering operational, human/organizational, and contextual issues. Another weak pattern can be identified, where terms focus on the geographical areas to which the work applies, e.g. 'Baltic Sea', 'Gulf of Finland', 'China', and 'Istanbul'. Finally, it is evident that work focuses on human safety, with terms as 'life', 'fatality', and 'injury' present in the result.

4.3. Author collaboration analysis for the global dataset

Fig. 6 shows a co-authorship analysis of the global dataset. This analysis measures the strength of collaborations between authors, using the approach described in van Eck and Waltman (2007, 2010). Co-authorship analyses provide insight in the social dynamics of the research

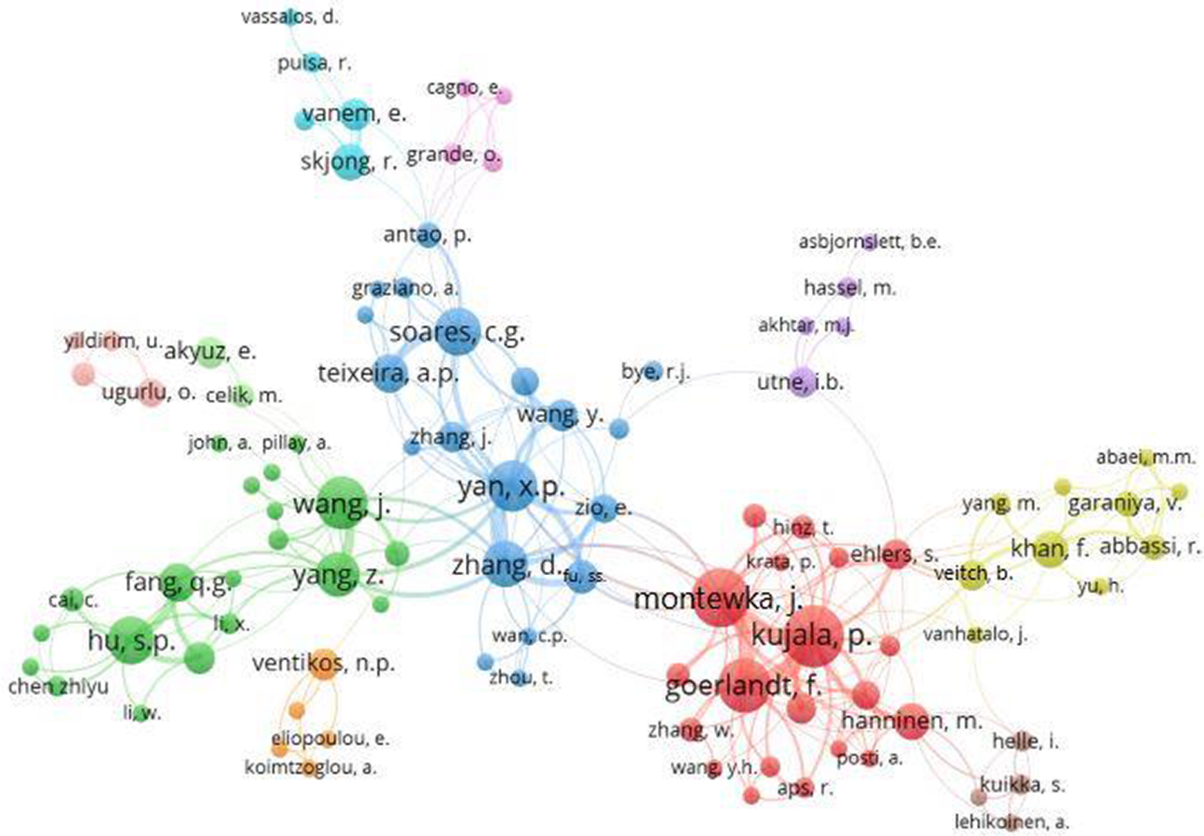

Fig. 6. Largest connected author network of global dataset, obtained using procedure of Fig. 1.

domain, which links to the direct exchange of ideas, and to the development and maintenance of networked expert communities within and across different geographical areas. In line with the stated research objectives in the introduction, this co-authorship analysis contributes to gaining insight in the structure of the scientific community concerned with waterway risk assessment, and especially how research groups in the Baltic Sea Region connect to one another, and to other groups worldwide. Such social aspects of author collaborations are commonly performed in bibliographic research, e.g. Van Nunen et al. (2018) and Luo and Shin (2019).

The analysis shows the co-authorship of authors with 2 or more publications, where only the largest connected network is retained. In the figure, the node size is indicative of the number co-authored articles of an author, whereas the size of links between authors indicates their level of collaboration. A clustering algorithm groups authors using a color code, facilitating the interpretation.

The network of Fig. 6 shows 11 clusters. A first key groups can be identified around Jin Wang and Zaili Yang (Liverpool John Moores University, UK), and Shenping Hu and Quangen Fang (Shanghai Maritime University, CHN). A second key group includes Xinping Yan and Di Zhang (Wuhan University of Technology, CHN), and Carlos Guedes Soares and Ângelo Teixeira (Instituto Superior Técnico, POR). A third key group includes Pentti Kujala (Aalto University, FIN), Jakub Montewka (Aalto University/Gdynia Maritime University, FIN/POL), and Floris Goerlandt (Aalto University/Dalhousie University, FIN/CAN). An emerging fourth group includes Faisal Khan and Brian Veitch (Memorial University of Newfoundland, CAN), and Rouzbeh Abbassi and Vikram Garaniya (University of Tasmania, AUS).

Smaller groups in the network of this research domain include those of Nikolaos P. Ventikos (National Technical University of Athens, GRE), Emre Akyuz and Metin Çelik (Istanbul Technical University, TUR), Özkan Uğurlu (Karadeniz Technical University, TUR), Rolf Skjong and Erik Vanem (Det Norske Veritas, NOR), Ingrid Bouwer Utne (Norwegian University of Science and Technology, NOR), and Sakari Kuikka (University of Helsinki, FIN).

Focusing on the Baltic Sea area, the network in Fig. 6 shows that the groups in this area collaborate mostly with groups in the same geographic region. Within Finland, the strongest collaborations occurred between Aalto University (FIN) and University of Helsinki (FIN), mostly through Maria Hänninen, Inari Helle, and Annukka Lehikoinen. Regional collaborations in the Baltic Sea area occurred mostly between Aalto University (FIN) and University of Tartu (EST) through Robert Aps, between Aalto University (FIN) and Norwegian University of Science and Technology (NOR) through Sören Ehlers, and between Aalto University (FIN) and Tallinn University of Technology (EST) through Kristjan Tabri.

Wider international collaborations occurred mainly between Aalto University (FIN) and its international partners: Memorial University of Newfoundland (CAN) through Brian Veitch, University of Washington (USA) through Weibin Zhang, and Wuhan University of Technology (CHN) through Shanshan Fu. Collaborations between University of Helsinki (FIN) and Memorial University of Newfoundland (CAN) occurred through Jarno Vanhatalo. Stein Haugen implemented a collaboration between Norwegian University of Science and Technology (NOR) and Wuhan University of Technology (CHN). Finally, collaborations between Det Norske Veritas (NOR) and Instituto Superior Técnico (POR) occurred through Pedro Antão.

Fig. 7 shows a co-authorship analysis of the second largest network in the Baltic Sea area. This clearly shows a cluster around Lucjan Gucma of the Maritime University of Szczecin (POL), who has collaborations with Peter Vidmar and Marko Perkovic of the University of Ljubljana (SLO), and with J.K. (Han) Vrijling and Nguyen Minh Quy of TU Delft (NLD).

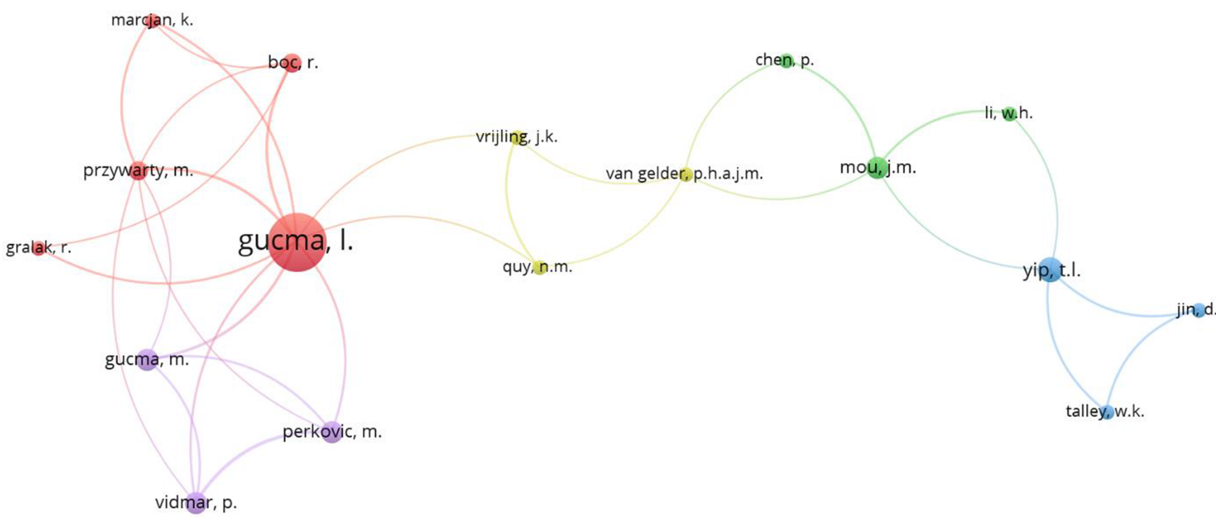

Fig. 7. Secondary Baltic Sea area network and its international connected network, obtained using procedure of Fig. 1.

5. Waterway risk research in the BSR: conceptual, process, and theoretical issues

An important goal of this article is to review, critique, and synthesize the scientific literature on prevention-oriented waterway safety risk management, with an emphasis on the Baltic Sea Region. In this section, an in-depth analysis of the articles is presented, focusing on review issues in focus for the literature emerging from the Baltic Sea Region, introduced in Section 4.2.

5.1. Review issue 1: Type of work performed

The first review issue addresses the type of work in each article. Table 2 shows the summary numbers for the reviewed articles. The columns indicate a comparison between NB and BSR contributions to each type of work. As mentioned in Section 3.3, five categories are chosen for this analysis: empirical analysis, application of existing methods, testing/comparing methods, proposing a new method and others. These categories are not mutually exclusive. An article could possibly include any number of the types of works. For example, Zhang et al. (2016) and Chen et al. (2018) propose new methods for detecting near misses from AIS data, and compare this with results of an existing risk analysis. Therefore, the rows in Table 2 show not just standalone types of works, but also combinations of two or more types in an article.

Table 2
Number of articles in each category and combination of categories in prevention-oriented waterway risk management in each region and in each year, as specified in Section 3.3.

Type of work done					Total	NB	BSR	%BSR
EA	PNM	TCM	AEM	O				
x					113	75	38	34
	x				53	39	14	26
		x			5	3	2	40
			x		63	22	41	65
				x	41	22	19	46
x	x				26	14	12	46
x		x			16	11	5	31
x			x		67	31	36	54
x	x	x			8	3	5	63
x	x		x		13	9	4	31
x		x	x		17	9	8	47
x	x	x	x		1	1	0	0
	x		x		28	14	14	50
		x	x		5	1	4	80
	x	x	x		1	0	1	100
Total					463	257	206	45

Notes: EA = empirical analysis | PNM = proposing new method | TCM = testing/comparing methods | AEM = application of existing method | O = other.

Overall, 110 out of the 463 articles are works of empirical analysis. The earlier works in empirical analysis such as Oshima and Fujii (1974) estimated values for factors like collision frequency based on analyses of records of location, number of vessels, time and weather. More recently, statistical analyses of accident databases and AIS data such as in Gilberg et al. (2017) have increased in number. For the Non-Baltic region, standalone empirical analysis accounts for nearly 30% of the work. For the Baltic Sea Region, however, the work is more uniformly spread across application of methods, empirical analysis and a combination of the two. The BSR leads the standalone contributions in application of methods, with nearly 65% of all articles in this category coming from it. Interestingly, standalone works proposing entirely new methods account for only 11% of the total articles. For instance, Szwed et al. (2006) propose a new method using Bayesian statistics and a paired comparison approach for estimating relative accident probabilities, and Qu et al. (2011) propose an indicator-based collision risk analysis method. Several articles such as Kujala et al. (2009), van Dorp and Merrick (2011) and Silveira et al. (2013) apply existing models to estimate the risks for new sea areas. Very few articles are dedicated to purely comparative studies, a notable exception being the work by Goerlandt and Kujala (2014). The *others* category includes reviews articles such as Li et al. (2012a,b) and Chen et al. (2019), guidelines (Ruggieri 2006), feasibility studies (Hänninen et al. 2013), and other qualitative discussions (Reunanen and Tuominen 1997).

Fig. 8 shows the trends of types of work done across the years, for the Baltic Sea Region and the Non-Baltic region. The first graph shows the BSR trends, followed by the NB trends in the second graph. The figures show the 4 main categories of work. The *other* category is not plotted, since it includes a wide range of articles, from guidelines and reviews to frameworks and case studies.

In the Non-Baltic region, empirical analysis was predominant during 2001–2009. After 2009, new methods began to be proposed, along with extended applications of existing methods. The BSR shows a more even distribution among types of work, with slight preference for application of existing methods.

5.2. Review issue 2: Aspects of risk management process

The article set was scrutinized to note which aspects of risk

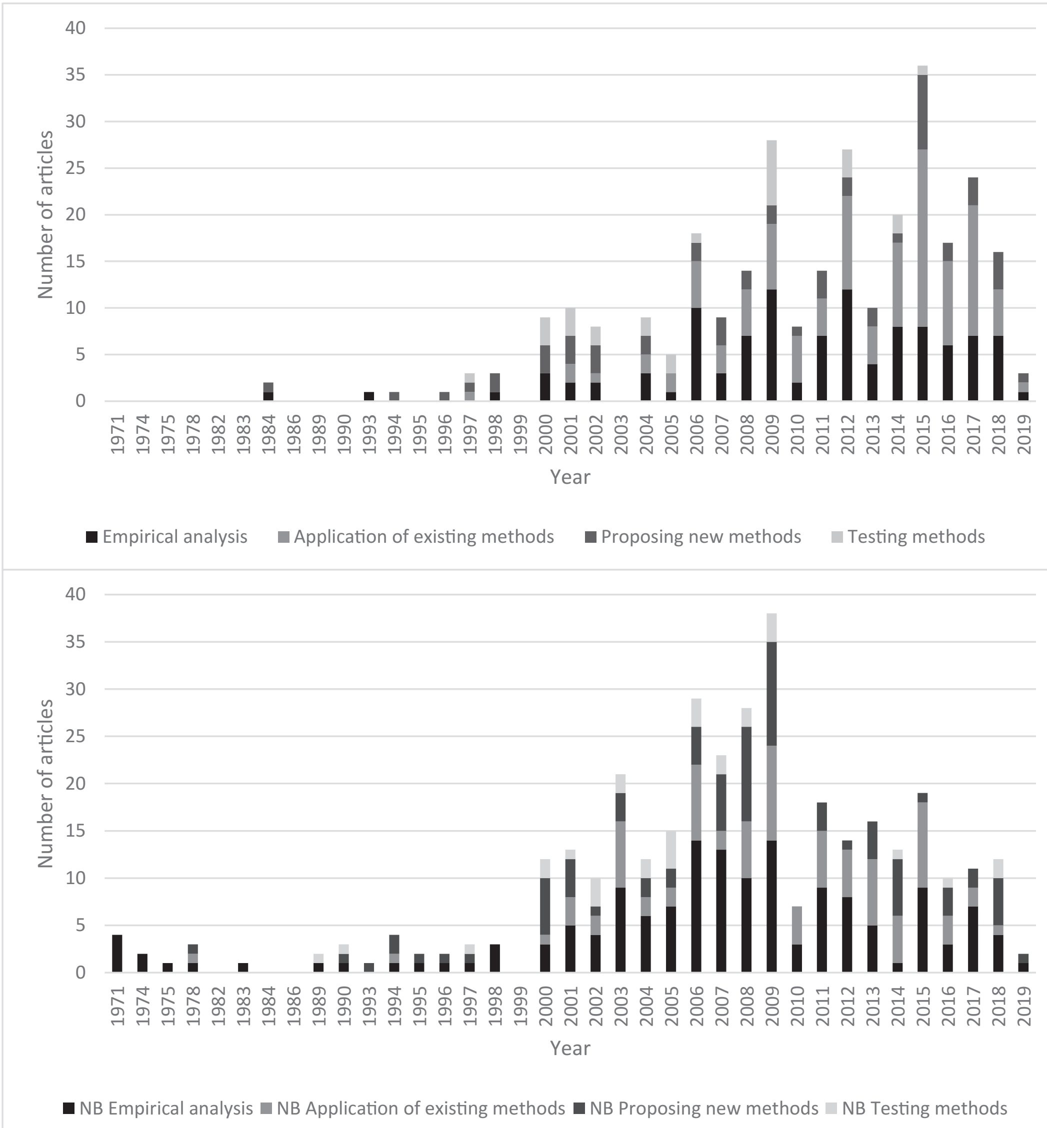

Fig. 8. Number of articles of different types of work in prevention-oriented waterway risk management in each region and in each year as specified in Section 3.3, Top: Baltic Sea Region, Bottom Non-Baltic region.

management were addressed: identification, analysis, evaluation or proposal of a new risk management process. All articles that listed potential risks and described their characteristics were documented under "risk identification" such as Chen et al. (2019). An article was said to include "risk analysis" if it considered the probabilities of potential risks, their consequences and/or strategies to mitigate risks such as Bubbico et al. (2009). To qualify under "risk evaluation", an article had to compare the results from risk analysis with parameters/criteria such as Gucma (2002). This article focuses on reviewing different aspects of risk analysis. Therefore, technical details pertaining to the underlying models of the various risk analysis methods mentioned in this section are not described in detail. Readers interested in details of modelling and computational methods in maritime risk analysis are referred to the reviews by Li et al. (2012a,b), Lim et al. (2018a,b) and Huang et al. (2020).

Table 3 presents the summary of numbers for this review issue. An article may address one aspect of risk management, or multiple of these. Nearly 50% of the articles address all three aspects of risk assessment: identification, analysis and evaluation, such as Merrick et al. (2005) and Gucma et al. (2015). Further, an article may propose a new risk management approach, such as Haapasaari et al. (2015), or not address any risk assessment stage, e.g. Skjong and Soares (2008). In this latter case, it is classified as 'Other'. As shown in the following table, there are several articles addressing a combination of these categories.

Fig. 9 shows the risk assessment trends for NB and BSR articles over the years. As mentioned above, an article can be assigned to multiple categories, so that it can be counted in more than one row of Table 3 above, and also be included in multiple categories in Fig. 9. Although the review issue was analysed for 5 options, the figures only shows three of these. This is because the number of articles in the categories 'Proposals for new risk management approach' and 'Other' is insignificant and not observable along with the three stages of risk assessment.

From 2005, the 'Evaluation' aspect seems to show a marginal increase. However, for both the regions, most of the work predominantly falls under identification and analysis categories. For NB region, the year 2009 saw maximum number of articles addressing all RM aspects, while for BSR, it was the year 2015. However, this trend did not carry over to the subsequent years. The trends seem to indicate that the current research practices involve fewer studies with all aspects of RM considered, as opposed to the past.

Table 3
Number of articles considering an aspect of risk management, or a combination of these, as specified in Section 3.3.

Type of work done					Total	NB	BSR	%BSR
Identification	Analysis	Evaluation	New RM	Other				
x					16	7	9	56
	x				16	11	5	31
		x			2	1	1	50
			x		2	1	1	50
				x	11	8	3	27
x	x				173	102	71	41
x	x	x			4	4	0	0
	x	x			5	2	3	60
x	x	x			232	120	112	48
	x	x	x		1	1	0	0
x	x	x	x		1	0	1	100
Total					463	257	206	45

Notes: New RM = proposing a new risk management approach.

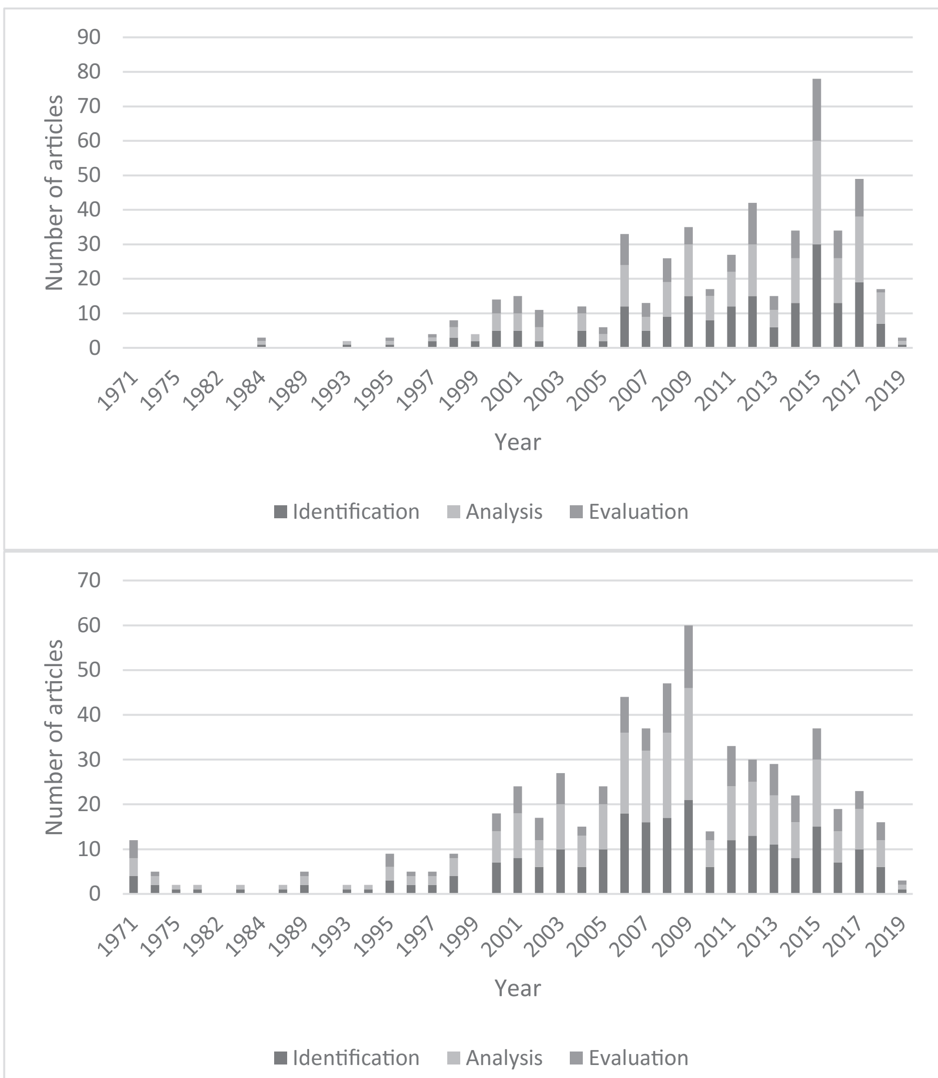

Fig. 9. Number of articles in each region in each risk assessment stage as defined in Section 3.3, by year of publication, Top: Baltic Sea Region, Bottom: Non-Baltic region.

5.3. Review issue 3: Accident theory

The articles were investigated to identify the underlying accident theories, if any. The first theory considered is Heinrich's theory, often known as pyramid or domino theory as well. The theory focuses on the analysis of five sequential factors: social environment, fault of person, unsafe act or condition, accident, and injury (Heinrich 1931). The theory simplifies the cause of an accident to a single root cause that triggers an effect on the following sequential factors. All articles that focussed on a singular cause for accidents, considering their impact only on the immediate next step, were classified as following the pyramid theory. The work captured by this theory includes statistical analysis, qualitative discussions and simple probabilistic estimations. This theory has influenced many of the research done between the 1970ies and 1980ies when the theory became more utilized in the analysis of the accidents in the maritime industry, and it influences the development of more sophisticated linear models (Weaver 1971, Bird 1974).

The next theory is the complex linear theory. This theoretical approach refers to the analysis of the act and interaction of different components in a system (Reason 1997). This is approached through analytical reduction, i.e. considering the system as a collection of interacting components. The focus is on analysing and explaining how these interact in a complex fashion, where linear sequences of component failures lead to accidents. All articles that modeled accidents as complex events comprised of multiple interlinked factors, were considered to follow this theory. Some of the works that followed this theory focussed on setting appropriate controls in the system for mitigating risk. Several varieties of models are captured by this theory, such as probabilistic and statistical modelling, time sequence models and simulation models. The theory has been utilized for elaborating new models to analyse the complex interactions of the maritime traffic system in the Baltic Sea Region, e.g. Hänninen and Kujala (2012), Valdez Banda et al. (2016), and in the Non-Baltic region, e.g. van Dorp and Merrick (2011), Afenyo et al. (2017).

The third theory is the Systems-theoretic accident model and processes (STAMP). STAMP is an approach to depict and review the function of safety from a systemic perspective. According to its proponents, it attempts to efficiently face the fast pace of technological change, increase the ability to learn from experience, understand the changing nature of accidents, and particularly deal with the complexity from the interaction among diverse system components (Leveson 2004). STAMP is a relatively new theory and articles highlight its application right at the onset. Most of the work in STAMP connected to the analysis of maritime risk and safety comes from Baltic Sea Region. It has been implemented in an adaptive integrated safety management approach of the eco-socio-technical maritime transport system in Aps et al. (2017), for designing a maritime safety management system for VTS Finland as presented in Valdez Banda and Goerlandt (2018), and recently for the analysis of risks linked to the foresee operational concept of autonomous shipping in Wróbel et al. (2018) and Valdez Banda et al. (2019).

The fourth theory is Functional Resonance (FRAM). This theory provides a way to describe outcomes using the idea of resonance arising from the variability of everyday performance. It is composed of five steps: identify and describe system functions, check the consistency of the model, check model variability, define functional resonance based on dependencies, and identify means to monitor the development of resonance (Hollnagel 2012). This is a newer concept and articles applying this concept usually explicitly say so, either in the title or in the abstract. There are few studies using this relatively new accident theory. One example is the analysis of the safety of ship navigation in the Arctic with operational safety variation among ship crews (Smith 2019). Praetorius et al. (2017) propose to introduce FRAM as tool to enrich the application of the Formal Safety Assessment by IMO.

Table 4 shows the number of articles under each type of accident theory as described in Section 3.3. The categories are not mutually exclusive, and an article may include multiple theories. Hence, the table below shows rows for individual categories as well as combinations.

Table 4
Number of articles under each accident theory or combination of accident theories by region, as specified in Section 3.3.

Accident theory					Total	NB	BSR	%BSR
Pyramid	Complex Linear	STAMP	FRAM	No theory				
x					83	51	32	39
	x				297	164	133	45
		x			11	2	9	82
			x		4	1	3	75
				x	65	36	29	45
	x	x			1	1	0	0
	x	x	x		2	2	0	0
Total					463	257	206	45

Fig. 10 shows the trends of accident theories for the Baltic Sea Region and the Non-Baltic region over the years. The work from the Non-Baltic region is predominantly in the categories of complex non-linear and pyramid theories. Occasionally, FRAM appears in the recent years, but it is highly limited. The Baltic Sea Region also has produced a large number of articles based on the complex linear and pyramid theories. However, in recent years, the Baltic Sea Region is exploring the newer theories like FRAM and STAMP. STAMP in particular has attracted much more researchers in the Baltic Sea Region than elsewhere.

About 15% of the articles did not mention any accident theory and no accident theory could be inferred from the article. These articles mostly included focussed case studies, literature reviews, qualitative discussions and guidelines.

5.4. Review issue 4: Human and organizational factors

Another important aspect is the consideration of human and organizational factors. While modelling and analyzing accidents such as groundings or collisions, it is important to consider the people and organizations involved, in addition to contextual aspects such as the ship movement and weather conditions. The integrative review however revealed that nearly 56% of the articles do not consider human and organizational factors, either qualitatively or quantitatively.

Table 5 shows various factors included by the articles. The articles considered under "Yes" incorporated at least once factor related to humans and one factor related to organizations, such as (Valdez Banda et al. 2016). Articles under "No" did not consider human or organizational factors in either a qualitative or quantitative manner, for instance (Qu et al. 2011). Some articles only considered human factors such as human errors (Abramowicz-Gerigk and Hejmlich 2015).

Fig. 11 shows the trends of the consideration of human and organizational factors in work on prevention-focused maritime waterway risk management work over the years, for both the Baltic Sea Region as the Non-Baltic regions. The figure shows the number of articles of each region that consider human and organizational factors as a percentage of the total number of articles in that year. Very few articles in the early years incorporated these factors. After 2000 however, the numbers began to increase. The peak for both regions is in the year 2009.

5.5. Review issue 5: Modelling approaches

The fifth review issue identified the modelling techniques and approaches used by the researchers. The review indicated that the most common approaches included Bayesian Networks, Fault Trees, Fuzzy Sets, Simulation and other mathematical models. The "no model" category includes articles focussing on qualitative discussions, reviews,

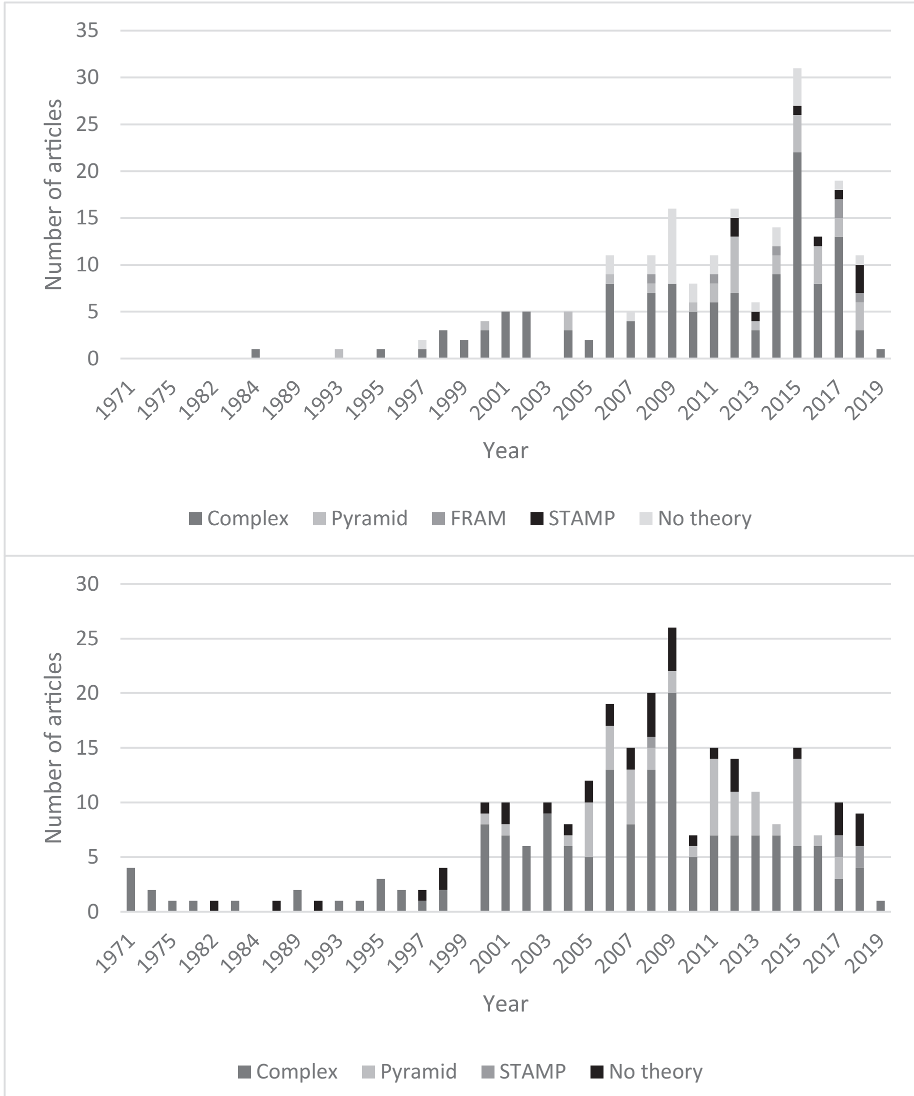

Fig. 10. Number of articles in each accident theory as defined in Section 3.3, by year of publication, Top: Baltic Sea Region, Bottom: Non-Baltic region.

Table 5
Summary of how articles have incorporated human and organizational factors by region, as specified in Section 3.3.

Factors included	Total	NB	BSR	%BSR
Human and organizational factors	170	96	74	44
Only human factors	19	13	6	32
Only organizational factors	14	12	2	14
Neither human nor organizational factors	260	136	124	48
Total	463	257	206	45

guidelines and frameworks. Table 6 shows the number of articles under each modelling category for both NB and BSR. The five categories mentioned in Section 3.3 and shown in Appendix A do not lead to exclusive classifications, i.e. an article may employ more than one modelling techniques. Hence the rows in Table 6 show the number of articles in standalone categories along with a combination of categories.

Fig. 12 shows the trends of modelling techniques across the years for the Baltic Sea Region and the Non-Baltic region. The plots include the four modelling techniques mentioned in Section 3.3: Bayesian networks, Fault trees, Fuzzy sets and Simulation. From the 'Other' category shown in Appendix A, other numerical models and qualitative analyses are included as well in this figure. The "other numerical models" category captures other mathematical approaches which differ from the most used mathematical modelling techniques such as Bayesian Networks, Fault Trees and Fuzzy Sets (Lim et al. 2018a,b). For both regions, early research revolved around numerical models (primarily probabilistic models), such as Oshima and Fujii (1974). The late 1990ies saw the rise of simulation techniques, e.g. Harrald et al. (1998), which have since been used as standalone models as well as in combination with diverse mathematical models. Bayesian models began to appear around the early 2000s, e.g. Friis-Hansen and Simonsen (2002), and have gained popularity since then. Fuzzy sets and qualitative analyses are comparatively less frequently applied.

5.6. Review issue 6: Uncertainty treatment

Identifying, analysing, and evaluating the shipping risks in waterways is important for accident prevention. In the general literature on risk analysis and management, there has been a significant focus on the need to assess various sources of uncertainties in the risk assessment, to inform decision makers about what is known about the risks and with what level of certainty, see Section 3.3.

After analysing the set of articles, it is found that approximately 51% of the articles do not consider uncertainty, neither qualitatively nor quantitatively. Quantitative consideration of uncertainty includes

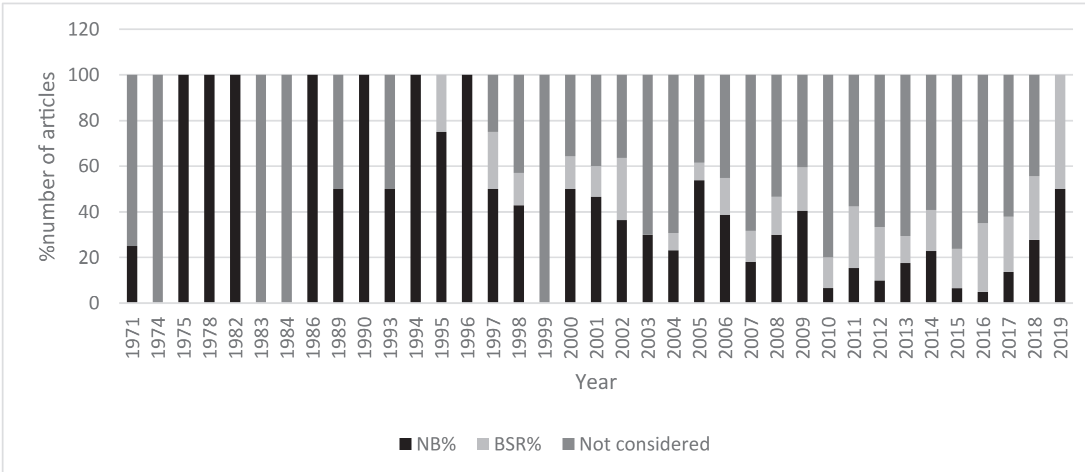

Fig. 11. Articles considering human and organizational factors in each region as a percentage of total number of articles, by year of publication, NB = Non-Baltic | BSR = Baltic Sea Region.

the identification of uncertainties about model parameters or model structure, which is then incorporated in the models. See e.g. Merrick and van Dorp (2006) and Zhang et al. (2018) for examples of methods for accounting for parameter uncertainty, and Goerlandt and Montewka (2015a) for an example of accounting for model uncertainty. Qualitative uncertainty consideration indicates that although the model does not capture uncertainty in terms of parameters or structure, a discussion is presented on the assumptions underlying the analysis, e.g. using a strength-of-evidence assessment scheme, as in Valdez Banda et al. (2016). Table 7 shows the number of articles from each region in relation to the consideration of uncertainty.

Fig. 13 shows for each region, the percentage of articles considering uncertainty from the total articles focusing on modelling and analysis. A marked fluctuation can be seen, showing that uncertainty treatment is not yet generally considered an essential aspect of risk analysis in the application domain. Nevertheless, since about 2005, uncertainty has been more regularly considered in the published literature.

5.7. Review issue 7: Technology Readiness level

Fig. 14 compares the Technology Readiness Levels (TRL) of the articles from the Baltic Sea Region and the Non-Baltic region. A large number of articles are of level 2, which corresponds to “formulation of technology concept”. Some research works are of TRL 3, which implies that experimental proof of concept is presented. TRL 5 to 8 require that the technology is tried out in relevant environments and prototypes are built. From the summary, it is observed that only few research contributions have been tested in real organizational environments.

The last level of TRL is 9, which corresponds to system prototyped, tested and completed and operational in the real environment. Based on the descriptions of the articles in the dataset, no work has achieved this level, although from other reports, e.g. IALA (2013) and HELCOM (2018), it is known that some tools and software is available which implement models proposed in the academic literature. This includes for instance the iWRAP Mk II model, of which an early software version is presented in Otto et al. (2002), and the PAWSA tool, which is based

Table 6
Number of articles employing each modelling technique and combinations of these, by region.

Modeling technique												Total	NB	BSR	%BSR
BN	FT	FS	LR	ONM	PM	QA	SI	SA	STPA	O	N				
x												36	13	23	64
	x											16	8	8	50
		x										16	8	8	50
			x									9	8	1	11
				x								31	17	14	45
					x							68	34	34	50
						x						12	7	5	42
							x					52	28	24	46
								x				62	36	26	42
									x			4	1	3	75
										x		17	15	2	12
											x	90	50	40	44
x	x				x							5	3	2	40
x	x	x					x					2	2	0	0
x		x										1	1	0	0
x					x							6	2	4	67
x							x					5	4	1	20
		x		x			x					5	3	2	40
				x			x					12	7	5	42
					x		x					14	6	8	57
Total												463	257	206	

Notes: BN = Bayesian Networks | FT = Fault Tree | FS = Fuzzy Set | LR = Logistic Regression | ONM = Other Numerical Modelling | PM = Probabilistic Modelling | QA = Qualitative Analysis | SI = Simulation | SA = Statistical Analysis | STPA = Systems-Theoretic Process Analysis | O = Other | N = No model

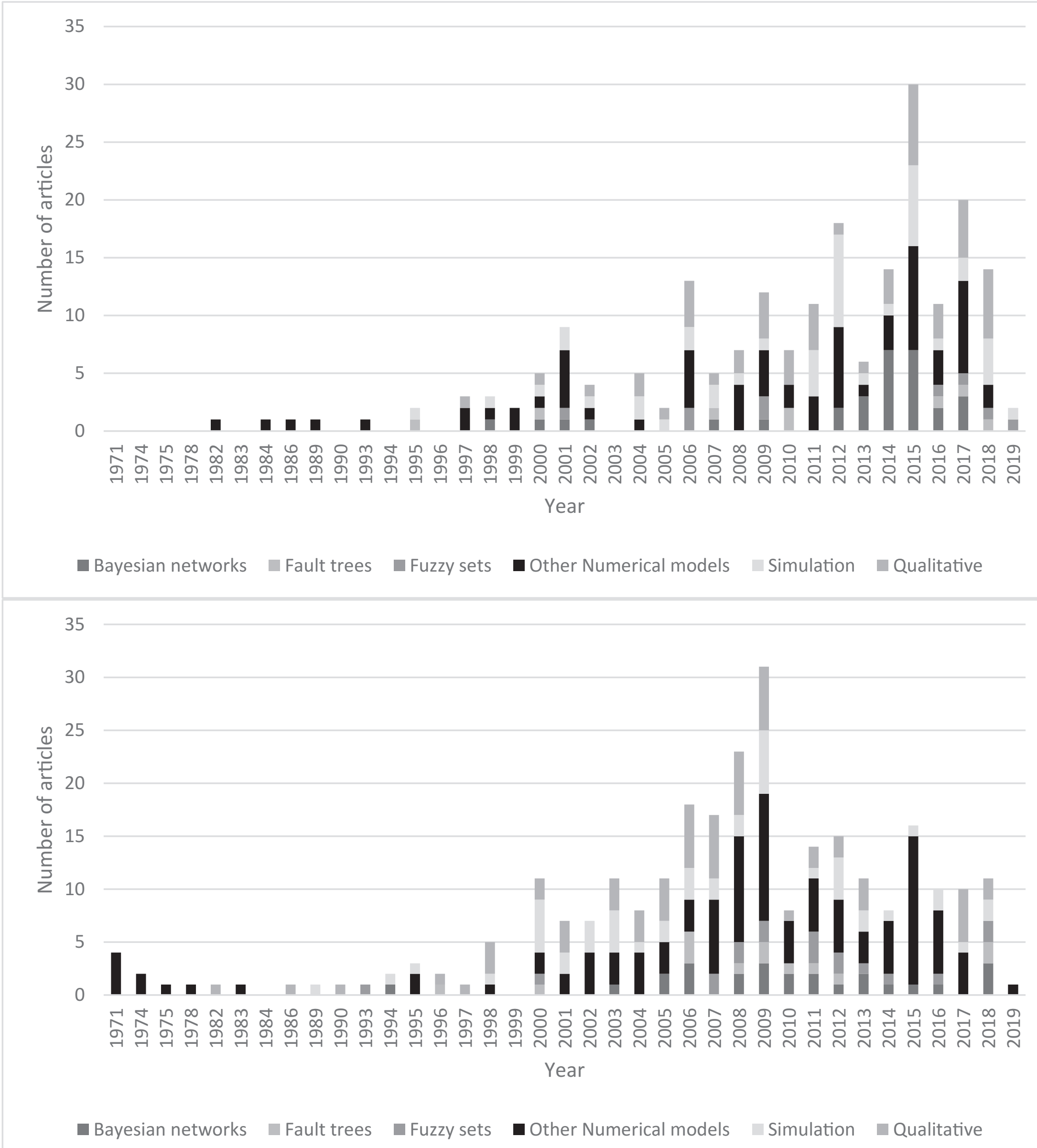

Fig. 12. Number of articles applying each modelling technique as defined in Section 3.3, by year of publication, Top: Baltic Sea Region, Bottom: Non-Baltic region.

Table 7
Number of articles considering uncertainty, by region.

Consideration of uncertainty	Total	NB	BSR	%BSR
Qualitatively considered	52	30	22	42
Quantitatively considered	169	88	81	48
Qualitatively and quantitatively considered	5	4	1	20
Not considered	237	135	102	43
Total	463	257	206	45

on work by Merrick and Harrald (2007). Furthermore, it is interesting to note that although in Section 5.1 a high number of articles are under the category of “application of existing methods”, there are few articles in TRL 4–8 range. From the review, it is observed that while researchers have successfully applied existing models to different scenarios and sea areas, very few of these have been tested in real organizational contexts, and most work stays on the level of proposing new methods, showing illustrative case studies.

The primary means of validation have been through simulation experiments or with historical data. There are not many instances of thorough laboratory validation of the risk models or their results, reminiscent of the findings by Goerlandt et al. (2017a,b) that risk analysis validation is a relatively little addressed topic. These limitations have been highlighted by several authors over the years, see e.g. Psaraftis (2012) and Goerlandt and Montewka (2015b).

6. Discussion: Past and current trends, and future outlook

This article has presented a review of the published literature on prevention-oriented waterway risk management in the period from 1971 to May 2019. A systematic approach has been taken to identify the relevant literature, which has been explored through bibliographic analyses and a more in-depth review focusing on seven review issues providing insight in the scientific commitments, modelling approaches, scope of risk management addressed, and the readiness of the published models for practical use.

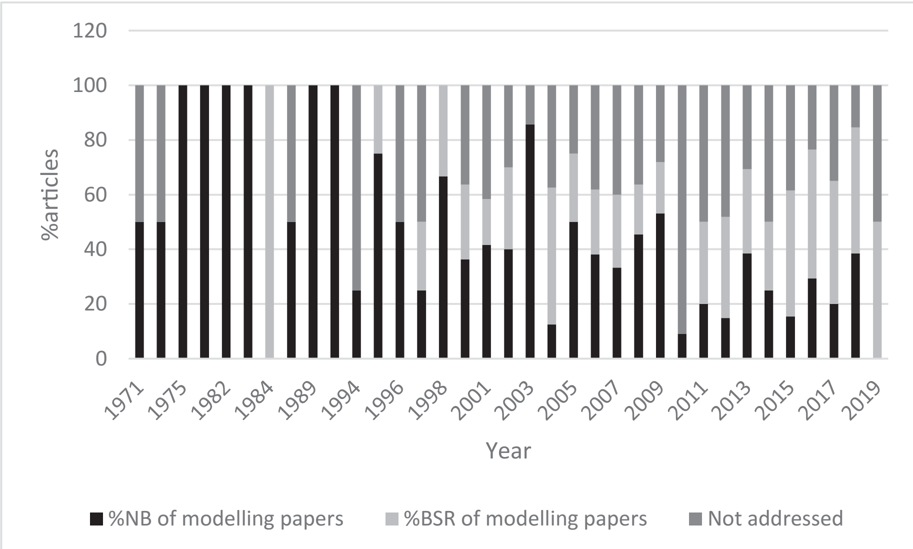

Fig. 13. Percentage of articles focusing on risk modelling and analysis in which uncertainty is considered, in each region, by year of publication, NB = Non-Baltic | BSR = Baltic Sea Region.

6.1. Historic patterns

Through the bibliometric analysis in Section 4, several dominant narrative clusters have been identified, which focus on accident probability modelling using traffic flow or simulation models, accident data analysis and work addressing human and organizational factors, and Bayesian network modelling. A term map further highlights narrative patterns in the research domain, showing the focus on accident prevention to avoid loss of human life. Dominant ideas relate to traffic analysis and modelling, for which data from the Automatic Identification System (AIS) is important. Environmental aspects are taken to be important factors in accident occurrence of ship navigation and maritime operations, and the human contributions to accidents are primarily seen as human error and failures. Narrative links with the Formal Safety Assessment procedure at the International Maritime Organization were stronger than with other maritime risk management guidelines.

In terms of the social structure of the scientific domain, the author collaboration network shows that there are currently less than 10 active collaborative research clusters worldwide, which frequently publish work on this domain of research. The currently active groups are mainly located in the Baltic Sea Region (Finland, Poland, and Norway), Europe (Portugal, United Kingdom, and Greece), China, and Canada. Some previously active groups, even some with a great influence on the research domain (e.g. the GWU-VCU-RPI cluster mentioned in Section 4.1), have not been actively contributing to the domain over the last decade. In addition, there are several smaller groups across the world, but these publish smaller volumes of work in the research domain, and are not connected through collaborations to other groups. This shows that the maritime waterway risk research field is, compared to other domains of academic activity such as safety culture research (van Nunen et al. 2018) or resilience in health care (Ellis et al. 2019), is relatively small and predicated on the activity of relatively few actors. On the one hand, this facilitates building a scientific community around the themes. However, the comparatively small number of continuously active groups, along with the disappearance of even influential groups and the more ad-hoc nature of contributions from other groups (which are likely linked to the temporary nature of research projects), also carries risks. For instance, it may limit the initiation and development of substantially new research directions, limit the formation of a long-standing research community focusing on fundamental scientific theories and issues, and may hamper the transfer of academic knowledge to end-users and professional communities.

The focusing on particular review issues in Section 5 has provided

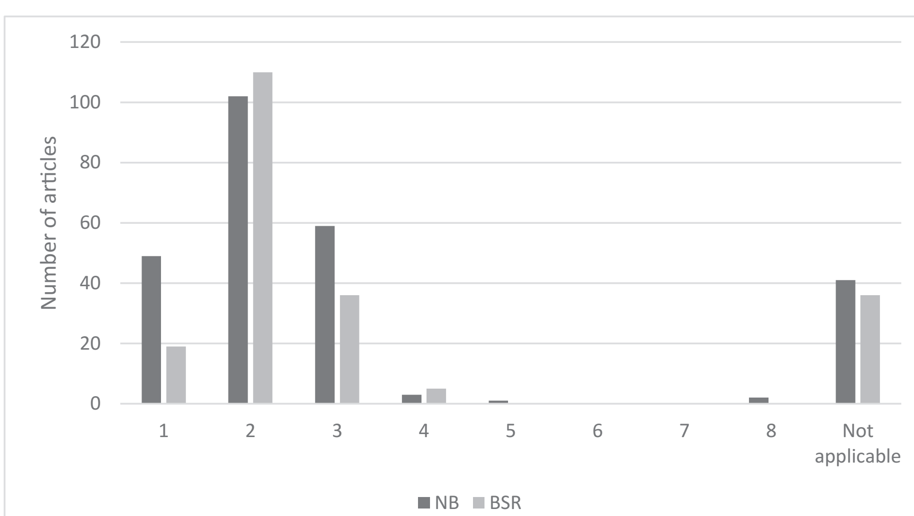

Fig. 14. Number of articles for each Technology Readiness Level in each region.

further insights in the contents of the articles. This has revealed that most work focuses on empirical analyses of accident data, the development of new modelling approaches, and applications of these to case studies. Correspondingly, the main focus in the research domain has been on the risk identification and risk analysis phases. There has been considerably less specific focus on risk evaluation and mechanisms to incorporate risk assessment in organizational processes through risk management processes. In the proposed models, various types of probabilistic models, Bayesian Networks, and simulation have been developed, but most of these have remained at the stage of concept development and demonstration, with very few models having been extensively tested and validated, and developed in user-friendly tools and software. In terms of scientific commitments, most work has been made based on complex linear accident theories, the pyramid accident model, or without an accident-theoretical basis. Only recently, work based on the STAMP and FRAM accident theories has been published. A large share of the work does not consider human or organizational factors, despite the fact that the importance of these aspects has been much highlighted. Where there has been a focus on these factors, this has mostly been approaches through human errors and organizational failures, in line with complex linear accident theories. Finally, many articles do not explicitly account for uncertainties in the risk assessments, whereas this has been raised an essential feature in the generic risk research literature.

6.2. Contemporary trends and future outlook

The most visible contemporary trend is probably the increased academic focus on the developments towards autonomous vessels. For instance, existing risk models have been evaluated in light of their usefulness for autonomous vessels (Thieme et al. 2018), and methods have been proposed to assess the safety of these vessels within their operational context (Wróbel et al. 2018, Valdez Banda et al. 2019). This follows general industrial developments towards increased levels of interconnectivity, automation, and artificial intelligence in maritime business environments. Another trend showing the response of academic communities to industrial developments and regulatory need is the increased focus on the risks of Arctic shipping, see e.g. Afenyo et al. (2017). With the diminishing extents of sea ice in the Arctic, linked to climate change effects, maritime operators see opportunities for cost-saving and improved efficiency, although uncertainties remain, see e.g. Beveridge et al. (2016). Considering the continued focus on autonomous vessels and Arctic shipping, it can be expected that future academic work will focus on risk management, analyses, and modelling for these emerging new challenges.

Another trend concerns the analysis of maritime accident data. While earlier work has focused on accident data analysis without consideration of contextual factors, such as Dai et al. (2002) and Kujala et al. (2009), there is a recent trend to combine maritime accident data with other data sources, such as data from the Automatic Identification System (AIS) and environmental datasets, see e.g. Goerlandt et al. (2017a,b), Ventikos et al. (2018), and Rezaee et al. (2016). This can provide more elaborate insights in the conditions under which shipping accidents occur, which may be more useful for accident prevention purposes than a more basic focus on the types of accidents occurring in a waterway. The use of AIS data in risk analysis could be considered as an application of big data technology. With the advent of big data, and the development of dedicated databases for analysis of maritime transportation, e.g. Lensu and Goerlandt (2019) and Bye and Almklov (2019), it can be expected that this trend will continue also in the future. Future applications of big data may be expected to include multi-source heterogeneous information from varied equipment such as radars and cameras along with contextual and temporal (AIS) data.

A related issue is the analysis of accidents. Earlier work has considered maritime accidents primarily as a matter of human errors, see e.g. Grabowski et al. (2009), and has consequently applied human error focused accident analysis methods to obtain insights in the causal mechanisms of accident occurrence, e.g. Celik and Cebi (2009) and Chauvin et al. (2013). However, more recent work on maritime accident analyses is increasingly rooted in systemic accident theories, see e.g. Kim et al. (2016), Puisa et al. (2018), and Lee and Chung (2018). These trends may be expected to continue in the future, as there is an increased consideration of the systemic nature of accidents in the general scientific literature, as opposed to an earlier focus with component failures, linear causal mechanisms, and human errors (Dekker et al. 2011).

This focus on systemic accident theories is emerging also in the contemporary literature on accident modeling, e.g. Praetorius et al. (2017) and Patriarca and Bergström (2017), and related developments for approaches for maritime waterway safety, e.g. Valdez Banda and Goerlandt (2018). Another trend, which also steps away from a focus on linear accident modeling, is the development of approaches for detecting near misses from vessel traffic data, e.g. Zhang et al. (2016). These are expected to provide more indirect insights in maritime safety than a direct focus on accidents per se, which is limited due to the relatively rare nature of such events. It is expected that combining near misses with other maritime safety related information can lead to insights in structural patterns of maritime safety, as in Hänninen and Kujala (2014).

The review indicates a generally limited focus on testing and validation of proposed models for maritime waterway risks, as observed from the analysis of Technology Readiness Levels. This is in line with findings from the generic risk and safety literature, where the limited focus on validation has been raised as an important future development path (Goerlandt et al. 2017a,b, Hale 2014). Therefore, validation of maritime risk models is considered an important area of future research. Closely related to this is the issue of the consideration of uncertainty in risk models and analysis. The review indicates that while the research domain does include various proposals to incorporate uncertainties in models and analysis, see e.g. Zhang et al. (2018) and Goerlandt and Montewka (2015a) for recent methodological contributions, there is not yet a broad commitment to the consideration of uncertainties in method proposals or in applications. This is therefore recommended as a future focus area.

Finally, the relatively limited scientific attention to the implementation and use of risk analysis models in organizational contexts, observed from the relatively few proposals for frameworks on how to apply risk models, analyses, and assessments in maritime waterway decision making, indicated an area of possible future developments. The actual organizational use of risk analyses has been pointed out as a central aspect of the validity and usefulness of risk management (Lathrop and Ezell 2017). Nevertheless, apart from some proposals for evidence-based stakeholder interaction processes for maritime safety related decision making (Haapasaari et al. 2015), this has received little attention and could be an important area of work for ensuring the relevance and usefulness of academic work for professional end-user environments.

7. Conclusions

This article has presented a review of the academic literature on waterway risk management, which focuses on prevention-oriented work. Through bibliometric analyses, insights in dominant narrative patterns and research clusters have been identified, and the social structure of collaboration networks in the research domain has been mapped. Various review issues have been analysed in more detail. These have focused on the type of academic work performed, the aspects of risk management which have been addressed, the modelling approaches applied in risk models and analyses. Other issues provide insights in the scientific commitments underlying the research field, including accident theories, the consideration of human and organizational factors, and uncertainty treatment in risk analysis. Finally, the technological readiness of the models has been analysed, addressing the bridge between the academic and end-user professional communities. Through the review, various patterns, focus areas, and emerging trends have been identified. Finally, a discussion has also identified current trends, and has made suggestions for future research directions. It is hoped that this review can contribute to further developments in the research domain, also considering its relevance and usefulness for professional environments.

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Appendix A

Fig. A.1 shows the form used for integrative review introduced in Section 3.2, addressing the review issues described in Section 3.3. As explained there, this form was used to ensure consistency in the analysis of the articles by different authors.

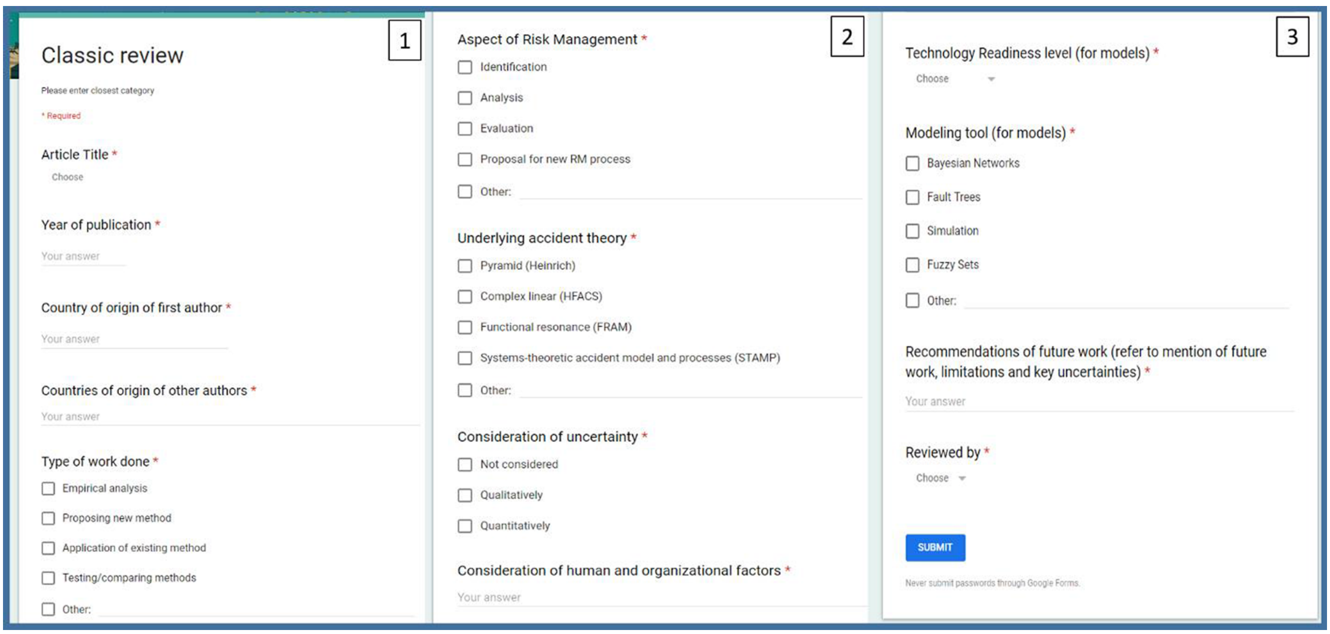

Fig. A.1. Review issues form used for data recording in integrative review.

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