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Mapping the evolution of sea outfall research: insights for marine environmental sustainability

Deniz deşarjı araştırmalarının evriminin haritalandırılması: deniz çevresinin sürdürülebilirliği için öneriler

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Mapping the Evolution of Sea Outfall Research: Insights for Marine Environmental Sustainability

Highlights

- *This study presents the first systematic assessment of the sea outfall literature.*
- *A new and comprehensive classification of sea outfalls is introduced.*
- *Themes and methods for further research on sea outfalls are explored.*
- *New perspectives on the sustainability of the marine environment are provided.*
- *Future research should focus on the effects of climate change on sea outfalls.*

Graphical Abstract

The development of publications in the field of sea outfalls is analyzed according to the steps outlined in Figure 1.

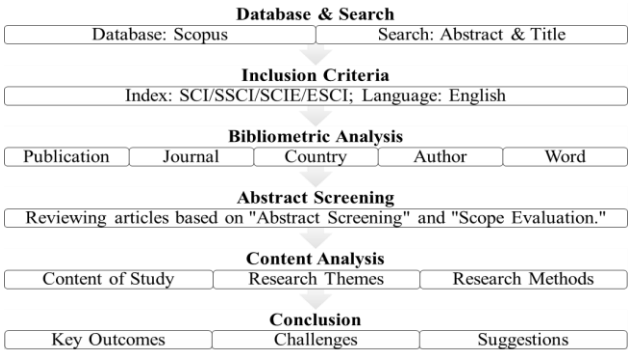

Figure 1. Methodological framework of the study

Aim

This study represents the first systematic assessment of sea outfall literature over the past five decades. It aims to introduce a new classification of sea outfall research to guide future studies and determine sustainability strategies.

Design & Methodology

Bibliometric and content analysis techniques are employed to evaluate the evolution of sea outfall research, and network analysis and VOSviewer are used to visually represent a detailed classification of the findings.

Originality

This study presents the first comprehensive and systematic evaluation of the sea outfall literature. It introduces a novel classification framework, categorizing the research into key themes, including field studies, laboratory experiments, and data analysis.

Findings

The study identifies dominant research themes, contributing countries, and methodological approaches in sea outfall research. It highlights the necessity of addressing climate change effects and adopting innovative technologies to enhance environmental outcomes.

Conclusion

Global research is crucial to address regional variations in sea outfall systems and their environmental impact, with future studies focusing on climate change effects and sustainable solutions for marine ecosystems.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Mapping The Evolution of Sea Outfall Research: Insights for Marine Environmental Sustainability

Araştırma Makalesi / Research Article

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ABSTRACT

Effective management of sea outfall is a critical topic in marine environmental science, sustainability regulations, and adaptation for the road maps. Therefore, the development of sea outfall research is mapped in this study by addressing 248 articles published during 1970 – 2023. A detailed assessment of the field's evolution is provided through a combination of bibliometric and content analysis. Network analysis techniques, including co-occurrence, co-authorship, citation, and bibliographic coupling, are used to identify dominant research topics, citation patterns, and productive authors and countries. Subsequently, content analysis is applied to investigate the attributes, research methods, and gaps in the existing research. A new and detailed classification of sea outfall research is obtained from the content analysis namely: field studies, laboratory experiments, and data analysis, with consideration to the methodologies applied in the studies (modelling, numerical analysis, experimental techniques, simulation, and field studies). The findings not only highlight the progression of sea outfall research but also offer new perspectives that could inform future research and strategic investments aimed at enhancing marine environmental sustainability and managmenet.

Keywords: Bibliometric analysis, research policy, sutainability, VOSviewer

Deniz Deşarji Araştirmalarinin Evriminin Haritalandirilmasi: Deniz Çevresinin Sürdürülebilirliği İçin Öneriler

ÖZ

Deniz deşarjının etkin yönetimi, deniz çevre bilimi, sürdürülebilirlik düzenlemeleri ve yol haritalarına uyum açısından kritik bir konudur. Bu nedenle, bu çalışmada 1970 - 2023 yılları arasında yayınlanan 248 makale ele alınarak deniz çıkışı araştırmalarının gelişimi haritalandırılmıştır. Bibliyometrik ve içerik analizinin bir kombinasyonu yoluyla alanın gelişiminin ayrıntılı bir değerlendirmesi yapılmıştır. Ortak araştırma konularını, atıf modellerini, üretken yazarları ve ülkeleri belirlemek için eş-oluşum, eş-yazarlık, atıf ve bibliyografik bağlantı dahil olmak üzere ağ analizi teknikleri kullanılmıştır. Daha sonra, mevcut araştırmadaki nitelikleri, araştırma yöntemlerini ve boşlukları araştırmak için içerik analizi uygulanmıştır. İçerik analizinden, çalışmalarda uygulanan metodolojiler (modelleme, sayısal analiz, deneysel teknikler, simülasyon ve saha çalışmaları) dikkate alınarak saha çalışmaları, laboratuvar deneyleri ve veri analizi olmak üzere yeni ve ayrıntılı bir deniz deşarjı araştırması sınıflandırması elde edilmiştir. Bulgular sadece deniz deşarjı araştırmalarının gelişimini vurgulamakla kalmamakta, aynı zamanda deniz çevresinin sürdürülebilirliğini ve yönetimini geliştirmeyi amaçlayan gelecekteki araştırmalara ve stratejik yatırımlara bilgi sağlayabilecek yeni perspektifler sunmaktadır.

Anahtar Kelimeler: Bibliyometrik analiz, araştırma politikası, sürdürülebilirlik, VOSviewer

1. INTRODUCTION

Wastes are generated as a result of human activity and expected to be removed with the help of proper ecological and sustainable methods.

Seas, which provide a high dilution rate, offer a very effective area for the elimination of pollutants. Likewise, sea outfall is a practice that aims to dilute wastewater in the receiving environment by transporting wastewater of different densities to a certain distance from the shore. There are three types of dilution in wastewater outfall. The first dilution is the near-field dilution in which the receiving medium and the fluid physically mix and the movement of wastewater continues vertically [1]. In the second dilution phase, vertical movement ends and

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horizontal movement begins. The dispersion model developed by Brooks is frequently used to evaluate dilution in this respect [2]. In the third dilution, however, the bacteria present in the wastewater are affected by sunlight, temperature, salinity, etc. This is the stage where the wastewater disappears due to these effects. As a result, the total dilution is expressed by multiplying these three dilutions. Total dilution is desired to be at maximum level. It is typically characterized by three regions along with the plume orbit. The first one is the onset, active mixing region, near field region. The outlet flow, direction, and geometry are effective in this region. The second region is the intermediate region and is the transition phase between the near and far field regions. Finally, it is the passive mixing region, that is, the far field region. This is the region where ambient flow conditions dominate the plume behavior [3]. This disposal, which is carried out in a way that meets environmental standards, needs to be designed with extreme precision to carefully examine the spread and circulation and to minimize its effects on living life [4].

In this context, there are two main methods for the numerical solution of wastewater outfall problems, which are briefly summarized as following [5]. Integral models, the first method, solve the mass and momentum conservation equations based on the assumptions that the velocity profiles of the jets do not have radial variation and that the jet profile is axisymmetric and Gaussian [6]. To model the plume trajectory accurately, it is necessary to examine the near and far fields separately [7]. To describe the near-field behavior of a plume, jet-integral models such as CORMIX, CorJet (part of CORMIX), VISJET, or Jet3D are often applied [8]. To evaluate the far-field behavior of an outfall cloud, hydrostatic far-field simulation programs such as Delft3D-FLOW or POM are used [9]. The second method is the frequently used Computational Fluid Dynamics (CFD) model. The CFD model has improved compared to parameter-based jet integral models and is a branch of fluid mechanics that uses high-capacity computers to model and analyze engineering problems involving phenomena caused by fluid flow, heat transfer, and chemical reactions on a parameter basis [10]. Turbulent flow models are often solved with a turbulence model to parameterize unresolved mixing and dispersion scales. When using a CFD model, it can be difficult to create the network, solve the created network, and define appropriate boundary conditions [5]. Even if the turbulence model is a good match, high mesh resolution is often needed for a stable solution. In turbulent flows, it is necessary to apply an appropriate turbulence model and to mesh intelligently for each problem. There are two programs frequently used in CFD modelling. The first is OpenFOAM, a free and open-source program developed by the OpenFOAM Foundation and written in C++ [11]. The other one is ANSYS Fluent, a commercial package program that uses the finite volume method for solving equations.

Conventional methods of conducting a literature review play a crucial role in pinpointing the areas of deficiency in a specific field and offering insights into its present state. However, these methods are often time-consuming, involving a deep dive into numerous sources and subjective interpretations influenced by the reviewer's perspectives. In contrast, bibliometric analysis emerges as an innovative and efficient methodology, providing a more holistic and objective view of a field's structure, prevailing topics, and the voids within research. Although it might lack the depth of a traditional review, bibliometric studies leverage statistical and computational techniques to analyze patterns within the literature, offering valuable insights based on quantitative data. By examining citation networks, co-citation analysis, and other metrics, it unveils connections between publications, identifies key contributors, and maps out prevalent themes, providing a broader, more unbiased overview. Its ability to unveil the historical trajectory of a research field empowers stakeholders to navigate the stages of development, while also facilitating the construction of adaptable, reproducible workflows. This method not only helps researchers quickly grasp the overarching trends but also reveals potential areas for further exploration and study within the field. The complementary nature of both traditional literature reviews and bibliometric analyses offers an opportunity for researchers to combine qualitative insights with quantitative data, thereby enriching the comprehension and direction of scholarly investigations.

Bibliometric analysis has been applied to various fields. For instance, the topics related to climate change [12, 13], drought [14], environmental science [15, 16], education [17-19], chemistry [20], economics [21, 22], computer science [23], materials science [24], business/ management [25, 26], logistics/supply chain [27] energy [28,29] and medicine [30] have benefited from biblometric research. These examples demonstrate the wide-ranging applications of bibliometric analysis across various fields, providing valuable insights into research trends, influential works, and future directions.

As of the latest review, a comprehensive bibliometric study centered on the field of research related to sea outfall has yet to be located in the existing academic literature. This notable absence of such an analysis presents a noteworthy gap in the assessment of this critical research domain. Hence, within the scope of this study, our main focus is analyzing the publications which pertain to sea outfall, with a twofold purpose in mind. Firstly, we aim to offer valuable insights and guidance to authors who harbor an interest in delving into the complex subject of sea outfall. Secondly, our broader

objective is to undertake a systematic and in-depth assessment of the extensive body of literature concerning sea outfall. By embarking on this comprehensive exploration, we intend to elucidate the existing approaches, unearth any limitations, and chart the course for potential future research directions within this field. To fulfill our goals, we employ a multifaceted analytical approach that combines both bibliometric and content analysis techniques. This comprehensive strategy enables us to thoroughly scrutinize the sea outfall research landscape. Through a qualitative lens, we aim to uncover the intricacies and nuances that often elude a purely quantitative analysis. In tandem, we present a quantitative assessment of the field as a whole, incorporating numerical data and statistical insights to provide a holistic view of the research landscape. In addition to this quantitative perspective, we delve into the methodologies that are prevalent within the realm of sea outfall research. By evaluating the methods commonly utilized by researchers in this field, we seek to shed light on the strategies employed for data collection, analysis, and experimentation. This offers a critical understanding of the tools and techniques that underpin the body of research, which can in turn inform future studies and help researchers make informed choices about their investigative approaches.

2. MATERIALS AND METHODS

The selection of source documents or texts plays a critical role in shaping the ultimate outcomes and relevance of research findings. At this stage, establishing a reliable data source, often through an online database, is essential. Numerous databases encompass peer-reviewed scientific literature. These include Scopus, Web of Science, and Google Scholar. Scopus offers broader content coverage compared to other databases, making it the preferred source for the present study [31, 32]. Making the results clearer by creating tables, graphs, charts, and maps to explain complicated data and relationships is one of the main aims of bibliometric and content analysis. Hence in this study, we utilized software packages such as Microsoft Excel and VOSviewer (https://www.vosviewer.com/) to achieve this aim. In this regard, the spread sheets of Microsoft Excel played a pivotal role in data acquisition, initial processing, and statistical analysis, facilitating the generation of tables and graphs that offer insights into publication types, trends, and subject categories. Meanwhile, VOSviewer was invaluable for graphical network analysis, offering clear advantages such as extensive data format handling, advanced filtering, adaptable analysis methods, and improved clustering capabilities. Notably, VOSviewer was employed to depict co-word, citation, and co-authorship analysis. To structure our study framework, achieve our research objectives, and optimize corpus usage, we employed the methodology depicted in Figure 1.

This study aims to investigate the themes and methods within research outputs covering approximately 54 years in the domain of sea outfall. The research in this context focuses on the following questions:

1) How has the configuration of this research field evolved over the years?
2) Who are the influential authors, countries, and publications, and what collaborative patterns are at play?
3) What are the most used keywords and title words?
4) What subtopics or focal points are prominent in the literature?
5) What themes and methods are employed to measure sea outfall? Which research methods are most preferred in studies in this field? Is it more common to use experimental studies, modelling, or observation?
6) What are the current gaps and potential for research in the field of sea outfall research?

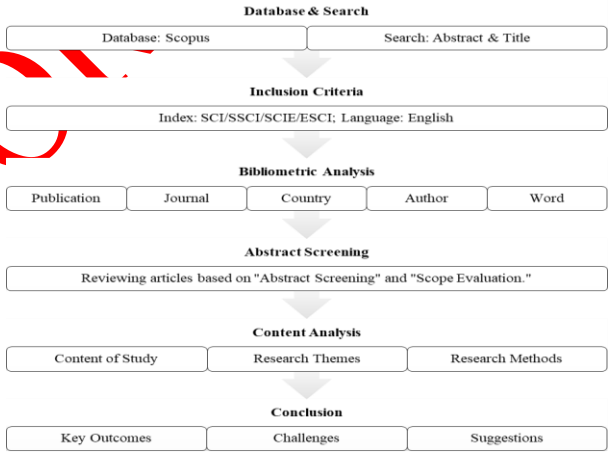

Figure 1. The research methodology utilized in the study.

2.1. Materials

To ensure the inclusion of the most rightful and pertinent publications, we devised a search protocol employing four distinct search strings. The first string incorporates terms such as “submarine outfall” OR “marine outfall” OR “sea discharge” OR “effluent discharge” OR “ocean disposal” OR “wastewater disposal” OR “outfall” OR “sea outfall”. The second string includes phrases like “outfall sewer*” OR “Wastewater” OR “Domestic wastewater” OR “Effluent*” OR “Wastewater effluent*” OR “Sewage effluent*”. The third string contains such as “buoyant jet*” OR “positively buoyant jet*” OR “jet*” OR “plume*” OR “buoyant plume*” OR “positive buoyant jet*” OR “positively buoyant*” OR “positive buoyant” OR “negatively buoyant jet*” OR “inclined

dense jet*" OR "dense jet*" OR "negative buoyant jet*" OR "negative buoyant" OR "negatively buoyant". The last string comprises expressions such as "near field dilution" OR "dilution" OR "near field".

To include studies that covered different variations of keywords, the asterisk wildcard "*" was used. The search method was designed to search the title, abstract, and keyword headings fields to include different types of publications (articles, conference papers, books, and book chapters) containing the selected subject headings. With these settings, the search yielded a total of 272 items. When the document language was restricted to English, this number was reduced to 248 documents. It's important to note that the retrieved documents covered all co-authorship analyses and exclusively included those published in English. While there might be a language bias in the results, it's unlikely to significantly impact the overall trends, given that the vast majority of scientific publications are written in English. Comprehensive information including authors' names, contact details, publication titles, publication years, keywords, subject categories, journal names, yearly citation counts, abstracts, references, and other relevant data, was downloaded and stored in .csv file format.

2.2. Methods

In this study, a two-tiered approach was employed to comprehensively examine the collected literature. Initially, a bibliometric analysis was conducted, which was then followed by a thorough critical content analysis. Pritchard introduced the notion of bibliometric analysis as "the use of mathematical and statistical methods to analyze books and other communication forms." Since its introduction, it has gained widespread acclaim for scrutinizing the structure and evolution of knowledge across diverse domains [33]. Bibliometric analysis uses quantitative and statistical methods to explore the landscape of knowledge, producing results that are less influenced by bias and subjectivity, unlike traditional literature reviews. In the case of network analysis, which is widely used in the field of bibliometrics, it is possible to identify the productivity of the authors, the influence of their publications, and the main areas of concentration within the field of study. To attain our research goals, we employed the bibliometric analysis conceptual model presented in Figure 2. Following this, our study performs content analysis to gain a deep understanding of the research themes and the methods employed. In the study's context, content analysis acts as a valuable tool, allowing us to explore and extract relevant information from the materials, thereby enabling a comprehensive examination of the available data. As a result, content analysis not only reveals the primary subject matter but also sheds light on the specific research methods and approaches used, ultimately enhancing the depth and intricacy of our study's objectives. Further details of these techniques and the results obtained are presented in the following sections.

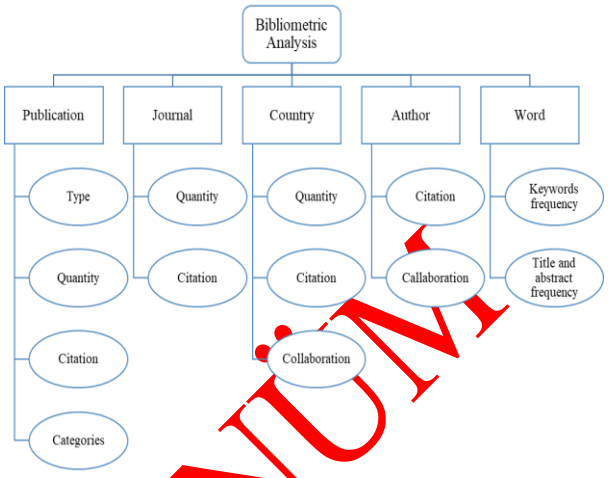

Figure 2. The components studied in bibliometric analysis.

3. RESULTS AND DISCUSSION

3.1. Publication Analysis

Table 1 provides a summary of the publication types within the final database. Approximately 78 percent of the entries consist of articles, while conference papers make up 20 percent, with the remaining publications classified as book chapters.

Table 1. Categorization of publications.

Document Type	Number	Percentage
Article	193	77.82
Conference paper	50	20.16
Book chapter	5	2.02
Total	248	100

The quantity of publications related to a research topic over time serves as a vital indicator of its development. In Figure 3, the publication trends for sea outfall over the past 54 years are illustrated. These trends exhibit periods of both growth and decline during the defined study period, spanning from a single publication in 1970 to 2023, totaling 248 publications, primarily consisting of articles, in the database. The initial publication was authored by Csanady, and the number of publications peaked at 13 in 2011 [34]. The trend experienced a resurgence since 2020, with a noted decrease in 2023 due to incomplete data. In particular, a significant increase in the number of citations indicates a recent increase in interest in the subject.

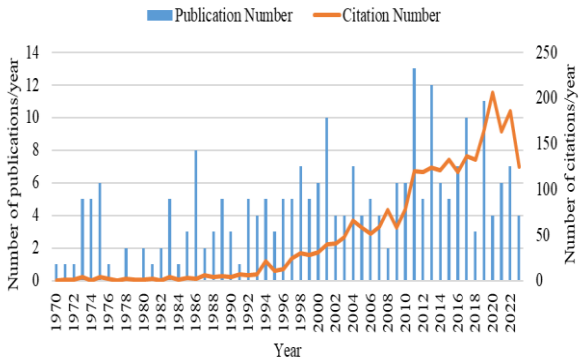

Figure 3. Publishing trends related to sea outfall.

The majority of publications are within the field of "Environmental Sciences," accounting for 36.0% of the studies (Figure 4). In the second position, we have "Engineering," comprising 30.0% of the studies. "Earth and Planetary Sciences" take the third spot with 10.7% of the publications, followed by "Agricultural and Biological Sciences" and "Chemistry and Chemical Engineering" at 6.0% and 5.8% of the studies, respectively. The remaining 11.6% of documents were shared between various fields. The distribution of research across various knowledge domains can be attributed to the inherent multidisciplinary character of the sea outfall field. The complex and interconnected nature of sea outfall necessitates contributions from diverse academic areas such as environmental sciences, engineering, earth and planetary sciences, agricultural and biological sciences, chemistry, and chemical engineering. This interdisciplinary approach enables a comprehensive exploration of sea outfall, ensuring a thorough examination of its multifaceted aspects.

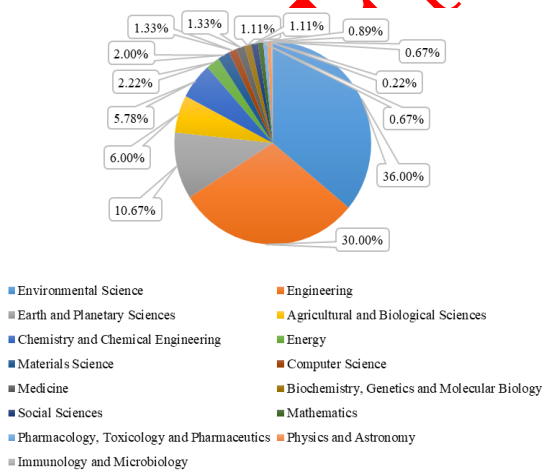

Figure 4. The categorization of publications by field.

Citation analysis is a powerful tool that offers a multifaceted understanding of the popularity and impact of publications in various research fields. It provides insight into how research publications are interconnected, referenced, and contribute to the collective knowledge of a particular domain of study [35] By visually representing these interconnections between publications, VOSviewer exposes the underlying structure of knowledge dissemination, thereby assisting researchers in making well-informed decisions.

In this regard, Figure 5 is a map of publications that have a minimum of 10 citations in the search results. After several attempts to ensure that the resulting citation network was readable, clear, and representative of the field studied, a threshold of ten citations was chosen. A higher citation threshold would have excluded some relevant publications, while a lower threshold would have produced a network that was too complex to interpret effectively.

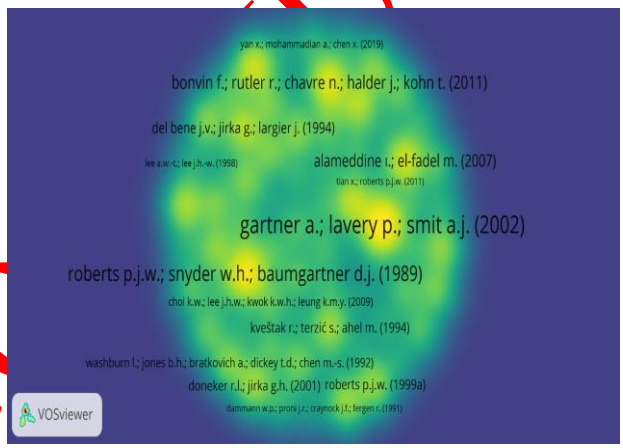

Figure 5. Co-citation network of most cited documents.

To gain insight into the most influential studies, their respective authors, and, perhaps most importantly, the extent of their integration, we also examined the most cited publications. A list of the most frequently cited studies in this field of research can be found in Table 2. The categories from the Journal Citation Reports (JCR) within the Web of Science (WoS) database and the CiteScore metrics from the Scopus database are also provided in Table 2. In the WoS, a category classifies journals into specific academic fields, while quartiles rank these journals based on their Impact Factor within that category. This ranking indicates their relative impact and prestige in the field. CiteScore, calculated using Scopus data, is another citation-based metric for measuring journal impact. It reflects the average number of citations received per document published in a journal and is similar to the Impact Factor used in WoS. CiteScore provides a more comprehensive, transparent, and current view of a journal's influence. It is noteworthy that half of these articles were published before the 2000s. Notably, Gartner et al. [36] tops the list with 130 citations, followed by Roberts et al. [37] and Bonvin et al. [38] with

104 and 80 citations, respectively. The presence of multiple authors in papers underscores the common necessity for a multitude of contributions to attain high citation rates. In some cases, this might be required due to the interdisciplinary nature of the work that might be beyond the scope of a single author. By leveraging the collective knowledge and experiences of multiple authors, these papers can provide a more comprehensive and well-rounded exploration of their chosen subject. Collaborative efforts, inherent in their nature, enable the integration of diverse insights and methodologies, leading to more robust and comprehensive studies.

Table 2: The most highly cited ten papers.

Author(s)	Title	Journal	Category[(1)]	Impact[(2)]	Citation	Year
Gartner et al.	Use of $\delta^{15}N$ signatures of different functional forms of macroalgae and filter-feeders to reveal temporal and spatial patterns in sewage dispersal	Marine Ecology Progress Series	Q1 (Marine & Freshwater Biology)	5.3	130	2002
Roberts et al.	Ocean outfalls. I: Submerged wastefield formation	Journal of Hydraulic Engineering	Q3 (Water Resources)	5.1	104	1989
Bonvin et al.	Spatial and temporal presence of a wastewater-derived micropollutant plume in Lake Geneva	Environmental Science & Technology	Q1 (Environmental Sciences)	17.5	80	2011
Alameddine and El-Fadel [39]	Brine discharge from desalination plants: a modeling approach to an optimized outfall design	Desalination	Q1 (Water Resources)	14.6	72	2007
Gagnon and Saulnier [40]	Distribution and fate of metals in the dispersion plume of a major municipal effluent	Environmental Pollution	Q1 (Environmental Sciences)	16.0	70	2003
Chan et al. [41]	Real-time forecasting of Hong Kong beach water quality by 3D deterministic model	Water Research	Q1 (Water Resources)	20.8	64	2013
Del Bene et al. [42]	Ocean brine disposal	Desalination	Q1 (Water Resources)	14.6	57	1994
Robinson et al. [43]	Survey of receiving-water environmental impacts associated with discharges from pulp mills: 1. Mill characteristics, receiving-water chemical profiles and lab toxicity tests	Environmental Toxicology and Chemistry	Q2 (Environmental Sciences)	7.4	57	1994
Pincince and List [44]	Disposal of brine into an estuary	Journal of the Water Pollution Control Federation*	*	*	54	1973
Kveštak et al. [45]	Input and distribution of alkylphenol polyethoxylates in a stratified estuary	Marine Chemistry	Q1 (Oceanography)	6.0	50	1994

(1) Quartile ranking based on JCR from WoS.
(2) Impact measured using CiteScore for 2023 from Scopus.
**Note: Information regarding the category and CiteScore for the Journal of the Water Pollution Control Federation is unavailable. The SCImago Journal Rank (SJR) for 2019 is 0.100. The years currently covered by Scopus are 1961 and from 1964 to 1989 (coverage discontinued thereafter).*

3.2 Journal Analysis

Table 3 shows the 10 journals that have published more than 3 papers, and also shows how many papers they have published compared to the total publications. Table 3 also includes the categories from the JCR in the WoS database and the CiteScore metrics from the Scopus database. These 10 journals collectively contribute to approximately 37 percent of all the publications. The "Journal of Hydraulic Engineering" emerges as the most productive outlet, responsible for nearly 12 percent of all publications. It is closely followed by "Water Science and Technology," "Desalination," and "Desalination and Water Treatment".

Table 3. The top ten most productive journals in sea outfall.

Journal	Number of Papers	Percentage	Category[1]	Impact[2]
Journal of Hydraulic Engineering	29	11.6	Q3 (Water Resources)	5.1
Water Science and Technology	17	6.8	Q2 (Water Resources)	4.9
Desalination	7	2.8	Q1 (Water Resources)	14.6
Desalination and Water Treatment	7	2.8	Q4 (Water Resources)	2.2
Journal of Environmental Engineering	5	2	Q4 (Environmental Sciences)	4.4
Marine Pollution Bulletin	5	2	Q1 (Environmental Sciences)	10.2
Oceans Conference Record (IEEE)	5	2	-	0.8
Journal of Coastal Research*	4	1.6	Q4 (Environmental Sciences)	1.8*
Journal of Marine Science and Engineering	4	1.6	Q1 (Engineering, Marine)	4.4
Water (Switzerland)	4	1.6	Q2 (Water Resources)	5.8

[1] Quartile ranking based on JCR from WoS.
[2] Impact measured using CiteScore for 2023 from Scopus.
**Note: CiteScore 2022 for the Journal of Coastal Research is 1.8. The years currently covered by Scopus are from 1984 to 2023 (coverage discontinued thereafter*

3.3 Country Analysis

Through VOSviewer, we crafted a network representation illustrating the collaborative co-authorship relationships between countries. The utilization of VOSviewer allowed us to meticulously map the intricate web of international partnerships, revealing the intricate patterns of collaboration and information exchange between countries. Out of the 42 countries, only 21 were able to meet the requirement of producing a minimum of three publications. The decision to set the threshold at three publications resulted from numerous trials aimed at creating a co-author network in the field under investigation that is both legible, clear, and representative, facilitating the identification of the most influential authors. Adopting a higher publication requirement would have led to the exclusion of certain countries from the network, whereas a lower threshold would have created a network that was overly congested and difficult to comprehend.

In Figure 6, it is evident that 18 of these countries are organized into six distinct clusters. Three countries were omitted from the analysis as they lacked connections to other authors. Among the contributing countries, the United States took the lead with 80 publications, followed by Canada, Brazil, China, and Australia, which produced 30, 13, 11, and 11 publications, respectively. The United States held a prominent position in international collaborations due to its significant publication outputs and distinct advantages. The United States proved to be the most active collaborator among nations with a total link strength of 12. On the other hand, China and Brazil closely followed with link strengths of 7 and 6, respectively. Notably, with a link strength of 4, researchers from the United States had the strongest collaborative links with their Australian counterparts. These countries are members of the International Maritime Organization (IMO), a specialized agency of the United Nations responsible for regulating shipping and promoting maritime safety and environmental protection (Url-1). Through their involvement in the IMO, these countries work together with the international community to develop and implement global standards related to sea outfall and the prevention of marine pollution.

Figure 6. Network of co-authorship among countries.

As can be seen in Figure 6, research is generally concentrated in countries that have established policies to protect water resources and improve water quality by studying the impacts of sea outfall systems. These countries often have large economic and industrial

activities, which may require studying the various impacts of sea outfall systems. In countries that are active in marine resource protection and the sustainability of marine ecosystems, more resources can be devoted to research on sea outfall systems. These countries often emphasize such research to support environmental policy and conservation efforts. At the same time, some of these countries have developed expertise and capacity in sea outfall systems. Therefore, there is more scientific work being done. In conclusion, the relationship between co-authors is mainly influenced by the collaboration preferences of the individual researchers. However, it's important to note that national initiatives can have a substantial impact on strengthening these connections. Collaborative international endeavors and the sharing of knowledge in the realm of sea outfall research are pivotal in tackling worldwide environmental issues and progressing the field of coastal management.

3.4 Author Analysis

Co-citation analysis stands out as one of the most effective and efficient methods for knowledge mapping [46]. Co-citation analysis involves identifying pairs of highly cited papers, which serve as accurate markers for the emergence of new topics. It is a valuable tool for uncovering the underlying knowledge base that underpins a field. Scholars frequently cited by authors within a specific line of inquiry can be considered significant sources of theoretical influence on the trajectory of scholarship [47]. In this context, the co-citations of authors were scrutinized to identify grouped networks, selecting more than 30 cited authors for analysis. The results revealed a total of 32 authors grouped into four clusters, with Roberts P.J.W. emerging as the most influential author in these networks (Figure 7).

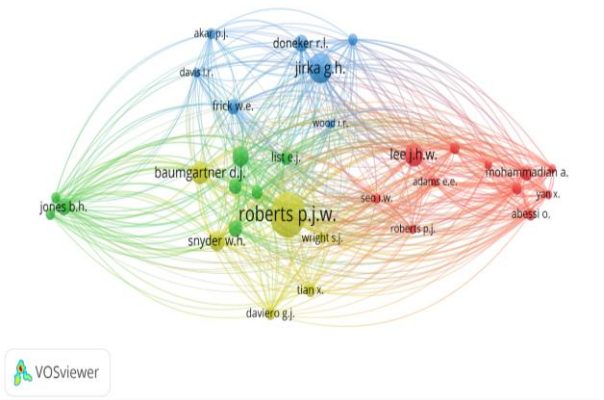

Figure 7. Map of the co-citation network of the authors.

Figure 7 visually represents these networks, with the first cluster (red) encompassing 11 authors. Lee J.H.W. emerges as the most cited author in this cluster, amassing 142 citations and a total link strength of 2456, followed by Mohammadian A. with 68 citations. The second cluster (green) comprises 8 authors, led by Brooks N.H. with 112 citations and a total link strength of 2242, followed by Koh R.C.Y. with 83 citations. Moving to the third cluster (blue), which includes 7 authors, Jirka G.H. takes the lead with 209 citations and a total link strength of 3741, followed by Doneker R.L. with 82 citations. The fourth and final cluster (yellow), consisting of 6 authors, is headed by Roberts P.J.W. with an impressive 414 citations, followed by Baumgartner D.J. with 129 citations.

3.5. Keywords, Title, and Abstract Analysis

Conducting keyword analysis, examining abstracts, and scrutinizing titles as part of bibliometric analysis is a valuable approach for gaining a deeper understanding of the prevailing research priorities and the dynamic shifts in a particular field of study. Additionally, it allows us to identify the areas within that field that have not received sufficient attention or remain unexplored. Authors' keywords, along with the keywords found in the titles and abstracts of academic publications, essentially provide a concise yet comprehensive representation of the core themes and content within a research work. By thoroughly dissecting these elements, researchers can not only gain a profound understanding of the current research landscape and its changing trends but also pinpoint gaps and underexplored areas within the field, thereby informing future research directions and priorities.

The analysis of keyword co-occurrence plays a crucial role in delving into the intricate intellectual structure and prominent themes that define the landscape of this specific research domain. Out of the 483 authors' keywords analyzed, VOSviewer determined 36 keywords that appeared more than three times in the dataset. Among these recurrent keywords, "dilution" and "outfall" stood out prominently. Beyond these two, the most frequently employed keywords were "wastewater disposal", "mixing zone", "ocean outfall", and "marine outfall" with 16, 15, 12, and 12 instances, respectively. These particular keywords underscore the substantial attention and relevance accorded to topics related to wastewater management, dilution processes, and outfall mechanisms in the scholarly literature, shedding light on their significant presence and importance within the research domain. Title and abstract keywords serve as a concise glimpse into the content of a publication, providing a distilled representation of its subject matter. The examination of co-occurrences between these titles and abstract keywords is a valuable tool for unraveling the highlighting of dominant themes within a particular research field. Of the 6361 title and abstract keywords, VOSviewer identified 24 which were reported more than 25 times. In addition to the prominent keywords "outfall" and "dilution" other frequently utilized terms include

"model", "plume", and "water" appearing 130, 125, and 122 times, respectively.

Integrating the temporal dimension into our keyword analysis, as illustrated in Figure 8, provides valuable insights into the evolutionary trajectory of the research field and the shifting trends over time. Notably, the terms "dilution" and "outfall" held a dominant position in the research landscape up until around 2010, signifying their central importance. However, as we progressed into the mid-2010s, a new set of terminology, including "effluent outfall", "negatively buoyant jet", "buoyant jet", and "visual plumes" came to the forefront, indicating a changing research emphasis. With the advent of the 2020s, the research landscape further evolved, with terms such as "CFD", "desalination", and "crossflow" gaining prominence, reflecting the evolving interests of the scholarly community. In the most recent years, additional terms of significance, including "inclined dense jet", "shallow water", and "OpenFOAM" have emerged, underscoring the ongoing dynamism and evolution within the field.

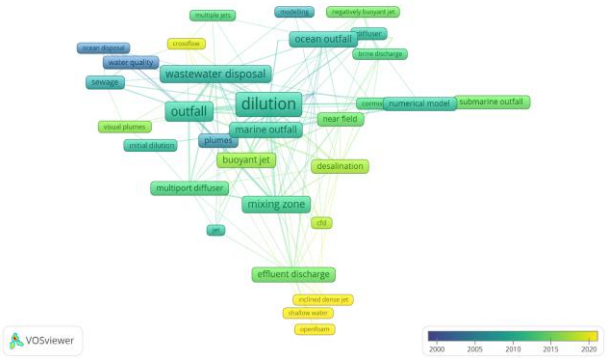

Figure 8. The evolution of co-occurring author keywords over time.

3.6 Thematic Clusters

Examining the references cited in a publication is a fundamental method for uncovering the knowledge foundation that supports it. One potent approach for accomplishing this is bibliographic coupling, which acts as a semantic tool to reveal connections between publications and systematically explore the landscape of a specific research field. When employing bibliographic coupling, the goal is to identify common themes among publications, often denoting shared research interests. This is achieved by linking papers that share similarities in their lists of references, indicating a higher likelihood of addressing related topics. The concept of bibliographic coupling by creating connections between two publications that both reference the same source, thereby showcasing their shared research focus. These linked publications form clusters, highlighting their thematic resemblance and setting them apart from others. This network visualization technique not only aids in comprehending the interconnected nature of research works but also offers valuable insights into the thematic structure of a particular academic domain. In this study, bibliographic coupling analysis was performed using the normalization of associations and the full counting algorithm [48].

The results of the bibliographic coupling analysis are visually presented in Figure 9, where a thematic map reveals various clusters. A total of 47 documents met the criterion of having at least 20 citations. In this map, each node's location and color serve to group articles from the same cluster, while the node size corresponds to the weight of citations for each article. Six distinct clusters are identified in Figure 9, each represented by a different color: red, green, blue, yellow, purple, and light blue. In the first cluster, denoted in red, the article "Brine discharge from desalination plants: a modeling approach to an optimized outfall design" by Alameddine and El-Fade stands out as the most significant [36]. This article primarily focuses on simulating the dispersion of brine plumes in the marine environment and exhibits the highest total link strength of 15 within the red cluster.

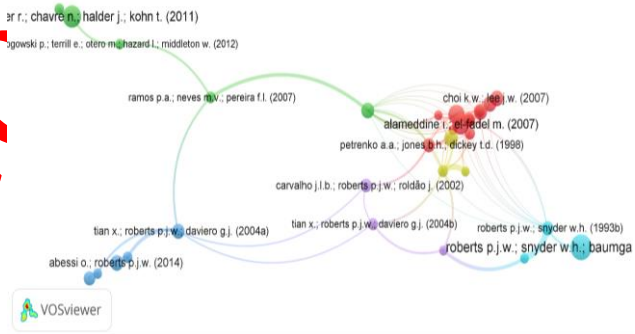

Figure 9. Visualizing the bibliographic coupling of publications in a network.

Moving to the green cluster, featured in green in Figure 9, the most influential article is "Plume tracking and dilution of effluent from the Boston sewage outfall" by Hunt et al. [49]. This article's key emphasis is on testing and certifying the initial dilution of the outfall, and it possesses the highest total link strength of 16 in the green cluster. In the blue cluster, indicated in blue on the map, the article "Marine wastewater discharges from multiport diffusers. I: Unstratified stationary water" by Tian et al. takes the spotlight. It delves into laboratory experiments concerning the near-field mixing of buoyant plumes discharged from multiport diffusers into unstratified stationary water and boasts the highest total link strength of 6 within the blue cluster [50]. In the yellow cluster, "Modelling the dispersion of wastewater discharges from offshore outfalls: a review", the most important article was the one by Zhao et al., which focuses on reviews of

modelling techniques associated with the simulation of wastewater dispersion discharged from offshore outfalls based on the type of method and the physical process of the ocean discharge [51]. The article had the highest total link strength of 13 in the yellow cluster. Within the purple cluster, the study titled "Marine wastewater discharges from multiport diffusers II: Unstratified flowing water," authored by Tian et al., primarily delves into laboratory experiments concerning the near-field mixing of buoyant plumes discharged from multiport diffusers into unstratified flowing water [52]. In addition to this, the cluster includes the article "Field observations of Ipanema Beach outfall" by Carvalho et al. [53]. These two articles collectively held the highest total link strength, indicating a research value of 4 within this particular cluster. In the light blue cluster, represented by the color light blue in Figure 9, the most crucial article is "Hydraulic model study for Boston outfall. I: Riser configuration" by Roberts and Snyder [54]. This article is centered around a hydraulic model study aimed at determining diffuser design and possesses the highest total link strength of 19 within the light blue cluster.

Following the successful identification of thematic clusters, a detailed examination of all articles encompassed within each cluster was undertaken. The primary objective of this meticulous review was to unveil the paramount contributions within these articles, shedding light on their key insights and novel perspectives. Simultaneously, a comprehensive analysis was conducted to ascertain the predominant research methodologies and theoretical frameworks that underpinned the investigations within each cluster. As Alayo et al. (2021) point out, the results of bibliometric analysis should be interpreted and complemented by extensive reading [55]. This process of extensive reading serves as an essential companion to the quantitative insights offered by bibliometric studies. It enables researchers to delve deeper into the multifaceted landscape of scholarly work, facilitating a more nuanced understanding of the field's intricacies and dynamics. Such an assessment allows us to delve further into the central findings derived from bibliometric studies, offering valuable insights into critical facets of the research, the identification of potential gaps in existing literature, and insights into the future direction of the field.

3.7 Content Analysis

Content analysis is a robust research method that serves as a valuable tool for exploring determined research themes and research methods. This methodical approach empowers researchers to systematically categorize and interpret content, ultimately yielding valuable insights and contributing to a deeper understanding of their chosen research themes. The outcomes related to the study's research themes are presented in the following section (Section 3.7.1), while the results related to the research methods are detailed in the next section (Section 3.7.2).

3.7.1 Research themes

In Figure 10, themes other than data analysis did not exhibit consistency, despite their temporary popularity. Data analysis studies show a continuously increasing trend due to the development of mathematical models and data mining techniques. Yet, there has been a significant decline in field studies since 2013 and it has been replaced by joint field/laboratory studies. Alternatively and based on the temporal analysis (yearly), a total number of 25 articles during 1970-1983 was published, while this number increased to 64 articles between 2014-2023 as a result of the joint work of different methods on the subject.

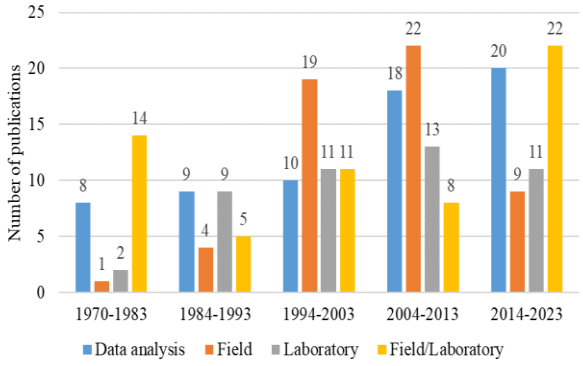

Figure 10. Temporal changes in the number of studies linked to the Data, Field, Laboratory, and Field/Laboratory studies

3.7.2 Research methods

According to the 226 studies selected for this topic, Figure 11 illustrates the number of studies related to each categorical field, while Figure 12 represents the development of these categories over the years. In these illustrations, studies that applied more than one method are called mixed studies. Alternatively, the application of each method separately and together with mixed models are illustrated and compared in Figure 13.

Figure 11 shows the number of publications in which different research methodologies (experimental, modelling, numerical, simulation, and field studies) were used. Figure 11 reveals how different research methodologies are related to each other. It also shows that the researchers with a perspective on the number of publications related to different methodologies and also depicts information such as which methods are more popular, used together, or which methodology combinations are less common in practice. Figure 11 shows the modelling studies constitute approximately

26% of the total study. Experimental methods are the main methods that these studies are used together.

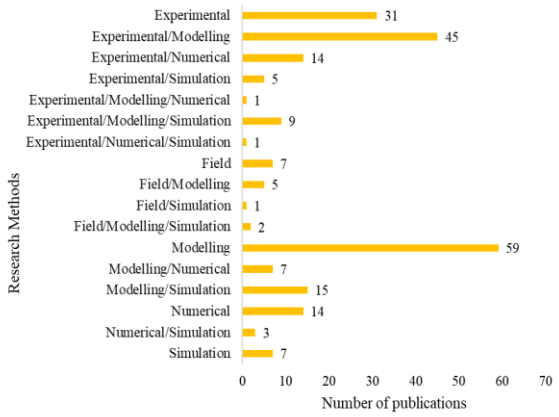

Figure 11. Number of studies based on the methodology applied in the study

When the studies were analyzed, the methods mostly used were determined and categorized into 5 different categories experimental, numerical, modelling, simulation, and field. Among the listed categories, modelling and simulation studies were found to form a common group with other methods. The definition of the selected categories can be established as follows. *i)* A model is considered to be the product (physical or digital) that represents a system of interest. It is similar to but simpler than the system it represents while approximating as closely as possible many of the salient features of the real system. A good model maintains a reasonable balance between realism and simplicity. *ii)* Simulation is the process of using a model to study the behavior and performance of a real or theoretical system. In a simulation, models can be used to study existing or proposed characteristics of a system. The purpose of a simulation is to study the properties of a real-life or fictional system by manipulating variables that cannot be controlled in a real system. Simulations allow the evaluation of the model to optimize system performance or to make predictions about a real system. Simulations are useful for studying the properties of a model of a real-life system that is very complex, of different sizes, very fast/slow, and difficult to access. While a model aims to be faithful to the system it represents, a simulation can use a model to explore situations that are not possible in the original system [56].

There are different stages used by each method in the studies. In modelling and simulation methods, various programs were used according to the contents and aspects of the study. In simulation studies, different scenarios are introduced to the program and various numerical modelling bases of package programs such as Cormix, VISJET, US EPA Visual Plumes (VP), etc., which are approved by official authorities accepted in hydrodynamic investigations of sea discharge water jets, can be used in practice, e.g. the design of domestic wastewater discharges with positive jets [57]. Simulation research of these models for negative jets is also quite common. Software such as Ansys Fluent, Star-CCM+, and OpenFOAM is also used in modelling studies. These programs provide detailed information about the morphological characteristics of the discharge by using different turbulence models with the finite volume method.

Synthesis of modelling studies with experimental studies is very popular [58, 59]. Laser-Doppler-Velocimetry (LDV), Particle Image Velocimetry (PIV), and Laser Induced Fluorescence (LIF) methods, which are frequently used in experimental studies in recent years, have made a great contribution to the development of past studies. While PIV focuses on measuring fluid velocities by tracking the motion of tracer particles, LIF is used to visualize and measure the concentration of specific substances in a liquid through the detection of fluorescence. Both techniques have their specific applications and contribute in different ways to the understanding of fluid dynamics [60]. LDV provides high accuracy, especially for velocity measurements at specific points, but is often more limited than localized measurement techniques such as PIV due to its ability to measure at a specific point. Therefore, the choice of which techniques to use depends on the specific objectives of the study and the capabilities of the laboratory [61].

In the field studies, the Acoustic Doppler Current Profiler (ADCP) was used to analyze the marine environment and the changing characteristics of the receiving environment. In the studies, an ADCP fixed to the seabed can measure the current velocity not only at the bottom but also at equal intervals up to the surface [62]. The device can be mounted horizontally on seawalls in rivers and canals to measure the current profile from shore to shore to take constant current measurements of the movement of boats and up to the bottom of ships. The researchers who presented field studies presented their studies with satellite images supported by programs with a Geographical Information System (GIS) database. According to these studies, there is an increase in field studies yearly with the use of devices such as ADCP. Field studies pose challenges in terms of reaching the outfall location, conducting measurements, and evaluating the data. As a result, the development of field studies has taken considerably more time compared to other methods.

In summary, Figure 11 offers a comprehensive overview of the number of publications on research methodologies, serving as a valuable resource for researchers. It concisely

presents information that aids in understanding popular methodologies and identifying research areas.

According to Figure 12, studies in the field of sea outfall started primarily with experimental studies. These studies were presented with two or more methods as technologies were developed that allowed different methods to work together. It is seen that studies using more than one method have a higher rate of interest in recent years. This shows that the validity of single-method studies is decreasing day by day. In recent years, especially modelling studies have been combined with experimental studies.

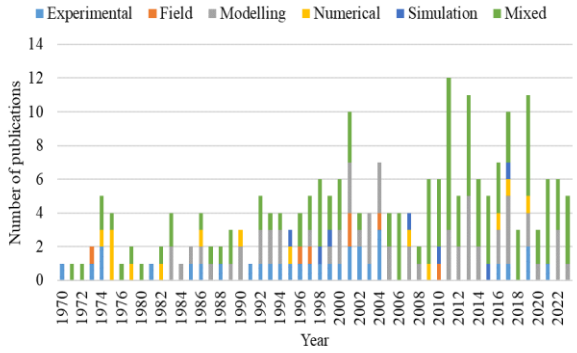

Figure 12. Number of publications per year

Figure 13 shows the contribution of single and mixed studies based on the defined categories. The most frequently used mixed methods were seen in simulation studies with 84%. This is followed by experimental studies with 71%. In field studies, single and mixed methods were used almost equally. This analysis provides valuable insights into the distribution of research output across different methodologies and approaches within the field of sea outfalls. By distinguishing between single and mixed studies, researchers can identify trends in research methods and assess the effectiveness of interdisciplinary approaches in addressing complex marine and water management challenges. In addition, understanding the distribution of studies across categories can help to prioritize future research directions and resource allocation, thus enhancing the sustainability and effectiveness of marine and water management strategies.

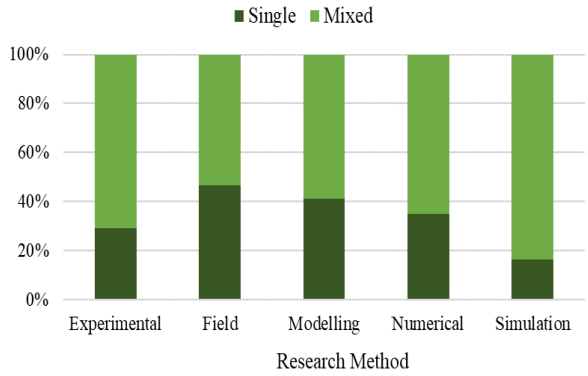

Figure 13. The contribution of single and mixed studies based on the categories defined

Table 4 also shows the temporal development of those studies based on the categories introduced above. Experimental studies decreased after 2004, whereas Experimental/Modelling studies increased. Similarly, the results reveal that modelling studies have become more popular in recent years. In addition, the simulation method was mostly preferred to be used together with other models instead of using it single by the researchers. As a result, the previous studies were more of a theoretical kind and used modelling as the pivot method in the conceptualization, evaluation, and analysis of the studies. In recent years was revolutionized by the focus on mixed studies as given in Figure 13, in all the categories, mixed studies were found to be more eligible and fulfilling by the authors, reviewers, and editors.

Table 4. Temporal changes in the direction of the studies and methods used in the analysis

Research Methods	1970-1983	1984-1993	1994-2003	2004-2013	2014-2023	Total
Experimental	5	6	12	3	5	31
Experimental/Modelling	5	4	7	10	19	45
Experimental/Modelling/Numerical	-	-	-	1	-	1
Experimental/Modelling/Simulation	-	-	2	4	3	9
Experimental/Numerical	5	3	1	2	3	14
Experimental/Numerical/Simulation	-	-	-	-	1	1
Experimental/Simulation	1	-	-	2	2	5
Field	1	-	4	2	-	7
Field/Modelling	-	-	2	1	2	5
Field/Modelling/Simulation	-	1	-	-	1	2

Table 4. (cont.) Temporal changes in the direction of the studies and methods used in the analysis

Research Methods	1970-1983	1984-1993	1994-2003	2004-2013	2014-2023	Total
Field/Simulation	-	-	1	-	-	1
Modelling	2	11	13	18	15	59
Modelling/Numerical	-	-	1	4	2	7
Modelling/Simulation	-	-	4	8	3	15
Numerical	6	2	1	2	3	14
Numerical/Simulation	-	-	-	2	1	3
Simulation	-	-	3	2	2	7
Total	**25**	**27**	**51**	**61**	**62**	**226**

4. CONCLUSION

Analysis of sea outfalls is an integral part of the development of environmental, economic, and social sustainable marine and water management strategies. By understanding the environmental impacts of sea outfalls, monitoring water quality, studying ecosystem responses, and implementing effective management measures, it can strive for a balanced relationship with marine environments while meeting growing demands on water resources. Moreover, integrating economic and social considerations into the analysis of sea outfalls is critical to ensuring long-term sustainability. By considering the economic impact of marine management decisions and addressing social equity in resource allocation, it can develop resilient communities that depend on healthy marine ecosystems. This interdisciplinary approach is essential to enhance environmental, economic, and social sustainability and ensure the health and resilience of our marine environment.

The study addresses the development of published articles in the field of sea outfall. Information regarding the aim of the studies, the scope of the articles, most successful authors, countries and their contribution, most interested journals, and methods used in the evaluation of the studies are evaluated.

The key findings are as follows:

i. The evolution over time of research themes was demonstrated by analyzing keywords.

ii. Contributing authors, countries, and journals were identified in the field.

iii. A new and detailed classification of marine discharge studies was introduced.

iv. Common themes among publications were determined using bibliographic coupling.

v. Research methods in studies on sea discharge were analyzed.

vi. Development and application of innovative technologies and engineering solutions to minimize the environmental impacts of sea outfall systems are needed.

vii. Comparative studies would bold the difference between various sea outfall designs, their locations, and management practices to identify the best option.

viii. Global perspectives on sea outfall research to account for regional differences are needed.

It is worthy of discussion that the advances in sensor technologies, remote sensing, and data analysis have made it possible to apply more comprehensive and hybrid methods to sea outfall research. These technologies allow large amounts of data to be collected and analyzed more efficiently. Emerging technology allows researchers to integrate data from different disciplines and provide a multidisciplinary perspective. Advances in numerical modelling and simulation techniques have been used to better understand the complex processes involved in sea outfall and to study these processes through modeled scenarios. Concentration in certain countries may be directly linked to industrial activities as sea outfall is often linked to the dumping of industrial waste into the sea. Coastal cities or industrial areas may often face more sea outfall problems. Concentration in particular countries may also be linked to their research infrastructure and funding opportunities.

Sea outfalls play a critical role in achieving marine environmental sustainability by creating significant environmental impacts on marine ecosystems. Advanced numerical modelling and simulation techniques are effective tools to better understand the environmental impacts of sea outfalls and optimize management strategies. The integration of these technologies makes data collection and analysis processes more comprehensive and effective. However, international research perspectives can be developed, taking into account regional differences. There is a need to increase knowledge and skills in marine outflow management,

especially in developing countries. Industrialization and environmental impacts in these countries can make it difficult to develop sustainable management strategies. Training programs and technical assistance can help these countries to increase their capacity in outfall management. Furthermore, wastewater reuse and advanced treatment technologies can provide effective solutions to outfall problems. In conclusion, the management and sustainability of sea outfalls require a multidisciplinary approach. Mitigation of environmental impacts, integration of economic and social factors, and the use of innovative technologies will be the keystones in achieving sustainability objectives in this area.

The main limitation of this study relies on the application of more specific keywords, in-depth discussion on the introduced studies, comparison between models, and addressing environmental and socio-economic impacts of different approaches which was not the primary goal of this study. Yet we believe that in-depth discussion in this study would avoid having a general picture and avoid a conclusion on the topic.

As a last word, we think the interested reader may want to delve into the following topics and address new subjects in future studies.

i. Future studies need to address the role of climate change on the sea outfall and related roadmaps and resilience against upcoming events

ii. Developing countries need to enhance their knowledge and ability on the sea outfall as the industrialization and environmental impacts may be troublesome

iii. With the development of advanced treatment technologies, the reuse of wastewater is increasing and can be applied to sea outfall problems.

DATA AVAILABILITY

Data will be made available on request.

FUNDING

No funding was received for conducting this study.

CONTRIBUTIONS

Damla YILMAZ: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Writing – original draft

Hulya YILMAZ: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Software, Visualization, Writing – original draft

Elif Aybike ERDEM: Data curation, Formal analysis, Investigation, Resources, Writing – original draft

Mustafa Utku YILMAZ: Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing

Babak VAHEDDOOST: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing

Egemen ARAS: Conceptualization, Methodology, Supervision, Writing – original draft, Writing – review & editing

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose, and they have no conflicts of interest to declare that are relevant to the content of this paper and its publication.

DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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