A Review of Numerical Simulation Advances and The Role in Evaluating Erosion Control and Shoreline Management

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***Abstract*— Numerical simulations are crucial in coastal management, serving a key function similar to their role in other engineering disciplines. They deliver crucial insights into complex coastal dynamics, including erosion, which is affected by factors such as climate change, sea level rise, and human interventions. Using a bibliometric analysis approach, this study assesses the evolution and future trends of numerical simulation applications for coastal erosion and shoreline management actions. By exploring databases like Scopus and Google Scholar and visualizing key data with VOSviewer, the research identified publication trends, citation metrics, and emerging study areas. The analysis reveals a substantial increase in relevant research over the past decade, with a notable surge in activity post-2018. The identified key advancements include the integration of Digital Elevation Models (DEM), machine learning, and process-based modeling, all of which significantly enhance simulation accuracy and predictive capabilities. Further, a comparative analysis of models including Delft 3D, SWAN, XBeach, and MIKE underscores their unique strengths and highlights the importance of selecting appropriate models based on specific project conditions. The study concludes that multidisciplinary parameters integrated with technological advancements are crucial for developing effective and sustainable coastal management strategies, emphasizing the need for model selection tailored to address specific erosion and shoreline management project needs.**

Keywords—Coastal Management, Numerical Simulations, Emerging Trends, Bibliometric Analysis, Erosion, Shoreline

I. Introduction

Coastal management has become critical due to the increasing environmental challenges driven by industrial development, urbanization, and technological advancements [1]. The problems which come with the progress of some industries include the destruction of habitats in natural ecosystems, pollution of the environment, and even the rate of coastal erosion. Building of structures like ports, dams, and other developments along the shoreline has adjusted the deposition of sediments and waves which has intensified the rate of shoreline erosion [2]. Such changes as well as climate change factors including increased storm surges and sea levels also expose the coastal regions to various natural disasters. As much as these challenges are contextualized by technological advancement, the same advancement has been applied to come up with solutions to these problems. In coastal management, numerical simulations have been adopted in predicting the behaviour of coastal systems that would assist decision-makers in designing better erosion control and shoreline protection [3]. In the past, the numerical simulations for application in coastal engineering were done using primitive linear models which are rather crude in approximations to provide essential characteristics of wave, sediment, and tidal actions. Some of these early models were used to guide the construction of coastal features such as breakwaters, seawalls, groins and other structures meant for controlling erosion [4].

Modern advances in computing power and mathematical modelling have revolutionized numerical simulations in coastal management. Modern models are capable of simulating complex coastal dynamics, predicting long-term changes, and evaluating the impacts of specific storms. As a result of this, computational modelling has become a strong numerical approach for assessing several biophysical interactions in natural coastal environments and anthropogenic impacts[5]. However, the utilization of these tools has its drawbacks, which include computation, data, access and qualification of performing proper model calibration and setting up. For example, Delft3D and MIKE 21; despite their efficiency, these models demand huge computational power as well as technical proficiency to yield precise solutions. Furthermore, big models used for accurate long-term simulations or the detailed assessment of a storms' potential effects, may prove not only lengthy but also expensive. However, the prospect of applying numerical simulations in coastal management is full of significant advantages. These tools help make very precise forecasts of coastal processes thereby helping the planner to plan efficient sustainable interventions [6]. They provide a better understanding of the long-term impacts of climate change, rising sea levels, and human infrastructure on coastal systems. By simulating various scenarios, decision-makers can explore the potential outcomes of different management strategies and make informed choices that balance environmental conservation with economic development.

In recent years, the rapid development of modern technologies has pushed numerical simulation to the forefront of coastal management. Several numerical simulation models have been developed for different focused areas. The objective of this paper is to examine how advancements in numerical simulation are used to evaluate coastal erosion control and management, with a particular focus on measurement and monitoring for improved management. Additionally, the study aims to identify emerging trends in these simulations and explore their potential for adoption in ongoing and future coastal projects, ensuring more effective and sustainable management strategies.

II. Methodology

A bibliometric analysis approach was employed in this study to identify the evolution of numerical simulation and current and future advances. Figure 1 shows the methodology flow chart which was followed in the analysis.

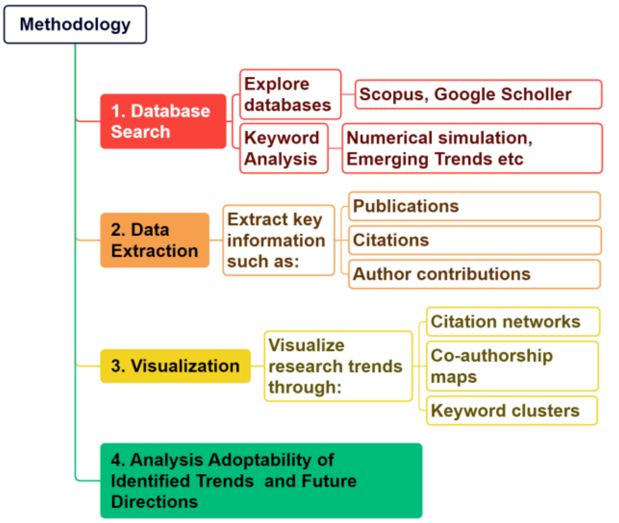


Figure 1: Methodology flowchart which was followed in the study

A. Database Search

The first step involves exploring academic databases (Scopus and Google Scholar) to find relevant studies. These databases were chosen for their extensive coverage of scholarly articles across various subfields under coastal engineering. A keyword analysis was conducted using the major keywords "*Coastal Erosion, Shoreline Management, Numerical Simulation* " to refine the results and ensure they align with the scope of this review. This approach ensured that only researches pertinent to the topic of interest were included, narrowing down the vast pool of potential publications.

B. Data Extracting

After identifying relevant papers, key information was extracted for further analysis. This included the number of publications available in the selected databases, citations to assess the impact of these publications, and author contributions to highlight key researchers or research groups driving innovation in the field. This extraction process ensured that both quantitative (publication and citation numbers) and qualitative (researcher influence) metrics were considered.

C. Data Visualization

To understand patterns and trends within the extracted data, visualization techniques were employed. Using VOSviewer, a specialized tool for bibliometric analysis, various data points were transformed into visual representations. Citation networks showed how different papers were interlinked, indicating knowledge transfer between them. Co-authorship maps revealed collaboration patterns among researchers, helping to identify prominent research groups or institutions. Additionally, keyword clusters were generated to identify emerging trends and research hotspots. These visualizations enabled a clearer understanding of the relationships between research outputs, author contributions, and thematic developments over time.

D. Analysis of Adoptability and Future Directions

The final step involved analyzing the trends uncovered through the previous phases to assess their relevance and future potential. By examining citation networks, co-authorship patterns, and keyword clusters, the author evaluated the adaptability of the identified trends for future studies or practical applications. This step also helped in identifying gaps in the current literature and proposing new areas for exploration or improvement, guiding the direction of future research.

III. Analysis Results and Discussion

A. Quantitative analysis of conducted studies related to numerical simulation in the coastal management field

Research activities in coastal hydrodynamics are continuously conducted worldwide. Numerical simulation has been used as an important tool for those studies. Figure 2 illustrates the quantitative variation in the number of papers published in the last decade, as revealed by the bibliometric analysis.

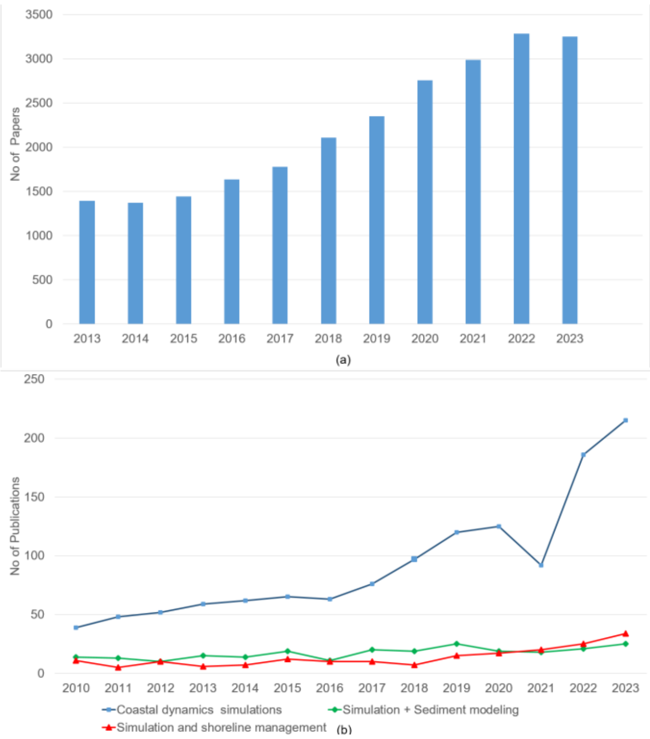
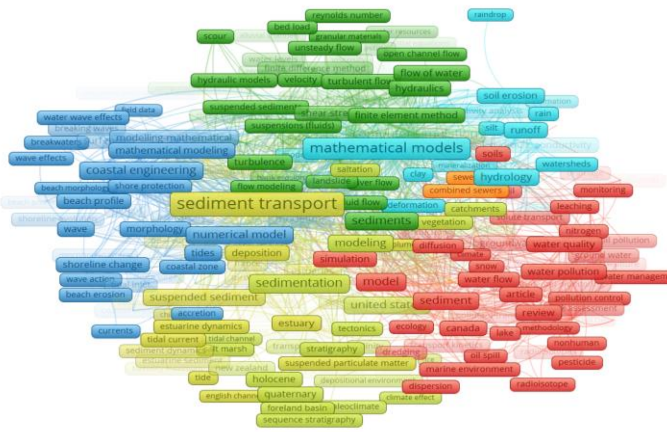


Figure 2: (a) The number of papers published from 2013 to 2023 related to numerical simulation (Scopus database) (b) Variation of simulation studies in key integrated areas of coastal engineering

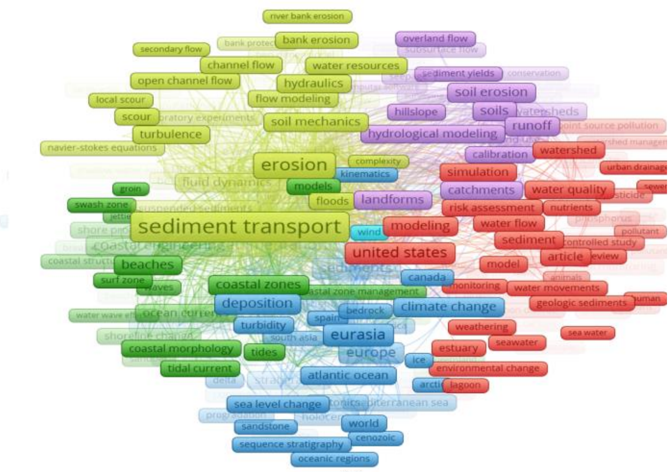
Figure 2 (a) presents the number of papers published between 2013 and 2023 related to Numerical Simulation. It demonstrates a consistent upward trend in publications, indicating a steady growth in research interest. A notable surge begins after 2015 reflecting an accelerated focus on these topics, possibly caused by upgraded computational power. Simultaneously, Figure 2(b) shows a significant rise in research on numerical simulations in coastal engineering, which saw steady growth from 2010 and a notable surge after 2020, reaching over 200 publications by 2023. This highlights the growing interest in using simulations to address coastal erosion and dynamic processes. In contrast, research on integrated sediment modeling and shoreline management has remained relatively stable, with minor increases. This indicates the need for more integrated shoreline and erosion management studies using numerical simulation approaches to better address complex coastal challenges.

B. *Bibliometric Analysis*

The keyword analysis revealed the following networks and clusters, as illustrated in Figure 3. These figures depict the relationships and thematic groupings of key terms within the research domain, providing insights into the main areas of focus and emerging trends in the field.



(a)



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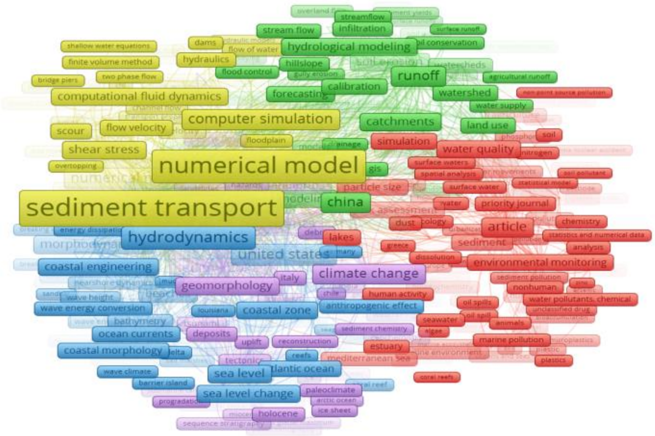
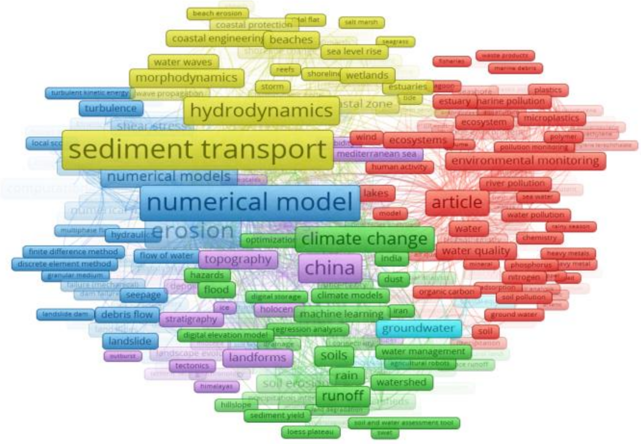


(c)



(d)

Figure 3: (a) Main keywords clusters and Network diagram of studies from 1990-2000 (b) Main clusters and Network diagram of studies from 2001-2010 (c) Main clusters and Network diagram of studies from 2011-2020 (d) Main clusters and Network diagram of studies from 2021-2024

Figure 3 illustrates the evolution of key research areas and methodologies related to numerical simulations between 1990 and 2024 with the size of each bubble representing the frequency of keyword occurrence in the literature. Figure 3(a) highlights the early focus on simple mathematical models and sediment transport simulations from the 1990s, where basic computational approaches were used to understand sediment dynamics in various water systems. By Figure 3(b)**,** reflecting research after 2000, sediment transport remained central, but models began to incorporate erosion processes, reflecting an increased emphasis on how sediment dynamics contribute to environmental changes. The period also saw a growing interest in coastal morphodynamics**,** where advanced simulations were used to study the changing morphology of coastlines influenced by waves, tides, and sediment movement. After 2010, as shown in Figure 3(c), and Figure 3 (d), a notable expansion in numerical modelling is observed, indicated by the larger bubble size, and the development of a separate cluster for numerical simulation (Refer 3d), highlighting the increasing role of simulations in researches. This includes the incorporation of machine learning, digital elevation models (DEM), and regression analysis, which emerge as newer, data-driven approaches. The prominence of bubbles related to climate change, groundwater, and flood management further underscores a shift toward studying environmental impacts in conjunction with sediment dynamics. Additionally, machine learning and algorithmic approaches show growing influence in simulation studies, marking a significant trend toward predictive modeling. Overall, the increasing bubble sizes for simulation-based methods emphasize their rising preference, making computational techniques a cornerstone of post-2020 research in this field.

The keyword evolution (See Table 1) from 1990 to 2024 shows a clear shift in coastal engineering research, emphasizing more complex and advanced methodologies over time. In the early period (1990-2000), simpler concepts including coastal sediments, estuary dynamics, and sediment transport dominated, reflecting a focus on foundational processes. From 2001 to 2010, a transition towards more applied studies, like erosion and flow modeling, emerged, alongside an increasing focus on climate change and environmental monitoring. By 2011-2020, advanced tools including numerical models and computational fluid dynamics became central, while concerns about climate change, geomorphology, and water quality intensified, highlighting the growing integration of modeling with environmental impacts. The recent period (2021-2024) underscores a focus on numerical models, erosion, and hydrodynamics, showing heightened concern for predictive and simulation techniques to address complex challenges like sea level rise and morphodynamics. The consistent rise in keywords such as sediment transport and climate change across periods indicates persistent challenges, while the increasing prominence of advanced modeling techniques suggests a critical need for innovation in managing coastal and environmental processes.

Table 2 further indicates the evolution of keywords related to modelling and numerical simulation. The evolution of numerical simulation and modelling in coastal management in this time shows a progressive adoption and integration of advanced computational technologies. In the early period (1990-2000), methods such as computational methods, finite difference methods, and wave modeling were foundational but relatively simplistic, emphasizing basic numerical techniques for modeling water flow, sediment transport, and hydrological processes. As technology advanced into the 2001-2010 period, it can be observed that the increasing use of advanced models including climate modeling and computational fluid dynamics (CFD), indicates the growing complexity of models and their application to simulate dynamic coastal processes. The rise of numerical models and environmental modeling during this phase also shows a transition from conceptual models to more data-driven approaches for understanding coastal systems.

The major shift was observed during 2011-2020, where numerical models became the dominant tool, with a massive surge in research (3500 publications), alongside the broad adoption of computer simulations and digital elevation models (DEM) for precise, large-scale coastal management. This period also saw the integration of wave modeling and rainfall-runoff models, showing how coastal management began adopting an interdisciplinary approach that accounts for various environmental and hydrodynamic factors. From 2021-2024, cutting-edge technologies such as machine learning, artificial neural networks, and unmanned aerial vehicles (UAVs) emerged, indicating the convergence of numerical modeling with automation and AI. The continuing dominance of computational fluid dynamics and morphodynamic modeling shows how science has increasingly evolved into applied technology in coastal engineering, with a strong emphasis on predictive modeling to address complex issues like coastal erosion, sea level rise, and sediment transport. This progression highlights not only the development of technology but also the critical need for interdisciplinary tools to meet the growing challenges in coastal management.

As per the observations, coastal erosion emerged as a prominent problem during the last 2 decades as the number of publications has drastically increased during that period. The focus on erosion in coastal engineering research has grown significantly over the past two decades, as reflected by the steady increase in studies. During 2001-2010, there were 130 publications related to erosion, which surged to 395 in 2011-2020, and then sharply rose to 1,650 by 2021-2024. This sharp increase underscores the growing concern over coastal erosion, likely driven by climate change, rising sea levels, and the need for sustainable coastal management. The surge in research indicates a heightened awareness of erosion's impact on coastal environments, infrastructure, and human populations. The integration of numerical models and computational fluid dynamics (CFD) into erosion studies, particularly in recent years, reflects the reliance on advanced simulation tools to predict and mitigate erosion processes more effectively. This trend highlights the evolving role of technology in developing innovative solutions for erosion control, reinforcing the importance of interdisciplinary research to address these pressing coastal challenges.

Table 1: Frequency of occurrence (f) of most frequent author-keywords for (a) 1990–2000, (b) 2001–2010, (c) 2011-2020 and (d) 2020–2024 periods. (Searched Main Keywords: Coastal *Erosion, Shoreline Management, Numerical Simulation)*

Cluster	(a)1990-2000		(b)2001-2010		(c)2011-2020		(d)2021-2024	
	Keywords	**f**	**Keywords**	**f**	**Keywords**	**f**	**Keywords**	**f**
Fluid Dynamics	1. Coastal Sediments	18	1 Erosion	128	1 Numerical Model	3511	1. Numerical Models	1922
	2. Estuary Dynamics	13	2. Channel Flow	89	2.Computational Fluid Dynamics	572	2. Erosion	1653
	3.Flow of Sediments	11	3.Sediment Transport	76	3.Erosion	394	3. Hydrodynamics	1202
	4. Hydraulics	9	4.Flow Modeling	44	4.Channel Flow	198	4. Computational Fluid Dynamics	607
Sediment Dynamics	1.Sediment Transport	16	1.Sediment Transport	127	1.Sediment Transport	4241	1. Sediment Transport	2291
	2. Deposition	15	2.Coastal Engineering	80	2. Coastal Engineering	648	2. Morphodynamics	498
	3. Estuary	10	3. Coastal Zones	77	3. Morphodynamics	862	3. Beaches	366
	4. Suspended Sediment	8	4. Ocean Currents	26	4.Ocean Currents	458	4. Wetlands	259
Coastal Processes & Engineering	1. Beach Erosion	39	1.Climate Change	84	1. Climate Change	1056	1 Climate Change	1033
	2.Beach Morphology	38	2.Climate Modeling	84	2. Geomorphology	699	2. Sea Level Rise	500
	3 Coastal Engineering	21	3.Coastal Morphology	79	3 Coastal Zone	604	3. Coastal zone	428
	4.Shoreline Change	6	4.Ecological Modeling	56	4.Sea Level Change	592	4. Geomorphology	400
Environmental Impact & Water Quality	1. Monitoring	13	1.Environmental Monitoring	52	1. Water Quality	593	1.Runoff	641
	2. Groundwater	10	2.Pollution Monitoring	23	2.Environmental Monitoring	524	2. Water Quality	593
	3. Hydrology	9	3.Risk Assessment	22	3.Risk Assessment	484	3.Environmental Monitoring	524
	4. Water Pollution	5	4. Water Quality	12	4.Prediction	425	4.Risk Assessment	484

Table 2: Frequency of occurrence (f) of numerical simulation related author-keywords for (a) 1990–2000, (b) 2001–2010, (c) 2011-2020 and (d) 2020–2024 periods. (Searched Main Keywords: Coastal *Erosion, Shoreline Management, Numerical Simulation)*

Rank	(a)1990-2000	f	(b)2001-2010	f	(c)2011-2020	f	(d)2021-2024	f
1	Computational Methods	17	Channel Flow	89	Numerical Models	3511	Numerical Model	1922
2	Computer Simulation	17	Climate Modeling	84	Computer Simulation	1114	Computational Fluid Dynamics	607
3	Finite Difference Method	12	Computational Fluid Dynamics	75	Computational Fluid Dynamics	592	Machine Learning	342
4	Flow Modeling	11	Ecological Modeling	56	Digital Elevation Models (DEM)	250	Rainfall-Runoff Models	294
5	Water Flow Modeling	11	Environmental Modeling	52	Wave Modeling	199	Climate Models	212
6	Hydrological Models	9	Flow Modeling	44	Rainfall-Runoff Modeling	139	Artificial Neural Network	202
7	Mathematical Models	8	Hydrodynamics	35	Finite Difference Method	133	Digital Elevation Models (DEM)	162
8	Numerical Models	8	Hydrological Modeling	34	Climate Models	101	UAV	112
9	Wave Modeling	5	Numerical Modeling	26	Morphodynamic Modeling	95	Morphodynamic Models	98
10			Rainfall-Runoff Modeling	22	Sediment Transport Models	94	Wave Modeling	91

Table 3 highlights the emerging trends in the application of numerical simulation and modeling in coastal erosion and shoreline management, demonstrating how innovative methods are enhancing the accuracy and predictive power of simulations.

Table 2: Emerging trends in the application of numerical simulation and modeling in coastal erosion and shoreline management

	Emerging Trends
Digital Elevation Models (DEM)	Increased use of DEM for terrain and coastal erosion modeling, aiding in accurate topographical simulations [8] ,[9].
Machine Learning	Applied for predictive modeling and optimization in coastal erosion, enhancing simulation accuracy [10].
Regression Analysis	Utilized alongside simulations to predict erosion impacts and evaluate coastal changes over time [11].
Climate Change	Increasing focus on modeling the effects of climate change on coastal erosion and sediment transport [12].
Process-Based Modeling	Modeling physical processes that drive coastal erosion and sediment transport, providing detailed simulations of natural systems [13].
Coupled Models	Increased use of coupled models to simulate interactions between water flow and sediment movement in coastal regions [14].
Long-Term Morphological Modeling	Simulations that predict long-term changes in coastal landscapes due to sediment transport and erosion processes [15].
Nature-Based Solutions in Models	Integration of green infrastructure and nature-based approaches (e.g., dunes, wetlands) in coastal erosion models [16].
Integration of Real-Time Data	Leveraging real-time data inputs (e.g., tide levels, wave data) to enhance model accuracy and responsiveness in simulations [17].
Multi-Objective Optimization	Applied to balance different goals in coastal management (e.g., environmental protection, economic benefits) in simulation-based models [18].

Numerical simulation plays a crucial role in erosion and shoreline management by enabling early forecasting and detailed analysis of coastal processes. Through advanced models like Digital Elevation Models and machine learning, simulations offer proactive management solutions, allowing for informed decisions before erosion escalates. This approach helps prevent damage, optimize resource allocation, and support sustainable practices, shifting the focus from reactive responses to proactive, long-term coastal protection strategies.

C. Comparative analysis of key simulation models

In the analysis, several key models were identified as widely used in coastal erosion and shoreline management, each serving different purposes. These include Delft3D, SWAN, XBeach, Mike, Wave Watch III, ROMS (Regional Ocean Modeling System), TELEMAC, and ADCIRC. Each model plays a distinct role in simulating coastal and environmental processes. ROMS and TELEMAC are recognized for hydrodynamic simulations, ADCIRC is widely used for storm surge and tidal modeling, while Wave Watch III excels in large-scale wave prediction by simulating wind-generated waves and integrating real-time data [19].

The four models selected for comparison—Delft3D, SWAN, XBeach, and Mike—were chosen based on their frequent appearance in the keyword analysis and their extensive use within the scientific and engineering communities. These models have consistently demonstrated their reliability and accuracy in coastal management studies. Comparing them is essential for understanding their specific strengths, limitations, and suitability for different coastal applications. This comparison enables researchers and practitioners to choose the most appropriate model, ensuring accurate simulations, optimized resource use, and effective long-term coastal management strategies. Table 4 reflects a comparative analysis of key simulation models.

Table 3: Characteristics of key simulation models

Criteria	**Delft 3D**	**SWANN**	**Xbeach**	**Mike 21**
Parameters that can be modelled	Wave, dispersion Hydrodynamics, Sediment Transport, Ecological modeling	wave generation, propagation, and dissipation processes	Wave propagation, flow, sediment transport	Hydrodynamic Sediment Transport Water Quality Parameters
Open-Source (OS) or Proprietary (PR)	OS -Some packages require a subscription	PR -OS version available with limited options	OS	PR
Accurate Evaluations	High accuracy in simulating hydrodynamics and sediment transport.[20]	Focuses on wave dynamics, providing reliable data for coastal processes [21]	Good accuracy for beach erosion and accretion modelling [22]	High accuracy in hydraulic and hydrological modelling [23]
Comprehensive Evaluation	Offers a wide range of modules for different environmental processes [24]	Limited to wave interactions and coastal processes [25]	Comprehensive for beach and coastal dynamics [26]	Comprehensive, integration various environmental factors [2]
Cost-effective Evaluations	High initial setup cost, but cost-effective for large projects.	Generally lower cost, suitable for smaller projects.	Cost-effective (open source)	Moderate cost, but offers extensive features justifying expense.
Physics-based Evaluation over Statistics	Strong physics-based	Physics-based,	Physics-based,	Strong physics-based modeling,
Optimize Multiple Objectives Simultaneously	Capable of multi-objective optimization in simulations [20], China .	Limited multi-objective optimization capabilities [27]	Can optimize for specific beach profiles [13],.	Strong multi-objective optimization features available [13].
Reliability of Evaluation	Highly reliable with extensive validation studies.	Reliability can vary based on input data quality.	Reliable for specific coastal scenarios.	Highly reliable, backed by extensive research and validation.

This comparative analysis indicates that different models have unique characteristics, and the selection of a suitable model should be based on the specific modeling and simulation requirements according to the scenario. When selecting an appropriate coastal modeling tool, the process begins by evaluating cost and accessibility alongside project requirements. Delft 3D, a versatile tool offering both open-source and proprietary packages, provides flexibility depending on project scale and budget. It is well-suited for large projects requiring diverse environmental modeling capabilities. In contrast, XBeach stands out as a fully open-source tool, specifically designed for beach erosion and dune dynamics, making it a more cost-effective option for projects focused on those areas. Mike 21 is a proprietary system, known for its extensive feature set, which justifies its higher cost in cases requiring advanced hydrodynamic, sediment transport, and water quality modeling. SWAN offers both open-source and proprietary versions but focuses on wave dynamics, making it ideal for projects with simpler, wave-centric objectives.

In terms of capabilities, the models vary significantly. Mike 21 excels in simulating a wide range of coastal processes, from hydrodynamics to sediment and water quality, allowing it to handle complex environmental assessments. Delft 3D also provides a broad range of modeling capabilities, including wave generation and ecological dynamics, making it suitable for integrated coastal management projects. Meanwhile, XBeach is highly specialized, focusing on erosion and near-shore beach profile modelling, which limits its utility to more targeted coastal applications, such as storm impact simulations and long-term simulations [28]. On the other hand, SWAN is more limited in its focus, excelling at wave generation and propagation, but is not suitable for comprehensive coastal simulations involving sediment or ecological processes.

Accuracy and reliability are critical factors in model selection. Delft 3D and Mike 21 are both validated extensively in the literature, showing high reliability and accuracy for complex, long-term coastal process simulations [29]. XBeach demonstrates strong accuracy in simulating beach erosion and accretion [30] though it is less versatile for applications beyond coastal erosion. When evaluating comprehensiveness, Delft 3D and Mike 21 stand out due to their ability to simulate a wide range of coastal processes, from hydrodynamics to ecological interactions, and their support for multi-objective optimization [29].

In terms of post-simulation analysis, Mike 21 and Delft 3D provide sophisticated post-processing tools, allowing for detailed visualization and analysis of simulation results. This makes them valuable in decision-making processes, particularly in projects that require the integration of multiple environmental factors. XBeach is useful for specific coastal erosion projects but lacks the broad analytical capabilities of Delft 3D and Mike 21. SWAN, while effective for analyzing wave dynamics, has limited post-processing features, which may hinder more complex environmental assessments. Overall, the selection of a model depends on the project's specific needs, balancing cost, capabilities, accuracy, and comprehensiveness.

Based on this review, it can be suggested that, decision-makers in coastal management can select specific simulation models tailored to address unique challenges, using sophisticated tools designed for particular issues. With a range of free and proprietary models available, they can choose the best fit based on the project’s specific modeling requirements. Free models offer accessibility and flexibility, especially valuable for academic research or smaller projects, while proprietary models often provide enhanced features, advanced data integration, and technical support, making them ideal for complex projects requiring high accuracy. For instance, long-term projects focused on integrated coastal stability and multi-objective optimization may use sophisticated models like Delft 3D or MIKE, whereas models like SWAN and XBeach are preferred for short-term erosion or wave dynamics studies. Also, coupled models can be used when required to overcome challenges related to model capabilities. Especially, coupled models, such as Delft3D-FLOW with SWAN, MIKE 21 coupled with MIKE 3, and XBeach, integrate processes like hydrodynamics, sediment transport, wave dynamics, and runoff to offer a comprehensive view of coastal environments. This approach allows decision-makers to select the most suitable model based on the project’s goals, data requirements, and budget, optimizing resources for effective coastal management.

However, a notable gap in these models is the integration of social impact parameters and other multidisciplinary aspects particularly economic value attribution, essential for sustainable decision-making. Incorporating these additional parameters is vital to enhance the models' effectiveness in managing coastal environments, ensuring that decision-making reflects not only environmental but also social and economic dimensions. This integration is crucial for developing more sustainable coastal management strategies that can adapt to the complex interplay of factors influencing coastal dynamics.

IV. Conclusion

This study highlights a significant rise in coastal erosion research, with publications increasing from 130 in 2001-2010 to 1,650 in 2021-2024, reflecting a growing awareness of climate change, sea-level rise, and human impacts on shoreline management. Over the past decade, numerical simulation studies have surged, with advancements in tools like Digital Elevation Models (DEM), machine learning, and process-based modeling, which have improved accuracy and predictive capabilities. Computational fluid dynamics (CFD) combined with sediment dynamic modeling has become essential for predicting and managing erosion, while high-performance computing and artificial intelligence (AI) now enable real-time data integration and optimization. Among reviewed models, Delft 3D and MIKE were identified as the most sophisticated tools for long-term, integrated modeling, supporting comprehensive multi-objective optimization, while SWAN and XBeach excel in specific functions. Decision-makers now utilize specific models tailored for problem-solving, with sophisticated models developed for particular issues. Hence, decision-makers can select most suitable models based on the project’s goals, data requirements, and budget, optimizing resources for effective coastal management. Further, it can be suggested that, integrating nature-based solutions into these models marks a shift toward sustainable practices, though a gap remains in developing fully integrated models that incorporate social and economic factors for managing the complex, multidisciplinary demands of sustainable coastal management. By focusing on advancing current cutting-edge simulation techniques into integrated modeling approaches, coastal management decisions can be made with greater precision, addressing the complex interactions among various factors and ultimately leading to more sustainable practices.

V. ACKNOWLEDGEMENT

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