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A Comprehensive Review of AI and ML Applications in Coastal Engineering

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Review

A Comprehensive Review of AI and ML Applications in Coastal Engineering

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Abstract: This manuscript reviews the current state and advancements in applying Artificial Intelligence (AI) within coastal engineering. It encapsulates some journal articles, emphasizing the role of Machine Learning (ML) algorithms in fostering sustainable management of marine and coastal environments. The review delves into various aspects of ML applications, including data preprocessing, modeling algorithms for distinct phenomena, model evaluation, and utilizing dynamic and integrated models. The study highlights the significance of coastal areas, underlining their role in biodiversity, economic activity, cultural heritage, climate regulation, food security, recreational opportunities, and strategic importance. It addresses the challenges in ensuring the sustainability of these areas, particularly in the face of climate change, beach protection, and water quality management. The manuscript underscores the necessity of effective data analysis and augmentation for informed decision-making and sustainable management of coastal systems, noting the recent surge in data availability related to coastal systems. Furthermore, the review examines the efficacy of different ML methods in predicting wave heights and other oceanographic parameters. It identifies areas where ML has been successfully applied, such as data collection and analysis, pollutant and sediment transport, image processing and deep learning, and identifying potential regions for aquaculture and wave energy activities. Additionally, it discusses the application of ML in structural design and optimization. Despite the potential benefits, the manuscript notes that dynamic and integrated ML models are still underutilized in marine projects. It concludes with insights into the application of ML in marine and coastal sustainability and calls for future research to explore the untapped potential of ML in this domain.

Keywords: Coastal Engineering; Artificial Intelligence; Machine Learning; Data processing; Modelling

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1. Introduction

Coastal Engineering studies and manages coastal areas, which are dynamic and vulnerable to various natural processes such as erosion, sedimentation, and sea level rise. In recent years, the integration of artificial intelligence (AI) techniques has significantly impacted the field of coastal engineering, offering innovative solutions to address complex challenges. This literature review aims to explore the diverse applications of AI in coastal engineering and discuss how AI tools can support and enhance research in this domain (Pourzangbar, Jalali et al. 2023). Coastal areas support biodiversity, economic activities, cultural heritage, climate regulation, food security, and recreational opportunities. Ensuring their sustainability requires addressing various factors, including climate change adaptation, beach protection, and water quality management (Beuzen, Goldstein et al. 2019). In recent years, the amount of data related to coastal systems has significantly increased, necessitating effective data analysis and augmentation for informed decision-making and sustainable management (Pourzangbar, Jalali et al. 2023).

Integrating Artificial Intelligence (AI) into coastal engineering has opened new avenues for research and development in the field (Salehi and Burgueño 2018, Manzoor, Othman et al. 2021). AI's ability to process large datasets and uncover patterns has proven invaluable in addressing the complex challenges coastal environments face (Dong, Xu et al. 2022, Kamyab, Khademi et al. 2023). This review will explore the fundamental concepts of AI and their relevance to coastal engineering, supported by recent advancements in the field.

2. What is AI, and How is it Relevant to Coastal Engineering?

A branch of computer science called artificial intelligence (AI) seeks to build machines that can carry out tasks that normally require human intelligence (Konar 2018, Shabbir and Anwer 2018, Korteling, van de Boer-Visschedijk et al. 2021, Sarker 2022). These tasks include learning, decision-making, and problem-solving. In coastal engineering, AI's relevance is profound, offering innovative approaches to managing and protecting our coastlines. By harnessing AI, engineers can analyse vast datasets - from satellite imagery to sensor data on tides and sediment movement - more efficiently than ever before (Kapoor, Kumar et al. 2024, Rane, Choudhary et al. 2024). This capability enables the prediction of coastal changes with high accuracy, facilitating better planning and decision-making. (Barzehkar, Parnell et al. 2021, Eapen 2023).

AI techniques, such as ML and deep learning (DL), are instrumental in modeling complex coastal phenomena like erosion patterns, wave dynamics, and the impact of climate change on coastal structures (Fogarin, Zanetti et al. 2023, Tsiakos and Chalkias 2023, Thanh, Van Phong et al. 2024). These models can predict how coastlines will evolve over time, allowing engineers to design more resilient coastal defense systems. Furthermore, AI-driven analytics can optimize the placement and design of structures like seawalls, breakwaters, and groins, ensuring they provide maximum protection while minimizing environmental impact (Stansby 2013, Grove, Rickards et al. 2023). Artificial Intelligence (AI) has revolutionized numerous scientific disciplines, with coastal engineering emerging as a significant beneficiary of this technological renaissance (Schwab and Davis 2018, Beuzen, Goldstein et al. 2019, Weber-Lewerenz 2021). This field is pivotal for the sustainable management of coastal zones under increasing stress due to anthropogenic activities and climate change (Marr 2019, Mastrocicco and Colombani 2021, Lawyer, An et al. 2023, Srivastava and Maity 2023, Bibri, Krogstie et al. 2024, Kapoor, Kumar et al. 2024).

Coastal regions, characterized by their dynamic nature, are subject to complex processes that necessitate sophisticated analytical approaches for their understanding and management (Nebbioso and Piccolo 2013, Werner, Bakker et al. 2013, Bachmann, Tripathi et al. 2022). Recent advancements in AI, particularly Machine Learning (ML), have provided unprecedented opportunities to address these complexities (Dwivedi, Hughes et al. 2021, Guo, Yang et al. 2021, Gill, Xu et al. 2022, Kasula 2023). ML algorithms have demonstrated remarkable capabilities in enhancing predictive accuracy and computational efficiency in various coastal engineering applications, ranging from shoreline change prediction to optimizing coastal structures (Abujaber, Nashwan et al. 2022, Torens, Durak et al. 2022, Santorsola and Lescai 2023, Sharma, Lysenko et al. 2024).

Integrating AI into coastal engineering aligns with the global thrust towards smart, data-driven solutions for environmental challenges. (Chen, Huang et al. 2022, Dong, Xu et al. 2022, Shafiq 2023) highlight the transformative impact of AI tools in identifying, forecasting, and parameterizing ocean phenomena, which are integral to coastal engineering practices. Similarly, (Nieves, Radin et al. 2021) underscore the potential of ML in predicting regional coastal sea level changes, emphasizing the importance of such predictions for strategic planning and coastal protection measures.

Furthermore, the sustainable use of coastal areas has been significantly advanced by applying various ML methods. For instance, Artificial Neural Networks (ANNs) have been employed for water quality predictions, while Decision Trees (DTs) and Random Forests (RFs) have been utilized for classifying environmental factors and predicting human impacts on coastal environments (Ahmed, Othman et al. 2019, Gambín, Angelats et al. 2021, Ewuzie, Bolade et al. 2022, Sinha, Gupta et al. 2022, Wai, Chia et al. 2022, Pourzangbar, Jalali et al. 2023). These applications underscore the versatility and adaptability of ML methods in addressing diverse coastal engineering challenges (Ghani, Kumar et al. 2023, Wang, Liu et al. 2023, Okem, Nwokediegwu et al. 2024, Ro, Li et al. 2024).

The burgeoning field of AI in coastal engineering is not only limited to predictive modeling but also extends to real-time monitoring and decision support systems (Marinakis, Doukas et al. 2020, Venketeswaran, Lalam et al. 2022, Damodaran, Kumar et al. 2024, Waqar 2024). The integration of Internet of Things (IoT) devices and sensors with AI algorithms has enabled the real-time collection and analysis of coastal data, leading to more responsive and adaptive management strategies (Palaniswami, Rao et al. 2017, Glaviano, Esposito et al. 2022). For example, the work of Pourzangbar et al. (2023) demonstrates the use of ML algorithms in real-time monitoring of coastal erosion and accretion patterns, providing valuable insights for coastal zone management. Moreover, the application of AI in coastal engineering has facilitated the development of autonomous systems for the maintenance and inspection of coastal infrastructure. Autonomous drones equipped with AI-powered image recognition capabilities can efficiently monitor the condition of coastal defenses, as discussed by (Elnabwy, Elbeltagi et al. 2022, Kapoor, Kumar et al. 2024), thereby ensuring their integrity and performance.

The potential of AI to enhance the resilience of coastal communities against extreme weather events is another area of active research (Nichols, Wright et al. 2019, Saravi, Kalawsky et al. 2019, Singh and Goyal 2023). AI-driven simulation models can predict the impact of storms and sea-level rise on coastal infrastructure, allowing for the design of more robust and adaptable structures (Koks, Le Bars et al. 2023, Ye, Du et al. 2023, Kapoor, Kumar et al. 2024). This is corroborated by recent studies that have employed ML techniques to simulate storm surge scenarios and assess the vulnerability of coastal regions (Al Kajbaf and Bensi 2020, Hadipour, Vafaie et al. 2020, Zhang, Zhang et al. 2022).

Furthermore, AI applications’ ethical considerations and socio-economic implications in coastal engineering are gaining attention. The need for transparent and accountable AI systems that consider the well-being of coastal communities is paramount, as highlighted in the work of (Cabral and Aliño 2011, Nieves, Radin et al. 2021), which emphasizes the importance of incorporating social dimensions into AI-driven coastal management solutions (Adeshina and Aina 2023, Kulkov, Kulkova et al. 2023, Bibri, Krogstie et al. 2024).

3. Roles of AI in Coastal Engineering

Artificial Intelligence (AI) in coastal engineering plays a pivotal role in various aspects related to coastal and marine environments:

1. Biodiversity:

Monitoring and Conservation: AI models analyze data from sensors, satellites, and underwater cameras to track biodiversity. They identify species, assess population dynamics, and detect changes in ecosystems (Lahoz-Monfort and Magrath 2021, Ditria, Buelow et al. 2022).

Habitat Mapping: AI helps map critical habitats (e.g., coral reefs, seagrass beds) and assess their health. This information guides conservation efforts (Zhang 2015).

2. Economic Activity:

Port Operations: AI optimizes port logistics, vessel scheduling, and cargo handling. It enhances efficiency and reduces costs (Kumari 2021).

Aquaculture: AI predicts optimal conditions for fish farming, monitors water quality, and automates feeding processes (Lafont, Dupont et al. 2019).

Tourism: AI assists in managing tourist flows, predicting beach erosion, and ensuring sustainable tourism practices (Lukoseviciute and Panagopoulos 2021).

3. Cultural Heritage:

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Preserving Coastal Heritage: AI aids in documenting and preserving historical coastal structures, shipwrecks, and submerged archaeological sites (Khakzad 2015, Bulut and Yüceer 2023).

Underwater Exploration: AI-driven underwater robots explore ancient ruins and artifacts, contributing to cultural heritage research (Landeschi, Caiti, Casalino et al. 2006, Jing 2019).

4. Climate Regulation:

Carbon Sequestration: AI models predict the impact of coastal vegetation (mangroves, seagrass) on carbon sequestration. This informs climate change mitigation strategies (Claes, Hopman et al. 2022).

Storm Surge Prediction: AI analyses weather data to predict storm surges, helping coastal communities prepare (Sahoo and Bhaskaran 2019, Tiggeloven, Couasnon et al. 2021).

5. Food Security:

Fisheries Management: AI models estimate fish stocks, recommend sustainable fishing quotas, and prevent overfishing (Stafford 2019, Perryman, Hansen et al. 2021).

Aquaculture Optimization: AI enhances fish and shellfish production, ensuring a stable seafood supply (Rowan 2023).

6. Recreational Opportunities:

Beach Safety: AI analyses real-time data (waves, currents, pollution) to issue beach advisories and enhance safety (Chen, Zhong et al. 2020, García-Alba, Bárcena et al. 2023).

Surf Forecasting: AI predicts wave conditions, benefiting surfers and water sports enthusiasts (Mach, Ponting et al. 2020).

7. Strategic Importance:

Coastal Defence: AI models assess vulnerability to erosion, storm damage, and sea-level rise. They inform coastal protection strategies (Bonaldo, Antonioli et al. 2019).

Maritime Security: AI aids in detecting illegal fishing, smuggling, and maritime threats. AI in coastal engineering contributes significantly to sustainable management by integrating data-driven decision-making, conservation efforts, and risk assessment across various dimensions of coastal and marine environments (Octavian and Jatmiko 2020, Pekkanen, Aoki et al. 2022, Amuthakkannan, Vijayalakshmi et al. 2023).

4. Machine Learning (ML) Algorithms

Machine Learning (ML) algorithms play a crucial role in advancing sustainable management of marine and coastal environments in the following ways:

1. **Species Identification and Monitoring**: ML models can analyse underwater imagery, such as photos and videos, to automatically identify marine species. This aids in biodiversity assessment and tracking population changes over time (Danovaro, Carugati et al. 2016).
2. **Oceanographic Data Analysis**: ML algorithms process large volumes of oceanographic data, including temperature, salinity, and currents. These insights help predict ocean behaviour, such as upwelling events or harmful algal blooms (Sadaiappan, Balakrishnan et al. 2023).
3. **Predictive Modeling for Ecosystem Health**: ML models predict the impact of climate change, pollution, and human activities on marine ecosystems. This informs management decisions and conservation efforts (Ditria, Buelow et al. 2022).
4. **Marine Spatial Planning**: ML assists in optimizing marine resource allocation by analysing spatial data. It helps identify suitable locations for aquaculture, marine protected areas, and offshore energy installations (Ditria, Buelow et al. 2022).
5. **Ocean Noise Monitoring**: ML algorithms process acoustic data to detect and classify underwater noise sources (e.g., ships, seismic surveys). This aids in minimizing disturbances to marine life (Parsons, Lin et al. 2022).

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6. **Early Detection of Harmful Events**: ML models can predict harmful events like oil spills, algal blooms, or coral bleaching. Timely detection allows for rapid response and mitigation (Zohdi and Abbaspour 2019).
7. **Fisheries Management**: ML assists in estimating fish stock abundance, predicting fishing yields, and optimizing fishing practices. This promotes sustainable fisheries (Precioso Garcelán 2023).
8. **Coastal Hazard Assessment**: ML analyses satellite imagery and sensor data to assess coastal erosion, storm surge risks, and sea-level rise impacts. This informs adaptation strategies (Acosta-Morel, McNulty et al. 2021).

Integrating AI into coastal engineering enhances the precision of project outcomes and significantly reduces the time and resources required for data analysis and modeling. As a result, engineers can focus on innovation and design, pushing the boundaries of what's possible in coastal management and protection (Kamphuis 2020).

5. Current Applications of AI in Coastal Engineering

The applications of AI in coastal engineering are as varied as they are transformative, marking a new era of innovation and sustainability in the field. Find below how AI is currently being applied to tackle coastal challenges:

1. **Machine Learning Models in Coastal Phenomena Prediction:** Machine learning (ML), a subset of AI, has been extensively applied to predict various coastal phenomena. ML mo**dels in coastal phenomena prediction** is the application of different ML models, such as Artificial Neural Networks (ANNs), Decision Trees (DTs), and Random Forests (RFs), in predicting wave heights, sediment transport, and coastal erosion patterns (Tarekegn, Ricceri et al. 2020, Pourzangbar, Jalali et al. 2023, Pourzangbar, Jalali et al. 2023). Numerous studies have explored using ML algorithms to promote the sustainable management of marine and coastal environments (Mahrad, Newton et al. 2020, Glaviano, Esposito et al. 2022).
2. **AI-Driven Data Collection, Analysis, and Environmental Monitoring**: AI technologies have significantly improved data collection and analysis, leading to more accurate environmental monitoring (Sun and Scanlon 2019, Himeur, Rimal et al. 2022). ML methods aid in collecting and analysing data related to coastal phenomena (Van de Plassche 2013). These algorithms handle large datasets efficiently, enabling a better understanding of coastal processes (Alloghani 2023, Mandal and Ghosh 2024).
3. **Real-Time Monitoring and Adaptive Management**: The real-time capabilities of AI have enabled more responsive and adaptive management strategies for coastal areas (Nichols, Wright et al. 2019, Ditria, Buelow et al. 2022, Glaviano, Esposito et al. 2022). AI has been used for real-time monitoring of coastal erosion and accretion patterns, providing valuable insights for coastal zone management.
4. **Autonomous Systems and Infrastructure Inspection**: AI has facilitated the development of autonomous systems for the maintenance and inspection of coastal infrastructure. AI-powered image recognition capabilities have been employed in drones to monitor the condition of coastal defences (Nieves, Radin et al. 2021).
5. **Enhancing Coastal Resilience Against Extreme Weather Events**: AI-driven simulation models have been instrumental in predicting the impact of storms and sea-level rise on coastal infrastructure. Coastal resilience has employed ML techniques to simulate storm surge scenarios and assess the vulnerability of coastal regions (Pourzangbar, Jalali et al. 2023).
6. **Ethical Considerations and Socio-Economic Implications**: AI applications' ethical considerations and socio-economic implications in coastal engineering are critical. This create the need for transparent and accountable AI systems that consider the well-being of coastal communities (Sineviciene, Hens et al. 2021).
7. **Enhanced Emergency Response and Recovery:** AI systems can play a pivotal role in emergency response and recovery efforts following coastal disasters (Abid, Sulaiman et al. 2021). By

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analysing data from multiple sources, including social media, emergency services can use AI to prioritize response efforts, allocate resources more efficiently, and better understand the impact of disasters on coastal communities (Sun, Bocchini et al. 2020).

6. Enhancing Coastal Engineering Projects with AI

Enhancing Coastal Engineering Projects with AI involves the integration of advanced artificial intelligence (AI) technologies to improve the design, analysis, and management of coastal infrastructure (Kumar and Leonardi 2023). AI can provide significant benefits in various aspects of coastal engineering, from predictive modeling and data analysis to real-time monitoring and decision support systems. The integration of Artificial Intelligence (AI) into coastal engineering not only promises enhanced predictive and analytical capabilities but also introduces innovative solutions to longstanding challenges (Glaviano, Esposito et al. 2022). Here's an overview of how AI can enhance coastal engineering projects:

- **Predictive Analytics and Modeling:** AI algorithms, especially machine learning models, can analyse vast datasets to predict coastal phenomena such as erosion patterns, wave dynamics, and the impact of climate change on coastal structures. These predictions help engineers design more resilient coastal defense systems (Morris, Konlechner et al. 2018, Ojewumi, Kayode et al. 2019).
- **Data Analysis and Environmental Monitoring**: AI can process and analyse data from satellite imagery, sensors, and other sources to monitor environmental conditions in coastal areas. This enables a better understanding of coastal dynamics and supports informed decision-making for sustainable management (Himeur, Rimal et al. 2022).
- **Real-Time Monitoring and Adaptive Management:** The real-time data processing capabilities of AI allow for the implementation of adaptive management strategies. AI systems can provide immediate insights into coastal changes, enabling quick responses to emerging issues like erosion or pollution (Casazza, Lorenz et al. 2023).
- **Infrastructure Inspection and Maintenance:** AI-powered autonomous systems, such as drones equipped with image recognition technology, can efficiently monitor the condition of coastal defense and infrastructure, ensuring their integrity and performance (Kapoor, Kumar et al. 2024).
- **Decision Support Systems:** AI can assist in the evaluation of different coastal protection options, optimizing the placement and design of structures like seawalls, breakwaters, and groins to provide maximum protection with minimal environmental impact (Ojewumi, Emetere et al. 2017, Ojewumi and Roosevelt 2022, Kumar and Leonardi 2023).
- **Challenges and Ethical Considerations:** While AI offers numerous advantages, it also presents challenges such as ensuring the accuracy of models, dealing with complex environmental data, and addressing ethical considerations related to the impact of AI-driven decisions on coastal communities (Nishant, Kennedy et al. 2020).

By leveraging AI, coastal engineering projects can achieve enhanced efficiency, accuracy, and sustainability, leading to better protection and management of valuable coastal resources. As AI technology continues to evolve, its applications in coastal engineering are expected to expand, offering new solutions to the challenges faced by coastal areas worldwide.

Table 1 presents a compilation of previously published manuscripts focusing on AI Applications in Coastal Engineering. It outlines the perspectives, identifies gaps, and summarizes each author's work.

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Table 1. Previous work done.

S/N	Article	Perspectives	Gaps	Summary	Ref.
1.	Machine learning application in modeling marine and coastal phenomena: a critical review	The article extensively reviews over 200 journal papers focusing on using Machine Learning (ML) algorithms for sustainable management of marine and coastal environments.	Despite the potential advantages, dynamic and integrated ML models remain underutilized in marine projects	The research covers various facets of ML algorithms, including data preprocessing, modeling algorithms for distinct phenomena, model evaluation, and the use of dynamic and integrated models. It invites future investigations to exploit ML's untapped marine and coastal sustainability potential.	(Pourzangbar, Jalali et al. 2023)
2.	Exploring deep learning capabilities for surge predictions in coastal areas	Based on regional weather circumstances, the study investigates the potential of artificial intelligence, especially four deep-learning techniques, to forecast the surge component of sea-level variability.	The improvement in performance remains insufficient to fully capture observed dynamics in some regions, such as the tropics	The article suggests that the Neural Network (NN) models could be adapted for use in forecasting extreme sea levels or emergency response	(Tiggeloven, Couasnon et al. 2021)
3.	Recent Developments in Artificial Intelligence in Oceanography	This paper reviews the applications of AI tools in identifying, forecasting, and parameterizing ocean phenomena.	There is a need for causality-adherent physics-informed neural networks and Fourier neural networks in oceanography	The review stimulates future research toward the usage of these advanced AI methodologies in oceanography	(Dong, Xu et al. 2022)
4.	Conceptual prediction of harbor sedimentation quantities using AI approaches to support integrated coastal structures management	The article discusses how AI can be harnessed to revolutionize coastal engineering, making the complex interplay between man-made structures and natural forces not just manageable but also predictably beneficial	The complexity of coastal environments creates obstacles for emergency responders and coastal management	AI offers innovative approaches to managing and protecting coastlines with its predictive analytics and design optimization	(Elnabwy, Elbeltagi et al. 2022)

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5.	**Predicting Sea Level Rise Using Artificial Intelligence: A Review**	The paper discusses the development of AI and forecasting approaches for sea level rise.	The complexity of processes affecting predictions at various periods poses significant challenges	The review assesses studies conducted between 2010 and 2022, focusing on prediction methodologies, modeling accuracy, and parameter assessment for anticipating sea level rise.	(Bahari, Ahmed et al. 2023)
6.	Review on Applications of Machine Learning in Coastal and Ocean Engineering	Discusses ML applications for predicting wave formation, tidal changes, and hydraulic properties around structures	The article does not explicitly mention gaps. However, it's essential to recognize that the field of coastal and ocean engineering is continually evolving, and there may be unexplored areas where ML techniques could be further applied	The article reviews the use of ML in coastal and ocean engineering, emphasizing its potential for improving predictions and understanding complex marine processes.	(Kim and Lee 2022)
7.	Application of artificial intelligence in geotechnical engineering: A comprehensive review	Focuses on AI methods in geotechnical engineering	While the article provides a comprehensive overview of AI applications in geotechnical engineering, there is room for more research on specific AI techniques' performance and robustness in geotechnical modeling and analysis	The article provides a comprehensive review of AI applications in geotechnical engineering, covering various techniques and their impact on geotechnical analysis and design	(Khatti and Grover 2022)
8.		The review highlights the growing interest in AI and big data applications in the maritime sector	The article does not explicitly mention gaps.	This bibliometric review explores the applications of big data and artificial intelligence (AI) in the maritime industry. It	(Munim, Dushenko et al. 2020)

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	covers predictive maintenance, vessel performance optimization, safety, and environmental impact. The study emphasizes the growing interest in AI and big data within the maritime sector

7. Challenges and Limitations of AI in Coastal Engineering

Integrating Artificial Intelligence (AI) into coastal engineering can revolutionize the field, offering advanced tools for predictive modeling, real-time monitoring, and decision-making. However, the application of AI in this domain is not without its challenges and limitations. Here are some of the key issues that need to be addressed:

- **Data Availability and Quality**: For AI models to train efficiently, vast quantities of high-quality data are needed. Because coastal settings are dynamic and data collecting is expensive, obtaining such datasets for coastal engineering might be difficult(Glenn, Dickey et al. 2000, Mills, Buckley et al. 2005).
- **Model Accuracy and Reliability**: While AI can provide predictions, the accuracy of these models is crucial, especially when they inform decisions that affect public safety and infrastructure (Abduljabbar, Dia et al. 2019, Sun, Bocchini et al. 2020). Ensuring the reliability of AI predictions in the face of complex, changing coastal processes is a significant challenge (Tiggeloven, Couasnon et al. 2021).
- **Interpretability and Transparency**: AI models, particularly deep learning models, are often seen as “black boxes” due to their complex nature. This lack of transparency can be a barrier to their acceptance and use in critical engineering decisions (Carabantes 2020, Hassija, Chamola et al. 2024).
- **Ethical Considerations**: Using AI in coastal engineering raises ethical questions, particularly regarding the impact of decisions on local communities and ecosystems. Ensuring that AI applications are developed and used ethically is a key concern (Galaz, Centeno et al. 2021).
- **Integration with Existing Systems**: Incorporating AI into existing coastal management frameworks and systems can be difficult. Compatibility with legacy systems and the need for specialized knowledge to operate and maintain AI tools can be limiting factors (Abioye, Oyedele et al. 2021, Chen, Li et al. 2021).
- **Overreliance on Technology**: There is a risk of becoming overly dependent on AI technologies, which could lead to a reduction in human expertise and oversight in coastal engineering practices (Galaz, Centeno et al. 2021).
- **Environmental and Social Impact**: AI-driven decisions in coastal engineering must consider the potential environmental and social impacts. Balancing technological capabilities with sustainable and socially responsible practices is essential (Demianchuk, Bezpartochnyi et al. 2021).

Large amounts of high-quality data are required for AI models to train well. Obtaining such datasets for coastal engineering may be challenging due to the dynamic nature of coastal locations and the high cost of data collection (Nishant, Kennedy et al. 2020). Collaborative efforts between researchers, practitioners, and policymakers are necessary to develop AI applications that are not only technologically advanced but also socially and environmentally responsible (Dwivedi, Hughes et al. 2021, Rakova, Yang et al. 2021). As the field progresses, continuous evaluation and adaptation

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of AI tools will be crucial to overcome these limitations and fully harness the benefits of AI in coastal engineering (Salehi and Burgueño 2018).

Despite these challenges, the potential benefits of integrating AI into coastal engineering are undeniable. Overcoming these hurdles requires concerted efforts from engineers, researchers, policymakers, and technology developers. Continuous innovation, coupled with responsible practices, will pave the way for the successful adoption of AI in coastal engineering, leading to more resilient and sustainable coastal communities.

8. The Future of AI in Coastal Engineering

The future of AI in coastal engineering looks promising, with advancements poised to further revolutionize how we manage and protect our coastlines. As we navigate the challenges and harness the potential of AI, several key trends and innovations are likely to shape the future of this field (Kamphuis 2020).

Integrating AI into coastal engineering is not just about technological advancement; it's about reimagining our relationship with the coastal environment. By leveraging AI, we can create a future where coastal communities are safer, ecosystems are protected, and the natural beauty of our coastlines is preserved for generations to come (Shuster 2019, Berglund, Monroe et al. 2020).

The future of AI in coastal engineering is poised to be transformative, with advancements in technology expected to further enhance the capabilities and applications of AI in this field (Galaz, Centeno et al. 2021, Kapoor, Kumar et al. 2024). Here are some key areas where AI is likely to shape the future of coastal engineering:

Advanced Predictive Modeling: AI will continue to improve in its ability to predict complex coastal phenomena with greater accuracy. This includes more sophisticated models for forecasting erosion, sea-level rise, and the impact of extreme weather events on coastal infrastructure (Brown, Hanson et al. 2014, Nourani, Baghanam et al. 2014, Goldstein, Coco et al. 2019).

Integration with IoT: The Internet of Things (IoT) will increasingly be integrated with AI to collect and analyse real-time data. This will enable more dynamic and responsive coastal management strategies, allowing for immediate action in response to environmental changes (Brown, Hanson et al. 2014, Nazarnia, Nazarnia et al. 2020).

Autonomous Systems: The use of autonomous drones and underwater vehicles equipped with AI will become more prevalent for monitoring and maintaining coastal infrastructure. These systems will be able to operate in challenging environments, providing critical data and performing tasks without human intervention (Brown, Hanson et al. 2014, Ubina and Cheng 2022).

Enhanced Decision-Making: AI will offer more powerful decision support systems, utilizing vast amounts of data to inform the design and implementation of coastal projects. This will lead to more efficient and effective solutions for coastal protection and management (Westmacott 2001, Brown, Hanson et al. 2014).

Ethical AI Development: As AI becomes more integrated into coastal engineering, there will be a greater focus on developing ethical AI systems. These systems will need to consider the potential impacts on local communities and ecosystems, ensuring that AI-driven decisions are made responsibly (Brown, Hanson et al. 2014, Walsh, Levy et al. 2019).

Interdisciplinary Collaboration: The future of AI in coastal engineering will likely involve increased collaboration between engineers, computer scientists, environmental scientists, and policymakers. This interdisciplinary approach will be essential for addressing the complex challenges faced by coastal regions (Brown, Hanson et al. 2014, Nichols, Wright et al. 2019).

Education and Training: With the growing importance of AI in coastal engineering, there will be a need for specialized education and training programs. These programs will prepare the next generation of engineers with the skills necessary to leverage AI in their work (Brown, Hanson et al. 2014, Baidoo-Anu and Ansah 2023, Türkistanli 2024).

In summary, AI is set to play a crucial role in the future of coastal engineering, offering innovative solutions to some of the most pressing challenges faced by coastal areas. As technology continues to evolve, it will be important for professionals in the field to stay informed and adapt to these changes to ensure the sustainability and resilience of coastal environments.

9. Conclusion

Integrating AI technologies offers immense potential for advancing research and innovation in coastal engineering, enabling more accurate predictions, sustainable management practices, and informed decision-making processes. By harnessing the capabilities of AI tools, researchers can enhance the effectiveness and efficiency of literature reviews, gain deeper insights into complex coastal systems, and contribute to developing resilient and adaptive coastal infrastructure solutions. Further interdisciplinary collaboration and research are essential to harness the full potential of AI in addressing emerging challenges and opportunities in coastal engineering. Highlighting the increasing availability of data pertaining to coastal systems, the manuscript advocates for robust data analysis and augmentation techniques to inform evidence-based decision-making processes. It elucidates the diverse applications of ML across various domains within coastal engineering, including wave prediction, pollutant transport modeling, image processing, structural design optimization, and identification of suitable areas for aquaculture and renewable energy initiatives. However, despite the promising potential of ML, the manuscript identifies a gap in the utilization of dynamic and integrated ML models in marine projects, suggesting an area ripe for further exploration and research. It concludes with a call to action for future studies to delve deeper into the untapped possibilities of ML in enhancing marine and coastal sustainability efforts.

In essence, this manuscript serves as a valuable resource for researchers, practitioners, and policymakers seeking to harness the power of AI, particularly ML, to address the complex challenges facing coastal regions and pave the way toward a more resilient and environmentally sustainable future.

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References

Abduljabbar, R., et al. (2019). "Applications of artificial intelligence in transport: An overview." Sustainability **11**(1): 189.

Abid, S. K., et al. (2021). "Toward an integrated disaster management approach: how artificial intelligence can boost disaster management." Sustainability **13**(22): 12560.

Abioye, S. O., et al. (2021). "Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges." Journal of Building Engineering **44**: 103299.

Abujaber, A. A., et al. (2022). "Enabling the adoption of machine learning in clinical decision support: A total interpretive structural modeling approach." Informatics in Medicine Unlocked **33**: 101090.

Acosta-Morel, M., et al. (2021). "Shoreline solutions: guiding efficient data selection for coastal risk modeling and the design of adaptation interventions." Water **13**(6): 875.

Adeshina, S. A. and O. Aina (2023). The Role of AI in SDG: An African Perspective. The Ethics of Artificial Intelligence for the Sustainable Development Goals, Springer**:** 133-143.

Ahmed, A. N., et al. (2019). "Machine learning methods for better water quality prediction." Journal of Hydrology **578**: 124084.

Al Kajbaf, A. and M. Bensi (2020). "Application of surrogate models in estimation of storm surge: A comparative assessment." Applied Soft Computing **91**: 106184.

Alloghani, M. A. (2023). "Using AI to Monitor Marine Environmental Pollution: Systematic Review." Artificial Intelligence and Sustainability: 87-97.

Amuthakkannan, R., et al. (2023). "A Review to do Fishermen Boat Automation with Artificial Intelligence for Sustainable Fishing Experience Ensuring Safety, Security, Navigation and Sharing Information for Omani Fishermen." Journal of Marine Science and Engineering **11**(3): 630.

Bachmann, N., et al. (2022). "The contribution of data-driven technologies in achieving the sustainable development goals." Sustainability **14**(5): 2497.

Bahari, N. A. A. B. S., et al. (2023). "Predicting sea level rise using artificial intelligence: a review." Archives of Computational Methods in Engineering **30**(7): 4045-4062.

Baidoo-Anu, D. and L. O. Ansah (2023). "Education in the era of generative artificial intelligence (AI): Understanding the potential benefits of ChatGPT in promoting teaching and learning." Journal of AI **7**(1): 52-62.

Barzehkar, M., et al. (2021). "Decision support tools, systems and indices for sustainable coastal planning and management: A review." Ocean & Coastal Management **212**: 105813.

Berglund, E. Z., et al. (2020). "Smart infrastructure: a vision for the role of the civil engineering profession in smart cities." Journal of Infrastructure Systems **26**(2): 03120001.

Beuzen, T., et al. (2019). "Ensemble models from machine learning: an example of wave runup and coastal dune erosion." Natural Hazards and Earth System Sciences **19**(10): 2295-2309.

Bibri, S. E., et al. (2024). "Smarter eco-cities and their leading-edge artificial intelligence of things solutions for environmental sustainability: A comprehensive systematic review." Environmental Science and Ecotechnology **19**: 100330.

Bonaldo, D., et al. (2019). "Integrating multidisciplinary instruments for assessing coastal vulnerability to erosion and sea level rise: Lessons and challenges from the Adriatic Sea, Italy." Journal of Coastal Conservation **23**: 19-37.

Brown, S., et al. (2014). "Implications of sea-level rise and extreme events around Europe: a review of coastal energy infrastructure." Climatic Change **122**(1): 81-95.

Bulut, N. and H. Yüceer (2023). "A literature review on the management of underwater cultural heritage." Ocean & Coastal Management **245**: 106837.

Cabral, R. B. and P. M. Aliño (2011). "Transition from common to private coasts: Consequences of privatization of the coastal commons." Ocean & Coastal Management **54**(1): 66-74.

Caiti, A., et al. (2006). "Innovative technologies in underwater archaeology: field experience, open problems, and research lines." Chemistry and Ecology **22**(sup1): S383-S396.

Carabantes, M. (2020). "Black-box artificial intelligence: an epistemological and critical analysis." AI & society **35**(2): 309-317.

Casazza, M. L., et al. (2023). "AIMS for wildlife: Developing an automated interactive monitoring system to integrate real-time movement and environmental data for true adaptive management." Journal of environmental management **345**: 118636.

Chen, G., et al. (2022). "Deep blue AI: A new bridge from data to knowledge for the ocean science." Deep Sea Research Part I: Oceanographic Research Papers **190**: 103886.

Chen, H., et al. (2021). "Explore success factors that impact artificial intelligence adoption on telecom industry in China." Journal of Management Analytics **8**(1): 36-68.

Chen, J.-G., et al. (2020). "Risk management of coastal water safety for recreational activities: The case of Taoyuan coast." Applied geography **117**: 102173.

Claes, J., et al. (2022). "Blue carbon: The potential of coastal and oceanic climate action." McKinsey & Company: Hong Kong, China.

Damodaran, D., et al. (2024). Futuristic Disaster Mitigation: The Role of GPUs and AI Accelerators. Predicting Natural Disasters With AI and Machine Learning, IGI Global**:** 173-201.

Danovaro, R., et al. (2016). "Implementing and innovating marine monitoring approaches for assessing marine environmental status." Frontiers in Marine Science **3**: 213.

Demianchuk, M., et al. (2021). "The model of achieving a balanced balance between economic efficiency and ecological-social responsibility of digitalized enterprise." Journal of Optimization in Industrial Engineering **14**(Special Issue): 45-52.

Ditria, E. M., et al. (2022). "Artificial intelligence and automated monitoring for assisting conservation of marine ecosystems: A perspective." Frontiers in Marine Science **9**: 918104.

Dong, C., et al. (2022). "Recent developments in artificial intelligence in oceanography." Ocean-Land-Atmosphere Research.

Dwivedi, Y. K., et al. (2021). "Artificial Intelligence (AI): Multidisciplinary perspectives on emerging challenges, opportunities, and agenda for research, practice and policy." International Journal of Information Management **57**: 101994.

Eapen, T. (2023). "Augmenting Creativity using Generative AI: The Method of Trisociation." Available at SSRN 4603145.

Elnabwy, M. T., et al. (2022). "Conceptual prediction of harbor sedimentation quantities using AI approaches to support integrated coastal structures management." Journal of Ocean Engineering and Science.

Ewuzie, U., et al. (2022). "Application of deep learning and machine learning methods in water quality modeling and prediction: a review." Current trends and advances in computer-aided intelligent environmental data engineering: 185-218.

Fogarin, S., et al. (2023). "Combining remote sensing analysis with machine learning to evaluate short-term coastal evolution trend in the shoreline of Venice." Science of The Total Environment **859**: 160293.

Galaz, V., et al. (2021). "Artificial intelligence, systemic risks, and sustainability." Technology in Society **67**: 101741.

Gambín, Á. F., et al. (2021). "Sustainable marine ecosystems: deep learning for water quality assessment and forecasting." IEEE access **9**: 121344-121365.

García-Alba, J., et al. (2023). "SOSeas Web App: An assessment web-based decision support tool to predict dynamic risk of drowning on beaches using deep neural networks." Journal of operational oceanography **16**(2): 155-174.

Ghani, S., et al. (2023). "Machine learning approaches for real-time prediction of compressive strength in self-compacting concrete." Asian Journal of Civil Engineering: 1-18.

Gill, S. S., et al. (2022). "AI for next generation computing: Emerging trends and future directions." Internet of Things **19**: 100514.

Glaviano, F., et al. (2022). "Management and sustainable exploitation of marine environments through smart monitoring and automation." Journal of Marine Science and Engineering **10**(2): 297.

Glenn, S. M., et al. (2000). "Long-term real-time coastal ocean observation networks." Oceanography **13**(1): 24-34.

Goldstein, E. B., et al. (2019). "A review of machine learning applications to coastal sediment transport and morphodynamics." Earth-science reviews **194**: 97-108.

Grove, K., et al. (2023). "Becoming non-commensurable: synthesis, design, and the politics of urban experimentation in post-Superstorm Sandy New York." Sustainability: Science, Practice and Policy **19**(1): 2225339.

Guo, K., et al. (2021). "Artificial intelligence and machine learning in design of mechanical materials." Materials Horizons **8**(4): 1153-1172.

Hadipour, V., et al. (2020). "Coastal flooding risk assessment using a GIS-based spatial multi-criteria decision analysis approach." Water **12**(9): 2379.

Hassija, V., et al. (2024). "Interpreting black-box models: a review on explainable artificial intelligence." Cognitive Computation **16**(1): 45-74.

Himeur, Y., et al. (2022). "Using artificial intelligence and data fusion for environmental monitoring: A review and future perspectives." Information Fusion **86**: 44-75.

Jing, Y. (2019). "Protection of underwater cultural heritage in China: new developments." International Journal of Cultural Policy **25**(6): 756-764.

Kamphuis, J. W. (2020). Introduction to coastal engineering and management, World Scientific.

Kamyab, H., et al. (2023). "The latest innovative avenues for the utilization of artificial Intelligence and big data analytics in water resource management." Results in Engineering: 101566.

Kapoor, N. R., et al. (2024). Artificial intelligence in civil engineering: An immersive view. Artificial Intelligence Applications for Sustainable Construction, Elsevier: 1-74.

Kasula, B. Y. (2023). "Harnessing Machine Learning for Personalized Patient Care." Transactions on Latest Trends in Artificial Intelligence **4**(4).

Khakzad, S. (2015). "Integrated approach in management of coastal cultural heritage." Unpublished PhD thesis, University of Leuven.

Khatti, J. and K. S. Grover (2022). Application of Artificial Intelligence in Geotechnical Engineering: A Review. Techno-Societal 2016, International Conference on Advanced Technologies for Societal Applications, Springer.

Kim, T. and W.-D. Lee (2022). "Review on applications of machine learning in coastal and ocean engineering." Journal of Ocean Engineering and Technology **36**(3): 194-210.

Koks, E. E., et al. (2023). "The impacts of coastal flooding and sea level rise on critical infrastructure: a novel storyline approach." Sustainable and Resilient Infrastructure **8**(sup1): 237-261.

Konar, A. (2018). Artificial intelligence and soft computing: behavioral and cognitive modeling of the human brain, CRC press.

Korteling, J., et al. (2021). "Human-versus artificial intelligence." Frontiers in artificial intelligence **4**: 622364.

Kulkov, I., et al. (2023). "Artificial intelligence-driven sustainable development: Examining organizational, technical, and processing approaches to achieving global goals." Sustainable Development.

Kumar, P. and N. Leonardi (2023). "A novel framework for the evaluation of coastal protection schemes through integration of numerical modelling and artificial intelligence into the Sand Engine App." Scientific reports **13**(1): 8610.

Kumari, S. (2021). "Interplay of AI-Driven Maritime Logistics: An In-Depth Research into Port Management, Advanced Operations Automation, and CRM Integration for Optimized Performance and Efficiency." ESP Journal of Engineering and Technology Advancements **1**(1): 1-5.

Lafont, M., et al. (2019). Back to the future: IoT to improve aquaculture: Real-time monitoring and algorithmic prediction of water parameters for aquaculture needs. 2019 Global IoT Summit (GIoTS), IEEE.

Lahoz-Monfort, J. J. and M. J. Magrath (2021). "A comprehensive overview of technologies for species and habitat monitoring and conservation." BioScience **71**(10): 1038-1062.

Landeschi, G. "AI-based approaches in Cultural Heritage." KI-Kritik/AI Critique Volume 6: 197.

Lawyer, C., et al. (2023). "A Review of Climate Adaptation Impacts and Strategies in Coastal Communities: From Agent-Based Modeling towards a System of Systems Approach." Water **15**(14): 2635.

Lukoseviciute, G. and T. Panagopoulos (2021). "Management priorities from tourists' perspectives and beach quality assessment as tools to support sustainable coastal tourism." Ocean & Coastal Management **208**: 105646.

Mach, L., et al. (2020). "Riding waves of intra-seasonal demand in surf tourism: Analysing the nexus of seasonality and 21st century surf forecasting technology." Annals of Leisure Research **23**(2): 184-202.

Mahrad, B. E., et al. (2020). "Contribution of remote sensing technologies to a holistic coastal and marine environmental management framework: a review." Remote Sensing **12**(14): 2313.

Mandal, A. and A. R. Ghosh (2024). "AI-driven surveillance of the health and disease status of ocean organisms: a review." Aquaculture International **32**(1): 887-898.

Manzoor, B., et al. (2021). "Influence of artificial intelligence in civil engineering toward sustainable development—a systematic literature review." Applied System Innovation **4**(3): 52.

Marinakis, V., et al. (2020). "From big data to smart energy services: An application for intelligent energy management." Future Generation Computer Systems **110**: 572-586.

Marr, B. (2019). Artificial intelligence in practice: how 50 successful companies used AI and machine learning to solve problems, John Wiley & Sons.

Mastrocicco, M. and N. Colombani (2021). "The issue of groundwater salinization in coastal areas of the mediterranean region: A review." Water **13**(1): 90.

Mills, J., et al. (2005). "A geomatics data integration technique for coastal change monitoring." Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group **30**(6): 651-664.

Morris, R. L., et al. (2018). "From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence." Global change biology **24**(5): 1827-1842.

Munim, Z. H., et al. (2020). "Big data and artificial intelligence in the maritime industry: a bibliometric review and future research directions." Maritime Policy & Management **47**(5): 577-597.

Nazarnia, H., et al. (2020). "A systematic review of civil and environmental infrastructures for coastal adaptation to sea level rise." Civil engineering journal **6**(7): 1375-1399.

Nebbioso, A. and A. Piccolo (2013). "Molecular characterization of dissolved organic matter (DOM): a critical review." Analytical and bioanalytical chemistry **405**: 109-124.

Nichols, C. R., et al. (2019). "Collaborative science to enhance coastal resilience and adaptation." Frontiers in Marine Science **6**: 404.

Nieves, V., et al. (2021). "Predicting regional coastal sea level changes with machine learning." Scientific reports **11**(1): 7650.

Nishant, R., et al. (2020). "Artificial intelligence for sustainability: Challenges, opportunities, and a research agenda." International Journal of Information Management **53**: 102104.

Nourani, V., et al. (2014). "Applications of hybrid wavelet–artificial intelligence models in hydrology: a review." Journal of Hydrology **514**: 358-377.

Octavian, A. and W. Jatmiko (2020). Designing intelligent coastal surveillance based on big maritime data. 2020 International Workshop on Big Data and Information Security (IWBIS), IEEE.

Ojewumi, M., et al. (2019). "Statistical optimization and sensitivity analysis of rheological models using cassava starch." International Journal of Civil Engineering and Technology (IJCIET) **10**(1): 623-639.

Ojewumi, M. and E. Roosevelt (2022). "Optimization of Bleaching Crude Palm Oil with Activated Snail Shell using Central Composite Design [CCD]."

Ojewumi, M. E., et al. (2017). "In situ bioremediation of crude petroleum oil polluted soil using mathematical experimentation." International Journal of Chemical Engineering **2017**(1): 5184760.

Okem, E. S., et al. (2024). "Civil engineering and disaster resilience: A review of innovations in building safe and sustainable communities." International Journal of Science and Research Archive **11**(1): 639-650.

Palaniswami, M., et al. (2017). "Real-time monitoring of the great barrier reef using internet of things with big data analytics." ITU J. ICT Discov **1**(1).

Parsons, M. J., et al. (2022). "Sounding the call for a global library of underwater biological sounds." Frontiers in Ecology and Evolution **10**: 39.

Pekkanen, S. M., et al. (2022). "Small Satellites, Big Data: Uncovering the Invisible in Maritime Security." International Security **47**(2): 177-216.

Perryman, H. A., et al. (2021). "A review of applications evaluating fisheries management scenarios through marine ecosystem models." Reviews in Fisheries Science & Aquaculture **29**(4): 800-835.

Pourzangbar, A., et al. (2023). "Machine learning application in modelling marine and coastal phenomena: a critical review." Frontiers in Environmental Engineering **2**: 1235557.

Pourzangbar, A., et al. (2023). "Machine learning contribution for a sustainable management of the marine and coastal environments: A critical review." Available at SSRN 4463562.

Precioso Garcelán, D. (2023). Applications of machine learning and data science to the blue economy sustainable fishing and weather routing.

Rakova, B., et al. (2021). "Where responsible AI meets reality: Practitioner perspectives on enablers for shifting organizational practices." Proceedings of the ACM on Human-Computer Interaction **5**(CSCW1): 1-23.

Rane, N., et al. (2024). "Transforming the Civil Engineering Sector with Generative Artificial Intelligence, such as ChatGPT or Bard." Available at SSRN 4681718.

Ro, S. H., et al. (2024). "A Machine learning approach for Post-Disaster data curation." Advanced Engineering Informatics **60**: 102427.

Rowan, N. J. (2023). "The role of digital technologies in supporting and improving fishery and aquaculture across the supply chain–Quo Vadis?" Aquaculture and Fisheries **8**(4): 365-374.

Sadaiappan, B., et al. (2023). "Applications of Machine Learning in Chemical and Biological Oceanography." ACS omega **8**(18): 15831-15853.

Sahoo, B. and P. K. Bhaskaran (2019). "Prediction of storm surge and inundation using climatological datasets for the Indian coast using soft computing techniques." Soft Computing **23**(23): 12363-12383.

Salehi, H. and R. Burgueño (2018). "Emerging artificial intelligence methods in structural engineering." Engineering structures **171**: 170-189.

Santorsola, M. and F. Lescai (2023). "The promise of explainable deep learning for omics data analysis: Adding new discovery tools to AI." New Biotechnology.

Saravi, S., et al. (2019). "Use of artificial intelligence to improve resilience and preparedness against adverse flood events." Water **11**(5): 973.

Sarker, I. H. (2022). "AI-based modeling: techniques, applications and research issues towards automation, intelligent and smart systems." SN Computer Science **3**(2): 158.

Schwab, K. and N. Davis (2018). Shaping the future of the fourth industrial revolution, Crown Currency.

Shabbir, J. and T. Anwer (2018). "Artificial intelligence and its role in near future." arXiv preprint arXiv:1804.01396.

Shafiq, S. I. (2023). "Artificial intelligence and big data science for oceanographic research in Bangladesh: Preparing for the future." J. Data Acquis. Process **38**: 418.

Sharma, A., et al. (2024). "Advances in AI and machine learning for predictive medicine." Journal of Human Genetics: 1-11.

Shuster, L. A. (2019). "What Lies Ahead?" Civil Engineering Magazine Archive **89**(6): 56-63.

Sineviciene, L., et al. (2021). "Socio-economic and cultural effects of disruptive industrial technologies for sustainable development." International Journal of Global Energy Issues **43**(2-3): 284-305.

Singh, S. and M. K. Goyal (2023). "Enhancing climate resilience in businesses: the role of artificial intelligence." Journal of Cleaner Production **418**: 138228.

Sinha, K. K., et al. (2022). "Neural network-based modeling of water quality in Jodhpur, India." Hydrology **9**(5): 92.

Srivastava, A. and R. Maity (2023). "Assessing the potential of AI–ML in urban climate change adaptation and sustainable development." Sustainability **15**(23): 16461.

Stafford, R. (2019). "Sustainability: A flawed concept for fisheries management?" Elem Sci Anth **7**: 8.

Stansby, P. K. (2013). "Coastal hydrodynamics–present and future." Journal of Hydraulic Research **51**(4): 341-350.

Sun, A. Y. and B. R. Scanlon (2019). "How can Big Data and machine learning benefit environment and water management: a survey of methods, applications, and future directions." Environmental Research Letters **14**(7): 073001.

Sun, W., et al. (2020). "Applications of artificial intelligence for disaster management." Natural Hazards **103**(3): 2631-2689.

Tarekegn, A., et al. (2020). "Predictive modeling for frailty conditions in elderly people: machine learning approaches." JMIR medical informatics **8**(6): e16678.

Thanh, B. N., et al. (2024). "Prediction of coastal erosion susceptible areas of Quang Nam Province, Vietnam using machine learning models." Earth Science Informatics **17**(1): 401-419.

Tiggeloven, T., et al. (2021). "Exploring deep learning capabilities for surge predictions in coastal areas." Scientific reports **11**(1): 17224.

Torens, C., et al. (2022). Guidelines and regulatory framework for machine learning in aviation. AIAA Scitech 2022 Forum.

Tsiakos, C.-A. D. and C. Chalkias (2023). "Use of machine learning and remote sensing techniques for shoreline monitoring: A review of recent literature." Applied Sciences **13**(5): 3268.

Türkistanli, T. T. (2024). "Advanced learning methods in maritime education and training: A bibliometric analysis on the digitalization of education and modern trends." Computer Applications in Engineering Education **32**(1): e22690.

Ubina, N. A. and S.-C. Cheng (2022). "A review of unmanned system technologies with its application to aquaculture farm monitoring and management." Drones **6**(1): 12.

 doi:10.20944/preprints202501.0600.v1

Van de Plassche, O. (2013). Sea-level Research: a Manual for the Collection and Evaluation of Data: a Manual for the Collection and Evaluation of Data, Springer.

Venketeswaran, A., et al. (2022). "Recent advances in machine learning for fiber optic sensor applications." Advanced Intelligent Systems **4**(1): 2100067.

Wai, K. P., et al. (2022). "Applications of deep learning in water quality management: A state-of-the-art review." Journal of Hydrology **613**: 128332.

Walsh, T., et al. (2019). The effective and ethical development of artificial intelligence: an opportunity to improve our wellbeing, Australian Council of Learned Academies.

Wang, J., et al. (2023). "Review of large vision models and visual prompt engineering." Meta-Radiology: 100047.

Waqar, A. (2024). "Intelligent decision support systems in construction engineering: An artificial intelligence and machine learning approaches." Expert Systems with Applications **249**: 123503.

Weber-Lewerenz, B. (2021). "Corporate digital responsibility (CDR) in construction engineering—ethical guidelines for the application of digital transformation and artificial intelligence (AI) in user practice." SN Applied Sciences **3**: 1-25.

Werner, A. D., et al. (2013). "Seawater intrusion processes, investigation and management: Recent advances and future challenges." Advances in water resources **51**: 3-26.

Westmacott, S. (2001). "Developing decision support systems for integrated coastal management in the tropics: is the ICM decision-making environment too complex for the development of a useable and useful DSS?" Journal of environmental management **62**(1): 55-74.

Ye, X., et al. (2023). "Developing human-centered urban digital twins for community infrastructure resilience: A research agenda." Journal of Planning Literature **38**(2): 187-199.

Zhang, C. (2015). "Applying data fusion techniques for benthic habitat mapping and monitoring in a coral reef ecosystem." ISPRS Journal of Photogrammetry and Remote Sensing **104**: 213-223.

Zhang, S., et al. (2022). "Estimating the grade of storm surge disaster loss in coastal areas of China via machine learning algorithms." Ecological Indicators **136**: 108533.

Zohdi, E. and M. Abbaspour (2019). "Harmful algal blooms (red tide): a review of causes, impacts and approaches to monitoring and prediction." International Journal of Environmental Science and Technology **16**(3): 1789-1806.