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System Dynamics Modeling for Effective Strategies in Water Pollution Control: Insights and Applications

S. Hooman Mousavi [1,*], M. R. Kavianpour [1], Jorge Luis García Alcaraz [2] and Omid A. Yamini [1]

[1] Department of Civil Engineering, K. N. Toosi University of Technology, Tehran 19967-15433, Iran; kavianpour@kntu.ac.ir (M.R.K.); o.aminoroaya@mail.kntu.ac.ir (O.A.Y.)
[2] Department of Industrial Engineering and Manufacturing, Institute of Engineering and Technology, Universidad Autónoma de Ciudad Juárez, Ciudad Juárez 32310, Chihuahua, Mexico; jorge.garcia@uacj.mx
* Correspondence: h.mousavi@mail.kntu.ac.ir

Abstract: Water pollution is a significant environmental challenge with implications for both the natural world and human well-being. To better understand and manage the complex interactions within water pollution systems, such as waste dumping in the sea, system dynamics modeling has emerged as a valuable tool. This simulation-based approach employs feedback loops and cause-and-effect relationships to capture the dynamic behavior of such systems over time. By simulating various waste disposal scenarios and assessing their impacts on the environment and human health, system dynamics modeling aids policymakers and waste managers in devising effective strategies for the sustainable management of dumping sites into the sea. In this manuscript, we present a system dynamics approach to model water pollution control. Our study entails the development of a conceptual model that encompasses pollution sources, pollutant transport and fate, and their effects on water quality and human health. By calibrating and validating the model using data from a case study in Charleston Harbor, South Carolina, United States, we ensure its accuracy and reliability. The results highlight the model's versatility in simulating different pollution control scenarios, particularly those involving dredging discharge and powerhouse effluent. Through these simulations, we gain valuable insights into the potential impacts of various pollution control measures on water pollution dynamics. Our research underscores the significance of system dynamics modeling in comprehending intricate water pollution systems, including those associated with waste dumping in the sea. By identifying effective strategies for water pollution control, this approach offers invaluable support in safeguarding marine ecosystems and human communities. In conclusion, system dynamics modeling proves to be a powerful tool for sustainable water pollution management. This research demonstrates its utility in analyzing dumping sites in the sea and provides essential findings to inform effective pollution control strategies. Emphasizing the broader context of water pollution, this study contributes to advancing knowledge and fostering sustainable practices to protect our precious water resources.

Keywords: marine environment; dumping sites; system dynamics; water pollution

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1. Introduction

Water pollution is one of the most significant environmental challenges facing the world today. It is caused by a variety of sources, including industrial processes, agricultural activities, and domestic waste. The pollution of rivers, lakes, and oceans can have severe consequences for the environment and human health, ranging from the loss of biodiversity to the outbreak of water-borne diseases. One of the critical contributors to water pollution is the dumping of waste into the sea [1,2].

Dumping sites in the sea are areas where waste is deposited, usually in the form of solid or liquid materials. Waste dumping can be intentional or accidental, and it can come from a variety of sources, including shipping, oil and gas exploration, and offshore industries. The dumping of waste can have significant impacts on the marine environment and human health, depending on the type and quantity of waste and the location of the dumping site [3–5].

The issue of dumping waste into the sea has become a growing concern for policymakers and environmental organizations worldwide. Many countries have enacted regulations to prevent the dumping of waste in the sea, and international treaties, such as the London Convention and Protocol, have been established to regulate the practice. However, despite these efforts, illegal dumping of waste continues to be a problem, and many marine ecosystems remain threatened by pollution [6,7].

In recent years, system dynamics modeling has emerged as a valuable tool for understanding the complex dynamics of water pollution systems, including the impacts of waste dumping on the marine environment. System dynamics modeling is a simulation-based approach that uses feedback loops and cause-and-effect relationships to capture the dynamic behavior of a system over time [8,9].

A system dynamics model of a water pollution system typically includes sources of pollution, transport and fate of pollutants, and impacts on water quality and ecosystem services. In the case of dumping sites in the sea, the model would also include factors such as ocean currents, the type of waste being dumped, and the potential effects on marine life and human health. By simulating different scenarios of waste disposal methods and exploring the impacts of dumping on the environment and human health, system dynamics modeling can help policymakers and waste managers develop effective strategies for sustainable management of dumping sites in the sea [10–12].

In this context, this article aims to provide an overview of the issue of dumping waste into the sea and the role of system dynamics modeling in managing the problem. The present research first discusses the sources and types of waste commonly dumped in the sea and the impacts of waste dumping on the marine environment and human health. It then introduces system dynamics modeling and demonstrates its utility in understanding the complex dynamics of water pollution systems, including those involving waste dumping in the sea. Finally, case studies that illustrate the application of system dynamics modeling to managing dumping sites in the sea are presented, and the potential for future research in this area is discussed.

Water pollution is a complex and multifaceted problem, and the dumping of waste in the sea is one of the primary contributors to this issue. The literature on waste dumping in the sea is extensive and covers various aspects, including the types and sources of waste, the impacts on the environment and human health, and the management strategies to mitigate the problem.

The previous studies provided an overview of the key findings and trends in the literature on waste dumping in the sea. The types of waste that are commonly dumped in the sea include industrial waste, domestic sewage, and offshore drilling waste. Industrial waste can come from a variety of sources, such as chemical plants, oil refineries, and pulp and paper mills. Domestic sewage, which contains human and animal waste, is a significant source of pollution in many coastal areas. Offshore drilling waste includes drilling muds, cuttings, and produced water, which can contain high levels of heavy metals, hydrocarbons, and other pollutants [13,14].

The impacts of waste dumping in the sea can be severe and far-reaching. The pollutants in the waste can cause harm to marine ecosystems, leading to the loss of biodiversity, fish kills, and other ecological disturbances [15]. The pollutants can also accumulate in the food chain, posing a risk to human health through the consumption of contaminated seafood. In addition, the waste can damage coastal habitats and affect recreational activities such as swimming and surfing [16].

To mitigate the problem of waste dumping in the sea, various management strategies have been developed. These strategies range from regulations and enforcement to technology-based solutions. For example, regulations such as the London Convention and Protocol regulate the dumping of waste in the sea and require signatories to take measures to prevent pollution. Technology-based solutions include the development of wastewater treatment facilities and the use of bioremediation to clean up contaminated sites [17,18].

System dynamics models can capture the relationships and feedback loops between different components of the system, such as waste sources, transport and fate of pollutants, and impacts on the environment and human health. By simulating different scenarios, policymakers and waste managers can identify effective strategies for sustainable management of dumping sites in the sea [19–21].

Several case studies have been conducted to demonstrate the application of system dynamics modeling to managing dumping sites in the sea. For example, Kumar and Mizunoya (2022) developed a system dynamics model to simulate the impacts of a river restoration project. The conclusions can aid in the development of sustainable practices and the choice of the best approach for cleaning up polluted rivers [22]. Similarly, Stronkhorst et al. (2003) developed a system dynamics model to evaluate the impacts of different policies on marine waste management in the North Sea. The model showed that a combination of policy measures, including waste reduction, recycling, and waste-to-energy conversion, was necessary to achieve sustainable waste management [23].

Other studies have also investigated the impacts of waste dumping in the sea on various components of the environment, such as coral reefs [24], estuaries [25], and deep-sea ecosystems [26]. Furthermore, researchers have studied the impacts of waste dumping on human health, such as through the consumption of contaminated seafood and exposure to beach water pollution [27,28].

In addition to research on the impacts of waste dumping in the sea, the literature also highlights the importance of public awareness and engagement in addressing the problem. Public participation can help increase the effectiveness of waste management strategies and improve the sustainable use of marine resources. Moreover, interdisciplinary approaches, such as integrating social, economic, and environmental considerations, are necessary for addressing the complex and multifaceted nature of waste dumping in the sea [29].

Sharma et al. (2022) presented valuable insights into the importance of removing toxic elements from wastewater effluent and how nanohybrid absorbents can contribute to improving the quality of treated water. This advanced remediation technology offers great potential for the reuse of wastewater, ensuring a cleaner and healthier environment for all. Overall, they have shown the use of nanohybrid absorbents in wastewater treatment holds great promise for improving the quality of treated water by enhancing adsorption capacity, selectivity, and catalytic capabilities, while also offering cost-effectiveness and environmental sustainability [30].

Rafiq et al. (2021) studied information about the impact of textile industry wastewater on water resources and the role of semiconductor photocatalysts in addressing this issue. In summary, semiconductor photocatalysts contribute to the degradation of dyes in industrial water pollution by generating highly reactive species that can break down organic pollutants, including dyes, into simpler, less harmful compounds. This technology is considered favorable for industrial wastewater treatment due to its environmentally friendly method, low cost, and lack of secondary pollution. However, the efficiency of photocatalysts depends on operational parameters, and it is important to explore the nature of the sample to be degraded to optimize the technology's effectiveness [31].

Yavari and Qaderi (2018) proposed a method for detecting thermal pollution using remote sensing and satellite imagery, specifically utilizing Landsat 8 with OLI and TIRS sensors. The results indicate an increase in temperature in the western channel. This research provides valuable insights into monitoring and addressing environmental concerns related to power plant operations [32].

Sharma and Chatterjee (2017) worked on the threat that microplastics pose to both marine ecosystems and human health. According to their study, common sources of microplastic pollution in the ocean include wastewater, rivers, and wind currents, as well as ship-generated litter and careless handling of plastic fishing gear. Additionally, microplastics and nanoplastics can enter the water channels via household and industrial drainage systems as domestic effluents, such as cosmetic products, toothpastes, hand cleansers, and cleaning products. Additionally, microplastic pollution can have negative impacts on marine ecosystems, including reduced biodiversity and ecosystem function. specifically mentions that corals can ingest microplastics, which can affect their energy sources and food supply [33].

Overall, the literature on waste dumping in the sea demonstrates the need for comprehensive management strategies that take into account the types and sources of waste, the impacts on the environment and human health, and the socio-economic factors that drive the problem [34,35]. However, further research is needed to address the gaps in our understanding of the problem and to develop innovative solutions that can protect the marine environment and support sustainable development [36].

Research Objective

The objective of this study is to employ system dynamics modeling as a valuable tool to comprehensively understand and manage water pollution systems, particularly those involving waste dumping in marine environments. By simulating diverse pollution control scenarios and analyzing their impacts on the environment and human health, the study aims to develop effective strategies for sustainable management of dumping sites and contribute to improved water pollution control practices.

2. Materials and Methods

The research design for this study involves a System Dynamics modeling approach, which is a method for modeling complex systems over time [37,38]. The study involves developing a model that simulates the dynamics of waste dumping in the sea and exploring the potential impacts of different policies and interventions.

The first step in the research process involves developing a conceptual model of the waste dumping system in the sea. This process includes identifying the key variables and factors contributing to waste dumping, as well as understanding the relationships and feedback loops between these variables.

2.1. Data Collection

Data have been collected to support the development and validation of the conceptual model. The data sources include:

Historical data: Historical data on waste production and disposal in the study area have been collected to validate the conceptual model.

Literature review: A comprehensive review of existing literature on waste dumping in the sea has been conducted to identify the key variables and factors that contribute to waste dumping.

In this study, we utilized data from various reliable sources to conduct a comprehensive analysis of waste dumping in Charleston Harbor. The data collection process involved accessing information from reputable platforms such as "www.epa.gov, (accessed on 01 December 2022)" "www.usgs.gov, (accessed on 01 December 2022)", "www.datacommons.org, (accessed on 01 December 2022)", among others. These sources provided a diverse range of data related to water quality, waste production, marine ecosystems, and other relevant variables. By gathering data from multiple sources, we aimed to ensure the accuracy and representativeness of the information used in our research. The combination of datasets from these reputable platforms allowed us to construct a robust and well-informed System Dynamics model to examine the dynamics of waste dumping in Charleston Harbor. Through this approach, we endeavored to enhance the credibility and validity of our findings, enabling meaningful insights into the environmental challenges posed by waste dumping in this critical coastal area.

2.2. Model Development and Validation

The conceptual model has been translated into a formal System Dynamics model using specialized software, such as Vensim or Stella. In the present study, we have used Vensim PLE software version 9.3.5 to simulate our model. The model has been validated using historical data. Sensitivity analysis is conducted to test the model's robustness and explore the impacts of different assumptions and parameters.

2.3. Policy Analysis

Once the model has been validated, it is used to explore the potential impacts of different policies and interventions aimed at reducing waste dumping in the sea. These policies may include waste reduction measures, improved waste management practices, and regulations or incentives to discourage waste dumping. The model simulates the impacts of these policies over time to identify the most effective and efficient approaches for waste reduction.

2.4. Limitations

Some potential limitations of the study may include the difficulty of obtaining accurate and reliable data on waste production and disposal, as well as uncertainties about the effectiveness and feasibility of different policies and interventions. Additionally, the model may be limited by the scope of the study area and the assumptions and simplifications made in the model.

In conclusion, the study employs a System Dynamics modeling approach to develop a model of waste dumping in the sea and explore the potential impacts of different policies and interventions. The model is developed and validated using a combination of literature reviews and historical data. Additionally, the study considers the model's limitations and uncertainties while aiming to communicate the results in a way that is accessible and relevant to stakeholders.

2.5. Study Area

Charleston, a coastal gem nestled in the southeastern United States, is renowned for its historic charm, vibrant culture, and captivating harbor. The city's harbor, located at the confluence of the Ashley and Cooper rivers, has played a pivotal role in shaping Charleston's history, economy, and overall character (see Figure 1).

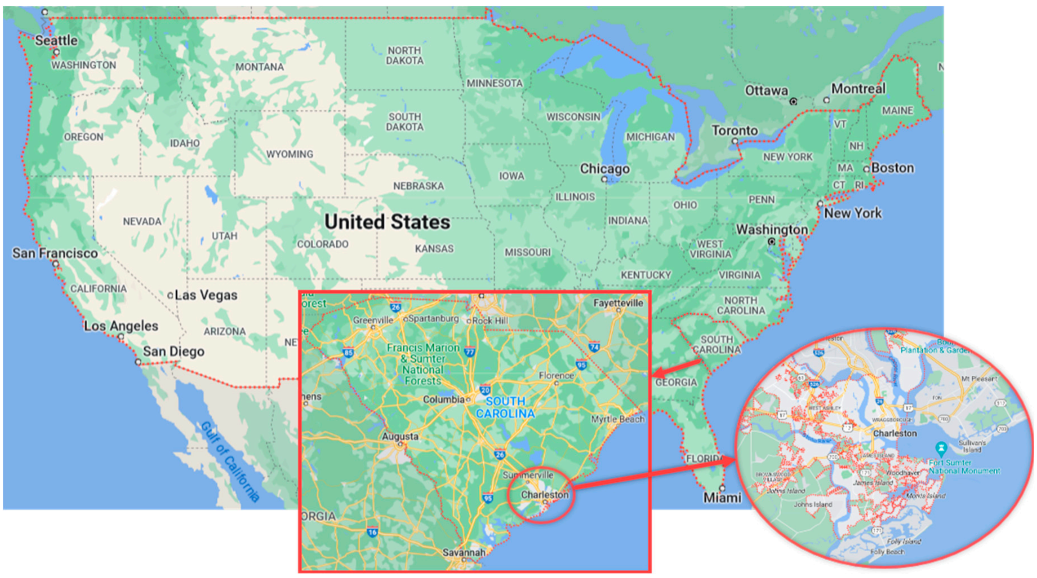

Figure 1. Location of the study (Source: Google Maps).

The Charleston Harbor serves as a gateway to the city and has been a bustling hub of maritime activity for centuries. Its strategic location along the Atlantic coast made it a crucial port for trade, commerce, and naval operations. The harbor witnessed the arrival and departure of ships carrying goods, people, and ideas from around the world, contributing to the city's cosmopolitan atmosphere and diverse influences.

The environmental condition of the Charleston Harbor is a topic of significant concern and attention due to the delicate balance between economic development and the preservation of the surrounding ecosystem. While efforts have been made to improve water quality and protect the harbor's natural resources, challenges persist.

Water pollution is a primary environmental concern in the Charleston Harbor. Runoff from urban areas, industrial activities, and agricultural practices can introduce pollutants such as sediment, nutrients, and chemicals into the water. These pollutants can have detrimental effects on aquatic life and water quality. Steps have been taken to implement stormwater management strategies, improve wastewater treatment facilities, and promote sustainable agricultural practices to mitigate pollution.

3. Results and Discussion

This section may be divided into subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1. Conceptual and General Scheme of the System

Figure 2 presents a simplified representation of the interconnectedness among different elements of a problem in a broad and conceptual manner. It offers a high-level overview of the proposed model, highlighting the interactions between various components within the system. The model comprises four fundamental elements: population, industry, water pollution, and dumping sites.

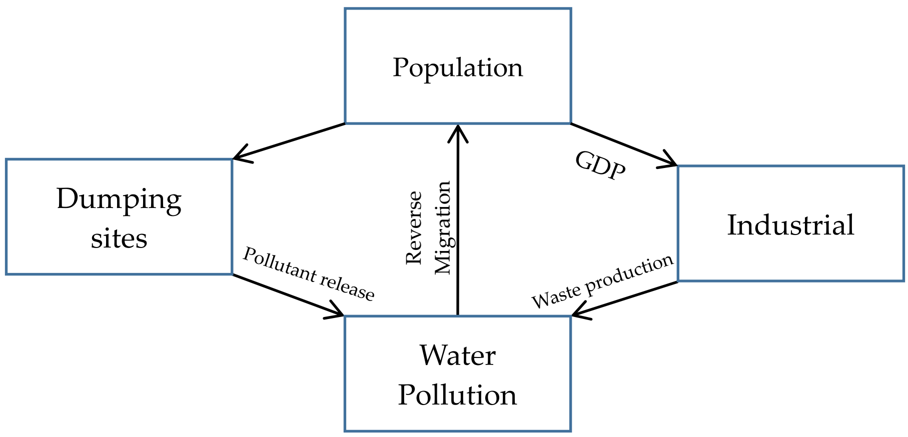

Figure 2. Conceptual model of subsystems [39].

3.2. Stock-Flow Diagram

In our previous study, the causal loop structure of the model was described in order to create a deep understanding of the system and its intensifying and controlling loops [39]. The causal loop diagram is a very good tool for showing the dependence between variables and drawing the feedback processes of the system, which can be used to draw the mental model of the system. In the present research, the Stock and Flow model of the system, which indicates the state of the system and can be formulated using mathematical equations, has been explained. The current Stock and Flow model can be the basis for decision-making.

The structure of the Stock and Flow diagram is presented in Figure 3, followed by an explanation and interpretation of the most crucial parts of the model.

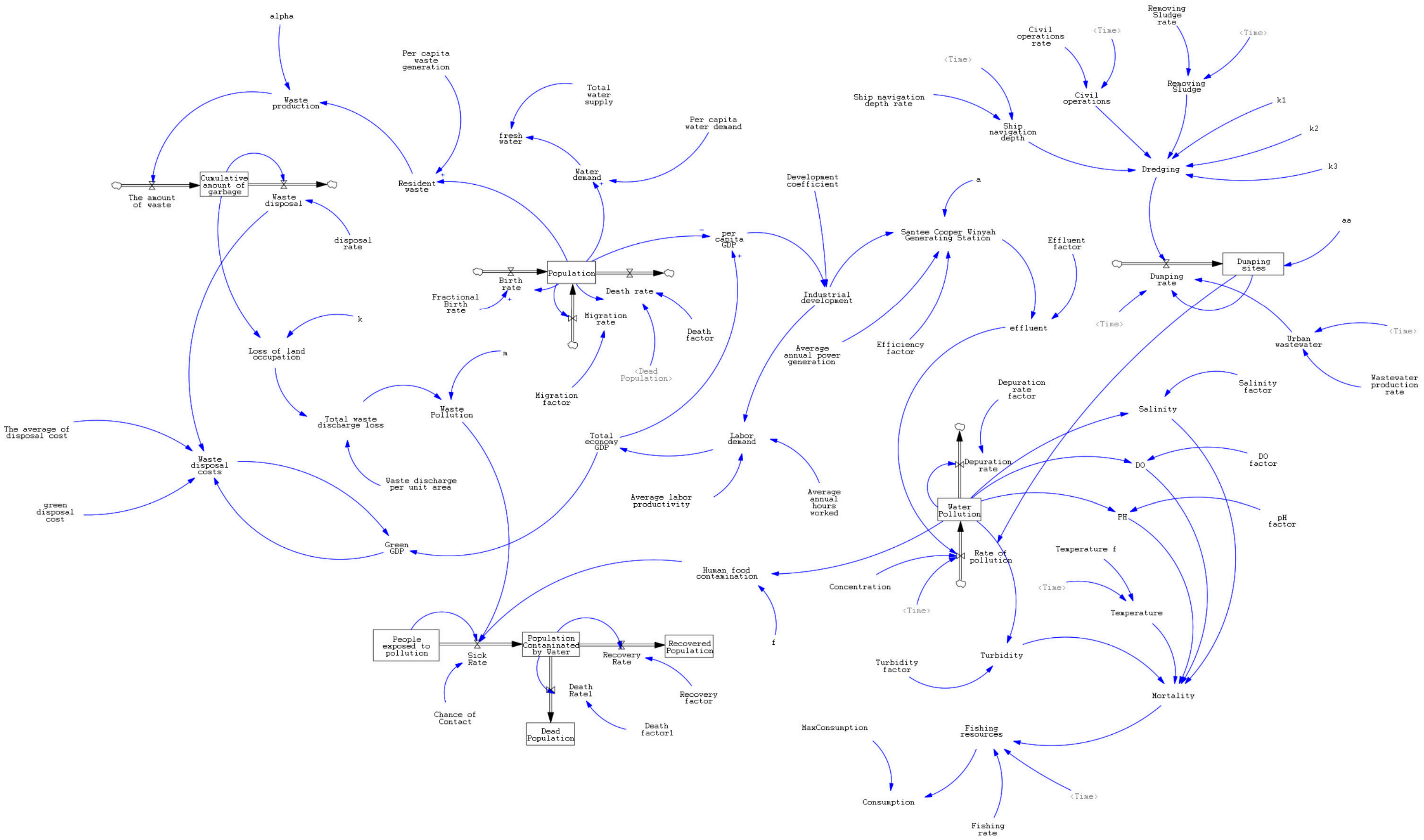

Figure 3. Stock-Flow diagram of the system.

3.3. Model Calibration and Verification

The ultimate objective of the validation process in system dynamics is to ensure the accuracy of the model's structural behavior while also emphasizing the modeling process. This is a crucial and significant aspect since system dynamics models are primarily aimed at evaluating different structures (i.e., strategies) that influence system behavior. Given that system dynamics models aim to provide an analysis of the long-term consequences of various policies, the focus during validation should be on the overall pattern of the system's structural behavior rather than the point-by-point prediction of some variables. However, if the structure of the model has sufficient validity, in the next steps, the validation of the model can also be considered.

3.3.1. Historical Data

Validating the model's performance is primarily achieved through the utilization of historical data. The ability of a model to accurately replicate past data is vital, as it serves as a foundation for future predictions. Once the model is constructed, its outputs are compared and aligned with actual historical data. The presence of a strong correlation between the model's outputs and the real data instills confidence in the model's results, affirming its capacity to accurately forecast future events.

By calibrating the model with these historical datasets, it becomes possible to discern complex relationships and dynamics between dumping sites, water pollution, fishing resources, the total economy, and the population. The interpretation of this calibrated model provides a holistic understanding of the system, enabling informed decision-making, policy formulation, and the identification of potential areas for intervention to achieve sustainable development and environmental protection goals.

During the calibration phase, the model is adjusted to ensure that it accurately represents the historical data and captures the relationships between different variables. This process fine-tunes the model's parameters and equations, enabling it to replicate past events and patterns effectively. By achieving a close match between the model's outputs and the historical data, confidence is gained in the model's ability to capture the underlying dynamics of the system.

The calibration process serves as a critical step in verifying the model's reliability and suitability for simulating real-world scenarios. It involves comparing the model's simulated outputs with actual data collected from past events or experimental studies. During this process, discrepancies between the model's outputs and the observed data are carefully analyzed, and adjustments are made to minimize these differences.

Ultimately, a well-calibrated model serves as a powerful tool for understanding the dynamics of waste dumping in the sea and predicting the potential outcomes of various policy interventions and management strategies. The calibration process's comprehensive nature contributes to building confidence in the model's outcomes, facilitating informed decision-making, and supporting sustainable solutions for addressing water pollution challenges.

Figures 4–8 represent the calibration of the model simulation with historical data for various variables related to dumping sites, water pollution, fishing resources, the total economy (GDP), and population. These calibration figures showcase the comparison between the model's simulated outputs and the observed historical data for each respective variable. As shown in these figures, the present model is properly verified with actual historical data, and the model's performance and predictive capabilities can be assessed and validated.

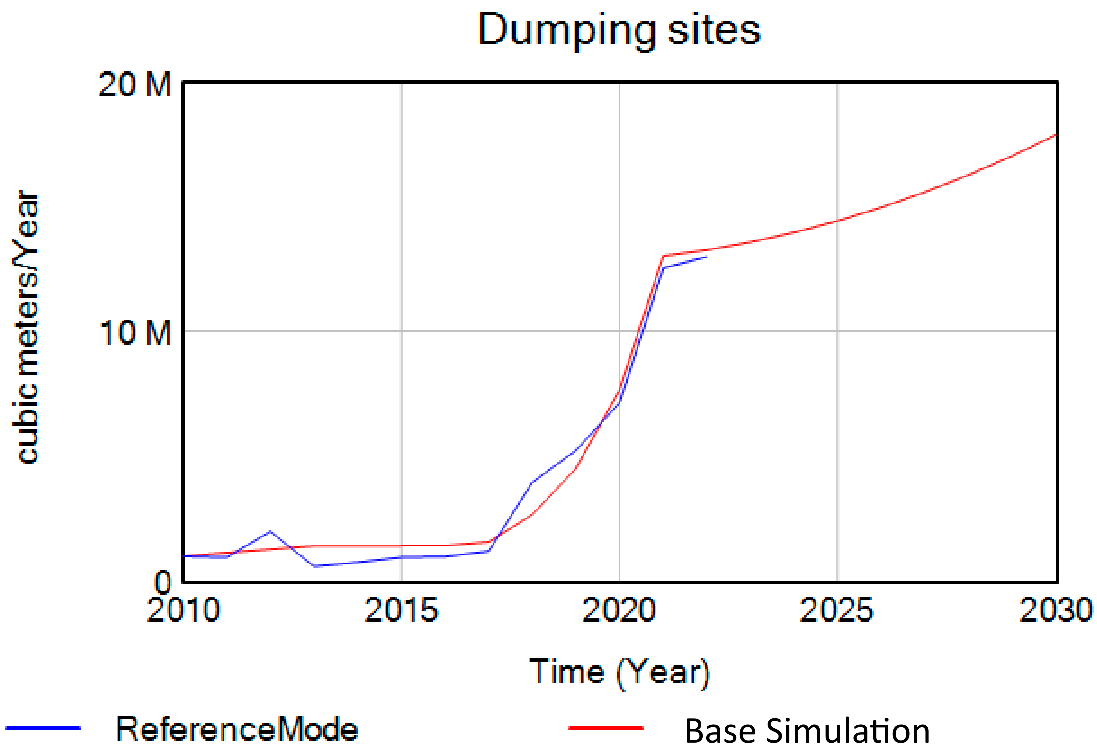

Figure 4. Calibration of the simulation with historical data for dumping sites.

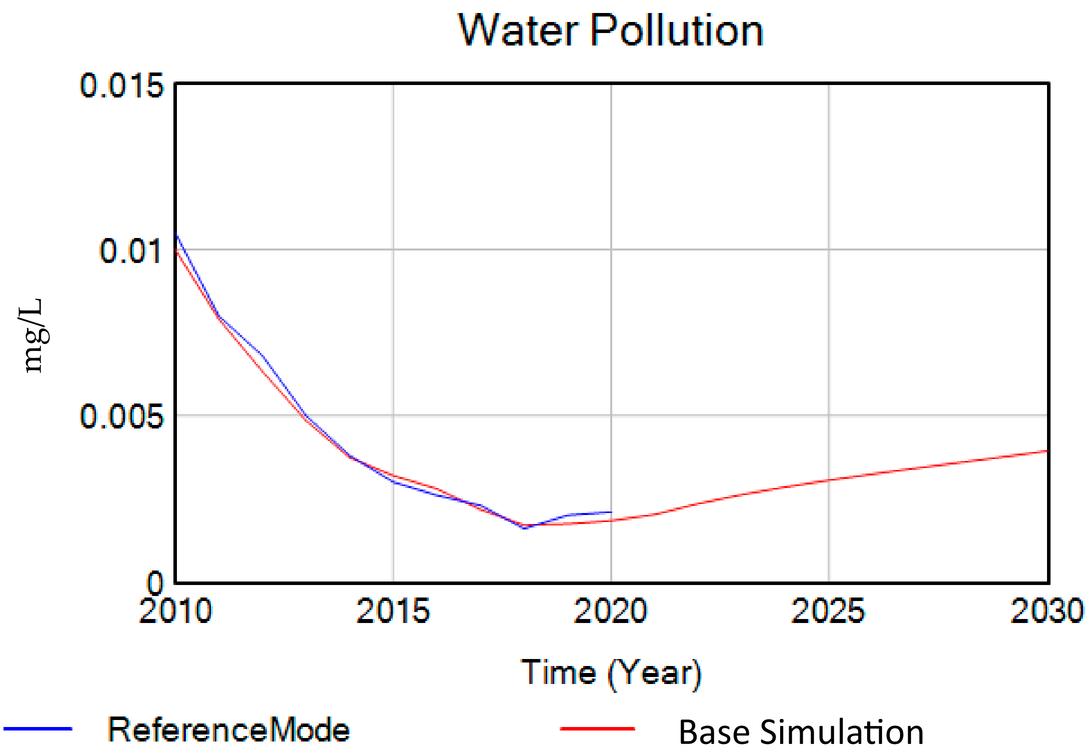

Figure 5. Calibration of the simulation with historical data for water pollution.

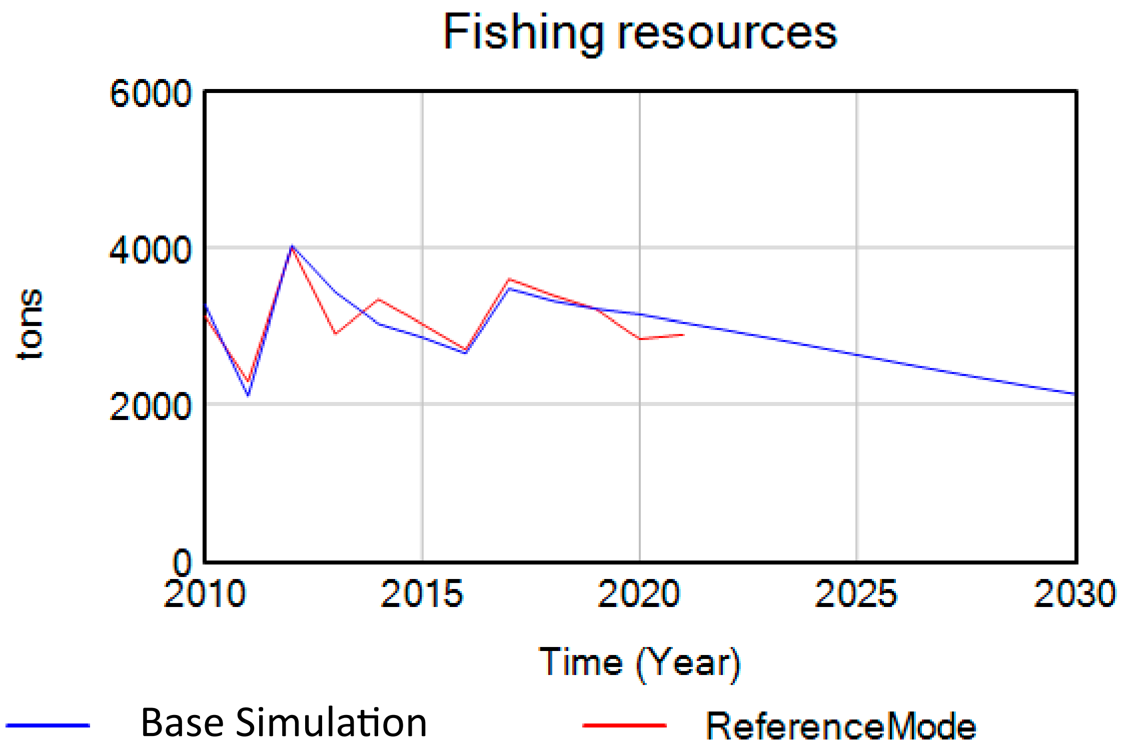

Figure 6. Calibration of the simulation with historical data for fishing resources.

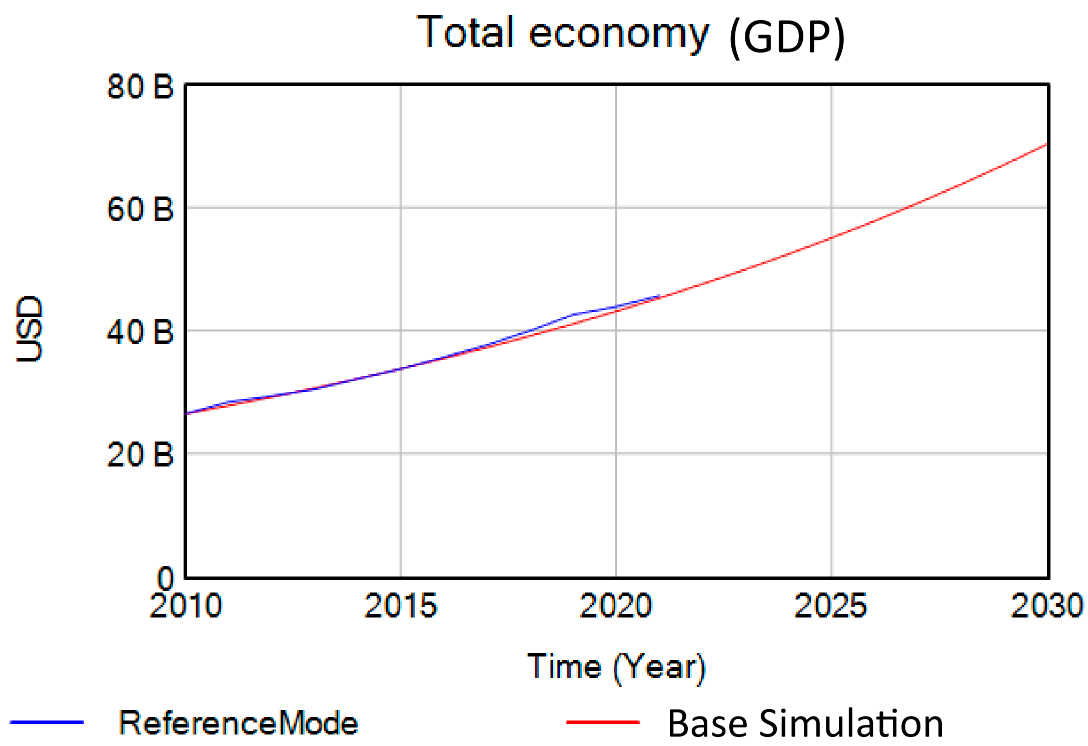

Figure 7. Calibration of the simulation with historical data for the total economy (GDP).

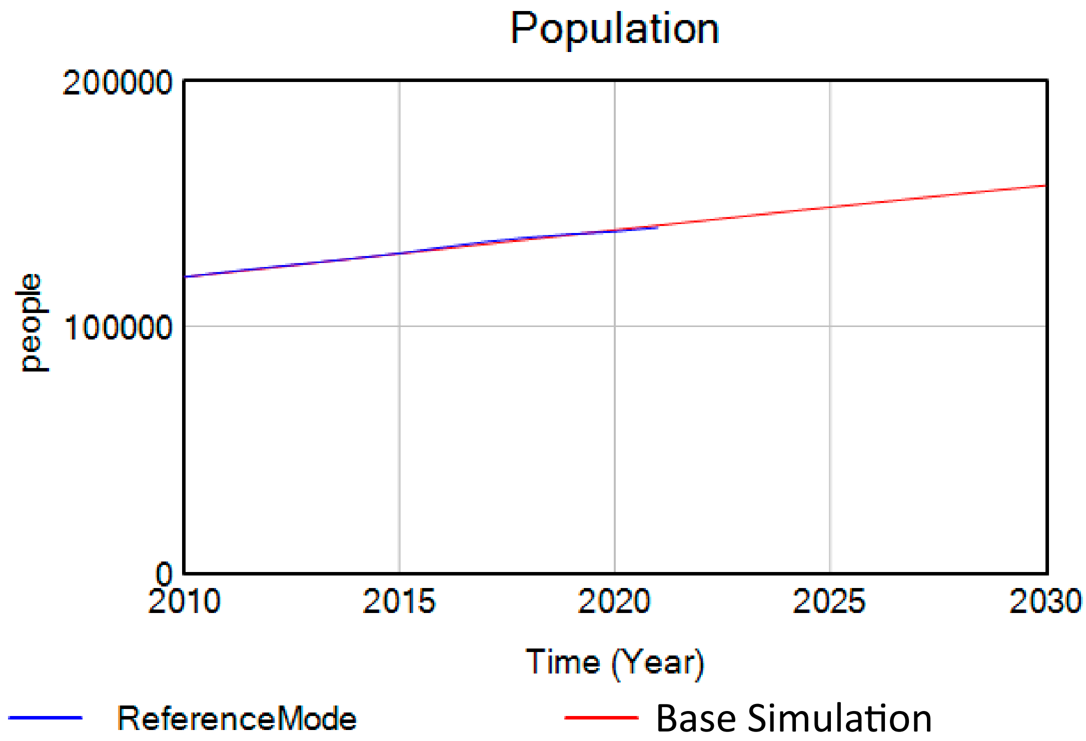

Figure 8. Calibration of the simulation with historical population data.

Table 1 presents the calibration results of the system dynamics model, where simulation outputs are compared with historical data related to dumping sites. The present calibration is a crucial step in validating the model's performance. It ensured that the model aligned with historical trends and reproduced past events accurately, increasing confidence in its ability to make reliable forecasts for future scenarios. With an average error of 8.94%, it demonstrates that the model's outputs are relatively close to the historical data, indicating a reasonable level of accuracy in capturing the dynamics of the dumping sites. Given the complexities and uncertainties often associated with environmental systems, achieving an average error of less than 10% is often considered acceptable and indicative of a well-calibrated model.

3.3.2. Structure Assessment Test

The simulation results of the model with the corresponding initial values for various variables show a behavior corresponding to the expected behavior of those variables. In this section, we have examined the structural behavior of one of the most significant variables in this model.

The relationship between dumping sites and water pollution is a critical aspect to consider when assessing the environmental impact of waste disposal. Dumping sites, where waste materials are discarded, can have a significant influence on water pollution in various ways. Therefore, the impact of dumping sites on water pollution is significant. It highlights the importance of implementing proper waste management practices, such as appropriate site selection, containment measures, and adequate treatment of leachate, to minimize the release of pollutants and protect water quality. Proper regulation, monitoring, and enforcement of waste disposal practices are essential to mitigating the adverse effects of dumping sites on water pollution and preserving the health of aquatic ecosystems.

Figure 9 correctly shows the relationship between the impact of dumping sites on water pollution in this study. As shown in this figure, during 2010–2017, the rate of dumping materials and wastes on the sea was constant, so water pollution decreased during these years. After increasing the amount of dumping materials, water pollution increased gradually.

Table 1. Calibration of the simulation with historical data for dumping sites.

Time (Year)	Historical Data (m^3/Year)	Simulation (m^3/Year)	Error (%)
2010	986,659	986,659	0.00%
2011	942,819	1.12×10^6	18.79%
2012	1.98×10^6	1.76×10^6	11.11%
2013	580,818	6.50×10^5	11.91%
2014	741,968	8.90×10^5	19.95%
2015	944,319	1.01×10^6	6.96%
2016	973,934	1.03×10^6	5.76%
2017	1.18×10^6	1.26×10^6	6.78%
2018	3.95×10^6	3.65×10^6	7.59%
2019	5.23×10^6	4.51×10^6	13.77%
2020	7.15×10^6	7.67×10^6	7.27%
2021	1.25×10^7	1.30×10^7	4.00%
2022	1.30×10^7	1.33×10^7	2.31%
2023	-	1.36×10^7	-
2024	-	1.40×10^7	-
2025	-	1.44×10^7	-
2026	-	1.50×10^7	-
2027	-	1.56×10^7	-
2028	-	1.63×10^7	-
2029	-	1.70×10^7	-
2030	-	1.79×10^7	-

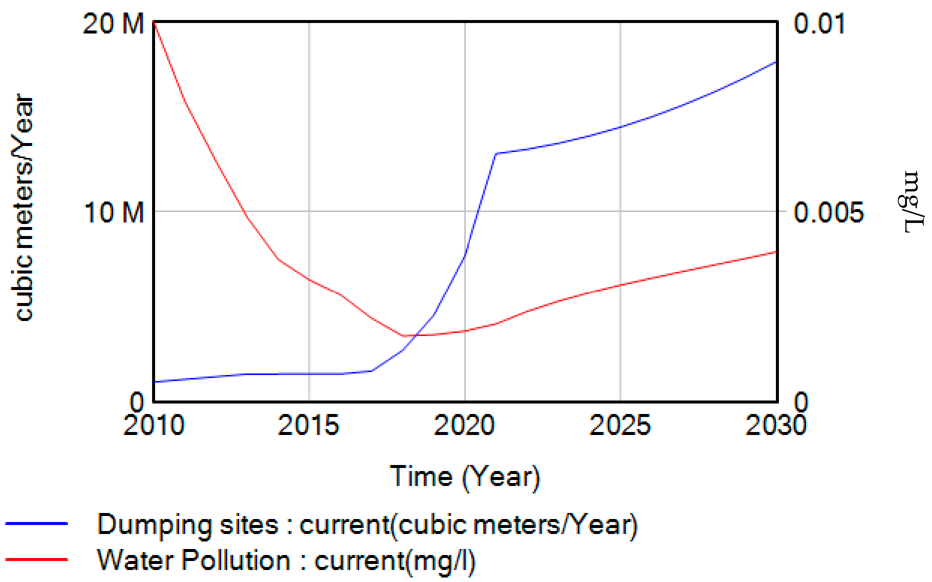

Figure 9. The relationship between the impact of dumping sites on water pollution and its changes.

3.3.3. Extreme Condition Test

The extreme condition test in system dynamics is a method used to evaluate the behavior and robustness of a model when subjected to extreme or highly challenging scenarios. It involves pushing the model to its limits by introducing inputs or conditions that go beyond typical ranges or exceed normal operating conditions. This test is particularly valuable for assessing the model's performance, identifying potential vulnerabilities, and understanding how the system responds under extreme circumstances. By subjecting the model to extreme conditions, it becomes possible to observe how the system behaves and whether it exhibits any unexpected or undesirable outcomes. This test helps uncover potential risks, weaknesses, or limitations in the model's structure, assumptions, or feedback mechanisms.

It also provides insights into how the system may respond to unprecedented events or disruptions, allowing for a better understanding of its resilience.

In this test, the input value of the model takes its limit value, and its effect on the variables of the model is investigated. As an example, with an 80% reduction in the impact of dumping sites and almost making the variable ineffective, water pollution will decrease significantly to 2.22 µg/L (approximately 43% decrease) (see Figure 10). By observing the results of this change or other changes to the input variables, practically no unreasonable behavior has been created.

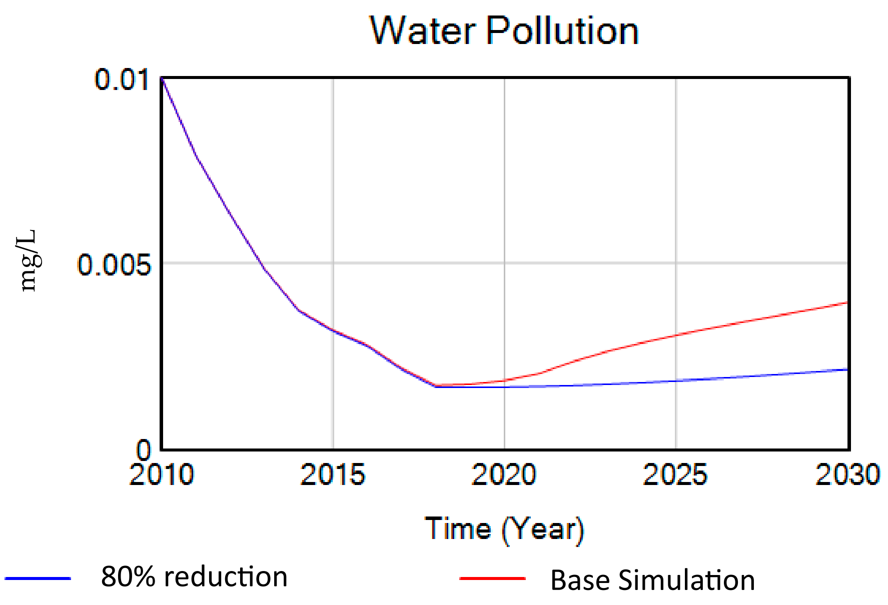

Figure 10. The relationship between the impact of the reduction of dumping sites on water pollution.

In addition to the above example, Figure 11 shows that with an 80% decrease in Santee Cooper Winyah Generating Station effluent, water pollution will decrease significantly to 1.97 µg/L (approximately 50% decrease) (see Figure 11).

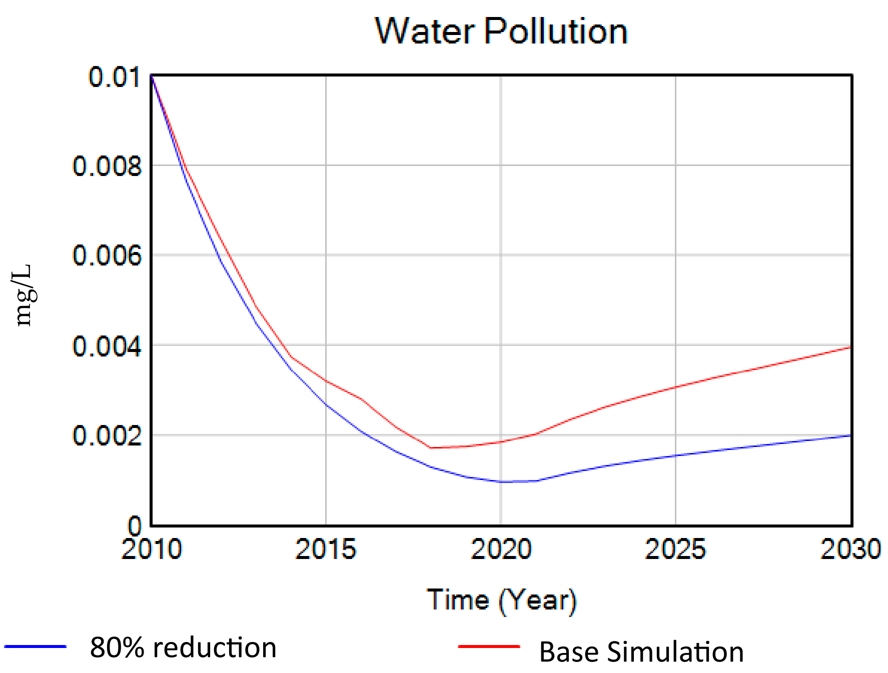

Figure 11. The relationship between the impact of the reduction of Santee Cooper Winyah Generating Station effluent on water pollution.

3.4. Scenario Analysis

Scenario analysis in system dynamics is a technique used to explore and understand the behavior of complex systems under different hypothetical conditions or future scenarios. It involves creating and simulating multiple scenarios that represent plausible future states of the system, allowing decision-makers to assess the potential outcomes and implications of different circumstances. The process of scenario analysis begins with the identification and definition of relevant scenarios based on key factors, trends, uncertainties, or policy changes that may impact the system of interest. These scenarios can range from optimistic to pessimistic or from conservative to radical, representing a range of possible future conditions.

Once the scenarios are defined, the system dynamics model is used to simulate the behavior of the system under each scenario. By adjusting the input parameters, policy settings, or external conditions specific to each scenario, the model generates projections and insights into how the system may respond and evolve over time.

3.4.1. Scenario 1: Reducing the Effect of Dredging Discharge

The first scenario is to consider reducing the discharge of dredging materials at the dumping site by 20–40 percent. This reduction can be achieved through effective management practices in the dredging sector, such as optimizing dredging amounts, utilizing landfills instead of sea dumping, and increasing waste recycling capacity. In the initial stage of this scenario, the discharge at the site was reduced by 20% (refer to Figure 12a). As shown in Figure 12b, a 20% reduction in material discharge resulting from dredging at the dumping site leads to a corresponding 7.5% decrease in total dumping. Furthermore, with a 40% decrease, the reduction in dumping will reach 14.9% by 2030 (see Table 2).

Table 2. Reducing the effect of dredging discharge.

Time (Year)	Total Amount of Dumping: Base Simulation (m^3/Year)	Total Amount of Dumping: 20% Reduced (m^3/Year)	Total Amount of Dumping: 40% Reduced (m^3/Year)
2010	986,659	986,659	986,659
2011	1.12×10^6	1.12×10^6	1.12×10^6
2012	1.26×10^6	1.26×10^6	1.26×10^6
2013	1.40×10^6	1.40×10^6	1.40×10^6
2014	1.41×10^6	1.41×10^6	1.41×10^6
2015	1.41×10^6	1.41×10^6	1.41×10^6
2016	1.41×10^6	1.41×10^6	1.41×10^6
2017	1.56×10^6	1.56×10^6	1.56×10^6
2018	2.65×10^6	2.65×10^6	2.65×10^6
2019	4.51×10^6	4.51×10^6	4.51×10^6
2020	7.67×10^6	7.67×10^6	7.67×10^6
2021	1.3038×10^7	1.30×10^7	1.30×10^7
2022	1.33×10^7	1.33×10^7	1.33×10^7
2023	1.36×10^7	1.35×10^7	1.34×10^7
2024	1.40×10^7	1.38×10^7	1.36×10^7
2025	1.44×10^7	1.41×10^7	1.38×10^7
2026	1.50×10^7	1.45×10^7	1.40×10^7
2027	1.56×10^7	1.49×10^7	1.43×10^7
2028	1.63×10^7	1.54×10^7	1.45×10^7
2029	1.70×10^7	1.59×10^7	1.49×10^7
2030	1.79×10^7	1.65×10^7	1.52×10^7

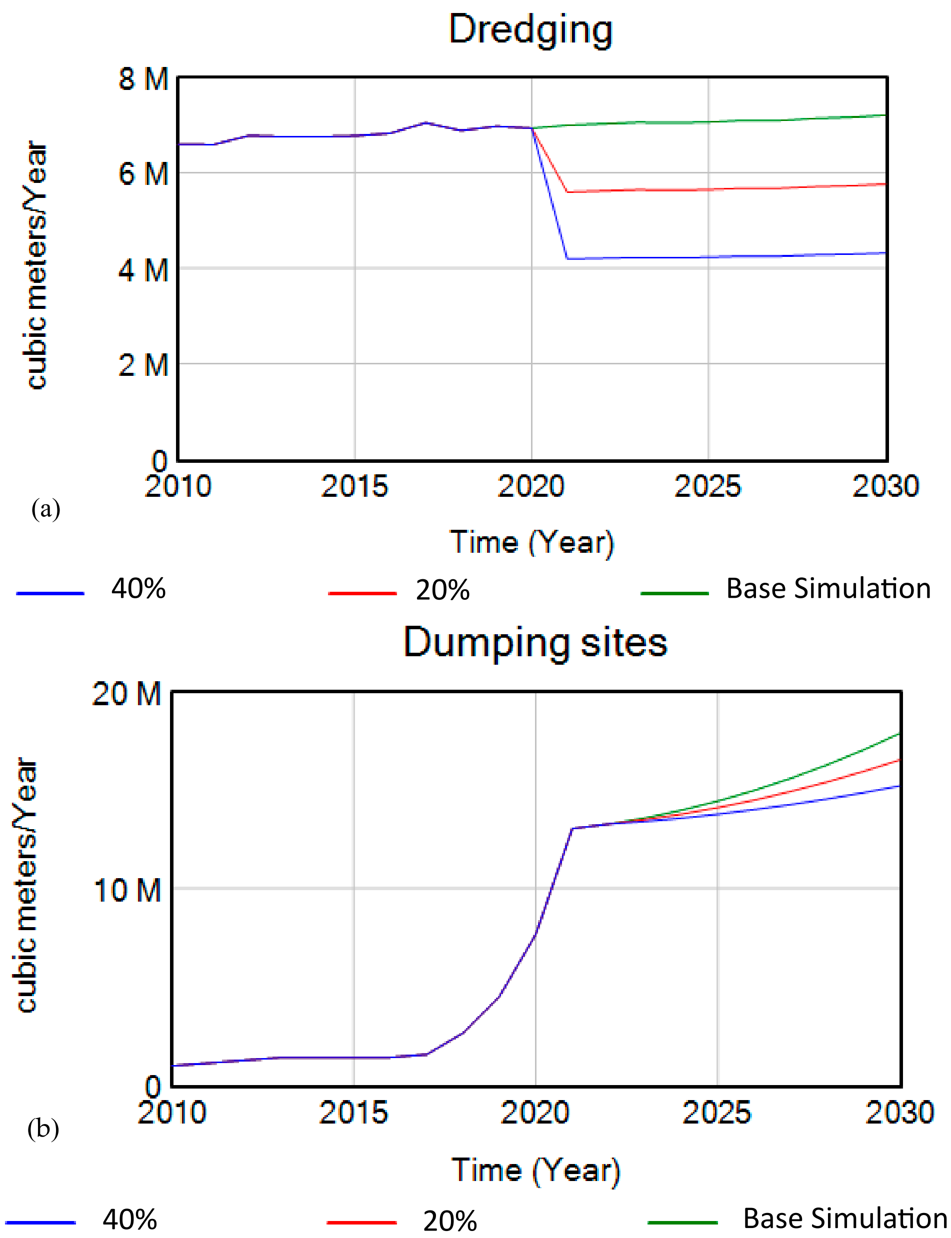

Figure 12. Reducing the effect of dredging discharge: (**a**) amount of dredging discharge; (**b**) Total amount of dumping at sites.

We should clarify that the pollution reduction scenarios were implemented as a sudden reduction in 2021. Specifically, a sudden reduction of 20–40% in pollution levels occurred in that year. The subsequent effects of these reductions were then traced until 2023, through our system dynamics model.

Reducing the impact of dumping sites on water pollution in Charleston Harbor requires a comprehensive approach involving waste management practices, regulatory measures, and community engagement. Here are some strategies to mitigate the effects of dumping sites on water pollution:

- *Enhanced Waste Management Practices:* Implementing proper waste management practices is crucial to minimizing the pollution caused by dumping sites. This includes the establishment of secure landfill facilities, recycling and composting programs, and the promotion of responsible waste disposal techniques. Encouraging individuals, businesses, and industries to reduce waste generation and adopt sustainable practices can significantly reduce the amount of waste ending up in dumping sites.

- *Strict Regulatory Framework:* Enforce and strengthen regulations governing waste disposal and dumping activities. Implement robust monitoring and enforcement mechanisms to ensure compliance with waste management regulations. This includes conducting regular inspections, imposing penalties for non-compliance, and promoting responsible waste disposal practices.
- *Promote Recycling and Reuse:* Emphasize the importance of recycling and reuse to reduce the amount of waste that needs to be disposed of at dumping sites. Implement recycling programs at the community level and promote initiatives that encourage the reuse of materials. This not only reduces the waste sent to dumping sites but also conserves resources and mitigates pollution.
- *Improved Monitoring and Surveillance:* Enhance monitoring and surveillance systems to detect illegal dumping activities. Utilize technologies such as satellite imagery, drones, or remote sensing to identify and address unauthorized dumping sites promptly. Prompt reporting and investigation of illegal dumping incidents can help mitigate their impact on water pollution.

By adopting these strategies, it is possible to reduce the effect of dumping sites on water pollution in Charleston Harbor, safeguarding the health of the marine ecosystem and preserving the water quality for present and future generations.

3.4.2. Scenario 2: Reducing the Effect of Powerhouse Effluent

The effluent from powerhouses can have a significant impact on water pollution in Charleston Harbor. Powerhouses, which generate electricity through various means such as burning fossil fuels or nuclear power, often release wastewater or cooling water into nearby water bodies, including harbors. The effluent from powerhouses can introduce various pollutants into the water, including thermal pollution, heavy metals, organic compounds, and nutrients. Thermal pollution occurs when heated water is discharged into the harbor, resulting in elevated water temperatures. This increase in temperature can disrupt aquatic ecosystems, affect oxygen levels in the water, and harm marine life that is sensitive to temperature changes.

Powerhouses may also release heavy metals, such as mercury, lead, and arsenic, into the water through their effluent. These metals are often byproducts of power generation processes and can have toxic effects on aquatic organisms. The accumulation of heavy metals in the harbor ecosystem can pose risks to the health of marine life and potentially impact the food chain.

It is essential for continuous monitoring, compliance with regulations, and ongoing efforts to improve wastewater treatment technologies to mitigate the potential impacts of powerhouse effluent on water pollution in Charleston Harbor. The second scenario that affects water pollution is the reduction in power plant effluent discharge by 20 and 40 percent. This amount of reduction can be achieved by managing the power plant's wastewater discharge and increasing its treatment capacity. In the first stage of this scenario, the amount of wastewater discharge was reduced by 20% (Figure 13a). As shown in Figure 13b, a 20% reduction in the discharge of power plant effluent into seawater leads to a 9.5% reduction in water pollution, which is a 40% reduction that will reach 19% in 2030 (see Table 3).

Reducing the impact of powerhouse effluent on water pollution in Charleston Harbor requires a combination of preventative measures, regulatory actions, and the adoption of cleaner technologies. Here are some strategies that can help mitigate the effects of releasing powerhouse effluent:

- *Implement Advanced Wastewater Treatment:* Powerhouses can invest in advanced wastewater treatment technologies to remove or minimize pollutants from the effluent before it is discharged into the harbor. This may include using filtration systems, sedimentation tanks, chemical treatments, and biological processes to remove contaminants and improve water quality.

- *Employ Best Management Practices:* Powerhouses should implement comprehensive best management practices (BMPs) to prevent or minimize the release of pollutants. This may include proper storage and handling of fuels, chemicals, and waste materials, regular maintenance of equipment to prevent leaks, and implementing spill prevention and response measures.
- *Monitor and Report Effluent Quality:* Regular monitoring and reporting of effluent quality are crucial for ensuring compliance with regulatory standards. Powerhouses should establish robust monitoring programs to assess the quality of discharged water and promptly identify and address any deviations or issues.
- *Compliance with Environmental Regulations:* Powerhouses must comply with local, state, and federal environmental regulations governing effluent discharge. These regulations often impose limits on pollutant concentrations and require the implementation of specific control measures. Adhering to these regulations is essential for minimizing the impact of powerhouse effluent on water pollution.
- *Promote Renewable Energy Sources:* Encouraging the transition to renewable energy sources, such as solar, wind, or hydroelectric power, can help reduce the reliance on powerhouses that generate electricity from fossil fuels. Renewable energy generation has lower or negligible emissions and can significantly reduce the environmental footprint associated with power generation.

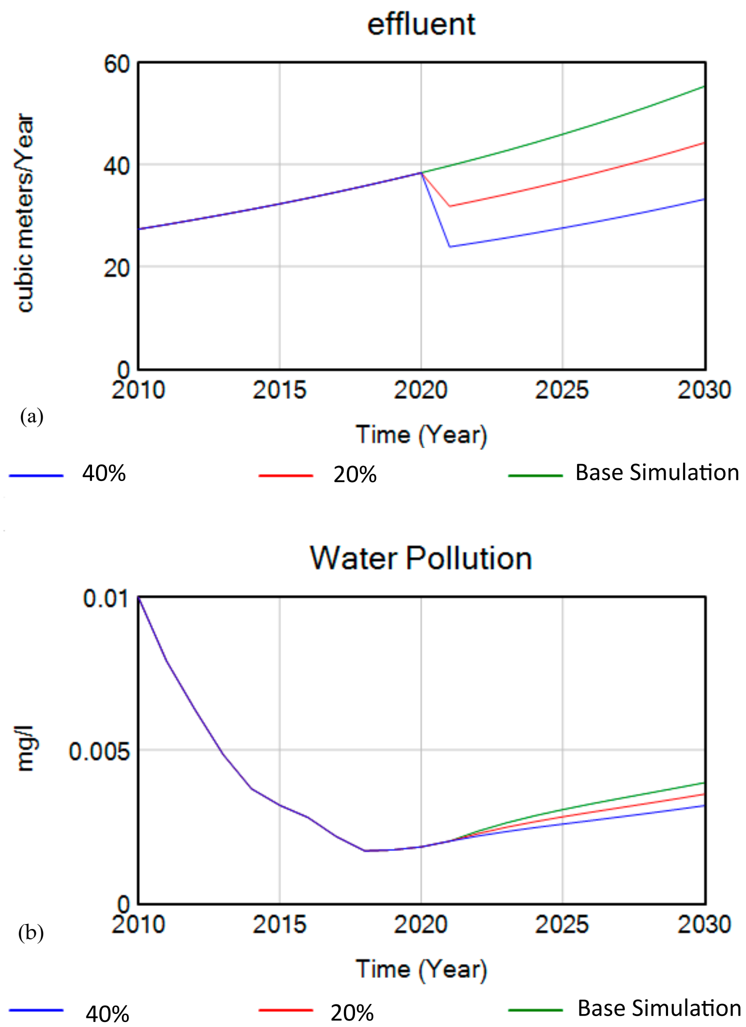

Figure 13. Reducing the effect of powerhouse effluent on water pollution: (**a**) amount of dredging discharge; (**b**) total amount of dumping at sites.

Table 3. Reducing the effect of powerhouse effluent on water pollution.

Time (Year)	Water Pollution: Base Simulation (mg/L)	Water Pollution: 20% Reduced (mg/L)	Water Pollution: 40% Reduced (mg/L)
2010	0.01	0.01	0.01
2011	0.007905	0.007905	0.007905
2012	0.006326	0.006326	0.006326
2013	0.004851	0.004851	0.004851
2014	0.003734	0.003734	0.003734
2015	0.003195	0.003195	0.003195
2016	0.002796	0.002796	0.002796
2017	0.002173	0.002173	0.002173
2018	0.001705	0.001705	0.001705
2019	0.001738	0.001738	0.001738
2020	0.001835	0.001835	0.001835
2021	0.002022	0.002022	0.002022
2022	0.00235	0.00227	0.002191
2023	0.00262	0.002477	0.002334
2024	0.002851	0.002657	0.002463
2025	0.003054	0.002818	0.002582
2026	0.00324	0.002969	0.002698
2027	0.003415	0.003114	0.002813
2028	0.003586	0.003258	0.002931
2029	0.003757	0.003405	0.003053
2030	0.00393	0.003556	0.003183

By implementing these strategies and prioritizing environmental stewardship, powerhouses can contribute to the protection and preservation of water quality in Charleston Harbor, reducing the potential adverse effects of effluent discharge on the marine ecosystem.

We acknowledge the crucial role of easily accessible historical data in accurately predicting and addressing marine pollution challenges. As exemplified by the comprehensive data availability in Charleston Harbor, SC, USA, we recognize the importance of transparency and data sharing to foster effective pollution control strategies and environmental management. Charleston Harbor's data-driven approach serves as a model for encouraging authorities worldwide to prioritize data transparency and establish sustainable partnerships with scientists and research institutions. By instituting regular, accurate data recording and making such data readily available, we can collectively uncover the true extent of marine pollution and develop solutions to one of humanity's most pressing issues. The proposed system dynamics modeling approach in the present study offers a versatile and powerful framework for understanding and addressing complex environmental issues, such as marine pollution. One of its key advantages is its ability to provide a holistic understanding of the intricate interactions within complex systems. By capturing the feedback loops and cause-and-effect relationships between different variables, system dynamics models reveal the dynamic behavior of the system over time. In the context of marine pollution, this approach allows researchers to comprehensively explore the sources of pollution, transport mechanisms, and their potential impacts on water quality and human health.

To address the challenges posed by limited historical data in various locations and harbors, the manuscript underscores the need for collective efforts to promote data accessibility and foster international collaborations. The proposed model, inspired by Charleston Harbor's data-rich case study, serves as a steppingstone for inspiring other regions to adopt transparent data collection and sharing practices. By recognizing the vital role of data availability in marine pollution studies, we advocate for the active involvement of local authorities in contributing to comprehensive data sets. Sustainable and unbiased partnerships between local authorities, scientists, and research institutions are crucial in ensuring the availability of accurate data, which will drive evidence-based policy-making and environmental management. Moreover, the manuscript emphasizes the model's adaptability to diverse locations once data becomes available, making it a valuable tool for addressing pollution challenges worldwide. By emphasizing the importance of data transparency and collaborative efforts, our study seeks to promote a global commitment to understanding and mitigating the impacts of marine pollution on our ecosystems and human well-being.

4. Conclusions

Water pollution remains a critical environmental concern with far-reaching impacts on ecosystems and human well-being. In this study, we utilized a System Dynamics modeling approach to gain insights into the complexities of water pollution systems, particularly those involving waste dumping in marine environments. By employing simulation-based techniques, we investigated various waste disposal scenarios and their effects on the environment and human health, facilitating the development of effective strategies for sustainable dumping site management.

Through meticulous calibration and validation using data from Charleston Harbor, South Carolina, our model demonstrated its ability to accurately capture the dynamics of water pollution. The presented scenarios of reducing dredging material discharge and power plant effluent discharge by 20% and 40% allowed us to assess potential pollution reductions.

In the dredging material discharge scenario, our simulations revealed that a 20% reduction corresponded to a 7.5% decrease in total dumping, with the possibility of reaching a 14.9% reduction by 2030 with the 40% decrease. Similarly, in the power plant effluent discharge scenario, a 20% reduction led to a 9.5% reduction in water pollution, and a 40% reduction showed the potential to achieve a 19% decrease by 2030.

Moving forward, our system dynamics model serves as a valuable tool for policymakers and waste managers to devise effective pollution control strategies. To further enhance the utility of the model, future research can explore additional scenarios and test the impacts of combined pollution control measures. Moreover, considering long-term forecasts beyond 2030 would enable a more comprehensive assessment of the model's contributions to sustainable water pollution management.

In conclusion, our study showcases the potential of system dynamics modeling to address water pollution challenges, particularly in marine environments with dumping sites. The findings highlight the importance of adopting efficient pollution reduction strategies and underscore the significance of holistic approaches in preserving water quality and safeguarding human health. We remain committed to advancing our research and contributing to the collective efforts to ensure a cleaner and more sustainable aquatic environment.

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