Applied Water Science (2023) 13:109
https://doi.org/10.1007/s13201-023-01910-9

ORIGINAL ARTICLE

The impacts of dumping sites on the marine environment: a system dynamics approach

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Received: 23 January 2023 / Accepted: 19 March 2023 / Published online: 6 April 2023

Abstract
The various forms of anthropogenic pollution of seas and oceans have been extensively studied in recent decades. The most significant factors are the destructive environmental impacts of marine dumping sites. These sites put soil and coastline, water quality, mangroves and coral reefs, marine animals, food chains and plankton, and fishery at serious risk and alter the surrounding economic, social, and cultural conditions. The destruction of marine ecosystems by dumping sites causes severe environmental damage. With the ever-increasing anthropogenic environmental pollution of the seas and the drastic reduction in the self-purification mechanism of marine ecosystems, it is necessary to charter practical solutions with a holistic perspective and implement novel designs using system dynamics. System thinking and system analysis are essential tools in analyzing and solving important economic and management issues. System analysis investigates and evaluates the system complexities, determines the relationship between all factors, and then presents appropriate solutions to the problem. The increasing severity of the problems caused by marine dumping in recent years and the existing research gap in this area have highlighted the need for effective, comprehensive, and integrated solutions. The process of findings such solutions is critical and challenging. This study explores the most significant factors that directly and indirectly impact marine life using system dynamics.

Keywords Marine environment · Dumping sites · System dynamics · Site selection

Introduction

Over the last century, the rapid development of urban and industrial areas on rivers and coasts has introduced serious environmental contaminants into the marine environment. Because of its potential toxicity and propensity to bioaccumulate, heavy metal pollution has become a significant problem in marine environments. The mobility and bioavailability of metals may be altered by slight changes in the water and sediment conditions, such as those that happen during dredging and disposal operations (Donázar-Aramendía et al. 2020). From 1988 to 2015, three ocean dumping sites in South Korea's Yellow Sea (YS) and East Sea (ES) accumulated terrestrial waste. Most of this waste comprised industrial wastewater and sewage sludge, which are sources of microplastics. The historical trend of microplastic pollution in age-dated core sediments from East Sea dumping site (EDP) and Yellow Sea dumping site (YDP) aligned well with the amount of historical ocean dumping. As the level of ocean dumping has gradually reduced since 2006, and was finally banned in 2015, the microplastic abundance decreased accordingly ("Underwater Hidden Microplastic Hotspots: Historical Ocean Dumping Sites". 2022).

Coastal and offshore operations worldwide, including land reclamation, shoreline development, dredging, and isolation of contaminated sediments (i.e., isolating or removing contaminating sediments) dispose of their sediment into seawater. Sediment pollution is one of the most significant challenges associated with materials dredged from ports and waterways. An estimated 10% of the 190 to 230 million cubic meters of sediment dredged annually in the United States contain heavy metals and organic compounds (Suedel et al. 2008). The aforementioned land uses raise concerns regarding the precise accumulation of sediments

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in the specified area as well as increased sediment losses as a result of environmental flow during disposal operations (the diffusion of sediments in the water column). As a result of deposition, suspended sediments increase turbidity, damage marine life, and generally degrade water quality, disrupting the natural cycle of the environment. Since water covers more than two-thirds of the earth's surface and the world's most important cities are located in coastal regions, protecting the environment in these areas is critical. The development of ports and beaches is one of the key factors for the growth of these regions. Marine structure engineers and designers, including port engineers and designers, are at the forefront of the dredging operation and determining the location of dredging material disposal. Due to the high cost of transporting dredged materials from the sea to land, engineers prefer sea disposal sites (Chu and Yao 2020; Dong et al. 2021).

In contrast, multiple factors should be taken into account in the discharge of marine sediments from one area into another. The environment of the dumping site is an important factor. Water turbidity is a critical environmental issue that poses a threat to marine life and can cause significant changes to the local ecosystem. Accordingly, all the factors and parameters affecting the environment should be thoroughly explored to find the best solution and minimize environmental damage (Beecroft et al. 2019).

There is a substantial research gap concerning this topic, and the connection between problems imposed on the marine environment by dumping sites has not been fully addressed. This paper presents a comprehensive analysis and modeling of all the dimensions of the problem and proposes one or more solutions. The modeling was performed using the system dynamics approach. Among the most notable recent studies are Todd et al. (2014), which investigated the environmental impacts of dredging operations on marine animals and aquatic life, and Erftemeijer et al. (2012), which studied the environmental impacts of dredging on corals. As previously stated, in each of the conducted studies, only one or two cases of adverse effects were reported, and almost all the studies proposed viable solutions (Todd et al. 2014; Erftemeijer et al. 2012; Mymrin et al. 2021; Svensson et al. 2022; Hieb et al. 2021).

Dredging and dumping sites

To choose the optimal method for disposing of dredged materials, an environmental understanding of materials settling, induced energy regimes, and the reasons for dredging and dumping is required. Preliminary prediction of the fate of materials involves a hydrodynamic knowledge of the system and a mathematical model to explain the complex processes of dredging, transportation, and sedimentation (UASCE 1983). There are four aquatic ecosystems for disposing of dredged materials: the ocean, the estuary, the river, and the lake. Dredging aims to achieve three primary objectives: facilitate shipping (estuary depth), conduct civil operations (sand extraction from the bottom of the sea), and decontaminate (seabed cleaning) (Rahimikelarijani et al. 2018). Generally, the dredge materials are disposed of in three environments, including marine and terrestrial environments and specific sites.

Dredged-sediment dumping phases

Special barges for dredging materials are typically used for unloading marine sediments. Over the years, various experimental, numerical, and analytic projects have been completed or are under completion in this regard.

Release

The main objective of material release is to confine the materials in one place to contain the entire pollutants and isolate them from the environment, allowing the diffusion of pollutants to the environment to be acceptable (Berenjkar et al. 2019). In a broader sense, the phrase "release" can also refer to handling materials to separate or stabilize pollutants or alter them into harmless materials (see Figs. 1, 2).

Environmental impacts

Dredging projects require the excavation, movement, and transportation of vast quantities of seabed material. In addition, the dumping sites have both direct and indirect positive and negative effects on the marine ecosystem. This section reviews the most relevant international studies on various environmental impacts of dumping sites. Dredging-related sediments can be divided into two broad categories: non-polluted and polluted. The vast majority of materials dredged

Fig. 1 Turbidity of seawater due to the diffusion of dredged materials (short-term impact) (Saremi 2014)

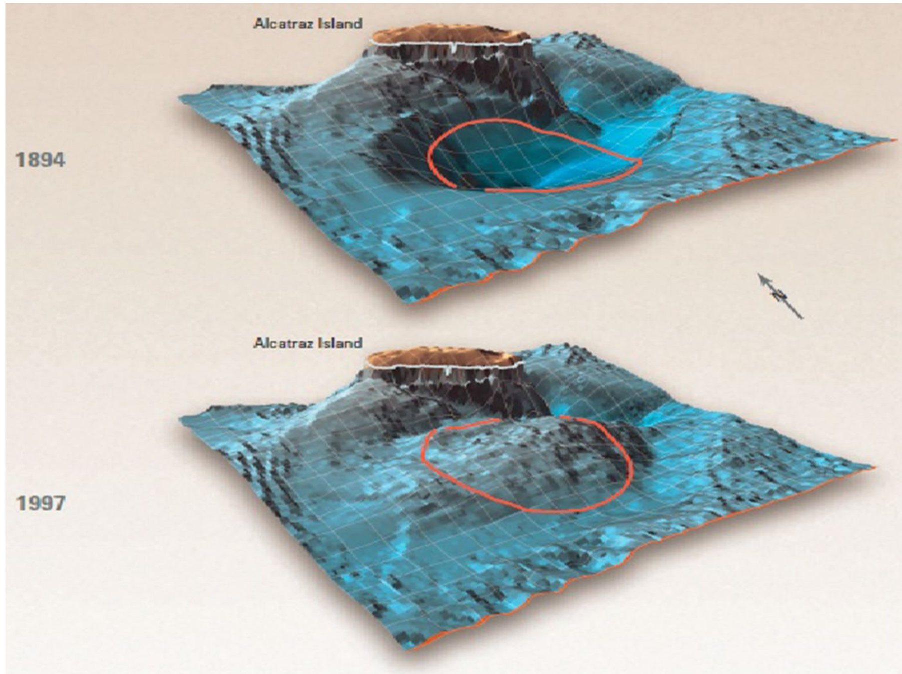


Fig. 2 The distribution of dredged materials resulted in the filling of the Alcatraz site between 1894 and 1997 (long-term impact) (USGS 2008a, 2008b)

from the seafloor are contaminant-free. Some of the most important factors in dredging operations are the disturbance of bed sediments, sediment suspension, and the formation of suspended material stains in seawater. Contaminated sediments include substances with detrimental chemical concentrations and adverse environmental impacts. For many years, uncontrolled pollution discharge into the sea has been contaminating seabed sediments in the central regions of well-known ports, with the main contaminants being heavy metals, and in some cases, hydrocarbons converted into PCBs. On the one hand, a significant layer of seabed soil has been contaminated by large amounts of organic pollutants and metals, including copper, chromium, and mercury. These pollutants occasionally reach substantial depths by penetrating ship anchors on the seafloor. Numerous distinct methods have been developed and implemented to treat polluted sediments. These contaminated sediments may be transferred to a disposal site and covered with a layer of clean material, such as sand.

Oil and gas drilling operations at sea can discharge various chemical substances into the environment through excavated materials and drilling mud. Since the advent of drilling operations, drilling and waste materials have been a source of concern. Accordingly, many attempts have been made to reduce the toxicity and biodegradability of drilling mud. However, the discharge of drilling materials severely impacts marine and threatens the ecology and the restoration of marine species, especially in tropical and subtropical climates. As a result, quantifying the environmental effects of drilling waste during and after disposal can be an effective and viable strategy (Foster et al. 2010). Considerable amounts of hydrocarbons are mixed with sediments via water flow and biological mixing. Material depletion can lead to eutrophication (algal bloom), which increases an ecosystem's biological oxygen demand (BOD). Toxic hydrocarbon molecules can shock the environment and reduce the number of living organisms. Aerobic and anaerobic organisms within the sediment can decompose hydrocarbons under aerobic conditions at the water–sediment interface (Mojtahid et al. 2006; Gailani et al. 2016).

Environmental impacts on marine animals

Direct impacts

The primary outcomes of dredging for marine mammals are collisions, noise production, and increased turbidity, which lead to physical injury or mortality. All dredging phases involve vessel movement, from transport from the extraction and dumping sites to the operation of the dredger. Thus, collision with dredgers is a potential risk (Neilson et al. 2012). Research into marine mammals and vessel collisions, in general, has shown that the likelihood of collision varies based on various factors, including vessel type, speed, location, species, and behavior (Waerebeek et al. 2007).

Despite the reports of vessel strikes on all marine mammals, most studies mainly deal with mysticetes. Research shows that the risk of collision and the subsequent likelihood of severe or fatal injury increases when vessels exceed 10–14 knot (1knot = 0.5144m/s) (Gende et al. 2011). It appears that the effect of vessel size or type is less significant. Right whales, humpback, and fin whales are among the most susceptible to collisions. Laist et al. (2001) stated that resting or feeding whales are at greater risk (Laist et al. 2001). Panigada et al. (2006) show that the number of collisions with fin whales varies with the season, likely because feeding animals are distracted and less attentive to vessel movements (Panigada et al. 2006).

Marine mammals are acoustically dependent creatures that use sound for prey detection, navigation, and communication. Over the past two decades, extensive research has increased our understanding of the effects of anthropogenic noise on marine mammals, but there are still many gaps in our knowledge (Iorio and Clark 2009). The reported effects include temporary threshold shift (TTS) and permanent threshold shift (PTS). PTS is considered an auditory injury (Clark et al. 2009). Changes in behavior caused by noise exposure can occur at great distances from the source and may be biologically harmful, as they may reduce energy expenditure or time spent feeding or resting. It has been hypothesized that the impact of noise can induce stress. Stress could decrease marine mammals' hunting ability or increase their disease susceptibility and toxins (Geraci and Lounsbury 2002). Recent reviews, such as CEDA (2011) and WODA, highlight the published noise results for the most frequently used dredgers. Dredging generally generates continuous, broadband sound, with most energy occurring below 1 kHz. Sound pressure levels (SPLs) can vary significantly based on factors such as dredger type, operational phase, and environmental conditions (CEDA 2011; WODA 2013).

The extraction, rejection, and disposal of sediments, as well as the outwash of excess materials, can raise turbidity and increase the formation of sediment plumes by disturbing the seafloor. Sediment plumes can extend the physical effects of dredging to larger areas that would otherwise be unaffected. The effects are generally narrow, lasting no more than four or five tidal cycles, and are confined to a few hundred meters from the point of discharge (Hitchcock and Bell 2004). Numerous marine mammals use sophisticated sonar systems to detect their surroundings in turbid environments. Literature provides no evidence that turbidity directly affects cetaceans or sirenians, and the feeding methods of some mysticetes, such as grey whales and sirenians, produce sediment plumes, indicating that individuals must have some level of tolerance and can feed in turbid conditions (Au Fay Popper 2000).

Indirect impacts

Dredging alters physical characteristics like topography, depth, waves, tidal currents, sediment particle size, and suspended sediment concentrations, but changes also occur naturally due to disturbance events like tides, waves, and storms. As a result, while minor changes are unlikely to impact the marine ecosystem significantly and may even increase biodiversity, large-scale repeated changes can affect the entire food web up to marine mammals (Vali 2021). Indirect effects can be positive or negative, but they are most likely species-specific, so it is unclear how dredging affects different marine organisms. Given the diverse and vast amount of data on the subject, literature reviews need to be more comprehensive. However, the goal here is to provide a good indication of how the dredging effects on the marine environment, fauna, and flora may indirectly affect marine mammals, even though the high level of the site and species specificity means assessment of impacts is somewhat subjective (Maser and Strehse 2021).

Governments and people have always been concerned about environmental degradation to combat which actions must be taken at national and international levels. The destruction of marine ecosystems and surface waters has caused irreversible environmental damage. Because of the extensive use of the sea and the varying discharge rates, marine ecosystems have lost their ability to self-purify, hardly mitigating the associated effects. Current waters and coastal industries significantly contribute to marine pollution. Natural oil spills, air fallout, direct contact between the water's surface and the surrounding air, and the deliberate dumping of materials into the sea all contribute to marine ecosystem pollution (Kazour et al. 2019; Vanninen et al. 2020).

Research methodology

This research uses system dynamics to comprehend the environmental impacts of dumping sites. This model is founded on the principle that "everything is interdependent and changing." Compared to static models, the models used in system dynamics can better demonstrate long-term impacts (Rassafi et al. 2014). The current tool and strategy have been successfully applied to solving environmental challenges caused by air and noise pollution. Given the research gap on the environmental impacts of dredging and dumping, here, this technique was used to address the problem systemically and comprehensively.

Proposed research method

System dynamics

The surrounding environment is dynamic and ever-changing. Sometimes changes are abrupt and drastic. Our world is analogous to a system in which humans play a role; thus, to better comprehend this vast, complex, and dynamic system, one must adopt a systemic perspective to comprehend its interconnections and interdependencies. Increasing economic, technological, social, and environmental changes, coupled with system complexity and the gradual evolution of life, necessitate that managers and politicians acquire new knowledge quickly. Many of the issues and problems humans face today are the unintended results of human actions in the past. System thinking is necessary to define the parameters of the mental model and produce a tool for comprehending the structure and behavior of complex systems and learning and making decisions in a world where dynamic complexity is continuously increasing. Occasionally, in an attempt to solve current problems, people resort to alternative strategies, resulting in the emergence of a new issue. In this regard, systems dynamics is recommended as a super-discipline. The system dynamics method is a professional modeling technique that employs computer simulation to understand system characteristics that can be used to develop effective policies (Sterman 2000).

Theoretical foundations related to system models

This section presents the definitions and concepts used in systems modeling analysis.

System

Any subset of components that is formed influences the behavior of the entire system, which depends on at least one other subset of the system. In other words, the components of a system are so interconnected that they cannot form an independent subgroup (Chen et al. 2021).

Systematic approach in modeling

System thinking is a method for a deeper understanding of complex management issues. When a model represents reality accurately, it produces results that are effective and reliable. System characteristics almost make it impossible to design and create a model that fully and accurately depicts the system's reality. However, as modeling errors are eliminated, the model will become closer to reality. Typically, system modeling consists of the following three steps:

- Defining the problem: what is the issue we wish to investigate, what are the essential variables, and examining the structure and past behavior of the model.
- Model simulation: This step discusses the formulation of variables and estimating unknown parameters.
- Examining policies and decision-making: charting various future policies, examining the sensitivity of these changes, decision-making, and taking measures close to the objective using systemic thinking. A system's essential characteristics result from its components' interaction, not from their actions. Since it is a generic system that cannot be comprehended through decomposition, decomposing a system results in the loss of critical features (Forrester 1994).

System dynamics

In 1950 (Forrester et al. 1976), Jay Forrester invented systems dynamics. Systems dynamics is a strategy for evaluating complex systems and constructing a model to acquire an in-depth comprehension of real-world occurrences. In the early 1990s, Forrester and his colleagues switched from manual calculations to computer simulation for systems dynamics. SIMPLE 3 was the first computer model of system dynamics created by Richard Bennett. For decades, the systems dynamics technique has been applied to the study of cause-and-effect relationships. System components and individuals interact via feedback loops, in which a change in one variable affects other variables over time, which in turn impact the first variable. An interest-bearing account is an excellent example; the interest on these accounts will increase in the next phase, and the trend of raising account interest will continue (Eberlein 2007).

The system dynamics technique was able to address several previously unsolvable problems. It is important to note that in 1961, Forster released the first book on this subject, titled Industrial Dynamics. DYNAMO was the initial software associated with this approach, followed by DYSMAP. In the early 1990s, other software was introduced, including STELLA, HTHINK, and VENSIM. The VENSIM software generates graphs by solving a set of (frequently nonlinear) first-order differential equations using the Euler or Runge–Kutta technique. Modeling in VENSIM progresses from generic to detailed, and additional functions and related components are continuously added to produce a comprehensive model for implementation (Eberlein 2007).

General theory of systems

System dynamics is a problem-solving method employed at the highest management and macro levels. Quantitative decision-making is challenging and risky, which highlights one of the most significant benefits of system dynamics: the transition of qualitative interactions into quantitative and observable relationships. The International System Dynamics Society describes this technology and its uses as follows: systems dynamics is the study and management of complex feedback systems, such as those found in business and other social issues. This concept is thus applicable to all feedback systems (March and Smith 1995).

Today, most management concerns are related to making strategic and unstructured decisions, as there are numerous contradictions in addition to people changing when confronted with problems and exhibiting unpredictable behavior. Various factors in every economic and social system contribute to system instability, such as resource constraints, insufficient input supply, excessive output demand, destruction factors, etc. Some factors are within the system's control, while others depend on external pressures. Due to most systems' complexity and unknown nature, the cause-and-effect relationships between them are frequently ambiguous (Montazemi and Conrath 1986).

The foundations of system dynamics are modern dynamics theory and control theory. In other words, system dynamics serves as a precise foundation for theories and models. It assists politicians in resolving organizational challenges. This strategy responds to problems primarily through insight, spiritual understanding, and thought processes, reducing the researcher's reliance on mathematical relationships. This method identifies, comprehends, and analyzes system component behavior. The system allows for modeling a wide array of simple and complex problems, studying the changes due to variable interactions, and predicting their future behavior over varying periods. The causal loop diagrams illustrate the link between variables, their interaction, and how they influence feedback loops, indicating the causal linkages between system variables. The arcs in this diagram denote the direction of the link between the variables. A feedback process, also known as a causal loop, is a conceptual tool that illustrates the dynamic process by which causal chains establish a closed set of relationships that ultimately lead to the fundamental variable. A causal loop is created when a group of variables is connected in a dependent route.

Results and discussion

Innovations and research objectives

The coastal zone is a significant interface between the oceans and continents. Sedimentation is a common issue for ports, which is the case for many ports around the globe. Dredging, a process of reverse sedimentation, has numerous environmental impacts. Similar to sedimentation, dredging has numerous environmental effects. In addition, open-water sediment disposal is linked to numerous coastal and offshore locations worldwide, including land reclamation, coastline expansion, dredging, and the isolation of polluting sediments (Reisenbüchler et al. 2021; Sharafati et al. 2020; Tao et al. 2021). The impact on the marine environment is one of the most important aspects of dredging and resulting materials from ports and waterways. The sediments that are suspended during discharge disrupt the natural cycle, which is exasperated by increased turbidity, compromising marine vegetation, harming marine organisms' lives, and generally degrading water quality. We found that the lack of a link between the issues posed by dredging and dumping sites for the marine environment is its primary flaw; the developed problems have yet to be explored comprehensively, and their impacts have not been observed. In this regard, the system dynamic method employed in this paper is innovative and capable: It offers viable solutions to complicated problems.

Conceptual and general scheme of the system

Figure 3 illustrates the relationship between the various problem components in a generic, non-detailed manner. The figure provides a conceptual and general overview of the proposed model and a broad view of the interaction between various system components. The model's four fundamental components include population, industry, water pollution, and dumping sites (Table 1).

Causal loop diagram (CLD)

The third step in systems dynamics is to draw a causal loop diagram to illustrate the mental model and better understand the system. According to the assumptions stated in the preceding section, Fig. 4 depicts the system's causal loop diagram before examining each component's causal loop diagrams.

Causal loop diagram for dumping sites selection

Figure 5 shows the relationship between industrial expansion and dumping locations. Population growth in the examined region has led to an increase in the gross domestic product, which has prompted the expansion of industries. Examples of such industries include refineries, power plants, factories, and oil well drilling. Given that the industries mentioned above play a significant role in producing waste and pollution, it is vital to select an appropriate dumping site to mitigate this issue. As a result of selecting the optimal dumping site, seawater pollution has decreased, and the community's health has suffered less harm.

The variables associated with the reinforcing loops (+) of the causal loop diagram shown above are explained as follows:

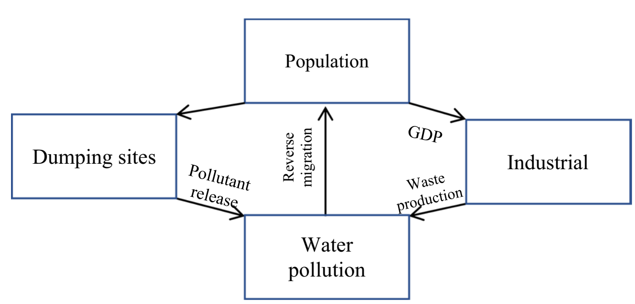


Fig. 3 Conceptual model of subsystems

Table 1 Variables considered in the main causal loop diagram

Subsystems	Variables	Type
Industrial	Labor demand	endogenous
	Total economy GDP	endogenous
	Refineries	endogenous
	Oil well drilling	endogenous
	Powerhouses	endogenous
	Factories	endogenous
Population	Immigration	endogenous
	Total economy GDP	endogenous
	Resident waste	endogenous
	Area situation	endogenous
	Birth rate	endogenous
	Mortality rate	endogenous
	Water demand	endogenous
	Resorts	endogenous
	Consumption	endogenous
Water pollution	Human food contamination	endogenous
	Turbidity	endogenous
	DO	endogenous
	PH	endogenous
	Salinity	endogenous
	Dumping sites	endogenous
Dumping sites	Radioactive waste	endogenous
	Drilling mud	endogenous
	Waste Refinery	endogenous
	Acidic wastes	endogenous
	Urban wastewater	endogenous
	Dredging	endogenous
	Site no. 1	exogenous
	Site no. 2	exogenous
	Site no. 3	exogenous

Black reinforcing loop population, consumption, urban sewage, dumping site, water pollution, food pollution, community health, population;

Purple reinforcement loop: Population, GDP, Industry, Power Plants, Power Plant Waste, Dump Site, Water Pollution, Food Pollution, Community Health, Population;

Orange reinforcement loop: Population, GDP, Industry, Oil Well Drilling, Drilling Mud, Dump Site, Water Pollution, Food Pollution, Community Health, Population;

Green reinforcement loop: Population, GDP, Industry, Refinery, Refinery Waste, Dumping Site, Water Pollution, Food Pollution, Community Health, Population;

Red reinforcement loop: Population, GDP, Steel Plant, Acid Waste, Dump Site, Water Pollution, Food Pollution, Community Health, Population.

Cieślikiewicz et al. (2018) associated a decision-making process with the designation of marine dumping sites for locations for dredged material that should involve. In this study, they studied some limited parameters, such as the depth of the natural bottom, allowing for the deposition of a considerable amount of the excavated material, as well as the relevant hydrodynamic parameters (it should be noted that, we also considered these parameters here) (Cieślikiewicz et al. 2018).

Causal loop diagram for the industrial sector

Figure 6 shows the industry sector's causal loop diagram. As shown, with the increase in population, the growth of GDP increased in this loop of industries in the studied area, indicating the development of various industries, such as refineries, oil wells, power plants, and other factories.

The factors in the black reinforcing loop in the figure above are industrial growth, labor demand, immigration, population, and GDP. Marine debris networks cover a broad range of activities in order to protect our oceans. By following a common vision and a collective systematic approach, these networks are capable of creating synergies among all relevant stakeholders, thus reducing the flow of waste into our oceans (Kandziora et al. 2019).

Causal loop diagram for population sector

Figure 7 shows a causal loop diagram of the indicators that affect the population or vice versa. These indicators include immigration, the birth rate, the mortality rate, the demand for water, resorts, consumption, gross domestic product, and resident waste.

Marine pollution impacts coastal nations around the world, and more so: (a) in confined maritime areas with significant marine traffic, (b) where exploitation of natural and mineral resources is taking place, or (c) in regions witnessing pressure from tourism, local population growth, and industry (Alves et al. 2021).

Causal loop diagram for the water pollution sector

The impact of increased water contamination on human health is depicted in Fig. 8. Increased sewage flow from urbanization, industries, and dredging at dumping sites has increased marine water pollution, threatening marine life. This damage is significant in two ways: (1) the population of aquatic animals has dropped as a result of water pollution and turbidity, and (2) as a result of the depletion of fishing resources, human consumption will fall. (3) The

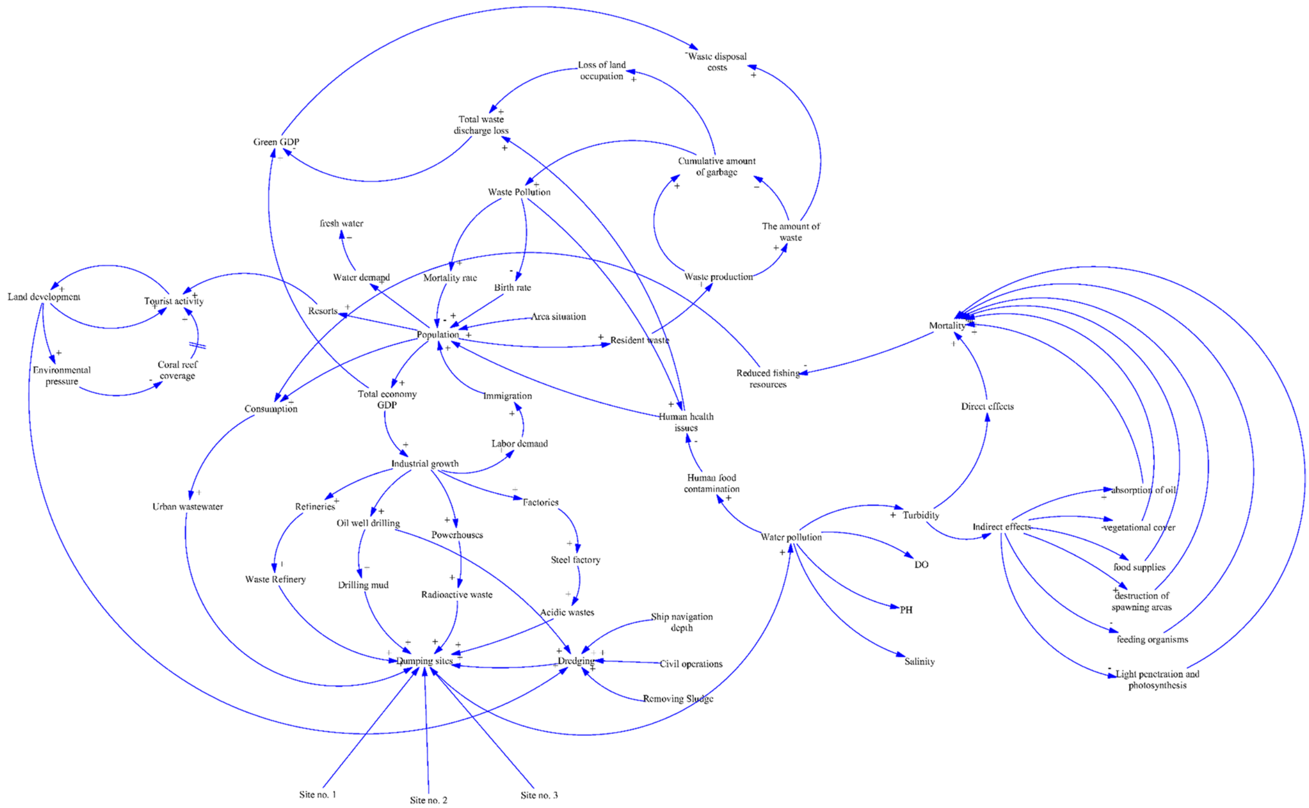
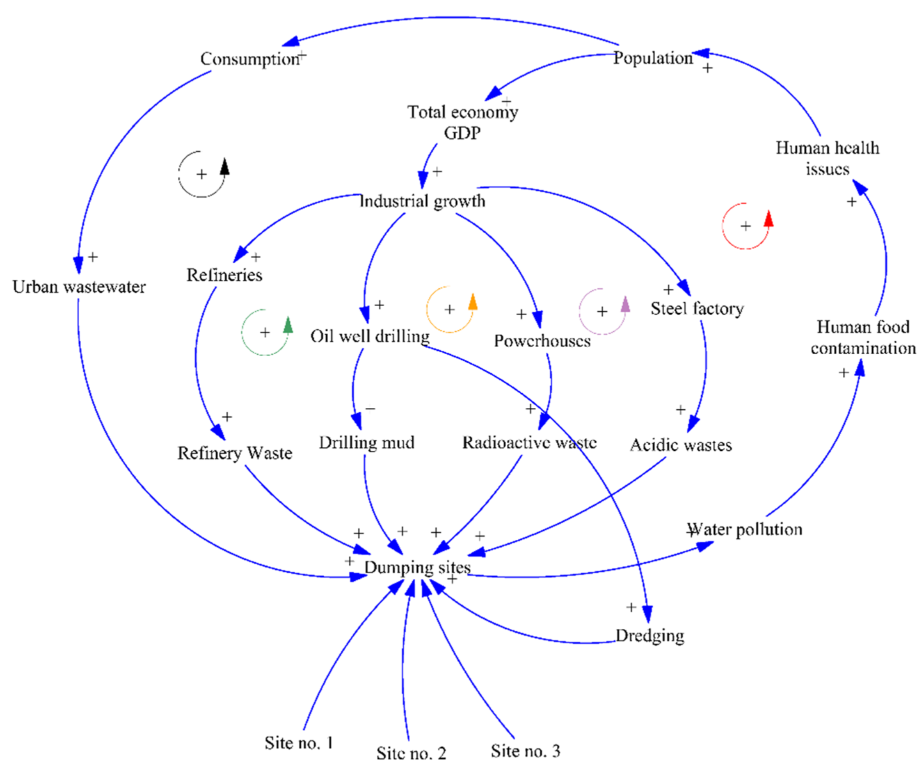


Fig. 4 Causal loop diagram

Fig. 5 Causal loop diagram for dumping site selection



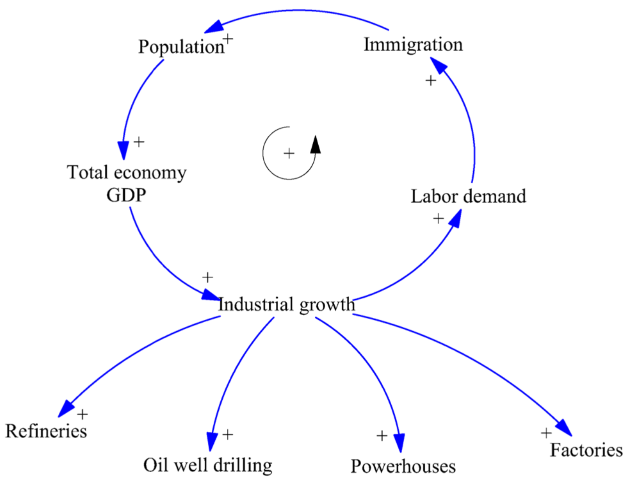


Fig. 6 Causal loop diagram for the industrial sector

contamination of aquatic life by water pollution endangers the public's health in many coastal communities where marine life is the primary source of nutrition for residents.

The variables associated with the reinforcing and balancing loops (+) of the causal loop diagram shown above are explained as follows:

Black reinforcing loop: population, consumption, urban sewage, waste generation, waste pollution, community health, population;

Green reinforcing loop: water pollution, human food pollution, community health, population, consumption, urban sewage, dumping sites, water pollution;

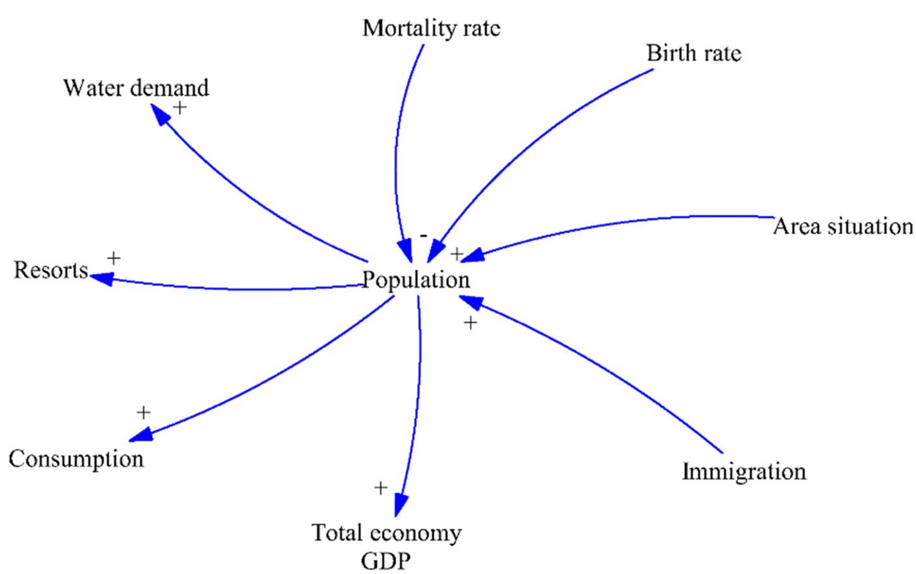
Red balancing loop: water pollution, water turbidity, aquatic mortality, fishery resources, consumption, urban sewage, dumping sites, water pollution.

Conclusion

This study adopted a dynamic systems approach to examine the most significant aspects that directly and indirectly impact the marine environment. Our results suggest that CLDs are a reliable tool for comprehending social impacts and processes as the first step toward quantitative modeling. There were discovered visualizations, exchanges, and dynamic processes that could aid policymakers and decision-makers in reinforcing positive changes, avoiding negative changes, and, if necessary, balancing the impacts. It is suggested that the determining variables should be filled with data and incorporated into relevant factors. The suspended sediments and sewage disrupt environmental cycles at dumping sites during discharge. By increasing turbidity, this issue impacts the lives of marine species, degrades water quality in general, and has negative consequences on human health.

Due to the significance of the topic and recent studies, the most significant of which have been addressed, we observe a research gap: there is no correlation between the problems caused by dumping sites and the marine environment. As a result, the issues raised have not been thoroughly examined, nor have their consequences been observed. The most significant aspects that directly and indirectly impact the marine environment have been thoroughly examined in this study by applying the dynamic system.

Fig. 7 Causal loop diagram for population sector



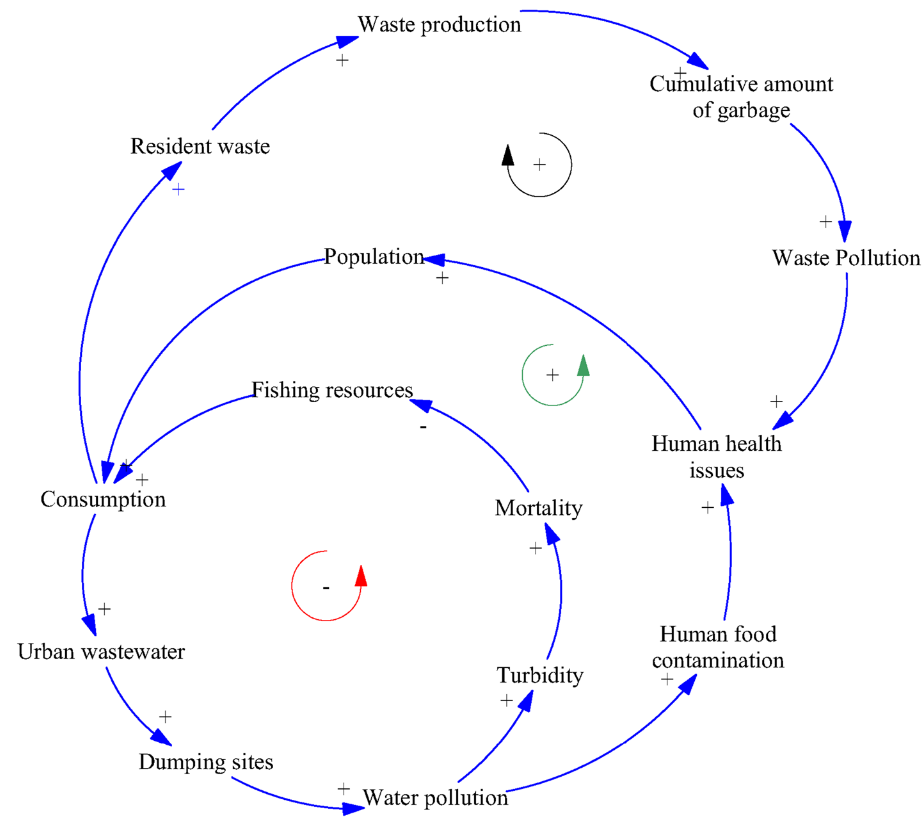


Fig. 8 Causal loop diagram for the water pollution sector

Author contributions Conceptualization, SHM, and MRK; methodology, SHM.; software, SHM.; formal analysis, SHM.; investigation, SHM.; writing—original draft preparation, SHM; writing—review and editing, SHM, MRK, and JLGA; supervision, MRK. and JLGA. All authors have read and agreed to the published version of the manuscript.

Funding The authors received no financial support for this article's research, authorship, and publication.

Data availability statement The data presented in this study are available on request from the corresponding author.

Declarations

Conflicts of interest The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and falsification, double publication and submission, and redundancies, have been completely observed by the authors.

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