POLITECNICO DI TORINO

Master's Degree in Environmental and Land Engineering

Climate Change

Master's Thesis

Sustainable coastal development: a comparative analysis of environmental impacts between floating platforms and dredging

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Glossary

BD Bucket Dredger. 7, 9, 10

BHD Backhoe Dredger. 7, 9, 10, 32

CSD Cutter Suction Dredger. 7, 9, 32, 34

DVM Diel Vertical Migration. 84

FNU Formazin Nephelometric Turbidity Unit. 26

GD Grab Dredger. 7, 9, 10, 32

GHG Greenhouse gas. 4, 97

GMSL Global Mean Sea Level. 4

MOREnergy Lab Marine Offshore Renewable Energy Laboratory. 13

NTU Nephelometric Turbidity Unit. 26, 68

OWF Offshore Wind Farm. 17, 34, 51, 52, 86

PTS Permanent Threshold Shift. 66, 67

RCP Representative Concentration Pathway. 4

SDG Sustainable Development Goals. 13

SI Surface Irradiance. VI, 75, 79

SLR Sea Level Rise. 4, 10, 13, 95

SPL Sound Pressure Level. 32, 89

SPM Suspended Particle Matter. 79

SS Suspended Sediments. 68, 69

SSC Suspended Sediment Concentration. 26, 79

SSP Shared Socioeconomic Pathway. IV, VI, 4, 5, 95, 96

TSHD Trailing Suction Hopper Dredger. 7, 8, 9, 32, 33, 34, 46

TSS Total Suspended Solids . 26

TTS Temporary Threshold Shift. 66, 67, 72

VLFS Very Large Floating Structure. 25, 50

Abstract

The rising sea levels and scarcity of available land for construction in rapidly growing coastal cities have led to the necessity of expanding towards water, in a process known as land reclamation. The SEAform project is designed to address these challenges by creating self-sufficient communities integrated with the marine environment, using interconnected modular floating platforms. The aim of this thesis is to assess the environmental impacts of the floating platforms within the marine ecosystems and to demonstrate the sustainability of this solution by comparing it with dredging, the most commonly used technique in land reclamation projects.

Through a comprehensive literature review, the thesis examines both documented and anticipated impacts of similar projects.

It provides an overview of the interactions between floating platforms and the marine environment – including shading effects and the creation of new habitats underneath the structure – as well as the impacts of dredging, such as turbidity and the physical destruction of habitats, distinguishing between the construction and operational phases.

A systematic and non-site-specific comparison is facilitated by developing an impact matrix that assigns scores to evaluate the spatial and temporal extent of each stressor. Furthermore, the thesis identifies potential receptors, including marine mammals, fish and benthic ecosystem, describing their sensitivity towards the stressors.

The results of the analysis concludes that floating platforms have a considerably lower environmental impact than dredging, thus validating the sustainability of the SEAform solution.

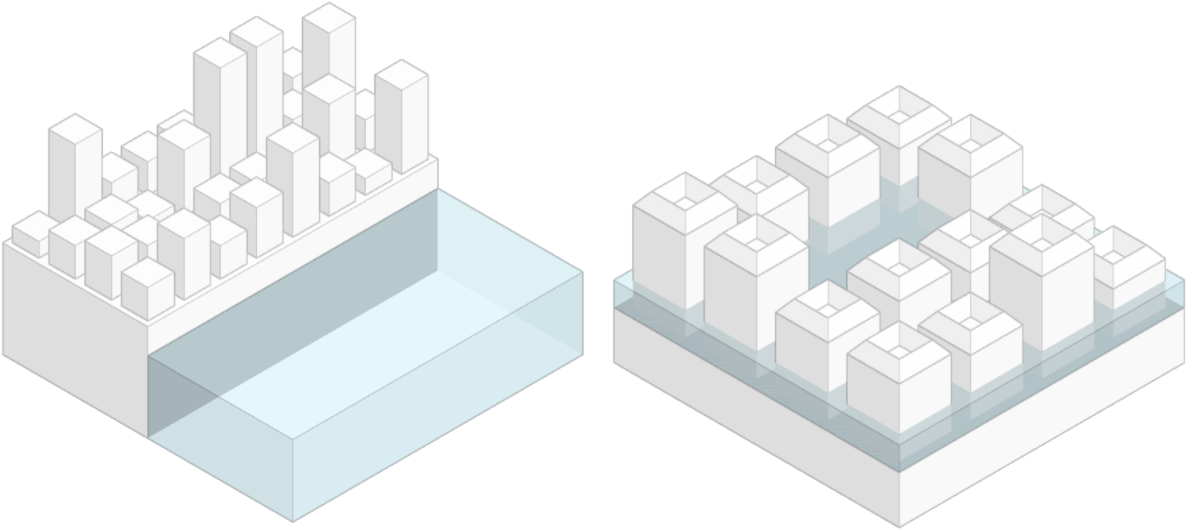
Finally, the thesis offers recommendations and guidelines for the SEAform project, rooted in the evaluated environmental aspects.

In conclusion, this thesis offers a comprehensive analysis of the environmental impacts of dredging and floating platforms, the greater sustainability of the floating platform solution, and presents project guidelines to ensure an environmentally conscious urban development in marine ecosystems.

Chapter 1

Introduction

Major coastal cities are globally expected to face, or are already experiencing, two main challenges: population growth and rising sea level, as shown in Fig. 1.1.



(a) Increasing urbanization (b) Rising sea level

Figure 1.1: The two main challenges of coastal cities: on the left, the need of land due to rapid urbanization; on the right, the risk of flooding due to sea level rise. From [1]

Currently, half of the global population resides in cities, and by the year 2050 over 80% of the anticipated global population of 9 billion individuals is projected to reside in urban areas [2]. Additionally, it is expected that 50% of the population will be living within a 100 kilometer distance from the coast [3]. This trend is likely to result in a scarcity of land in urban regions and escalate both the quantity and susceptibility of individuals exposed to the risks of flooding [4].

The ongoing trend of population convergence into urban areas is leading to the persistent conversion of rural land into urban spaces, creating a scarcity of available land for essential functions such as food production [5].

This extensive transformation not only affects the quantity of land dedicated to agriculture but also induces changes in land permeability. Urbanized land tends to suppress natural water filtration processes, which generates an imbalance in the urban water cycle.

This creates a potential hazard for flooding due to increased volume of storm water runoff coupled with potential sewer overflows [6].

Regarding climate change challenges, more extreme weather conditions and rising sea levels lead to vulnerability of coastal cities to the risk of flooding. As explained in the IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019) [7], the future increase in Global Mean Sea Level GMSL, driven by glacier and ice sheet melting, thermal expansion and changes in land water storage, is significantly influenced by the choice of Representative Concentration Pathway RCP emission scenario. The RCPs outline four distinct trajectories for greenhouse gas GHG emissions, air pollutant emissions,atmospheric concentrations and land use throughout the 21^{st} century [8]. These paths include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0), and one characterized by very high GHG emissions (RCP8.5); these scenarios correspond to radiative forcings of 2.6, 4.5, 6 and 8.5 W/m^2 respectively. Scenarios lacking additional measures to reduce emissions, often referred to as 'baseline scenarios,' fall within the spectrum of RCP6.0 to RCP8.5, while RCP2.6 represents a scenario designed to limit global warming to below 2^oC above pre-industrial temperatures [8]. Projections indicate a faster sea level rise (SLR) by the end of the century across all RCP scenarios. With respect to the reference period 1986–2005, GMSL is expected to increase between $0.43m$ (likely range: $0.29\breve{}0.59m$, RCP2.6) and $0.84m$ (likely range: $0.61\breve{}1.10m$, RCP8.5) by the year 2100 [7]. Under the RCP8.5 scenario, the rate of SLR is projected to be $15mm$ per year by 2100, potentially exceeding several centimeters per year in the 22^{nd} century [7].
An additional group of potential scenarios, known as Shared Socioeconomic Pathway (SSP), examines 5 different trajectories in which global society, economics and demographic could evolve over the next century, depending on the extent of climate policy implementation [9]. In Fig. 1.2 four SSP scenarios of global SLR are presented [10]; the first three projections have a medium confidence, while the fourth scenario has a low confidence but cannot be ruled out due to the high uncertainties in ice-sheet processes. This scenario would have severe impacts, since the projected SLR could reach $2-5m$ by 2150 [9].

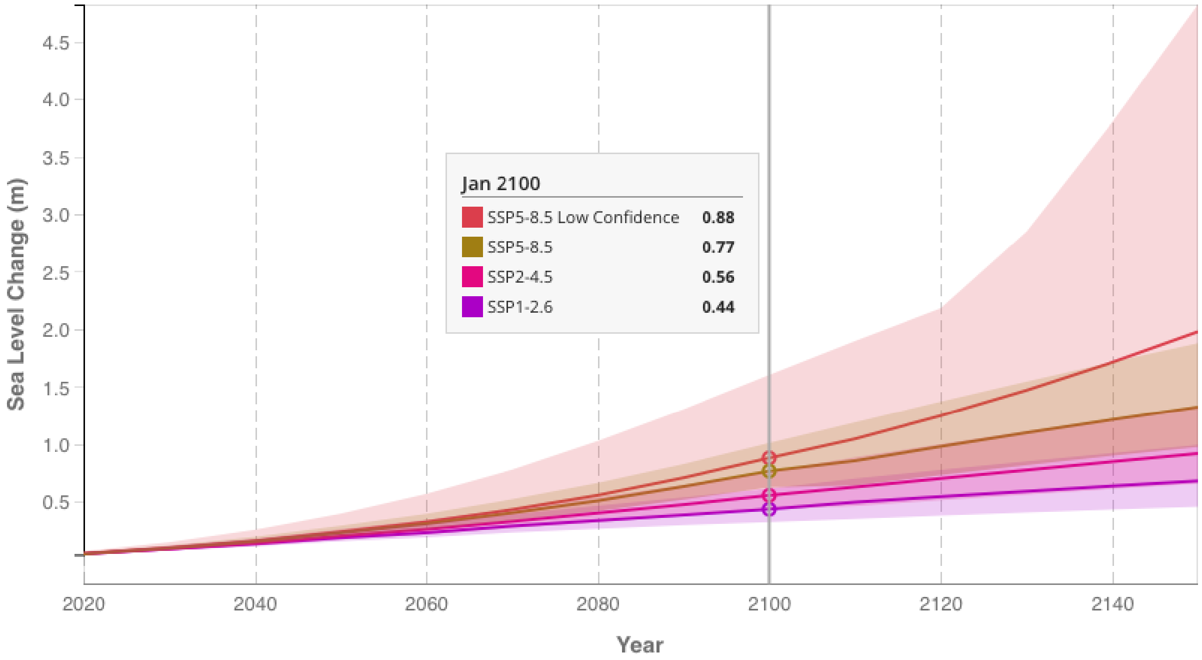


Figure 1.2: Global sea level rise for four different SSP scenarios. The shaded regions depict the $17^{th} - 83^{rd}$ percentile ranges, and the projections are relative to a baseline period of 1995-2014. Obtained from [10]

The expected sea level rise poses a threat for coastal cities, both for the further reduction of land and for the increased flood risk [4].
A solution to these problems is the expansion of urban areas over open water surfaces through the creation of new land, a process commonly referred to as land reclamation [5].

Land reclamation, the process of creating new land from the sea, typically involves filling an area with heavy rock, cement, clay, and soil until the desired height is achieved, in a process called filling [11]. The modern era of land reclamation began in the 1970s with significant projects like the extension of the Port of Rotterdam in the Netherlands, which covered an area of 2000 ha and employed 170 $million\ m^3$ of construction materials [12]. The practice swiftly expanded globally, with notable examples such as the Netherlands, Singapore, Hong Kong [12], and a significant portion of the mainland China coastline [13]. For instance, Singapore's Changi Airport was constructed with over 40 $million\ m^3$ of sand reclaimed from the seabed [11]. Artificial islands, such as Kansai International Airport in Japan and Hong Kong International Airport, are another example of land reclamation projects. The Flevopolder, with an area of 970 km^2 in the Netherlands is the largest reclaimed artificial island globally [11]. Within the OSPAR region, which refers to the North-East Atlantic [12], the Netherlands has the largest land reclamation sites, either completed or planned, in terms of amount of construction materials employed and surface area [12]. The spatial extent of land reclamation sites of the OSPAR Contracting Parties is presented in Fig 1.3. The scale of land reclamation activities reported by Ireland and the Netherlands significantly surpasses those of the other countries. In Ireland's case, all reported reclamation activities occurred before the 1980s and involved the improvement or reclamation of land that had formerly been below the high water mark [12].

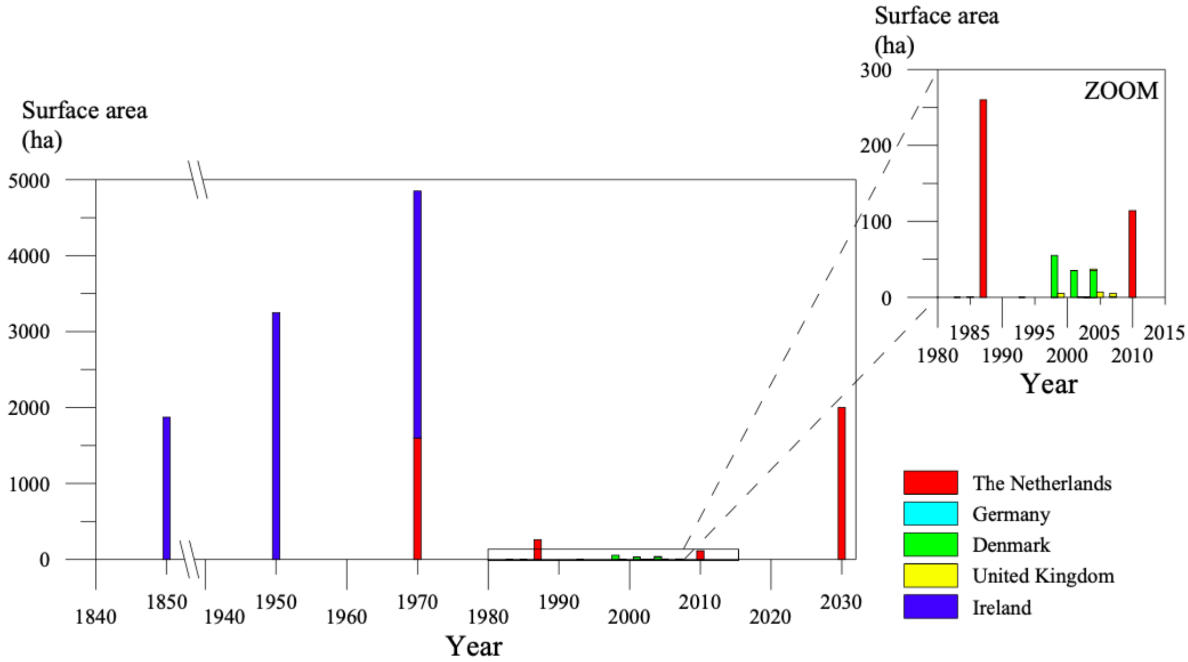


Figure 1.3: Surface area of land reclamation sites of the OSPAR Contracting Parties by year of completion. Obtained from [10]

However, land reclamation comes at a cost. The permanent loss of marine habitats is a significant consequence, with approximately 51% of coastal wetlands in China estimated to have been lost due to this process [13].
Hence, the demand for a more environmentally conscious land reclamation method arises. This need is met by a novel adaptive urban development method over water, represented by floating structures, that will be described in more detail in paragraph 1.2.

The flow-path from coastal cities challenges to land reclamation solution is provided in Fig. 1.4:

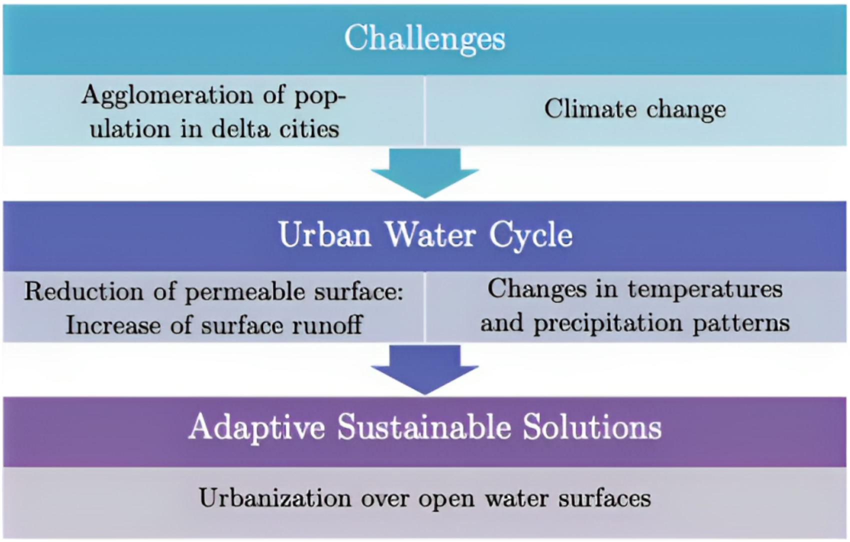


Figure 1.4: Flow-path of the problem that leads to the necessity of land reclamation. From [5]

1.1 Dredging

As mentioned, filling for land reclamation foresees the use of external material to fill an underwater area. Said material can be obtained from dry earth movement, and from excavation of material from underwater environment, with a process called dredging. In case dredged material is used, the type of filling is called “hydraulic” [14].
Dredging is a very ancient technique [15], with earliest mentions in Tacitus’ “Annals” [16], and direct archaeological evidence for the ancient harbours of Naples and Marseille [17]. The typical use of dredging, in fact, is not land reclamation but expansion, cleaning from soil or debris and maintenance of harbour, basins, and canals. When dredging is used with this scope, it is also known as “capital dredging” [18]. When the removed material is intended to be used in land reclamation activity, dredging is called “borrow dredging” [18]. Any dredging process follows the same 4 consecutive activities:

i Dislodging of the dredged material: dredgers, which can be of different types described in paragraph 1.1.1, dislodge, with various possible mechanisms, the material in the dredged site. The type of material dictates the type of dredger to be used, as for example, hard rock material will require the use of the cutter head present on CSD [18].

ii Raising the material to the surface: the obtained material, whether through borrow or capital dredging, needs to be collected to be either relocated or anyway removed from the interest site. This can be performed with mechanically raising the material with a bucket (as happens in so-called mechanical dredgers GD, BHD and BD), or with a suction (in the so-called suction dredgers, CSD, TSHD) [18].

iii Transport of the material to the placement site: depending on the type of dredger, the material is moved with different techniques. Mainly, it can be stored in on-board or off-board barges, or directly transported with hydraulic pipelines (more common for hydraulic dredgers) [18].

iv Placement of the material at the placement site: this phase differs between capital dredging and borrow dredging. For capital dredging, disposal site choice is only dictated by potential contamination due to the disposal [18]. A classification of sediments contamination was developed by Van de Guchte *et al.* (2000) [19] to formulate the Dutch policy, and it divides them in five classes, ranging from 0 to 4 as described in [20]:

  - Class 0: clean sediments, with a concentration lower then the negligible concentration NC, calculated as 10% of the NC_5;
  - Class 1: with a concentration lower than the maximum permissible concentration MPC, defined as the concentration at which 95% of the species are protected NC_5
  - Class 2: with a concentration lower than the limit between dispersible and non-dispersible sediment EQS_{n-nd}, calculated as the geometric mean of HC_5 and HC_{50};
  - Class 3: with a concentration lower than the intervention value IV, defined as the concentration at which 50% of the species are protected NC_{50}

- Class 4: with a concentration higher than IV.

Only class 0, 1 and 2 are allowed to be dispersed in the environment, with remediation to increased risks to be foreseen for class 2. Class 3 and 4 are not suitable for environment disposal but have to be stored in depots, or remediated [20].
In borrow dredging, instead, the retrieved material is used in the target site. Placement of the material may happen underwater, as is possible on TSHD, where the hopper bottom doors are opened and the material is free to fall on the water bed, or directly on the land. Placement on the land may happen via pumping of the mixture of dredged material and water through pipelines, or via rainbowing, which is a technique consisting in spraying the mixture through a nozzle, in a bow shape resembling a rainbow [18].

Most of the literature present, and cited in this work, refers to capital dredging. Due to the fact that removal of material is also present during borrow dredging activity, these publications have been considered to be applicable also for the environmental impacts of borrow dredging.

Land reclamation with dredging has been extensively used in the past, and is still at the center of future expansions. A few notable examples, taken from [21], include:

- Palm Jumeirah, Dubai: maybe the most recognisable land reclamation project, Palm Jumeirah is an artificial island with a surface of 5.6 km^2 shaped as a palm tree enclosed by a crescent moon, built between 2001 and 2008. The island was created to increment the economy of Dubai, as it is home to luxury hotels and housing. Along with sister islands Palm Jebel Ali and Palm Deira, they form the Palm Islands complex, with a projected total surface of $\sim 60\ km^2$, once construction of Palm Deira, the biggest one, will be completed [21].

- World Islands, Dubai: alongside the Palm Islands, this is a 300-islands archipelago with the shape of the world when seen from above, destined to luxury housing. It covers a surdace of $\sim 54\ km^2$ [21].

- Lantau Tomorrow Vision, Hong Kong: this project, still to be started, aims to create up to 1.1 million of new homes for the overcrowded Honk Kong, with creation of a 18 km^2 system of artificial islands off the Lantau Island. Its incredibily high cost (HK\$624 bn) and environmental concerns have caused fierce opposition from its first publication [21].

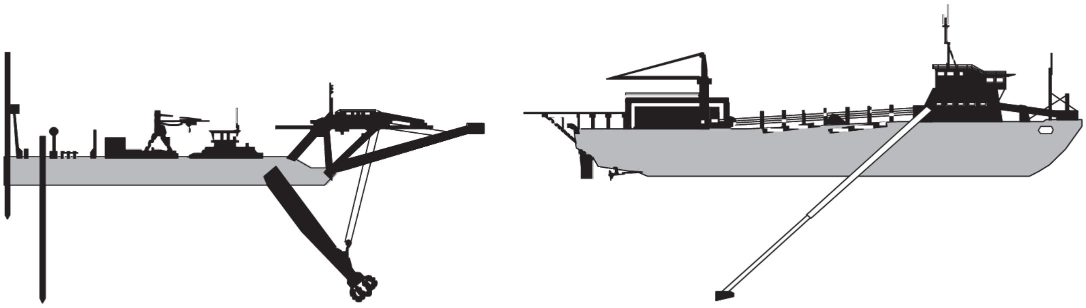
- The Great Garuda, Indonesia: this project, which takes the name from the mythical bird present on Indonesia's coat of arms, foresees the creation of 17 artificial islands, of which only 4 have been completed to date, to defend Jakarta from the extreme sinking that it is experiencing. The projected total surface would be 12.5 km^2 [21].

- Eko Atlantic City, Lagos, Nigeria: this project is a planned city in the Lagos State with a total surface of 25^2, planned to reduce erosion and provide housing to at least 250000 residents. Despite the motivation being the reduction of erosion, this project has been ovserved to create a change in water flows, causing a greater erosion in neighbouring areas [21].

- Marina Bay, Singapore: this 3.6 km^2 area, which nowadays constitutes the downtown of Singapore, was built entirely on reclaimed lands, with activities started in the 1970s and concluded 1992 [21].

1.1.1 Dredger types

There are two categories of dredgers: the suction dredgers and the mechanical dredgers [14].
Suction dredgers take advantage of the erosive power of water flow, often helped by jets attached to the suction mouth of the dredger. This process dislodges the material to be dredged, creating a sand-water mixture, which is then pumped through a discharge pipeline, either directly to the reclamation site or into a barge located alongside the dredger. This method efficiently transports the dredged material for further use or disposal. Typical suction dredgers are Cutter Suction Dredgers (CSD) and Trailing Suction Hopper Dredgers TSHD.
Both CSD and TSHD use a combination of mechanical and suction dredging. Both break the soil with a mechanical action, which is then loosened with the water motion and subsequently suctioned out by the pumping action of the dredger. The main difference between the two types is that the cutter head equipped on CSD is able to break soil that could be too hard for a TSHD. Other differences include the mobility, as are typically self-propelled, whereas CSD are more commonly non propelled, even if self-propelled CSD exist, and the storage of dredged material, as are equipped with a hopper contained within the hull of the dredger, capable to store the material, with capacities up to 40000 m^3, whereas CSD typically offload the material through pipelines to an external hopper or directly ashore [22].



(a) Cutter Suction Dredger CSD (b) Trailing Suction Hopper Dredgers TSHD

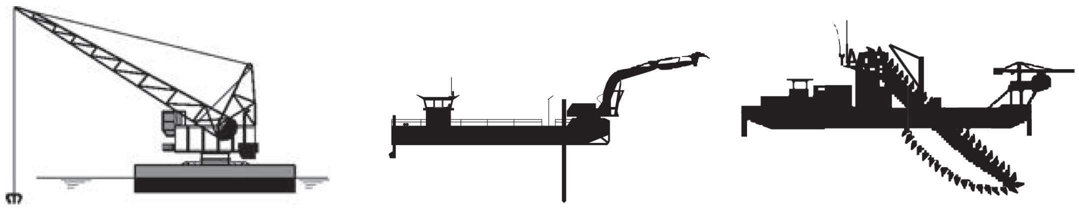
Figure 1.5: The two types of suction dredgers. From [14]

Mechanical dredgers are stationary and they use a grab or a bucket to cut and collect the material, which can be subsequently placed on land or in a barge near the dredger, or stored in the dredger's hopper [14]. Typical mechanical dredgers are Grab Dredgers (GD), also referred to as Clamshell dredgers, BackHoe Dredgers BHD and Bucket dredgers BD [14].

The GD consists in a wire crane mounted on a pontoon and is anchored either by spuds or wires. This type of dredger employs a wire-suspended grab, so its maximum dredging force depends solely on the grab's weight and design and it can extract less strong materials compared to the BHD [14].

The BHD is a hydraulic excavator mounted on a pontoon, equipped with spuds that anchor it and elevate the pontoon, enabling significant excavation forces on the seabed. Backhoe dredgers can be employed for compacted sand, stiff clay, and weak rock, varying based on pontoon size and capacity [14].

The BD consists in a series of buckets, mounted on a ladder driven by a chain. The material is cut by the buckets themselves, which are also used to bring the material on board, where they are turned upside down and emptied on a tumbler [14].



(a) Grab Dredger GD (b) Backhoe Dredger BHD (c) Bucket Dredger BD

Figure 1.6: The three types of suction dredgers. From [14]

1.2 Floating structures

The concept of living on water is not new. Floating houseboats are currently present worldwide, especially in the Netherlands [5]. However, there's a renewed perspective on this idea, particularly in terms of future implementation. Current designs of floating houses allow for the expansion of cities over water surfaces, from ponds and lakes to potential ocean locations.

Floating structures, as shown in Fig. 1.7, have many benefits compared to traditional inland buildings, as discussed by Porporato (2023) [23]:

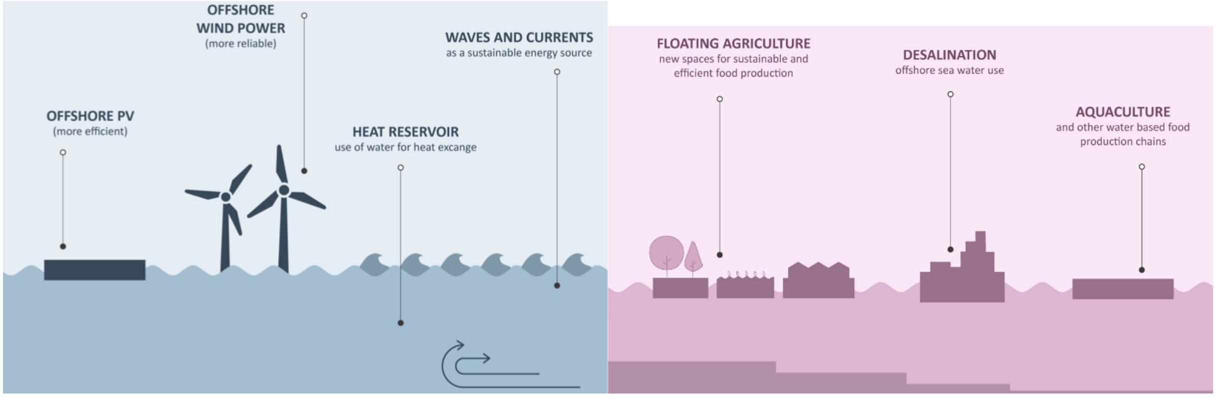
- Additional construction ground (Fig. 1.7a): as previously explained, urban expansion towards water is a solution for coastal cities with a lack of space problem [5].
- Mobility (Fig. 1.7b): if necessary, floating structures can be relocated, either due to changes in local conditions, personal necessities or optimization of solar energy inputs [24]. This additional flexibility and reversibility is a valuable advantage in addressing uncertain future developments, including the impacts of climate change [25].
- Resilience and adaptation (Fig. 1.7b): due to their ability to remain above the water surface during level changes and extreme weather conditions, floating structures are virtually immune to SLR and flooding. Implementing this technology to vulnerable cities provides secure housing for populations in flood-prone areas [23]

- Use of alternative energy resources (Fig. 1.7c): floating architecture offers significant opportunities for harnessing renewable energy from seas and oceans, with technologies such as offshore wind farms and floating photovoltaic plants. In open sea environments, these systems can optimize solar radiation access, achieving efficiencies 10-15% higher than land-based photovoltaic systems due to the cooling effect of water [26].
  Moreover, the flat landscape of water bodies and the consistent sea breeze contribute to a more continuous and reliable wind regime compared to the unreliable production of wind energy in inland areas [27].
  Additionally, innovative systems, such as wave energy converters, are able to harness the energy of waves and currents, introducing new renewable energy sources [23].
  Seawater's potential as a heat reservoir is also being explored for heating and refrigeration systems, with the unique temperature characteristics of seawater presenting opportunities to reduce the energy demand of floating buildings [28].

- Food and water access (Fig. 1.7d): expanding food production on water through floating architecture offers a sustainable solution to meet and diversify the global demand for increased food production [29]. For agricultural production, greenhouses and correlated innovative techniques, such as hydroponic, can benefit from the unlimited space, sun radiation and water [25]. Moreover, the higher resilience to droughts and temperature extremes contributes to global food security [23]. Aquaculture, including fish and mussel farming, is an additional source of food production suitable for floating structures [23]. For water availability, floating desalination plants could sustain both agricultural and human consumption, and could represent a solution for countries with unreliable water access in case of emergencies [30].

- Urban strategies (Fig. 1.7a): floating structures provide a chance for urban densification by utilizing gaps in existing cities near water bodies. Moreover, they can be an opportunity for upgrading vacant and degraded water lots in delta regions and coastal cities, such as ports that have lost their commercial function [25], old docks and post-mining lakes [24]. These areas, impacted by historical industrial activities, often suffer from low water quality and biodiversity [23]. Floating architecture offers a promising approach to repurpose these underutilized spaces, with a focus on minimizing environmental impacts within already altered ecosystems [23].

(a) Urban development (b) Resilient housing



(c) Alternative energy resources (d) Food and water production

Figure 1.7: Four categories of floating architecture's advantages: (a) urban development, (b) resilient housing, (c) alternative energy resources, (d) food and water production. From [23]

On the other hand, floating structures may encounter challenges due to the unique environment of water and its physical and chemical properties, which include strong environmental loadings such as winds, waves and currents, material corrosion and the more complex management of energy and water supply compared to inland conditions [24]. Furthermore, for a comprehensive overview of the challenges posed by floating communities, additional factors should be taken into account. These include societal acceptance, legal and governance considerations, as well as the comfort of occupants [31]. Moreover, the incorporation of a floating structure into the aquatic ecosystem needs a thorough analysis of its impacts to ensure the sustainability of the solution [23].

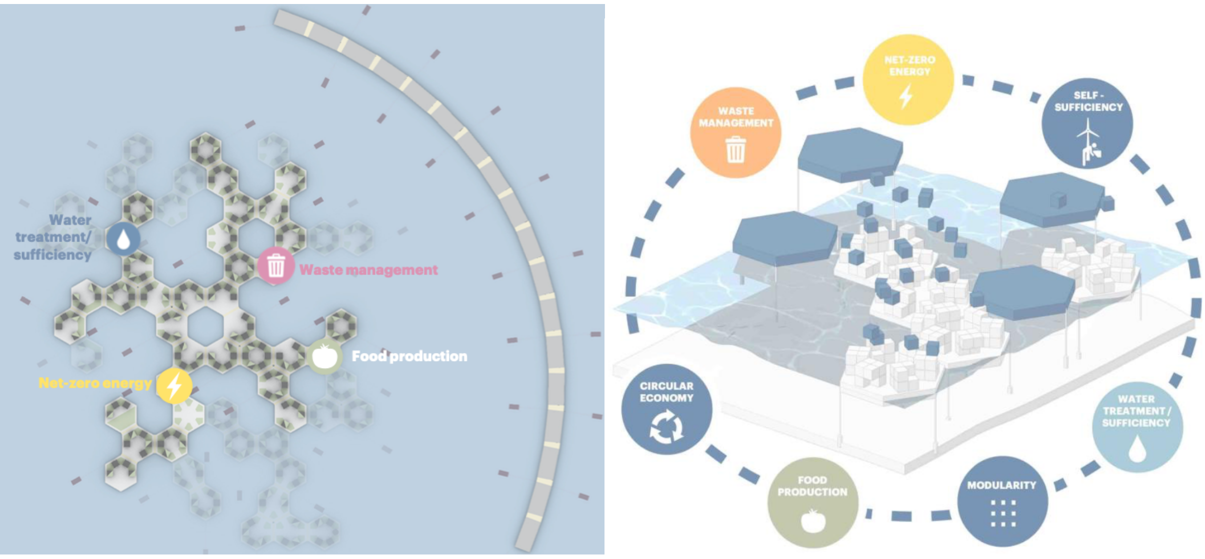
The creation of an entire floating community is evidently a complex process that involves a broad spectrum of aspects to take into account, making a multidisciplinary approach crucial for addressing these challenges comprehensively. However, this thesis will specifically concentrate on the challenges arising from the environmental impacts, limiting the scope to this aspect.

1.2.1 SEAform

SEAform is a project created within the Marine Offshore Renewable Energy Laboratory (MOREnergy Lab), which is a research centre at Politecnico di Torino, specialised in offshore renewables [32]. The project vision is “to make life on water possible, sustainable and non-impacting for the ecosystem”, while its mission is “to support the gradual migration to the sea with engineering solutions and technologies” [1]. The Sustainable Development Goals (SDG) that this project aims to address are shown in Fig. 1.8:

Figure 1.8: Sustainable Development Goals that SEAform project aims to address. Adapted from [33]

The SEAform project is designed to address the coastal cities challenges by creating self-sufficient communities integrated with the marine environment, using interconnected modular floating platforms [1]. The platforms are anchored to the seabed and, if in open sea, protected from wave action by floating breakwaters. In order to ensure self-sufficiency, energy and food production as well as waste treatment and water management will be integrated in the solution, creating floating communities based on the concepts of sustainability and circular economy [34]. The aim of SEAform is to minimize the impacts of its solution on the marine environment, creating a viable solution for cities facing SLR and increasing urbanization [1]. Concept designs are provided in Fig. 1.9:



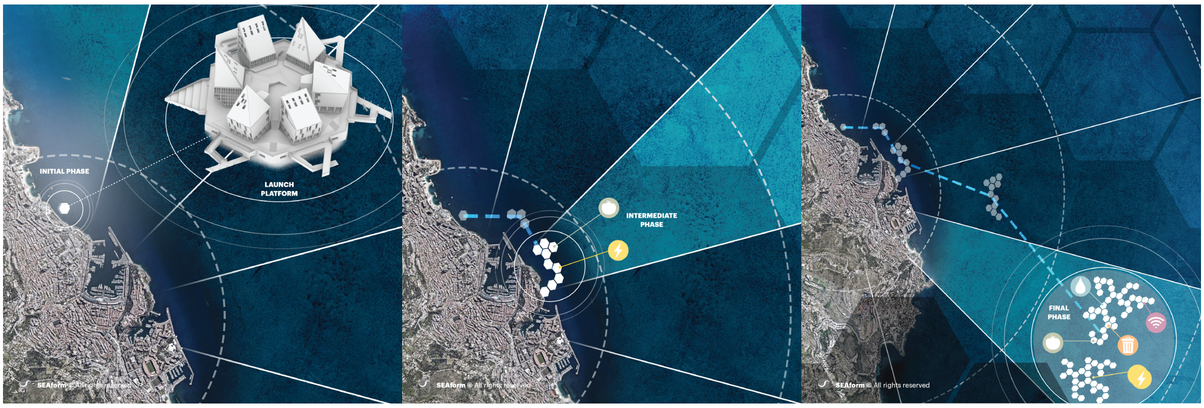
(a) Project concept 1 (b) Project concept 2

Figure 1.9: SEAform concept. From [34]

SEAform advantages with respect to other land reclamation techniques are [34]:

- Low environmental impact: compared to dredging technique, the proposed solution does not interfere with current circulation and sediment transport. Furthermore, unlike traditional floating structures, the mooring system has a minimal impact on the seabed, as there are no mooring lines on the seafloor.
- Adaptability to various bathymetries: the suggested solution enables installation at greater depths than dredging, with a significantly lower increase in costs.
- Scalability and modularity: the modular and standardized approach, compared to monolithic structures, permits the extension of the surface freely, based on investment requirements. The platforms can be linked, seamlessly transitioning from block size to the scale of a floating city. The structures of the buildings can be readily disassembled and repurposed, and the entire project is easily transportable [1].
- Lower construction costs and times: standardizing the platform system allows replicapibility, leading to cost savings.

SEAform's program comprises three key milestones, as shown in Fig. 1.10: the initial phase starts with the design and realization of a small-scale floating pavilion, useful to perform the first tests for both design and technology; the intermediate phase would consist in a full-scale floating complex, characterized by an urban extension intervention; the final step is the establishment of a repeatable, expandable, and scalable model for autonomous and sustainable floating cities [23].



(a) Initial phase (b) Intermediate phase (c) Final phase

Figure 1.10: The three steps of SEAform's project development. From [1]

Chapter 2

Objectives

Due to the increasing and pressing demand for land in coastal cities, the significance of land reclamation projects is on the rise. It is imperative to minimize the environmental impact of these projects, particularly on the marine ecosystem. Among the potential solutions, floating platforms emerge as the most suitable option to strike a balance between meeting the growing need for additional space and protecting the marine environment. However, dredging has been the primary method for land reclamation, with extensively documented environmental drawbacks. To encourage attention and potential investment towards the adoption of floating platforms projects, such as SEAform, instead of dredging, it is imperative to clearly demonstrate the environmental benefits of this alternative approach.

Therefore, the primary objective of this thesis is to conduct a comprehensive evaluation and comparison of the environmental impacts associated with floating platforms and dredging. The underlying problem addressed is the lack of holistic comparisons between these two land reclamation methods, with a particular emphasis on the scarcity of information regarding the documented environmental impacts of floating platforms, given their relatively recent introduction. This study aims to answer key research questions: are the impacts of floating platforms on the marine environment lower than dredging? How can the higher environmental sustainability of floating platforms be demonstrated with support from existing literature? How can the identified impacts of floating platforms be mitigated through the implementation of project guidelines?

The scope of this thesis is to provide a generalized comparison that does not depend on the project's specific location, through a comprehensive literature review of the reported or predicted impacts of dredging and floating platforms. The comparison is expected to be mainly qualitative due to the nature of available data. Furthermore, the research aims to contribute to future floating platforms projects, such as SEAform, by formulating guidelines to mitigate and minimize the identified impacts and by proposing recommendations for integrating sustainable practices into the design and execution of these projects.

The research outcomes could be of interest to the scientific community engaged in land reclamation studies and stakeholders associated with the SEAform project or similar initiatives.

Chapter 3

Materials and method

To evaluate precisely the potential impacts of the two investigated land reclamation technique, a thorough literature review was in the early stages of this work.
Relevant works were searched mainly on the ResearchGate search engine, accessible at the address `https://www.researchgate.net/`. The main strings used to search the literature include, but are not limited to, a combination of the technique, which could be *"dredging"*, *"floating platform(s)"*, *"land reclamation"*, and of the aspect of environmental impact, adding with the *AND* boolean functions keywords such as *"impact"*, *"environmental impact"*. Other searches were focused on the stressors described in paragraph 4.2, combining the technique with the stressor, resulting in a search string as *"dredging" AND "noise"* or *"floating platform" AND "shading"*. Due to the fact that studies on floating platforms for land reclamation is still relatively low, studies for similar floating structures has been included in this review, with the scope to carefully extent the described impacts and characteristics to floating platforms. The majority of the environmental impact assessment has been performed for offshore wind farms OWFs [35], [36], and floating houses especially in the Netherlands [37], [38]. Similarly, for dredging often a classification in "capital" and "borrow" dredging is not made in the vast part of publications, results for both the scopes have been evaluated. In principle, environmental effects are similar for the two techniques, especially in the zone were the dredged material is obtained.
Results obtained were very diverse both in term of type of publication and of year of publications. Results found, analyzed and cited in this thesis, include environmental impact assessments of past [39] and future [40] projects, guidelines for land reclamation activities [18], manuals [14], literature reviews [41] and of course scientific articles, with older contributions coming from the 1960s [42].
Due to the dredging technique being relatively older, especially if considering not only the borrow dredging but also the capital dredging used for cleaning and freeing harbours and canals, the volume of literature for dredging was expected to be higher than the one for floating platforms. A graphic visualization of the yearly publications resulting from keyword "dredging impact" and "floating platform impact" searches in ResearchGate for the period 1974 to 2022 is provided in Fig. 3.1:

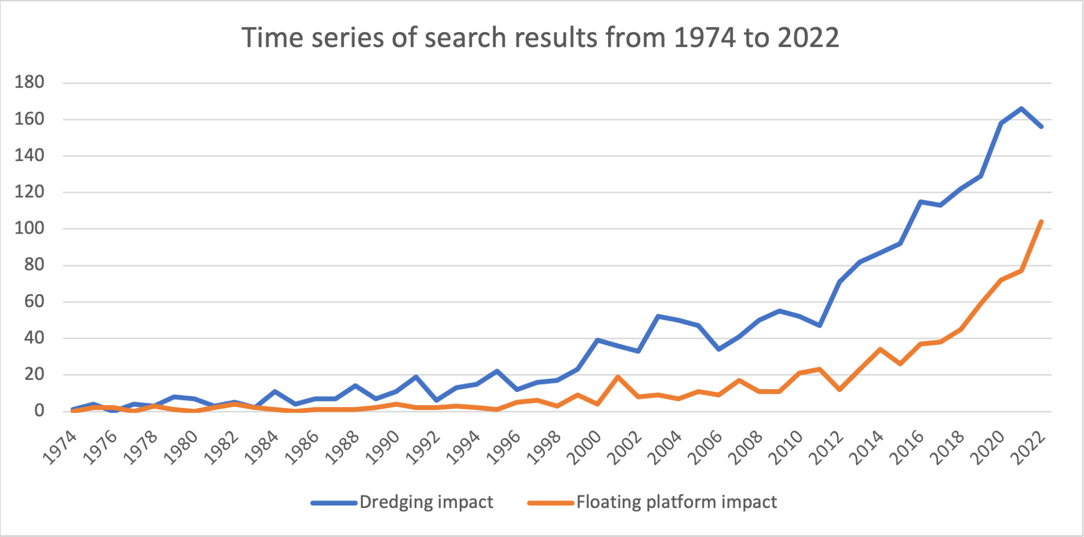


Figure 3.1: Overview of publications resulting from keyword searches “dredging impact” and “floating platform impact” from 1974 to 2022

It can be clearly see that the volume was bigger in this time frame for the dredging impacts, with a total of 2068 works published in this time frame, versus the 736 for the floating platform. It is otherwise visible how interest in recent years, especially the last decade, is rising: for example, in the latest complete year (2022), the output was closer between the two, with 156 publications for dredging and 104 for floating platforms.

Chapter 4

Results

In this chapter, a comprehensive analysis of the results obtained through the literature review is presented.

Firstly, a general overview of the interactions occurring between floating platforms and dredging and the marine environment is explained.

Subsequently, in order to perform a non-site-specific comparison, the main stressors that can act during the construction or operational phase of floating platforms and dredging are identified, described in detail and evaluated assigning a score to their spatial extent and duration. Each stressor significance is then assigned by combining the spatial and temporal extent values. The obtained stressor matrix for floating platforms and dredging are discussed and compared, arriving to the conclusion that floating platforms have a lower environmental impact.

Furthermore, a list of potential receptors that can be affected is described, assessing their sensitivity to the identified stressors.

4.1 General overview of impacts

Land reclamation projects always have an impact on the marine environment in which they take place. These impacts are often correlated to each other [12]. In this thesis the focus is on environmental impacts only, but it has to be noted that projects of this magnitude would also have major socio-economic impacts, that need their appropriate impact assessment [43]. In order to best describe and compare the environmental impacts that dredging and floating platforms have, it is useful to divide them according to the different phases of the project, as shown in figure 4.1:

- **construction phase**: in the case of dredging, it refers to the dredging of material, transport and placement of dredged material to create the land [14]; in the case of floating platforms, it involves transport and installation through mooring anchors and lines [44]. The construction phase of floating platforms on land is not described in this thesis, since the focus is on the impacts on the marine ecosystems;

- **operational phase**: it refers to the interactions occurring between the floating platforms or the dredged land and the marine environment in which they are located [45]. These interactions and their impacts can be further divided into those solely caused by the presence of a structure in the marine environment and those resulting from the activities that take place above the land or platform. While the first class can be generalized at some extent, the second class strongly depends on the land reclamation project's purpose, since a wide variety of activities can take place on the platforms or land. For this reason, the impacts that the activities can have on the marine environment are briefly described in this paragraph, but won't be included in the further detailed description about stressors. However, an example of a major impact caused by anthropogenic activities that is likely to occur in every land reclamation project is the artificial lightning, which is presented in paragraph 4.2.9.

- **decommissioning**: in the case of dredging, this phase corresponds to the cessation of activities carried out above the land and their impacts [45], but the impacts caused by the presence of the land itself remain, since it cannot be removed.
  On the contrary, floating platforms can be removed or relocated if needed [24]. The problem that arises considering this phase is the lack of practical experience so far [46], also considering similar existing projects such as the offshore wind farms. The potential impacts of this phase largely depend on the approach employed; for instance, the decision to remove all structures or leave below-ground elements like mooring anchors will significantly influence the outcome [46]. It can be assumed that the decommissioning process will involve many of the activities conducted during the construction phase, but at a reduced impact level [46]. Due to the lack of information and examples in literature, it is not currently possible to make further considerations on the decommissioning phase of floating platforms.

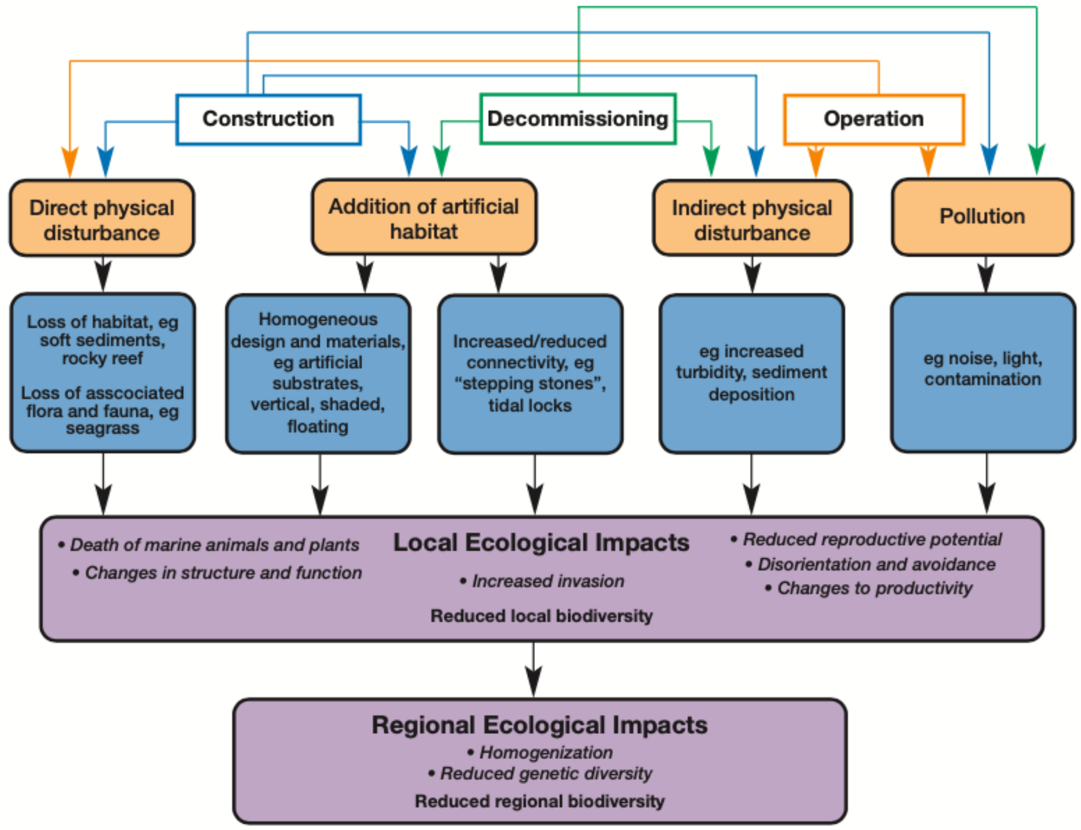


Figure 4.1: Three engineering phases (construction, operation and decommissioning) and their impacts. Habitat alteration in the orange boxes, examples of physical/chemical modifications in blue boxes, potential ecological impacts at local and regional scale in purple boxes. From [45]

The construction of new land by dredging takes place in several stages, each of which can have a major impact on the surrounding environment. Indeed, it is necessary to excavate the required material, lift it to the surface, transport it to the designated site, and then position it [14]. The main environmental impacts at these stages include:

- increased water turbidity and sedimentation, which causes a reduction in water transparency, visibility, light availability, and several major impacts on benthic organisms, reducing their feeding and reproduction rates and sometimes burying or even smothering them [47], [48], [49];
- resuspension of sediment and possible release of organic compounds, which can lead to a beneficial effect on benthic habitat, but can also cause eutrophication, reduced oxygen quantity due to an increased oxygen demand, and general deterioration of water quality [48], [50];
- potential release of contaminants if suspended sediments are contaminated, leading to mortality and effects on the trophic web [48], [51];
- physical destruction or damage to seafloor habitat, benthic organisms, and coral reefs and seagrass beds, causing a reduction both in biodiversity and suitable areas for shelter and breeding for many animal species, with effects on the trophic web [52], [51];

- noise produced by machinery used to excavate and transport sediments, possibly affecting the behavior of marine mammals and their ability to reproduce for example [53], [47], [54];
- increased collision risk between marine megafauna and vessels used to transport sediment [55].

Once the construction phases are completed, the main interactions that the new landmass will have with the surrounding environment are as follows:

- changes in hydromorphological regime, which includes alterations in currents, water circulation, wave motion, tides, and bathymetry [48]. These changes could lead to reduced water quality, coastal erosion, and modifications in habitat [56];
- changes in water physical-chemical parameters, such as temperature, salinity and pH [57], [58], [39].

Additionally, it is essential to consider the impacts on the surrounding environment caused by activities carried out on the constructed land. This land might be utilized not only for residential purposes but also for constructing major infrastructures such as ports, airports, and industrial zones, which can have a significant environmental impact. These activities typically affect the marine ecosystem through factors like noise, presence of artificial light, significant changes in water temperature, and water pollution due to improper management of residential wastewater and the release of toxic compounds from industries.

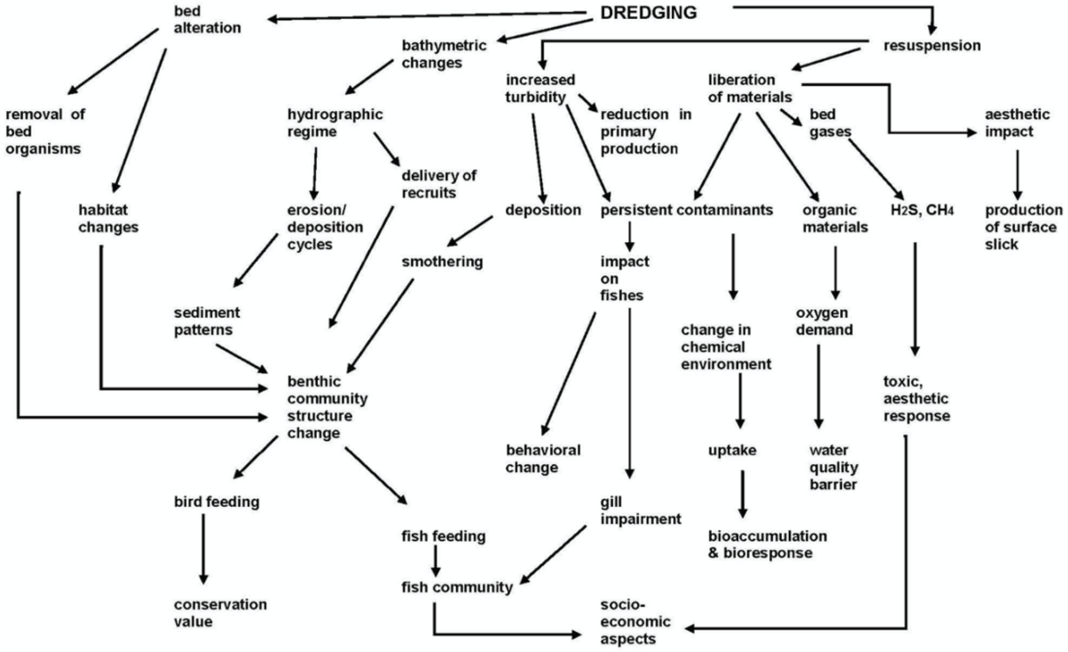


Figure 4.2: Scheme of potential impacts of dredging on the marine ecosystem, from [59]

On the other hand, the construction phase of floating platforms takes place mainly on land, and the only stages that have interaction with the sea are transport and installation. In these operations, the possible impacts are:

- Increased noise levels caused by ships transporting the platforms and by the installation of mooring anchors, which can then have effects on animal physiology and behaviour, based on the magnitude of increase [44];
- Water turbidity caused by the installation of mooring anchors, with temporary suspension of sediment causing a reduction in water transparency [60];
- Direct collisions between vessels used for transportation and marine megafauna and potential entanglement on mooring lines [61].

After its placement, the interactions the platform will have with its surroundings and the resulting impacts are:

- Reduced light exposure caused by the fact that the platform blocks incident sunlight, reducing photosynthesis both in the upper layers of water, where phytoplankton and small algae operate, and on the bottom [4], [44];
- Slight changes in water temperature trends ($\sim 0.5^oC$ [5]), also caused by the platform preventing solar radiation from reaching the water, heating it, and by the platform collecting heat during the first few hours of light and releasing it later, delaying the temperature peak, with negligible effects [62], [63];
- Slowing of surface currents, potentially resulting in sedimentation, or increased speed of surface currents, resulting in an increased erosion [44];
- Decreased dissolved oxygen, caused by the combined effects of limited water movement, sessile organisms colonizing the bottom of the shelf and consuming oxygen, and photosynthesis reduced by shade, resulting in reduced water quality [62];
- Release of toxic substances into the water from construction materials, such as concrete, plastics, wood, and steel components, which can have a major impact on the ecosystem in the case of release of heavy metals, even in small quantities [44];
- Creation of new habitat below the platform, which can be colonized by sessile organisms, increasing biodiversity and providing shelter and food for numerous species [4]. In particular, the bottom of the platforms is colonized by bivalves, which filter plankton and particles suspended in water by consuming or rejecting them, decreasing suspended sediment but increasing sediment deposition on the bottom. An accumulation of live and dead bivalve shells then forms beneath the shelf, creating an additional substrate for sessile organisms, but also increasing decomposition, further reducing oxygen levels near the water bottom [60], [4].

For the aim of this thesis, the impacts of further activities on the floating platform were not taken into account“ The goal of the SEAform project is to house independent floating communities on the platforms; consequently, the platforms will be primarily for residential use, and the activities that will take place will include energy production, food production, wastewater treatment, and waste management.
The impacts that these activities can have on the marine ecosystem must be minimized, and include noise, presence of artificial light, rising temperatures due to air conditioning

or heating systems, the release of substances used in agriculture that can lead to eutrophication of water, and the release of nutrients from wastewater, which must then be treated and filtered carefully, ideally going so far as to reuse it completely [44].

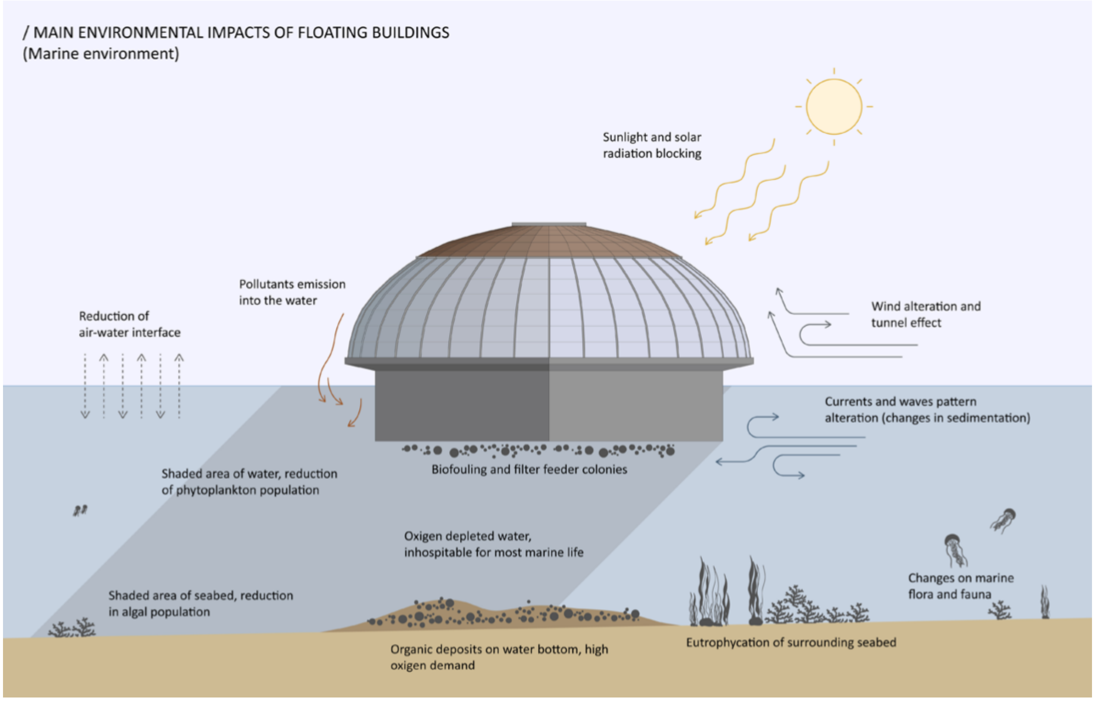


Figure 4.3: Scheme of main environmental impacts of a floating structure. From [60]

The extent of environmental impacts is influenced by a multitude of variables, with the selection of the land reclamation site being a significant factor. To facilitate a comparison of the environmental effects of dredging and a floating platform, it is necessary to initially delineate the stressors that can occur regardless of the project's location. Subsequently, we must specify the receptors that may be impacted by these described effects, which are contingent on the specific project location.

4.2 Stressors

A stressor, also known as pressure, is defined as a physical, chemical or biological change that can can cause an environmental alteration [64]. It is important to highlight that a stressor doesn't necessarily causes a negative impact on the environment.

4.2.1 Indexes identification for stressor matrix

After the identification of the main impacts, it is necessary to assign a score to them. The two characteristics that have been evaluated for each impact are the spatial extent and the duration. Other environmental impact assessments [44], [65] estimate also the magnitude and likelihood of each stressor. However, these factors are highly dependent on the specific site, whereas spatial and temporal extents can be generalized. Therefore, this thesis focuses solely on spatial and temporal extent, striving for a comparison that

is not site-specific. In order to ensure the independence of the assigned indexes from the specific location, percentages have been chosen over absolute values.
The spatial extent describes the area that is affected by the impact, and can assume the following values, as shown in Tab. 4.1:

1: $0-100\%$ of the dredged area/of the floating platform

2: $100-200\%$, covers an area that goes from the whole dredged land / floating platform to twice the dredged land / floating platform

3: $200-1000\%$, covers an area that goes from 2 times to 10 times the dredged land / the floating platform

4: $>1000\%$, covers an area more than 10 times larger than the dredged land / the floating platform

The duration describes the time over which the impact is happening, and can assume the following values, as shown in Tab. 4.1:

1: $0-25\%$ of each phase duration

2: $25-75\%$ of each phase duration

3: $75-100\%$ of each phase duration: the impact lasts up to the whole duration of the phase

4: $>100\%$ of each phase duration: the impact duration extends beyond the phase duration, resulting in its persistence even after the phase has concluded

Value	1	2	3	4
Spatial extent	0-100% dredged land/FP	100%-200% dredged land/FP	200%-1000% dredged land/FP	>1000% dredged land/FP
Duration	0-25% phase duration	25%-75% phase duration	75%-100% phase duration	>100% phase duration

Table 4.1: Impact matrix values

In the case of dredging, values have been assigned reviewing existing projects and the reported impacts that these projects had on the environment, and the results have been summarized in table 4.4. In the case of floating platforms, due to the innovation of this solution, few studies are currently available on the documented effects of similar projects, such as singular floating houses, very large floating structures (VLFS) or platforms used for offshore wind farms. Most researches regarding floating communities have only developed an environmental impact assessment, which is based on estimations of potential effects that floating platforms can have on marine ecosystem and freshwater, such as [44] or [65]. For this reason, a detailed table with numerical values can't be developed yet.

Once the values of spatial extent and duration have been assigned to each impact, impact significance can be estimated as a combination of the two, and can range from low (green) to medium (yellow) to high (orange) to critical (red), according to Fig. 4.4, which has been adapted from a similar impact significance table, described in [65]. The impacts classified as high and critical have to be carefully monitored and, when possible, mitigated, while the medium and low impacts could be acceptable, depending on the specific site's receptors sensitivity.

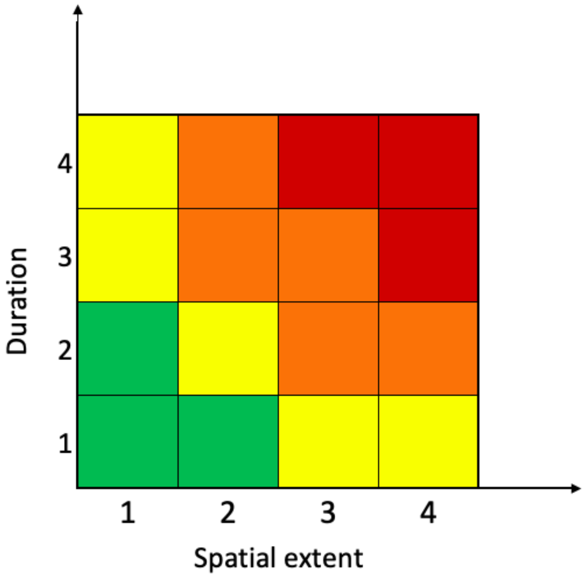


Figure 4.4: Impact significance matrix. The significance of green values is low, medium for yellow, high for orange, critical for red. Adapted from [65]

4.2.2 Turbidity and suspended sediments

Any activity that remobilizes the bottom material can cause the release of suspended sediments and, consequently, turbidity [66].

Turbidity is an optical property of water, that causes light to be scattered or absorbed rather than transmitted [48]. It is defined as "reduction of transparency of a liquid caused by the presence of undissolved matter" by ISO7027-1:2016 [67]. A turbidity plume is defined as "the horizontal (2D) and vertical extent of the water body containing suspended sediments" [68]. The term turbidity has therefore a dual meaning, indicating both the water transparency and the suspended sediments, since the transparency reduction is caused by suspended solids in the water column that, depending on their shape, size and refractive index, scatter light through absorption, reflection and refraction [48]. For these reasons, the concepts of suspended sediments and turbidity are discussed together.

Turbidity can be measured as Nephelometric Turbidity Unit (NTU) and Formazine Nephelometric Unit FNU, which refer to the light scattering in water, or as Suspended Sediment Concentration (SSC) and Total Suspended Solids (TSS), which refer to the amount of suspended sediment [66].

It depends on various factors, such as:

- Metocean (meteorological and oceanic) conditions: turbidity levels are influenced by the weather, bathymetry, morphology, currents, tides and waves typical of the specific location. Waves and currents in particular produce turbulence, which affects erosion, sediment resuspension, transport and deposition and thus turbidity [66];

- Water system: the type of water system influences the transmittance of surface light and therefore the water transparency. For instance, estuarine and coastal waters, which are characterized by an elevated concentration of dissolved material and plant pigment, often have a 56% transmittance, while the transmittance of the clearest oceanic waters can be as high as 98.2% [48];
- Sediments characteristics: sediments properties, such as type and size, determine the deposition velocity and light availability. Suspended sediments include organic material, such as algae and plankton, and inorganic solids, such as sand, silt and clay [69]. Large particles settle back quickly, whereas finer sediments could tend to be cohesive, sticking together and forming aggregates, in a process called flocculation, which increases their deposition rate [70].

The reduction of underwater light availability due to turbidity can lead to a decrease in photosynthetic processes, causing lower concentrations of dissolved oxygen in water. Additionally, animals that rely on vision for orientation, navigation and prey detection could be impacted by excessive lack of transparency. Suspended sediments could clog fish gills [48], and, when they redeposit on the seabed, they could cause coverage and smothering of benthic organisms, such as corals and seagrass [71].
A final aspect to consider is the fact that transitioning from a clear to a turbid environment is much more rapid than the reverse process, due to an effect known as hysteresis effect. As reported by the Foundation for Applied Water Research in 2008 [72], when a water system reaches a certain nutrient load it passes from a clear to a turbid state. Indeed, an higher amount of nutrients, such as phosphorus or nitrogen, attracts various organisms, such as algae and grubbing fish, which further increase turbidity [72]. Subsequently, the nutrient load that allows the system to transition back to a clear state is much lower, as shown in Fig. 4.5.

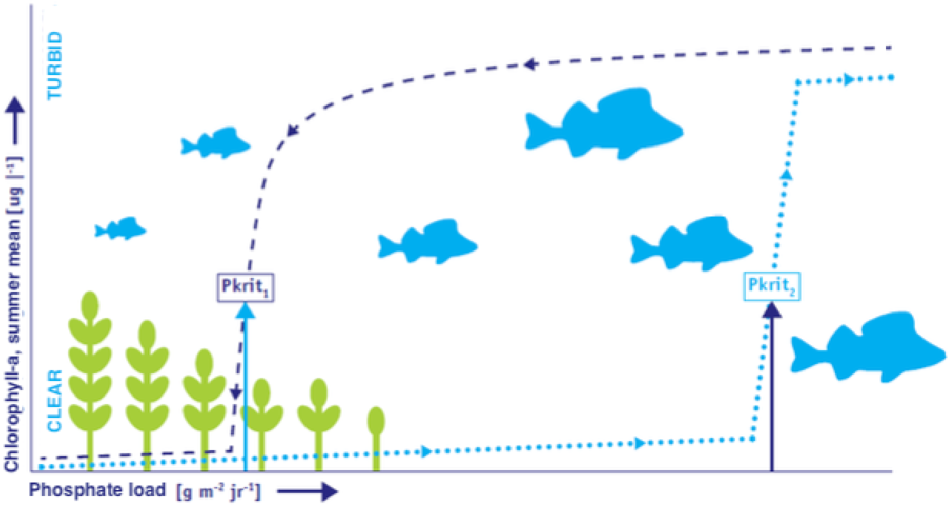


Figure 4.5: The light blue line shows the transition from clear to turbid water, the dark blue line shows the path back. The critical load at which the passage from clear to turbid occurs is $Pkrit_2$, the lower critical load needed to return from a turbid to a clear state is $Pkrit_1$. From [72]

Due to this important hysteresis effect, maintaining low turbidity levels is crucial to avoid very long times to reach the levels of transparency of the undisturbed state [69].

Floating platform During the construction phase of floating platforms, mooring is a necessary step. The mooring system has to endure storms, currents and tides, as well as the weight of the platform, so it has to be securely anchored to the seabed in order to maintain the platform in the desired position [44]. Besides having to withstand extreme loads, the mooring system of floating platforms has to cope with the daily load variations over many years. Depending on the type of mooring system and its installation, bottom sediments may be resuspended, leading to increased turbidity, and there may be a localized habitat destruction, in correspondence to the anchor site [44].
The most suitable mooring configuration for floating platforms is the spread mooring, where mooring lines are spread over multiple points and maintain the platform at a fixed heading [73]. There are two different configurations: catenary and taut leg, as shown in Fig. 4.6.

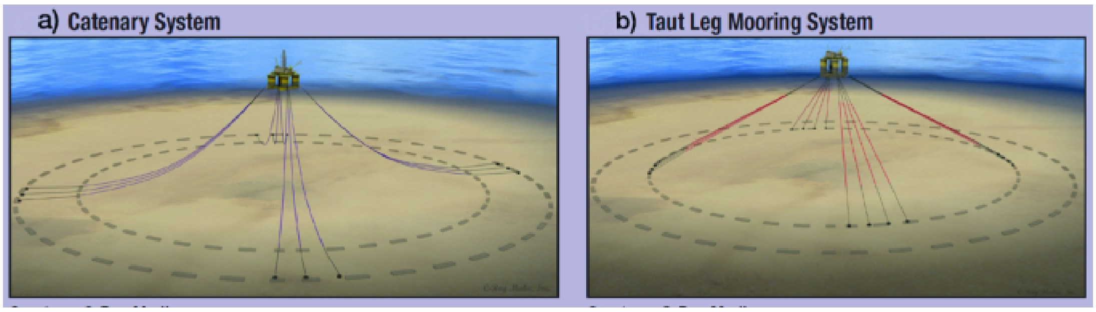


Figure 4.6: Mooring configurations of offshore floating structures: catenary system on the left and taut system on the right. From [73]

Catenary system is a parabolic configuration where mooring lines, usually steel chains, lay in part on the seabed and are then connected to the platform. Taut leg system is a straight configuration where mooring lines, usually polyester ropes, are stretched between the seabed and the platform. This second configuration is preferable, since it has many advantages: the polyester ropes are lighter, easier to transport and more elastic compared to steel chain, they produce less noise in the marine environment and corrosion is not an issue. Additionally, in a catenary system part of the mooring lines rests on the bottom of the sea, potentially smothering and destructing the benthic habitat beneath them, so taut leg system has a lower environmental impact [73].

No dedicated researches have been conducted to investigate the amount of sediments that would be displaced and the turbidity produced during the installation of a mooring system for floating structures. However, impact assessments of potential environmental impacts on the marine environment of floating structures [44], [65] and offshore wind farms [36] generally report a low to moderate impact, which affects a limited area around the mooring installation site, depending on the water flow.
A study concerning the impact of floating platforms on the benthic ecosystem [4], reported that no variations in turbidity levels between the area under and around the platform could be detected. This research didn't focus on the turbidity produced during the construction phase, but demonstrated that floating platforms don't influence turbidity during the operational phase.

For these reasons, the spatial extent that could be assigned to the turbidity and suspended sediments resulting from the installation of a mooring system during the construction phase of floating platforms is **2**. The index value that could be assigned to the duration of this stressor is **2-3**, considering potential variations in the deposition velocity of suspended sediments. It has to be noted that these values have been determined solely on the basis of assessments of potential impacts, lacking documented data from existing projects. Therefore, further research is necessary.

Dredging The construction phase of dredging involves a significant resuspension of sediments which varies throughout the water column, with higher turbidity and suspended sediment plumes expected closer the sea bottom, where the excavation of material occurs [48]. Therefore, the benthic ecosystem could be particularly affected by this stressor. However, if an overflow of the hopper, where the dredged material is placed, occurs, turbidity would increase at the water's surface level too. Additionally, turbidity can be generated at the disposal site of the dredged material [74]. As shown in Fig. 4.9, a TSHD generates a sediment plume on the bottom due to the action of the drag head used to excavate the material, as well as a plume at the surface due to overflow spill from the hopper [75].

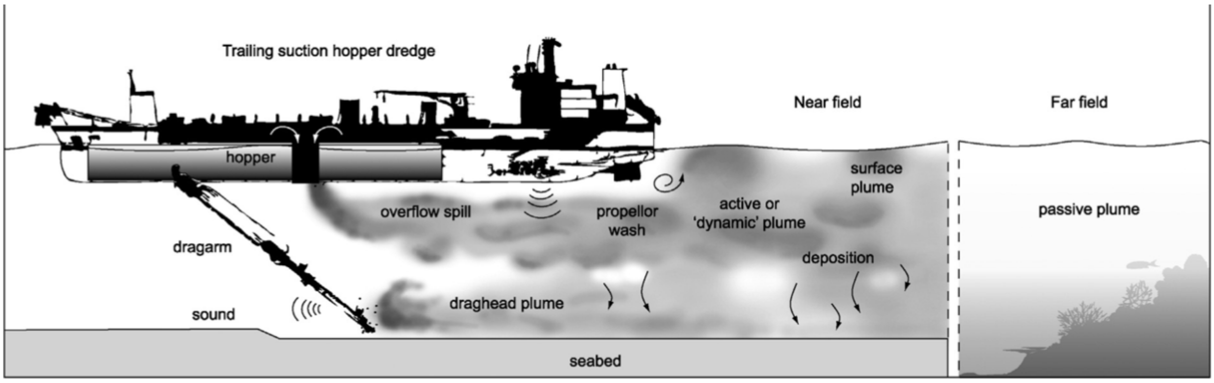


Figure 4.7: Representation of a turbidity plume generated by a TSHD. From [75]

In this representation, two zones are differentiated: the near-field and the far-field. These zones distinguish sediment plumes based on their behavior in relation to the distance from the dredging site. Near-field, or active, plumes exhibit dynamic behavior with rapid sediment deposition on the seabed, especially coarser particles settling within the first 10–20 minutes. Far-field, or passive, plumes have lower Suspended Sediment Concentrations (SSCs), and the finer sediments can travel for many kilometers, persisting for several hours [75].

As discussed by LaSalle (1990) [76], the amount of suspended sediments and resulting turbidity depends on the dredger type: bucket dredgers may generate elevated levels of suspended sediments, up to 2.5 times more compared to CHD and TSHD. This is a result of material spillage from the bucket, which occurs at various stages of the dredging process: during the transit of the bucket full of sediments through the water column, when the bucket emerges from the water surface and during barge loading [76]. As a consequence, bucket dredgers produce a turbidity plume not only near the seabed but also in surface waters and throughout the entire water column.

The differences in sediment plumes generated by different types of dredgers have also been investigated by Havis (1988) [77]. This study has explored the distribution of sediments resuspension generated by three types of dredgers: cutterhead, clamshell and trailer hopper dredger. As shown in Fig. 4.8, clamshell dredgers produce a concentration of TSS an order of magnitude higher compared to CHD, and the sediment plume is distributed throughout the entire water column, due to the spillage of material from the bucket occurring as it is lifted from the seabed to the surface. Conversely, sediment resuspension caused by CHD is concentrated near the bottom, while the TSHD could generate high concentrations of TSS throughout the water column in the case of overflow of the hopper.

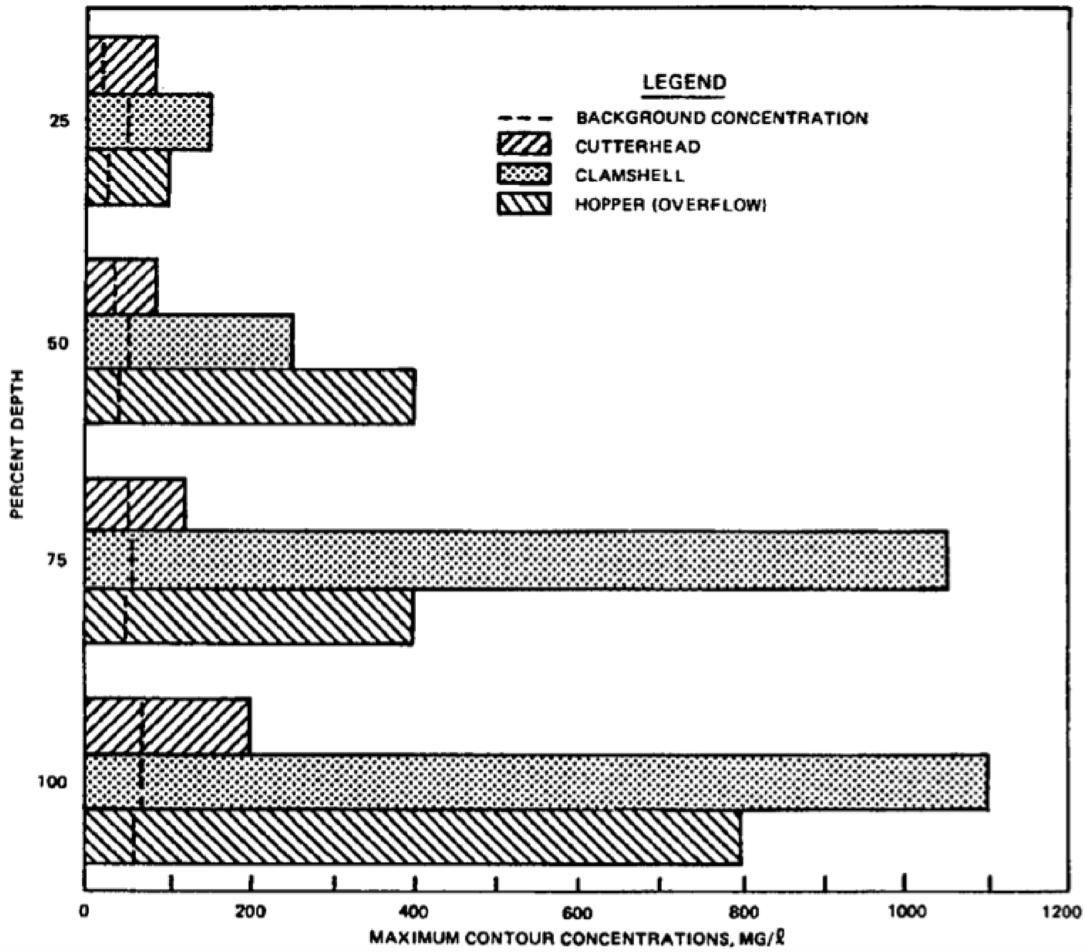


Figure 4.8: Maximum concentration of total suspended solids (TSS), expressed in mg/l, measured for cutterhead, clamshell and trailer hopper dredgers, at different depths. The background concentration is reported with dotted lines. From [77].

In general, mechanical dredgers lead to greater suspended sediment concentration compared to hydraulic dredgers [78].

The relationship between turbidity and distance from dredging location has been investigated by Fisher et al. (2015) [74]. Analyzing the data collected at three major capital dredging projects in Australia, it was observed that turbidity followed a power-law decay relationship with distance from the dredging site. Increased turbidity levels were, in two locations, not detectable beyond $3km$ from the dredging site, while in one location it extended as far as $15 - 20km$. The higher distance was a consequence of the unique metocean conditions present during the Barrow Island dredging project, which led to an

unusual and almost unidirectional flow. Consequently, the suspended sediments mainly travelled in one direction over longer distances. This differed from the other two dredging sites, where the turbidity plume exhibited spatial heterogeneity, resulting in a lower overall travelled distance but in various directions. Concerning the Barrow Island project, the turbidity generated at the dredged material disposal site appears to be lower than the one generated at the excavation site [74].
Another study regarding the extent of the turbidity plume generated during the dredging project in Barrow Island, Australia, was performed by Evans et al. (2012) [79]. Employing remote sensing techniques, the turbidity plume could be observed over $30km$ away from the dredging site. It has to be noted that this location is characterized by clear and shallow waters and, during the dredging period, by an unidirectional flow, which contributed to increase the spatial extent of the plume.
The difference in turbidity between the baseline conditions and the dredging period in Barrow Island is provided in Fig. 4.9. Turbidity, expresses in NTU, initially decreases rapidly as the distance from dredging increases. However, turbidity levels differences with the baseline are detectable up to $15 - 20km$ from the dredging site and remain for up to 30 days.

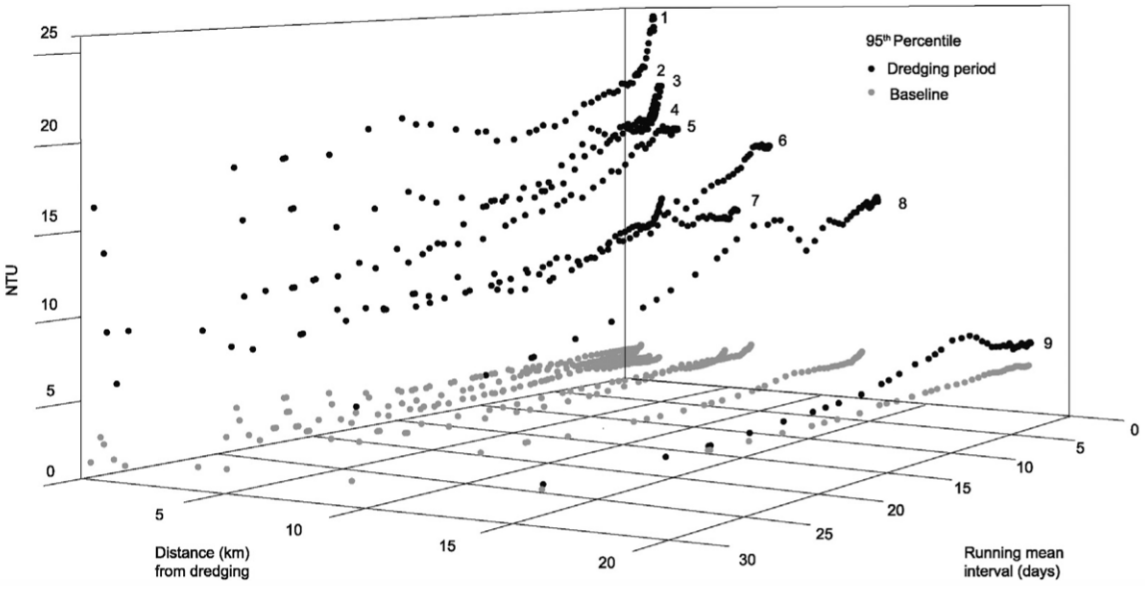


Figure 4.9: Representation of a turbidity plume generated by a TSHD. From [75]

Dredging significantly increases the frequency of extreme turbidity values and alters the intensity, duration, and frequency of turbidity events compared to background levels. Upper percentile values (p95) of turbidity can sharply rise over short periods, exceeding hundreds of mg/l within hours. Over longer periods, these values reach the tens of mg/l, typically remaining below 10 mg/l over weeks and months [75].
A study regarding the Palm Jumeirah project [80] estimated that the suspended sediment plume would cover an area of $25km^2$ on both sides of the Palm. The study reported that even three years after the initiation of the construction phase, turbidity levels remained significant, resulting in a limited visibility along the bottom.

The spatial extent index value that can be assigned to suspended sediments and turbidity generated during the construction phase of dredging is **4**, as turbidity plumes have the potential to extend over several kilometers from the dredging site. The duration index value is **4**, indicating that turbidity levels don't immediately return to their original values after the construction end, but can persist at higher levels for days, months or even years.

4.2.3 Noise

Sound is a vibration that propagates through an elastic medium, such as a gas, liquid or solid, and it occurs when particles in the medium are excited by an external force, causing them to oscillate around their initial position; consequently the nearby particles also start to oscillate and the initial disturbance propagates through the medium as a wave [81].
Sound can be quantified by assessing the changes in pressure within the medium in all directions, referred to as sound pressure and measured in Pascal (Pa), defined as force (Newton, $[N]$) per unit area (m^2) [82].
A sound wave is characterised by two components: the pressure component, measured in Pa, and the particle motion component, indicating the molecules' displacement (m), velocity (m/s) and acceleration (m/s^2) in the sound wave. Marine organisms can be sensitive either to the pressure component, the particle motion component or both, depending on the receptor mechanism.
Considering the wide range of pressures at different frequencies that aquatic organisms are capable of detecting, it is necessary to employ a logarithmic scale to describe them. This allows to condense the extensive range of perceptible sound pressure values into manageable values, and the most used scale for this purpose is the decibel scale (dB). The sound pressure level (SPL) of a sound of pressure p is given in decibels (dB) by:

$$SPL[db] = 20 \log 10(p/p_0) \tag{4.1}$$

where p is the measured pressure level and p_0 is the reference pressure.
The reference pressure in water is 1 microPascal $[\mu Pa]$, while in air the typical reference pressure is $20 \mu Pa$ [82].

Dredging Noise caused by dredging depends on many factors, such as the type of dredger, the activity, the type of dredged material, the water depth and sediment type and the local ambient sound [83]:

- type of dredger: as explained in paragraph 1.1, there are four types of dredgers that can be used: Cutter Suction Dredger (CSD), Trailing Suction Hopper Dredger (TSHD), Grab Dredger (GD) and Backhoe Dredger (BHD) [14].
  As shown in fig. 4.10, sound sources vary depending on the dredger type, and they include internal engines, suction pipes, dredge pumps, propellers and excavation. Depending on the specific design and maintenance of the dredger, these sounds can vary in intensity and frequency. Internal engines produce a strong, continuous and constant sound with respect to intensity and frequency; the suction pipes, used by CSD and TSHD to transport the material, produce a rumbling noise with irregular peaks in the case of rocks, dredge pumps produce a constant and continuous sound,

the continuously active propellers of TSHDs produce high frequencies sounds, but since these dredgers leave the dredging site periodically for material placement, exposure to these high-frequency sounds is limited to active excavation periods; the sound produced during excavation depends on the type of soil, because to dislodge hard and cohesive materials the dredger must exert greater force, resulting in more intense sounds. Mechanical dredgers in general produce low frequency sounds. [83] [84]

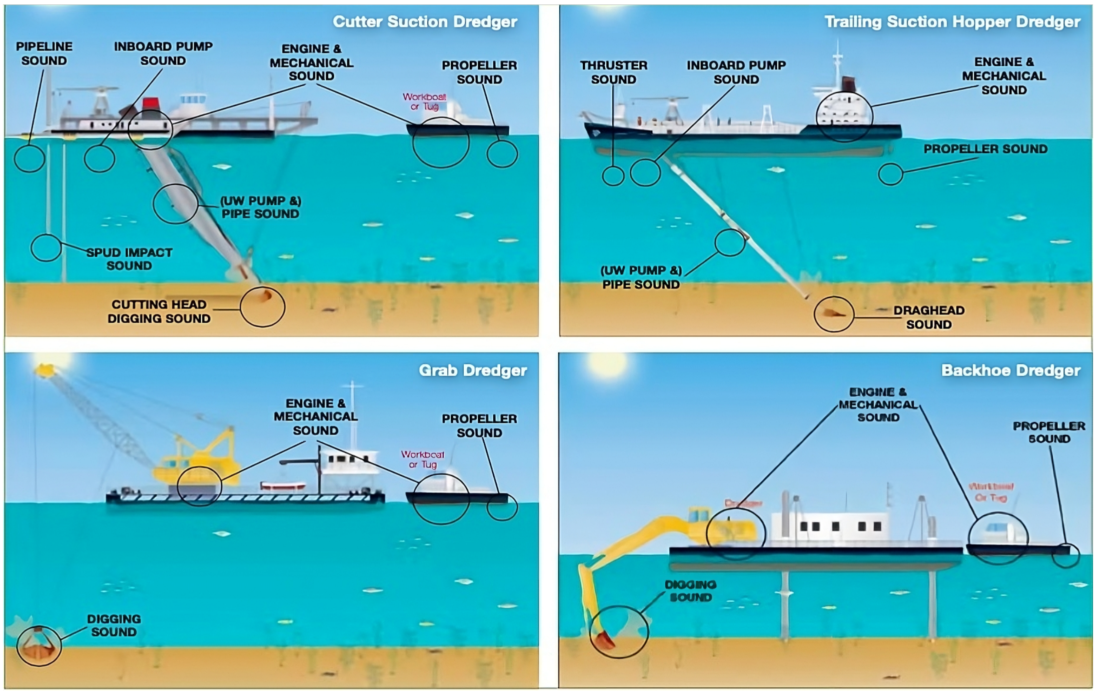


Figure 4.10: Sound sources for main dredger types, from [85]

- activity: dredging operations consist in a series of activities that produce different noise levels, and the main sound sources can be associated to the excavation of sediments, the vessel transport and the placement of material at the disposal site [83]
- type of dredged material: the type of sediments extracted affect the overall noise. As demonstrated by Robinson et al. [86] , extracting coarser sediments such as gravel produces higher sound levels compared to sand. Moreover, if the soil is particularly hard, it can be necessary to first use explosives to break it up, producing considerably strong sounds [83].
- water depth and sediment type: these aspects affect the distance over which the noise produced can be detectable, especially low frequency. In an environment characterized by shallow water and soft seabed sediments, the sound will propagate over shorter distances as opposed to in an environment with deep water and coarser sediments [87];

- background noise: it is crucial to assess if the dredging or mooring anchors installation activity takes place in a pristine environment or in an area already affected by other industrial activities or heavy shipping traffic. In busy areas, the noise produced by the land reclamation activity will be detectable over shorter distances compared to an area with lower ambient sound levels [87].

Since noise is influenced by this wide range of factors, its spatial extent can have very different values too. To describe the spatial extent of a sound it is useful to consider the detection range, which is defined as the distance at which the dredging/drilling noise falls below the ambient noise [81].
For example, a study from Greene et al. [88], regarding the sound emitted by three TSHDs and two CSDs, reported that the detection range was $25km$. In another study about two grab dredgers[89], the detection range computed was $7km$, which suggests that these dredgers are relatively quieter compared to CSDs and TSHDs [81]. However, as discussed before, dredger type isn't the only aspect to take into account, but also ambient sound and water depth are important. For example, a study conducted by [90] regarding engine sounds produced by a backhoe dredger in New York Harbour reported a detection range of 330 m, with ambient sound levels of $99 - 113dB\ re1\mu Pa$ and water depths of $3 - 7{,}5m$, while the detection range of noise produced by TSHDs was $14 - 30km$, with ambient sound levels of $99dB\ re1\mu Pa$ and water depth of $13 - 46m$.

The spatial extent of noise caused during construction phase can assume an index value of **4**.
As far the duration is concerned, the noise is emitted continuously by the dredgers [81], and ceases with the ending of construction works. For this reason, the index value for duration is **3**.

Floating platform Noise is produced during the construction phase of floating platforms too, in particular during the transport of the platforms to the site and the installation of mooring anchors, which is likely to be the most significant source of noise pollution affecting the site [44]. Specific data regarding the actual noise generated during the installation of anchors for floating platforms is not available in the literature. Comparable floating structures, such as OWF, are commonly installed using pile driving, a process known for its highly intense and impulsive noise [61]. However, due to the absence of specific information on the installation of floating platforms, it would be speculative to assume a similar installation method. The potential installation techniques vary, and include drilling, suction pile anchors, and vibratory pile driving [44]. The selection of a particular installation method is mainly contingent on the seabed type, with sandy bottoms having different requirements than rocky ones. While noise can propagate over considerable distances, the possible spatial extent is conservatively assumed to be **3**. Considering that the construction phase involves the transportation and installation of the platform, and both activities contribute to noise production, the duration is assumed to be **3**.

4.2.4 Physical destruction of habitat

In all dredging projects, the dredged area where material is excavated and the area where the dredged material is placed to create new land is affected by a permanent total destruction of habitat. This is an intrinsic aspect of land reclamation projects that employ dredging, and it is one of the major impacts that can be avoided almost completely with floating platforms, since their construction does not involve the complete smothering and burial of the seabed and benthic communities, excluding the small area where the anchor system is placed.

During the construction phase, the immobile benthic ecosystem, including coral reefs and seagrass, can be either uprooted, sucked up, dislodged or completely buried, leading to a complete destruction of a crucial habitat for various organisms [52].

The suction field of dredgers that uptakes water and sediments may trap marine organisms, in a process known as entrainment [91]. Entrainment rates depend on depth, type of dredger and strength of suction field, which is higher for hydraulic dredgers with respect to mechanical dredgers [91]. Not only the benthic community can be vulnerable to entrainment, but also epibenthic and demersal organisms that live in close proximity to the seabed, including crabs, burrowing shrimps and fish [48]. Moreover, eggs and larvae of marine organisms, as well as young fish, are at high risk of entrainment due to their reduced ability to avoid the suction field [91]. A study conducted by McGraw *et al.* (1990) on entrained fish by dredgers [92] revealed a mortality rate of 99% , with the remaining 1% showing signs of internal injuries.

The effects of physical destruction of habitat are summarized in Fig. 4.11.

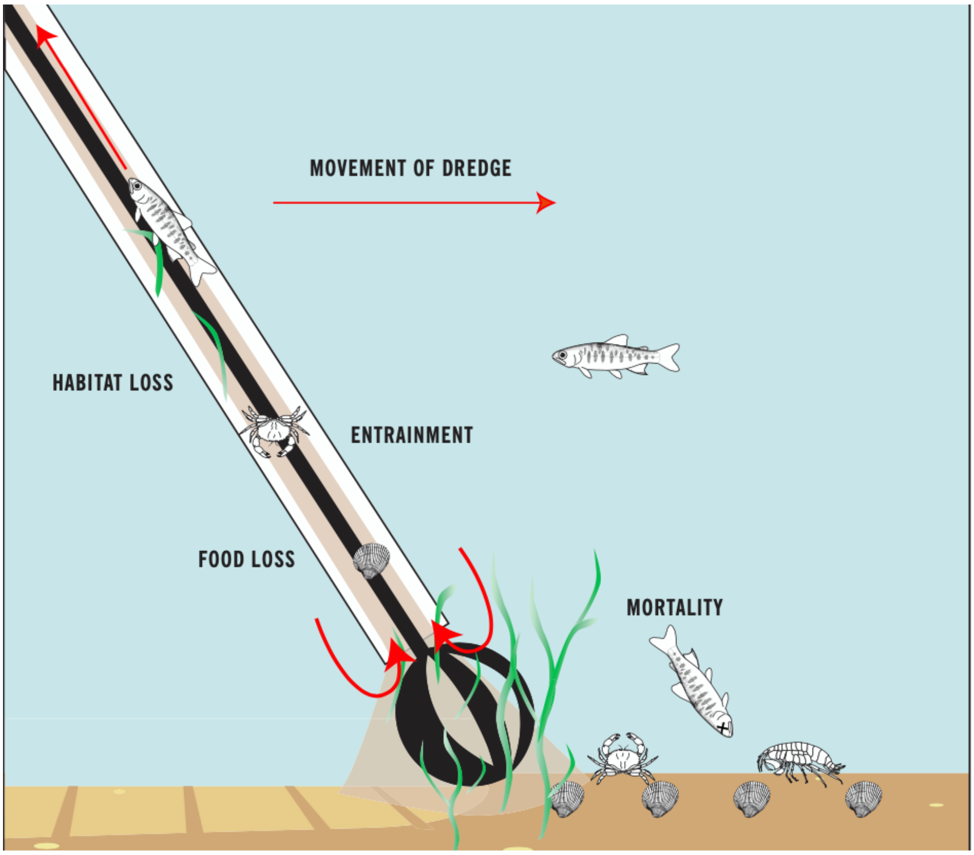


Figure 4.11: Physical destruction of marine ecosystem caused by a dredger. From [51]

The dredged area where the material is excavated becomes a new substrate that can be recolonized, either by the same organisms that were present before dredging or by opportunistic species that can adapt easier to the new conditions [51]. It has been observed that organisms inhabiting offshore deep water exhibit a slower recovery process in comparison to organisms that inhabit shallow water, which are more accustomed to variations in their environment [93]. The creation of a stable benthic ecosystem may require several months or years. After the disturbance, the recovery process occurs in two phases, involving opportunistic species initially and recruitment of organisms from undisturbed areas later. The success of recovery depends on the type of environment and the speed of migration or recruitment from adjacent undisturbed areas [93].
It has to be noted that also the changes in physical-chemical properties and hydromorphological regime will lead to an indirect modification and disruption of habitats and biodiversity, but these aspects are described in separate dedicated paragraphs.

The spatial extent index value of the direct destruction of habitat which occurs during the construction phases of dredging is **1**, since it corresponds to the dredged area, and the duration index value is **4**, because it is permanent.

4.2.5 Hydromorphological changes

Horizontal and vertical flows and water currents, as well as surface winds, are always present in a water body, allowing the water mixing [60]. Adding a new object in the water body can influence currents, waves, flows and tides in various ways, either redirecting water along different pathways, creating new flows, changing the current velocity or physically blocking waves.

This is an intrinsic effect of the operational phase of land reclamation projects, and it is expected to occur mainly near the surface in the case of a floating object, while a dredged land can interact with the whole water column, potentially having major impacts on the hydrodynamic regime.

Alterations in the direction and speed of water are directly linked to variations in the morphology of both the water bottom and the coastline, leading to either sedimentation or erosion. For this reason, these aspects are considered together as a unique stressor called "hydromorphological changes", as changes in one directly result in changes in the other [44].

Apart from shifts in water dynamics, the presence of an object in the water body also induces changes in air movement. Winds close to the surface have an influence on water circulation and mixing, surface currents and temperature gradients, as any air movement reverberates in the liquid it comes in contact with [5]. Regardless of the purpose of the land reclamation project, the presence of buildings on the surface of the floating platform or dredged land is expected. These structures will interact with the air movement, locally changing its speed and direction and creating different wind speed regions.

Floating platform Floating platforms could both speed up the flow in certain areas and slow down the flow in other zones. Slower currents may lead to water stagnation, to an increased sedimentation of suspended sediments which affects the water bottom, and to a decreased water mixing, consequently affecting water quality. Faster currents, on the contrary, can remove finer materials and increase land erosion of both the seabed and the coastline. These effects depend on the floating platform draft and shape, as well as on the water depth and speed and the sediment load[44].

Regarding air movement changes, the shielded area behind a floating house could experience slow air movement and calmer water, consequently decreasing the water mixing and, therefore, the water quality. On the other hand, faster air flows will form on the sides of the structure, especially when two buildings are very close to each other. In this case, the combination of the increased wind speed by the two buildings will create the so called "wind tunnel effect" [5], which increases water mixing and may result in the formation of turbulent flows between the floating platforms [60]. These effects depend on the orientation of the floating platforms with respect to the main local wind orientation [62], and are shown in Fig. 4.12.

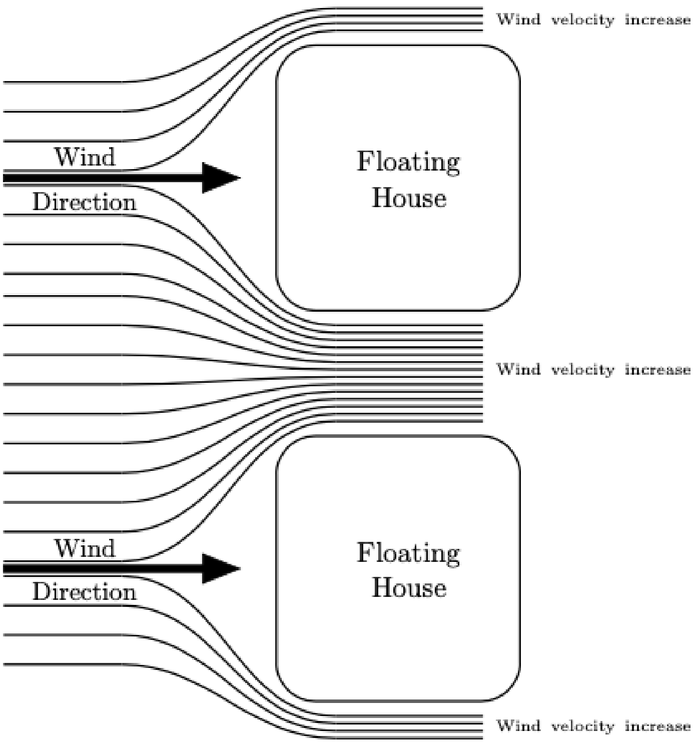
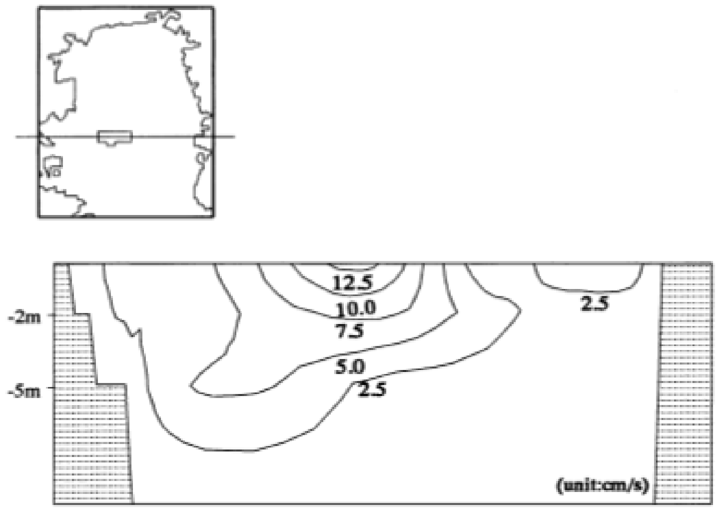
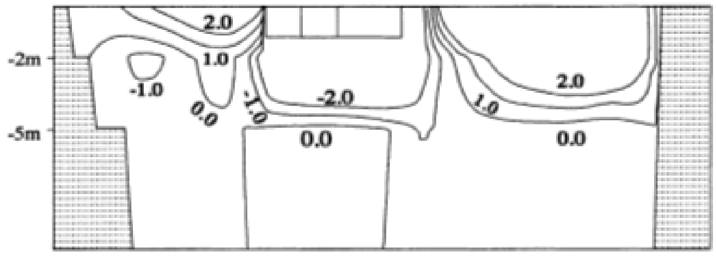


Figure 4.12: Different wind speed regimes created by the presence of a floating house. From [5]

A study conducted by Huguet et al. in 2020 [94] regarding the impacts of floating structures on the hydrodynamics of La Rochelle Marina, reported a significant reduction in microscale tidal generated eddies due to an attenuation of current, leading to a decrease in velocity by more than 30% throughout the marina. Residual circulation, which is "the circulation left after removal of the oscillatory tidal component from the current observation" [95], is also affected, as residual eddies are attenuated by slower currents, and their form and size are modified by wind.
The numerical study concerning the potential environmental impacts of the Mega-Float in Japan [96], reported that the presence of the VLFS would indeed form areas with different flow rates, but the changes are minimal and not detectable below a water depth of $5m$, as shown in Fig. 4.13.



without Mega-Float



difference

Figure 4.13: Profile of the residual flow on the Y-Z plane. The upper profile is without the Mega-Float, the lower profile is the difference between with and without the Mega-Float. From [96]

The presence of a floating object in a water body can modify surface water and air regime. Since this alteration affects the upper layers of the water column, changes on the seabed are more significant in shallow waters, as the modified currents directly interact with the seabed, possibly carrying away the finer fraction of bottom sediments and changing the seabed granulometry [60].

The spatial extent score that can be assigned to this stressor is **2**, since these changes seem to have an impact only on a limited area surrounding the platform.
Since hydromorphological changes are caused by the presence of the floating platform, they will last as long as the platform is in water, resulting in a duration score of **3**.
If the floating object is removed, the water and air patterns will return to their previous state, indicating reversibility. However, any potential changes in the seabed morphology and granulometry may not be reversible, since they could have resulted in an ecosystem alteration. For instance, increased sedimentation could stabilize the sediments, possibly leading to the growth of macrophytes that could not previously grow on unstable sediments [44]. Conversely, when the finer fraction of sediments is carried away by fast currents, the seabed becomes coarser, and the consequent lack of anchor points may facilitate the growth of more adaptable, exotic species [60].

Dredging A land built with dredged materials can influence the whole water column hydrodynamics, potentially causing significant morphological changes. Moreover, the dredged hole created during the construction phase could also have an impact on the hydromorphological regime.

Dredged land could alter habitats, transforming an intertidal environment into a shallower, subtidal habitat, affecting the organisms that have adapted to the specific intertidal habitat conditions [48]. Natural beach dynamics involve daily shifts in alluvial sand, where erosion is countered by the transport and redeposition of sand from the sea floor by natural currents. The creation of a land that changes these natural currents pattern could therefore affect beaches. A demonstration of this effect is given by the Palm Jumeirah [52], a land mass with an area of $25000m^2$ and an average depth of $10m$. The construction of the Palm Island disrupted the coastal currents and reduced the waves force. This force dampening has impaired the natural deposit of sand on beaches, resulting in significant beach erosion. By 2006, the Palm Island had caused a substantial reduction in sediment deposits along approximately $41km$ of Dubai's shoreline [52].

A paper addressing land reclamation projects developed along the Chinese coastline during the last decades [97], reports that the main impacts of these projects include changes in the water exchange capacity of bays, tidal systems near the shore, shoreline and topography. For instance, China's reclamation activities have resulted in the disappearance of 65% of the tidal flats surrounding the Yellow Sea. This paper also reports that land reclamation's influence on tides extends beyond the immediate vicinity of the reclaimed areas, impacting zones far from the reclamation site, creating a so called "far-field effect“. In the context of China's coastal tidal flat regions, land reclamation modifies tides' phase angles and amplitudes, not only locally but also in areas distant hundreds of km, such as the Bohai Sea, Yellow Sea, and East China Sea.

Furthermore, the dredged hole that forms where the material for the new land is excavated has an impact on waves and, as a consequence, on the shoreline. As reported by Demir et al. (2004) [56], the modified bathymetry changes sediment transport and waves, influencing the coastline in the long-term (years) and at large-scale ($1 - 10km$) through a direct and indirect effect.

The direct effect is the cross-shore transport of sediments from the beach into the dredged pit, directly reducing the sand of the beach. Depending on the local sediments and environment, the dredged hole infilling is proportional to its distance from shore, and could take many years. The scheme of this direct shoreline erosion is provided in Fig. 4.14:

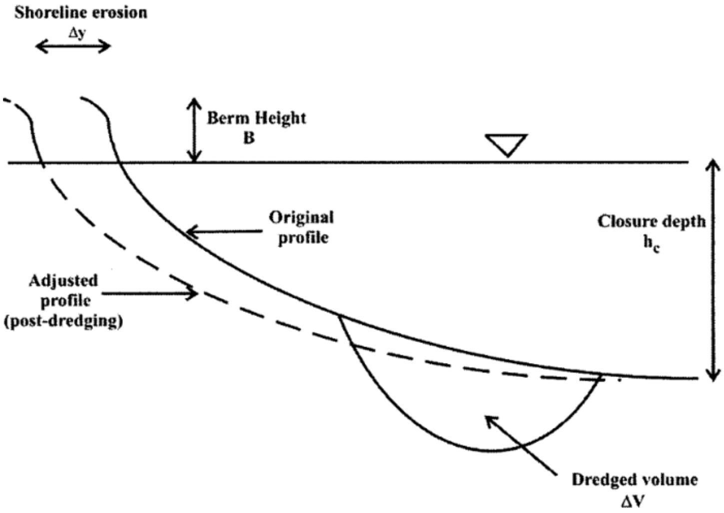


Figure 4.14: Scheme of beach profile changes before dredging and after infilling of dredged hole, from [56]

The dredged pit changes wave patterns, consequently altering the sediment transport rate and indirectly affecting the shoreline, as shown in Fig. 4.15. The figure illustrates accretion behind the hole in correspondence to wave sheltering created by the hole itself. However, whether erosion or accretion occurs behind the pit depends on the specific configurations of the pit and waves.

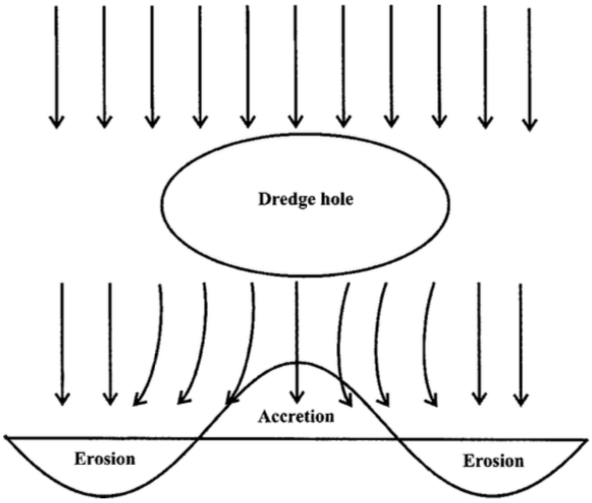


Figure 4.15: Planar view of the indirect effect of a dredged hole on the shoreline, from [56]

In conclusion, hydromorphological changes caused by dredging could have ”far-field effects“, changing not only the local environment but also distant coastlines. As a result, the assigned spatial extent score is **4**. This effect will last as long as the land mass is present and interferes with the whole water column, while the consequent coastal morphological changes would remain even after the land removal. For this reason, the temporal extent score is **4** and the stressor can be considered irreversible.

4.2.6 Physical-chemical properties

Changes in the hydromorphological regime can modify physical and chemical properties of the water body, affecting water quality. In particular, changes in temperature, dissolved oxygen, salinity and pH have been observed.

4.2.6.1 Dissolved oxygen

Dissolved oxygen is a key indicator for water quality [98]. The quantity of oxygen that can dissolve in water depends on many factors, such as time of the day and season, and diminishes as elevation, salinity and temperature increase.
The input and output processes of dissolved oxygen in dissolved water are described in Fig. 4.16: oxygen can enter and be dissolved in a water body through the atmosphere and the photosynthesis by aquatic plants, and can be consumed through respiration of aquatic organisms, decomposition of organic materials and chemical oxidation of sediments.

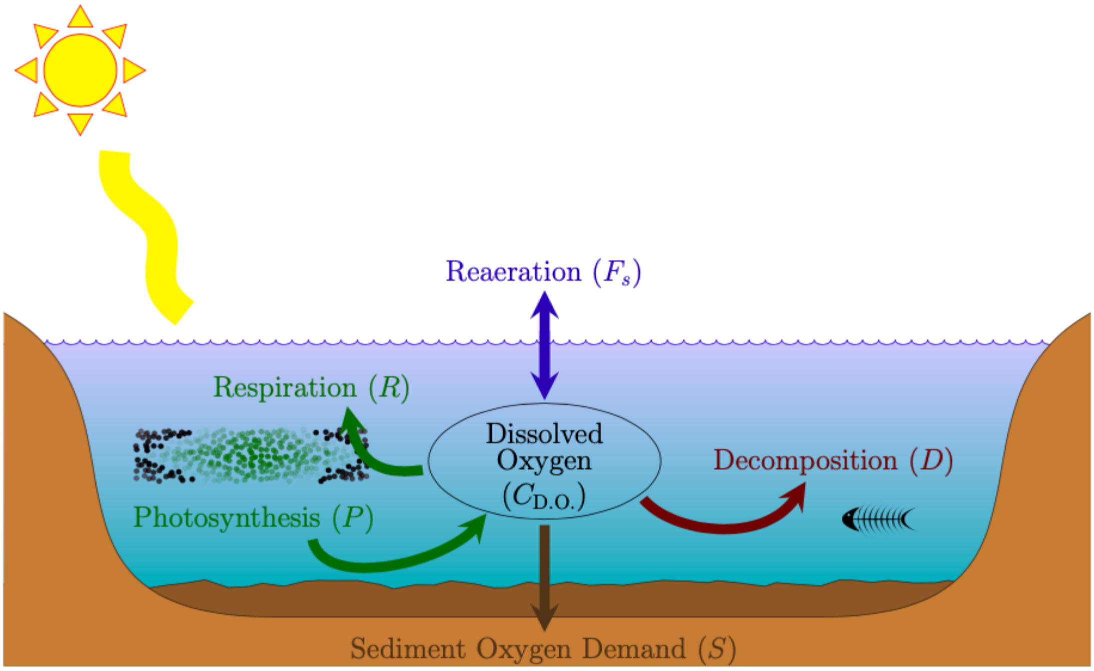


Figure 4.16: Main dissolved oxygen processes, from [5]

Floating platform Since the main process that provides dissolved oxygen is the reaeration happening between the atmosphere and the surface layer of water, a decrease in the area that allows this diffusion might lead to a decrease in the amount of dissolved oxygen, particularly in stationary waters, where the mixing from currents and wind is not enough to increase the rate at which oxygen can be dissolved.
For this reason, the presence of floating platforms in slow-moving waters can decrease the oxygen exchange between atmosphere and water and, as a consequence, the amount of dissolved oxygen, while in more dynamic waters this effect would be counteracted by a sufficient water mixing. Moreover, the shade created by the floating platform can decrease photosynthesis and therefore the oxygen production; an additional increase in oxygen depletion could be caused by the decomposition of organic matter resulting from

the colonization of sessile organisms underneath the platform [62].
On the other hand, as discussed in paragraph 4.2.5, the presence of a floating platform can create a wind-tunnel effect between the floating houses, increasing the mixing rate and therefore the amount of dissolved oxygen [5].
The effects of floating structures on dissolved oxygen have been analyzed and monitored in different papers, such as a research carried out by Bol and Tobè in 2015 [69] and two studies conducted by de Lima et al. in 2022 [62], [63]. The first study of de Lima [62], has analyzed the collected data about the dissolved oxygen concentration under and near floating structures, and in open water, at the same depth. These data have been collected at 18 different locations in the Netherlands, raging from ponds to larger water bodies. At most locations, the differences between the below, near and far area were statistically significant, with a noticeable decrease of dissolved oxygen beneath the floating platform. In particular, data collected at the Floating Pavilion in Rotterdam in 2020 are shown in Fig. 4.17

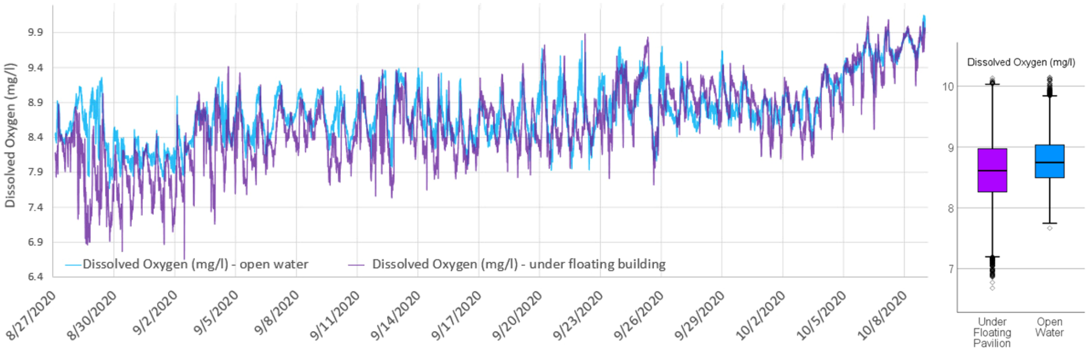


Figure 4.17: Dissolved oxygen data and boxplots collected at the Floating Pavilion in Rotterdam during the monitoring period. In blue, dissolved oxygen concentration in open water, in purple, dissolved oxygen concentration under the floating platform. [62]

It can be observed that dissolved oxygen underneath the floating structure is indeed lower compared to open water, as expected. However, this difference is small and the dissolved oxygen concentration is always above the threshold of $5mg/l$, which is the concentration below which the majority of fish display a distressed behaviour [99].
A further example confirming that these differences in dissolved oxygen between the under-platform and open water area, though present, are usually small is provided by another study conducted by de Lima et al. (2022) [63]. As shown in Fig. 4.18, the linear regression fitting line ($R^2 = 0.9124$) of the measured differences between dissolved oxygen in open water (y-axis) and under/near floating platforms (x-axis), at 10 locations in The Netherlands, is slightly above the 1:1 line: this suggests that the dissolved oxygen concentrations in open water are typically higher than under the structure, but the difference is minimal.

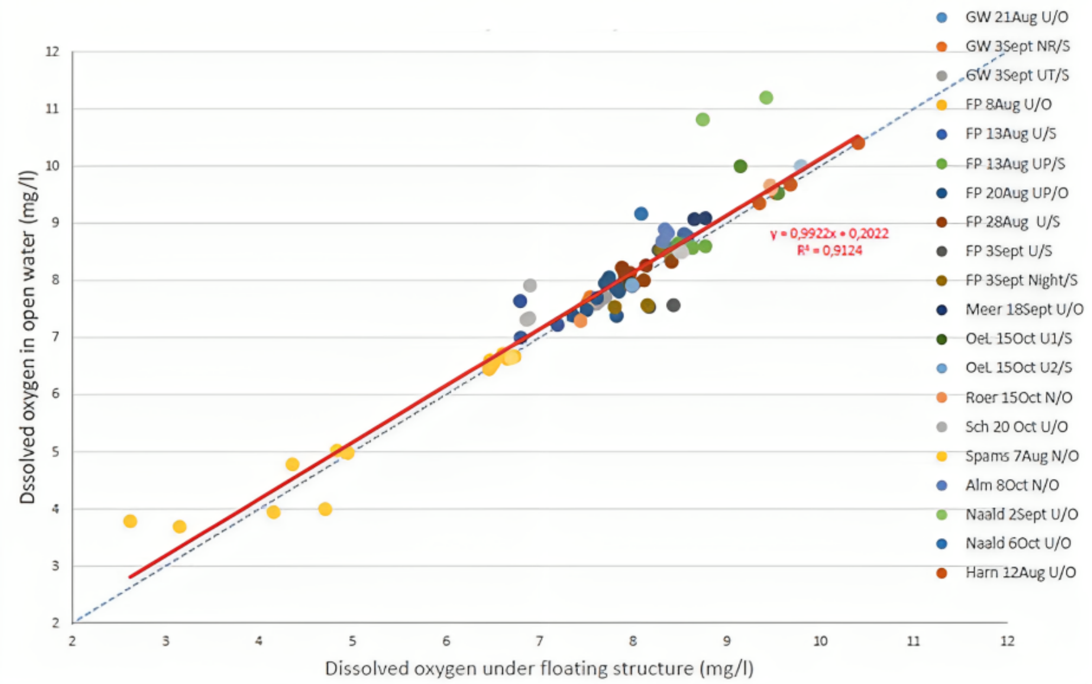


Figure 4.18: Comparison between dissolved oxygen concentrations below the platform (x-axis) and in open water (y-axis) at each location; linear regression fitting line in red, from [63].

An additional aspect considered in this study is the possible correlation between dissolved oxygen variations and the water depth below the floating structure: the most noticeable differences have been observed in locations characterized by shallow waters, whereas no significant variation has been detected at depths greater than 1,5 $- 2m$ at most locations. This is likely due to the fact that the water depth beneath the floating structures, as well as their proximity to the shore and the presence of vegetation affect water mixing and flow, and therefore the renewal rate of water below the structure and the dissolved oxygen. On the other hand, no strong correlation has been found between the platforms' dimensions and the dissolved oxygen underneath them.

Another research, conducted by Bol et al. (2015) [69], has monitored three water quality parameters, dissolved oxygen, temperature and salinity, in 5 locations in the Netherlands. The measurements of one location are particularly relevant for the SEAform project's size because, as opposed to the majority of the existing studies, they focus on a floating community instead of an isolated floating structure. This floating community is located in Ijburg, Amsterdam, and the analysis of the collected data show how all the parameters measured under/near the floating structures and in open water are compliant with the highest scores of water quality standards, as defined by the Water Framework Directive [100], and don't present major differences between the three zones. This represents an initial assessment of the impacts of a floating community on the aquatic environment, and, in this particular case, the physical-chemical parameters under investigation do not exhibit adverse effects.

To conclude, it has been observed that the presence of a floating platform may reduce the amount of oxygen dissolved in water underneath and near it for a combination of factors,

such as the reduced area available for aeration and the diminished photosynthesis due to the shade. However, the reported values in literature of dissolved oxygen below the platform have always been higher than the values required for a healthy aquatic life, and the difference with the concentrations in open water are usually of low magnitude (not more than $1 - 2mg/l$ [63]).
The score that can be assigned to the spatial extent of this stressor is **2**, because minor changes have been observed under the platform and in the surrounding area, while the stressor is present as long as the floating structure is in the water, resulting in a duration of **3**. If the platform is moved, the dissolved oxygen values should return to their initial condition, therefore this stressor can be considered reversible.

Dredging The changes in dissolved oxygen concentration may happen during the construction phase, due to the resuspension of sediments and to the decrease of photosynthesis caused by turbidity, as well as during the operational phase, due to the modifications in currents, waves and winds and the consequent change in the water mixing rate. The construction phase of dredging involves the resuspension of bottom sediments. Since they are assumed to be anoxic, dissolved oxygen is expected to decrease due to oxidation [48]. However, evidences in literature don't always report a significant dissolved oxygen reduction during dredging operations. For instance, a review paper has reported a number of studies where the dissolved oxygen reductions have been minimal, as shown in Tab. 4.2.

Location	Dredge	DO Reductions	References
New York-Hudson River	Bucket	$< 0.2mg/l$ in lower water column	[101]
Grays Harbor	Cutterhead	reduced by $2.9mg/l$ (periodic reduction)	[102]
Oregon tidal slough	Hopper	reduced by $1{,}5 - 3{,}5mg/l$ during slack tide in lower water column and increase by $2mg/l$ with flood tide	
Coos Bay, OR	Hopper	minimal to no change	[103]

Table 4.2: Dissolved oxygen reductions measured at different dredging sites. Adapted from [48]

Conversely, a study conducted by Brown et al. in 1968 [50], concerning a tidal waterway in the New York Harbor, reported that dissolved oxygen concentration, measured after the resuspension of oxidable sediments due to dredging, had decreased between 16-83% with respect to the values before dredging, as reported in Fig. 4.19.

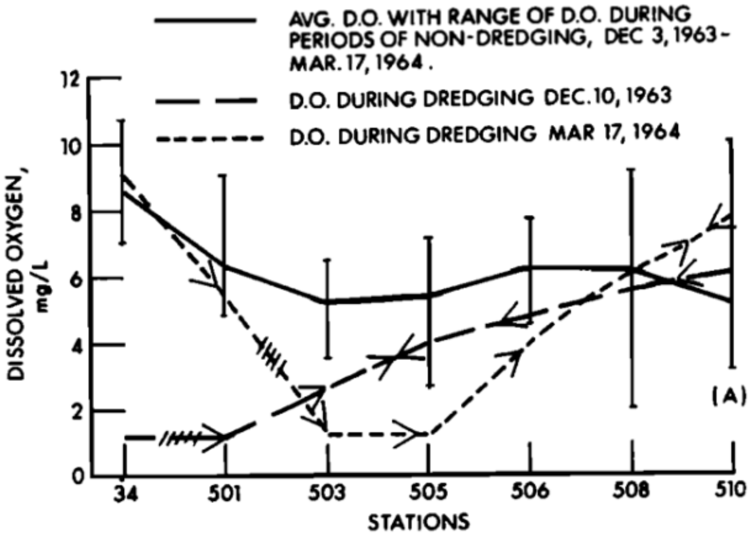


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Figure 4.19: Dissolved oxygen levels during the dredging and non-dredging periods. The symbol /// indicates the dredged area, the symbol >< indicates the direction of the current. From [50]

Another study [39], regarding the effects of dredging on water quality parameters of Ekole creek in Nigeria, showed how the dissolved oxygen concentration decreased in correspondence to the dredging site, and couldn't return to its previous value at the $2km$ downstream measurement point. These major differences in results could be due to the wide variety of factors that can affect dissolved oxygen levels in water, such as type and amount of resuspended sediment, duration of resuspension, season, turbidity levels that can decrease photosynthesis.
In summary, dredging has the potential to reduce dissolved oxygen levels in water, although the extent of this reduction can be minimal. Special consideration should be given to areas characterized by oxygen-demanding sediments, including those containing reduced substances like hydrogen sulfide [51], to areas with already low background dissolved oxygen levels prior to dredging [48], and to the warmer months of the year, when the higher temperatures allow a lower dissolved oxygen saturation in water [50], in order to avoid going below the healthy threshold for aquatic life.

Assigning a general score for the spatial and temporal extent of this stressor can be challenging. Certain research findings report the effects of dissolved oxygen reduction as short term and confined to the disposal area and its nearby water [51], [48]. Other studies suggest that it can take a considerable amount of time for water quality to fully recover from the impact of dredging activities, such as in the case of an incident that affected a fish farm at the Sungai Sitiawan River in 2008 [104]. Fish of an aquaculture farm died due to a reduction in dissolved oxygen caused by dredging activities performed by a TSHD located $1.6km$ upstream, and reduced dissolved oxygen concentrations were detected 2 months after the incident.
For these reasons, the score assigned to the spatial extent of dissolved oxygen reduction during dredging construction phase is **2**, while the temporal extent is **4**, considering the worst-case scenario where the reduction persists even after the completion of the phase.

4.2.6.2 Temperature

Water temperature is a crucial parameter to consider, since it affects several aspects of the water system, such as oxygen solubility, biological and chemical processes, water density, stratification and species composition, because each organism can survive within a certain temperature range [98]. Therefore, changes in water temperature can have an impact on various factors.

Water temperature balance is complex, since it depends on incoming solar radiation, heat exchange with air, evaporation, condensation, precipitation, runoff, and can fluctuate depending on the time of the day and season [98].

A consistent water temperature with minimal fluctuations is essential. Significantly higher temperatures can increase respiration, metabolism and oxygen demand, while decreasing oxygen solubility and potentially reducing the rate of photosynthesis. Conversely, substantially lower temperatures may lead to decreased growth of phytoplankton and macrophytes, as well as a reduction in the rate of photosynthesis [44].

Floating platform Temperature changes may occur during the operational phase of a floating structure. The presence of the platform prevents the incoming solar radiation from entering the water column underneath it, potentially causing a reduction in temperature. However, most on-site assessments, especially those conducted on smaller-scale floating projects, have not identified notable alterations in water temperature, typically registering reductions below 0.5^oC when compared to open water [60].

For instance, a measurement campaign carried out during summer 2013 at a small floating residence in the area of Delft [5], revealed that the average water temperature between the floating houses was 0.5^oC (2.5%) lower than the open water temperature. More detailed temperature differences have been measured continuously for 19 days in September 2013, and the results are provided in Fig. 4.20.

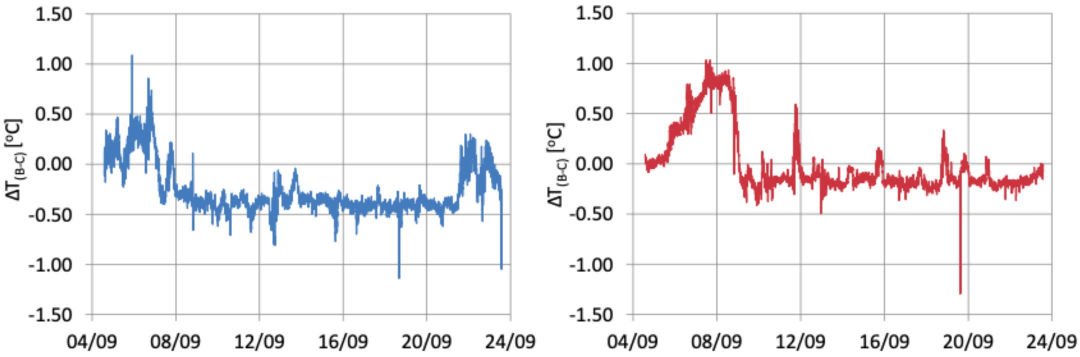

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Figure 4.20: Temperature differences between the floating houses area (B) and open water (C), measured for 19 days. In blue, temperature differences at a depth of $0.7m$, in red, temperature differences at a depth of $2.0m$. From [5]

The majority of temperature differences are negative and greater in the upper part of the water column, around 0.5^oC, indicating that floating houses slightly reduce the water temperature of their surrounding area. The opposite behaviour that can be observed in the first days may have been caused by the local ambient temperature trend during that period: measurements started in correspondence to a temperature peak, and the following days were characterized by a rapid decrease in ambient temperatures. This may indicate that water between floating houses adapts slower to the temperature drop with respect to open water, due to its confined nature.

On the contrary, some studies report a slight increase in water temperature near a floating structure [62], [38]. For example, the study conducted by de Lima in 2022 [62] regarding different floating locations in the Netherlands, already mentioned in paragraph 4.2.6.1, reported slightly higher temperatures under the floating structures in some locations, including the Floating Pavilion in Rotterdam, as shown in Fig. 4.21.

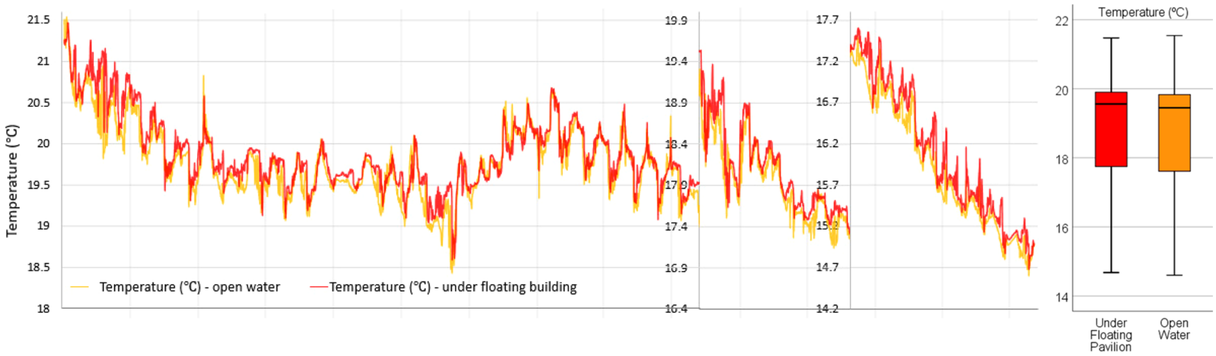


Figure 4.21: Water temperature data and boxplots collected at the Floating Pavilion in Rotterdam during the monitoring period. In orange, temperature in open water, in red, temperature under the floating platform. [62]

This unexpected trend could be explained considering that floating structures both reduce heat loss towards the atmosphere and transfer heat to water, especially during winter months. Floating structures can function as heat collectors, accumulating heat at the beginning of the day and subsequently releasing it into water, delaying the temperature peak and generally softening temperature fluctuations [60]. Moreover, it has to be taken into account that, during the operational phase, human activities carried out on the platform, such as heating and cooling systems for buildings and industrial plants, can increase the air temperature and partially nearby water temperature too.

As far as larger floating structures are concerned, a study regarding the Mega-Float project in Tokyo Bay [96], suggests minimal effects on water temperature, with differences between the area surrounding the structure and open water lower than 0.1^oC.

Additionally, temperature strongly depends on seasonality and weather conditions, which frequently have a larger effect than the impacts of a floating platform presence [44].

Despite the apparently negligible influence of floating platforms on water temperature, caution is required in the design phase, as even minor alterations can have adverse effects on local fragile organisms, particularly in smaller ponds with dense coverage, due to the low water column mixing [60].

Concerning the spatial extent of this stressor, temperature differences have been detected underneath the floating platform and in the nearby surrounding water, indicating a value of **2**. The duration of this stressor is **3**, since it occurs as long as the floating platform is present, and it is therefore reversible if the platform is removed.

Dredging Temperature changes may occur during the operational phase, when the presence of the new land modifies waves, tides, currents and winds and, as a consequence, the water mixing rate. However, few researches have focused on the temperature changes caused by dredging.

A severe temperature increase has been reported due to a disruption in tidal flows caused by dredging in Bimini, Bahamas [58], whereas no effects on temperature are expected from an assessment of potential effects of dredging in the Niger Delta [105]. Moreover, the activities performed on the top of the dredged land can impact the water temperature too: an environmental impact assessment regarding a land reclamation project at the Port of Rotterdam [12], predicts a slight temperature increase of less than $3°C$, caused by the release of cooling water by power stations and chemical companies.

Given the inconclusive and limited research on this topic, the potential temperature increase cannot be precisely assessed in terms of its spatial and temporal extent, and is included in the overall evaluation of changes in physical-chemical properties caused by dredging.

4.2.6.3 Salinity and pH

Salinity and pH are two important water properties that influence aquatic life, so alterations of these factors can cause variations in biodiversity.

For instance, an excessive increase in salinity may lead to the death of native aquatic vegetation, that would be replaced by non-native salt-resistant species, changing the ecosystem structure [106].

Regarding pH, any deviation from the typical pH range of 6 to 9, influenced by dissolved substances from soils and bedrock, could be able to disrupt biochemical reactions of aquatic organisms, posing a threat to their well-being and survival [107]. Moreover, with an increase in pH, smaller quantities of ammonia are required to reach toxicity levels for fish, while higher acidity may lead to a rise in the solubility and concentration of bioavailable metals, allowing them to be dissolved from sediments into the water [107]. Water acidification reduces the solubility of calcium carbonate, which is a useful resource for calcifying organisms, such as corals, to form skeletons and shells [44]. Even a minor alteration in water pH can create a chain effect: it can enhance the solubility of phosphorus and other nutrients, increasing their availability for plant growth, which can thrive and increase the oxygen demand [108].

Floating platform Local changes in physical-chemical properties such as pH and salinity may occur during the operational phase.

In particular, pH can be affected if the floating structure is made out of concrete. Concrete in sea water is subject to physiochemical corrosion, and the corrosion rate depends on water movement and CO_2 levels. Higher CO_2 concentration, typical of acidic waters, increases concrete corrosion and therefore carbonate leaching, which in turn increases the seawater pH [109]. This concrete carbonation may locally balance the negative effects of ocean acidification, which is caused by an increase in CO_2 dissolved in water [44].

Concrete leaching could have either a positive or negative impact on the marine ecosystem, which has to be assessed depending on the site characteristics. However, it is likely that these impacts will be minor and won't have a net effect on ocean acidification [44],

but further research is needed to measure pH variations in floating solution projects.
pH changes caused by concrete carbonation are very local, only related to the submerged area of concrete, while the duration will correspond to the whole lifespan of the concrete structure [44]. Hence, the spatial extent score is **1**, while the duration is **3**. Removing the concrete platform would stop the carbonate leaching, therefore pH variation is reversible.

A few researches have monitored possible salinity changes induced by floating platforms. For instance, as discussed in paragraph 4.2.6.1, the research conducted by Bol et al. (2015) [69] monitored the variations in temperature, dissolved oxygen and salinity in 5 floating project locations in the Netherlands. The results showed no significant differences in salinity between the area under/near the floating structures and open water, and the salinity values under/near platform and open water were compliant with the highest scores of water quality standards, as defined by the Water Framework Directive [100].
Similarly, changes in salinity under Mega-Float II, a prototype of a VLFS located in Tokyo Bay, were not detected following a monitoring campaign conducted between 1999-2000 [110].
These findings indicate that, in the literature, there is limited documented evidence demonstrating changes in salinity attributable to the presence of a floating platform. It is therefore not possible to assign a spatial and temporal extent score to this stressor.
As already discussed, activities occurring above the platform and their impacts may vary greatly. However, considering the ultimate goal of building self-sustaining communities on the floating platforms, a desalination plant might be required. This will produce a high salinity effluent that, if not properly treated, can modify the distribution and composition of the marine ecosystem [65].

Dredging Modifications in the hydrodynamic regime include changes in water mixing rate and resident time, which could lead to changes in salinity and pH.
A study concerning the impacts of habitat destruction due to dredging on the lemon shark in Bahamas [58], reported that the disruption of tidal flows led to a significant increase in water salinity and temperature, potentially creating an inhospitable environment for lemon sharks.
Changes in salinity can especially affect estuaries, which are dominated by the balance between fluvial and marine processes. For instance, channel deepening in estuaries disrupts the balance between fresh and saltwater, influencing the ecosystem, causing tidal waters to penetrate deeper, impacting salinity levels and potentially causing shifts in plant and animal communities [48]. In the case of Itajaí-Açú estuary in Brazil [57], dredging increased salinity of both the surface water and the bottom. The salinity stratification increased too, as well as the estuarine circulation, due to the increased salinity gradient and the decreased vertical mixing.
A slight pH increase has been observed in a few cases: a study regarding the effects of dredging on water quality parameters of Ekole creek in Nigeria [39] reported a change in water pH, which was slightly alkaline before the dredging and slightly acidic $2km$ downstream, after the dredging. Similarly, the potential impact of dredging in the Niger Delta [105] predicts a slight pH increase due to the acidic nature of the dredged sediments.
As reported in [51], dredged material disposal briefly influences local salinity in estuaries, with potential short-term changes due to increased vertical mixing. Salinity may also be

affected when material from saline waters is placed in freshwater areas. Moreover, disposing of dredged material can temporarily alter the pH of water in disposal sites, as the material is usually more acidic, but this effect is expected to be brief and confined to the disposal site.

The spatial extent that can be assigned to the modifications in water physical-chemical parameters due to dredging, including temperature, salinity and pH, is **2**, since the effects seem to be localized in the area surrounding the dredged site. The duration score is **3**, since the changes in these properties, mainly caused by alterations in the hydromorphological regime, depend on the land mass presence.

4.2.7 Collisions

Vessel movement is present at all the stages of the construction phase of dredged land and at the transport phase of floating platforms. Moreover, the presence of the reclaimed land or platform is likely to increase vessel traffic during the operational phase. The likelihood of a collision depends on many factors, such as vessel's type and speed, species behaviour and shipping traffic [55].

As far as floating platforms are concerned, the transport phase is the most critical one, partially due to the large size of the platform that has to be transported to the installation site. Since this stressor is strongly correlated to its receptors, mainly marine mammals [61], the risk of collisions between vessels and wildlife is described in more details in paragraph 4.3.1.1.

The spatial extent of collisions for both floating platforms and dredging is **1**, since it is a local impact, while the duration of the risk of collisions is as long as the construction phase, resulting in a score of **3**.

During the operational phase of floating platforms, an additional risk of collision is represented by the possible entanglement of animals in the mooring lines [61].

4.2.7.1 Entanglement

The risk of entanglement is correlated to the presence of underwater lines and cables, such as mooring lines, inter-connection cables, and electrical cables allowing connection to land-based power grids. In literature, this impact has been studied principally on OWFs [61] [35]. Due to the aim of achieving energetically independent communities on the floating platforms, it can be assumed that the terminal cables that lead to a land-based power grid are not present, lowering the risk with respect to the OWFs.

Entanglement risk is typically distinguished between *primary entanglement* and *secondary entanglement*:

- **Primary entanglement** happens when animals are entangled in the lines or cables of the floating structure. For OWFs, this risk is mainly relevant for marine mammals, but it is generally suggested to be low for a variety of reasons. In particular, the large diameter and general tautness of the cables and line are sufficient to avoid entanglement of large whales [111] [112]. Various species of marine mammals are also supposed to be able to detect the large diameter mooring lines [61]. The detection may occur through echolocation for odontocetes, vibrations sensed via vibrissae in the case of pinnipeds, or basic acoustic detection (hearing) of the noise produced by the ropes, which is depending to the current flow [112]. A further confirmation of the low potential risk of primary entanglement for marine mammals is given by the fact that it has not been observed for floating turbines in Scottish water since the beginning of the operations in October 2017 [61], even with a large presence of killer whales *(Orcinus orca)*, long-finned pilot whales *(Globicephala melas)*, sperm whales *(Physeter macrocephalus)*, fin whales *(Balaenoptera physalus)*, and minke whales *(Balaenoptera acutorostrata)* as well as pinnipeds of clade *Pinnipedia* in the area. A residual possible risk concerns baleen whales, which could suffer entanglement through the mouth since they feed keeping it open. The relative small density of baleen whales, which include fin whales and minke whales, from the area mentioned in [61] but due to their absence in the Scottish area, these results are not immediately extendable for areas with higher density.

- **Secondary entanglement** happens instead when animals are entangled in debris such as fishing gear in turn entangled on the mooring lines. This risk is considered to be greater than the one for primary entanglement: even if the actual impact on floating structures such as OWFs or floating platform is still under-studied, it is well known that entanglement with derelict fishing gear is one of the greatest threats to cetacean species [113]. The percentage of cetaceans affected by entanglement varies among different species and environment, but for example, 83% of North Atlantic right whale *(Eubalaena glacialis)*, which is a critically endangered species, showed evidence of entanglement as of 2009, with 26% of them showing new scars every year, and 50% of them having been entangled more than once [114]. Another possible mechanism is the secondary entanglement of diving seabirds, sea turtles, elasmobranches in derelict fishing gear or plastic pollution caught in the mooring lines. These animals, once trapped, could also serve as a prey for bigger predators, attracting them and putting them in danger of secondary entanglement [61].

In general, both primary and secondary entanglement risks are influenced mainly by the geometrical and constructive characteristics of the floating installation and by the disturbed environment, as reviewed by Benjamins et al. (2014) [112]:

- Geometrical and constructive characteristics: the mooring lines' diameter and whether they are taut or draped; in case they are draped, the depth of the draping. The installation of the mooring lines and their material can also influence the possible detection by animals, especially marine mammals;
- Environment characteristics: both the marine population and their behavior near the floating structure can influence the probability of entanglement. Moreover, secondary entanglement is influenced by the possible presence in neighboring areas of fishing grounds, which could bring derelict material towards the mooring lines.

4.2.8 Shading

The presence of a floating platform blocks the direct sunlight from entering the water column. As a consequence, the photosynthetic processes may be reduced or completely blocked, both on the seabed and in the upper layers of the water column, influencing the benthic community and macrophytes as well as the phytoplankton and macroalgae [60].
As shown in fig 4.22, the shadow location under the platform depends on many factors, such as the time of day and the season, meaning that some areas may be just temporarily shaded, and the water depth, the size, orientation and shape of the platform, meaning that an area towards the center of the platform may be shaded permanently [4].

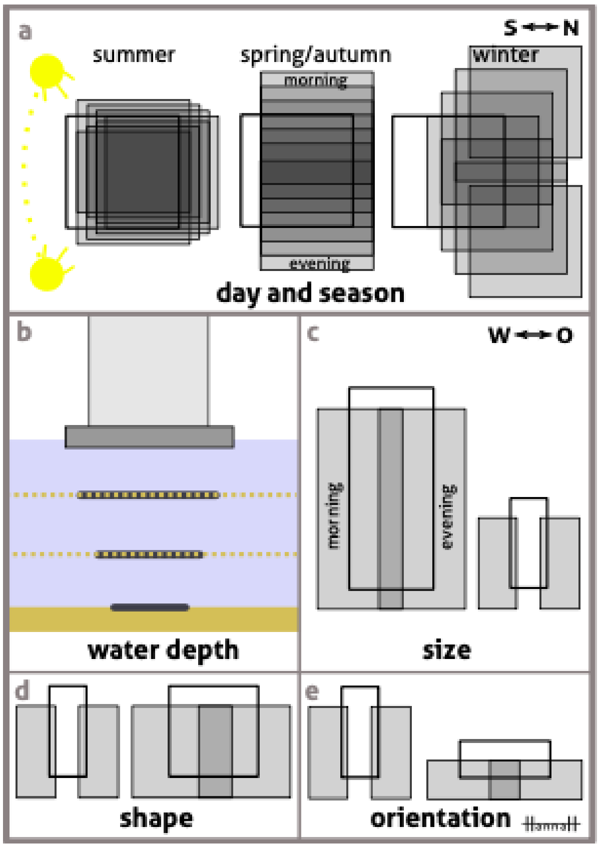


Figure 4.22: Factors influencing the shadow below a floating platform: a) time of day and season; b) water depth; c) size, d) shape, e) orientation of the platform (from [4])

Another aspect to take into account is the environmental conditions in which the platform is located: in turbid waters, where light is already of low intensity, an additional shading could reduce light levels to a point below the minimum required for photosynthetic reactions, whereas in clearer waters, the light reduction would be significant.
The reduction of light availability below the platform results in a reduction of photosynthetic processes, which causes a reduction in oxygen production, but it also results in a slight temperature change of the upper layer of water, which has an impact on aquatic processes too [62]. This aspect will be described in more details in paragraph 4.2.6.
Evidences of the effects of the shadow produced by floating platforms on the benthic cover have been presented by de Lima et al. (2022) [62]. In this paper, three distinct areas with varying benthic features were identified and visualized with a drone:

- areas away from floating structures, which showed varied benthic ecosystems ranging from bare sand to macrophytes and mussel beds;
- partly shaded areas, which showed differences in vegetation density between different sides of the floating houses, with macrophytes thriving in well-lit regions and being sparse in shaded parts;
- areas underneath floating houses, which lacked macrophytes and were marked by dead mussel shells, likely detached from the platform's bottom, and patches of bare sand.

This demonstrates that the spatial extent of the the shading caused by a floating platform and its effects is slightly larger than the platforms dimension itself, because it affects also its surrounding area. For this reason, the score that can be assigned is **2**.
Concerning the temporal extent, the floating platform will produce a shade beneath it as long as it is present in the water body, so the score is **3**.
If the platform is moved, the shadow produced in the original location will no longer be present, so this stressor can be considered reversible.

4.2.9 Activities on platform or land - artificial lightning

As explained in paragraph 4.1, a complete and generalized description of the stressors resulting from the activities that take place on the land or platform is not possible, due to their strongly correlation to the single project's purpose. However, to prove that these effects mustn't be underestimated, but have to be carefully taken into account based on the project's specifics, an example is reported in this paragraph.

The emission of artificial light during the night time can have an influence on the natural light regime of the surrounding environment [115]. This impact is commonly called as "light pollution" [116], even if the term has been used in recent years mostly to indicate the degradation of the view of the night sky. This is better defined by Longcore and Rich (2004) [116] as "artificial light pollution", whereas the effects on the ecosystem is defined as "ecological light pollution".
The sources of ecological light pollution are multiple, and include, as described by Longcore and Rich (2004) [116] "sky glow (the light reflected back from the sky), lighted building and towers, streetlight, fishing boats, security light, lights on vehicles, flares on offshore oil platforms, and even lights on undersea research vessel". They summarize these sources in figure 4.23:

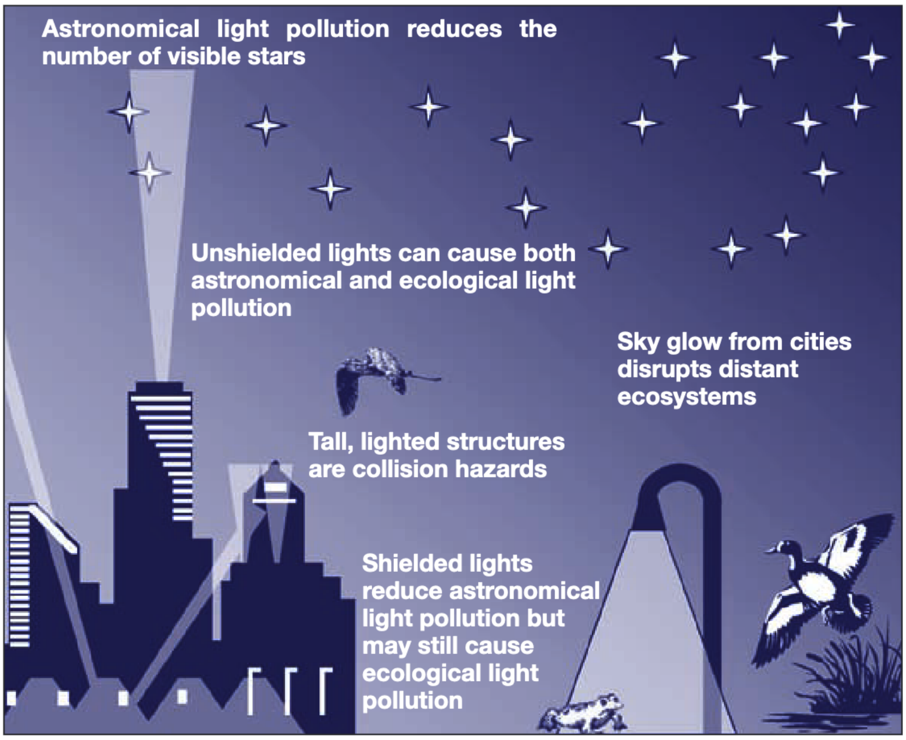


Figure 4.23: Diagram of ecological and astronomical light pollution, from [116]

Not all of these sources, but most of them, could be present in land reclamation areas, depending mostly on the purpose of use of the land, and less on whether the land is reclaimed through dredging or with the floating platforms.
Regarding in particular the marine ecosystem, the transitional zone between water and land has already been disrupted by the cities settled near water bodies such as seas, rivers and lakes [69]. A land reclamation project would increase the area affected by the ecological light pollution, in a way similar to the cities. The main sources of light pollution would be, typically, the light emitted by the lighted building and towers, streetlight, and eventual security lights around the floating platform.
Impacts on the marine ecosystem are multiple, and depend on the species that populate it, and on the location of the impacted zone. For example, the minimal variation of the light and dark daily cycles in tropical zone may expose tropical species to a higher sensitivity to shorter or brighter nights [117].
In general, the demonstrable impacts of ecological light pollution on the ecosystem range from changes in orientation, disorientation, and attraction or repulsion from the altered light environment [116]. These impacts may in turn affect foraging, reproduction, migration and communication [116].

- **Orientation/disorientation**: animals that use the light to orientate themselves may be impacted by increased illumination. Species that are used to navigate in dark environments can be disoriented by an artificial light. For example, hatching sea turtles that normally would use the silhouette of the dune vegetation as a landmark to navigate towards the ocean miss this important reference point in case of beachfront lighting [118]. An extended light period may cause diurnal animals such as birds [119] and reptiles [120] to forage in areas illuminated by artificial light, extending the foraging window thanks to an extended illuminated time frame, and in turn impacting their sleep/wake daily cycle. Of course, this impact is also detrimental for their preys. Other impacted species are birds, which can be disoriented and entrapped in lighted zones at night, without being able to leave them, causing collisions with each other or with structures, possible exhaustion and vulnerability to the predators, and disruption of migratory routes [121]. Various species of insects, such as moths [122], lacewings, beetles, bugs, caddisflies, crane flies, midges, hoverflies, wasps and bush crickets [123] [124] are attracted to lights, with various degree of attraction depending on the spectrum of lights and characteristics of additional lights in the proximity.

- **Reproduction**: artificial light can also affect negatively the reproductive cycle of various species. For instance, female *Physalaemus pustulosus* frogs exhibit reduced selectivity in choosing mate partners, opting for quicker mating to mitigate the heightened predation risk associated with mating activities. [125]. In birds, nest density is observed to be lower in artificially illuminated areas, for example for black-tailed godwits *Limosa l. limosa* in wet grassland habitats [126].

- **Communication**: Certain species employ light as their sole communication medium, such as the female glow-worms, that attract males with bioluminiscent flashes visible up to $45m$ away, or the fireflies, which communicate with a complex visual system [127]. The visibility of these signals can be reduced by the presence of light pollution [127] [116].

- **Predation and food web**: As previously mentioned, some species can benefit from an increased activity time due to the presence of artificial lighting, extending their diurnal or crepuscular behaviors into the nighttime. This apparent advantage can, although, expose the species to a higher risk of predation [128]. This balance can be particularly meaningful for small mammals, reptiles and birds [129], [130]. For floating platforms and dredging, a relevant impact is the one on the food web regarding fish, macro invertebrates and algae. As illustrated in figure 4.24, typically, during the night, macro invertebrates feed on the algae at the water's edge, where they are in turn predated by small juvenile fish, while the bigger fish regenerate, sleeping, at the bottom (panel A). In presence of artificial light (panel B), diurnal predators such as bigger fish become active, forcing the macro invertebrates to protect themselves from their predators, causing a lower consumption of the algae, which are free to spawn without predators. Additionally, bigger fish can also predate the insects attracted by the light [69].

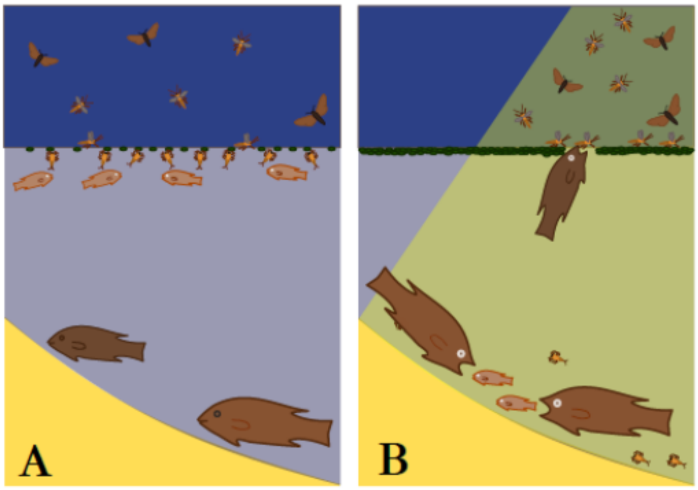


Figure 4.24: Disruption of natural food web due to artificial lightning. From [69]

The spatial and temporal extent of this impact do not vary much depending on whether it is caused by a floating platform or a dredged area.
For the spatial extent, not only the reclaimed area will be impacted, but also the immediately surrounding areas, due to the diffusion of the lighting and the reflected sky glow. For this reason, the score that can be assigned is **2**. The only difference could be in the fact that dredged land will have an impact on the neighboring marine and aerial areas, and on the aerial area above the dredged land, whereas the floating platform impact will also be on the underwater zone below the platforms.
The temporal extent is limited to the night times of the operational period for both land reclamation techniques, so an impact score of **2** can be assigned, considering that the night time is ∼ 50% of the operational period, averaging between winter and summer periods.

4.2.10 Matrix values for floating platforms and dredging

The assigned indexes for spatial extent and duration of each stressor are provided in the tables below, correlated with the literature references (Tab. 4.3, Tab. 4.4). Moreover, Tab. 4.5 provides the numerical ranges of spatial and temporal extent of each dredging stressor. These values were obtained through the literature review of measured impacts caused by existing dredging projects.

Impact	Spatial extent	Duration	Significance	References
Construction phase				
Turbidity and suspended sediments	2	3	High	[44] [65] [36]
Noise	3	3	High	[44]
Collision vessel-wildlife and entanglement	1	3	Medium	[55] [61] [112]
Operational phase				
Shading	2	3	High	[62] [4]
Hydromorphological changes	2	3	High	[96] [94] [5]
Dissolved oxygen and temperature	2	3	High	[69] [62] [63] [5]
pH	1	3	Medium	[44]
Artificial light	2	2	Medium	[69] [116]

Table 4.3: Impact matrix of floating platforms: indexes

Stressor	Spatial extent	Duration	Significance	References
Construction phase				
Turbidity and suspended sediments	4	4	Critical	[71] [52] [75] [49] [78] [131]
Noise	4	3	Critical	[87] [132] [81]
Physical destruction and entrainment	1	4	Medium	[52] [80] [51]
Dissolved oxygen	2	4	High	[48] [50] [39] [104]
Collision vessel-wildlife	1	3	Medium	[55] [53] [133]
Operational phase				
Hydromorphological changes	4	4	Critical	[48] [52] [97] [56]
Physical-chemical water parameters (T, salinity, pH)	2	3	High	[57] [51] [39] [58]
Artificial light	2	2	Medium	[69] [116]

Table 4.4: Impact matrix of dredging: indexes

Impact	Spatial extent	Duration	Phase	References
Turbidity and suspended sediments	$0 - 30km$	0 − 1095days	Construction, Land	[71] [52] [75] [49] [78] [131]
Noise	$330m - 30km$	Continuous	Construction	[87] [132] [81]
Physical destruction of habitat	Correspondent to area of land reclaimed	Long term (years)	Land	[52] [80]
Hydromorphological changes	$1 - 50km$	Long term (years)	Land	[48] [52] [97] [56]
Collisions vessel-wildlife	Vessel size		Construction	[55] [53] [133]
Dissolved oxygen	$0 - 2000m$	0 − 2 months	Construction	[48] [50] [39] [104]
Physical-chemical water parameters (T, salinity, pH)	/	Years	Land	[57] [51] [39] [58]

Table 4.5: Impact matrix of dredging: numerical values

4.2.10.1 Discussion

Using the combination between spatial extent and duration provided in Fig. 4.4, the significance of each stressor has been determined. To compare the stressors' significance of the two land reclamation methods, a useful way is to look at the percentages of low, medium, high and critical significance. No floating platform or dredging stressor has a low significance. 37.5% of both floating platforms and dredging stressors have a medium significance. 62.5% of floating platforms stressors and 25% of dredging stressors have a high significance. Finally, no floating platform stressor has a critical significance, whereas 37.5% of dredging stressors have a critical significance. Moreover, the mean spatial extent of stressors that arise during the construction phase is 2 and the mean duration is 3, while the mean spatial extent of stressors that arise during the construction phase of dredging is **2.4**, while the mean duration is **3.6**. Concerning the stressors of the operational phase, the mean spatial extent for floating platforms is **1.8** and the mean duration is **2.8**, while for dredging the mean spatial extent is **2.7** and the mean duration is **3**.

There are no stressors classified with low significance, indicating that all stressors, whether associated with floating platforms or dredging, possess at least a medium significance. This observation can be attributed to the fact that, although some stressors may have a spatial extent of **1**, suggesting a localized impact, none of them exhibit a duration index lower than **2**. This is because, as per the index definition presented in Tab. 4.1, no stressor has a temporal duration lower than 25% of the phase duration. This emphasizes that all stressors, even those originating from nearly instantaneous actions such as mooring anchor installation, persist for a certain amount of time rather than ceasing immediately. Furthermore, it can be noted that no stressor associated with floating platforms reaches a critical significance. This observation may come from the fact that no stressor related to floating platforms has a spatial or temporal extent index of **4**. This implies that the construction and operational phases of floating platforms do not generate stressors that remain detectable beyond the phase duration and extend to more than 10 times the project size. In contrast, a significant portion of dredging stressors, particularly during the construction phase, holds a duration index of **4**. This is attributed to the notably disruptive nature of the dredging construction phase, resulting in prolonged and irreversible effects on the ecosystem in which the dredging project is conducted.

Comparing the mean values of spatial and temporal extent of the two land reclamation methods, it can be observed that the mean of the stressors' extent is always higher for dredging than floating platforms, both for construction and operational phase. This is a further demonstration that, based on the matrixes obtained from an extensive literature review of measured or predicted impacts, floating platforms have a lower environmental impact compared to dredging.

A major difference between floating platforms and dredged land is the reversibility of their impacts on the marine environment: floating platforms can be moved in another location, due to for example project requirements or decommissioning, therefore the stressors on the environment can be considered reversible, whereas a landmass built through dredging can't be moved, so the impacts caused by its presence in water are not reversible.

A limitation of this comparison arises from the absence of reported stressor magnitudes and likelihoods. This omission is deliberate, aiming for the broadest possible comparison, as these aspects are inherently site-specific and cannot be reliably assigned in this generalized analysis. Magnitude and likelihood are strongly dependent on specific site conditions, making them highly variable. In a more detailed and site-specific analysis, these factors should be carefully assessed and integrated with spatial and temporal extents to achieve a more comprehensive understanding of impact significance.

For instance, the stressor related to the collision between vessels and wildlife shares the same spatial and temporal extent index as pH variations for floating platforms. However, the magnitude of impact differs significantly, as a collision could lead to the mortality of a marine mammal [55], whereas the pH change resulting from concrete carbonate leaching has a localized and low-magnitude impact, minimally affecting the surrounding water's pH [44]. Both impacts exhibit localized effects (index 1) lasting throughout the phase duration (index 3), yet their magnitudes are distinctly different. However, when considering likelihood, the collision between a dredger and a marine mammal is very low [133], while the concrete platform is highly likely to undergo corrosion, causing the slight pH change [44].

In summary, the direct comparison of stressor significances between floating platforms and dredging, which are based on a systematic review of reported or assumed spatial and temporal extents from the literature, unequivocally demonstrates a lower environmental impact of floating platforms, which is a key objective of this thesis. Moreover, the reversibility of the floating platform solution, which allows for project remobilization if necessary, provides further confirmation of its heightened sustainability. Nevertheless, for a comprehensive assessment of stressor significance, considering magnitude and likelihood is essential. These factors were intentionally omitted in this analysis due to their strong reliance on specific project location characteristics. Therefore, the accurate assignment of stressor significance should be meticulously undertaken for each project, accounting for the unique environmental conditions of the respective location.

4.3 Receptors

A receptor is defined as a species, resource or activity, present in the project area, that can be affected by the stressors. [64].

In an impact assessment, after the identification of the pressures and the evaluation of their severity, the following step is to establish the receptors that can be influenced by them and predict their responses and tolerance limits, based on site specific data. However, when these data are not available, it is useful to adapt literature values from comparable studies to the site. Tolerance levels depend not only on the impact significance, but also on the species sensitivity and on the baseline conditions of the specific location. For example, if an healthy reef is situated in a region regularly affected by sediment discharges from nearby rivers, it could have a higher tolerance for elevated turbidity levels with respect to reefs that are rarely affected by such plumes. On the contrary, a degraded reef in a similar environment might already be close to its tolerance limit for turbidity, and may not be able to withstand an additional turbidity increase [18].

The main identified receptors are mobile animals such as marine mammals and fish, benthos such as coral reefs and seagrass, macroplants such as mangroves and plankton, both zoo and phyto.

Stressor/Receptor	Marine mammals	Fish	Corals	Seagrass	Mangroves	Plankton
Turbidity and suspended sediments	x	x	x	x	x	x
Noise	x	x				
Collisions and entanglement	x	x				
Shading		x	x	x		x
Hydromorphological changes		x	x	x	x	
Physical destruction and entrainment		x	x	x	x	
Physical-chemical parameters		x	x			x
Artificial light		x				x

Figure 4.25: Overview of the stressors affecting each receptor.

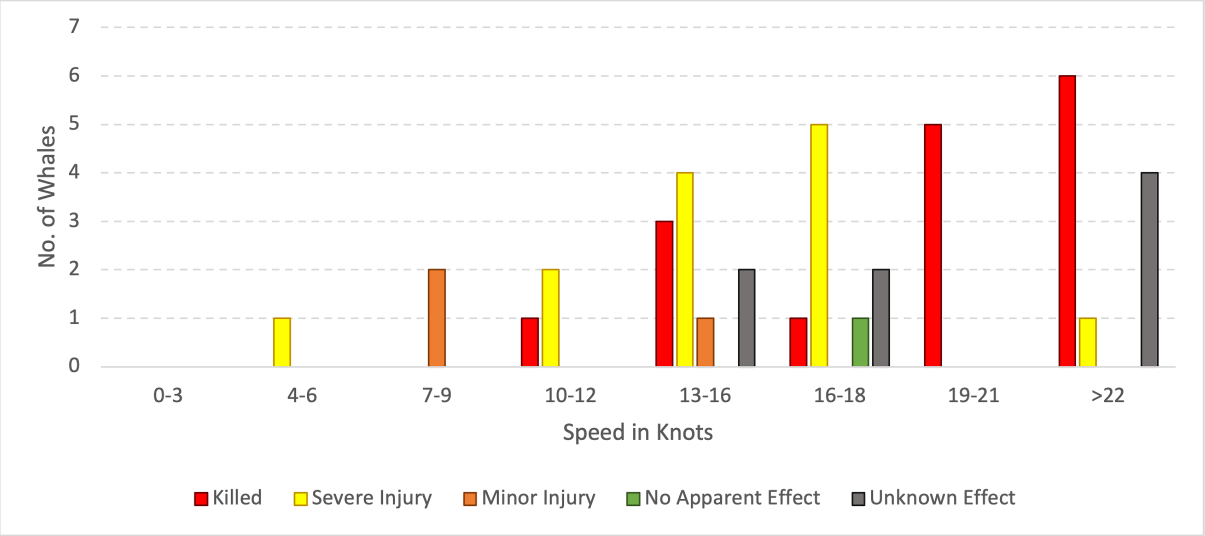
4.3.1 Mobile animals

4.3.1.1 Marine mammals

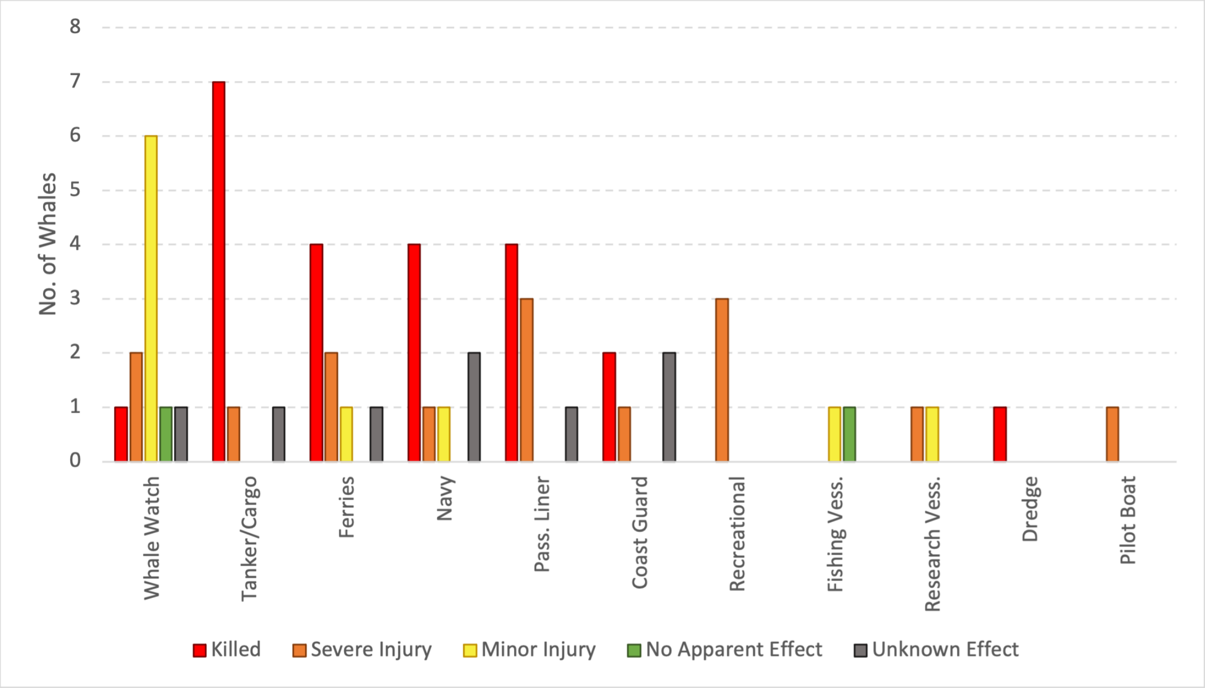
In general, marine mammals are widely spread, but their distribution is irregular, and specific species and populations can be concentrated only in certain regions. The most

crucial areas for species survival and growth are the ones where vital activities take place, such as breeding, nursing, and feeding. Therefore, the disruption of these areas can affect local distribution and population abundance.
The main direct impacts that can affect marine mammals are collisions and noise [53]

Collisions In a study conducted in 2001 by Laist et al. [55] about collisions between ships and whales, evidence of motorized vessel collisions with 11 species of great whales has been found. These collisions resulted in different degrees of injuries, ranging from no apparent effect to mortality. As shown in fig. 4.26a, collisions that cause more severe injuries to whales happen when the vessel has a speed of 14 knots or more. Moreover, although different types of vessels could collide with whales, the larger ones cause more severe injuries, as shown in fig. 4.26b.



(a) By speed of the vessel



(b) By type of vessel

Figure 4.26: Classification of impacts with whales by speed and type of vessel, from [55]

Among these reported collisions, only one was related to dredging activities [133]: in 1984 in South Africa an hopper dredger with a length of 110 meters collided with a southern right whale calf, which died after hitting the propeller. Such a low number could be due to the fact that dredgers in action are almost stationary or travel at very low speeds (1-3 knots), so the most critical phase is when dredgers are in transit, at speeds of 12-16 knots.

Marine mammals seem to be more prone to collisions when they are concentrated on other activities, such as feeding and resting, and it has been reported that collision frequency can be seasonal, being higher during intense feeding periods [134]. Moreover,

calves and juveniles are more likely to hit a vessel compared to adults [55], [135].
Another factor to take into account is the usual shipping traffic: in areas characterized by heavy traffic, adding dredging vessels or vessels to transport floating platforms would not increase the collision risk as much as it would in a less busy area [53].
Taking all these aspects into consideration, a good strategy to decrease the likelihood of vessel-marine mammals collision could be to reduce the vessels' speed and to pay more attention during the critical periods of feeding months or in spawning areas for calves and juveniles.

Noise Marine mammals rely on sound for many essential activities such as prey detection, navigation, and communication. If anthropogenic noise, like the noise generated during dredging operations or during the installation of moorings for floating platforms, overlaps with the hearing ranges of marine mammal species present in the area, it has the potential to affect both individuals and populations.
A first way to assess sound-related impacts is a model known as the "zone of influence model" by Richardson et al. [136]. It describes a series of zones of influence centered in the noise source, which become less severe as the distance between the receiver and the source increases. This scheme is based on the principle that sound intensity decreases with the increasing distance from the source. As a consequence, the noise impact is likely to decrease too, or at least change, with the distance.

- The most spread area is the detection one, also called audibility, and represents the zone where the receiver is able to detect the sound. It has a high variability because it depends on many factors, such as the sensitivity and hearing range of the receiver, the local conditions such as water temperature, density and depth of the sound source and the sound frequency.

- The masking zone is where the sound interferes with biologically significant signals such as communication or echolocation signals. It begins when the received sound level of the masking noise matches the ambience noise level at the signal's frequency, and it can reduce the detection range of sounds [82]. This phenomenon has been observed in marine mammals' communication, and it is also likely to affect fish, potentially impairing their ability to detect prey or predators. The extent of masking depends on the animal's auditory capabilities and the frequency range of the background noise. When important signals are masked, animals could display inappropriate responses due to the inability to perceive essential information, and the foraging capability and reproductive response could be impacted too, affecting the population [137].

- The response zone is where the animal has a behavioural response to the sound, and the individual reactions depend on auditory capability, behavioral state (such as hunger level and reproductive conditions) and surroundings characteristics (such as open or confined water). Intense sounds can trigger escape or avoidance reactions, while less intense sounds lead to subtler changes in movement patterns. Disrupted behavior can impact both individuals and populations, and chronic exposure may mitigate the sound's effects due to adaptation.

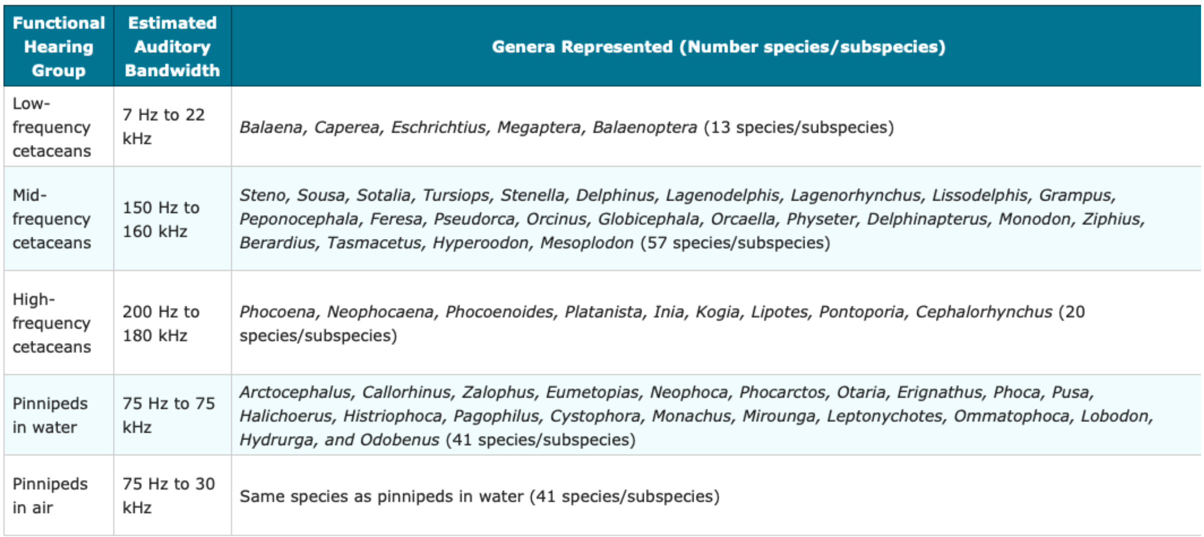
- The two zones closer to the source lead to physiological effects and to changes in the hearing ability of animals. The zones of Temporary Threshold Shift (TTS) and Permanent Threshold Shift (PTS) represent the spatial extent to which the exposure to sound causes a recoverable or permanent increase of the hearing threshold; the PTS is considered an auditory injury.

Figure 4.27: Zone of influences scheme adapted from Richardson et al. (2015) [85]

Even though the “zone of influence” model is a valid first assessment, in order to properly estimate the impacts and possible physiological effects of a noise on the receiver, in addition to the distance from the source of sound it is important to consider also the duration of exposure to that sound [138].

Moreover, a behavioural reaction to a sound could result in injuries and even mortality when it leads to stranding for example. To assess this aspect, a more detailed scale that describes the severity of behavioural responses of free-ranging marine mammals to noise exposure has been presented by Southall et al. in 2007 [139]. In this study, the response score goes in an ascending order of presumed consequences from 0 to 9, where scores of 0-3 can be classified as low severity, from 4-6 of medium severity, from 7-9 of high severity. The behavioural responses are divided into changes that affect survival, feeding and reproduction. For example, a brief orientation change has a score 1, so it is considered of low severity, whereas a prolonged change in locomotion is a medium severity response of score 5; the most severe response of score 9 can lead to mother-offspring separation, failure to successfully reproduce or feed and therefore mortality.

Understanding the potential effects of the noise, produced during dredging or mooring of floating platforms, on marine mammals is a complex task due to the simultaneous occurrence of various industrial activities and to the only partial knowledge of marine mammals hearing sensitivity. Typical hearing ranges of cetaceans and pinnipeds, divided into functional hearing groups of low, medium and high frequency, have been discussed by Southall et al. [139] [47] and are presented in table 4.28:



Functional Hearing Group	Estimated Auditory Bandwidth	Genera Represented (Number species/subspecies)
Low-frequency cetaceans	7 Hz to 22 kHz	*Balaena, Caperea, Eschrichtius, Megaptera, Balaenoptera* (13 species/subspecies)
Mid-frequency cetaceans	150 Hz to 160 kHz	*Steno, Sousa, Sotalia, Tursiops, Stenella, Delphinus, Lagenodelphis, Lagenorhynchus, Lissodelphis, Grampus, Peponocephala, Feresa, Pseudorca, Orcinus, Globicephala, Orcaella, Physeter, Delphinapterus, Monodon, Ziphius, Berardius, Tasmacetus, Hyperoodon, Mesoplodon* (57 species/subspecies)
High-frequency cetaceans	200 Hz to 180 kHz	*Phocoena, Neophocaena, Phocoenoides, Platanista, Inia, Kogia, Lipotes, Pontoporia, Cephalorhynchus* (20 species/subspecies)
Pinnipeds in water	75 Hz to 75 kHz	*Arctocephalus, Callorhinus, Zalophus, Eumetopias, Neophoca, Phocarctos, Otaria, Erignathus, Phoca, Pusa, Halichoerus, Histriophoca, Pagophilus, Cystophora, Monachus, Mirounga, Leptonychotes, Ommatophoca, Lobodon, Hydrurga, and Odobenus* (41 species/subspecies)
Pinnipeds in air	75 Hz to 30 kHz	Same species as pinnipeds in water (41 species/subspecies)

Figure 4.28: Typical hearing ranges of marine mammals, divided in functional hearing groups depending on the estimated auditory bandwidth from [47]

Considering the match between dredging noises and the suspected hearing sensitivity of marine mammals, it is likely that all of them are susceptible to noise impacts from dredging at some extent [53]. This impact might be more critical for baleen whales, that communicate at very low frequencies.

As discussed in paragraph 4.2.3, the noise produced by dredging operations depends on many factors. However, based on the typical noise values presented in paragraph 4.2.3, the sound levels experienced by marine mammals generally remain below suspected PTS, but TTS cannot be excluded if they are exposed to prolonged noise.

The reactions of different species to dredging noise vary considerably, and in many cases it is difficult to link avoidance reactions from marine mammals solely to dredging activities, because these usually happen at the same time as other industrial activities and shipping, which produce noise and can potentially create disturbances too.

In some cases, areas characterized by intense industrial activities, including dredging, exhibited a long-term decrease in baleen whales population, such as grey whales (*Eschrichtius robustus*) [54] and bowhead whales (*Balaena mysticetus*) [140].

In a study from Pirotta el al. (2013) [141] it has been possible to uniquely link the decrease in bottlenose dolphin (*Tursiops truncatus*) population to dredging activity, since it happened in an area already affected by heavy traffic, to which the species already adapted, and therefore the additional dredging noise in this case can be considered as the primary cause of avoidance.

Some pinnipeds, such as Hawaiian monk seals (*Monachus schauinslandi*) [142], New Zealand fur seals (*Arctocephalus forsteri*) and Australian sea lions (*Neophoca cinerea*) [143], seem relatively unperturbed, exhibiting limited disturbance even in close proximity to dredgers. On the other hand, grey seals (*Halichoerus grypus*) have shown avoidance behaviors in Ireland to high construction vessel traffic [144].

Some avoidance responses have been also observed in sirenians: for instance, it has been found that Florida manatees (*T. manatus latirostris*) tend to choose seagrass bed sites with less low-frequency noise, indicating their ability to adapt their habitat preferences based on noise levels [145].

To conclude, observations suggest that auditory injury is improbable under typical exposure conditions; however, temporary hearing loss becomes a concern if marine mammals remain in close proximity to the dredger for prolonged periods. Moreover, short to medium-term avoidance, masking of low-frequencies calls and change in species distribution have been reported.
For these reasons, it is important to avoid prolonged construction operations in breeding, spawning and feeding areas to not affect the population, especially if they are prolonged over time.

4.3.1.2 Fish

The potential environmental impacts of land reclamation projects on fish vary depending on their stage of life, with fish at an early life stage exhibiting higher vulnerability compared to adult fish, which can avoid affected areas more easily [51]. Due to turbidity, suspended sediments, noise, entrainment, hydromorphological and physical-chemical changes, fish species distribution, behavior, migration, feeding, spawning and development may be affected, leading to disturbance, displacement, avoidance, injury or mortality.

Suspended sediments and turbidity Marine organisms have developed different levels of tolerance and survival mechanisms to cope with natural events, such as storms, that lead to sediment disturbance and elevated turbidity. However, the increase in turbidity due to land reclamation activities may surpass natural levels or occur at different times, potentially challenging the survival abilities of certain organisms [53].
High concentrations of suspended sediments have been observed to significantly influence fish behavior, affecting aspects such as avoidance responses, territoriality, feeding, and homing behavior [146]. For instance, avoid reactions have been observed in Atlantic herring *(Clupea harengus)* and rainbow smelt *(Osmerus mordax)* when exposed to SS concentrations of $20mg/l$ and $10mg/l$ respectively [147]. Short-term pulses of sediments can lead to disruptions in the social organization of coho salmon, with behavioural changes to territorial defense and feeding success observed at turbidity higher than $30-60NTU$ [148]. It has been found that certain increased turbidity levels prompt juvenile coho salmon to increase feeding rates. However, when turbidity surpasses a critical threshold of $200mg/l$, significant behavioral changes occur, impacting prey responses and predator avoidance [149].
High levels of suspended sediments may impact migration of certain species, such as juvenile coho salmon and steelhead trout, which migrate towards clearer water if possible [150].
Fish development may be affected by increased turbidity. Studies indicate that fish eggs and larvae, particularly of sensitive fish species like herring, are highly susceptible to harm from increased turbidity, often resulting in suffocation [151]. Elevated suspended sediment levels have been associated with reduced survival, abnormal development, and slower growth rates in various fish species, including coho salmon and steelhead trout [152]. While some studies suggest potential benefits such as earlier hatching [153], overall, the impact on fish health and growth is negative [51].
Moreover, the deposition of suspended sediments may lead to the burial of benthic ecosys-

tem, potentially burying spawning areas [153], as shown in Fig. 4.29. For instance, laboratory investigations on the survival of herring eggs have shown that elevated sedimentation levels lead to increased mortality [51].

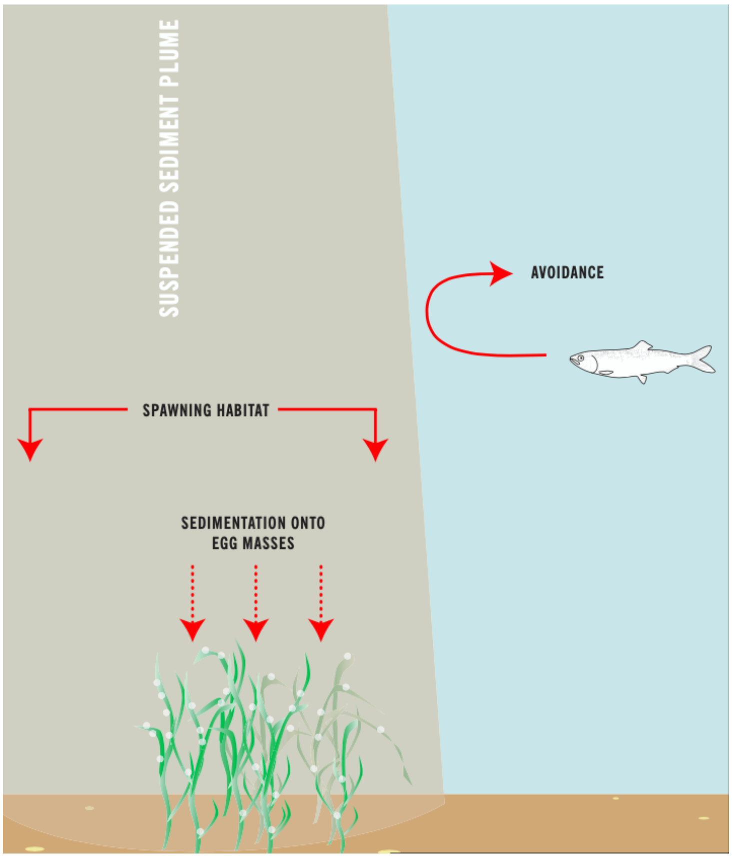


Figure 4.29: Potential burial of fish spawning habitat due to suspended sediments deposition. From [51]

Feeding success has been found to be linked to turbidity levels, with higher turbidity reducing prey capture success. This can be explained considering that light availability plays a crucial role in the lives of larval and juvenile fish, particularly salmonids, since they are visual feeders. A reduction in light availability due to increased turbidity could affect not only their feeding ability, but also other behavioural aspects, such as schooling, detecting potential predators, migration and orientation [48].

Suspended sediments could provoke gill injuries and difficulties in breathing, depending on their concentration and shape. Fish gills are essential for oxygen exchange, and at high suspended sediments concentration fish have a cough reflex in order to keep the gills clear and maintain ventilation [154]. A study regarding the effects of different sediment shapes on coho salmons *(Oncorhynchus kisutch)* [155], observed that angular sediments are associated to higher stress responses at lower concentrations, suggesting that their shape may irritate fish gills, increasing the mucus production and decreasing the oxygen transfer, leading to stress. However, the observed 20% fish mortality at a SS concentration of $100g/l$ did not significantly differ between angular or more natural shaped sediments. Another research regarding coho salmons [154] reported that, following an exposure of $96h$ to SS concentration of $16 - 41mg/l$, an average of 1500 particles with an irregular

and angular shape were found in the fish gill epithelia.
Moreover, the presence of large coarse suspended particles has the potential to cause harm to fish through abrasion or crushing. The abrasion of the fish's body surface could result in the removal of protective mucus, thereby increasing their susceptibility to invasion by parasites or diseases [151].

In conclusion, due to the high variability of fish sensitivity and adaptability to turbidity and suspended sediments, the behavioral responses of various fish species encountering increased turbidity plumes cannot be exactly determined [48]. Therefore, it is not possible to quantitatively assess the biological response to threshold suspended sediment concentrations and the exposure duration tolerated by different species, mainly due to the very high number of fish species, compared to the investigated ones. The main factor influencing the level of impact is likely the overlap in space and time between the increased turbidity zone, the extent of turbidity increase, the presence of fish, and the available choices for fish to perform their vital functions. Certain species exhibit lethal effects at concentrations of several hundred mg/L within a 24 hour period, while other species show no adverse effects even at concentrations exceeding $10000 mg/l$ over a 7 day period [48]. Overall, the influence of suspended sediments extends to various aspects of fish behavior, with potential ecological consequences, particularly to fish at early stages of life. A representation that summarizes possible behavioural responses of fish to a suspended sediment plume is provided in Fig.4.30

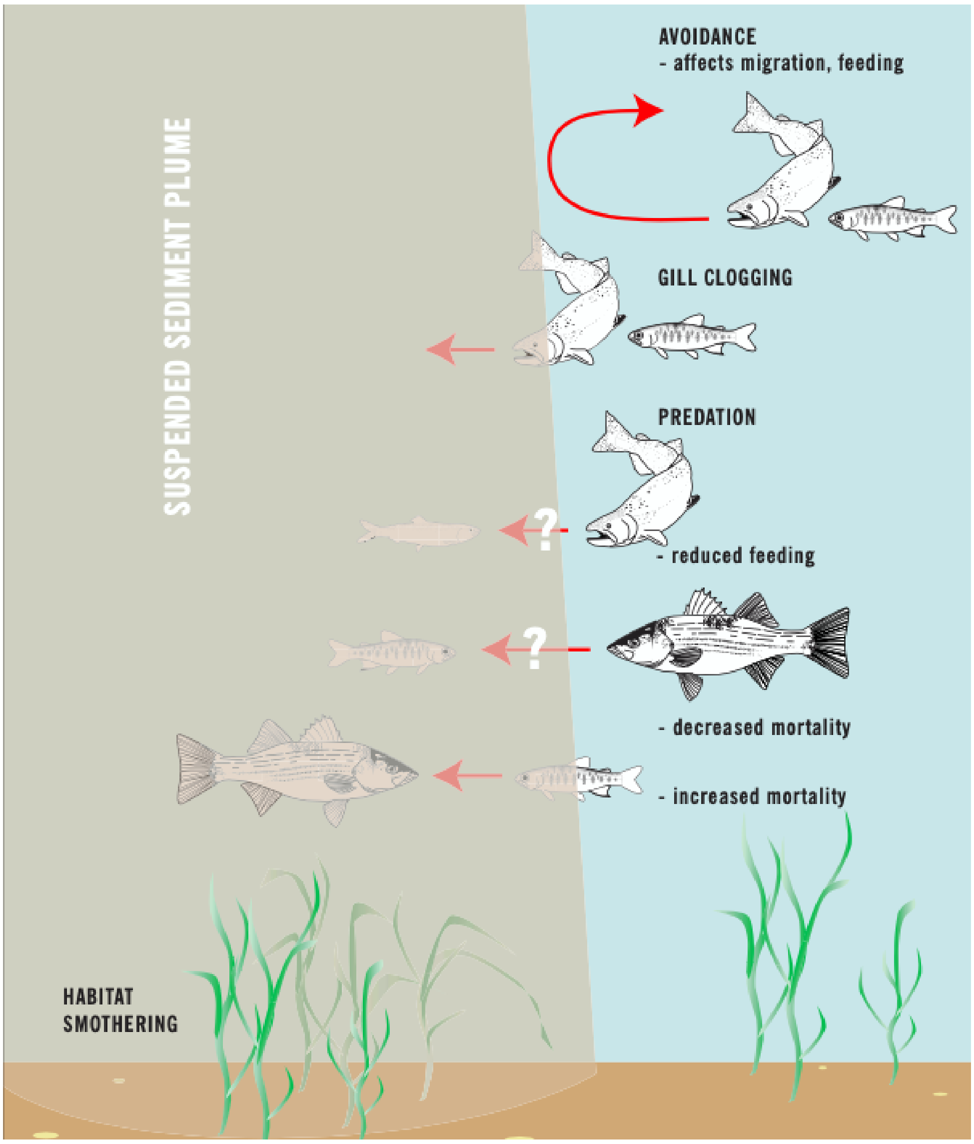


Figure 4.30: Potential effects of suspended sediments plume on fish. From [51]

Noise The zones of influence model [136] described in paragraph 4.3.1.1 is valid to first assess sound-related impacts on fish. As shown in Fig. 4.31, the closer the fish is to the sound source the more its behaviour is influenced. It has been documented that noise affects fish behaviour, including their ability to detect preys and predators and to communicate [156], [157]. Fish species have a wide variety of hearing sensitivity, but they are generally sensible to low frequencies [158], typical of dredging activities and vessel noises. Moreover, pile driving noise can influence the behaviour and distribution of nearby fish schools, being detectable by juvenile salmonids at a distance of at least $600m$ from the source [159]. Fish startle and alarm response threshold is $150dB\ re\ 1\mu Pa$ [160], while a sound $15dB\ re\ 1\mu Pa$ higher than ambient noise could increase fish egg mortality by 25% and embryos mortality by 85% [161].

Avoidance reactions have been observed for Atlantic herring [160] and Pacific herring [162]. Auditory masking and adaptation to persistent loud noise could potentially reduce the ability of salmonids to detect approaching predators [159]. The masking of noises produced

by larval organisms may affect their ability to orientate towards an ideal settling location [163]. Besides masking of communication signals, other observed behavioural changes include a diminished feeding efficiency [164] and an increased motility [165]. Furthermore, TTS caused by the exposure to low-frequency white noise and vessel noise has been observed in marine fish [166]. High intensity sounds, such as pile driving noise, could lead to fish injury, which include swim bladders ruptures and deflation, bleeding and bruising in various tissues and organs and immediate mortality [167].
While high intensity pile driving noise could directly harm fish, dredging noise would unlikely cause direct mortality due to the lower noise intensity [82]. However, continuous long-term exposure could affect prey availability, larvae survival and feeding efficiency, potentially influencing overall species distribution and survival [53].

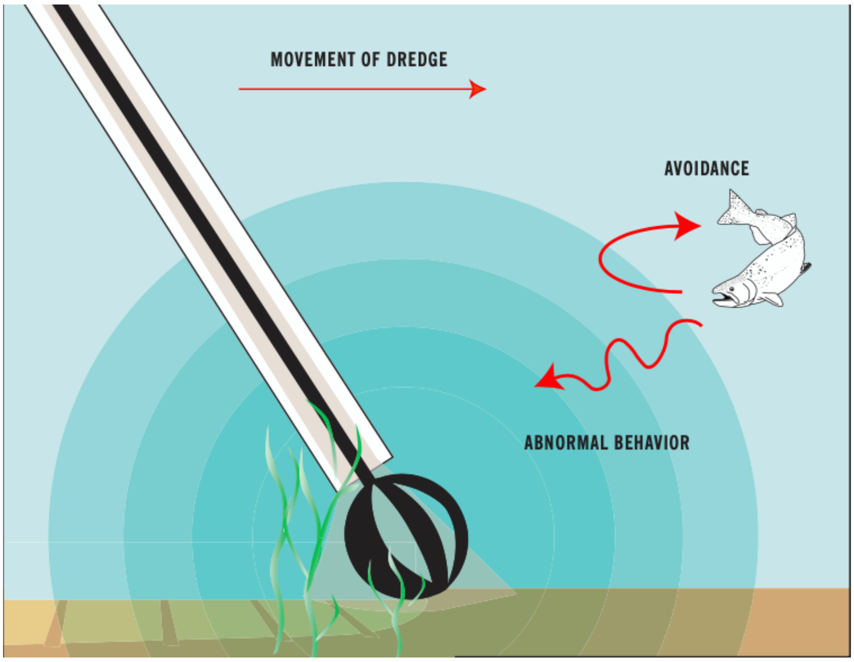


Figure 4.31: Behavioural effects of dredging noise on fish [51]

Shading The shade produced by a floating platform may affect fish population. Fish species that rely on vision to detect their prey would be directly impacted, while indirect effects may include changes in prey availability and dissolved oxygen concentration [5]. Moreover, the floating platform would provide a sheltered environment, that could be used by fish to hide from predators or to protect themselves from UV-B irradiance [168]. Helfman (1981) [169] discussed the advantages provided to fish by the shade produced by floating objects. The study suggests that fish are attracted to floating objects, as they offer a visual advantage by diminishing both background light and veiling brightness. Veiling brightness is a phenomenon occurring underwater, where suspended particles near the eye reflect light, forming a bright region near the observer, which hinders visibility of distant targets. Therefore, the shade produced by a floating platform would reduce this brightness, enabling the fish to see farther and detect predators more easily. Indeed, a shaded fish could see an approaching sunlit prey or predator considerably before the sunlit prey or predator can detect the shaded fish. Moreover, the study found a positive correlation between fish density and float surface area. The highest number of fish attracted under a floating structure has been observed during the sunniest hours of the day, especially in clear sky conditions, further demonstrating that the shade is the main factor that attracted fish.

Physical-chemical parameters An increase in water temperature may be detrimental to fish, since it leads to a higher metabolic oxygen demand [154]. This effect, combined with potential lower dissolved oxygen levels and higher suspended sediment concentrations that clog gills, could result in the fish inability to meet the oxygen demand, eventually leading to mortality [154].
As discussed in paragraph , the estuarine ecosystem is particularly susceptible to long-term shifts in salinity distribution caused by dredging. Salinity changes in estuarine ecosystem and their potential impacts on fish has been analyzed by Nightingale et al. (2001) [48]. Anadromous fish, which are defined as fish that live at sea and migrate to freshwater to spawn, as well as fish at early life stages, are particularly sensitive to salinity variations, especially during transitions from fresh to saline waters caused by dredging of estuarine channels. Channel deepening may lead to tidal waters intruding further up the estuary, altering salinity levels and potentially affecting demersal fish and benthic macroinvertebrates. The impact depends on factors governing estuarine circulation. Changes in surface salinity regimes, dictated largely by water mixing, can significantly impact intertidal organisms. While periodic small changes may be accepted, significant dredging projects require careful consideration of their potential impact on estuarine biota [48].

Physical destruction and entrainment As discussed in paragraph 4.2.4, entrainment caused by dredging affects not only the benthic ecosystem, but also mobile epibenthic and demersal organisms. In particular, dungeness crabs and demersal fish are most likely to be entrained, as they reside on or in bottom substrates, burrowing or hiding [48]. Juvenile white sturgeons are especially susceptible to entrainment because of their small size, limited swimming ability, and tendency to orient with bottom habitats, which makes them more prone to be entrained or buried [170]. However, the ability to evade the dredger is not necessarily correlated with fish size, as evidenced by a reported case of a $234mm$ tomcod being entrained [171]. Moreover, the destruction of benthic habitat affects fish species that depend on it to spawn, shelter and feed.

Hydromorphological changes Changes in hydrodynamics and the action of sediment removal modify habitat morphology, potentially affecting fish that inhabit them. As discussed by Nightingale et al. (2001) [48], loss or alteration of critical habitats can diminish primary and secondary production, affecting the food web. Land reclamation projects could transform a shallow subtidal habitat into a deeper subtidal habitat, or an intertidal habitat into a shallow subtidal one. These habitat conversions can affect the species that were uniquely adapted to the original habitat morphology, substrate characteristics and hydrodynamic regime. For instance, the disappearance of vegetated shallow-water nearshore habitats, caused by coastal erosion and morphological changes, is particularly concerning due to their vital functions as rearing and shelter zones for migrating juvenile salmon and other important fish species. This loss not only represents a reduction in landscape capacity but also has the potential to decrease overall landscape connectivity [48].

4.3.2 Benthos

Benthic environment is significantly affected by dredging operations, which cause physical destruction during material excavation and disposal, and leading to smothering and burial through the deposition of suspended sediments. Additionally, the photosynthetic processes may be impaired by increased turbidity and shading. The two primary and highly significant categories of benthic organisms impacted are corals and seagrass, which are further elaborated below.

4.3.2.1 Seagrass

Particular attention when planning land reclamation projects needs to be paid also for seagrass, the polyphyletic group of circa 60 species of submarine flowering plants, due to their key role in the coastal ecosystem [172]. Their roles include:

- Dissipation of wave energy: seagrass meadows' long blades and leaves increase the surface roughness of the water bed, contributing to attenuate the energy of short waves [173], [174] and currents [175]. Results from Jacob *et al.* [176] suggest that introducing seagrass meadow in German Wadden Sea could significantly reduce wave heights and current velocities, up to 30% in deeper areas and above 90% in shallow ones.

- Seabed stabilization: the rhizome and root network help stabilise the seabed and increase resistance to erosion and resuspension. The dissipative action described in the previous point help enhancing sediment deposition, futher increasing the resistance to erosion via accretion of material [176].

- Ecological role: seagrass are also involved in the ecological cycle, as they serve as a habitat, food source [177] and nursery ground [178] for a very ample variety of species [179].

- Carbon storage: seagrass meadows are a very efficient ecosystem in terms of carbon capturing and storage. They are able to bury carbon at a rate that is 35 times faster than tropical rainforest, without ever reaching saturation of their sediments [180], binding carbon for millennia, while terrestrial forests are able to do it for decades [181]. Globally, they are able to sequester about 27.4 million tons of CO_2 per year [182]. This very effective capture, on the other hand, constitutes a very high risk of leaking the captured carbon back into the atmosphere if the ecosystem is destroyed [182]. It has been estimated by Fourqurean *et al.* (2012) [183] that the present loss rate of seagrass could bring to a release of up to $299Tg$ of carbon, equivalent to 10% of the carbon dioxide generated by anthropogenic changes in land use.

Light requirements: shading and turbidity As photosyntethic organism, growth and survival of seagrass is strictly related to light availability. The minimum light requirement is considerably variable depending on species. In literature, the range for this requirement varies from 2.5% to 37% of the surface irradiance SI, and Erftemeijer and Robin Lewis (2006) [41] indicate a range of $15 - 25\%$ for most of the species. Some species, particularly the ones belonging to the genus *Halophila*, show values on the lowest end of the spectrum, between $3 - 8\%$ [184]. A collection of this threshold and relative variation for various species is presented in figure 4.32:

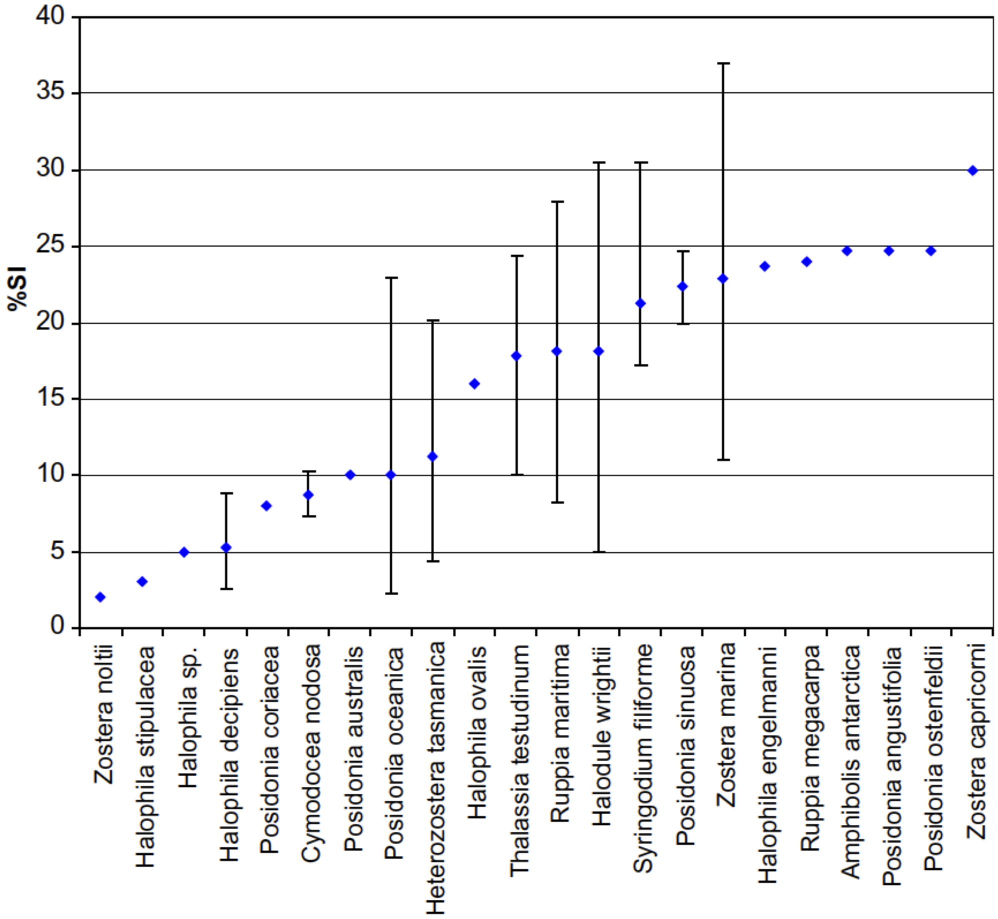


Figure 4.32: Range of threshold values and relative variation for light availability as % of SI for various seagrass species. From [41]

The amount of time where a seagrass can survive at low light level is also depending on the species. This period has been observed to range from a few weeks to several months [185], [186], [187], [188], [189], and in general a shorter resilience to low lights was observed in smaller species with low carbohydrate storage capacity [189], [190].

The amount of light that reaches seagrass can be mainly impacted by the augmented turbidity and concentration of suspended solids 4.2.2 and by the shading created by the installation of floating platforms 4.2.8.

The lethal and sublethal impacts of turbidity caused by dredging land reclamations are well documented in literature, for example in [191], [192], [193], [194], [195], [196]. Although Erftemeijer and Robin Lewis (2006) [41] have collected 45 cases of dredging operations near or around seagrass areas, the authors estimate that many activities are not very transparent in reporting the associated seagrass loss, leading to an almost certain

underestimation of the global impact.
In principle, the severity of the impact of dredging-related turbidity on the seagrass depend on many factors, including: type, quantity, frequency and duration of dredging, environmental properties such as composition of the dredged material, grain-size composition, and water depth, and also proximity to sensitive seagrass species [197]. For this reason, in literature it is possible to find relative small temporal and spatial impacts, as much as bigger ones, especially for longer projects. Reduction of light available to the seagrass due to dredging activities has been proved to be a major cause of loss of seagrass [198], [199].

For floating platforms, the literature on this topic is still under-studied. In principle, one can assume that the impact of turbidity would be lower and more localized for floating platforms, as estimated in [65], [44] and [36], thanks to the fact that it is related only to the installation of the mooring systems. Installation of a floating community would also reduce the available light due to the shading they cause, thus positioning them directly above seagrass meadows can be detrimental to their survival.
As discussed in paragraph 4.2.8, deLima et al [62] differentiated three areas - away from the platform, partially shaded and beneath the platform - with different benthic characteristics, and observed that macrophytes started to decrease near the floating platforms and abruptly disappeared under them. Another research, conducted by Härtwich in 2016 [4], employed underwater drones to acquire and analyze video recordings of the sediment surface under three floating platforms in the Netherlands. The video recordings showed that, beneath the floating platforms, macrophytes were consistently absent within approximately 1 meter from the platform edge, suggesting insufficient light intensity to sustain photosynthesis. However, no variations in the physiology of macrophytes with distance from the platform were observed. In one location, the southern part of the platform exhibited 5% macrophyte coverage, whereas the northern area at the same distance from the platform edge showed only 1% coverage. This discrepancy is likely caused by the lower average light intensities in the northern direction of the platform, due to the sun path in the Northern Emisphere [23]. The percentages of macrophytes covering the sediment surface under the three platforms are provided in Fig. 4.33.

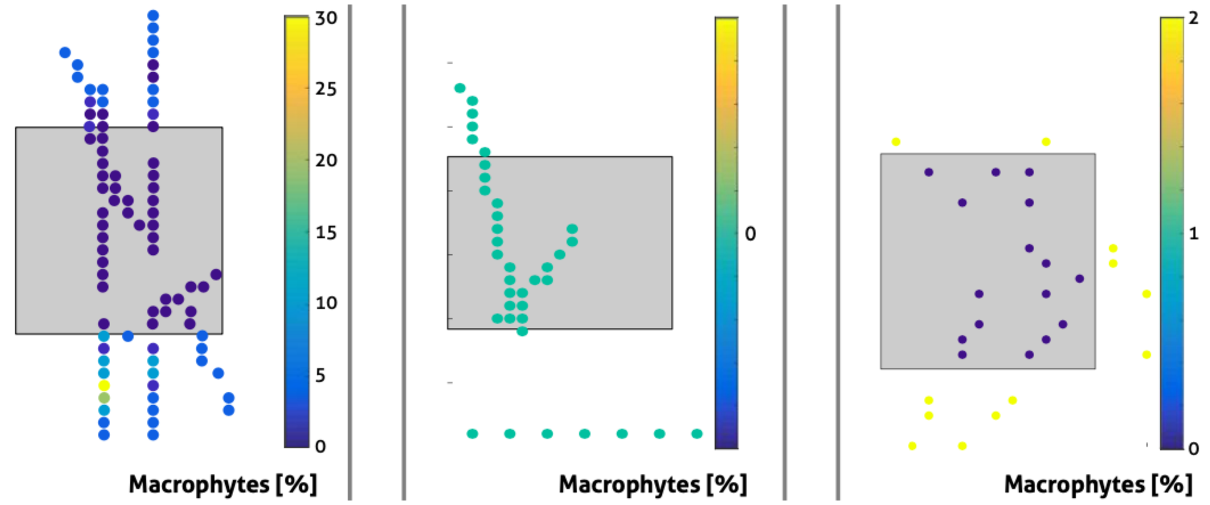


Figure 4.33: Graphs of the percentage of sediment surface coverage by macrophytes. The graph on the left refers to a $14.5mx14.5m$ platform at a water depth of $0.5m$, the central graph to a $7.7mx10m$ platform at a depth of $2.6m$, the graph on the right to a $10mx10m$ platform at a depth of $2.4m$. From [4]

Sedimentation Another impact of the turbidity and suspended solids caused by land reclamation projects is an excessive sedimentation rate, which can be harmful to seagrass species. Various maximum level of annual sedimentation rates are found in literature for different species. The ability to resist to an excessive sedimentation can vary depending on the depth of burial and life history [200]: for example, species with a vertical orientation may concentrate the resources to produce leaves at higher levels [201]. Sediment conditions can also play an important role on the seagrass resilience to sedimentation [202].
It may be thus difficult to rigorously identify critical threshold values. Values seem to range, especially in the work of Vermaat *et al.* (1997) [203], between $\sim 2cm/yr$ and $\sim 13cm/yr$. The lowest values were observed for *Zostera noltii* in the Mediterranean Sea and *Cymodocea rotundata* in the Philippines, whereas the highest for *Cymodocea rotundata* in the Philippines [203]. Very high burial of different plants have been demonstrated to be highly letal, as for the case of *Zostera marina*, for which a burial of more than 75% of their height caused a morality of 100% as reported by Mills and Fonseca (2003) [204], or for *Cymodocea nodosa*, that exhibited a mortality rate of 90% after 35 days after a sudden burial of $5cm$ [201].
It is nevertheless difficult to isolate this impact from the light reduction described beforehand. All the threshold reported here are derived from experimental activities and not from site inspection after or during dredging activities. As expected, this impact is still not studied for floating platforms.

Physical destruction of habitat Possible physical destruction of the seagrass meadows are not to be overlooked, especially due to the typical concentration of these organisms in shallower sea areas. This can happen mainly if the destination area is a seagrass meadow or the disposal site are seagrass meadows [205], in which case, respectively, the meadow will be removed or buried.
Cases of intentional removal of unwanted seagrass are also common using dredging, especially at the Maldives, to create more appealing areas near the resorts [41].

4.3.2.2 Coral reefs

Coral reef are a unique, diverse, ancient and endangered underwater ecosystem. The total extension of coral reefs varies with the estimation method, ranging from the 284300 km^2 estimated in the World Atlas of Coral Reefs by Spalding *et al.* [206] to the 423589 km^2 determined by the Allen Coral Atlas [207], and it is mainly concentrated in the Indo-Pacific region. Coral reefs are complex ecosystem, composed mainly by a calcareous skeleton built by reef-building corals such as *Cnidaria Scleractinia* which host colonies of small organisms. Between them, the dinoflagellates microalgae of the genus *Symbiodinium*, commonly know as *Zooxanthellae* form a fundamental symbiotic relationship with corals [42]. Coral heads, also called polyps, are not infact photosyntetic organisms, and without the nutrients provided by the Zooxanthellae with their own photosynthesis, their growth would be too slow to form relevant structures. In exchange, the coral reef provide shelter and CO_2 to the Zooxanthellae.

Despite this fundamental symbiotic relationship, many species of corals are also known to be active heterotrophs, ingesting organisms ranging from bacteria to mesozooplankton [208]. This feeding method can be used more when stressed and deprived of light, but it is also fundamental to assimilate nutrients like nitrogen, phosphorus, and other that are not a product of photosynthesis [208].

Coral reefs, despite to their relatively small extension, in the range of $0.1 - 0.2\%$ of the total ocean surface, coral reefs are the most diverse marine ecosystem per surface, and perhaps the most diverse overall, the other contender being the deep sea [209]. They are estimated to support over 25% of all the marine species [210]. Between them, fish, sponges, crustaceans, mollusks, sea squirts, echinoderms, and sea turtles. This diversity is favoured by the natural roughness and variety of growth forms, which helps create a high number of refuges [211].

A part from the invaluable described biodiversity, coral reefs provide a variety of contribution both to the environment and to the economy:

- Shoreline protection: similarly to other benthic ecosystems such as seagrass meadows (described in paragraph 4.3.2.1), thanks to their superficial roughness, coral reefs are able to provide a high degree of protection against natural damage caused by waves. As estimated by Ferrario *et al.* (2014) [212], they are capable of reducing wave energy by an average of 97%, and more than 100 million people benefit from this risk reduction.

- Fisheries: thanks to their high variety of fish that inhabit coral reefs, they contribute to the total yield of commercial fisheries. For example, Sarkis *et al.* (2013) [213] estimate that 42% of the total catch of commercial fisheries in Bermuda is reef-associated.

- Tourism: being one of the most fascinating environments in the world, coral reefs have a key role in attracting tourism, especially in countries where it is one of the key industries, such as tropical countries. Surveys conducted by Sarkis *et al.* (2013) [213] on more than 400 tourists found out that visiting coral reefs is a driving factor for 38.3% of interviewees, and that 14% of them would not come to Bermuda if its coral reefs were degraded. Based on the the 663767 tourists recorded in 2007, the author estimate a potential loss of 90000 tourists per year.

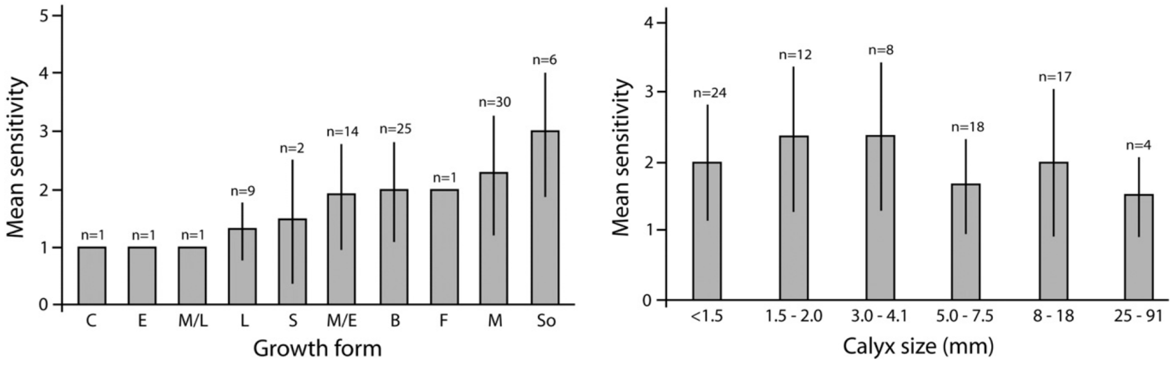
Coral reefs can be principally impacted by the suspended sediment production, which has a double effect of shading correlated to the associated turbidity, and of re-sedimentation, by the increased salinity and by the physical destruction of their habitat:

Shading due to turbidity Due to the symbiotic relationship with zooxanthellae, which provides energy for the coral growth, light availability has been reported to be a key factor to determine where coral reefs can grow, as rarely any significant formation is found below 10% of SI, with the maximal growth and development occurring down to 30% to 40% SI [214]. Corals are able to photoacclimate to different levels of light availability, varying the density, size, and/or amount of photosynthetic pigments within their zooxanthellae, and the number of polyps within a colony [215], or by adapting the morphology of the reefs, as for the mesophotic corals, which exhibit a flat plate-like structure to maximise the captured light [216]. When the available light is reduced, the coral may not be able to be autotrophic anymore, having to switch to heterotrophic feeding, bringing them to ingest some of the suspended particulate matter SPM. As observed by Anthony and Fabricius (2000) [217], response to diminished light absorption caused by suspended particles vary depending on the affected species and on the concentration of SPM. Photoacclimation to darker condition may result in darkening of the coral [215]. An experimental study carried out by Jones *et al.* in 2020 [218] found out that the mortality of 4 species (*Acropora millepora*, *Pocillopora damicornis*, *Porites lobata/lutea* and *Turbinaria reniformis*) exposed to different level of SSC and relative daily light integral for 42 days was never complete, but only partial, and for the 2 most severe conditions, respectively ~ 0 and $0.25\ mol\ quanta\ m^{-2}\ d^{-1}$. Significant bleaching was also observed for all species at the darkest condition.

Sedimentation In addition to the decrease in light available, suspended sediments may also deposit onto the corals themselves. Corals covered by sediments will try to clean themselves, with a combined action of increased ciliary or polyp activity [219], [220], [221], and mucous production [222], [223], [224]. These two actions have the goal to move the sediment away from the polyp, even if in some species, the accumulated sediment is brought to the oral disc and ingested [225]. Preferences in one or the other mechanisms depends on the species, with *Meandrina menadrites* preferring mucus production, whereas *Montastraea annularis* favoring ciliary action [225]. Production of mucus is, however, a very energy expensive activity [220], [226], and a prolonged sedimentation stress may lead to an excessive energy demand and to exhaustion, causing tissue thinning, loss of cilia and mucosecretory cells, and ultimately death [225]. Even when death is not reached, the diversion of energy to cleaning activity can slow growth of the coral and reduce metabolic processes [227], [228], [229]. Other impacts on the coral reef include inhibition of sexual population recruitment, change in the species composition, both of the coral itself and of the associated fauna, including fish [230], [231], [224], [232], [233], and interference with the feeding apparatus, impeding expansion of the polyps and thus making it impossible for the coral to compensate the lost autotrophic energy intake due to the reduced photosyntethic activity [225].

Adaptation to the SSC can also include morphological differentiation, as corals are able to adapt their shape in a way that sediments may runoff without active cleaning [234], with hemispheral and columnar shapes found to be efficient passive shedders [235], [227],

[222], [220].
There are many published values of critical threshold values of sediment concentration in literature, but they vary a lot depending on several factors, such as the interested species, the shape of growth form, the geographic reason, and calyx size. A classification of the mean sensitivity depending on the growth form and the calyx size was made by Erftemeijer *et al.* in 2012 [225]:



(a) By the growth form.

(b) By calyx size

Figure 4.34: Relationship between the sensitivity of corals to turbidity and their growth form, and their calyx size. Legend for figure 4.34a: B = branching; C = columnar; E = encrusting; F = foliaceous; L = laminar; M = massive; S = solitary; So = soft corals & gorgonians. From [225]

Smothering of corals due to dredging-related suspended sediment concentration was monitored by Jones *et al.* (2019) [71] during more than a year and a half between 2010 and 2011 in a large-scale dredging site ~ 50 km off of the Pilbara region of NW Western Australia. The authors found that the distance at which 90% of the smothering was dissipated was $3 - 3.3$ km away to the dredging, with a higher occurrence of bleaching and partial mortality on shapes that allowed sediments to pool.
Literature on floating platforms impact is, at the moment, non-existent. The same dissertation made for seagrass in paragraph 4.3.2.1 can be made for this receptor, too. In principle, one can assume that the impact of turbidity would be lower and more localized for floating platforms, as estimated in [65], [44] and [36], thanks to the fact that it is related only to the installation of the mooring systems. Installation of a floating community would also reduce the available light due to the shading they cause, thus positioning them directly above coral reefs can be detrimental to their survival. Of course, mooring installation on coral reefs would also imply physical destruction of the reef, making positioning floating platform above coral reefs to be avoided.

Salinity Due to the limited osmoregulation capacity of corals, both increased and decreased salinity, especially if acute and brief, can have catastrophic impacts on coral reefs, ranging from stress to partial and complete mortality [215]. Gilmour *et al.* (2006) [215] estimate that corals are in fact likely to be stressed when salinity levels are between 30 to 35‰ and 37 to 40‰, to suffer bleaching and partial mortality at 28 to 30‰ and 40 to 42‰, and to suffer widespread mortality at below 25‰ and above 42‰, highlighting a stress-free range of only 35 to 37‰ [215].
The few studies on salinity changes caused by floating platforms, such as [69] and [110]

respectively in the Netherlands and in Japan have not found significant differences in salinity levels. A desalination plant, installed to reach self-sustaining of the community, would create a high salinity effluent to treat properly not to cause potential impacts on sensible coral reefs.

Some cases of salinity increase in dredging activities were observed, such as in Itajaí-Açú estuary in Brazil [57]. This impact is however typically related to estuaries and the balance between fresh and saltwater, and thus not a zone typically populated by coral reefs. An impact was found in Bahamas [58] due to the disruption of tidal flows led to a significant increase in water salinity.

Habitat destruction Physical destruction of the coral reef may also happen, for negligence or non consideration of the impacted zone. To illustrate the severity of this impact, a notable example is the Palm Jumeirah project. As reported by Bayyinah in [80], considering that the Palm directly covers 8,33km^2, and that about 10-15% of this area was estimated to be covered by corals, the construction of Palm Jumeirah has directly buried and destructed approximately $0{,}83 - 1{,}25 km^2$ of coral. Moreover, due to the project size, an organism located at the center of the construction area would need to move $5km$ towards the Gulf or $35km$ along the coastline to avoid being buried or suffocated, so it may be possible that not only immobile organisms have been affected.

4.3.3 Macroplants: mangroves

Mangroves are a coastal ecosystem composed by salt-tolerant trees, shrubs and other vegetation, for an estimated 70 species divided in 20 genera according to Hogarth (2007) [236].

The total extension of mangrove forests was estimated by Giri *et al.* in 2011 [237] to be of 137760 km^2 in tropical and subtropical regions between latitudes of 5^oN and 5^oS. A map of the distribution zone and number of species per region, from [238], is presented in 4.35:.

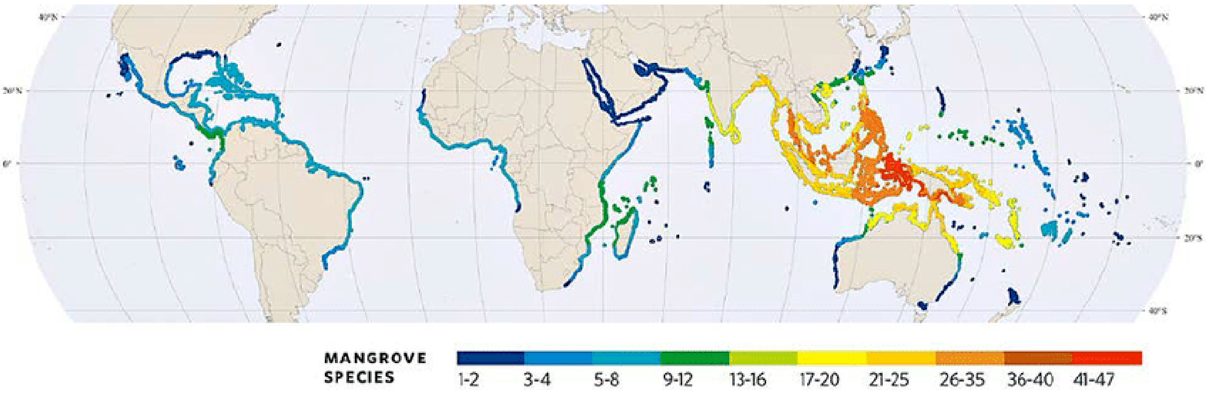


Figure 4.35: Global distribution of mangroves, by number of species. From [238]

The role of mangroves in the coastal ecosystem are multiple and significant. The main benefits of this peculiar biome are:

  - Benefits to the water quality: mangroves preserve the quality of the coastal water thanks to their filtering action of suspended materials and dissolved nutrients. This action protects seaward coral reef and seagrass habitats [239].
  - Protection of the reef and pelagic ecosystem: Mangroves promote sediment deposition from rivers and creeks [240], which allows to remove toxins bound to sediment particles.
  - Nursing and hatching ground: mangrove forest can also serve as favorable ground for growth for various species, such as fish, as observed in South Bontang Bay by Coppes *et al.* (1984) [240], and other species such as crabs, prawns and oysters. This can lead to a local exploitation of the organisms living in the mangrove forests: in the Ayeyarwaddy Region in Myanmar, for example, the products collected in the mangrove forest generate up to 43% of the income [241].
  - Protection against coastal disaster: it has been observed in multiple occasions that mangrove ecosystem have been able, thanks to its massive root system, to protect coastal villages reducing the death toll and mitigating material damages [242] [243].

- Carbon storage: mangroves are able to capture and store organic carbon, in a phenomenon also called ”■Blue carbon”. It has been estimated by Hamilton and Friess (2018) that the carbon stored by mangroves in 2014 was 4.19 Gt [244].

The mangrove biome can be principally impacted by the suspended sediment production and by the physical destruction of their habitat:

Turbidity and suspended sediments Thanks to their high filtration capacity, mangroves are significantly tolerant to the levels of suspended sediment loads deriving from dredging and land reclamation activities [245]. Nevertheless, potential risks from suspended sediment may arise in case of:

- Contamination of sediments [66];
- Excessive re-deposition that may choke the mangrove roots [66];
- Mangrove species with pneumatophore root system, which are more sensitive to sedimentation as observed by Thampanya *et al.* (2002) [246]. These mangroves are stressed when prolonged sedimentation reaches more than $10cm$. This degree of sedimentation is believed to be improbable to be reached beyond the designated work area [245].

Physical destruction of habitat It can occur, especially for dredging land reclamation project, to invade and thus destroy mangrove forest. Some example include:

- The land reclamation project for Tubli bay in Bahrain described in [43], the author states that the reduction of the bay by 40% has brought to destruction of most of the mangroves, along with a decreased presence of other marine ecosystem such as seagrass, macroalgae but also dugongs and turtles.

- The development of a large tourist resort in Bimini lagoon in the northern Bahamas, carried out with dredging, brought to an extensive destruction of the mangrove ecosystem, which served as an excellent nursery ground for the juvenile specimens of lemon sharks *Negaprion Brevirostris* [58]. Due to the strong attachment of lemon sharks to their birth place, at least during early phases of their life, destruction of the mangrove nursing ground can completely destroy the entire habitat of one or more juvenile lemon shark. In general, reducing their habitat can bring to a greater competition for space, food and shelter, and expose them to increased predation by older adults of the same species, but also from barracuda *Sphyraena barracuda* and bull shark *Carcharhinus leucas* [247].

- The land reclamation for housing and industry in Singapore, caused the total mangrove area to decrease from 12% of the total land in 1922 to only 3% in 1987 [248].

Moreover, morphological changes caused by dredging on the shoreline could lead to erosion of the mangrove habitat.
Dredging activity can also be beneficial to mangroves growth, especially if the land reclamation is planned accordingly. For example, the proposed dredging project at the Outer Bar area of the Pussur Channel of Mongla port [59], has taken into account where to dispose the dredged material not only to avoid loosing but also to encourage growth of the Sundarbans mangrove forest, the biggest in the world and UNESCO World Heritage since 1997.

4.3.4 Plankton

In biology, the term plankton is used to indicate all the organisms, also known as plankters, that are unable to independently direct their movement, at least in the horizontal direction, and as a results, they are passively transported by winds and currents. The term was introduced by Hensen in 1887 [249]. Being this classification related to the motility level, plankton include a variety of organism, typically divided by trophic level:

- Zooplankton: the animal component of the plankton, comprehending small protozoans or metazoans that are heterotrophic, as they feed on other plankton (typically, phytoplankton).

- Phytoplankton: the photosyntethic, and as such autotrophic, component of the plankton, comprehending bacteria such as cyanobacteria and single-celled plants as microalgae.

- Bacterioplankton: the bacteric component of the plankton, which can be both autotrophic and heterotrophic.

Many other classifications can be made, for example dividing the planktic community by size, taxonomy and habitat, but the impacts of floating platforms and dredging land reclamation properties are better distinguished in literature by trophic levels. Plankton plays a key role in the marine ecosystem, and its main contributions are:

- Food web role: plankton are at the bottom of the food chain. In particular, photosynthetic phytoplankton is predated by zooplankton, which in turn are food source for a variety of bigger predators, such as fish juvenile form as the haddock larvae (*Melanogrammus aeglefinus*) [250], and bigger marine mammals such as humpback whales [251]. It is important to notice that concept of a linear food chain, in which each component has a direct predator and prey, has been replaced by a more complex theory, including the microbial loop, as described by Ambler and Butler (2023) [251].

- Carbon cycle: phytoplankton consume carbon dioxide from the surface thanks to the photosynthesis, capturing and storing it. It is estimated that, despite amounting only to $\sim 1 - 2\%$ of the total global plant carbon, phytoplankton is able to fix $\sim 30 - 50$ billion metric tons of CO_2 annually, circa 40% of the total [252]. as phytoplankton are consumed by zooplankton, and in turn by other bigger predators, a small fraction of the captured CO_2 ends in the excretion or carcasses (upon death) of the predators. This biomass precipitates to the deeper level of the oceans, being denser than the water, storing the captured carbon in the ocean carbon sink.

- Oxygen production: Photosynthesis performed by phytoplankton has also the effect of oxygen production. It is estimated that this production contributes to about 50% of the world's oxygen production, with a similar amount to terrestrial plants [253].

Photosynthetic activity exposes especially phytoplankton to risk of reduced light availability, both due to turbidity and shading of the platforms, in a similar manner to other photosynthetic receptors described (4.3.2.1, 4.3.2.2). A decrease of phytoplankton biomass was reported by Jing *et al.* (2019) [254] in Dongqian Lake in China. A reduced phytoplankton biomass can result in an increased risk of predation for zooplankton [255].

At the moment, possible shading effect caused by floating platforms, both due to the induced turbidity and to the physical shading, is under-studied. As estimated for other photosynthetic receptors (4.3.2.1, 4.3.2.2), one can assume that the impact of turbidity would be lower and more localized for floating platforms, as estimated in [65], [44] and [36], thanks to the fact that it is related only to the installation of the mooring systems. Installation of a floating community would also reduce the available light due to the shading they cause, possibly causing phytoplankton underneath them to die or move away. Since, differently from seagrass and coral reefs, plankton are not static and more difficulty visible, identifying areas with low planktic density may be more difficult during the design phase.

Zooplankton, as well as other species such as the Humboldt squid (*Dosidicus gigas*) [256], bull trout (*Salvelinus confluentus*) [257] and codepods [258], have been observed [259] to follow a daily vertical migratory movement known as "diel vertical migration" or DVM. This periodic movement sees the organisms emerge to the photic zone of the water body during the night and to return to the bottom layer during the day. This behavior supposedly derives from a need to avoid predators during illuminated conditions [260]. This mechanism is a key factor in both the deep sea food webs and in the biological carbon sequestration known as biological pump [261].

It has been observed than the diel vertical migration is affected by the level of illumination, as patterns in the DVM can be reconducted to the lunar cycle. Indeed, an illumination dimmer than that of a half moon ($10^{-1} lux$) is able to impact the vertical distribution of certain invertebrates [262].

A possible influence of artificial illumination on this important phenomenon can be thus expected, and in particular it has been documented by Moore *et al.* [263] on the freshwater zooplankton *Daphnia* in the wild. Results were a diminution of the magnitude of the vertical diel migrations, both in terms of the vertical movement range and in the percentage of individuals migrating. The authors speculate that a decreased migration of the zooplankton to the photic zone could bring to an increased algae density, of which the zooplankton is a natural predator, resulting in a lower water quality.

To not disrupt this important ecological phenomenon, attention shall be paid to avoid excessive illumination in area where presence of zooplankton can be assessed.

Chapter 5

Recommendations and guidelines

New projects offer an opportunity to prioritize ecosystem health in the design of floating platforms. Guidelines are essential to ensure the consideration of mitigation and ecological restoration measures [62]. To mitigate, minimize or completely prevent potential adverse effects of the SeaForm project on the marine ecosystem, it is essential to implement appropriate measures, especially for impacts anticipated to have a significant or critical effect on the ecosystem and its receptors. Various mitigation strategies, employed in existing projects such as OWF [61] or suggested for future solutions [65], are provided in this chapter, and can be adapted to SeaForm case. These include both modifications to the design of structures and on-site measures to minimize or avoid the impact. Factors like platform shape and orientation can impact water quality, and their optimization can reduce negative effects [62]. Selecting suitable locations is key, considering ecosystem characteristics and sensitivity. Special consideration should be given to critical or priority habitats. They are defined as habitats that support breeding, rearing, migration and high densities and varieties of species. They can be vulnerable to modifications and limited in availability [48]. Therefore, before installation, an investigation of the physical and biological properties of each location is necessary. During construction, precautions such as planning work during wildlife-resistant periods, also called environmental windows, is vital to avoid unnecessary disturbances [62].
An overview detailing the platform design characteristics that can influence various stressors is presented in Tab. 5.1:

	Mooring	Platform density	Material, color, texture	Function / Use	Orientation	Shape	Covered area	Draft height	Construction height
Shading	x	x	x	x	x	x	x	x	x
Suspended matter and turbidity	x	x		x	x	x	x	x	
Dissolved oxygen		x			x	x	x	x	
Water temperature		x	x	x	x	x	x	x	x
Water alkalinity (pH)			x	x			x		

Table 5.1: Overview of project characteristics and their influence on each stressor. Adapted from [44]

Collisions As discussed in paragraph 4.3.1.1, in order to prevent collisions between marine mammals and vessels, employed during the construction and operational phase of floating platforms, a solution that has proven to be effective is to minimize the number of vessels and, crucially, to reduce their speed [264], [265]. An additional strategy to reduce this risk is to deploy trained marine mammal lookouts on vessels [266].

Another approach, referred to as dynamic management, relies on near real-time data to assess the safety of vessel transit in certain areas [61]. This method differs from the traditional spatial marine management techniques, such as marine protected areas, which establish stationary boundaries that don't take into account the rate and scale of changes occurring in the marine environment and species and could therefore be less effective [267]. Instead, dynamic management is defined by Maxwell et al. (2015) [267] as "management that changes rapidly in space and time in response to the shifting nature of the ocean and its users based on the integration of new biological, oceanographic, social and/or economic data in near real-time". By employing methods such as aerial surveys and acoustic monitoring, it is possible to detect the presence of marine mammals in a certain area, while through advanced modelling techniques based on environmental conditions and existing datasets, it is possible to predict the likelihood of species distribution in space and time [267]. In this way, vessel transit could be stopped or reduced during periods when sensitive species are likely to be present in the area. Existing near real-time dynamic management tools such as Whale Alert [268] and EcoCast [269], successfully employed in the fishing and shipping industries to minimize collision risks between vessels and marine mammals, can be adapted for the purpose of the SeaForm project.

Entanglement Risk for both primary and secondary entanglement can be mitigated during the design phase and monitored during the operational phase of the floating installations. During the design phase, a good practice is the installation of taut cables and lines to avoid or greatly reduce the probability of primary entanglement of large whales [111] [112].

Other mitigation strategies have been investigated in recent literature, focusing primarily on visual and acoustic deterrence. Visual deterrence involve applying a color or a pattern to help the animals detect and avoid the possible sources of primary of secondary entanglement, and it can be taken into account during the design phase. For example, Kot *et al.* [270] found an increased ability of minke whales to detect and avoid high contrast, black and white ropes, whereas North Atlantic right whales have a higher sensibility to red and orange ropes, with respect to the green ones [271].

Acoustic deterrence can be used to distract cetaceans and marine mammals away from the floating platform zone, reducing thus the risk of entanglement. For example, acoustic pingers have been shown to be able to reduce small cetacean and pinnipeds bycatch in fishing nets by significant amounts [272],[273]. Acoustic deterrence presents a number of challenges such as potential habituation to pingers, especially in pinnipeds [274], local habitat exclusion [275], device durability and maintenance [276], regulatory compliance [276], and finally possible attraction of other species to the interested area [273], [277], that all together may reduce the convenience of this deterrence method.

This impact may be more effectively managed paying attention to install the floating platform in not biologically important areas, avoiding possible migration routes and feeding grounds [35].

Monitoring possible entanglement on the platform during the operational phase is also a recommended strategy, to allow a quick as possible response to potential events. On power lines, entanglements could cause tension drops that can be detected via tension monitors, as is currently done on floating turbines in Scotland [61]. Moreover, visual inspection via remotely operated underwater vehicles and wireless video surveillance camera can be used both to detect animal and derelict gear. Since accretion of organisms on the underwater surfaces, also known as biofouling, can be source of attachment point for derelict gear, cleaning them can help to reduce probability of secondary entanglement. Cleaning could be done manually or with the help of specialized devices, such as the Wirewalker$^{\mathrm{TM}}$ from Del Mar Oceanographic, on the cables [61]

Suspended sediments and turbidity To mitigate the potential disruption of benthic habitat and the generation of suspended sediments and turbidity during the installation of the mooring system, careful design considerations are crucial. It is recommended to minimize the overall footprint of the mooring system, giving preference to a taut leg mooring over a catenary one. This helps prevent scouring of mooring lines on the seabed, thereby avoiding potential harm to the benthic ecosystem and the resuspension of sediments [61]. Minimizing the size and number of mooring anchors, as well as choosing less invasive installation methods, are other ways to reduce sediment resuspension [44].
Surely, to further minimize the impact on benthic organisms, it is crucial to install mooring systems in areas of low ecological importance, which can be identified through a thorough investigation of the site [61].
An additional approach to mitigate turbidity involves promoting the growth of macrophytes such as seagrass, which helps to slow water movement, trap sediments and avoid resuspension [278]. This can be achieved by designing the platforms to maximize the overlap between areas where large particles can settle and regions with adequate light intensity to support macrophyte growth [44].

Shading The presence of floating platforms can completely block the direct rays from reaching the water near the surface and directly under the floating platform. Here, if the water is clear enough, a portion of diffused indirect light, which is diffracted by water and suspended particles, might still reach, giving a chance for photosynthesis to still occur. However, since indirect light can travel limited distances in the water, structures with large areas are likely to generate almost completely dark zones of water, with insufficient light levels for photosynthesis [60]. Reducing the distance between the center of the platform and its sides is key to prevent the formation of completely dark areas [4]. This can be accomplished by favoring thin, elongated platforms over compact and wide ones. Even in the case of compact single platforms, like the hexagonal shape used by SeaForm, the desired rectangular shape can be achieved by arranging multiple compact platforms in a narrow, elongated layout [23].
Moreover, the best platform orientation to avoid a continuously shaded area is along the south-north main axis, as it ensures higher illumination of the water below the platform and on the seabed, compared to an east-west orientation [279]. Due to the sun path, in the Boreal Hemisphere shadowed areas form on the northern side of platforms, while the opposite occurs in the Southern Hemisphere, so opting for smaller northern sides results in reduced shadowed areas. Consequently, in a rectangular shape, aligning the main axis along the north-south direction ensures improved illumination of the water [23].

To prevent the seabed from being completely shaded, and consequently, to support photosynthetic processes in the benthic ecosystem, it is advisable to install floating platforms in deeper water bodies [23]. This is due to the fact that the deeper is the water, the more diffuse is the shadow cast on the water body's bottom during daylight hours [279].

Noise The installation of mooring for floating platforms may produce substantial noise and disturbance [44]. Besides minimizing as much as possible any activity that produces significant noise, it is advisable to take additional precautions. Employing bubble curtains, bubble clouds or bubble screens, is an effective method to limit sound intensity and speed underwater [280]. The presence of underwater bubbles can impede the transmission of sound through water by causing density mismatch between air and water and reflection and absorption of sound waves [281]. The presence of bubble clouds is usually a problem for commercial sonar operations, due to the attenuative properties of bubbles and the alterations they cause to the sound speed profile. However, these very properties are beneficially employed by implementing bubble screens to protect wildlife and structures during marine construction operations, such as pile driving [280]. Air bubble curtains can be either confined or unconfined [282]. Confined systems utilize flexible materials or rigid pipes to contain bubbles around the pile. The material of the casing doesn't affect overall sound reduction. These systems are ideal in areas with high water-current velocities. Unconfined systems lack such restraining mechanisms, and strong currents could sweep the bubbles away, reducing the sound attenuation [282]. The first documented application of air bubble curtains in a marine pile-driving project occurred in Hong Kong [281]. These curtains effectively decreased broadband pulse levels by $3-5dB$, providing protection for marine mammals. Sound intensities were measured from $100Hz$ to $25.6kHz$, and the most substantial sound reduction by the bubble curtain occurred within the frequency range of $400-6400Hz$. Observed reductions in SPL due to bubble curtains range from 5 to 30 dB [283] [282] [284], depending on the flow conditions, the pile dimensions, the frequency range considered and the use of confined or unconfined systems. Predicting sound reductions greater than $10dB$ with attenuation air bubble curtains cannot be reliably predicted [282]. Another approach to mitigate noise effects is preventing animals from being near the sound source, thereby reducing the impact on receivers [284]. This involves managing the noise exposure of animals without altering the sound field itself. Effective methods include implementing time-area restrictions, allowing noisy activities only when few or no animals are present, employing also dynamic management, which has been discussed above for collisions mitigation. In cases where time-area regulation is impractical due to steady or unpredictable animal presence, animals can be deterred to safer distances before initiating the noisy activity. Acoustic deterrence has been explained in more details

Another source of noise associated to floating platforms arises from the transit of vessels during both the construction and operational phase. It is recommended to exclusively utilize electric and non-motorized boats to reach and navigate near the floating platforms, preferably at reduced speed [44]. Depending on the scale and specific features of the floating project, water-based transportation can be achieved through either individual or collective means of transport. Additionally, connecting distant platforms through floating bridges could minimize the reliance on boats for transportation [44].

Physical-chemical parameters Water quality is significantly influenced by physical-chemical water parameters, including dissolved oxygen concentration and temperature. It is essential to design floating platforms in a manner that minimizes any potential decrease in water quality and, ideally, provides an opportunity to enhance it.

- Dissolved oxygen: as discussed in paragraph 4.2.6.1, the reduction in incoming solar radiation, which limits photosynthetic processes, along with the decrease in the available air-water surface, which leads to less reaeration, collectively result in a decline of dissolved oxygen levels beneath the platform [37]. Lower dissolved oxygen concentrations may lead to the buildup of deceased organic matter which, in turn, impacts turbidity and the penetration of sunlight. Furthermore, the settlement of deceased organic material into the sediment raises nutrient concentrations and further increase sediment oxygen demand [37]. To prevent dissolved oxygen to reach concentrations that are unsuitable for aquatic life, an effective strategy would be to minimize the platform coverage percentage of the water surface, allowing uncovered areas [60]. This allows light to partially penetrate the water column and ensures an open surface for the transfer of oxygen from the atmosphere to the water [44]. This reduction in coverage percentage is especially crucial for extensive floating projects, which can potentially cover a substantial surface area, as well as for smaller or confined water bodies, where water mixing is limited. Water mixing plays a vital role in distributing dissolved substances, balancing the areas beneath the floating structures with the surrounding environment [60]. Since the oxygen exchange with air can still occur around the floating objects, the presence of an open surface near a platform can potentially compensate the reduction in dissolved oxygen levels beneath it, reducing the maximum distance that water travels under the platform [44].

  Enhancing dissolved oxygen concentration in water can be achieved by placing submerged floating wetlands in close proximity to the floating platforms [44]. These wetlands utilize lightweight floating structures for buoyancy and support, allowing their roots to extend directly into the water. The macrophytes that grow on them facilitate the transfer of oxygen from the air to the water, releasing oxygen through their roots [285]. Moreover, floating wetlands adsorb nutrients from the water and can serve as an habitat for wildlife.

- Temperature: as discussed in paragraph 4.2.6.2, water temperature changes due to floating platforms are usually minimal (below $0.5C^o$ [5]). However, keeping water temperatures level within the tolerance range for local wildlife is a crucial aspect to achieve, and even the smallest changes can deeply harm local fragile organisms and must be avoided [44]. Materials used in floating structures often have high heat capacity and conductivity, allowing them to store heat during the day and release it at night [37]. Floating houses, especially when artificially heated in winter and cooled in summer, can act as a heat source to the surrounding water during colder periods. These characteristics have potential implications for water temperature, affecting factors like metabolic rates of aquatic organisms, nutrient cycles, growth of phytoplankton and macrophytes, photosynthesis, and solubility of dissolved oxygen [62]. While these changes can offer benefits and protection to certain species during colder periods [60], the heat transfer to the water should be minimized with

proper insulation of the buildings [44]. Moreover, changes in temperature below the platform can be balanced by a sufficient water exchange rate [44].
Further investigation is necessary to better understand how floating platforms affect water temperature, in order to identify which design characteristics could influence this impact [44].

- pH: as explained in paragraph 4.2.6.3, the presence of concrete structures in water may locally increase the seawater pH [44] through concrete carbonation. This effect could minimally balance the challenge of the ongoing ocean acidification process. Even if the effect is likely to minimal, concrete leaching should be monitored to evaluate if ecosystems are harmed or indeed might benefit from this phenomenon [44]. Increased CO_2 levels not only accelerate concrete corrosion but also diminish the concentration of carbonate ions, which are vital for the construction of structures by corals and shell organisms [109]. Therefore, incorporating plants on and around floating developments is recommended, as CO_2 absorption reduces corrosion and positively influences calcification [44].

Hydromorphological changes As explained in paragraph 4.1, the presence of floating platforms interferes with both wind and wave currents, changing their direction and speed.

- Air movement: the wind tunnel effect, which occurs between two adjacent buildings, can generate turbulent flows between floating platforms [5]. To prevent this effect, the project design should avoid narrow empty passages between the platforms [60]. Moreover, the presence of an obstacle can also create a shielded area behind the structure with little air movement [37]. The project design should guarantee effective water exchanges with the surrounding environment by avoiding the creation of such shielded or completely enclosed areas, which are characterized by a low water mixing that could lead, in extreme situations, to oxygen deficiency, accumulation of high concentrations of hazardous substances and eutrophication [60]. Moreover, it has to be considered that the magnitude of this effect is determined by the alignment of floating buildings relative to the prevailing local wind direction [62].

- Water movement: similarly to wind, water currents are disrupted by the presence of a floating structure in water. The platform tend to create areas with decreased or increased flow velocity [96], that lead to changes in sedimentation rate. This effect is particularly noticeable in shallow water bodies, and little to no variations are expected below $5m$ depth [96], so deeper and wider water bodies should be privileged, as they are less susceptible to changes in hydrodynamics and water quality due to better water column mixing [23]. It is crucial to prevent the formation of stagnant water areas by designing the project to avoid sheltered or enclosed zones, where low water mixing could lead to a degradation of water quality. Orienting the platforms according to the main flow direction would minimize their impact on the direction and speed of currents, as well as on sedimentation [23].

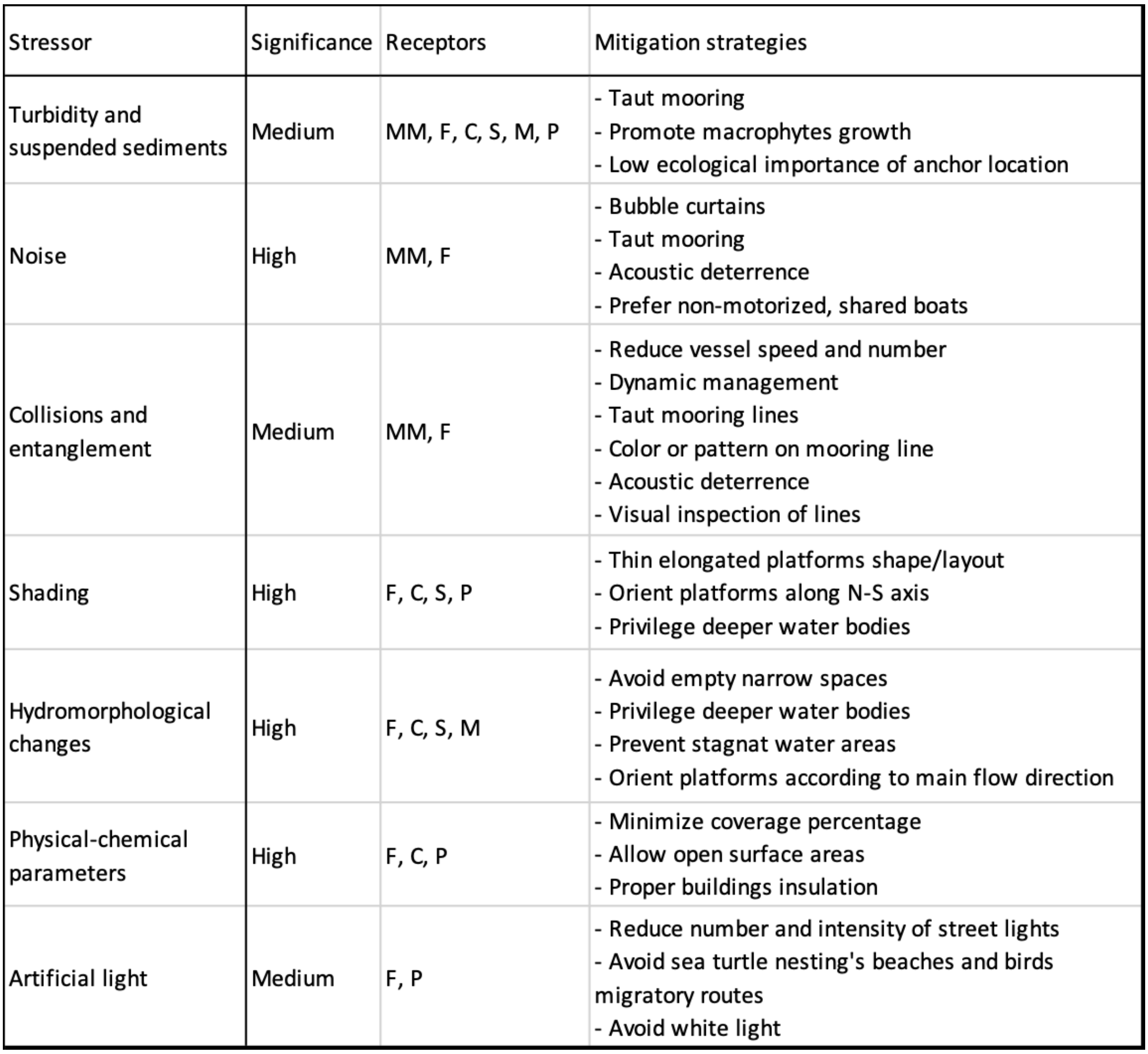
Moreover, the modeling of water movement around floating platforms is essential for predicting areas prone to sediment accumulation and erosion. In instances where undesired sedimentation or erosion is observed, adjustments to the design and placement of the platforms should be made [44].

Artificial lighting Since the physical sources of ecological light pollution are varied, as defined by Longcore and Rich (2004) [116] and reported in paragraph 4.2.9, possible mitigation strategy are depending from the source. They are listed below, following the division proposed by Deda *et al.* (2007) [115], focusing on those applicable to floating platforms installations:

- Lighthouses: their main impact is attraction of birds, with various degree depending on the location of the lighthouse, especially if it is found on a migratory route. If the presence of a lighthouse is foreseen for offshore floating platform, to avoid collisions with inbounding ships, the possible impact on bird migratory route shall be assessed when planning the installation. Nevertheless, a flashing or coloured light shall be favored, as they have been demonstrated to attract fewer individuals than fixed white lights [286].
- City lights and consequent sky glow: inhabited floating platform communities will feature streetlamps and illuminated buildings, with a structure similar to traditional cities on the mainland, albeit at a reduced scale. This nocturnal lighting and its associated sky glow are able to attract and disorientate nocturnal migratory birds, especially in foggy and rainy weather [115]. For this source of ecological light pollution, a possible mitigation strategy would be to reduce the number and intensity of street lights, to reduce the correlated sky glow [115]. This mitigation would also be in line with a conscious consumption of electricity typical of a sustainable and energetically independent floating community.
- Effects on sea turtles: artificial lighting can be very detrimental to the reproductive cycle of sea turtles, both interfering with the selection of nesting habitat by female specimens and disorienting the hatchlings, keeping them from finding their way to the ocean. When planning installation of floating communities, attention must be paid to avoid beaches known as sea turtles nesting areas. If some superimposition of turtles nesting areas and floating platform installation area shall arise, lighting of the floating platforms shall avoid possible illumination of those beaches, with more precise use of the lighting, which shall be less intensive and in longer wavelengths.
- Effects on fish: since response of fish to artificial light is depending on the species, a general guideline is difficult to be provided. A preliminary assessment shall be performed to know what species are typically present in the destination area and how artificial lighting would affect them. Both reaction of attraction and avoidance of artificial light are interfering with the natural behavior of the species and shall be minimized as much as possible, since they could also impact their food web as explained in 4.2.9. The most impacting wavelength emerging from literature is the white light [115], which shall be avoided if possible, especially if there is the risk to affect deep-sea fish, which are particularly sensible to bright lights, as their eyes have adapted to the low light level of deep sea environment [287].

Environmental windows Environmental windows are employed to limit construction operations within specific timeframes, protecting sensitive biological resources and their habitats from potential adverse effects [48]. These windows are defined as the remaining time period after mapping all temporal environmental restrictions onto the calendar [288]. They typically confine disruptive construction activities to critical spring and summer months to prevent disruption of migration, spawning, and nesting [48]. Nevertheless, the timing of habitat use by affected organisms can vary seasonally and regionally, demanding site-specific environmental windows. Tailoring project-specific conditions and procedures and the timing of seasonal and migration patterns, is crucial to avoid the disruption of sensitive environments, such as spawning and nursery grounds. This is essential to prevent a decline in the survival rate of organisms to adulthood, consequently impacting their overall abundance. [53].

A schematic representation outlining the primary project guidelines and mitigation strategies for each stressor is provided in Fig. 5.1, aiming to achieve SEAform's goal of zero expected environmental impact:



Stressor	Significance	Receptors	Mitigation strategies
Turbidity and suspended sediments	Medium	MM, F, C, S, M, P	- Taut mooring - Promote macrophytes growth - Low ecological importance of anchor location
Noise	High	MM, F	- Bubble curtains - Taut mooring - Acoustic deterrence - Prefer non-motorized, shared boats
Collisions and entanglement	Medium	MM, F	- Reduce vessel speed and number - Dynamic management - Taut mooring lines - Color or pattern on mooring line - Acoustic deterrence - Visual inspection of lines
Shading	High	F, C, S, P	- Thin elongated platforms shape/layout - Orient platforms along N-S axis - Privilege deeper water bodies
Hydromorphological changes	High	F, C, S, M	- Avoid empty narrow spaces - Privilege deeper water bodies - Prevent stagnat water areas - Orient platforms according to main flow direction
Physical-chemical parameters	High	F, C, P	- Minimize coverage percentage - Allow open surface areas - Proper buildings insulation
Artificial light	Medium	F, P	- Reduce number and intensity of street lights - Avoid sea turtle nesting's beaches and birds migratory routes - Avoid white light

Figure 5.1: Scheme of floating platforms stressors, their significance, the receptors they affect and the mitigation strategies and guidelines that can be adopted to minimize their impact. Receptors are abbreviated as follows: marine mammals (MM), fish (F), corals (C), seagrass (S), mangroves (M), plankton (P).

Chapter 6

Future steps and conclusions

This chapter firstly discusses potential suitable locations for the development of the SEAform project and identifies topics where further research is needed. Ultimately, the key research findings, the study limitations and the necessary further researches to achieve a comprehensive study of the potential environmental impacts of floating platforms are provided.

6.1 Future developments

The primary challenges in coastal cities addressed by floating platforms and, in particular, by the SEAform initiative, are climate change, which leads to sea level rise and the associated risk of flooding, and the increasing urbanization, which results in a shortage of available land for city expansion. In response to these challenges, two ideal candidates for the development of the SEAform project are Venice and Monaco, given their susceptibility to these specific issues [34].

Since these two sites are viable for establishing an experimental prototype and a larger launch project, a potential future development of this research, aimed at aiding SEAform in guaranteeing the sustainable realization of its solution, would involve conducting an environmental impact assessment for these specific locations. This process would begin with a comprehensive examination of the aquatic ecosystem at each location to identify existing receptors and assess how they might be affected by various stressors.

- Venice: an emblematic city affected by the problems of sea level rise and frequent flooding is Venice. Therefore, the decision to conduct experiments in this strongly symbolic location is particularly pertinent to the goals of the SEAform project. Venice is part of a vast marsh system that hosts unique ecosystems in its brackish waters. It is a transition area between the land and the sea, creating unusual conditions to host particular benthic communities, fish species and algae colonies [23]. Despite being an area of great natural, cultural, and economic value, Venice is also highly fragile, with substantial portions of land sitting just above or below sea level, making it susceptible to environmental changes. As shown in Fig. 6.1, by 2050 a SLR of more than $20cm$ is predicted by all SSP scenarios. This poses a potential issue as the average elevation of the land area is particularly low, making significant portions susceptible to disappearance even with minor increases in sea levels [23].

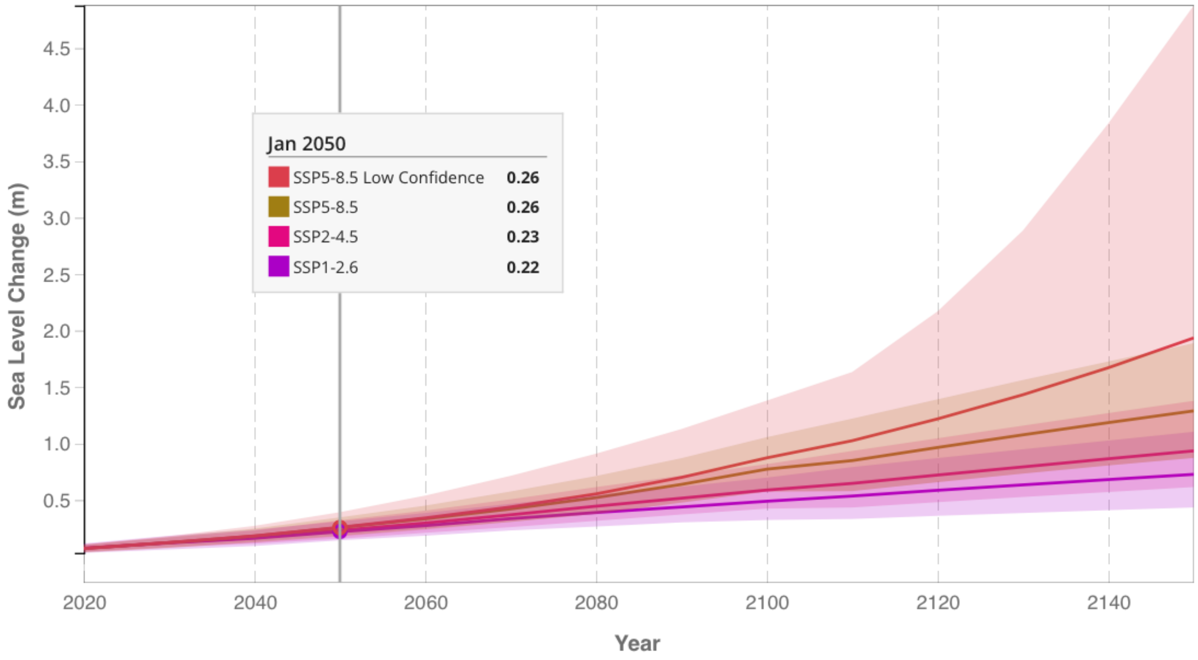


Figure 6.1: Sea level rise in Venice for four different SSP scenarios. The shaded regions depict the $17^{th} - 83^{rd}$ percentile ranges, and the projections are relative to a baseline period of 1995-2014. Obtained from [10]

In order to ensure the sustainable development of floating prototypes in the Venice lagoon, which are essential for conducting initial tests on SEAform design and technology, it is crucial to conduct a dedicated thorough study and analysis of the distinctive lagoon environment. This is necessary to accurately evaluate the potential impacts of floating structures on such a unique aquatic ecosystem.

- Monaco: the primary challenge in the Principality of Monaco is the scarcity of buildable land, contributing to the world's highest prices per square meter in the city center, followed by Hong Kong and George Town, as reported by the cost of living database "Numbeo" [289].
  To address this issue, the city has a longstanding tradition of land reclamation projects dating back to 1861, expanding the city area by approximately 20%, reaching a total area of more than 2 km^2. Given the city's inclination towards expanding over water and the escalating property prices, Monaco emerges as an ideal location for implementing the SEAform solution. However, it is crucial to carefully evaluate the marine environment impacted by the platforms to ensure sustainability and ideally achieve SEAform's core value of a zero environmental impact, autosufficient floating community [34].

In order to achieve a comprehensive understanding and overview of the overall environmental impacts of floating platforms, a future research should focus on the carbon footprint calculation for these structures. The carbon footprint is a method to calculate the GHG emissions of a particular activity, product, individual, event or organization [290].

This thesis has focused exclusively on the effects of floating structures on the aquatic environment, which begin from the transport of the pre-built platform to the installation site. However, it is necessary to acknowledge that environmental impacts in terms of emissions will also occur during the onshore construction phase of the platform. Consequently, an analysis of this inland construction phase becomes essential and should be addressed in future studies.

6.2 Conclusions

This study has focused on the environmental impacts of floating platforms, comparing them to the widely employed land reclamation technique of dredging in coastal areas. The findings underscore that floating platforms exhibit a lower environmental impact on aquatic ecosystems, positioning them as a more sustainable alternative.

While specific literature examples on the impacts of floating platforms remain limited, this thesis contributes by offering a generalized comparison of available studies.

Recognizing the limitations, which include the absence of site-specific assessments and a lack of magnitude and sensitivity evaluation for stressors and receptors, this study aims to encourage future research to refine the analysis. Suggestions for future research involve exploring specific locations, examining the environmental impacts of activities conducted on the platforms once the project purpose is determined, and incorporating the carbon footprint of floating platforms, thus broadening the analysis beyond the aquatic environment to include atmospheric considerations.

Practical implications of this research include a set of guidelines derived from the environmental aspects considered. These guidelines can inform the development of floating communities projects, such as SEAform, with the objective of minimizing their impact on aquatic ecosystems.

The primary motivations for this research were rooted in providing sustainable solutions to coastal cities issues of sea level rise due to climate change and land scarcity resulting from rapid urbanization. The aim was to present an environmentally conscious alternative to the traditional land reclamation technique of dredging, and to validate the sustainability of the solution proposed by SEAform.

In conclusion, this thesis offers a comprehensive analysis of the environmental impacts of floating platforms and dredging, demonstrates the greater sustainability of the floating platform solution, and presents project guidelines to ensure an environmentally conscious urban development in marine ecosystems.

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